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Depositional ramps: asymmetrical distribution structure in the Ata pyroclastic flow deposit, Japan

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Abstract. The asymmetrical distribution of the welded Ata large-scale pyroclastic flow deposit in Southern Kyushu, Japan was identified. This distribution pattern was defined as depositional ramps. Depositional ramps can be identified in valleys wider than 1 km and become smaller-scale with increasing distance from the source. Upslope directions of depositional ramps are generally radially away from the source caldera, suggesting that the structure was formed by the flow of pyroclastic material radially away from the source. The original depositional surface was reconstructed based on field mapping and density measurements of the pyroclastic flow deposit. Depositional ramps having a dip angle of more than 9° were reconstructed on the vent-facing slopes of the topography underlying the valley-filling deposits in the area within 10 km of the caldera rim. Such a dip angle is much larger than previously described dip angles. The size and gradient of the depositional ramps decreases with increasing distance from the source. Depositional ramps are recognized commonly in densely welded pyroclastic flow deposits. A high emplacement temperature is required to form the depositional ramps. This suggests that the pyroclastic flow was transported as a dense, fluidized layer to minimize heat loss.

Introduction

Depositional ramps are depositional features of large-scale pyroclastic flow deposits as proposed by Suzuki and Ui (1982). The upper surfaces of pyroclastic flow deposits prior to welding are generally thought to have very low angles of repose, usually less than 3.5° (Ross and Smith 1961; Yokoyama 1974; Sheridan 1979). The dip angle of the reconstructed original surface slope reaches up to 9° in the case of the Ata pyroclastic flow deposit, southwestern Japan (Suzuki and Ui 1982). The deposit is selectively distributed on slopes facing the source caldera. In this paper, structure and lateral change of depositional ramps in the Ata pyroclastic flow deposit are described, based on the detailed geological mapping and altimetry, and the origin of this stucture is discussed.

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Geological description and results of altimetry

The Ata pyroclastic flow deposit is one of several large-scale pyroclastic flow deposits which erupted approximately 80000-85000 B.P. (Machida and Arai 1983) in southwestern Japan. The source caldera of the Ata pyroclastic flow is located in the middle part of Kagoshima Bay (solid line in Fig. 1) (Hayasaka 1982; Suzuki and Ui 1983). The magma-equivalent volume of the deposit is more than 50 km^3 (Aramaki and Ui 1966; Suzuki 1983). The deposit is composed of lower non-welded facies and upper welded facies. The lower facies is present only in the areas east and southeast of the caldera. The upper welded facies is present all around the caldera. The upper welded facies is resistant to erosion, and so the flat upper surface of the Ata pyroclastic flow deposit is well preserved. Aramaki and Ui (1966, Fig. 5) described the inclined surface of the Ata pyroclastic flow deposit against the basement highland, but they did not specify the preferred orientation of such a slope.

Depositional ramps were first identified using aerial photographs of the Ata pyroclastic flow deposit. The asymmetrical distribution and steep surface slope was searched throughout the entire distribution of the deposit, and four areas (Fig. 1) were selected to make a precise determination of the original emplacement surface. Detailed geological mapping has been done for these areas to delineate the distribution of the deposit.

Two altimeters (American Paulin, type MDM-5) were used to measure the altitude of the surface of the Ata pyroclastic flow deposit. The precision of the altimetry is within 2 m. One altimeter was used to measure the altitude of the observed sites. The other altimeter was used at the base station to calibrate for temperature and atmospheric pressure. The altitude and temperature were recorded every 5 min at the base station. Both altimeters were read simultaneously and each cycle of measurements was finished within 1 h to obtain good calibration. If the observational error of the altitude exceeded 2 m, the procedure was repeated.

The depositional ramps' structure is extensively developed at MAK (Makurazaki) area, approximately 40 km west of the caldera (Fig. 1). In this area, the basement formations covered by the Ata pyroclastic flow deposit consist mainly of Cretaceous to early Tertiary flysch-type sediments (Shimanto Super Group), granodiorite stock, andesite lava flows and tuff breccias (Fig. 2a). The Ito pyroclastic flow deposit unconformably overlies the Ata pyroclastic flow deposit.

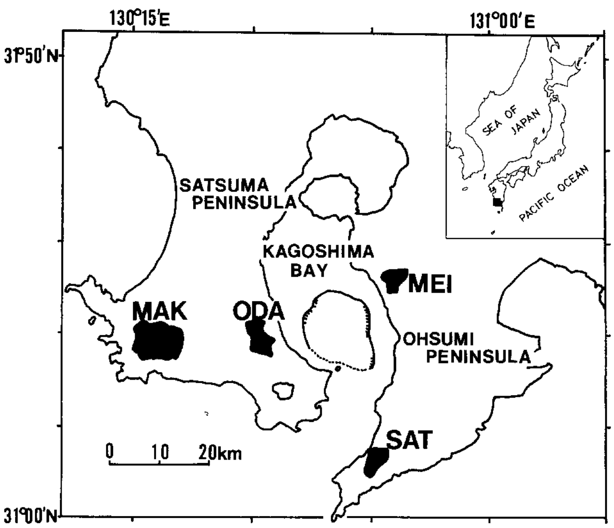

Fig. 1. Index map of four areas where geological mapping and altimetry confirm depositional ramps in the Ata pyroclastic flow deposit, Southern Kyushu, Japan

The Ata pyroclastic flow deposit fills three large valleys in the MAK area, extending generally from north to south. The deposit is distributed preferentially on the western side of each valley. The maximum thickness of the deposit in this area reaches hundreds of metres. The flat original depositional surface of the Ata pyroclastic flow deposit is partially preserved and slopes upwards away from the source caldera, forming depositional ramps.

