Satellite Observation of Volcanic Phenomena in Kyushu, Japan

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Abstract

Remote sensing data from earth observation satellites concerning active volcanoes in Kyushu and Ryukyu Islands, Japan are reviewed. The themes are volcanic topography, land cover, volcanic clouds and thermal aspects. The data on volcanic clouds detected by the NOAA meteorological satellites are also mentioned.

Key words : Sattellite image, volcano, Aso, Unzen, Suwanosejima, Kyushu

§ 1. Introduction

Monitoring Volcanic activity is one of the important uses of the earth observation satellites such us LANDSAT, MOS, SPOT, JERS-1 and newly launched satellite ADEOS. The regular surveillance of volcanoes serves to find anomalous changes and eruptions, understand their behavior, and predict their activities to avoid or minimize volcanic hazards [1, 2]. For analysis of the remote sensing data of volcanoes, it is important to compare with ground truth data. For this purpose, the well-observed volcanoes such us Aso, Unzen and Sakurajima in Kyushu, Japan provide precious testing grounds.

In this paper, we try to present the archives of satellite data detecting volcanic activities in Kyushu, one of four main islands in Japan. We also consider Ryukyu Islands, where many small volcanic islands are less well monitored on the ground. We discuss the topography and land cover characteristic of volcanoes, and try to give a short review of preceding works on remote sensing of the volcanoes in Kyushu. The general background of setellite imagery of volcanoes and ash clouds are discussed in a review book [2].

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In §2, We explain the geography of Kyushu and Ryukyu islands in relation to satellite scenes, and give introductory remarks on the satellite imagery of volcanoes. We discuss the topography and land cover of volcanic zones and islands in §3. Then volcanic clouds are discussed in §4, where lists of daytime satellite data are given. Thermal data from LANDSAT-5 are briefly discussed in §5. Concluding remarks are given in the last section.

§2. Geography and satellite scenes

2－1. Distribution of volcanoes in south-west Japan

Among the ring of volcanoes in the circum-Pacific area, there are many active volcanoes in the west-Japanese volcanic belt, as shown in Fig. 1. Numbers of them are ejecting ash clouds actively, while some others are dormant or quite quiescent. Among them, listed in a recent year report of world active volcanoes are Aso, Unzen, Kirishima, Sakurajima and Suwanosejima [3]. The seismicity of Kuchinoerabujima is also mentioned.

At Aso Volcano, one of the authors (S.I.) has been performing continuous monitoring of the vent by robot video-cameras located at the crater wall, and occasional video recording of ash clouds from 3 km west of the crater [4]. This is in addition to the seismic monitoring and other techniques used by Aso Volcanic Observatory of Disaster Prevention Institute, Kyoto University and Aso Station of Kumamoto Local Meteorological Observatory [5].

Unzen Volcano has been a subject of intensive studies of many volcanologists all over Japan since its eruption on 17 Nov. 1990 [6]. Volcano Sakurajima is one of the most well-monitored volcanoes in the world with the exception of the inside of the crater [7], and analyses of the satellite data in conjunction with the ground observation have been previously discussed [8].

In contrast to the above volcanoes on the mainland Kyushu, small volcanic islands in the southern sea belonging to Ryukyu Islands are not well monitored from the ground excect for the continuous recording of seismicity [9] and special intensive observation during limited periods [10]. Therefore, a general survey of satellite data for these volcanoes may also be worthwhile.

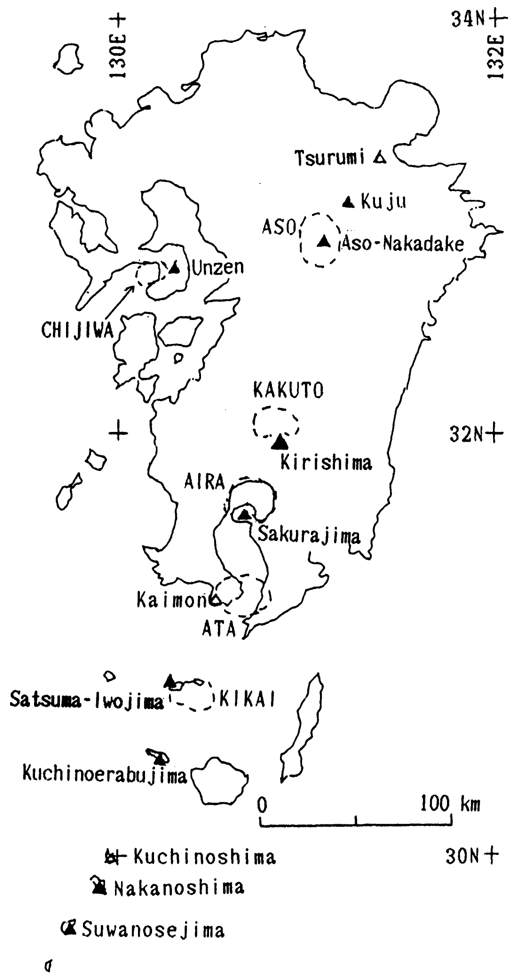

Fig. 1. The distribution of volcanoes in south-west Japan. Those with volcanic activities within these 100 years are indicated by solid triangles, while dormant ones by open triangles. Calderas are described by loops of broken lines.

2 − 2 . Satellite scenes of volcanoes

Nowadays there are many earth observation satellites (EOS) with high resolution sensors. With the spatial resolution of 10 - 80 m in visible and near-infrared bands, they are able to detect faint fumalolic plumes and ash falls on the ground. Furthermore, thermal activities can be monitored by means of the TM-6 sensor of LANDSAT-5 with a resolution of 120 m. This is in contrast to the 1.1 km at best of the AVHRR sensor on the NOAA weather satellite, which is able to detect volcanic clouds with large scale. The shortcomings of earth observation satellites are their limited perspectives and infrequent observation, subject to weather condition. However, the combined use of various satellites in a long term may enable us to accumulate considerable amounts of data for investigetion.

In Table 1, we list the path-row of EOS for each volcano, where a path number is specific to the sun-synchronized orbit of each satellite observing a volcano, and a row number is specific to the scene in one data set on computer compatible magnetic tapes. In the case of a volcano being located near the boundary of a scene with a specific path, it has a chance to be observed from the neighboring path, due to the overlapping of two scenes. The boundary of a row is flexible in the data processing. The EOS data are received and processed at Earth Observation Center (EOC), Hatoyama near Tokyo, of National Space Development Agency of Japan (NASDA). For easy handling, magnetic tapes are converted into magneto-optical disks, and further into floppy disks for sub-scenes.

Table 1. Path-rows of earth observation satellites vs. volcanoes.

Satellite	LANDSAT			MOS	SPOT		JERS	
No.	2～3	4	5	1～1B	1～3		1	
Duration	79～83	82～87	84～	87～96	86～		92.2～	
Period (day)	16	16	16	each 34	each 26		44	
Sensor	MSS	MSS	TM	MESSR	XS	Panchro	OPS	SAR
Resolution (m)	80	80	30	50	20	10	18*24	18
Scene width (km)	185	185	185	60	60	60	75	75
Aso	121-37	112-37 [A211-207]		25W(26E)-74	315-284		79-245	
Unzen	121-37	113-37 [A211-207]		26E-74	313-284		80-246	
Sakurajima	121-38	112-38 [A211-206]		25W(26E)-76	315(314)-287		79(78)-248	
Satsuma-Iwojima	121-39	112(113)-39 [A212-205]		25W(26E)-77	315-288		79-249	
Suwanosejima	121-39	112／113-39／40 [A212-205]		25W(26E)-78 ／79			79／80-251	

These are descending paths in daytime, except for ascending path-row [A**-***] of LANDSAT-5 in nighttime.
In addition to the above, there are a few LANDSAT-1 data in 1972 received in U.S.A.

In addition to the above volcanoes, the followings belong to the same LANDSAT scenes as the near-by ones indicated:

Kuju to Aso,

Kirishima and Kaimondake to Sakurajima,

Kuchinoerabujima and Nakanoshima to Satsuma-Iwojima.

As for other satellites, the scenes may be the same or neighboring ones as above listed.

2 − 3. Properties of satellite images

In this report, we limit ourselves to present monochromatic images which are composed of single band or a combination of two or three bands. A merit of monochromatic superposition of different bands is to indicate a signal image on a background indicating geographic situation. Another use of combination is the vegetation index − a combination of visible and near-infra-red bands. However, the properties of single bands are basically important. We summarize them concerning volcanic phenomena in Table 2, where NIR, SIR and TIR denote near, short-wave and thermal infra-red bands respectively, while Vis. stands for bands of light visible to the naked eye. We leave datailed specifications of satellite sensors to the literature.

Table 2. Properties of monochromatic images.

Type	Sensor	Band	Properties
Vis.	TM MSS MESSR XS OPS	1 - 3 4, 5 1, 2 1, 2 1, 2	Sensitive to faint plumes especially for shorter wave length, and so for ash cover. Bare lands without vegetation are bright, while forest and water areas are dark.
NIR	TM MSS MESSR XS OPS	4 6, 7 3, 4 3 3	Water areas are black , and bare lands are dark. Forest areas are bright, and the topography of mountainous regions can be seen owing to the shadow of the sunlight.
SIR	OPS TM	5~8 5, 7	Distinction of rock types by combinations. Very high temperature.
TIR	TM	6	Surface temperature even in daytime, but with upper limit around 70 degree.
Micro wave	SAR	1	Roughness and direction of the surface by an active rader.

