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The proximal facies of the Tosu pyroclastic-flow deposit erupted from Aso caldera, Japan

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Abstract. The Tosu pyroclastic flow deposit, a low-aspect-ratio ignimbrite (LARI), has widely distributed breccia facies around Aso caldera, Japan. The proximal facies, 9-34 km away from the source, consists of 3 different lithofacies, from bottom to top: a lithic-enriched and fines-depleted (FD) facies, a lithic-enriched (LI) facies with an ash matrix, and a fines- and pumice-enriched (NI) facies. Modes of emplacement of FD, LI, and NI are interpreted as ground layer, 2b-lithic-concentration zone, and normal ignimbrite, respectively. These stratigraphic components in the Tosu originated from the flow head (FD) and the flow body (LI and NI), and were generated by a single column collapse event. Remarkably thick FD and LI, in contrast to thin NI, suggest that due to high mobility most ash and pumice fragments in the Tosu were carried and deposited as NI in the distal area. Heavier components were selectively deposited as FD and LI in the proximal area. The rate of falloff of lithic-clast size in the Tosu shows an inflection at 20 km from the source. In a survey of well-documented pyroclastic flows, the inflection distance of a LARI is generally greater than that of a high-aspect-ratio ignimbrite, so that the eruption of the former is probably more intense than the latter.

Introduction

Aso caldera lies in the southwestern Japan Island Arc and is the largest caldera in this region. It has undergone four eruption cycles: the first (Aso-1) 300000 years ago and the most recent (Aso-4) 70000 years ago (Ono et al. 1977; Ono and Watanabe 1983a; Machida et al. 1985). Repose intervals of a few tens to hundreds of thousands of years occurred between eruption cycles. The Tosu pyroclastic flow deposit is one of eight pyroclastic flow members in the Aso-4 cycle (Watanabe 1978). Available evidence suggests that Aso caldera formed not by sinking of a coherent cylindrical block, as exemplified by Valles-type calderas, but by piecemeal collapse of roof rock (Ono and Watanabe 1983a). The Tosu pyroclastic flow was probably erupted from a central vent within Aso caldera.

The Tosu pyroclastic flow deposit has a prominent proximal facies on and adjacent to the Aso caldera wall. Typical proximal facies of the Tosu consists mainly of a breccia facies, which is rich in coarse-grained accidental lithic clasts, and overlying normal ash flow deposits. The proximal facies of the Tosu occurs as far as 34 km from the center of Aso caldera.

Proximal breccias have been previously reported in three pyroclastic flow deposits: the Cape Riva deposit at Santorini, Greece (Druitt and Sparks 1982), the Taupo ignimbrite, New Zealand (Wilson 1985), and the climactic ring-vent-phase ignimbrite at Crater Lake, Oregon (Druitt and Bacon 1986). Proximal breccias commonly occur in intimate association with ignimbrite (Druitt and Sparks 1982; Druitt and Bacon 1986) and have been interpreted as the products of deposition within the near-vent deflation zones of pyroclastic flows (Walker 1985; Druitt and Bacon 1986). However, in previous studies descriptions of the lateral variation of these breccias have been inadequate to test this interpretation.

In the Tosu pyroclastic flow deposit lateral variation of the breccia facies can be examined in detail because of the following advantages: (1) preservation is good because the deposits are relatively young; (2) most of the Tosu occurs on land so that cross sections of proximal and distal facies can be obtained over a radial distance of 155 km; (3) since the Tosu is the most recent pyroclastic deposit from Aso caldera, the complete sequences through the proximal facies are preserved in many places near the caldera rim; and (4) topographic effects are minimal, especially north of Aso caldera, because the underlying Aso-4A ignimbrite formed a vast flat plateau immediately before the Tosu eruption.

In this paper we present field descriptions and grain size analyses of the proximal facies of the Tosu pyroclastic flow deposit. We also compare the proximal fa-

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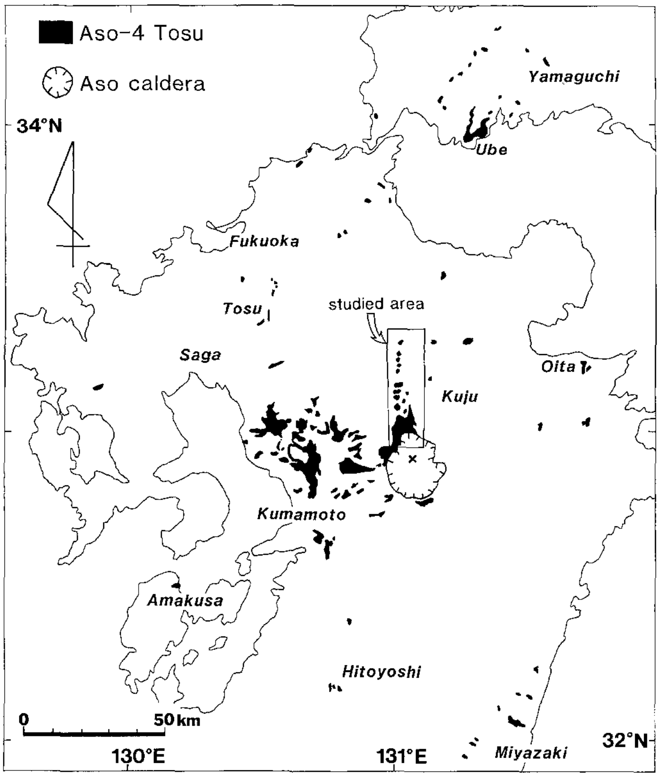


Fig. 1. Distribution map of the Tosu pyroclastic flow deposit, modified after Watanabe (1984)

cies with other examples and discuss the emplacement mechanism of the Tosu pyroclastic flow. Our main conclusion is that the proximal facies of the Tosu originated as deposits from the flow head and flow body, which were segregated from the lower and heavier portion of a single eruption column.

