Kagoshima Rift and Volcanism

An Introduction to the Geology of Kagoshima

Edited by

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Eruption of Sakurajima volcano on October 26, 2012 viewed from Shiroyama Park, Kagoshima City

The Kagoshima University Museum, Kagoshima University

Preface

The Kagoshima Rift is located in southern Kyushu, Japan. The rift includes Kagoshima Bay, Sakurajima, Kirishima and other active volcanoes, all of which constitute a pleasant, dynamic and captivating landscape. Flora and fauna in and around the Kagoshima Rift are diverse and representative of this subtropical to temperate oceanic climatic region. This publication provides a concise introduction of the tectonic and volcanic history of the region along with some additional topics of interest about the Kagoshima Rift. The efforts of all the contributors from Kagoshima University are greatly appreciated.

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1. Geologic development of the Kagoshima Rift

The Kagoshima Rift is an active intra-arc rift located in the southern part of Kyushu Island, Japan. The rift constitutes the northeastern-most part of the rift system developed behind the volcanic front of the Ryukyu Arc (Figure 1). The rift valley is 20–30 km wide and extends over 100 km or more in the north-south direction (Figure 2). The southern part extends through Kagoshima Bay beneath the sea to the northern island of Kikai. The rift valley is flanked by low-rise highlands with steeply dipping parallel walls. The rift accommodates four or five major calderas and many other volcanoes.

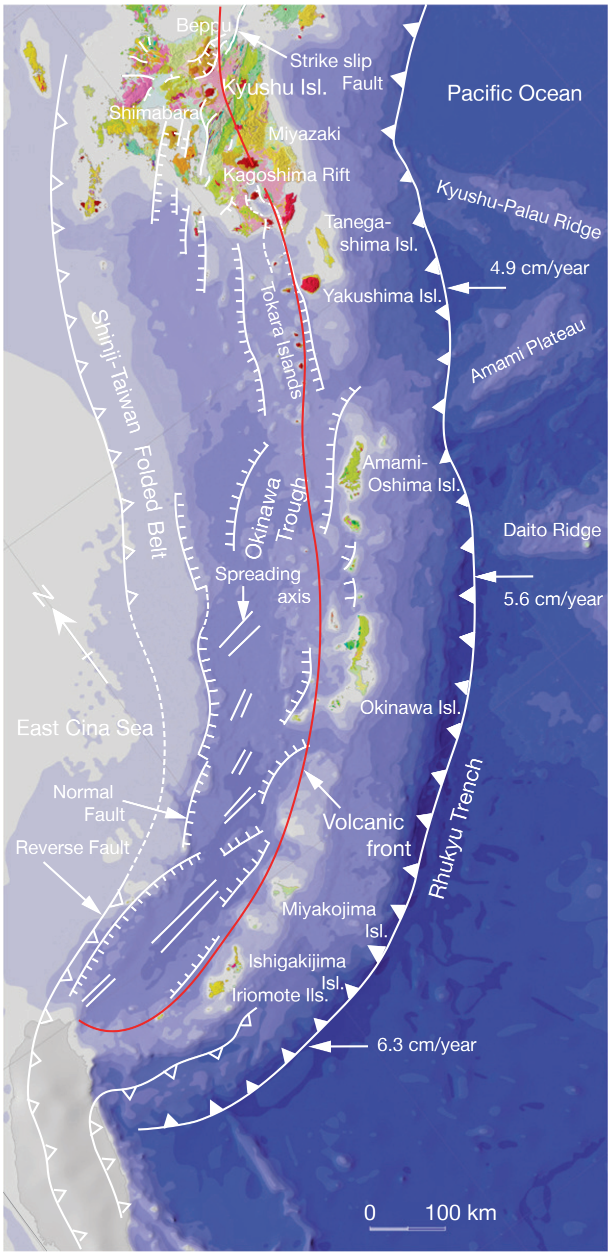


Figure 1. Tectonic map of the Ryukyu Arc. Kagoshima is located in the northern part of the arc behind the volcanic front. Modified after Letouzey and Kimura (1985). Geologic shaded map is adopted from Hanaoka *et al*. (1996).

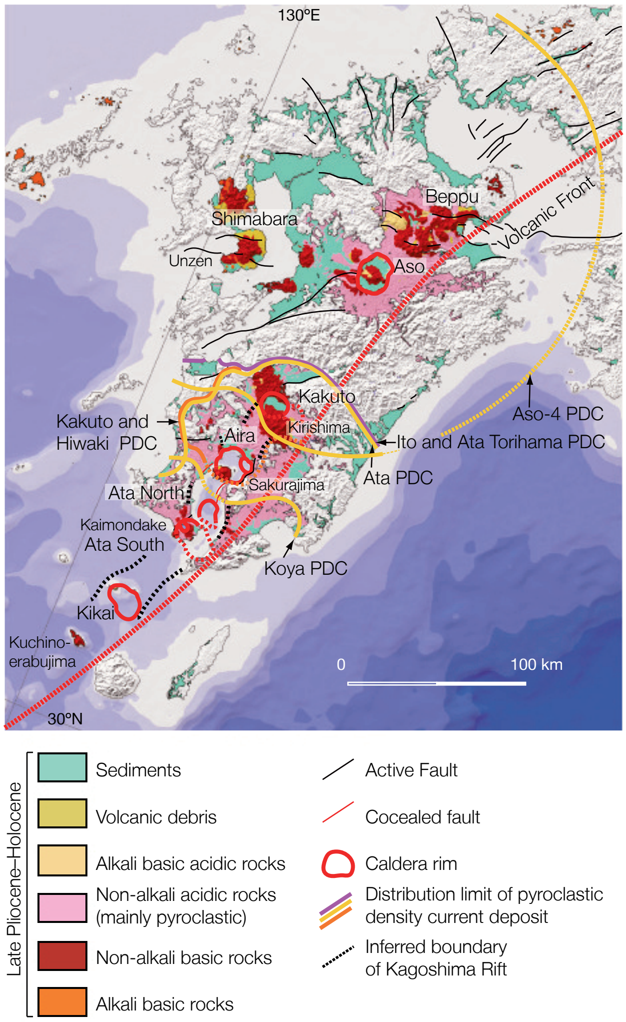


Figure 2. This geologic map shows the distribution of Late Pliocene to Holocene rocks, the Kagoshima Rift and other geologic features in Kyushu. The shaded relief geologic map is adopted from Hanaoka *et al*. (1996). Distributions of major pyroclastic density currents are adopted from Machida and Arai (2003). Active faults were obtained from the Geological Survey of Japan website: http://riodb02.ibase.aist.go.jp/activefault/.

The origin of the Ryukyu Arc volcanic front can be traced back to 6 Ma. The edge of the subducted Philippine Sea Plate sank to depths exceeding ~110 km (Figure 3). At these great depths, the mantle and/or crust were partially melted (Tatsumi, 1986). The melt produced a magmatic plume that began its rise to the surface. The resulting volcanic front migrated eastward toward the Pacific Ocean, and reached its present position 1 or 2 Ma (Figure 4). Fore-arc stress changed from compression to extension about 4 Ma and has remained unchanged since then. These stress changes are revealed by the fault sets developed in the deposits of the Miyazaki basin on the fore-arc side of Kagoshima Rift (Yamaji, 2003). These events collectively suggest that back-arc rifting started ~4 Ma in association with slab rollback (Yamaji, 2003). The back-arc rifting was initially slow but rapidly propagated ~2 Ma from the southwest to the northeast of the Okinawa Trough (Letouzey and Kimura, 1985) in association with uplifting of the fore-arc side of Ryukyu Arc (Ujiie, 1994). Rifting eventually reached Kyushu and formed the currently active Shimabara-Beppu and Kagoshima intra-arc rifts.

The beginning of the Kagoshima Rift is poorly constrained but presumably initiated no later than 800 ka as inferred from the deposition of shallow marine to coastal plain sediments of 800–500 ka. Marine to blakish deposits of the Kokubu Group (Kagawa and Otsuka, 2000) accumulated in the inner bay coastal areas. The thickness of this deposit suggests that a 50 m sea level rise occurred during the Pleistocene time (Miller *et al*., 2011) but the thickness of this deposit exceeds sea level rise, implying significant crustal subsidence. The Kekura Formation (correlative to the Kokubu Group) is thicker than 800 m on the western flank of Sakurajima volcano (Hayasaka, 1987).