Depositional ramps cannot be recognized in a narrow valley with a width of less than 1 km. The original depositional surface after welding was estimated, based on the geological mapping and altimetry (Fig. 2b). The Ata pyroclastic flow deposit reaches up to 200 m or more above sea level on the western side along the major valley. In contrast, the upper surface of the deposit is below 100 m above sea level on the eastern side of the same valley. Devitrification has occurred, except at the bottom of the deposit. Juvenile obsidian lenses and glassy matrix can be observed in the marginal area of the deposit, due to a lower degree of devitrification. The degree of welding at the marginal area is high, although the deposit is thin.

Area ODA (Odashiro) extends to near the water divide of Satsuma Peninsula, approximately 20 km northwestwards from the source caldera (Fig. 1). In this area the Ata pyroclastic flow deposit is underlain by the basement formations of late Cretaceous to early Tertiary flysch-type sediments intruded by felsic dykes, granite porphyry, andesite lava flows and tuff breccias (Fig. 3a). The Ata pyroclastic flow filled the topographical lowlands. The depositional ramps are recognized in the valleys TA and OD of Fig. 3b. The deposit fills the basement valleys up to 380–397 m above sea level on the northwestern side of slope, but is below 360 m above sea level on the southeastern side. The altitude of the surface of the deposit becomes gradually higher towards the northwest in this area. The directions of ramps are from southeast to northwest, subparallel to the direction towards the source vent. The welding process is much more developed in this area. Vesicules are commonly observed within the juvenile pumice and matrix glass of the densely-welded zone (Fig. 4). The deposit resting on steep slope locally shows secondary flowage structures (Ono and Watanabe 1974; Chapin and Lowell 1979; Wolff and Wright 1981) such as stretched pumice fragments or rotated lithic fragments.

Area MEI (Meino-o) is located approximately 20 km northeast from the source caldera (Fig. 1).