For color images, we are constructing a compilation of volcanic phenomena in Kyushu on the home page of Satellite Image Network Group in Kagoshima (SING-Kagoshima) :

http://www-rk.kagoshima-u.ac.jp/sing/index_e.htm.

Recent images of volcanic activities received by EOC may also be found on their home page,

http:/www.eoc.nasda.go.jp.

For convenience, we list the basic properties of typical patterns of simple color images in Table 3. For satellite sensors, we list the cases of LANDSAT/TM and MOS/MESSR only, as the other cases are essentially similar to them with corresponding bands. An exception is true color, where the blue band is unique to TM-1. False color images of type B are also limited to TM and JERS-1/OPS, since SIR sensors are specific to them. All types of images produced by assigning three bands to different colors are generally called "false color" in the literature.

Table 3.　Properties of color images.

Image type	Sensor	Band			Properties
		Blue	Green	Red	
True color	TM	1	2	3	Similar to naked eyes image and color photo. Forests depressed.
Natural color	TM MESSR	1 (2) 1	4 4 (3)	2 (3) 2	Vegetation areas are green. Bare lands tend to be pinky／reddish. Land-water separation is clear.
False color A	TM MESSR	2 1	3 2	4 3 (4)	Vegetation areas are brown or reddish.
False color B	TM	3	5	7	Vegetation areas are light green. Rivers tend to be blue.
Pseudo-color	Any single band				Differentiation of spectral emissivity by level slicing.

Instead of asigning a single band to one color, one may assign a numerical combination of different bands to a color for specific purposes. There are other methods of classification expressed by different color, such as the multi-level-slice and mininum-distance methods, not listed in Table 3.

In the original data around Kyushu provided by NASDA, the north direction is slightly shifted to the amounts 9.0, 10.4, 10.5 and 8.3 degrees for LANDSAT-5 in daytime, MOS, SPOT and JERS-1 images, respectivery. In this paper, we show the images with the original orientation with the indication of the north direction, or the altered ones to make the north direction exactly upward by cutting printer outputs or by the rotation of digital data sets using the cubic convolution.

§ 3. Volcanic topography and land cover

In this section, we review the characteristic features of topography and land cover of typical volcanic zones in the mainland Kyushu, and volcanic islands in the southern sea. There is an extensive compiration of aerial photographs of volcanoes in Japan [11]. The satellite data may add new points of view with wide perspectives and observation bands beyond the domain of visible lights. Understanding the capability of satellite imagery with limited space resolution compared with the aerial photographs is also a problem.

3－1. Aso Volcano

Aso Volcano in central Kyushu is characterized by a large caldera, 18 km from east to west and 25 km from north to south, and is shown on a map (Fig. 2) and MOS／MESSR images

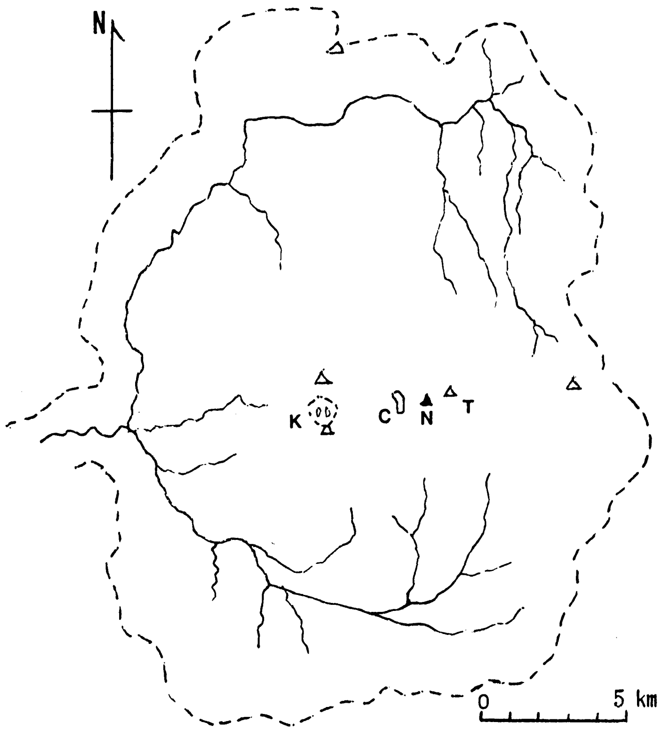

Fig.2. A map of Aso Caldera. The caldera walls are described by broken lines, while the rivers and streams by solid lines. C: the Nakadake crater, K: Kusasenri, N: Nakadake, T: Takadake.

(Fig. 3). The topography may be inferred from the NIR image (Fig. 3A) and gross features of land cover by visible image (Fig. 3B). At the center of Aso Caldera stand central cones such as the highest peak Takadake (1592 m) and the peakNakadake (1520 m) with an active crater on its flank (1300 m). The crater is constantly emitting high-temperature volcanic gas and sometimes ejecting ash clouds, as shown in close up images of LANDSAT-5/TM-3 in Fig. 4. On the ground, one can look inside the crater when it is relatively dormant. The basin of Aso Caldera is separated into north and south valleys by the central cones. There extend agricultural fields, villages and towns in both valleys, with about fifty thousand residents. Rivers in each valley join near the only exit in the west side break of the caldera. This break, clealy seen at lower west in Fig. 3A, is the Kitamukiyama Fault.

Forests are mainly located at the foot of the central cones and caldera walls seen as black belts in Fig. 3B. Outside the caldera wall (altitude about 900-1100m), there extend mild slopes of grasslands (bright in Fig. 3A and B) and forests (grey in Fig. 3A and dark in Fig. 3B).

At the mountain summit region, bare lands with heavy ash fall and volcanic gas are seen in the NIR image of Fig. 3A as a dark area not attributable to the shadow effect, while in visible red image as a somewhat bright area (Fig. 3B). In the close-up images of LANDSAT-5／TM-3 shown in Fig. 4, we may see the Nakadake crater where an open vent with white volcanic clouds is observed, For both images, heavy rains on preceding days had filled the vent with a pond of hot water, and strong steaming was observed by the robot video-camera. The grass covered old crater named Kusasenri is also seen with two small lakes inside. The relative brightness of the bare lands in these images is different compared to the grasslands on the slopes of central cones, as the growth of grass changes with seasons. We note here that, in order to see the crater structure, the visible band such as TM-3 ($0.63 \sim 0.69\ \mu m$) is appropriate, while the images of NIR are too dark.

3－2. Unzen Volcano

Unzen Volcano is located at the center of Shimabara peninsula. This area is densely covered with forests except for coastal zones and the paths of the pyroclastic flows and mud avalanche at the eastern slope, starting from the dome on the central peak, Fugendake (see Fig. 5B). In the NIR image shown in Fig. 5A, we can easily see the topographic structure of the peninsula due to the shadow of the sunlight. The Chijiwa fault is especially clear, and other faults can be seen nearly parallel to it in Fig. 5A. These are characteristic to Unzen Graben as indicated in the map (Fig. 7). On the other hand, these faults are not so easy to detect in the SAR image shown in Fig. 6, since the direction of the micro-wave beam from JERS-1 at east-side orbit was almost parallel to these faults. In general, the beam direction is very important revealing topographic structure oriented perpendicular to it best.

The multi-pass data sets of JERS-1／SAR are utilized by Fujii et al. [13] to evaluate the 2-dimensional ground deformation of the lava dome, however the accuracy is not sufficient for this due to the steep topographic gradients and the smallness of the horizontal deformation.

The activity of Mt.Unzen, ejecting volcanic plumes from Fugendake peak, started on 17 Nov. 1990 after 198 years of dormancy. At the peak, a lava dome with complicated lobe structure started to develope in May 1991, and pyroclastic flows from the dome occurred during May 1991 - Feb. 1995. The most hazardous flow on 3 June 1991 resulted in 43 casualties. The initial flows went toward the east, but later flows also went towards SE and NE. At the downstream of the pyroclastic flows, another type of flow called "dosekiryu" occurred, i.e., the avalanche flow of mud and rocks caused by intensive rain. These flows have had severe impacts on the lives of residents in this region during these years. The danger of a disaster from the dosekiryu is still persistent and construction works to prevent this are ongoing. The paths of pyroclastic and dosekiryu flows appear as lines of bare land, where the debris of the flows is deposited. In single band images, these flow paths are most evident in visible