Geology of the Tosu pyroclastic flow deposit

The Tosu pyroclastic flow deposit is distributed around Aso caldera and across the sea to the west, southwest, and north (Fig. 1). Remarkably, it reaches as far as 155 km from the source and contains low-density (0.2–0.3 g/cm^3) rhyolitic pumice (Watanabe 1978). The characteristic orange color of the matrix is useful for identification of the Tosu (Watanabe 1978). The thickness of the Tosu averages less than 2 m but is as much as 7 m at the north caldera rim. The Tosu is a low-aspect-ratio ignimbrite (LARI; Walker et al. 1980); it is composed mostly of a non-welded veneer deposit with an extraordinarily wide distribution. No valley-pond deposit is recognized in the Tosu. The Tosu consists of one flow unit, because neither flow unit boundaries (Smith 1960) nor any evidence of repose are found within the Tosu. The bulk and uncompacted volume of the Tosu is estimated to be about 10 km^3 (Watanabe 1978).

In the proximal area (9–34 km from the center of Aso caldera) the Tosu is less than 7 m thick and is composed mostly of heterogeneous breccias that display lateral variation in lithology and thickness over distances of meters to tens of meters. Near the caldera rim, the Tosu has abundant coarse accidental lithic breccias with small amounts of ignimbrite (Fig. 2), and lithic breccias comprise most of the deposit. In the distal area (34–155 km) the Tosu is less than 1.5 m thick and is mostly composed of poorly sorted ignimbrite that is massive and relatively homogeneous lithologically.

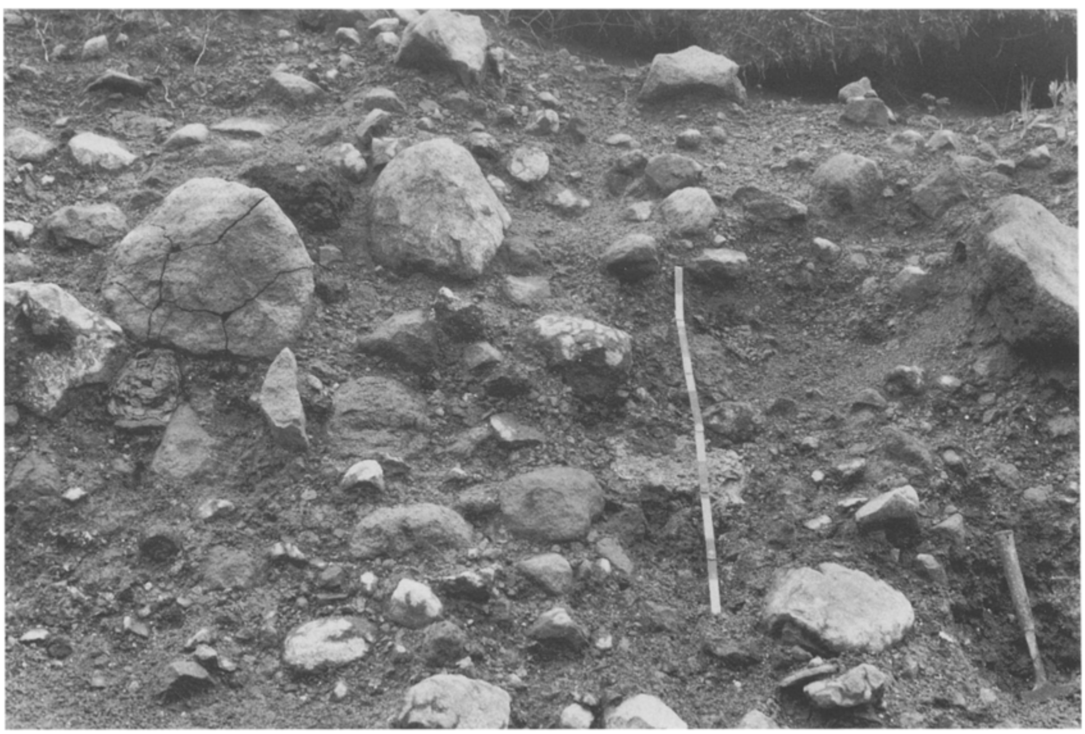


Fig. 2. Typical proximal breccia facies, displaying abundant coarse-grained accidental lithic blocks and small amount of rounded pumice with a fine-ash-depleted matrix (FD facies). The scale is 1 m long. Location, 14 km from the center of Aso caldera