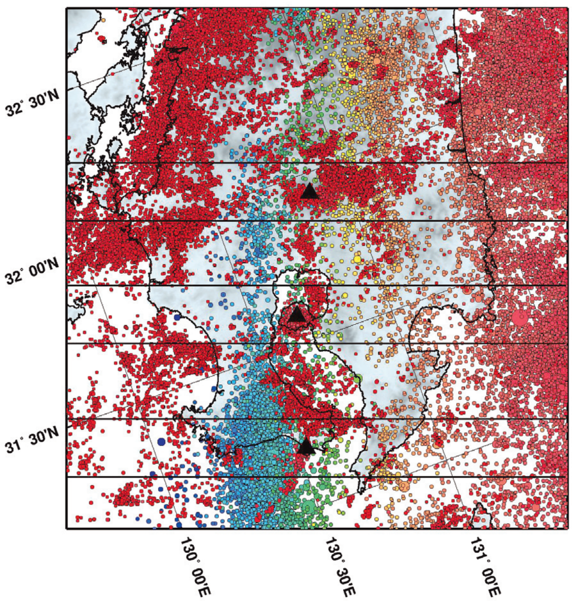
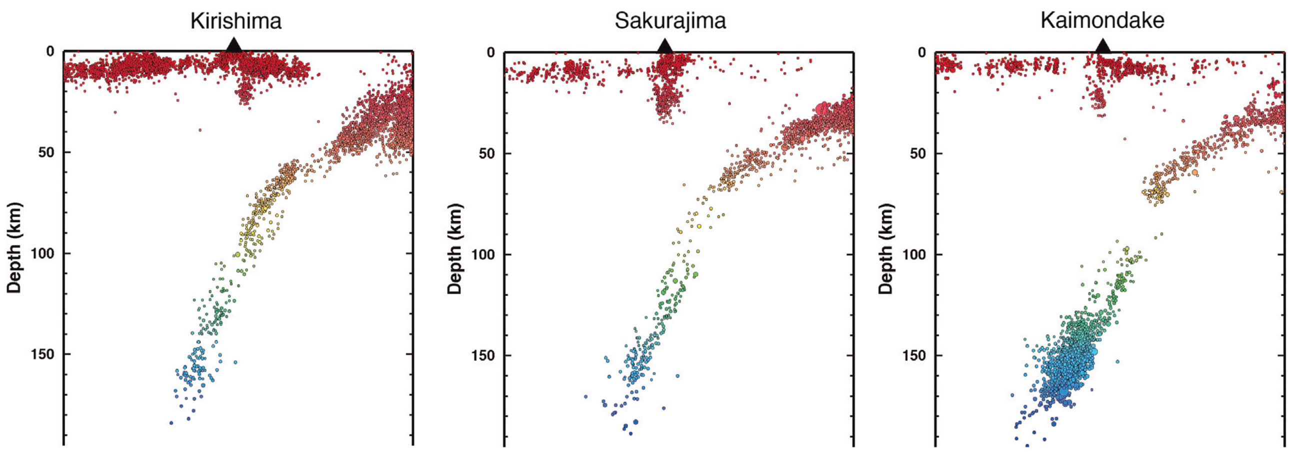


Figure 3. Distribution of epicenters in southern Kyushu (left) and distribution of hypocenters projected on the vertical sections (below) crossing Kirishima, Sakurajima and Kaimondake volcanoes, for the earthquakes larger than magnitude 0 that occurred during 10 years from 2002 to 2012. Compiled by K. Goto (Nansei-Toko Observatory for Earthquakes and Volcanoes, Kagoshima University) by using the earthquake database managed by his observatory.



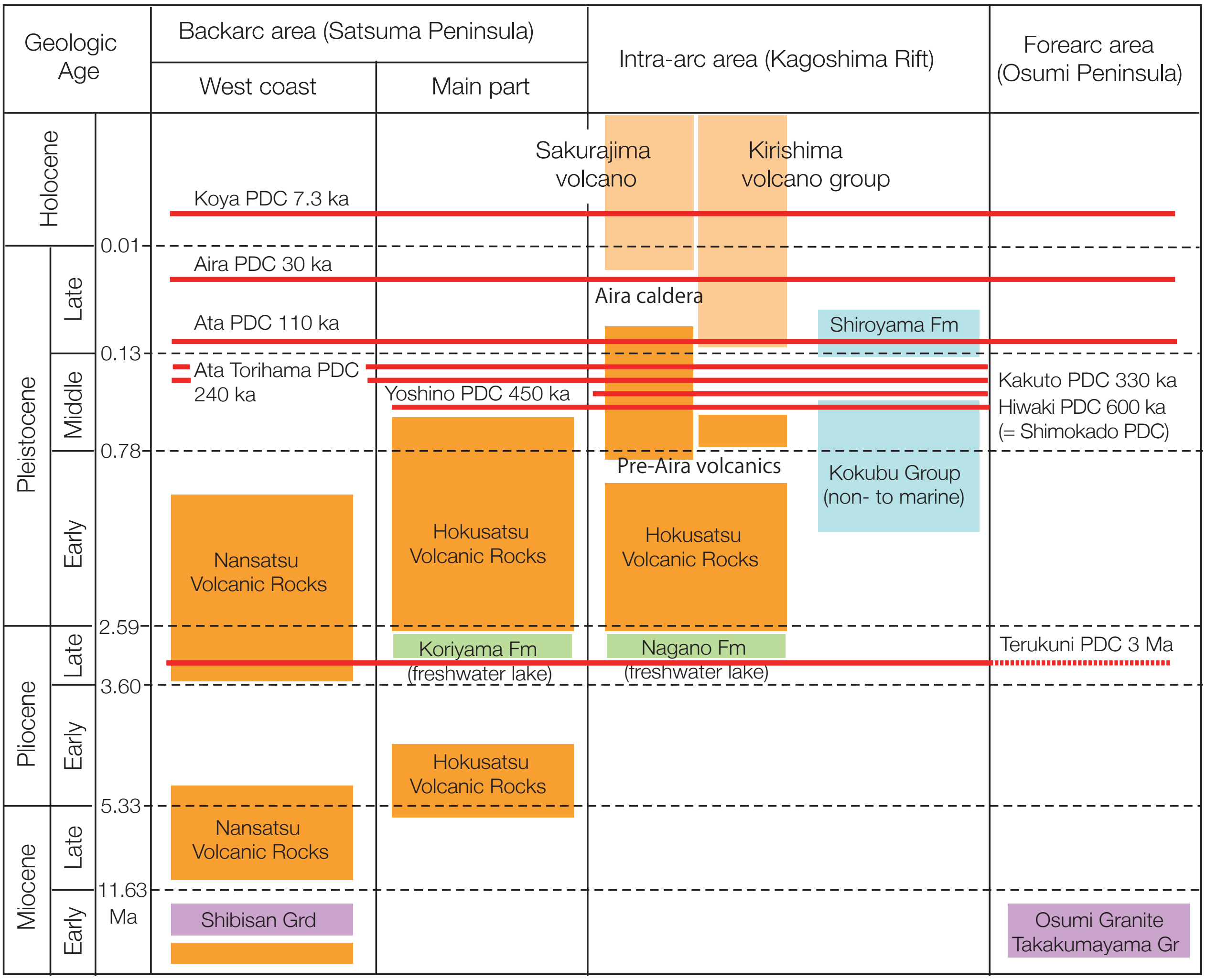


Figure 4. Miocene to Holocene stratigraphy in southernmost Kyushu Island. Modified from Uto *et al*. (1996)

Seismic profiles across the deep inner area of Kagoshima Bay reveal that the sediments and associated volcanic products of that time are confined mainly between the eastern and western bay-shores. Sediment thickness in the rift interior ranges from 0.8 to 1.6 km. Recent sediments are underlain by the Late Cretaceous accretionary sedimentary complex of the Shimanto Group (Figure 5). Gravity modeling of the subsurface structures across Sakurajima volcano also suggests the basement of the rift is 2.5 km below sea level (Figure 6). The subsidence rate during the past 800,000 to 500,000 is thus estimated to be 1–3 mm/year in the inner bay area. Boundary faults of the rift have been poorly identified on the ground surface, perhaps due to the surface sedimentary processes. Sediment accumulation rate during the last 100 years has averaged ~ 1 cm/year in the inner bay and exceeds the subsidence rate. Acoustic profiles across Kagoshima Bay reveal that acoustic layers are displaced by many minor normal faults (Chujo and Murakami, 1976; Hayasaka, 1987) and provide evidence for active rifting (Figure 7).

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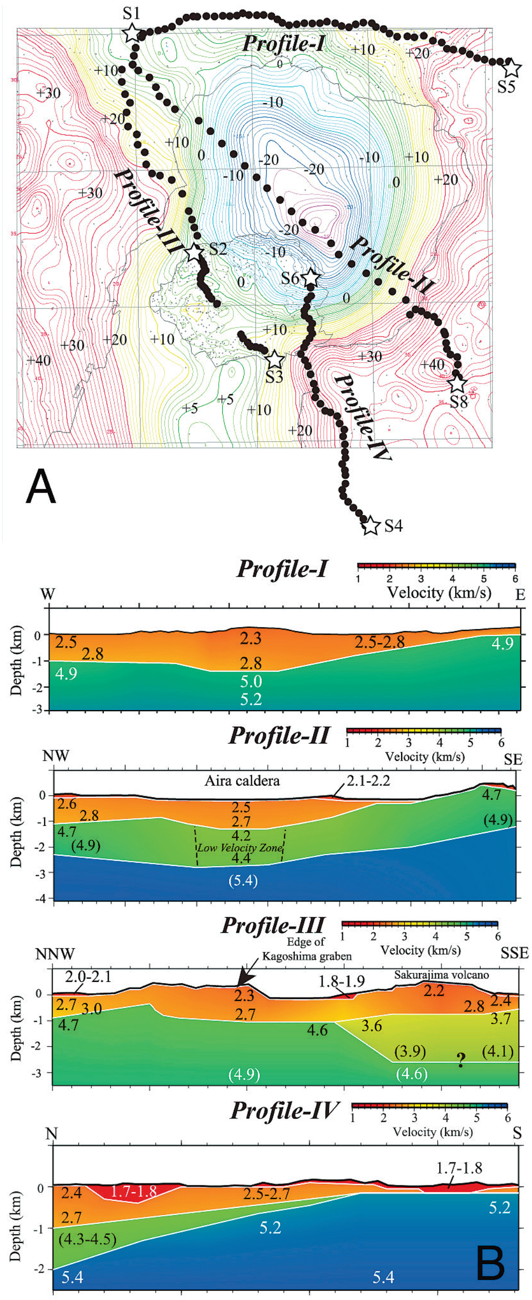

Figure 5. Geophysical data are presented along four profiles across the Kagoshima Rift near Sakurajima volcano. A) Shot locations (open stars) and temporary earthquake seismograph stations (solid circles) on a structure inferred from gravity anomalies along the NW-SE profile. Modified from Yokoyama and Ohkawa(1986). Bouguer anomaly map. B) P-wave velocity models. Modified from Miyamachi *et al.* (2013).