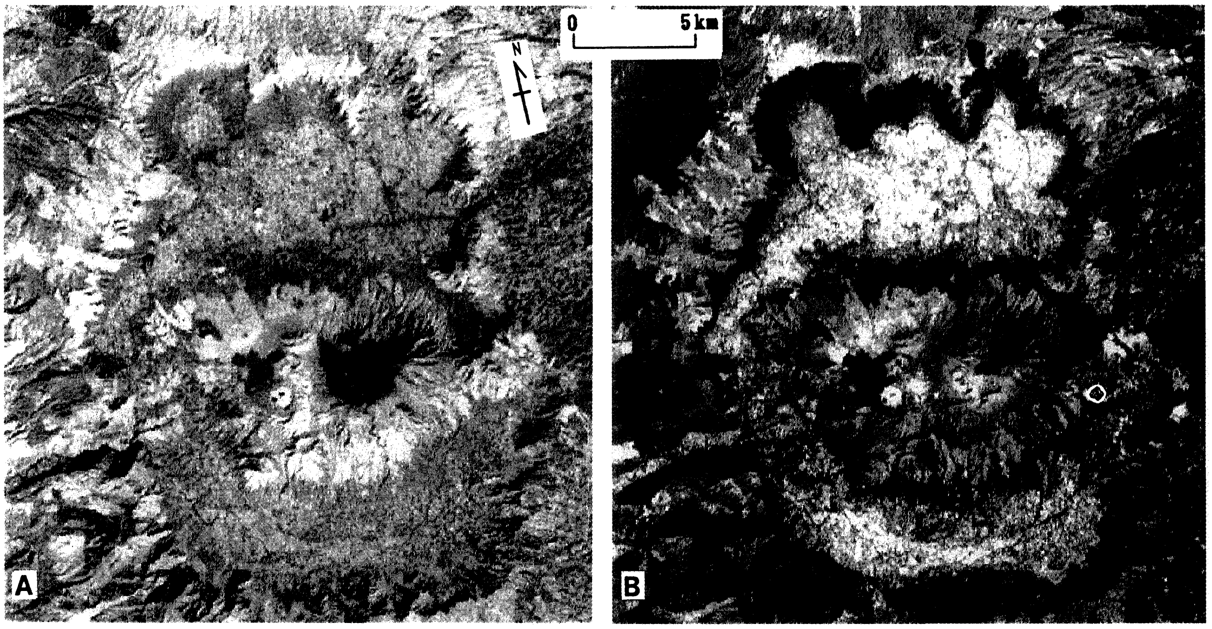

Fig. 3. MOS/MESSR images of Aso Caldera on 5 Nov. 1991.
(A) The NIR images of MESSR-4.
(B) The visible band image of MESSR-2.

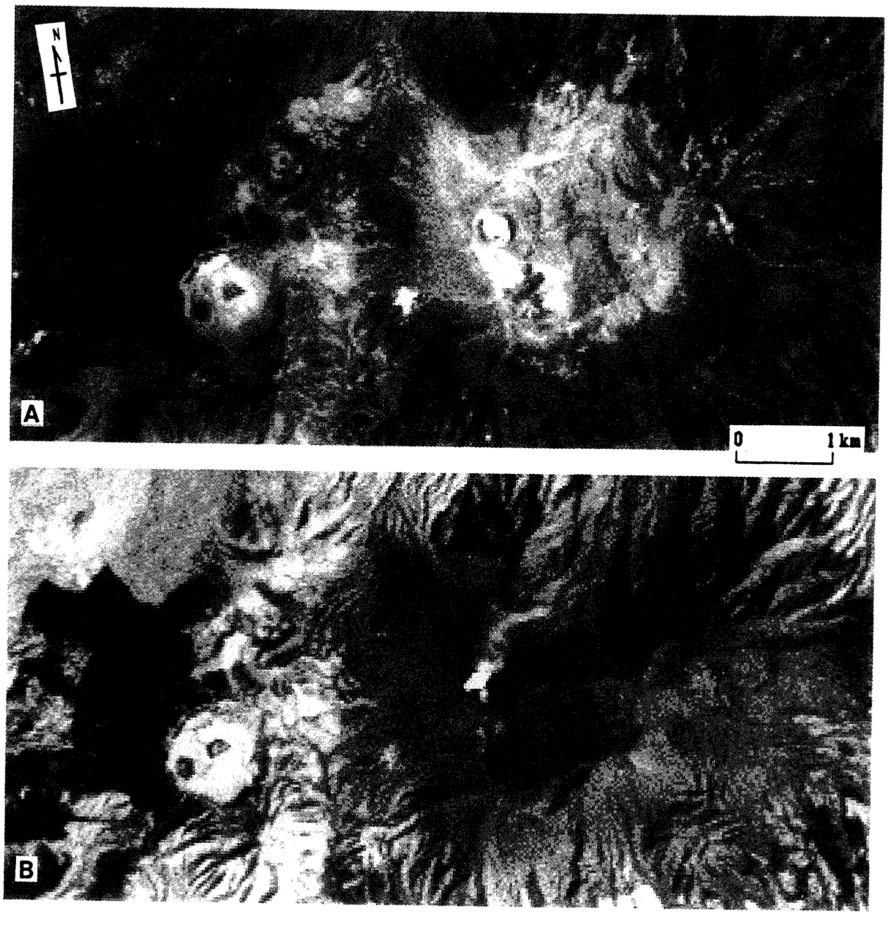

Fig. 4. LANDSAT-5/TM-3 images of summit region of central peaks of Aso Volcano. (A) May 21, 1992. (B) March 5, 1993.

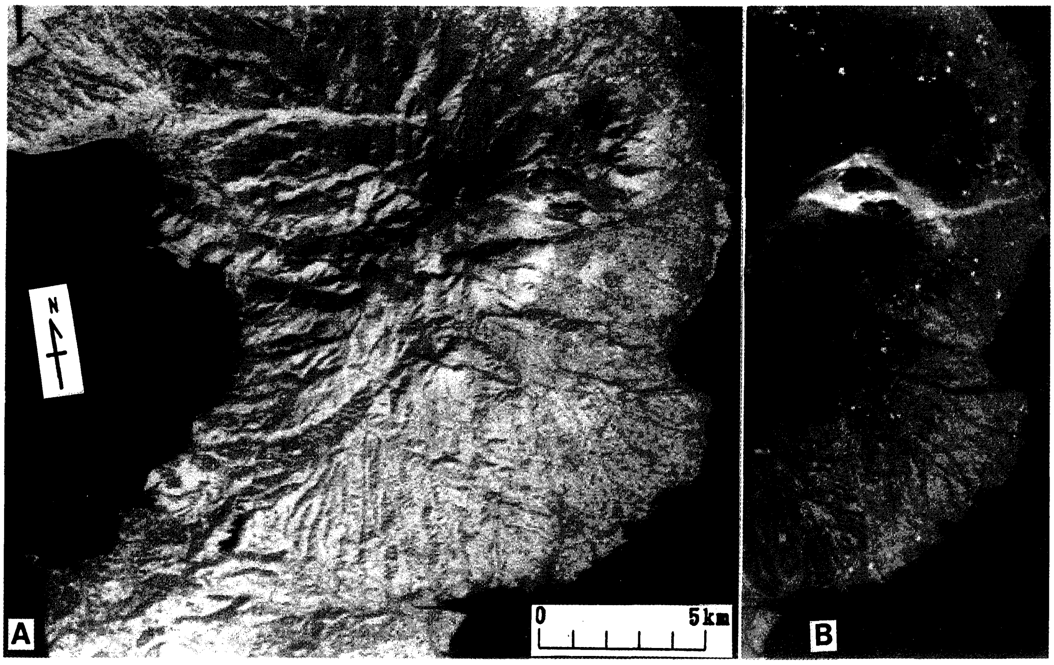

Fig. 5. MOS-1/MESSR images of Shimabara Peninsula on 6 Nov.1991.
(A) The MESSR-4 image of the main part.
(B) The MESSR-2 image of eastern part.

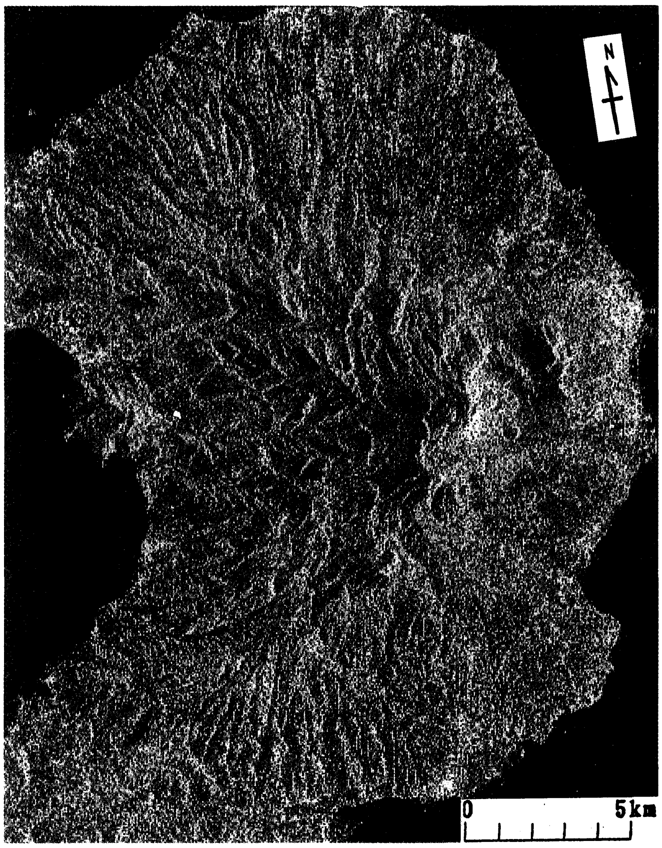

Fig. 6. JERS-1/SAR image of Shimabara Peninsula on 26 May 1994.