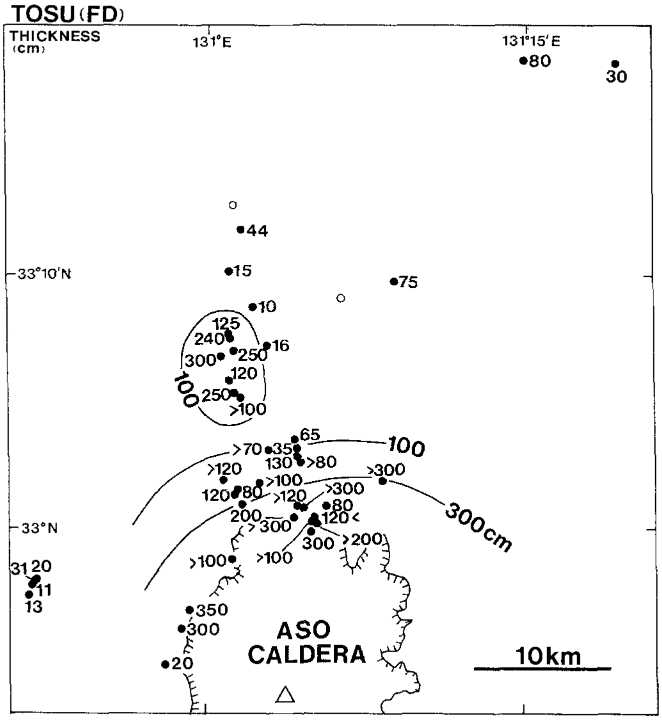


Fig. 3. Isopach map of FD facies; thickness in cm. *Dot*, location where FD identified. *Circle*, location where FD is absent. *Triangle*, the center of Aso caldera

Proximal facies of the Tosu pyroclastic flow deposit

The thickness of the proximal breccias of the Tosu is 7 m maximum at the caldera rim and less than 50 cm at

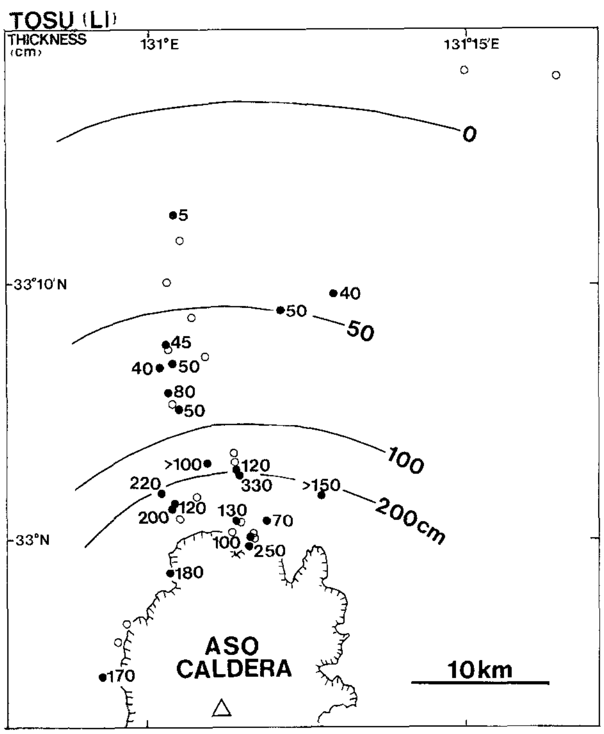


Fig. 4. Isopach map of LI facies; thickness in cm. *Dot*, location where LI identified. *Circle*, location where LI is absent. *Triangle*, the center of Aso caldera

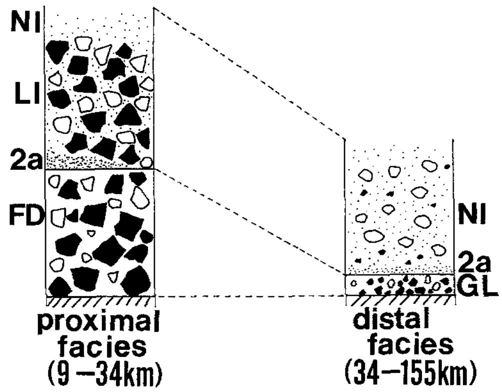


Fig. 5. Generalized stratigraphic column of the Tosu pyroclastic flow deposit. *NI*, normal ignimbrite; *LI*, lithic concentration; *2a*, layer 2a; *FD*, fines-depleted breccia; *GL*, ground layer

a distance of 30 km from source. Lithic clasts up to 3 m in diameter are present on the caldera rim, and the coarse nature of the breccias is maintained northward as far as 34 km from the center of Aso caldera.

In the proximal area north of the caldera (Figs. 1, 3, 4), the Tosu shows three different lithofacies, from bottom to top (Fig. 5): (1) A FD (fines-depleted) facies abundant in coarse-grained lithic fragments and depleted in fine ash; (2) an LI (lithic concentration) facies abundant in coarse-grained lithic fragments with fine-ash matrix; (3) normal ignimbrite (NI) abundant in fine ash and pumice and relatively poor in lithic fragments. FD is present everywhere at the base of the Tosu deposit (Fig. 5). Where NI is well preserved, it always overlies LI and/or FD. LI occurs between FD and NI and commonly pinches and swells laterally. Although the lithofacies vary in details among adjacent outcrops, the three lithofacies are generally identifiable in almost all outcrops in the proximal area (9–34 km).

FD facies

FD is clast supported, contains abundant lithic fragments up to 1.8 m in diameter, contains a small amount of rounded pumice, and has a matrix that is depleted in fine ash. The lithic clasts are heterolithologic with angular to subangular types that include andesite, rhyolite, scoriae, older Aso welded tuffs, altered andesite, amphibolite, granite, schist, and clots of soil. FD is less than 3 m thick at the caldera rim and less than 1 m thick more than 20 km from the center of Aso caldera (Fig. 3). FD is generally massive and has a darker color than NI and LI owing to its greater lithic concentration. At an outcrop on the north caldera rim (Daikanbou; 12 km from source) FD shows vague stratification as well as foreset bedding of the larger lithic-rich layers and of the layers abundant in smaller lithic fragments and pumice (Fig. 6). The contact between FD and overlying LI or NI is commonly sharp (Fig. 5). At 17 km from the source, massive FD intrudes into overlying LI as pipelike structures, and the boundary between FD and LI is irregular and wavy (Fig. 7).