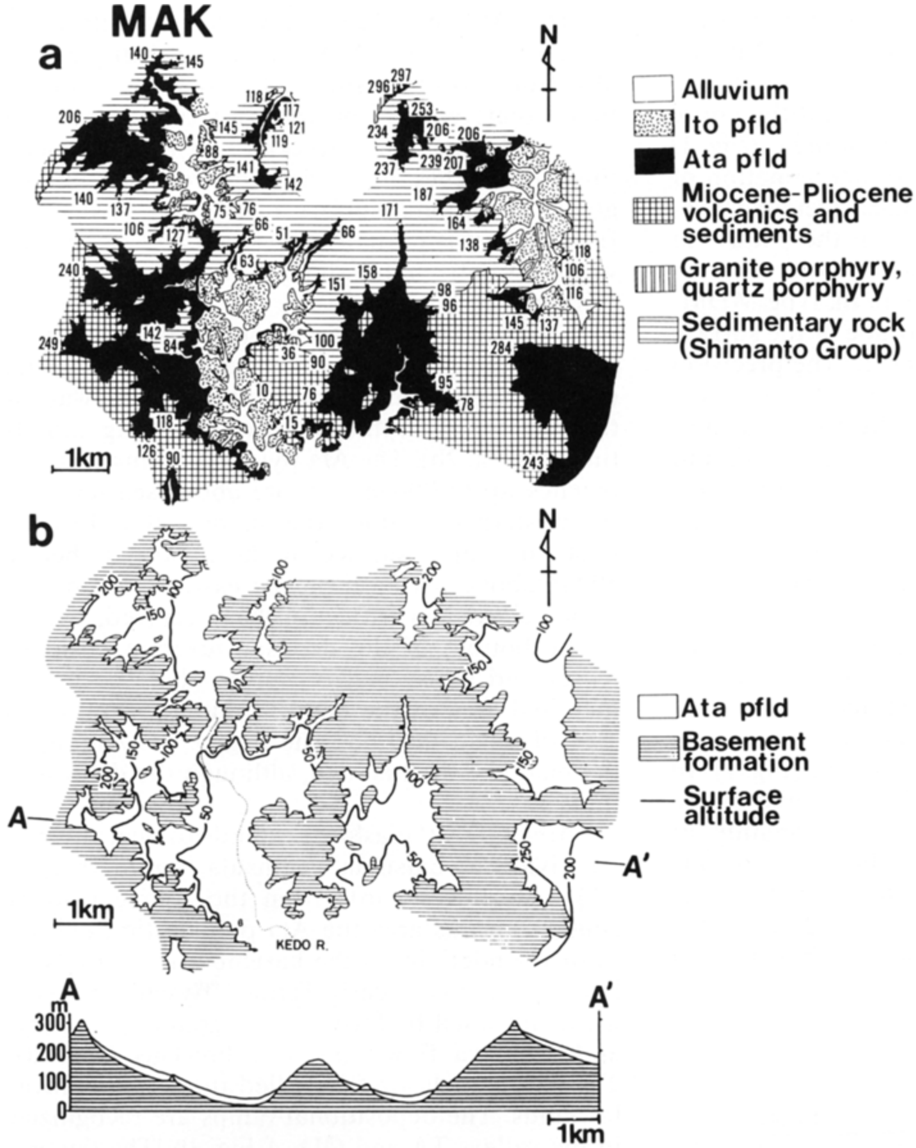

Fig. 2. **a** Geological map and the results of altimetry at area MAK (Fig. 1). **b** The *solid line* shows the contour line of the depositional surface after the welding process, based on altimetry. The *ruled area* is not covered with the Ata pyroclastic flow deposit. The altitude of the depositional surface becomes higher towards the west, within a valley. The thickness of the deposit for *cross section* was estimated, based on the lithological facies. The source caldera of the Ata pyroclastic flow is approximately eastward from this area (Fig. 1)

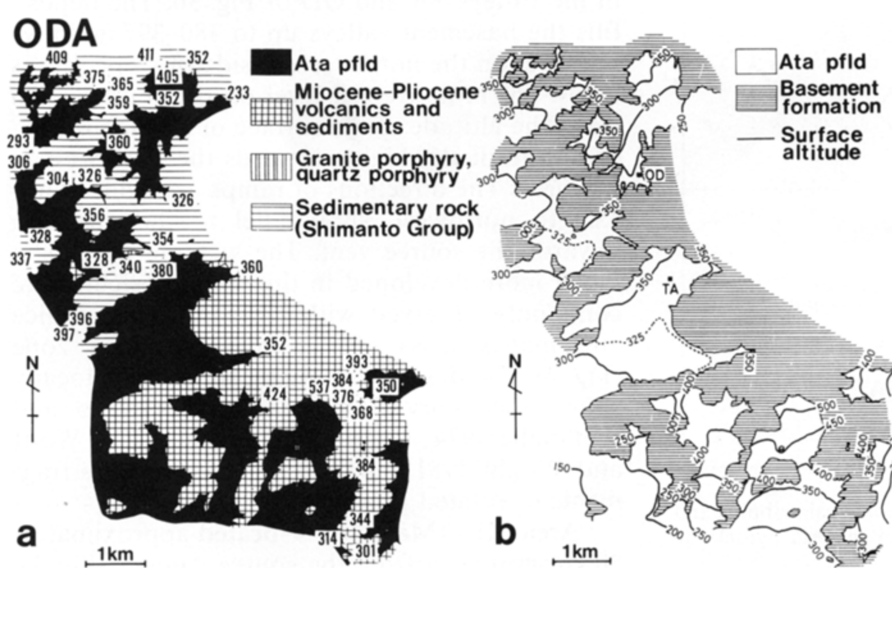

Fig. 3. **a** Geological map and the results of altimetry at area ODA (Fig. 1). **b** Reconstructed depositional surface after welding process of area ODA, based on altimetry. The *ruled area* shows the distribution of the basement formations. The altitude of the depositional surface becomes higher towards the northwest-west

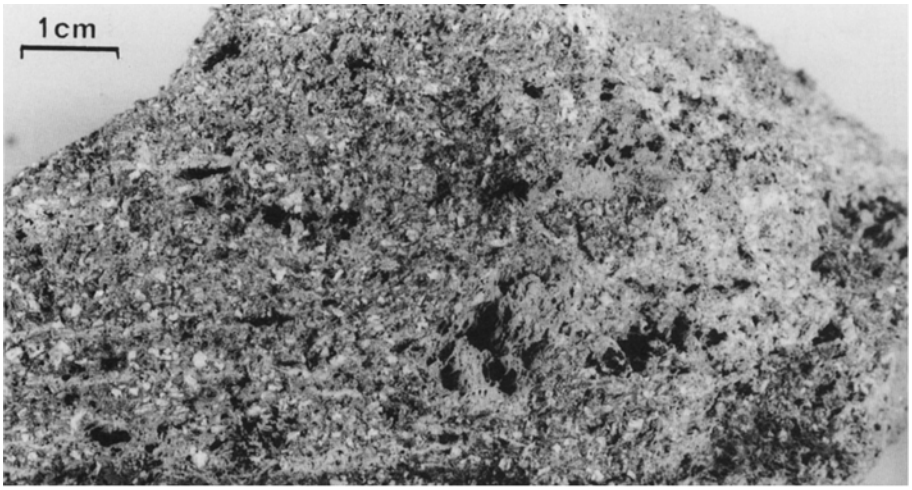

Fig. 4. Hand-specimen of the Ata pyroclastic flow deposit collected from a point 10 km west from the source caldera. Rounded vesicles are present in the flattened juvenile lenses and glassy matrix. These vesicles are considered to be formed by latent degassing within juvenile fragments after the emplacement and trapping of interstitial gas within the matrix, suggesting the high stickiness of essential fragments and matrix glass shards