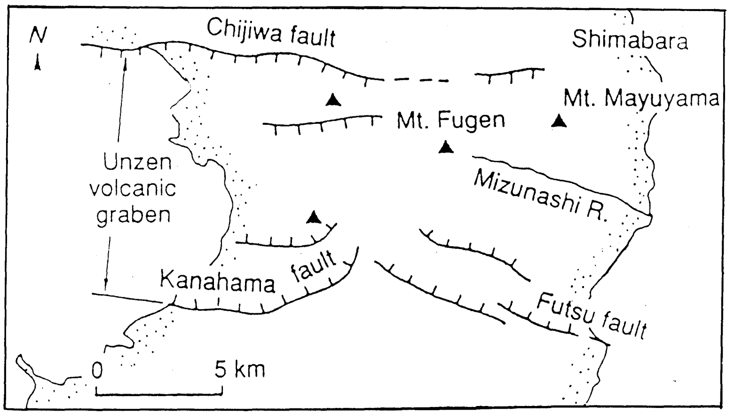

Fig. 7 . The faults in Shimabara Peninsula according to Nakada [12].

bands, as shown in Fig. 5B. Tracing the development of these paths from the EOS data has been done by Nakayama et al. [14].

As for the forest area of Mt. Unzen, Gotoh et al. [15] reported the damage due to the volcanic gas on the basis of NIR image and the vegetation index of EOS data sets. It should be remembered that ash-fall on the vegetation works to decrease the NIR brightness and thus also the vegetation index. As concentrations of sulfur-dioxide in the air (that causes forest damage) have been reported to be not so high in the surrounding areas [16], further studies may be required on the damage to forests.

3 − 3. Kirishima Volcanoes

There are more than twenty craters, cones and crater lakes in the Kirishima Volcano complex, southern Kyushu, as shown in Fig. 8. The Volcano complex is oval shaped with the axes along the NW-SE and NE-SW directions at about 30 and 20 km, respectively. Most of the volcanic bodies are inactive in these years, except for Shinmoe-dake crater and Iwo-yama with its occasional ejection of fumes, As the zone is mostly covered with vegetations, the NIR image is appropriate to reveal the topographic structure, as shown in Fig. 9A of LANDSAT /TM-4 data. Some of the craters can be seen in the visible red (TM-3) image of Fig. 9B, where the oval mountainous zone is apparent as the dark domain covered with vegetation except for the bared summits along a NW-SE line.

3 − 4. Sakurajima Volcano

Mt.Sakurajima stands at the southern rim of Aira caldera which was formed by gigantic explosions about 23,000 years ago and is now filled by the sea (see Fig. 1). It had been a volcanic island until the lava flow of the Taisho eruption in 1914 filled the canal at the southeast corner. The summit crater at Minamidake has had continuing Vulcanian type

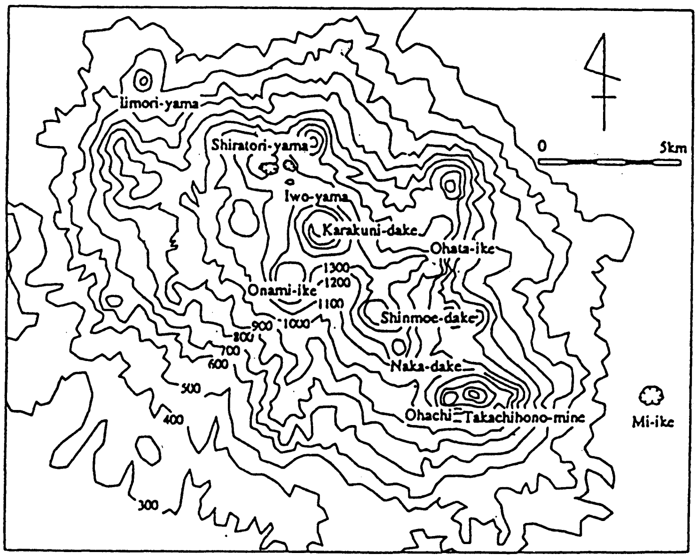

Fig. 8. Topographic map of Kirishima Volcanoes according to Kagiyama [17].

activity since 1955 [7]. Owing to the heavy ash fall and dense volcanic gas, the summit region is bare, and the vegetation coverage of Sakurajima half-island is not dense enough to reveal the topography by the shadow effect brightnesses in the NIR images. Instead, we see many volcanic topographies such as the lava flows at the Taisho (1914) and Showa (1946) eruptions, gullies on the mountain and delta-shaped piles of pyroclastic deposits called Jigoku-gawara. The NIR image is also useful to detect the ash-fall on the ground. which may be washed away by intensive rain and change between the dates of observation. These points are discussed in Tsutsumi et al. [18] based on the JERS-1／OPS and SAR data.

3－5. Kaimondake and the surroundings

The southern end of Satsuma Peninsula is very rich in volcanic topographies such as cone shaped Mt.Kaimondake and the crater lakes Ikedako and Unagi-ike [19], as shown in Fig. 10. There is also an old sea-filled crater Yamakawa-wan. There are geothermal areas and many hot springs at Ibusuki and other places along the coast, though explicit volcanic activity stopped after the big eruptions of Kaimondake in 874 and 875 forming the lava dome of the summit. In fact, this well-shaped mountain is not a single conide, but a troconide structure consisting of a stratified caldera at the base and a lava dome filling it. Since the mountainous regions are covered with forests, the NIR image shown in Fig. 10A is more than adequate to understand the topography, while the visible image such as shown in Fig. 10B of LANDSAT／TM-3 is appropriate to understand the cover.

This region is located at the north west rim of Ata Caldera which was formed about 85 thousand years ago with a similar scale to Aso and Aira Calderas [19], as indicated by the dotted line in Fig. 1. We may see the remnants of caldera walls at the north of Kaimondake in Fig. 10A.

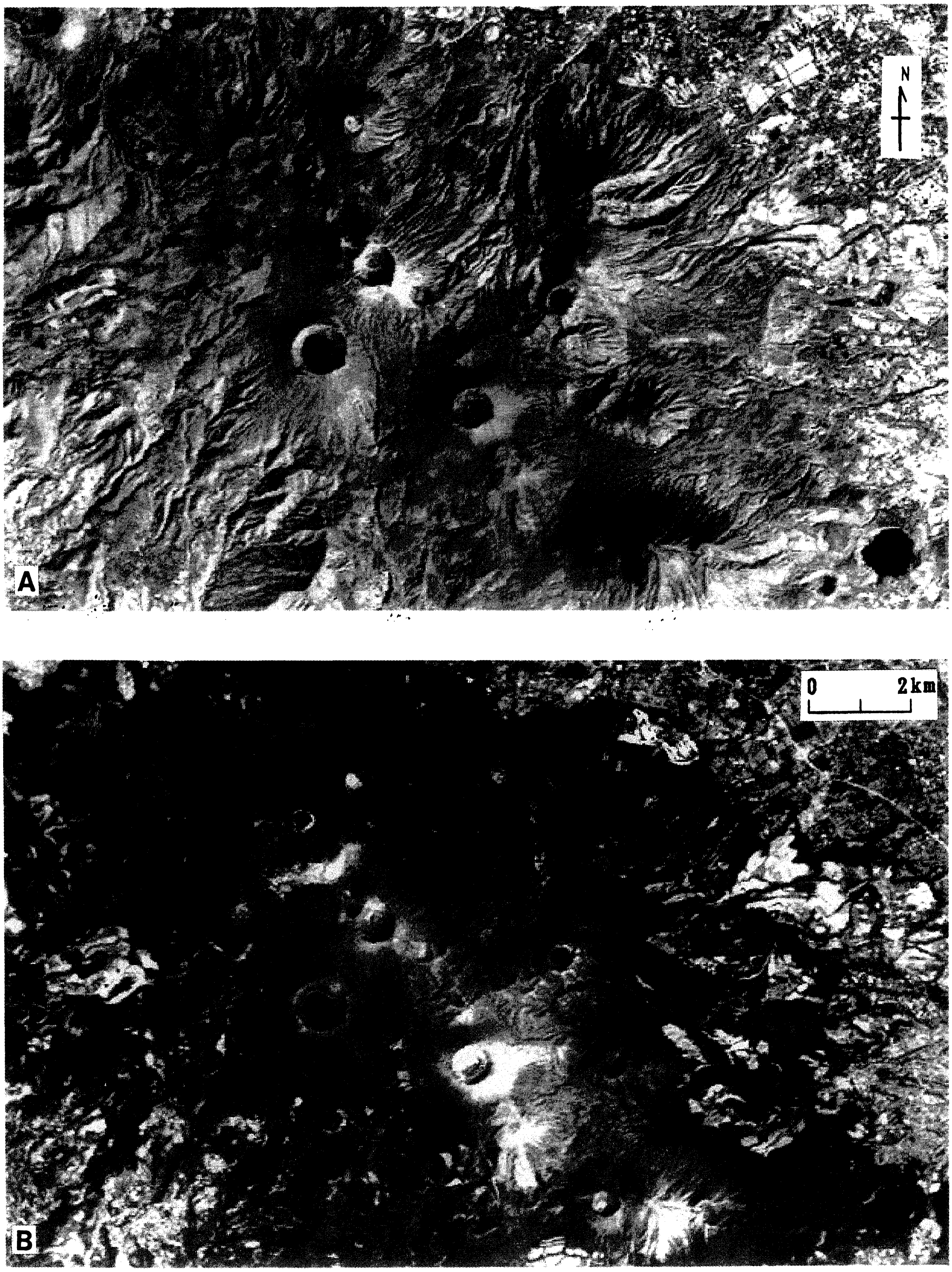

Fig. 9 LANDSAT-5/TM images of Kirishima Volcanoes on 5 Mar. 1993.
(A) NIR image of TM-4. (B) Visible band image of TM-3.