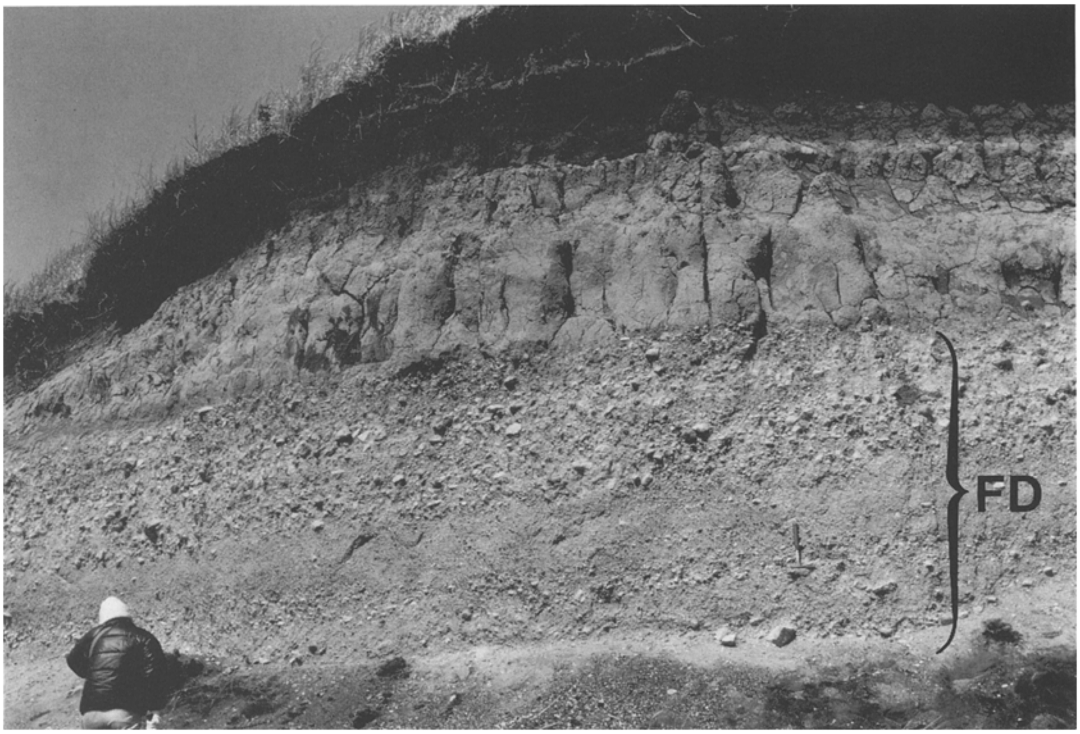


Fig. 6. FD facies showing vague stratification and foreset bedding of larger lithic-rich layers and layers abundant in smaller lithic fragments and pumice. The base of FD is not exposed. NI facies 30 cm thick overlies the FD facies. Hammer is 35 cm long. Location, 12 km from the center of Aso caldera

Cumulative-wt% diagrams indicate that FD is rich in coarse fragments and depleted in fine materials in comparison with NI (Fig. 8). FD has a bimodal distribution with a mode in the >4-mm fraction due to lithics, and another mode in the 1/2–1/4 mm fraction due to crystals. The diagram of median diameter (Md-phi) vs standard deviation (sigma-phi) shows that most plotted FD samples fall outside of the pyroclastic flow

Fig. 7. FD facies that intruded into the overlying LI facies showing segregation pipe structure. The boundary between FD and LI is wavy. The scale is 1 m long. Location, 17 km from the center of Aso caldera

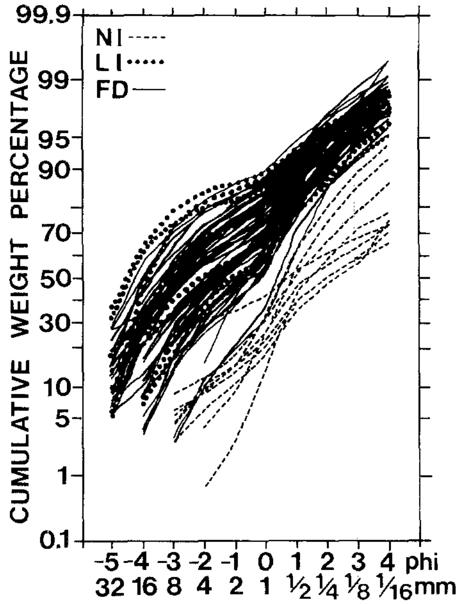


Fig. 8. Cumulative wt% curves of grain size data for *NI, LI,* and *FD* in the proximal area