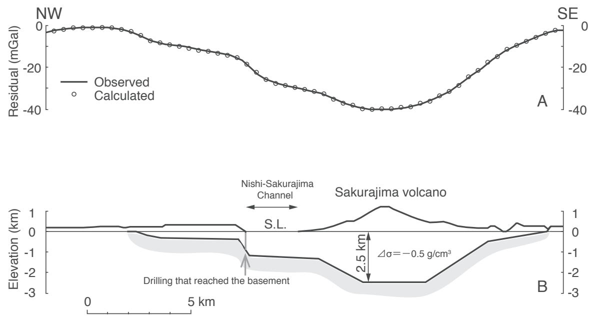

Figure 6. A) Residual Bouguer anomaly observed along a profile across Sakurajima volcano. B) Subsurface

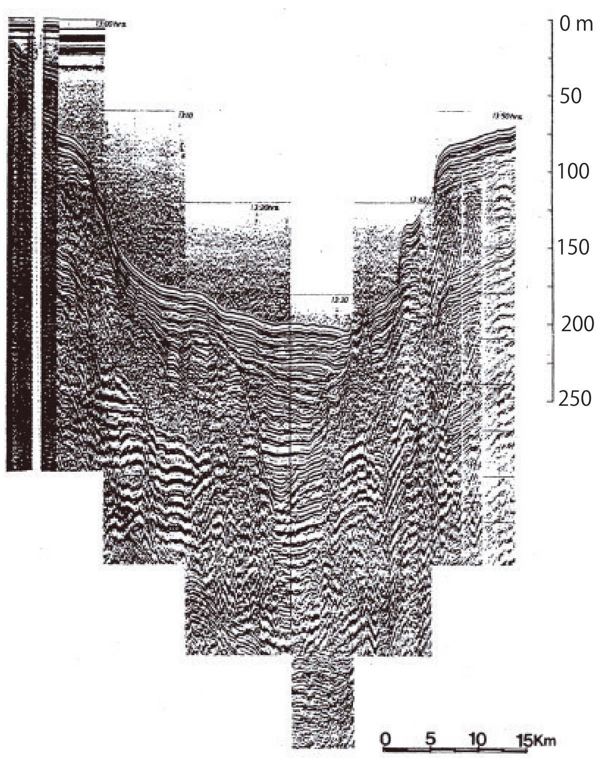

Figure 7. A reflection seismic profile across the southern side of Sakurajima volcano (modified after Hayasaka, 1987) reveals packages of sediments deposited through time. Normal faults are confirmed in areas where acoustic layers are displaced or sharply bent.

2. Rifting and caldera-forming eruptions

The fore-arc side of southern Kyushu is currently being displaced to the southeast or south-southeast against the Philippine Sea Plate. GPS derived horizontal displacement rates measured along the fore-arc area of southern Kyushu (Figure 8) during a one-year period extending from May 1996 to May 1997, for example, vary from 1–5 cm/year (Nishimura *et al*., 1999). This rate corresponds approximately to the subduction rate of the Philippine Sea Plate (Figures 1 and 2). Crustal faults produced by rapid crustal extension accommodate the rise of large amounts of magma generated through rapid plate subduction beneath the area. In the past 800,000 years, Kakuto, Aira, northern Ata, southern Ata and Kikai calderas formed from north to south along the Kagoshima Rift (Figure 2).

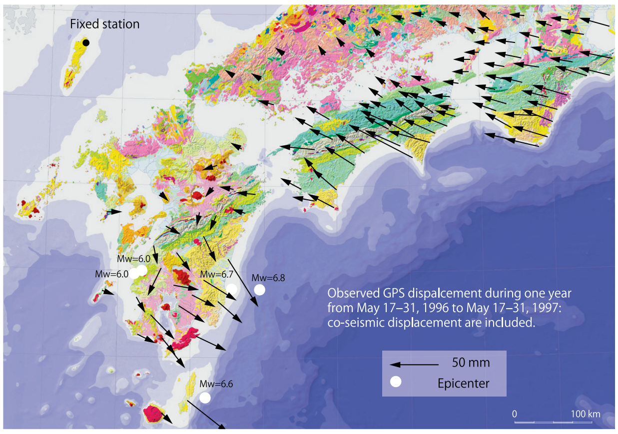

Figure 8. GPS displacements during one year extending from the week of from May 17-31, 1996 to May 17-31, 1997. Modified from Nishimura *et al*. (1999). Geologic shaded relief map is adopted from Hanaoka *et al.* (1996).

Kakuto caldera, 5 km by 15 km in dimension, is located in the northernmost Kagoshima Rift. This caldera was produced 330 ka by the explosive eruption of 100 km^3 of material including the Kakuto pyroclastic density current (PDC). The origin of the Hiwaki PDC (= Shimokado PDC) that erupted 600 ka is somewhat uncertain and may have resulted from eruptions of Kakuto caldera or Aira caldera to the southwest. An area characterized by a low gravity anomaly located on the east side of Kakuto caldera is associated with the Kobayashi caldera. Eruption of this caldera formed the Kasamori fallout tephra 520 ka.

Soon after Kakuto caldera formed, additional eruptions along the southern rim of the caldera produced deposits referred to as the Kirishima volcano group (Figure 4). Since then, Shinmoedake and other volcanic centers erupted intermittently and grew over the southern part of Kakuto and Kobayashi calderas.

Aira caldera is located on the southern side of the Kirishima volcano group and has a diameter of 20 km (Aramaki, 1984). This caldera is the largest in the Kagoshima Rift and formed about 30 ka with an explosive eruption volume of 450 km^3(Machida and Arai, 2003). Eruption of the Ito PDC represents the climactic stage of eruption from this large caldera. The Ito PDC spread over southern Kyushu and the overriding co-ignimbrite ash known as Aira Tn tephra. Ash deposits from this eruption have been located as far north as Hokkaido.

After this catastrophic event, the present-day Sakurajima volcano (located within the Aira caldera) began erupting about 22 ka under water near the southern caldera rim. Wakamiko caldera was later produced about 15 ka in the northeastern floor of Aira caldera by submarine explosive eruption. The eruption volume from Wakamiko caldera was relatively small (12 km^3) and the eruption plume likely collapsed under the sea by ingestion of ambient seawater.

Northern Ata caldera (Figure 2) is 16 km by 12 km in dimension and is located 200 m below sea level. This caldera is presumed to have formed 110 ka by an explosive eruption of over 320 km^3 of volcanic material that included the Ata PDC (Aramaki and Ui, 1966; Machida and Arai, 2003). The caldera structure, however, remains poorly defined by acoustic profiles, being disturbed by lava domes and intrusions (Hayasaka, 1987; Nagaoka *et al*., 1990).

Southern Ata caldera is 24 km by 14 km in dimension and is presumed to have formed 240 ka by explosive eruption of the Ata-Torihama PDC and associated fallout deposits. The total volume of the caldera-forming eruption exceeds 100 km^3. Nevertheless, the caldera structure remains poorly defined in topography, and acoustic profiles are too complicated to resolve the caldera structure (Chujo and Murakami, 1976). Subsequent eruptions occurred along the northwestern area of the presumed caldera. These included formation of the Ibusuki volcano about 30 ka, Yamakawa, Narukawa and Unagiike maars and Ikedako caldera, which opened about 5.5 ka, and Kaimondake volcano (Figure 2), which has been active in the last 4 ka.

Located 50 km to the south of the southern Ata caldera, Kikai caldera is 25 km by 15 km in dimension and almost completely submerged under the sea (Ono *et al.*, 1982). The islands, Satsuma-Iwojima and Showa-Iwojima (or Shin-Iwojima) are post- caldera lava domes that grew over the caldera rim. Small submarine volcanic edifices also occur on the caldera floor 400–500 m below sea level. Kikai caldera presumably formed about 95 ka by explosive eruption of 100 km^3 of volcanic material. This was one of the Earth's most explosive eruptions. Volcanic deposits from this eruption include the Koya Pumice Fall, Koya PDC (famous for its low aspect ratio) and Akahoya Ash Fall (K-Ah) about 7.3 ka. The volume of the latest large-scale eruption reached an estimated 170 km^3(Machida and Arai, 2003).

PDCs have repeatedly erupted from the major calderas spread throughout southern Kyushu. Co-ignimbrite ashes have been transported by westerly winds to northeast Japan and form useful stratigraphic markers throughout much of Japan. In the Kagoshima Rift, large-scale explosive eruptions of VEI (volcanic explosivity index) 6–7 have recurred at regular intervals of ~50,000 years during the past 300,000 years (Figures 4 and 9) and presumably caused serious damage to flora and fauna in ecosystems throughout Japan. Clear evidence of significant environmental impacts is lacking with the possible exception of one case from southern Kyushu. In this case, pottery excavated from settlements above the 7.3 ka K-Ah boundary differs from that found in earlier settlements. We cannot deny that such large-scale explosive eruptions will continue in the future and will have catastrophic impact on the southern Kyushu region.

Intermittent magma accumulation in the underlying reservoirs of volcanic centers in the region is best exemplified by the Aira caldera (Figure 2) that formed about 30 ka. Its initial formation was followed by eruptions of Sakurajima volcano, Wakamiko caldera, and domes of unconfirmed age. Leveling along the coastal areas of Aira caldera reveals uplift of the area during the past 200 years. Subsidence temporarily occurs in response to moderate scale eruptions of Sakurajima volcano; however, long-term uplift persists. Overall, there is a net uplift of between 7 to 15 m above sea level of Holocene coastal plain sediments across the region (Figure 10). The coastal plain sediments were deposited between 7–4 ka at the culmination of Holocene marine transgression. Subsequent uplift of the geomorphic and depositional surface is centered in the western part of the caldera. The findings for the long-term crustal movements associated with the Quaternary volcanic activities of the Aira caldera volcanic field provide us with fundamental data to evaluate future eruptions.