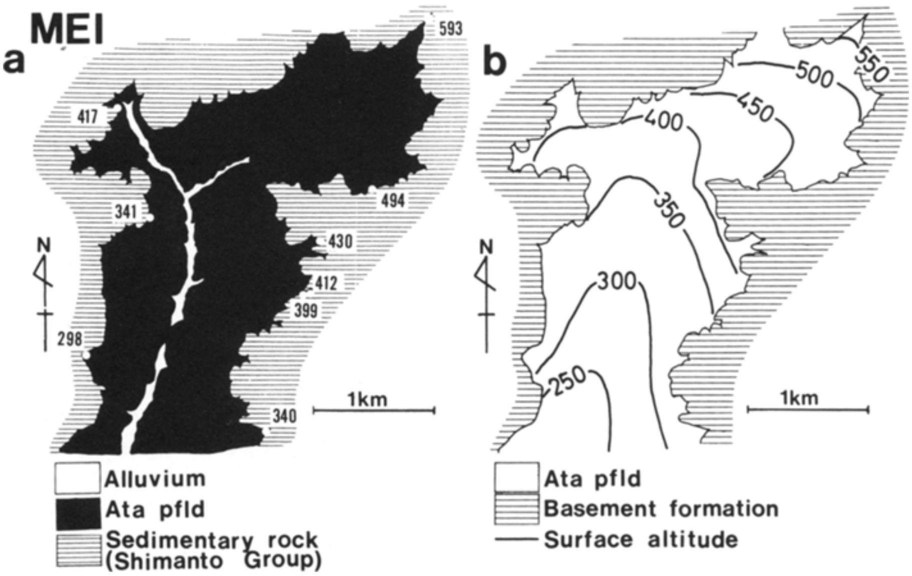

Fig. 5. **a** Geological map and the results of altimetry at area MEI (Fig. 1). **b** Reconstructed depositional surface of the Ata pyroclastic flow deposit in area MEI. The *ruled area* shows the distribution of basement formations. The altitude of the depositional surface becomes higher towards the northeast

The major valley channel within this area extends from north to south and is divided into northwestern and northeastern parts at its upper tributary. The basement formations of this area are Cretaceous flysch-type sediments (Shimanto Super Group) and granitic plutons (Fig. 5a). Pre-flow topography was generally higher towards the north. The level of the distribution of the Ata pyroclastic flow deposit in the eastern side of the paleovalley is approximately 50 m higher than that of the western side (Fig. 5a). The surface altitude is 298 m above sea level at the southwestern side of this area. The reconstructed depositional surface is gradually higher toward the northeastern corner of the valley, reaching 593 m above sea level (Fig. 5b). There are more deposits of the Ata pyroclastic flow in the northeastern fork of the valley than in the northwestern fork. The Ata pyroclastic flow deposit shows advanced devitrification at the centre of the valley, and shows glassy features at the marginal area.

Two pre-flow major valley systems were developed in the southeastern mapped area, SAT (Sata), approximately 30 km southeastwards from the source area (Fig. 1). The upper tributary of one valley is 2 km wide and trends eastwards. This valley system drains towards the mouth of Kagoshima Bay, just south of the caldera. Another valley is 1 km wide and trends southwestwards. This valley drains the Pacific Coast side, southeast of Osumi Peninsula. The basement formations of this area are Paleocene to Eocene flysch-type sediments and granitic complex (Fig. 6a). The Tashiro and Koya pyroclastic flow