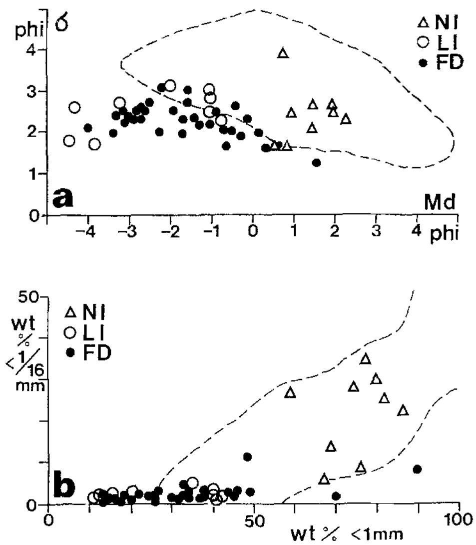


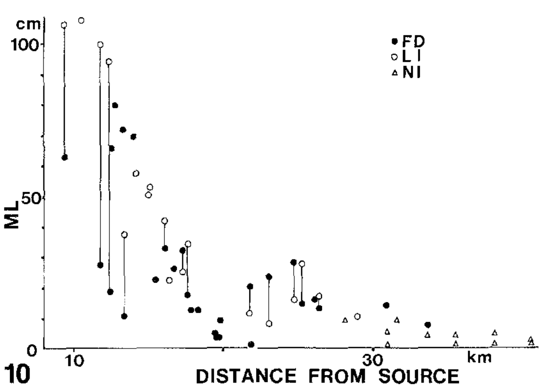
Fig. 9 a, b. Grain size characteristics of NI, LI, and FD. **a** sigma-phi vs Md-phi plot. *Dotted line* outlines pyroclastic flow field of Walker (1983). **b** fines depletion diagram (wt% sub-1/16 mm vs wt% sub-1 mm). *Dotted lines* outline pyroclastic flow field of Walker (1983)

field of Walker (1983), indicating that FD is better sorted than common ignimbrite (Fig. 9a). The diagram of wt% of < 1/16 mm vs < 1 mm shows that FD is more deficient in fine-ash material than common ignimbrite and the NI facies of the Tosu (Fig. 9b). Like air-fall deposits the FD is relatively well sorted. Unlike air-fall deposits, however, the FD has imbricated clasts, shows erosion of underlying beds, and lacks impact-sag structures at its base; underlying beds are largely undisturbed by even large clasts.

The average of three largest-maximum-lithic clasts (ML) in FD generally decreases steadily with distance from the source, but shows a slope change 20–30 km from the source (Fig. 10). Around 25 km from the source, where the pyroclastic flow passed over topographic ridges, FD displays secondary thickening (Fig. 3) and coarsening (Fig. 10) and shows dune structures with stratification resembling that of pyroclastic surge deposits. Suzuki-Kamata (1988) reported that in the Ata pyroclastic flow deposit, Japan, both ML and ground-layer thickness increase beyond a topographic ridge. Like the ground layer of the Ata, FD in the Tosu becomes thicker and coarser, occasionally showing dune structure, beyond a topographic ridge about 25 km from the source.

LI facies

LI is composed of abundant, coarse-grained, subangular lithic fragments and a small amount of rounded pumice in a fine-ash matrix. The matrix consists of poorly sorted ash and lapilli rich in juvenile components. Lithic clasts in LI are heterolithologic like those of FD, and we could not find any differences in lithology of clasts between LI and FD. LI commonly overlies FD with a sharp contact and underlies NI with gradational contact (Fig. 5). A layer 2a (Sparks et al. 1973), com-



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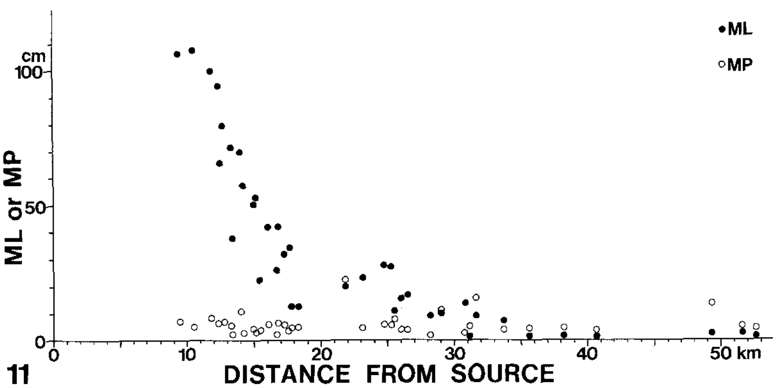

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Fig. 10. Average of the three largest-maximum-lithic clasts (*ML*) vs distance from the center of Aso caldera. *Tie lines* show data obtained from the same outcrop

Fig. 11. Average of the three largest-maximum-lithic clasts (*ML*) and average of the three largest-maximum pumice (*MP*) vs distance from the source

posed mostly of fine ash, locally occurs at the base of LI (Fig. 5). LI grades laterally into NI about 34 km from the source. LI is less continuous than FD and pinches and swells laterally among adjacent outcrops. The thickness of LI reaches a maximum of 3.3 m near the caldera rim and decreases monotonically with distance from the source (Fig. 4). On a smaller scale, thickness varies over lateral distances of a few tens of meters. LI contains lithic clasts up to 3 m in diameter; ML decreases steadily with distance from the source (Fig. 10). LI is generally massive within an outcrop that is several meters wide, but in some places it shows vague normal grading of lithic fragments. LI contains fines-depleted segregation pipes, whose diameter is less than 10 cm.

The cumulative-wt% diagram indicates that LI, like FD, contains abundant coarse fragments, and LI is difficult to discriminate from FD (Fig. 8). However, LI was easily discriminated from FD in the field because of the existence of fine-ash matrix within LI. LI has a bimodal grain size distribution, with a mode in the >4-mm fraction due to lithics, and another mode in the 1/2–1/4-mm fraction due to crystals. Figure 9a shows that most LI samples plot on the margin to or outside of Walker's (1983) pyroclastic flow field.