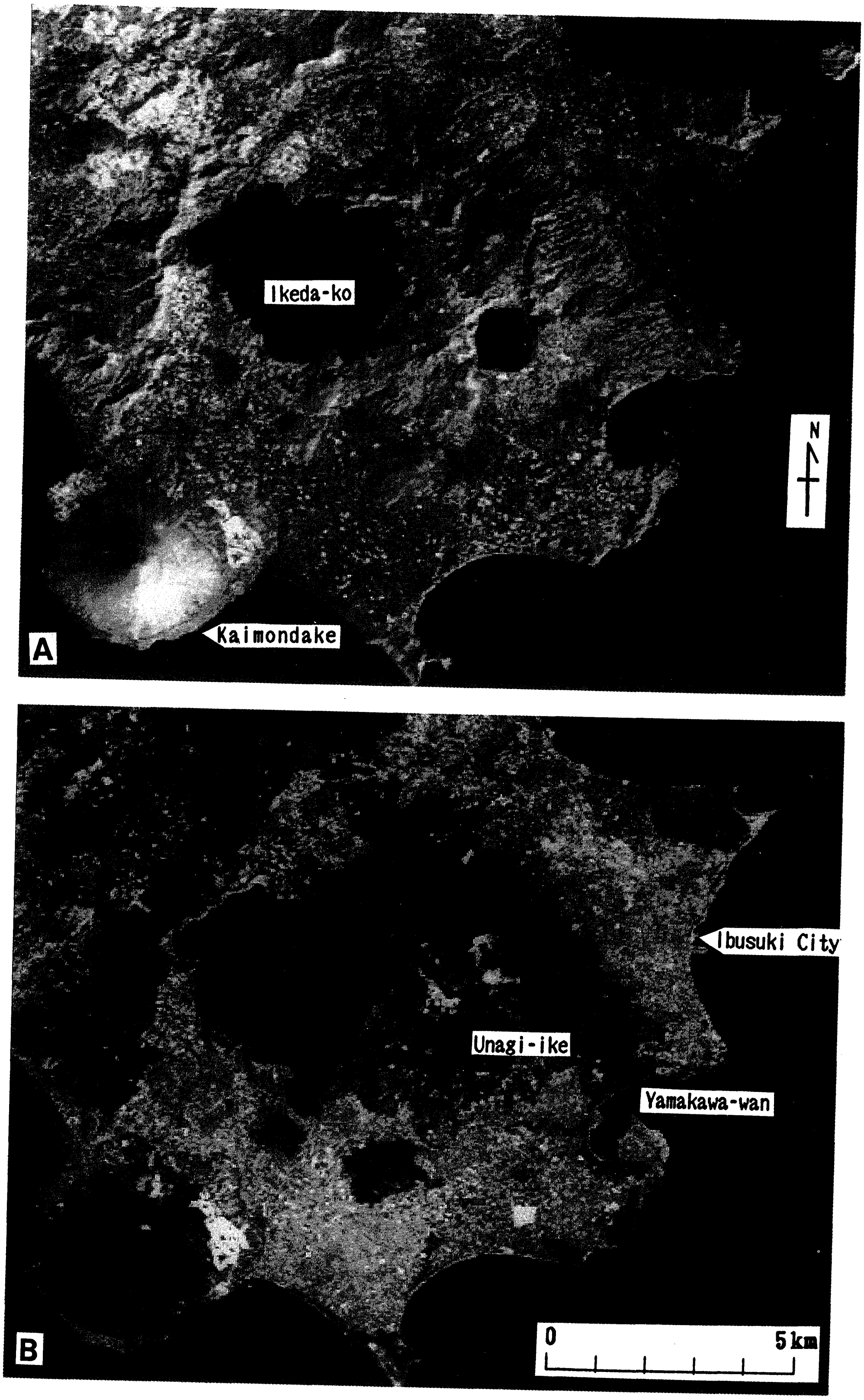

Fig. 10　LANDSAT-5/TM images of Kaimondake area on 5 Mar. 1993.
(A) NIR image of TM-4.　(B) Visible band image of TM-3.

3 − 6. Volcanic islands

In Fig. 11, we show the LANDSAT-5／TM images of volcanic islands Satsuma-Iwojima, Kuchinoerabjima, Kuchinoshima and Nakanoshima. Volcanic topographies such as cones and craters are clearly seen in NIR images of TM-4 (Fig. 11A, C, E, and G), while the vegetion may be inferred from visible band images of TM-3 (B,D,F and H). Suwanosejima, which is a volcanic island with several tens of inhabitants, is shown in Fig. 12, NIR and visible images of the JERS-1／OPS data taken on September 11, 1993. Suwanosejima Volcano is most active in Ryukyu islands, with Strombolian type eruptions. Others, except for Kuchinoshima, erupted at least once this centry, and volcanic activities of Satsuma-Iwojima and Kuchinoerabujima have been detected in these years [9]. Near the seashore of Satsuma-Iwojima, we may find the color of sea water changing into red or yellow in the true color image of LANDSAT／TM.

§ 4. Volcanic clouds

Since volcanic eruptions and ejected ash clouds undergo considerable changes with time, the compilation of their satellite images in a long term may be important to understand and improve the feasibility of satellite monitoring of volcanism. In this section, we give the archives of satellite images of volcanic clouds in south-west Japan since 1979 received by EOC. For the NOAA series of weather satellite, all the data around Kyushu during March 1990 and December 1991 compiled by Japan Weather Association (JWA) were analysed [20,21]. These NOAA data were received at Weather Satellite Center of Japan Meteorological Agency, and processed by JWA. Several NOAA data sets with volcanic clouds from the 1980's were analysed [22], and also the 1992 data [23]. These results will be discussed in contrast with the EOS data. The NOAA data mentioned above were treated as digital data sets for personal computers, as was a part of the EOS data. On the other hand, some of the latter were studied using the quick look photo and video images provided by Remote Sensing Technology Center. As for JERS-1 quick look images, we have utilized the facilities of Earth Remote Sensing Data Analysis Center.

Among the Volcanoes discussed in §3, the dormant volcanoes such as Kaimondake are out of the scope here, as is the active volcano Kirishima because its plumes could not be found in EOS images, although eruption clouds with a maximum height of 500m were reported from minor activity during 1991-1992. Instead, we start with short notes on Kuju-Iwozan with volcanic plumes since October 1995.

4 − 1. Kuju-Iwozan

Kuju-Iwozan is located about 27 km NNE from the Nakadake crater of Aso, where fumes of volcanic gas are continuously emitted. On 11 October 1995, small eruption started with white vaporous clouds after 257 years of dormancy. The level of activity has not changed from one year since then, and the future prospects are not clear. There are a few scenes taken by the French EOS SPOT-2 listed in Table 4.

Table 4.　Satellite data of volcanic clouds from Kuju-Iwozan (1995-1996).

Date	Time	Sat.	L km	W km	Xw km	Dir	Type
95.10.12	11:00	SPT-2	20	1	8	SW	Lin.
95.10.18	10:55	SPT-2	3	0.5	2	NE	Lin.
95.10.23		SPT-2					Spot
96. 6. 2	11:09	SPT-2	2				Spot

L, W, Xw are the cloud length, maximum width, and the distance from the vent where W is attained, respectively.

In this and following tables of volcanic clouds, we list the length L, the maximum width W, and the distance Xw from the source where W is attained. Where a plume extends out of the scene, the mark+ is attached to indicate that the value obtained from the scene is a minimum. The types of volcanic clouds are denoted as Lin., Belt, Con., Fan and Stag. for linear advection, belt type dispersion, small angle dispersion of conical type in horizantal view, fan type spread and stagnation, respectively. These patterns are discussed in preceding works [2,18,20-23].

4－2. Aso Volcano

In Table 5, we list the EOS data of daytime observation of volcanic clouds from Aso Volcano since 1979, where images with a white spot of clouds over the vent are omitted. The NOAA data exhibiting volcanic plumes during March 1990 and December 1991 [20,21] are also included in Table 5.

Table 5.　Satellite data of volcanic clouds from Mt. Aso (1979-1995).