[K. Kano and H. Moriwaki]

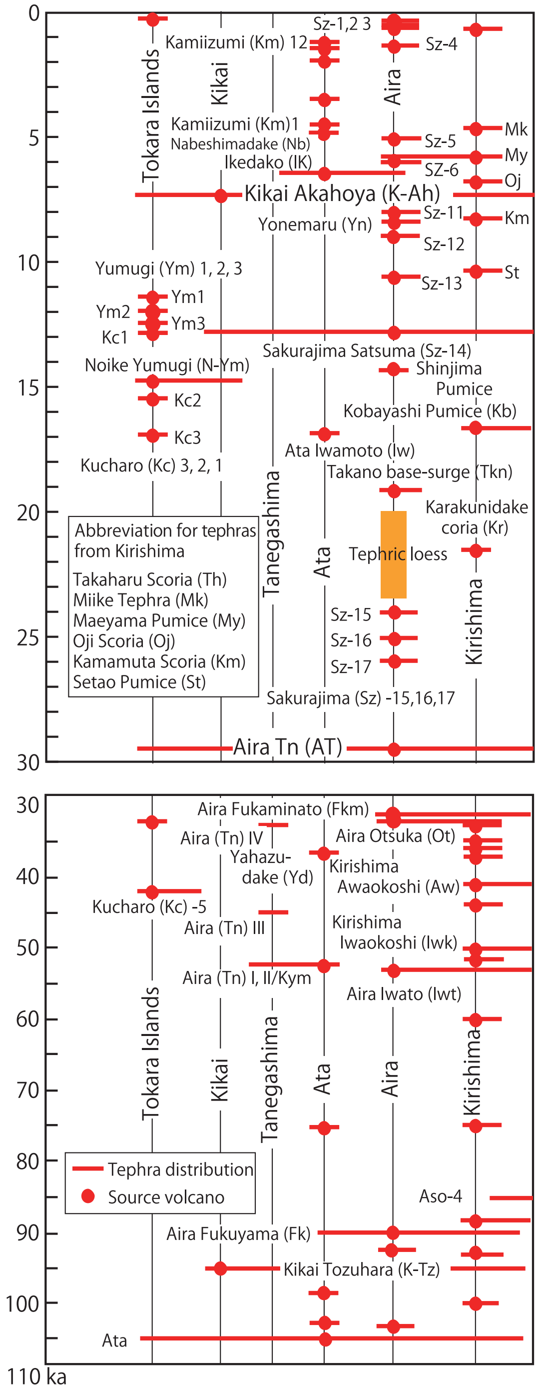

Figure 9. Distribution of tephras erupted in the past ~110,000 years from southern Kyushu Kagoshima Rift region. Modified from Moriwaki (2010).

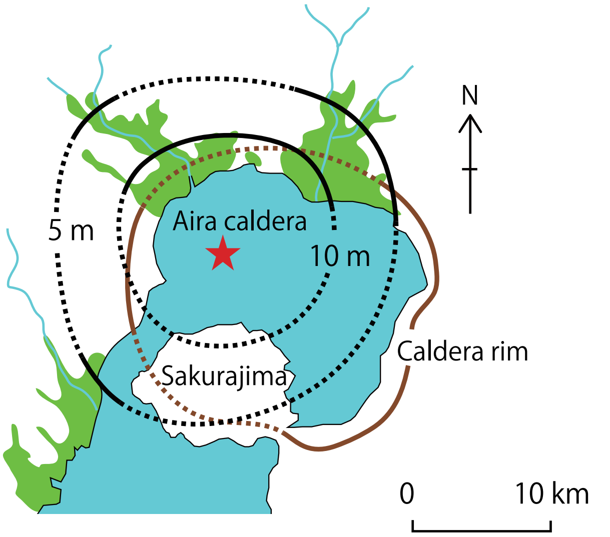

Figure 10. Uplift of the 7 ka isobase in the Aira caldera and its environs has a domal shape with relief in excess of 10 m. The center of the dome is most likely located at the point marked by red star. The presence of a large magma chamber beneath the area is inferred from gravity anomalies. Modified from Moriwaki (2010).

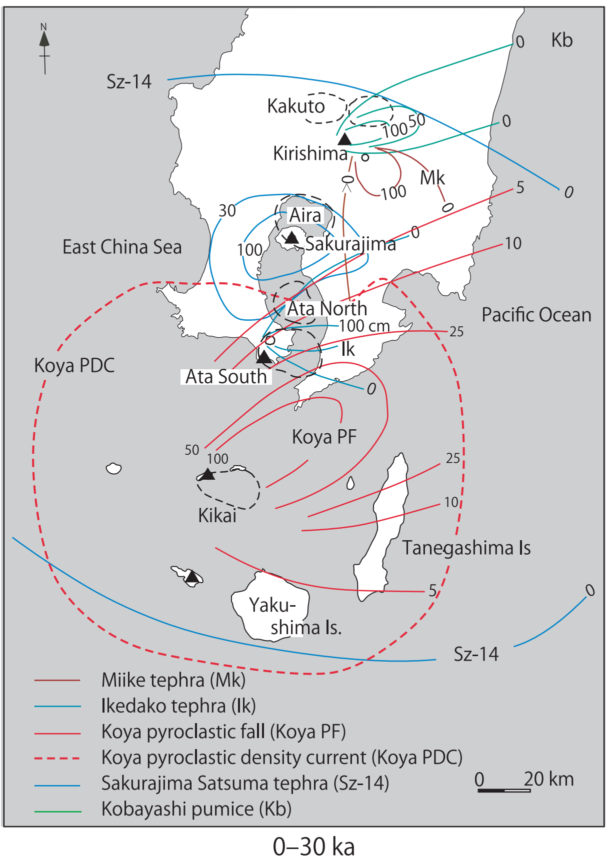

Figure 11. Isopach map of major tephras deposited during the last 30 kys. Thickness is given in centimeters. Modified from Moriwaki (2010).

3. Explosive eruptions and tephra dispersals

Numerous and extensive Quaternary tephras were deposited across the area (Figure 9). Sources included the Kakuto, Aira, Ata, and Kikai volcanic fields, Kagoshima Rift and even some from eruptions in the Tokara Islands southwest of the rift. Eruptions include plinian, sub-plinian and caldera-forming types. Of the eruptions identified so far, those that occurred in the last ~100,000 years are much better documented.

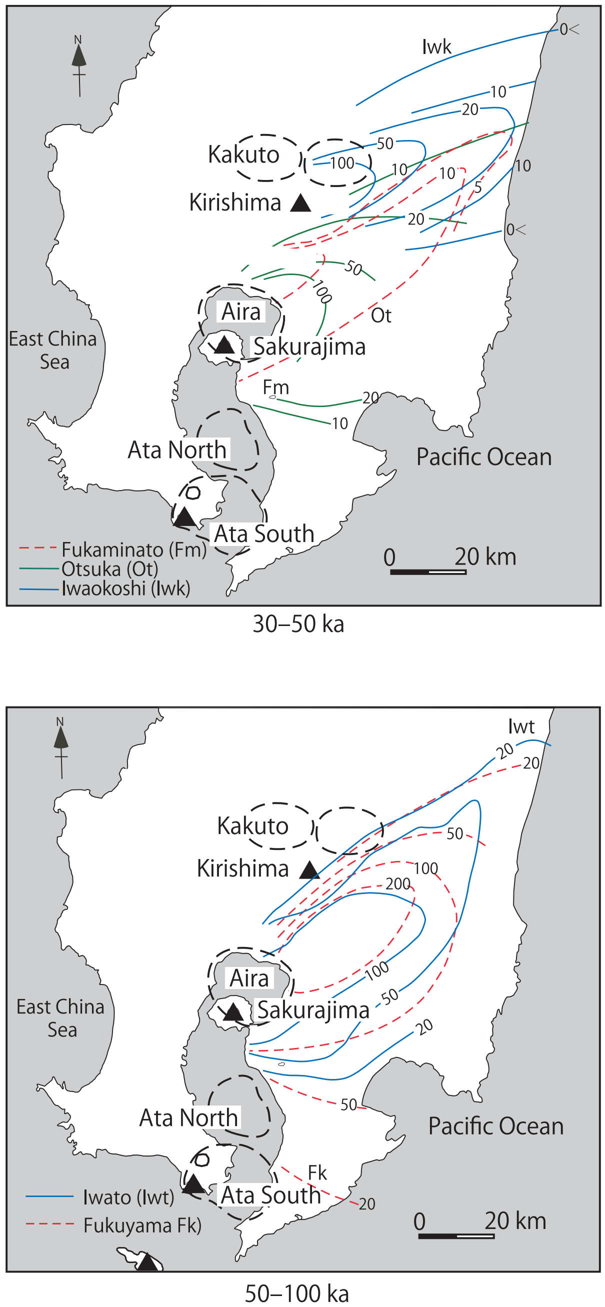

Figure 12. Isopach map of major tephras deposited from 30 to 110 ka. Thickness is given in centimeters. Modified from Moriwaki (2010).

Volcanic activity in the last 100,000 years has been quite intense with more than 100 explosive eruptions. These include ~30 eruptions from Kirishima volcano group (Kakuto volcanic field), ~25 eruptions from Aira volcanic field, ~25 eruptions from Ata volcanic field, ~5 eruptions from Kikai volcanic field, and ~10 eruptions from Tokara Islands (Figure 9). On average, eruptions occur approximately once every 1000 years. Tephra air-falls accumulated mainly to the east of individual sources being carried by prevailing westerly winds (Figures 11 and 12).

[H. Moriwaki]

4. Explosive eruptions from Sakurajima volcano

Sakurajima volcano is currently the most explosive volcano in the rift and the most recent three large explosive eruptions are known to have impacted surrounding populated areas. The first of these explosive eruptions occurred about 26 ka on the southern rim of Aira caldera. This eruption occurred only 3,000 years after the catastrophic eruption of Aira caldera. Since then, Sakurajima volcano has repeatedly erupted producing 17 tephra deposits (Sz-1~17 in Figure 9). 12 of 17 tephras have been identified in the Osumi Peninsula on the east side of Sakurajima volcano. They are intercalated with 5 tephras sourced from other volcanoes; two (Tkn and Yn) from other vents of Aira caldera, three (K-Ah. Ik and Mi) from Kikai caldera, Ikeda caldera, and Miike crater of the Kirishima volcano group (Figure 9). An important outlier marker tephra, K-Ah derived from the 7.3 ka eruption of Kikai caldera occurs in the succession of Sakurajima tephras exposed at Takatoge pass (Figure 12).