NI facies

NI is composed of fine ash and well-vesiculated pumice with a small proportion of lithic fragments. In the proximal area (9–34 km), NI is a minor deposit in comparison to the underlying LI and FD and is locally absent. Conversely, NI is the predominant constituent in the distal area (34–155 km; Fig. 5). In the proximal area, NI is less than 1 m thick, but in the distal area is about 1.5 m thick. The thickness of NI in the proximal area does not decrease systematically away from the source. The thickness of NI changes like that of LI, pinching and swelling among adjacent outcrops. NI is structureless in both proximal and distal areas, in contrast to the stratified veneer deposit of the Taupo ignimbrite (Walker et al. 1980). Layer 2a in places lies between NI and FD (Fig. 5). In the distal area a typical ground layer (Walker et al. 1981a) less than 3 cm thick occurs at the base of NI (Fig. 5).

A cumulative-wt% diagram indicates that NI is distinctly more abundant in fine ash than FD and LI (Fig. 8). Figure 9a shows that most NI samples yield values that plot in pyroclastic flow field of Walker (1983), although two NI values fall in the slightly better-sorted area. Figure 9b also indicates that NI is more abundant in fine ash than are FD and LI.

Mode of emplacement of FD, LI, and NI

The three subfacies of the proximal facies (FD, LI, and NI) are interpreted to be constituents of a single flow unit of a pyroclastic flow: the ground layer, 2b-lithic-concentration zone, and normal ignimbrite, respectively. The ground layer was derived from the flow head, and the other two facies were derived from the flow body.

The FD deposit of the proximal area has characteristics of the ground layer and is continuous with and stratigraphically correlative with the ground layer of the distal area (Fig. 5): FD was derived from the flow head of the pyroclastic flow by injection of air and was overridden by the flow body (Walker et al. 1981a).

LI is interpreted as a proximal lensoid variant of NI, in which coarser and heavier lithic fragments are selectively concentrated. This interpretation is supported by the following evidence: (1) LI occurs only in the proximal area (9–34 km); (2) LI commonly grades upward into NI in the proximal area; 30–40 km from source LI grades laterally into NI and gradually thins and disappears over distances of a few kilometers; (3) layer 2a lies at the base of LI in the proximal area but at the base of NI in the distal area (Fig. 5); (4) LI has fine ash in its matrix. These lines of evidence suggest that LI is equivalent to the layer-2b lithic-concentration zone of Sparks et al. (1973). The mode of occurrence of LI is also the same as that of the "basal-concentration zone of lithic fragments", which occurs as lensoid aggregations of breccias in the Ito pyroclastic flow deposit, Japan (Yokoyama 1974). We interpret LI in the Tosu as a lithic-segregation breccia formed by sedimentation of lithic blocks through the body of the pyroclastic flow.

NI is the uppermost facies in the proximal area, and is correlative with the dominant facies in the distal area (Fig. 5). We interpret NI as ignimbrite deposited from the body of the pyroclastic flow (Wilson and Walker 1982).

Comparison of the proximal facies with that of other deposits

A few reports have previously described the proximal facies of large-scale pyroclastic flow deposits, such as the Cape Riva deposit at Santorini (Druitt and Sparks 1982), the Taupo ignimbrite (Wilson 1985), and the climactic ring-vent-phase ignimbrite at Crater Lake (Druitt and Bacon 1986).

The stratigraphic sequence within the proximal facies of the Tosu resembles that of the Cape Riva but differs from that in the Taupo and Crater Lake deposits. The Taupo ignimbrite comprises, from bottom to top, jetted deposit, ground layer, and normal ignimbrite (Wilson 1985). The jetted deposit is a pumiceous, fines-depleted unit, generated by the expulsion of material from the flow front. The overlying ground layer is a fines-bearing variety in the proximal area, in contrast to a fines-depleted variety in the distal area (Wilson 1985). In the Tosu no jetted deposit underlies the ground layer, and no fines-bearing variety of ground layer occurs. The proximal facies at Crater Lake consists of fines-depleted, coarse-grained, poorly bedded, lithic breccias and an overlying veneer deposit (Druitt and Bacon 1986). No fines-enriched lithic breccia, like LI in the Tosu, occurs at Crater Lake. Because it is impossible at present to correlate different stratigraphic sequences between the Taupo, Crater Lake, and Tosu deposits, we will focus on a comparison of the stratigraphy of the Tosu and the Cape Riva deposits.

The stratigraphic sequence of the proximal facies of the Cape Riva comprises, from bottom to top, "ground breccia", "basal layer", "main lithic breccia", and "ignimbrite". The sequence in the Tosu comprises, from bottom to top, FD, layer 2a, LI, and NI (Fig. 5). We interpret FD in the Tosu as the ground layer of Walker et al. (1981), just as Druitt and Sparks (1982) interpreted the ground breccia in the Cape Riva. The basal layer in the Cape Riva was interpreted as layer 2a of Sparks et al. (1973), and we so interpret layer 2a of the Tosu. We interpret LI in the Tosu as layer-2b lithic-concentration zone of Sparks et al. (1973). We interpret the LI in the Tosu as having originated from segregation of lithic clasts within the bodies of dense, but strongly fluidized pyroclastic flows. Druitt and Sparks (1982) similarly interpreted the main lithic breccia in the Cape Riva.

Emplacement mechanism of the Tosu pyroclastic flow

A single column collapse

Stratigraphic components of the Tosu resemble those of a pyroclastic flow deposit generated from a single event of column collapse. The existence of a single ground layer and a single layer 2a overlain by a lithic-concentration breccia and by normal ignimbrite suggests that the Tosu deposit was laid down by a single pyroclastic flow. We therefore interpret the Tosu as the product of a single column collapse event.