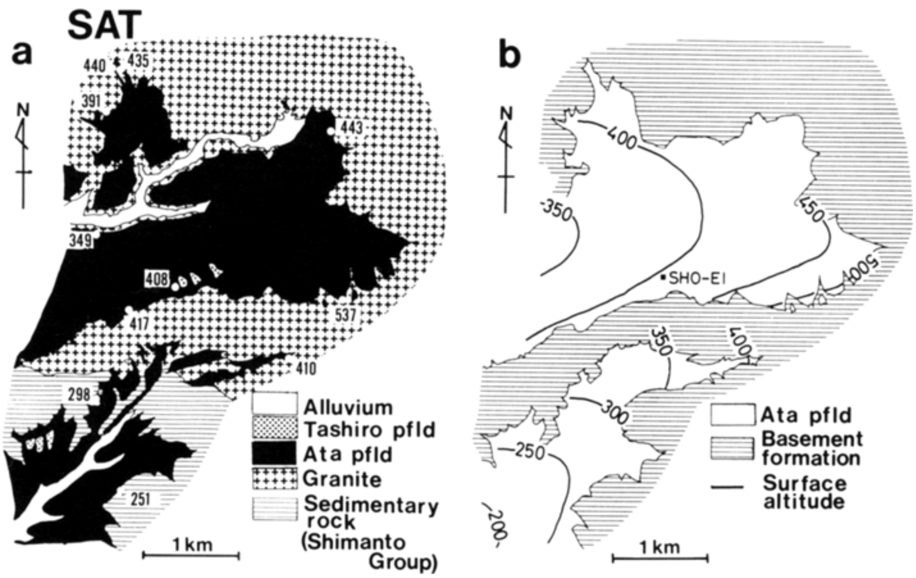

Fig. 6. **a** Geological map and the results of altimetry at area SHO (Fig. 1). **b** The reconstructed depositional surface of the Ata pyroclastic flow deposit in area SHO. The *ruled area* shows the distribution of basement formations. The altitude of the depositional surface becomes higher towards the southeast

deposits thinly cover the Ata pyroclastic flow deposit (Ui 1971; Sakaguchi 1981). The Ata pyroclastic flow deposit fills the paleovalleys forming the major topographical unit. Gully erosion is well developed on the surface of the Ata pyroclastic flow deposit. The thickness of the deposit is up to 50 m in the middle part of the northern valley. The contour map of the reconstructed depositional surface (Fig. 6b) shows that the elevation of the surface of the Ata pyroclastic flow deposit is progressively higher towards the southeast. The highest measured distribution of the deposit is 537 m above sea level on the southeastern side of the northern valley (Fig. 6a). In contrast, the deposit fills the valley until slightly above 400 m above sea level at the upper tributary of the southern valley.

Direction of the depositional ramps

The solid arrows in Fig. 7 show the direction of depositonal ramps based on field mapping and altimetry. The upslope directions of the depositional ramps' structure point generally radially away from the source caldera (Fig. 7). In order to simplify Fig. 7, the orientation of several nearby valley channels are compiled to a single arrow. The open arrows show the estimated directions determined only from the topographical maps and aerial photographs. In the northern area of the Ata pyroclastic flow deposit, it is difficult to identify depositional ramps due to a thick cover of younger pyroclastic flow deposits.

The systematic directional behaviour of the depositional ramps strongly suggests that they were formed by the flow of the pyroclastic flow in directions radial from the source. Depositional ramps develop in wide valleys, and also at marginal areas of pyroclastic flow plateaus where the slope of the underlying topography faces towards the source caldera. Therefore, this structure is interpreted to be formed by large-scale accumulation of pyroclastic flow materials on a source-facing slope rather than on a slope facing away from the source. In contrast, flow direction determined by grain orientation analysis reflects the local flow direction prior to the final emplacement (Suzuki and Ui 1982).

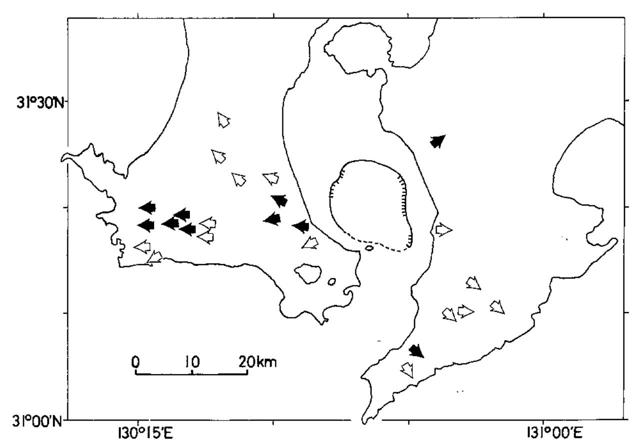

Fig. 7. Direction of depositional ramps: *solid arrow*, confirmed directions by field mapping and altimetry; *open arrow*, estimated direction from topographical maps and aerial photographs

Scale and lateral variation of the depositional ramps

The size and gradient of depositional ramps systematically change with increasing distance from the source, and with the size of valley. The size of depositional ramps was defined by two parameters H and L (Table 1, Figs. 8, 9). H is the difference in elevation from the point where the dip angle is zero near the centre of valley to the point at the edge of the deposit. L is the horizontal distance between these two points. The solid line in the cross-section of Fig. 9 shows the present surface of the Ata pyroclastic flow deposit; the dotted line shows the reconstructed depositional surface prior to welding based on the density measurements. H of the depositional ramps is higher with increasing L (Fig. 9). The depositional ramps cannot be recognized in valleys less than 1 km wide because H is too small.

Figure 10 shows the relationship between the height difference of the depositional ramps (H) and the distance of the ramps from the source caldera. The range of H data expressed as a vertical bar indicates the present topography for possible minimum H and the reconstructed pre-welding topography for maximum H. The relative height (H) decreases with increasing distance from the source. In the area approximately 12 km away from the source, H is 340 m, which is the maximum value for the Ata pyroclastic flow deposit.