The thick tephric loess deposited between Sz-14 and Sz-15 represents a long period of dormancy (Figure 13). Explosive eruptions resumed about 13 ka to produce the Sakurajima Satsuma (Sz-14) tephra with estimated volume of 20 km^3. It was the largest among all of the tephras from Sakurajima volcano and likely caused severe damage all over southern Kyushu. The Sz-13 tephra, which overlies the ruins of the Uenohara settlement, was the second largest (1.3 km^3). Ash fall more than 30 centimeters thick buried many farms and houses making life difficult for many years (Kobayashi and Tameike, 2002). In the past 26,000 years, ash falls from plinian scale eruptions of Sakurajima volcano repeatedly buried local dwellings. The ash served as the source of many lahars especially in areas of thicker ash accumulation.

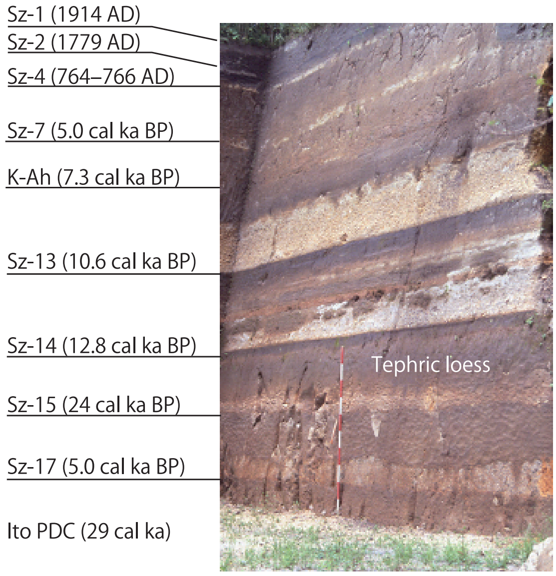

Figure 13. Tephra and soil layers exposed at Takatoge Pass, 15 km east of Sakurajima volcano. Modified from Moriwaki (2010).

Figure 14. Isopach map of the fallout tephra produced by the 1914 eruption of Sakurajima volcano. Modified from the original map prepared by Kanai in 1920. Unit thickness is *syaku* (classic length unit in Japan), which equals to 30 cm.

Tephras from Sakurajima volcano are also distributed mainly to the east or northeast, carried by the prevailing westerly winds (Figure 12). The influence of the westerly wind pattern in this region is highlighted by the pattern of thickness variations in the fallout tephra from the 1914 eruption (Figure 14). At present, Sakurajima eruptions are dominantly vulcanian. Ash falls precipitate many lahars on Sakurajima Island during periods of heavy rain. In order to reduce the volcanic hazard, it would be necessary not only to intensify hard countermeasures but also to conduct careful hazard mapping mitigation efforts along with significant disaster prevention education outreach programs.

[H. Moriwaki and T. Kobayashi]

5. Hydrothermal activity and epithermal gold-silver ore deposits

Hydrothermal activity has been prevalent in the Okinawa Rift System since 4 Ma, especially in the Okinawa Trough and associated minor rifts. Hydrothermal activity has been concentrated along the back-arc side of southern Kyushu. Hydrothermal systems are closely associated with volcanic activity in the region. Epithermal gold-silver deposits are found in the area. These deposits formed initially along the west coast of southern Kyushu. Their distribution spread into areas very close to the present volcanic front, following its easterly migration during the past 2 Ma (Figure 15).

The back-arc area of southern Kyushu, thus includes highly productive gold mines of Kasuga, Iwato, Akeshi, and Kushikino, which formed 4–3 Ma and of Fuke, Ohkuchi, Hishikari, Ohnoyama, Iriki and Hanakago, which formed 2–1 Ma (Watanabe, 2005). Among these, the Hishikari mine is the best mine, estimated to carry 250 tons of gold. The ores occur in quartz veins of Late Cretaceous sedimentary rocks and the volcanic succession emplaced 1–2 Ma. The ores contain 25~70 g/t on average and are remarkably superior to the world average of 2 or 3 g/t. Hot water with temperatures of 60–65°C often gush out of these ore veins, providing direct evidence for their hydrothermal origins.

Currently active hydrothermal activity is located along the Kagoshima Rift. Hot water spring emissions are observed even under water in some areas and are occasionally accompanied by CO_2 emissions and minor amounts of H_2S, CH_4 and other gases (Ossaka *et al*., 1992). The submarine Wakamiko caldera is a well-known location to observe these processes in action (Figures 15 and 16).

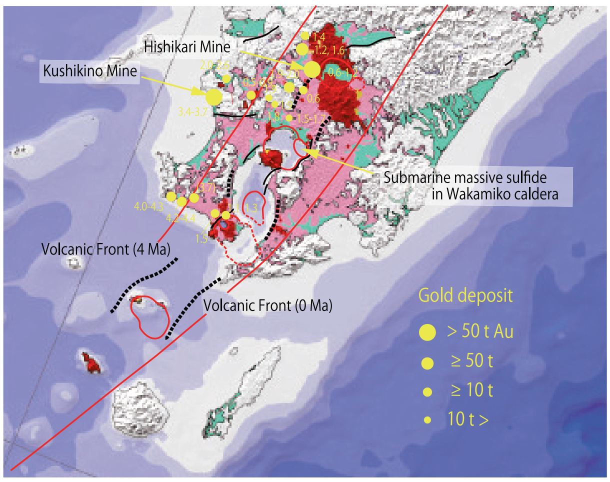

Figure 15. Distribution of gold-silver deposits in southern Kyushu. Modified from Watanabe (2005). Geologic shaded relief map is adopted from Hanaoka *et al*. (1996).

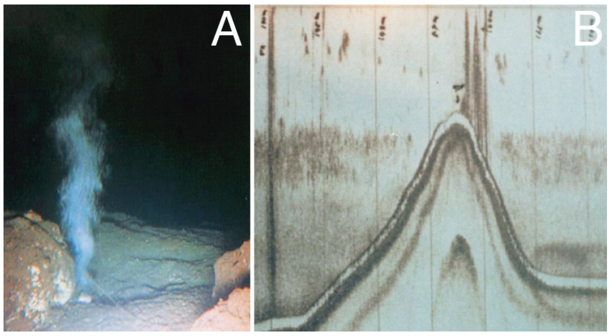

Figure 16. A) Submarine emission of hydrothermal water and gas from the floor of Wakamiko caldera (courtesy of H. Sakamoto, Kagoshima University); B) an acoustic profile across the submarine Wakamiko knoll in the Wakamiko caldera, showing volcanic gas plume from the eastern shoulder of the dome. The acoustic profile was recorded by the research vessel *Keiten Maru* of Kagoshima University in 1980.

Hydrothermal water is discharged from the caldera floor, 200 m below sea level, and a submarine lava dome. Hydrothermal activity forms chimneys (Figure 17A), stibnite crust (Sb_2S_3) (Figure 17B) and other minor sulfides of arsenic, gold, silver and copper together with talc or other secondary silicates (Ishibashi *et al*., 2008). *Tagiri* (which means boiling in Japanese) is well known on the sea surface. It consists of gas bubbles, mainly of CO_2, that rise up intermittently from submarine hydrothermal vents. Massive sulfide deposits in the area are estimated to contain approximately 900,000 tons of antimony.

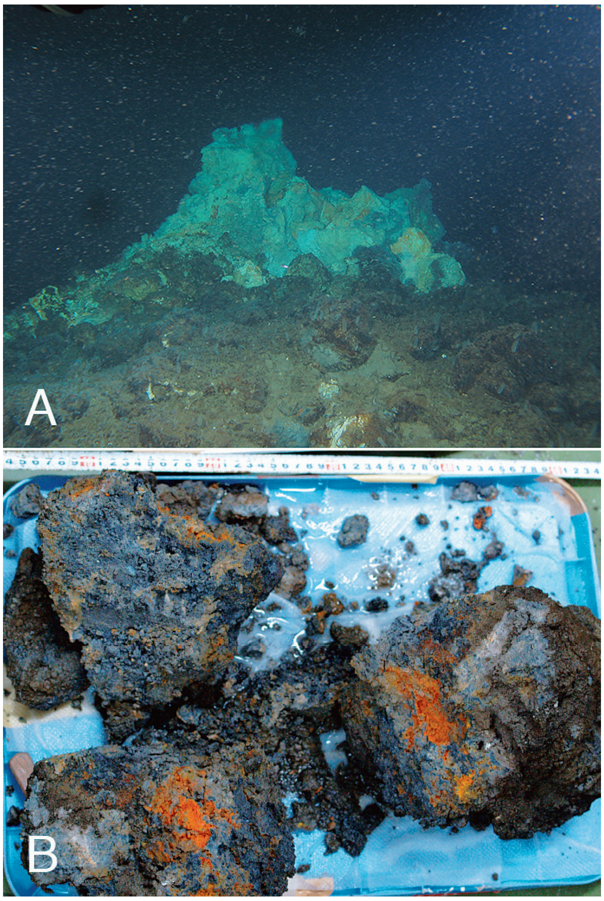

Figure 17. A) View of a chimney on the Wakamiko caldera floor and B) stibnite-bearing sulfide ore recovered from the floor. Courtesy of *JAMSTEC* and T. Yamanaka (Okayama University).

Wakamiko caldera is also a place of hydrocarbon generation (Figure 18). The mud and mudstone, and even mineral precipitates dredged from the caldera floor contain 5–50 mg/g bitumen from dried samples. The characteristic hydrocarbon parameters of the mud and mudstone samples suggest that the bitumen formed primarily through heating of land derived organic matter in the ambient hydrothermal system (Yamanaka *et al*., 2000). Methane released from fumaroles is also likely to be hydrothermal in origin.