Date	Time	Sat.	L km	W km	Xw km	Dir	Type
79. 9 .12	10:06	LST-2	18	10	14	NNE	Belt
79.10. 9	10:10	LST-3	10	3	8	SW	Con.
79.11.14	10:09	LST-3	75+	10	30	SSE	Lin.
85. 4 . 8	10:12	LST-4	12	2	8	SW	Lin.
85. 6 . 3	10:17	LST-5	8	3	7	NW	Lin.
89.10. 4	10:13	LST-5	20	8	12	SE	Con.
89.10.18	10:56	MOS-1	25	13	15	SE	Erup.
89.11.21	10:10	LST-5	50	30	30	SSE	Belt
〃	10:57	MOS-1					
90. 1 . 8	10:10	LST-5	18	3	15	ENE	Lin.
90. 5 .16	10:07	LST-5	10	1	6	WSW	Lin.
90. 6 . 7	11:18	SPT-1	3	1	2	SW	Lin.
90.11.18	13:23	N-11	20	10	10	WNW	Belt
90.12. 5	13:36	N-11	15	2	8	NE	Lin.
90.12. 6	13:24	N-11	10	1	5	ENE	Lin.
91. 2 .12	10:08	LST-5	5	1	4	NE	Lin.

Scenes only with white spots are omitted.

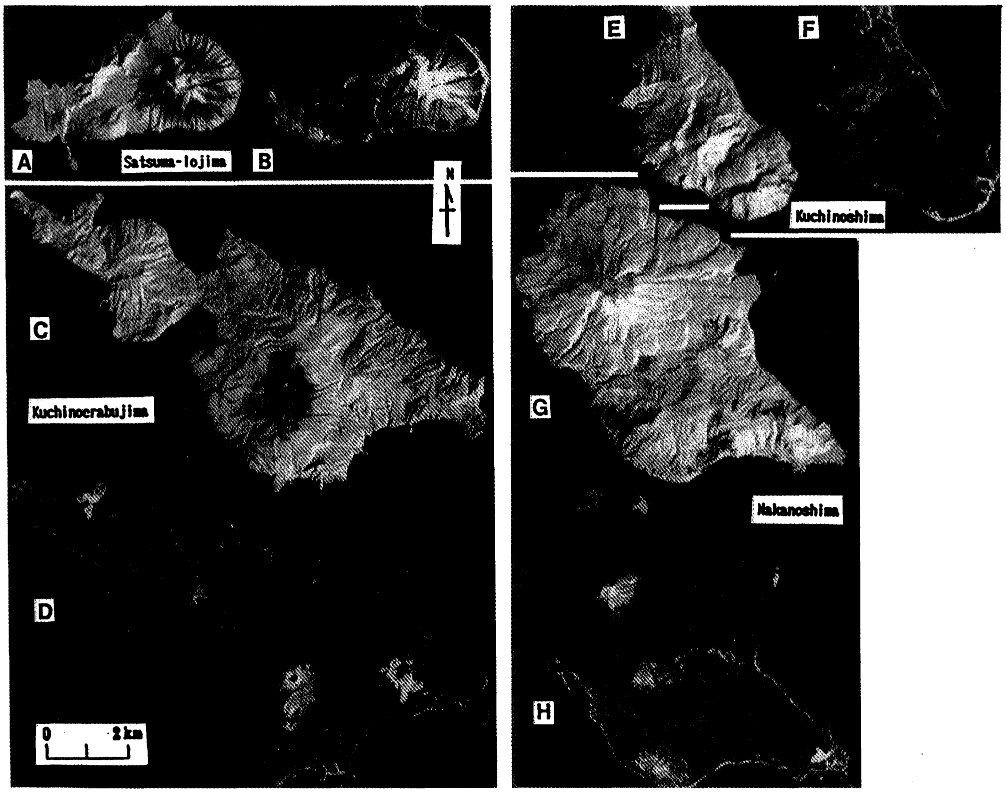

Fig. 11. LANDSAT-5/TM images of Volcanoes in Ryukyu Islands on 5 Mar. 1993.
TM-4 images for A, C, E and G; TM-3 images for B, D, F and H.

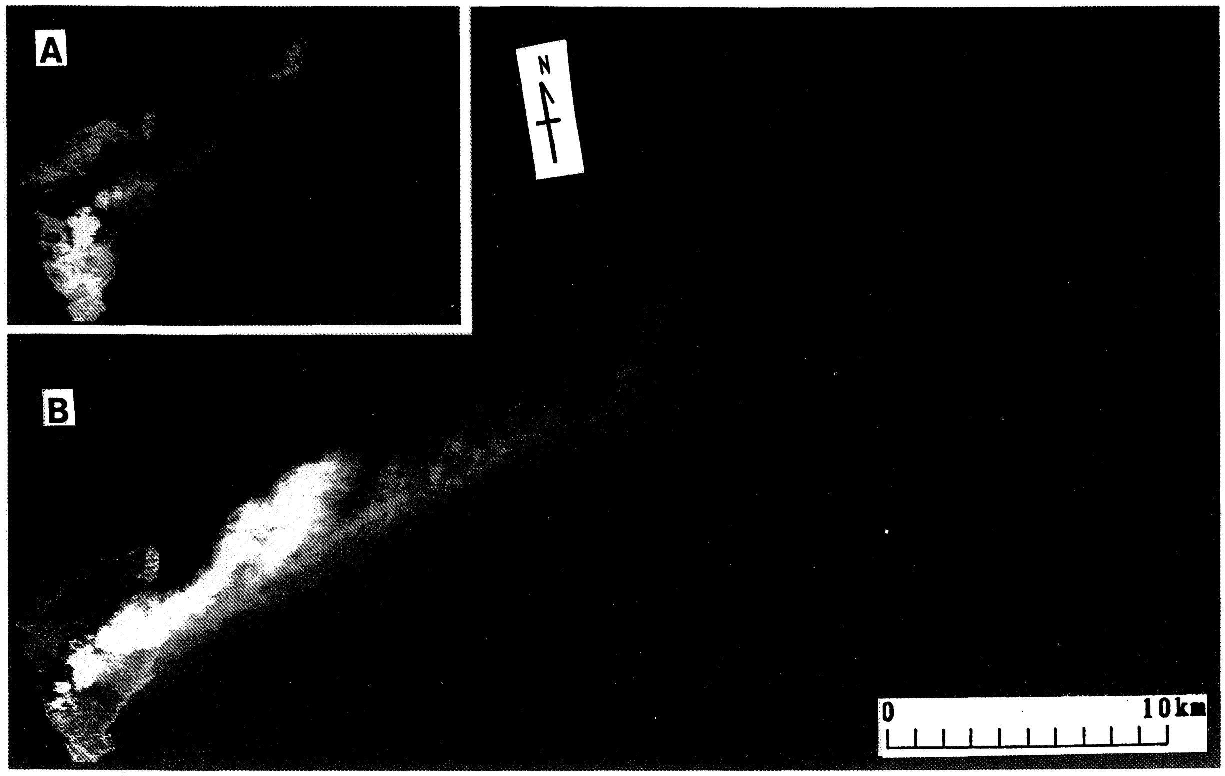

Fig. 12. JERS-1/OPS images of Suwanosejima and its volcanic clouds on 11 Sept. 1993.
(A) NIR image of OPS-3. (B) Visible band image of OPS-2.

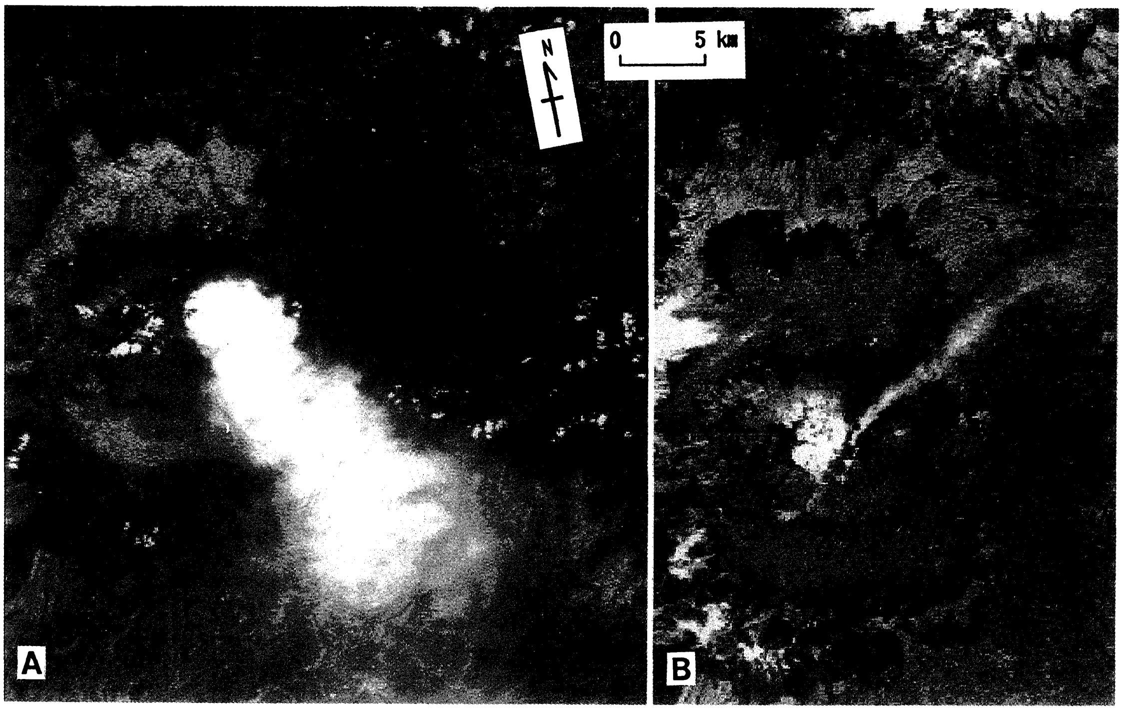

Fig. 13.　Satellite images of volcanic clouds from Aso-Nakadake.
(A) MOS-1／MESSR-1 image on 18 Oct.1989.
(B) LANDSAT-5／MSS-4 image on 8 Jan.1990.

