# Dispersal of ash in the great Toba eruption, 75 ka

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## ABSTRACT

**One of Earth's largest known eruptions, the Toba eruption of 75 ka, erupted a minimum of 2800 km$^3$ of magma, of which at least 800 km$^3$ was deposited as ash fall. This ash may be entirely of coignimbrite origin and dispersed widely because of high drag coefficients on the predominantly bubble-wall shards. Shards of this shape are broken from the walls of spherical vesicles, which formed in high abundance in isotropic strain shadows near phenocrysts in this crystal-rich magma.**

## INTRODUCTION

The Toba caldera, located in northern Sumatra (Fig. 1), was the site of the largest Quaternary volcanic eruption on Earth (Smith and Bailey, 1968). Volcanic eruptions at Toba have left an elongate caldera measuring about 100 by 30 km. Extensive ignimbrites covering an area of over 20 000 km$^2$ surround the caldera; estimates of the magma volume erupted range between 2000 and 3000 km$^3$ (Van Bemmelen, 1949; Aldiss and Ghazali, 1984). Ninkovich et al. (1978a) and Ninkovich (1979) have described an extensive rhyolitic-ash horizon found in deep-sea cores in the Indian Ocean (Bay of Bengal) (Fig. 1) and have correlated it with an eruption from Toba. Ninkovich et al. (1978a, 1978b) reported a biostratigraphic/oxygen isotope age for the deep-sea ash of 75 ka, a K-Ar age of the on-land ignimbrite of 75 ka, and estimated that the volume of ash is approximately 1000 km$^3$. Furthermore, they calculated that the ash column required to produce the size and thickness characteristics of the ash was 50 to 80 km high. Ledbetter and Sparks (1979) estimated that the associated eruption had a duration of 9 to 14 days.

Rhyolitic ash occurs on land in Malaysia at many localities and has long been attributed to the Toba eruptions on the bases of proximity, mineralogy, and relative age (Van Bemmelen, 1949; Stauffer et al., 1980). More recently, Williams and Royce (1982) have discovered a rhyolitic ash in India and have suggested Toba as the source.

This extensive ash blanket, covering at least 4 000 000 km$^2$, affords the opportunity to study and quantify the large-scale tephra distribution of the largest volcanic eruption of recent times. Description of such tephra dispersal is relevant when considering the effects on the human population of an eruption of this magnitude (Smith, 1985; Rampino et al., 1986). Comparison of the ashes with near-source tephra was used to reconfirm Toba as the source of the ash. Mineralogy and whole-rock and glass chemistry were used in this comparison. Next, a scanning electron microscope (SEM) and microprobe study of shard morphology and chemistry was made on the ash at varying distances from the source. This study allows evaluation of the controlling factors in the widespread tephra distribution.

## ERUPTIONS OF THE TOBA CALDERA

Three major eruptions have occurred at Toba in the past 1 m.y. The oldest unit was erupted about 840 ka ($^{40}Ar/^{39}Ar$ age) (Diehl et al., 1987), is present mostly around the southern part of Lake Toba, and is almost everywhere densely welded. A smaller ignimbrite of undetermined age crops out only around the northern part of the present caldera and is also densely welded. The youngest unit erupted from Toba about 75 ka and deposited an extensive nonwelded outflow sheet that surrounds the caldera. Locally, where deep stratigraphic sections are exposed and in the resurgent dome, this unit is incipiently to densely welded. The present shape and steep walls of the caldera are mostly attributed to eruption of the youngest unit. We focus on this youngest unit from Toba because the ash horizons so far discovered appear to be correlated with it only.