[K. Kano]

Figure 18. Oil seepage from a mud sample dredged from a hydrothermal vent area in Wakamiko caldera. Courtesy of T. Yamanaka (Okayama University).

6. Submarine seismic observation using ocean bottom seismometer in Kagoshima Bay

Nansei-toko Observatory for Earthquakes and Volcanoes (NOEV), Kagoshima University, has conducted seafloor seismic observations using ocean bottom seismometers (OBSs, Figure 19). Analysis of earthquakes recorded by this sensitive recording array has been used since 1990 to improve our understanding of the active tectonic processes around Kyushu and the northern part of Ryukyu Islands.

Figure 19. Deployment of an ocean bottom seismometer (OBS) in Kagoshima Bay.

The OBSs are high sensitivity ground motion sensors capable of detecting the frequent low magnitude earthquakes that occur in the vicinity of Sakurajima volcano. Data collected from the OBSs provide detailed information about hypocenter location and earthquake focal mechanisms. OBS observations have been undertaken in collaboration with SVRC (Sakurajima Volcano Research Center, Kyoto Univ.) since 2007 (Figure 20).

Figure 21 shows example waveforms produced by a volcanic tremor that occurred beneath Sakurajima volcano in November 2011. The tremor was detected at OBS-2 but not by the nearby land-based seismometer at FUK located on the opposite shore. The seismic recordings (Figure 20) indicate that the volcanic tremor reverberated within the water column throughout the inner bay.

In 2007 we deployed an OBS at station N1 of Wakamiko caldera (OBS-N1 in Figure 20). Soon after deployment, we saw gas bubbles rising from the release point and noticed that the OBS station was very close to a highly active fumarole. Signals recorded on this seismograph were not detected by any of the other stations in the network including the nearest station, OBS-N2, 430 m east of OBS-N1 (Figure 18). At this point, it was apparent that ground motions in the vicinity of this station resulted from fumarole activity. Fumarole emissions created considerable noise so that the seismometer location was not useful for detection of low magnitude earthquakes produced by the movements of magma beneath Sakurajima volcano.

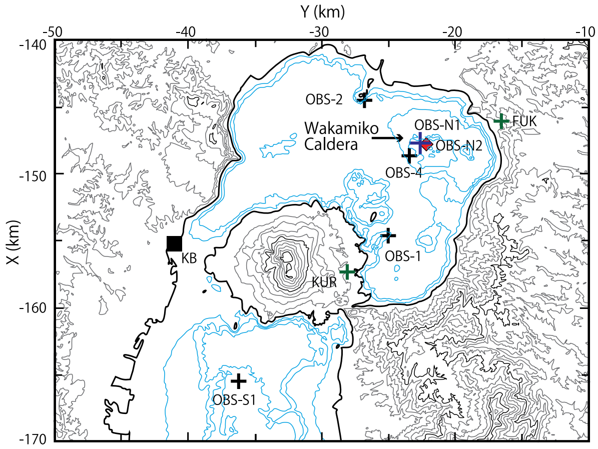

Figure 20. Submarine seismic stations OBS-1, 2, N1, N2, 4 and S1 (operated by NEOV) and on-land seismic stations KUR and FUK (operated by SVRC) and KG (operated by the Japan Meteorological Agency). OBS-N1was the only OBS deployed close to one of the seafloor fumaroles.

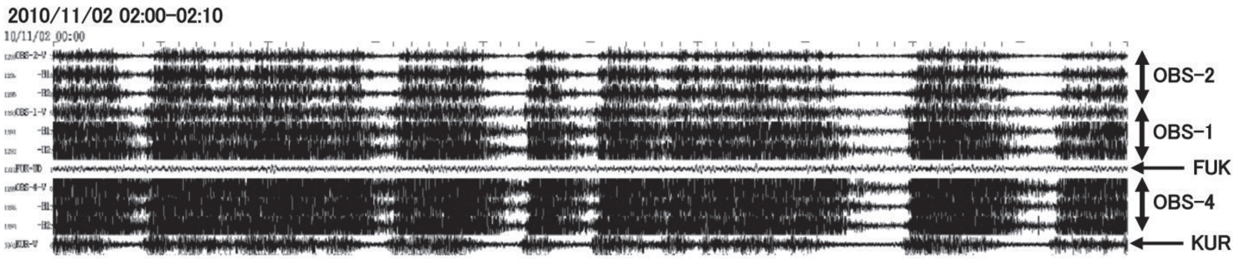

Figure 21. Ten minute long record of ground motion produced by a volcanic tremor sourced from Sakurajima volcano. The display consists of three-component observations from OBS 1, 2 and 4 and the vertical components measured by land-based seismometers FUK and KUR. Note the improved detection capabilities provided by the OBSs.

Nonetheless, some very interesting variations of seismic activity related to fumarole emissions were observed on this station. Since the data were quite noisy, it was decided to compute the root-mean-squares amplitudes (herein referred to as RMSAs) for one-minute time windows. Variations of RMSAs through time (Figure 22) revealed previously unknown behavior associated with daily fumarole activity.

The RMSA observation period (Figure 22) extended for three days from September 25 to 27, 2007. RMSAs of the vertical components of ground velocity at stations N1 and S1 shared no similarity (Figure 21). Fumarole activity (N1 RMSAs) was also compared to sea level changes observed by the Japan Meteorological Agency's Kagoshima Tidal Gauge at station KG during the period of observation. At station N1 the maxima and minima of the RMSAs (LA and HA in Figure 22) are preceded by low tide and high tide (LW and HW in Figure 21) by about one hour. Correlation between the RMSAs and the water-level peaks was not observed at station S1.

The comparison (Figure 22) reveals that variations of tidal gravity correlate positively with variations in fumarole activity: maxima and minima in the tidal gravities are synchronized with variations in the RMSA.

To our knowledge, the relationship between tidal and fumarole activity has never before been reported or observed.

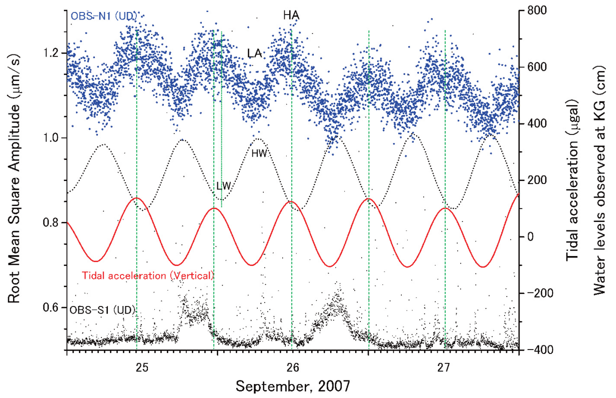

Figure 22. RMSAs observed over a 3-day period at station OBS-N1 (blue dots) and station S1 (small black dots across the bottom of the plot). Tidal water level changes observed at station KG are shown by the black dotted curve (second from top). The red curve depicts theoretically calculated changes in tidal gravity. Labels LW and HW indicate low and high water times, respectively.

The positive correlation between RMSAs and tidal gravities (accelerations) remained consistent over a one-month long observation period. The correlation suggests that the upward tidal forces enhance the activity of the submarine fumaroles. Time lags between the RMSAs and tidal accelerations are quite small. The response of fumarole activity to tidal acceleration is almost immediate. We speculate that fluids circulating in the underlying hydrothermal system are pressurized and discharged from fumaroles by increasing tidal forces.

[H. Yakihara]

7. Seasonal circulation and chemical variation of seawater in Kagoshima Bay

Kagoshima Bay has a depth that exceeds 200 meters and a narrow bay mouth. Circulation of seawater is slow, especially in the inner bay since the straight leading to the sea is quite narrow and shallow. Seawater enters from the Pacific Ocean through a 10 km wide inlet and circulates anti-clockwise through the bay before returning to the Pacific. Some of the seawater enters the inner bay area and returns to the straight which forms a connection to the outer bay. The surface water is warm in summer and cool in winter, and the resulting density contrast between shallow and deep water makes vertical water circulation pervasive during the winter but limited during the remaining three seasons (Figure 23).

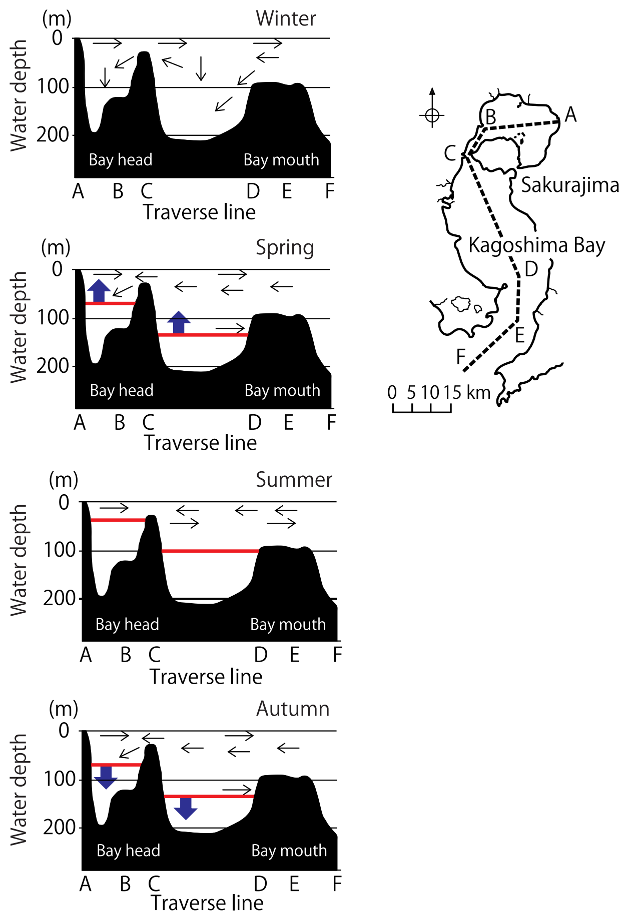

Figure 23. Longitudinal profile of seasonal water circulation in Kagoshima Bay. Modified from Chaen (1983).