Figure 11 shows the relationship between the mean gradient ($\theta = H/L$) and the distance from the source. Only data having L greater than 1 km are plotted. The mean gradient ($\theta = H/L$) decreases away from the source (Fig. 11). These data suggest that the gradient of depositional ramps decreases away from the source. The original dip of previously described large-scale pyroclastic flow deposits is less than 3.5° (Sheridan 1979). Such nearly horizontal depositional surface is regarded as evidence of low viscosity in the fluidized bed. The gradient of the depositional ramps observed in the Ata pyroclastic flow deposit is generally within 4°, but is beyond 9.1° after making the correction for welding compaction at the margin of the valley 10 km away from the source caldera. A dip angle of 9.1° is far beyond the repose angle of large-scale pyroclastic flow deposits previously described.

Table 1. The size (L, H) and gradient (θ) of the depositional ramps

Locality	L(m)	H(m)	H/L	$\tan^{-1}\theta$	Distance from the source (km)
MA 1	1125	60–110	0.053–0.098	3.1–5.6	40.0
MA 2	2000	140–190	0.070–0.095	4.0–5.4	39.0
MA 3	1125	10– 50	0.009–0.044	0.5–2.5	35.0
MA 4	1000	30– 60	0.030–0.060	1.7–3.4	33.5
MA 5	1125	50– 90	0.044–0.080	2.5–4.6	33.0
MA 6	500	10– 40	0.020–0.080	1.2–4.6	35.0
MA 7	250	10– 40	0.040–0.160	2.3–9.1	37.5
MA 8	2125	90–130	0.042–0.061	2.4–3.5	31.0
MA 9	1875	70–120	0.037–0.064	2.1–3.7	31.0
MA10	2750	170–220	0.062–0.080	3.5–4.6	39.0
OD1	1250	120–160	0.096–0.128	5.5–7.3	16.5
OD2	750	50– 80	0.067–0.107	3.8–6.1	16.5
OD3	125	10– 20	0.080–0.160	4.6–9.1	18.0
OD4	375	0– 20	0.000–0.053	0.0–3.1	19.0
OD5	175	0– 20	0.000–0.114	0.0–6.5	19.5
OD6	500	10– 30	0.020–0.060	1.2–3.4	17.0
OD7	1125	30– 60	0.027–0.053	1.5–3.1	17.5
OD8	2750	260–320	0.095–0.116	5.4–6.6	11.5
OD9	2125	280–340	0.130–0.160	7.5–9.1	12.0
ME1	2375	70–160	0.030–0.067	1.7–3.9	18.0
ME2	2500	160–270	0.064–0.108	3.7–6.2	17.5
ME3	1250	80–150	0.064–0.120	3.7–6.8	17.0
S1	1500	70–130	0.047–0.087	2.7–5.0	26.0
S2	1625	50–130	0.031–0.080	1.8–4.6	26.0
S3	425	0– 20	0.000–0.047	0.0–2.7	28.5

Possible mechanism to form depositional ramps

Depositional ramps are recognized only in welded large-scale pyroclastic flow deposits, not in unwelded deposits. Other examples of depositional ramps are the Aso-4 pyroclastic flow deposit erupted from the Aso caldera, Kyushu (Saito et al. 1958) and the Noboribetsu pyroclastic flow deposit erupted from the Kuttara caldera, Hokkaido (Minato et al. 1972). These cases were detected only from aerial photographs and published geological maps. Depositional ramps of both pyroclastic flow deposits developed in wide valleys sloping upwards away from the source caldera. Both deposits are densely welded. The depositonal ramps' structure is not detected in nonwelded pyroclastic flow deposits, for example, the Ito pyroclastic flow deposit in southern Kyushu. Wilson and Head (1981) described the nonwelded pyroclastic flow deposits of Mount St. Helens, which erupted on July 22 and August 7 1980. These retained low viscosity for several weeks after the emplacement. This evidence suggests that in the case of non-welded pyroclastic flows depositional ramps, if they formed they would adjust to form a horizontal depositional