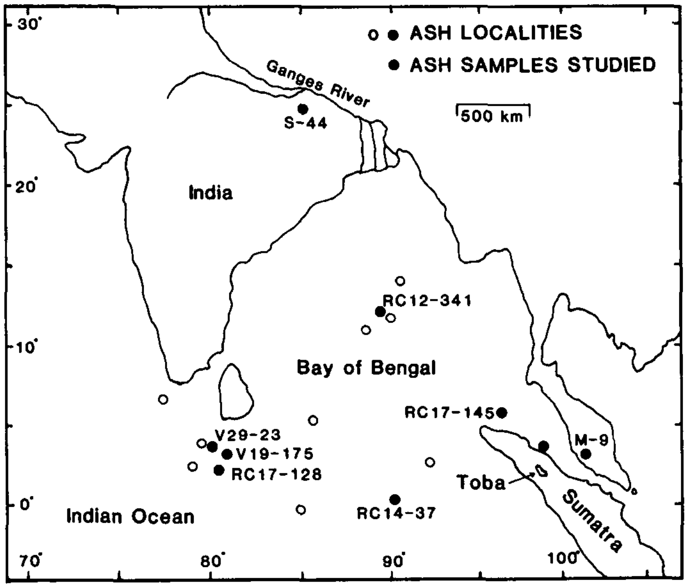

**Figure 1. Location map for Toba caldera, Toba ash localities, and ash samples used in this study.**

The outflow sheet from the 75 ka eruption covers a minimum area of 20 000 km$^2$ (Aldiss and Ghazali, 1984) and probably flowed into both the Strait of Malacca to the east and the Indian Ocean to the west. Outflow-sheet thicknesses are generally less than 100 m but locally are up to 400 m (Knight et al., 1986). Caldera fill exceeds 600 m, but its actual thickness is unknown because the base of the section is unexposed. This ignimbrite is generally poorly sorted and massively bedded. A striking feature of this ignimbrite is the lack of Plinian ash-fall deposits at its base, although this observation is predicated on only a few proximal exposures. Absence of a Plinian phase raises the question of the origin of the extensive ash fallout associated with this eruption. Could the ash be mainly of coignimbrite origin?

## TOBA TEPHRA

When considering the nature and origin of ash particles, it is important to study pumices large enough to represent the bulk composition of the erupted magma because fine ash is typically subject to crystal/glass fractionation during atmospheric transport. Pumices erupted during the 75 ka eruption are calc-alkalic quartz-latite to rhyolite and range from 68% to 76% $SiO_2$. The Toba rocks contain quartz, sanidine, plagioclase, biotite, amphibole, orthopyroxene, allanite, magnetite, ilmenite, fayalite, pyrrhotite, zircon, and apatite (Chesner, 1985). This diverse mineralogy has been especially useful for correlation.

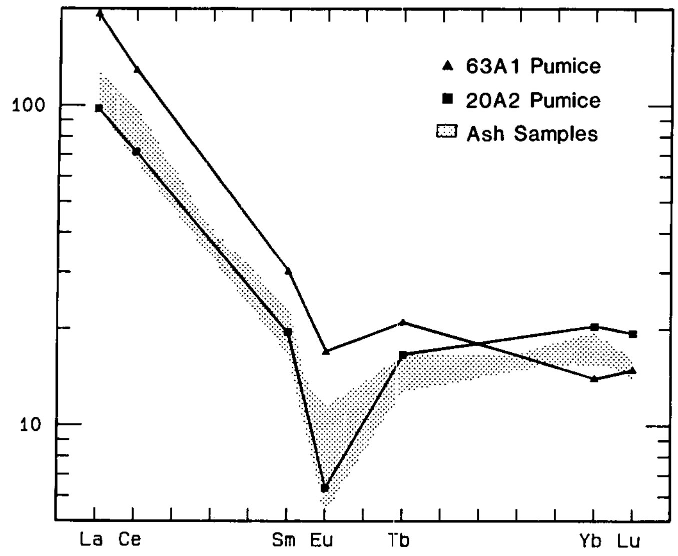

**Figure 2. Chondrite normalized REE plot of two pumices and five ash samples.**

Texturally, the pumices are dense and have a variety of vesicle types ranging from elongate to spherical. Many vesicle types commonly occur within the same pumice sample.