The prolonged period of stagnation extending from spring to autumn produces oxygen depletion in the deep water of the wider bay interior. Volcanic gas emissions are dissolved and hydrothermal water is mixed with the ambient deep water. Gas emissions are mainly composed of CO_2 (70–90 vol.%: Ossaka *et al*., 1992). This leads to acidification and enriched concentrations of mercury, antimony, arsenic and other concomitants especially in Wakamiko caldera. Although concentrations are extremely small, some circulation of these toxic elements does occur in association with hydrothermal activity and gas movements. Mercury up-take by plankton and other creatures could be especially problematic since this element will accumulate in fish.

Mercury in excess of the allowable amount, 0.4 mg/kg by law was actually detected in 1970's from 10 fish species caught in Kagoshima Bay. Since then, local fishermen have established self-imposed controls on selling problematic fish species. Public concern has also been raised about the source of mercury in the bay ecosystem. Since there were no factories using large amounts of mercury around Kagoshima Bay, organomercurial pesticide was initially suspected as a potential source. The pesticide was used until the early 1970s for the prevention of rice diseases. Rivers and streams draining rice-farming areas are believed to have carried the pesticide into the bay.

In 1977 a geothermal gas seep was found on the water bottom of Wakamiko caldera. Subsequent analysis of sediments retrieved from the area revealed the presence of 200 mg/kg of mercury in sediments near the fumaroles. These findings suggested that the submarine fumaroles are the major source of mercury contamination in Kagoshima Bay (Figure 24).

Subsequent surveys (Sakamoto *et al.*, 1995; Ando *et al.*, 2010) have disclosed that 1) bottom sediments of Kagoshima Bay contain mercury (II) sulfide (0.2–200 ppm as Hg), mercury (II) oxide (<0.04–11 ppm), organic mercury (0.04–0.9 ppm) and residual mercury (0.07–39 ppm); 2) mercury sulfide is abnormally concentrated in the sediments proximal to the submarine fumaroles of the Wakamiko caldera floor where fumarole mercury and hydrogen sulfide gas could be condensed to precipitate on the sediments; and 3) that filtered seawater and suspended matter collected from the fumaroles contain total mercury of 7.6 to 65.0 ng/L on average, which is much lower than that measured in the surface seawater collected in the bay mouth (1.0 to 0.5 ng/L on average). Together, these studies suggest that Mercury in the seawater and bottom sediments is most likely sourced mainly from submarine volcanic gas.

The distribution of mercury in the inner part of Kagoshima Bay was analyzed in detail to elucidate the behavior of the mercury released from the submarine fumaroles during continued geothermal activity (Figure 25). In February and June of 2012, seawater samples were collected every 50 m from the surface to 10 m above the bay floor with Niskin sampling bottle. For total mercury measurement, the water samples were filtered with 0.45-μm-membrane filter, and the total mercury was measured by cold vapor atomic absorption spectrophotometry after BrCl oxidation under UV radiation.

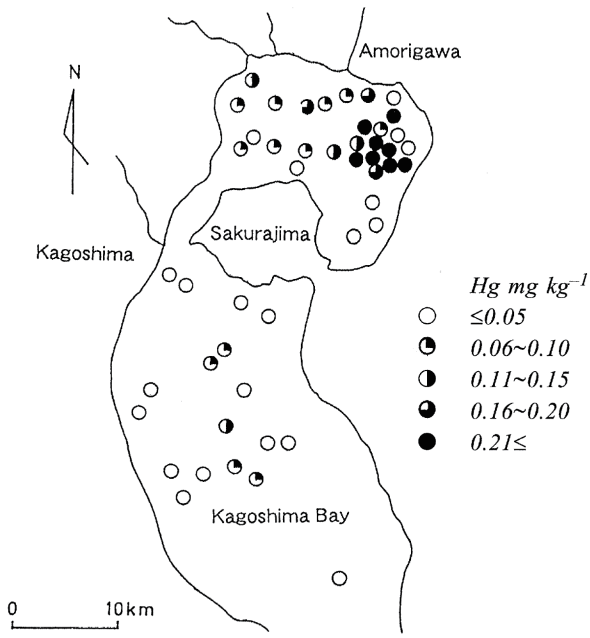

Figure 24. Distribution of total mercury in the bottom sediments of Kagoshima Bay. Modified from Sakamoto (1985).

Total mercury concentration in the water samples collected at the gas seeping site was 0.49±0.43 ng L^{-1} and the values showed no association with depth in February. In June, the thermocline extends from the surface to a depth of about 75 m. During June, the pH decreased sharply from depths of about 110 to 130 m. This drop in pH may be caused by the fumarolic activity. Significantly higher concentrations of total mercury were observed at depths of 150 and 190 m (Figure 25). Near surface concentrations of mercury are much lower above the pH transition zone. In all samples, concentrations were lower than 0.5 ngL^{-1}. During the warmer summer months, deepwater chemistry is significantly impacted by geothermal activity, which is interpreted to produce the decrease in pH value and increase in Hg concentration. These observations suggested that fumaroles are the main sources of mercury in the study area. The formation of a seasonal thermocline may have significant influence on the dispersion of the mercury released through the geothermal activity.

[T. Tomiyasu]

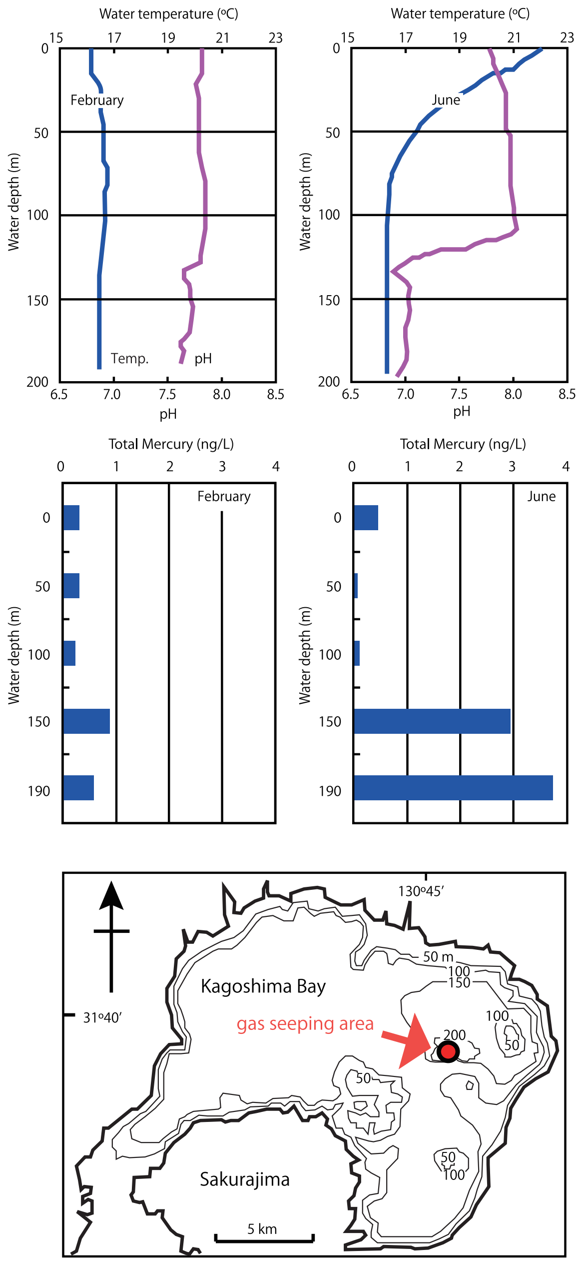

Figure 25. Vertical profiles of water temperature, pH and total mercury content in water collected in February and June at a site of the fumarolic area in Wakamiko caldera. Modified from Tomiyasu (2012).

8. Endemic creatures in the semi-closed water of inner Kagoshima Bay

The Wakamiko caldera accommodates some unusual creatures endemic to the semi-isolated deepwater environment. Especially noteworthy is the tubeworm *Lamellibrachia satsuma* that swarms 80–110 m below sea level in the areas proximal to the fumaroles of a lava dome located on the eastern caldera floor (Figures 26 and 27). This creature has a tube that is 8 mm or less in diameter with a length between 0.5–1 m. Their presence in the area is unusual since *Lamellibrachia* are generally found in much deeper waters. The tubeworm carries endosymbiotic bacteria in an internal organ called the trophosome. The tubeworm does not have an alimentary canal. It obtains nutrients directly from organic matter produced by the symbiotic sulfur bacteria in the trophosome. These bacteria live by oxidizing hydrogen sulfide in the ambient water. Sulfur utilized by symbiotic sulfur bacteria in the tubeworm is, however, not directly derived from fumaroles but produced from bacterial sulfate reduction using hydrothermal methane as an electron donor. Methane (5–20 vol.%) is released in much greater amounts than hydrogen sulfide (0.1–1.4 vol.%) (Ossaka *et al*., 1992). Tubeworms commonly live beneath the photic zone and inhabit areas surrounding submarine vents of thermal water and/or gas in much deeper water; the *Lamellibrachia satsuma* of Kagoshima bay live at the shallowest water depths in the world.