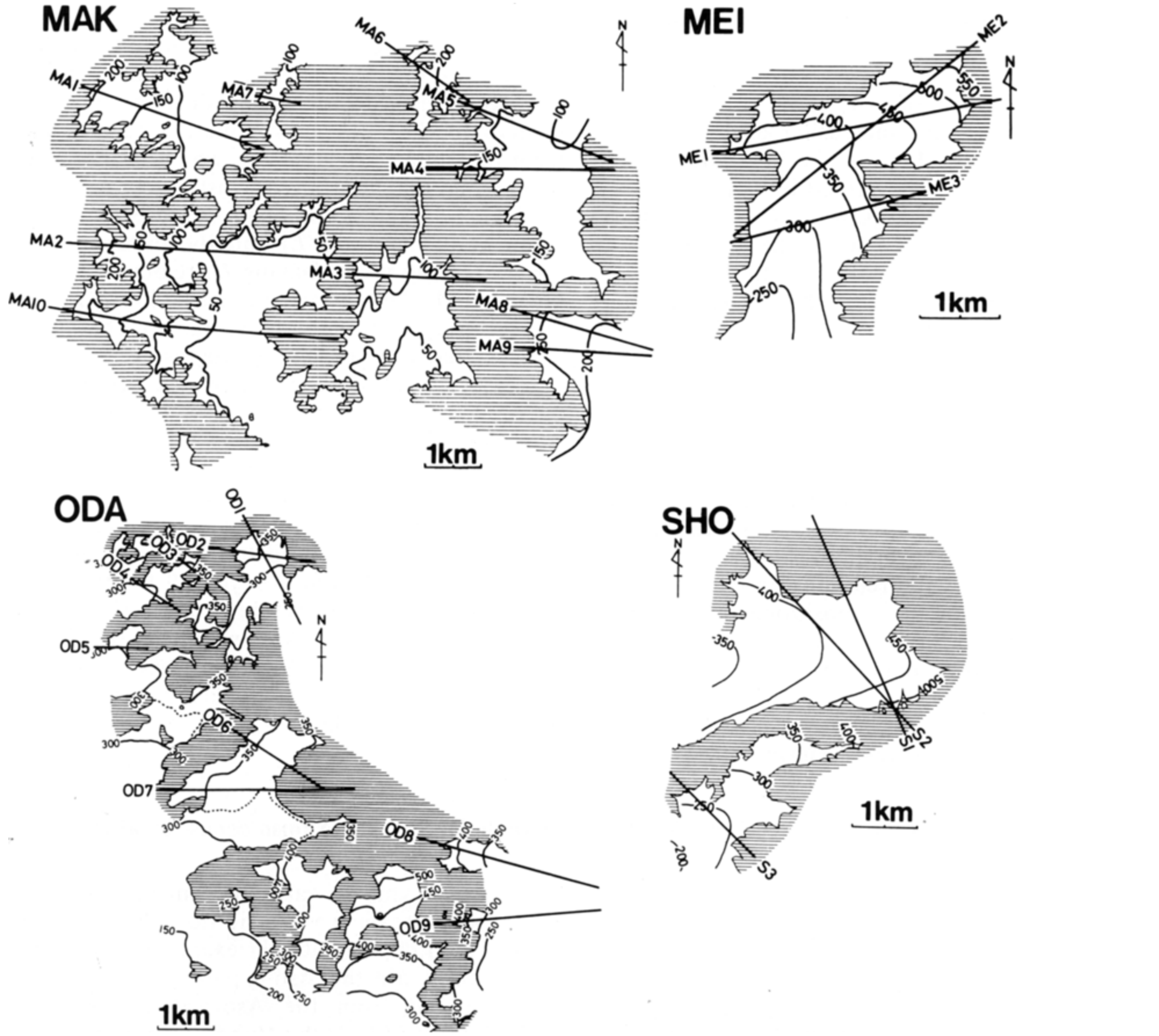

Fig. 8. Index map of cross sections to measure the size and gradient of depositional ramps in each valley at the four main areas

surface after the flow was trapped within a valley or basin.

A fluidization experiment using fine glass material at high temperature shows that the repose angle of hot fluidized material after settlement is larger than that of low temperature material (K. Yoshida, personal communication 1983). This suggests that high temperature glassy materials may easily stick together. It follows that the stickiness of pyroclastic flow materials controls the repose angle of the deposit and the formation of depositional ramps.

Round vesicles are observed within flattened juvenile fragments and also in the glassy matrix of the welded Ata pyroclastic flow deposit near the source (Fig. 4). The vesicles within juvenile fragments are thought to be formed by latent degassing after the emplacement. Interstitial gas within the matrix was also trapped to form tiny vesicles. This evidence suggest that welding compaction in the Ata pyroclastic flow deposit started soon after emplacement. This phenomenon supports the high sticky nature of the matrix portion of the Ata pyroclastic flow. Based on an experimental study, Boyd (1961) showed that heat loss during flowage was small. It follows that the most effective process of heat loss is cooling within the eruption column. The interpreted high temperature of the Ata

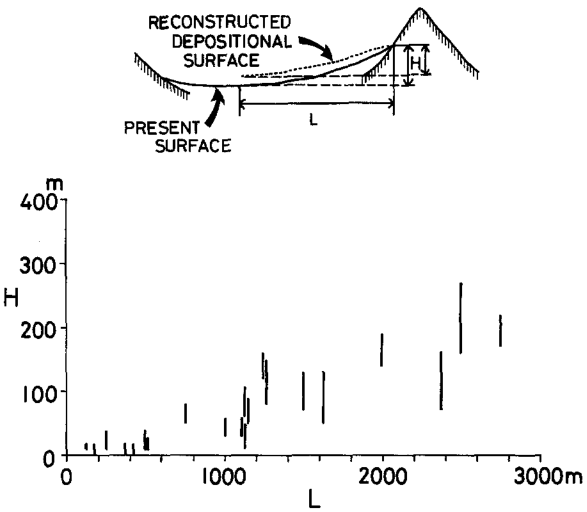

Fig. 9. Length (*L*) to height (*H*) relationship of depositional ramps. *L* is the distance between the distal distribution end and the nearest flat site. *H* shows the difference of altitude between the distal distribution end and the nearest flat site. The *vertical bar* expresses the height difference between the height of the present surface and the height of the original depositional surface prior to welding at the same points