Segregation of flow head from flow body

Existence of a ground layer in the Tosu suggests that a turbulent flow head and a flow body had already developed when the Tosu was emplaced in the proximal area. In the Tosu, FD (ground layer) is clearly separated from LI and NI in the most proximal outcrop on the caldera rim (9 km). This suggests that the flow body of the Tosu pyroclastic flow had developed a flow head within 9 km from the source. In the Cape Riva the ground layer was emplaced at the caldera rim, a few kilometers from the vent (Druitt and Sparks 1982). They proposed a similar interpretation to ours, suggesting that the flow head of the Cape Riva pyroclastic flow developed quite near the vent.

Previously, a proximal breccia facies was interpreted to be the product of a deflation zone, in which coarser fragments in the collapsing pyroclastic column were selectively deposited and accumulated around the source vent, just before the pyroclastic flow with a flow head and a flow body began to move laterally (Walker 1985). Walker suggested that the flow head was not developed in the deflation zone, and that the proximal breccia facies originated not from the pyroclastic flow itself, but from a chaotic protoflow regime. However, the existence of a nearly continuous ground layer from the caldera rim to the distal area in both the Tosu and the Cape Riva examples (Druitt and Sparks 1982) argues against the deflation zone model. Instead, the ground layer distribution argues for early development of a flow head and a flow body, i.e., for a single gravity current that formed within a few kilometers of the source.

High mobility

The most conspicuous stratigraphic feature of the proximal Tosu is its thick FD and LI and a remarkably thin NI. The ground layer constitutes a greater proportion of the proximal Tosu than that of the proximal Cape Riva. In the Cape Riva the thickness of the ground layer is less than 1.5 m, and the thickness of overlying lithic breccia and ignimbrite is ~25 m (Druitt and Sparks 1982). In the Tosu the thickness of the ground layer is more than 3 m around the caldera rim (Fig. 3), and the cumulative thickness of overlying LI and NI is less than 3.3 m.

In general, the average ratio of thickness of ground layer to that of the total deposit in the proximal area is about 1/10 to 1/100 (Walker 1972; Self 1976; Ono et al. 1977; Walker et al. 1981a, b; Kamata and Mimura 1983; Walker et al. 1984; Wilson 1985; Suzuki-Kamata 1988). We suggest that the abnormally high proportion of dense lithic components in the proximal area and the high proportion of light pumice in the distal area are due to the high mobility of the Tosu.

The following evidence suggests that the Tosu was highly mobile: (1) The Tosu has an extraordinarily wide distribution (~155 km from source) in spite of its modest thickness (Watanabe 1978). (2) The proximal breccia facies of the Tosu (FD and LI) reaches as far as 34 km from the source, an exceptionally long distance considering the Tosu's small volume (10 km^3). (3) Near the caldera rim the Tosu is characterized by an exceptionally thick ground layer, equivalent in thickness to the overlying ash-enriched deposits. (4) Part of the Tosu was emplaced after crossing an arm of the sea (Fig. 1); probably the low density of its flow body allowed the flow to move across water (Ono and Watanabe 1983b).

Origin of lateral variation

The lateral stratigraphic variation in the Tosu may be explained by the model of tephra size sorting within the eruption column before collapse put forth by Valentine and Wohletz (1989). They suggest from numerical modeling that coarser clasts fall from the column at lower elevations and hit the ground closer to the vent than finer clasts. Watanabe (1986) demonstrated that the smaller and lighter fragments in the Tosu were emplaced in more distant areas, suggesting that the collapsed column was separated into two layers, i.e., basal dense cloud enriched in lithic fragments and upper dilute cloud enriched in pumice and glass shards.

Exceptionally thin NI and thick FD and LI in the proximal area of the Tosu may reflect the lithic-enriched lower portion of the eruption column. By contrast, NI, which dominates the distal area, may reflect the ash-and-pumice-enriched higher portion of the column. We suggest that the lower portion of the column, which was richer in heavier materials, first collapsed and deposited FD and LI in the proximal area. Then, the upper portion of the column, poorer in lithic fragments and richer in fine ash and pumice, collapsed and was deposited; part of this material was emplaced as NI overlying LI and FD in the proximal area, but most was carried away to the distal area.

Intensity of pyroclastic flow

Although the proximal facies generally exhibits multiple depositional structures that may originate from different mechanisms, it still provides information on the initial intensity of the eruption. Walker et al. (1980) pointed out that pyroclastic flows with high momentum have a remarkably low aspect ratio. On the basis of their strong fines depletion, their ability to traverse topographic barriers, and their ability to cross water, Walker (1983) suggested that LARIs reflect high flow velocities, which, in turn, result from higher magma discharge rates. In this paper we use the term "intensity" as a general term including momentum, flow velocity, and magma discharge rate. We compare the intensities of eruptions that produce LARIs by analyzing the significance of inflections in the rate of falloff of lithic-clast size (ML).

The distance of the distribution limit of the proximal breccia facies from the source is a good parameter for characterizing the intensity of the eruption that produced the breccia. At Tosu this distance (34 km for LI) is incidentally the same as the distance (~35 km) at which MP (average of three largest-maximum pumice) exceeds ML (Fig. 11). In general, however, the distribution limit of the breccia facies is difficult to determine. Instead, diagrams of ML vs distance from the source caldera are reported in many cases, showing that ML decreases steadily away from the source. In the Tosu, ML shows a sharper decrease at 9–20 km than beyond 20 km (Fig. 11), indicating an inflection in the rate of falloff of ML at 20 km. We call the distance of this inflection point from the source the *inflection distance*. We suggest that the inflection distance reflects the intensity of a pyroclastic eruption, and that it be used as a substitute for the seldom-reported distribution limit of the proximal breccias.