Samples used in this study include three fresh pumice blocks from the nonwelded ignimbrite, which were chosen in order to compare the distal ash with tuffs adjacent to the caldera. Five samples of ash recovered from deep-sea cores located in the Indian Ocean at distances of 500 to 2100 km from Toba were studied. A sample from India, which represents the most distal ash occurrence known from the Toba eruption (3100 km away) (M.A.J. Williams, in prep.), was also studied, as was another ash, which fell on land in Malaysia 350 km away. Figure 1 shows the locations of the samples studied.

## ASH CORRELATION

Whole-rock and glass X-ray fluorescence (XRF) analyses, instrumental neutron activation analysis (INAA), microprobe analyses of glass shards, and mineralogy were all used to confirm Toba as the origin of the ash. Analyses of ash samples were found to lie along the same compositional trend as whole-rock and glass analyses of individual pumices. A plot of rare earth element (REE)-normalized chondritic abundances (Fig. 2) also shows the similarity between the ash deposits and pumices. Micro-

TABLE 1. AVERAGE COMPOSITION OF 88 INDIVIDUAL GLASS SHARDS FROM 7 DISTAL ASH SAMPLES DETERMINED BY ELECTRON MICROPROBE

| | Wt. % | 1σ** |
|---|---|---|
| $SiO_2$ | 78.28 | 0.4 |
| $Al_2O_3$ | 12.70 | 0.2 |
| $Fe_2O_3$* | 1.16 | 0.2 |
| MgO | .08 | 0.03 |
| CaO | .74 | 0.1 |
| $Na_2O$ | 2.71 | 0.1 |
| $K_2O$ | 4.26 | 0.2 |
| $TiO_2$ | .06 | 0.03 |

*All Fe as $Fe_2O_3$.