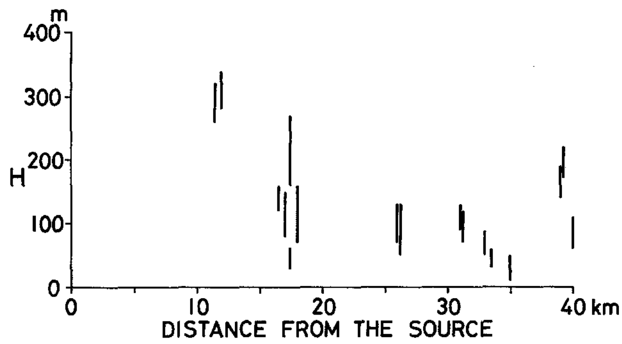

Fig. 10. The relationship between relative height (*H*) and the distance from the source for depositional ramps. Only data where length (*L*) is more than 1 km are plotted. The vertical bar of *H* is the same as Fig. 9. *H* becomes smaller with increasing distance from the source

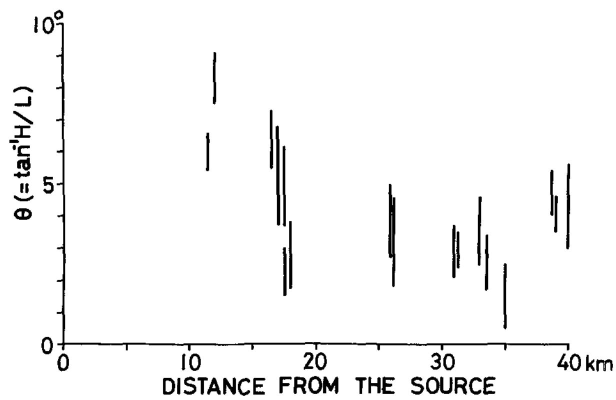

Fig. 11. Graph showing the relationship between $\theta = (\tan^{-1}(H/L))$ and the distance from the source. The *vertical bar* shows the range based on present *H* and original *H* prior to welding. θ becomes smaller with increasing distance from the source

pyroclastic flow at the time of emplacement suggests a relatively low-level collapse producing a dense fluidized layer, which effectively preserved heat energy until the emplacement of the pyroclastic flow deposit. Such a dense fluidized layer is suggested as the mechanism to form the depositional ramps in the Ata pyroclastic flow deposit. The depositional ramps' structure may develop extensively in a pyroclastic flow deposit which shows a secondary flowage structure.

Conclusion

Detailed geological mapping and altimetry shows an asymmetrical distribution within valleys in the Ata pyroclastic flow deposit. Such structures were named depositional ramps (Suzuki and Ui 1982). The direction of the ramps shows that the flow of the pyroclastic material was radial away from the source. The depositional ramps are recognized in valleys with widths of more than 1 km. The relative height difference within depositional ramps is greater in the wider valleys. The original depositional surface was reconstructed based on the density measurements and showed a high dip angle, which means a high angle of repose, considerably larger than non-welded large-scale pyroclastic flow deposits. The size and gradient of ramps decrease with increasing distance from the source. Depositional ramps are recognized at two other densely welded large-scale pyroclastic flow deposits.

The Ata pyroclastic flow deposit near the source includes rounded vesicles in flattened juvenile lenses and glassy matrix. These vesicles are thought to be formed by latent degassing within juvenile fragments after emplacement and by trapping of interstitial gas within the matrix, suggesting that matrix glass shards stick together. A denser fluidized layer is proposed to preserve heat during the flowage, and allow particles to stick together easily soon after emplacement.

The preferred orientation of the depositional ramps also suggests that the pyroclastic flow selectively emplaces at the side facing the source of a topographical barrier. This is because the velocity decreases when the flow climbs up the slope.

The following process is indicated for the formation of depositional ramps. The Ata pyroclastic flow started from a low-level column collapse and formed a dense fluidized layer that moved radially away from the source, ascending and descending topographical barriers. The pyroclastic flow tended to flow away from the lee-side slopes because the flow accelerates when it descends the slope. In contrast, the pyroclastic flow tends to form a deposit on the sourceward-facing side slope because the velocity decreases, and some parts of the pyroclastic flow materials flow back towards the bottom of the valley. The pyroclastic flow materials form a hot and dense fluidized layer that easily sticks together early on during emplacement. The sticking process may start at the final stage of flowage, just before emplacement. Because of advanced stickiness, the deposit forms the depositional ramps sloping upwards away from the lee-side, without permitting flow back towards the valley bottom.

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