Druitt and Bacon (1986) showed an inflection distance of 9 km at Crater Lake. They suspected that the inflection was an artifact, due to relatively poor exposures beyond ~9 km from the caldera center. In the case of Tosu, however, it is very unlikely that the inflection was produced as an incidental artifact because it is

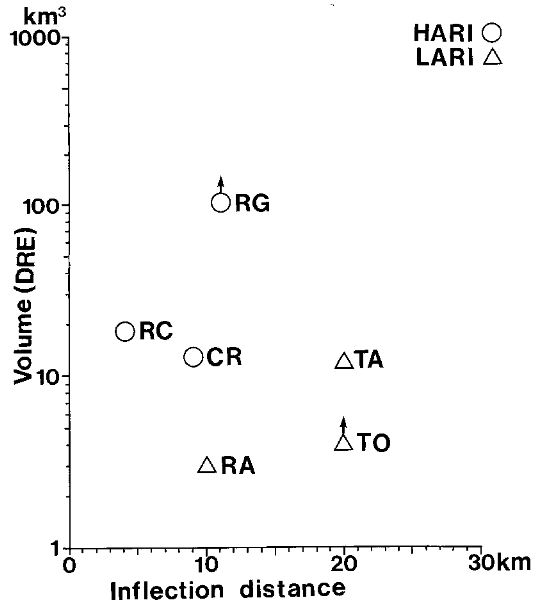

Fig. 12. Relationship between volume (dense rock equivalence, DRE) of pyroclastic flow deposits and distance of inflection point from the caldera center (inflection distance). Arrow indicates that the DRE volume may be greater than shown. *HARI*, high-aspect-ratio ignimbrite; *LARI*, low-aspect-ratio ignimbrite. *CR*, Crater Lake; *RA*, Rabaul; *RC*, Rio Caliente; *RG*, Real Grande; *TA*, Taupo; *TO*, Tosu

clearly defined by many closely spaced data points (Fig. 11). Inflection distances based on adequate data are also available for the Taupo ignimbrite (Wilson and Walker 1982). Therefore, we believe that the inflection is a recurring feature important in the genesis of LARIs.

Figure 12 shows the relation between the inflection distance and volume for several low- and high-aspect-ratio ignimbrites (HARI; Tosu, this study; Taupo, Wilson and Walker 1982; Rabaul, Walker et al. 1981b; Rio Caliente, Wright 1981; Real Grande, Sparks et al. 1985; Crater Lake, Druitt and Bacon 1986). The inflection distance of a LARI is generally larger than that of a HARI. For example, the inflection distance of the Taupo (TA) is larger than that of the Crater Lake (CR), and both have similar volumes (Fig. 12). This relation suggests that the eruption of LARI is more intense than that of HARI, even when the volume difference is normalized.

Summary

The Tosu pyroclastic flow deposit, a low-aspect-ratio ignimbrite (LARI) erupted 70000 years ago from Aso caldera, Japan, has a widely distributed breccia facies characterized by abundant coarse-grained accidental lithic fragments. In the proximal area (9–34 km from the center of Aso caldera), the Tosu is less than 7 m thick and shows three different lithofacies, from bottom to top: (1) abundant lithic fragments that are depleted in fine ash (FD), (2) abundant lithic fragments with a fine-ash matrix (LI), and (3) abundant fine ash and pumice that are relatively poor in lithic fragments (NI). The Tosu has thick FD and LI, in contrast to remarkably thin NI, in the proximal area.

FD underlies both NI and LI, commonly with a sharp contact, contains imbricated clasts, shows erosion of underlying beds, and lacks impact-sag structures. We interpret FD as a proximal and lateral equivalent of a ground layer, the deposit from the flow head of a pyroclastic flow. LI commonly grades upward into NI, pinches and swells within adjacent outcrops, and grades laterally into NI about 34 km from the source. The layer 2a facies (Sparks et al. 1973) in places lies between LI and FD. We interpret LI as a 2b-lithic-concentration zone, a lensoid lithic segregation breccia formed by sedimentation of lithic blocks through the body of a pyroclastic flow. NI is the uppermost ash flow facies in the proximal area and corresponds to the dominant facies in the distal area (34–155 km). We interpret NI as a proximal equivalent of a normal ignimbrite, which was deposited from the flow body of a pyroclastic flow.

The three-fold subdivision of the Tosu suggests an origin from a single column collapse event. The existence of the ground layer (FD) on the caldera rim suggests that a flow body and a highly turbulent flow head had already developed within a few kilometers of the source. Lateral variation of depositional features in the Tosu suggests that the lower portion of the eruption column, rich in heavy lithic debris, first collapsed and deposited FD and LI in the proximal area. The upper portion of the eruption column, which had relatively few lithic fragments and more fine ash and pumice, then collapsed and deposited NI.

The ML from the Tosu shows a sharper decrease between 9 and 20 km distance than beyond 20 km, indicating an inflection in the rate of falloff of ML at 20 km (the inflection distance). The inflection distance of a LARI is generally larger than that of a high-aspect-ratio ignimbrite (HARI), which suggests that the eruption of the former is more intense than is the latter.

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