**1σ value for subset of analyses from a single ash sample.

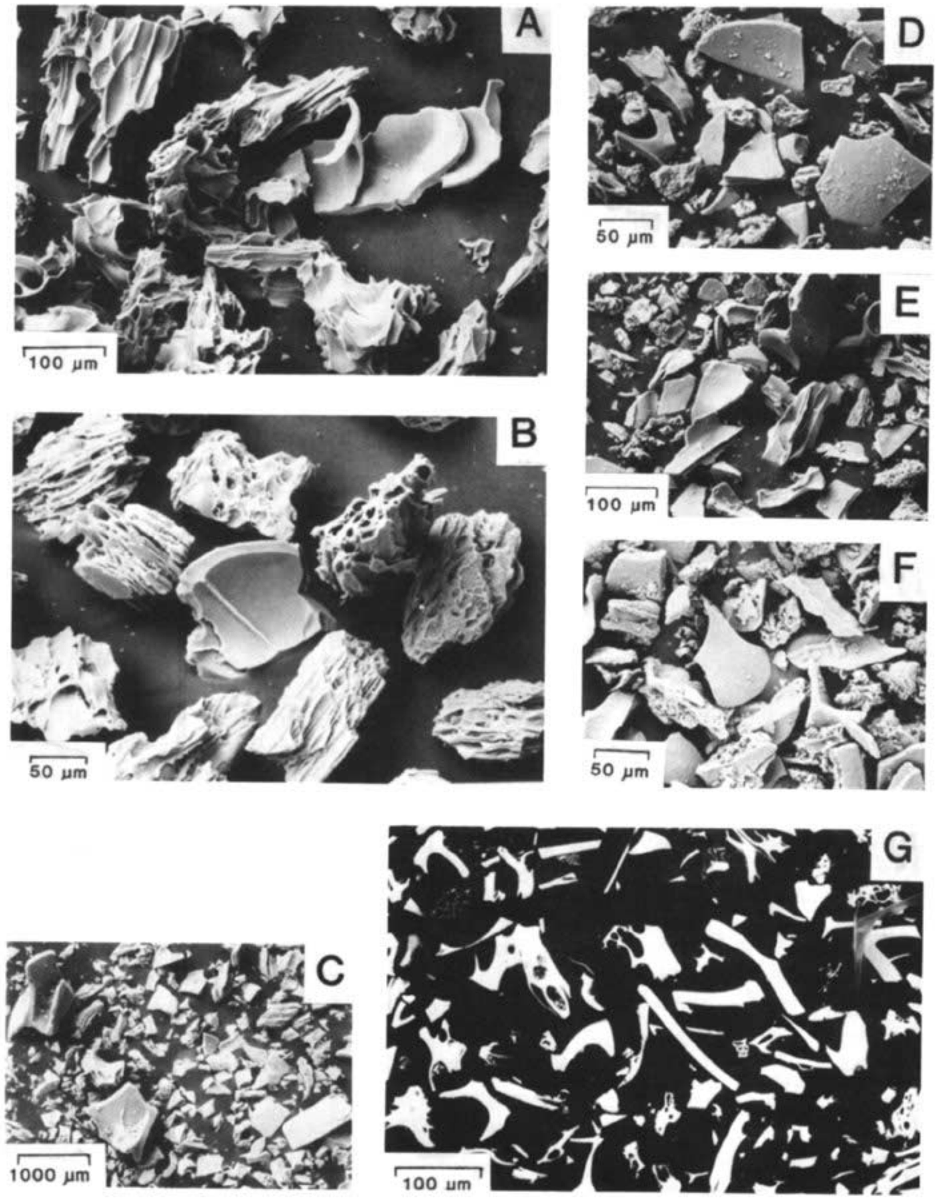

**Figure 3. SEM photomicrographs of Toba materials. A, B: Crushed pumice from Toba ignimbrite samples T63A1 and T97A2, respectively. C–F: Distal ashes from Toba in order of increasing distance. C is upper fine layer and D is basal coarse layer of core RC17-145, about 500 km from Toba. E is sample RC17-128, 2000 km away; F is sample S-44, 3100 km away. G: Polished mount of sample RC17-128 showing view analyzed by image processor.**

probe analyses of glass shards from multiple ash samples and ignimbrite matrix samples were made. Virtually no variation in glass composition exists, regardless of distance from the source. An average glass analysis is reported in Table 1. None of the analyzed samples had glass compositions that fell outside of the $1\sigma$ ranges shown in the table except for $Na_2O$. Mineralogically, the ash also contains distinctive phases from the Toba assemblage. We conclude that the ash erupted from Toba and its glass shards show no compositional variation with distance from the source.

## SHARD SHAPES

An extensive SEM study was performed on the ash samples. First, pumice from the ignimbrite was disaggregated and examined. Figures 3A and 3B show examples of these fragments, which consist predominantly of pumice shards that contain many elongate vesicles. Platy or bubble-wall shards are much less common than the pumice shards. The distal ash was examined and was found to consist mostly of bubble-wall shards (Figs. 3C–3F).

In order to quantify this observation, ash mounts were polished so that the three-dimensional ash particles could be viewed in two dimensions. The result of such polishing is that the platy shards now appear highly elongate in two dimensions and the more equant shards are not nearly as elongate (Fig. 3G). Next, an image analyzer found the geometric center of each shard, measured 8 diameters, calculated an average diameter, and used the following equation to calculate a shape factor.

$$\text{Shape Factor} = \frac{\text{Perimeter}^2}{\text{Area } (4\pi)}. \qquad (1)$$

These calculations were performed on hundreds of shards per sample. Table 2 gives some sample data for particles of different shapes, a bubble-wall shard and an equant shard (crystal fragment). Although the average diameter, area, and perimeter are very similar for these two particles, their shape factors are quite different. The greater the shape factor, the more elongate the particle is; for example, a shape factor of 2 has an aspect ratio of about 5:1, whereas a shape factor of 3 has an aspect ratio of about 10:1.