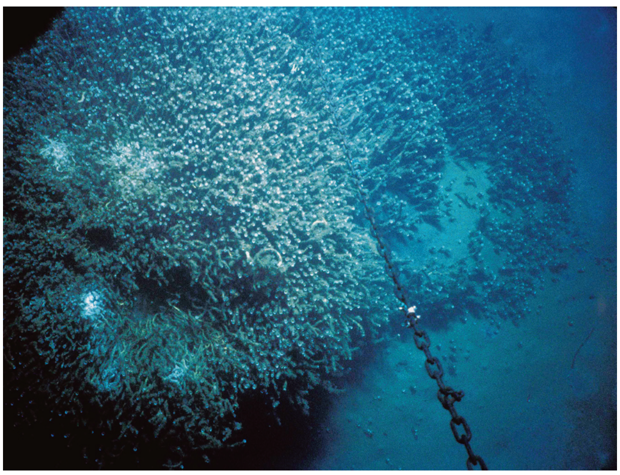

Figure 26. A swarm of *Lamellibrachia satsuma* on the mountainside of the submarine lava dome, Wakamiko Knoll. Courtesy of *JAMSTEC*.

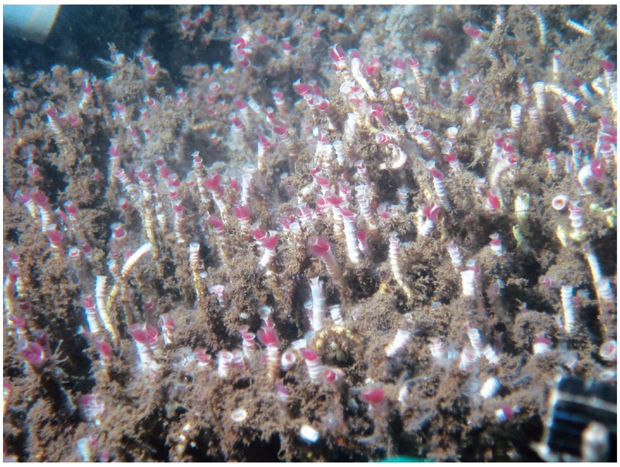

Figure 27. Close-up of *Lamellibrachia satsuma* on the mountainside of the submarine lava dome, Wakamiko Knoll. Courtesy of *JAMSTEC*.

Figure 28. *Periclimenes thermohydrophilus* resting on a tube worm in a water tank. Courtesy of *Kagoshima Aquarium*.

Periclimenes thermohydrophilus is a small shrimp, which inhabits areas near fumaroles along with the swarms of *Lamellibrachia satsuma* (Figure 28). Its ecology remains poorly disclosed. A shell named *Solemiya tagiri* inhabits the area called *Tagiri* where hydrothermal water and volcanic gas are discharged from fumaroles. It survives using the energy produced by symbiotic sulfur-oxidizing bacteria living in the epithelial cells of its gill.

The sea squirt known as *Ciona savignyi* normally inhabits shallow sea environments but also inhabits the deep floor of Wakamiko caldera (Figure 29). This creature has the ability to uptake organic particulates and planktons by filtrating water at a rate of 2–3 liters an hour and can survive even in deep water where food is limited. Their number increases in the spring when they feed on increasingly abundant planktons. Their life span is only 3 months so that their numbers drop off into the autumn and winter as water bottom oxygen levels decline.

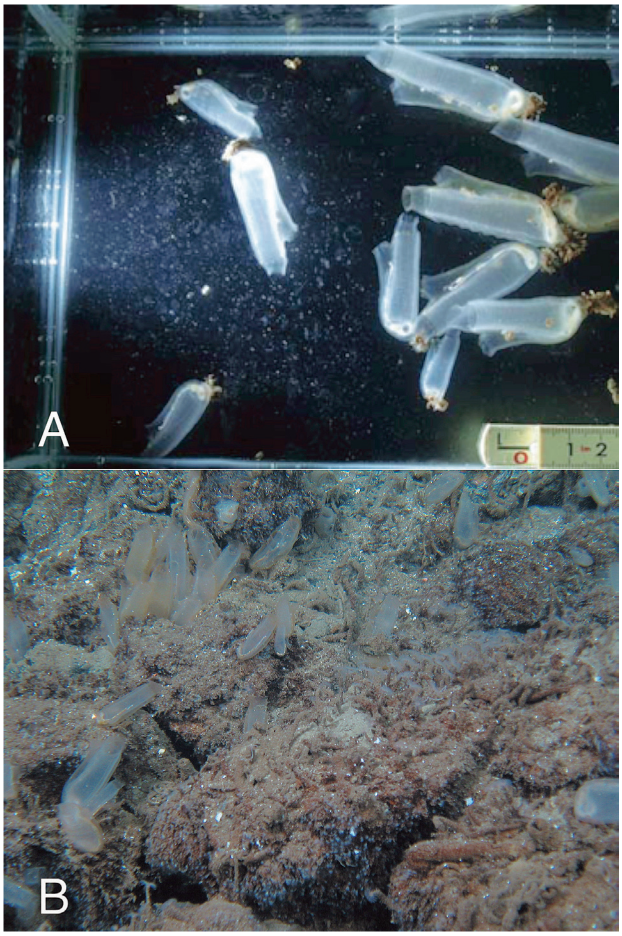

Figure 29. A) *Ciona savignyi* kept in a water tank. Courtesy of T. Yamamoto (Kagoshima University). B) A swarm on Wakamiko caldera floor. Courtesy of *JAMSTEC.*

Benthic foraminifera in Kagoshima Bay appear diverse, and constitute five communities A, B, C, D and E (Figure 30; Oki, 2000). Community A is distributed in areas under the influence of open-sea water. Community B is distributed in areas of water with slightly lower salinity, low transparency and high nutrient concentration and suggests inflow of sewage discharged from surrounding populated areas, mainly Kagoshima City. Community C is distributed in the boundary areas between water masses of different salinities and water temperatures. Community D is distributed on the basin floor. Community E is distributed on the basin floor of the bay head area characterized by acidic water. All the specimens of Community E are represented by the species having the agglutinated test, or in other words, in this area, the species provided with the calcareous test are entirely absent (Oki and Hayasaka, 1978; Oki, 1989). The absence of calcareous foraminifera is assumed to be closely related to the acidic water in this area of the bay caused by the fumarolic activities in Wakamiko Caldera.

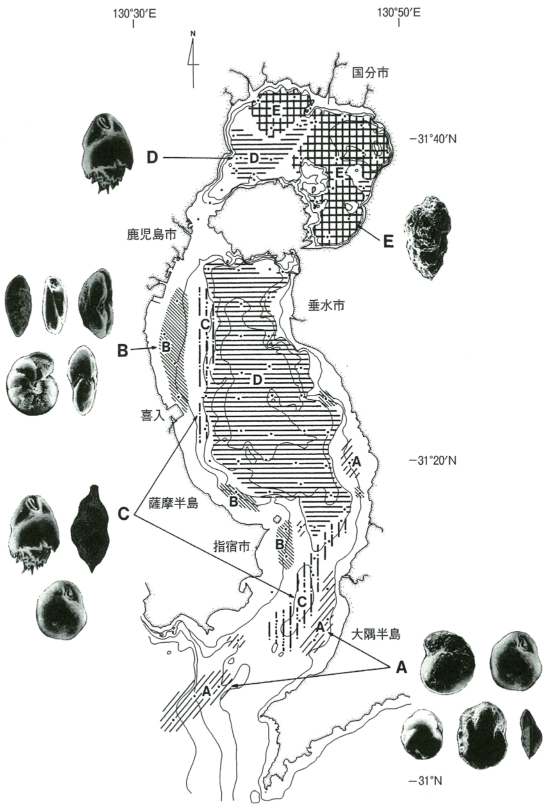

Figure 30. Distribution of benthic foraminiferal communities in Kagoshima Bay. See Oki (1989) for constituent species of the communities.

It is evident that submarine fumarolic activity in Wakamiko caldera creates a unique ecosystem in which unusual fauna thrive. The unique creatures found in the submarine caldera floor are likely to accumulate mercury as well as other elements derived from the fumaroles. *Lamellibrachia satsuma*, for example, were found to contain mercury along with much smaller amounts of gold and silver. Mercury concentrations observed in the anterior muscles of the body and the posterior trophosome were 238 ng/g and 164 ng/g, respectively. These concentrations represent 2.2×10^5 and 1.5×10^5 times those of the filtered ambient seawater (Ando *et al*., 2002).

[K. Oki and K. Kano]

9. *Shirasu* and *Bora* disasters

Shirasu and *Bora* are local (southern Kyushu) names for an unconsolidated mixture of pumice and ash (pyroclastic flow deposit) and well-sorted accumulation of pumice (pumice fall deposit), respectively. *Shirasu* means white sand in Japanese and appropriately represents its appearance. *Bora* is a local dialect word, meaning idiot, or more appropriately, uselessness. This name was employed because it has no ability to retain water and contains little nutrients required for agriculture.

Figure 31. Collapsed cliff of a Shirasu plateau caused by the heavy rains of August, 1993. A residential area, Aira New Town, was extensively developed at that time. Photo by Kokusai Kouku.

Figure 32. A cavern produced in *Shirasu* by piping of water at Nakoshi, Kagoshima City, during the heavy rains of August, 1993. Photo by K. Oki.

Derived mainly from repeated caldera forming eruptions, thick accumulations of *Shirasu* and *Bora* were formed in and around the Kagoshima Rift during the past 800,000 years. Destructive lahars and slope failures have occurred repeatedly in the steeply incised plateaus made mainly of *Shirasu*, especially during heavy rain falls (Figure 31). *Shirasu* surface soil beds are likely to slide under their own weight, particularly when bed thickness exceeds tens of centimeters during 80–100 year intervals of time.

Bora sandwiched between *Shirasu* along with internal cracks in *Shirasu* intervals facilitates water flow and weathering to clay. Heavy rains easily transport finer particles, enlarge interstices and cracks and accelerate water flow through the enlarged ‘pipes’ (Figure 32). Slope failure of Bora and Shirasu beds is particularly common during periods of heavy rain. In addition, water-saturated *Shirasu* lanslides often liquify during movement and are transformed into *Uki Shirasu*, a sort of dense lahar.

[K. Uchimura and K. Kano]

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