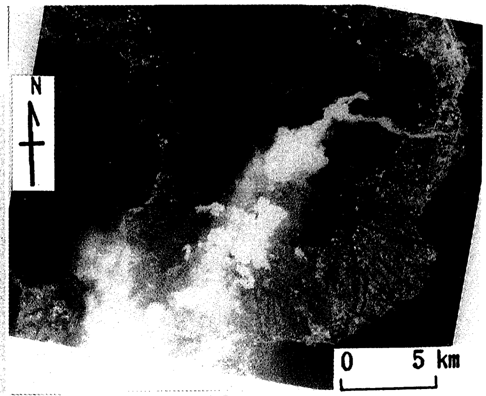

Fig. 14.　MOS-1b／MESSR-1 images of a plume from Unzen volcano on 8 Sept. 1991.

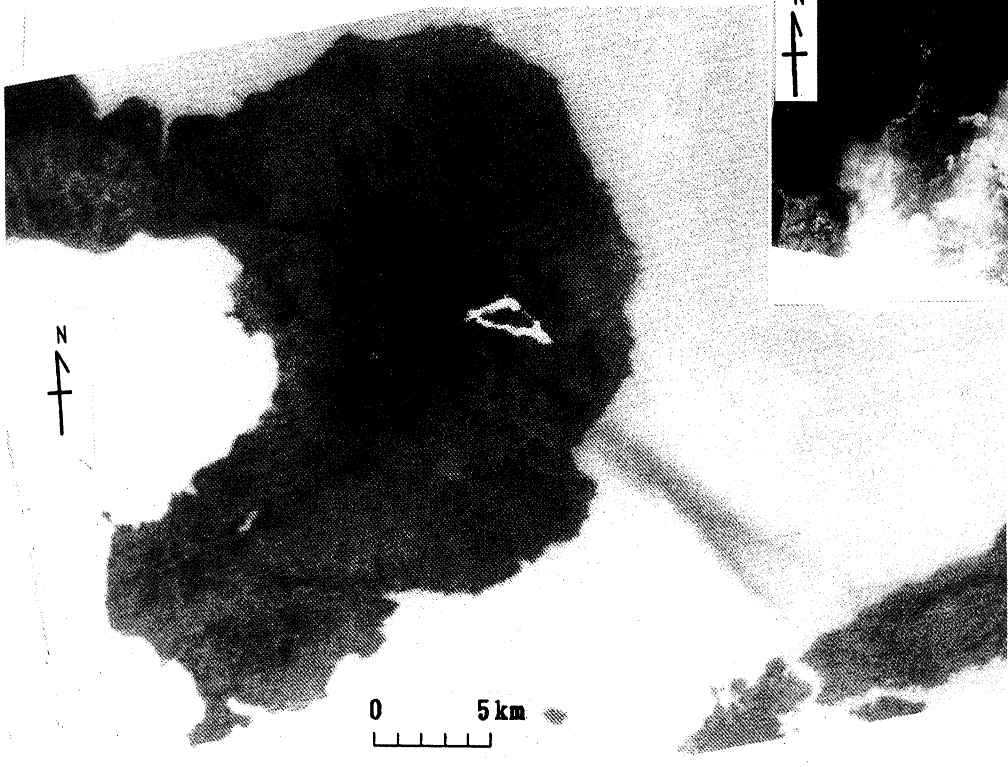

Fig. 15.　Thermal image of Shimabara Peninsula at 21:29 JST on 10 Mar. 1993 by LANDSAT-5／TM -6.

Since 1979, Aso Volcano was very active during three periods, June - November in 1979, April - June in 1985, and June 1989 - January 1991. Volcanic clouds observed were with a scale of around 10 - 70 km during these periods, while the satellite images with the clouds as white spots staying above the crater were obtained both in active and inactive periods, not listed in Table 5. In Fig. 13, we show two images of ash clouds from Mt. Aso during the latest period. In the autumn of 1989, heavy ash-falls seriously damaged agriculture and badly affected traffic inside the caldera and its neighboring regions [4].

4 — 3. Unzen Volcano

Though volcanic plumes had been observed from the ground since November 17, 1990, the remote sensing data from EOS were obtained only in August 1991 and thereafter, because of bad weather. Since then, there are many data sets of ash clouds with scales around 5 - 30 km as listed in Table 6, and also some clear data without any clouds. On the other hand, a plume of 12 km was found in NOAA image on 12 February 1991, prior to the stage of higher activity which caused the pyroclastic flows and associated clouds from the Fugendake lava dome after May 1991. Other NOAA images in 1991[20, 21] and 1992[23] are also listed, though the survey of 1992 data is partial.

As listed in Table 6, there are many data of ash clouds of scale around 10 - 40 km. We note that there are two kinds of clouds from Volcano Unzen, i.e., stationary plumes from the lava dome at the top of the mountain, and the ash clouds from Merapi type pyroclastic flows. In this table, comments are given for the clouds from pyroclastic flows (PCF). Fig. 14 is an example of a stationary plume from the lava dome.

4 — 4. Volcanic clouds from Mt. Sakurajima

The activity of Mt. Sakurajima since 1972 is to eject volcanic clouds almost daily from the summit crater at Minamidake, with the occasional eruption exhibiting quite different patterns of cloud dispersion. The present status of the understanding of the phenomena is summarized in [8]. In a previous report, a list was given of most of the prominent scenes of volcanic clouds taken by EOS during 1979 and 1991[22]. The NOAA data during March 1990 and December 1991 were also analysed[20, 21], finding in most good weather scenes, the volcanic clouds extend tens of km as the results of daily activity, and in some scenes extend a few hundred km when the volcano is highly active. For several scenes of NOAA data in 1992, see reference [23]. Two scenes of JERS-1／OPS data were also analyzed [18], and further data are under investigation.

Here we add a few remarks. Among the volcanoes in the Mainland Kyushu, the ash clouds from Mt. Sakurajima are the most vigorous on the average, with the length exceeding 100 km.

Table 6.　Satellite images of volcanic clouds from Mt. Unzen (1990 - 1995).

Date	Time	Sat.	*L* km	*W* km	*Xw* km	Dir	Type／Comment
91. 2 .12	14:12	N-11	12	3	10	SE	Lin.
91. 7 .18	14:49	N-11	20	4	8	SE	Belt
91. 7 .24	13:24	N-11	25	6	15	E	Con.
91. 8 .16	11:03	SPT- 2	8	5	6	SW	Lin.
91. 8 .18	13:53	N-11	20	8	18	W	Fan
91. 8 .26	11:11	SPT- 2	13+	8+	13+	SSW	PCF cloud & thin plume (9:30 etc.PCF)
91. 8 .30	10:17	LST-5	30+	15+	25+	ESE	PCFcloud & Lin. plume
〃	11:04	MOS-1	38+	20	20+	ESE	(10:00 etc.PCF110s)
91. 9 . 8	11:10	MOS-1b	30	13	20	SW	Con.
91. 9 . 9	14:42	N-11	10	2	5	E	Lin.
91. 9 .10	11:23	SPT- 2	15	13	8	SE	Fan of PCF cloud,
	14:30	N-11	20	12	5	SE	Stag.
91. 9 .11	11:03	SPT- 2	30	8	10	ESE	PCF cloud, Lin. plume
91.10. 2	13:36	N-11	30	7	7	SE-S	Fan
91.10.20	11:04	MOS-1	15	5	10	SE	Lin.
91.10.22	11:16	SPT- 2	10	1.5	3	S	Lin.
91.10.23	10:56	SPT- 2	15+	4	13	SSE	Lin.
91.11. 6	11:03	MOS-1	15	3	10	WSW	Lin.
〃	11:27	SPT- 2					
91.11. 9	14:37	N-11	20	8	18	S	Con.
91.11.15	11:11	MOS-1b	7	1	2	ESE	Lin.
91.11.20	14:09	N-11	20	8	18	SSE	Con.
91.12. 4	10:18	LST-5	20	2	8	ESE	Lin.
91.12.10	11:03	MOS-1	25	3	8	ENE	Lin., PCF cloud
91.12.13	11:16	SPT-2	14	2	8	SE	Lin.
91.12.15	14:18	N-11	30	5	20	S	Lin.
91.12.20	10:08	LST-5	10	3	1	NNE	Lin.
91.12.30	14:43	N-11	20	3	12	SSE	Lin.
92. 1 . 28	11:31	SPT-2	30	3	13	E	Lin.
92. 2 . 6	10:18	LST-5	30	10	25	NE	PCF fan cloud, (9:40 PCF)
92. 3 . 10	11:23	SPT-2	13	5	5	SE	PCF fan cloud
92. 5 .12	10:17	LST-5	10	4	5	E	PCF cloud
			40	4	20	N	
	11:12	SPT-2	20	3	18	NNW	
92. 5 .21	14:55	N-11	30	5	28	E	Lin.
92. 5 .28	10:17	LST-5	15	3	10	SE	Lin.
92.10.19	10:15	LST-5	13	6	9	ESE	
92.10.20	11:14	MOS-b	25	5	20	S	PCF cloud, Stag.
	11:16	SPT-2					Lin.
92.11.30	11:28	SPT-2	30	3	20	WNW	Lin.
93. 2 .12	11:05	SPT-2	30	3	14	SE	Lin.
93. 3 . 5	11:14	MOS-b	20	3	12	NE	Lin.
93. 8 .30	10:55	MOS-1	66	6	33	N	Lin.
93.12. 9	10:15	LST-5	36	2	30	E	Lin.
94. 1 .10	10:15	LST-5	30	3	25	E	Lin.