TABLE 2. EXCERPT OF RAW DATA FROM IMAGE ANALYSIS

| | Bubble-wall Shard | Crystal Fragment |
|---|---|---|
| Avg. diameter (μm) | 27.32 | 32.85 |
| Max. diameter (μm) | 113.08 | 46.51 |
| Min. diameter (μm) | 9.59 | 23.25 |
| Area (μm$^2$) | 638.17 | 868.26 |
| Perimeter (μm) | 157.56 | 118.61 |
| Shape factor | 6.91 | 1.28 |

Figure 4 depicts size and shape data for individual samples plotted against distance from Toba. Each sample represents the average of hundreds of measurements made on individual shards from that sample. Beyond 500 km from Toba the greatest mean diameter is always about 60 μm, and average mean distance is about 30 μm. Thus, the size of ash is constant over distances ranging from 500 to 3100 km. About 30% of all shards in each sample have shape factors greater than 3, and 50%–70% have shape factors greater than 2. The ash particles in the distal ash are very elongate in two dimensions, and conventional SEM examination (Figs. 3C–3F) shows they are predominantly bubble-wall shards. In summary, the average size and shape of the distal (⩾500 km) Toba ash particles do not change significantly over 3100 km of dispersal. Some of the more proximal sites (⩽500 km) from Toba have a coarse ash horizon overlain by a finer horizon (Ninkovich et al., 1978b). We interpret this observation to suggest that most of the larger ash particles have fallen out within the first 500 km.

## ERUPTION COLUMN HEIGHT

Wilson and Huang (1979) have done settling-velocity experiments in the laboratory on ash particles of various shapes. We have extracted some representative examples of their data to illustrate how particle shape affects settling velocity (Table 3). Their results show that equidimensional particles (low shape factors) such as feldspar crystals will have much higher

TABLE 3. RAW DATA SHOWING MEASURED TERMINAL VELOCITY OF SELECTED PYROCLASTS

| Pyroclast | Length (μm) a | b | c | T (cm/s) | ρ g/cm$^3$ | d (μm) |
|---|---|---|---|---|---|---|
| Glasses | | | | | | |
| 1 | 285 | 160 | 75 | 67.02 | 2.40 | 157 |
| 2 | 225 | 120 | 60 | 36.08 | 2.40 | 135 |
| 3 | 155 | 95 | 9 | 19.12 | 2.40 | 86 |
| 4 | 150 | 75 | 6 | 8.69 | 2.40 | 77 |
| 5 | 108 | 40 | 7 | 7.60 | 2.40 | 52 |
| Feldspars | | | | | | |
| 6 | 280 | 220 | 190 | 125.30 | 2.65 | 230 |
| 7 | 222 | 145 | 85 | 78.60 | 2.65 | 151 |
| 8 | 175 | 125 | 40 | 85.25 | 2.65 | 113 |
| 9 | 170 | 90 | 25 | 44.56 | 2.65 | 95 |
| 10 | 113 | 75 | 19 | 29.30 | 2.65 | 69 |

Note: a = longest diameter; b = intermediate diameter; c = shortest diameter; T = terminal velocity; ρ = density; d = avg diameter. From Wilson and Huang (1979).