PCF =pyroclastic flow.

As their vertical thickness is about 200 - 800 m, the pattern of their horizontal dispersion is sensitive to the vertical variation of wind direction and velocity at those altitudes. Typical dispersion patterns are linear advection, fan- and belt-types. In many cases, these features are well reproduced by a vertical shear model with the upper wind data as the inputs [23, 24]. The importance of wind shear with height for horizontal dispersion can be seen by direct observation of the deformation of the eruption columns into winds, as the upper and lower parts of a column drift in different directions [8, 25]. In contrast, the linear advection type dominates in the plumes from Aso and Unzen, since the vertical shear is not as large. On the other hand, ash clouds from pyroclastic flow at Unzen Volcano tend to stagnate near the source, since the winds below 1000 m are rather uncollimated and not very strong.

4 − 5. Volcanic clouds in Ryukyu Islands

Finally, let us consider volcanic islands. It was found that a white spot of clouds was seen above the vent of Volcano Satsuma-Iwojima in most clear scenes, indicating that the volcano was continuously ejecting white clouds which were diminishing in the dry air, while ash rich plumes are rarely seen (Table 7).

Table 7. Satellite images of volcanic plumes in Ryukyu Islands (1979 - 1995).

Date	Time	Sat.	*L* km	*W* km	*Xw* km	Dir	Type
(1) Satsuma-Iwojima							
92. 6. 6	11:14	MOS-b	10	1	5	N	Lin.
93. 2.15	11:08	MOS-b	8	5	7	N	Belt
(2) Suwanosejima							
85. 8.29	10:24	LST-5	35+	8+	25+	WSW	Belt
88. 4.15	7:55	N-10	310+	20	300	SSE	Lin.
	10:24	LST-5	140+	30+	60+	SSE	Belt
92. 4.15	11:08	MOS-b	20	12	14	NE	Fan
92. 5. 3	11:14	MOS-b	20	2	10	S	Lin.
92. 5.21	10:12	LST-5	25+	8	20	SSE	Lin.
93. 9.11	11:13	JERS1	50	8	40	ENE	Lin.
95. 8. 2	11:13	LST-5	30	6	10	ESE	Lin.
95. 8.18	11:13	LST-5	15+	4+	15+	N	Lin.

As for Volcano Suwanosejima, such a white spot was rarely seen. Instead, there are several scenes of plumes comparable to those of Sakurajima as listed in Table 7. Though the daily activity of this volcano is Strombolian, it is occasionally Vulcanian [9, 10]. Particularly, a large amount of grey ash cloud was observed from an airplane on 15 April 1988. NOAA data of this plume shows it extending 250 km in parallel with one from Sakurajima [26]. In Fig.12B, we have shown a recent OPS image taken by JERS-1. It shoud be mentioned here that this island was outside the scene in the survey of NOAA data during 1990-1991 [20,21].

In Table 8, we list the EOS images of white spot on volcanoes in Ryukyu Islands, and also some of clear scenes without cloud, because these volcanoes are not well monitored from the ground. As listed, a white spot was also seen once on Iwo-Torishima, near Okinawa.
A sample of a white spot on the vent of Satsuma-Iwojima can be found in the image of visible band in Fig.11B.

Table 8. Satellite images of small apots of volcanic clouds on the vents in Ryukyu Islands (1979-1995).

Volcano	Date	Sat.
Satsuma-Iwojima		
	84. 7.18	LST-5
	84.10.22	LST-5
	90. 3.13	LST-5
	90. 4. 6	MOS-1
	90. 5.16	LST-5
	90.9 .21	LST-5
	91. 4.15	MOS-1
	92. 5.21	LST-5
	92.11. 7	JERS1
	(93. 2. 3	JERS1)
	93. 2.15	MOS-b
	93. 3. 4	SPT-2
	93. 3. 5	MOS-b
	93. 3.19	JERS1
	93. 4. 5	SPT-2
	93. 9.11	JERS1
	(94. 6. 2	JERS1)
	95. 4. 8	MOS-6
	95. 9.11	LST-5
	95.11.12	JERS1
Kuchinoerabujima		
	84. 7.18	LST-5
	84.10.22	LST-5
Suwanosejima		
	91. 4.15	MOS-b
	93. 2. 3	JERS1
	93.10.26	JERS1
	(94. 6. 2	JERS1)
Iwo-Torishima		
	92. 5.28	MOS-1

( ) : Clear image without a spot of volcanic cloud.

§ 5. Thermal images of volcanism

For the monitoring of volcanic activity, TIR images are useful both in daytime and nighttime. The LANDSAT-5/TM-6 sensor is useful to detect thermal anomalies with the resolution 120 m, although it cannot measure very high temperatures above a upper limit of about 70 ℃. There are also problems of calibration and the absorption correction due to vapors [27]. The latter problem may be serious above a vent with dense vapors. Here we briefly discuss qualitative aspects of thermal images on the basis of recent works [28, 29].

5 − 1. Aso Volcano

The vent was relatively hot in two daytime images (92. 5. 21 and 93. 3. 5), and two nighttime images (92. 7. 29 and 93. 3. 10). However, the CCT temperature was unexpectedly low, suggesting shielding by dense vapors and／or fumarolic clouds. In these days, steaming hot pond filling the vent was observed in daytime (see the discussion concerning Fig. 4).

5 − 2. Unzen Volcano

The very high temperatures of the lava dome at Fugendake peak and the subsequent pyroclastic flow deposits are detectable in most nighttime scenes up to 19 July 1994 from the quick look video image. Among them, two scenes analyzed (92. 7. 29 and 93. 3. 10) were above the saturation temperature. One of them is shown in Fig. 15, where the plume flowing above the Ariake Sea is apparent because of its low temperature.

An extensive work on the evaluation of the nighttime temperature of the dome and the flow was done by Urai and Isobe [30], by utilizing NIR and SIR bands of LANDSAT／TM in addition to TM-6. In these bands, backgroud is completely dark except for manmade hot spots. Thermal images of Unzen Volcano were also obtained from aerial and ground observations [31].

5 − 3. Sakurajima Volcano

It is prohibited to go within 2 km from the active crater at the Minamidake peak of Sakurajima Volcano. Therefore, the remote sensings by TIR images from the space [32] and the ground [33] are important means to understand the activity of the volcano.

Among several scenes during 1989-1993 in daytime and nighttime, the vent was always very hot whenever it was not covered with dense ash clouds. However, the saturation temperature was not attained, indicating strong absorption of the radiation by the dense vapors and ／or clouds.

On the other hand, volcanic clouds are cold compared with surface temperatures of the land and the sea. Especially, tall eruption columns look very cold, as their surfaces are nearly in equilibrium with the surrounding air at high altitudes.

§ 6. Concluding remarks

We may summarize the main results as follows:

1. The NIR image is suited to reveal the faults and volcanic topography, especially of land covered with vegetation.

2. The visible band image is suited to reveal the land cover. It is also useful to show up the topography of bare land of very active volcanoes.

3. The SAR image with fixed beam direction is not always suited to reveal topographic structures parallel to it.

4. The TIR image is suited to find thermal anomalies of active volcanoes. The estimate of the temperature is subject to vapor corrections and upper limit.

5. The EOS and the weather satellite NOAA are complementary in detecting volcanic clouds in Kyushu and Ryukyu Islands, concerning the space resolution and the frequency in time. The TIR images are useful in both of them.

Here, let us make a few remarks and comment on remaining problems.

a. In the case of NIR images, a variety of the direction and angle of the sun can be obtained according to the seasonal change and to the difference of observation times of the satellites. Further studies of volcanic topographies in different conditions, including one of the space resolution, are important.

b. In order to study the vegetation coverage in detail, we may utilize the linear vegetation index [34], which is a weighted difference of the spectral emissivities at NIR and red bands such as $LVI = a\,TM\text{-}4 - b\,TM\text{-}3 + c$, where a, b and c are constants adjusted to a scene. Shadow effect is quite reduced by appropriate choice of the ratio a/b, and poor versus dense vegetation coverages are expressed to be dark versus bright, respectively. An analysis of the TM data on Sakurajima is given in [35].

c. Bare lands of very active volcanoes are the subject of lithlogic studies, to be worked out in near future.

d. Extensive studies of the NOAA data for Suwanosejima Volcano are wanted, as its activity may be comparable to Mt. Sakurajima, occasionally.

e. The vertical shear model for the dispersion of volcanic clouds should be tested for volcanoes other than Mt. Sakurajima.

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