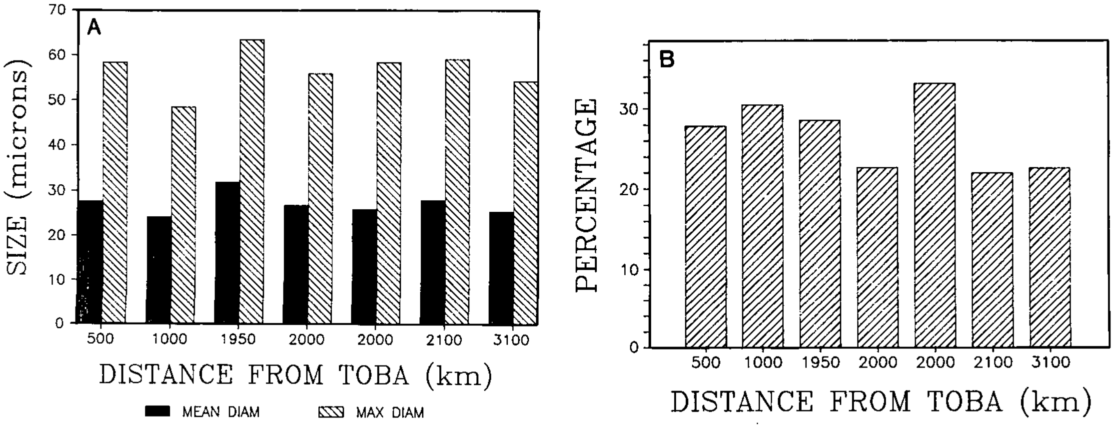

**Figure 4. Size and shape data for distal ashes. A: Mean and maximum shard diameters plotted as function of distance from Toba. B: Percentage of ash particles that have shape factors greater than 3 vs. distance from Toba.**

settling velocities than glass particles that have very different dimensions (high shape factors). The particles that have very different dimensions correspond to bubble-wall shards, and pyroclasts 3, 4, and 5 are very similar to the dominant shard shape of the distal ash of Toba. Particles of this shape have very high drag coefficients and are thus likely to be dispersed great distances.

Wilson and Huang (1979) showed that the drag coefficient is strongly influenced by particle shape by using a different shape factor, $F$, defined in terms of the three dimensional lengths $a$, $b$, and $c$ of particles ($a$ = longest, $c$ = shortest):

$$F = (b+c)/2a. \tag{2}$$

Although this definition of shape factor is not well suited to predict drag for bubble-wall shards that have $a \approx b >> c$, the shape factors of distal Toba ash particles are 0.5 or less. Using the drag coefficient ($C_\alpha$) equation of Wilson and Huang,

$$C_\alpha = (24\, F^{-0.828})/R_\alpha + 2\sqrt{(1.07-F)}\ , \tag{3}$$

where $R_\alpha$ = dimensionless Reynolds number, the change in $F$ from about 1 to <0.5 would be expected to increase $C_\alpha$ by at least a factor of 3, and probably by a factor of 5 or more. From this, we conclude that the terminal velocity at any level in the atmosphere of distal Toba shards is probably less than 20% of the terminal velocity of equidimensional particles having similar average or maximum diameters. Furthermore, because column-height estimates depend on reasonable estimates of terminal velocity and are a direct multiplier in such calculations, we conclude that the column-height estimates of Ninkovich et al. (1978b) of 50 to 80 km may be too high by a factor of 5 or more.

## ORIGIN OF HIGH-ASPECT-RATIO BUBBLE-WALL SHARDS

Because we have shown that bubble-wall shards are dispersed widely because of their high drag coefficients, the next question is, Where do these shards originate? By examining thin sections of pumices, we found that there was a high concentration of spherical vesicles (which when disaggregated produce bubble-wall shards) in shadow zones behind phenocrysts and surrounding phenocrysts (Fig. 5). It is possible that the crystals caused isotropic strain-free shadows on their margins which facilitated growth of equidimensional vesicles. Heiken and Wohletz (1985) suggested that vesiculation may begin at phenocryst surfaces and develop pockets of ovoid vesicles radial to or surrounding the phenocrysts. These pockets have higher viscosities than the surrounding melt and may resist the flow deformation that causes the late-stage vesicles, which form outside the pockets, to be sheared into highly elongate, tubelike forms. (For examples of other silicic pumices with spherical vesicles, refer to Heiken and Wohletz, 1985.) The Toba magma had a high crystal content and thus a greater number of favorable sites where spherical vesicles could form. Perhaps this led to the large amount of bubble-wall shards in the Toba ash. We suggest that magmas of high crystal content may thus give rise to widely dispersed ash falls upon explosive eruption.

## NEW VOLUME ESTIMATE

A minimum ash volume of 350 km$^3$ can be calculated by assuming an average thickness of 10 cm of ash covering 7000000 km$^2$ and correcting to dense rock equivalent (DRE) with a correction factor of 0.5. By using an integrated volume-estimate routine based on area/thickness relations of ash-fall blankets (Rose et al., 1974; Wunderman, 1980), a minimum ash volume of 800 km$^3$ DRE for the most recent Toba eruption is obtained.

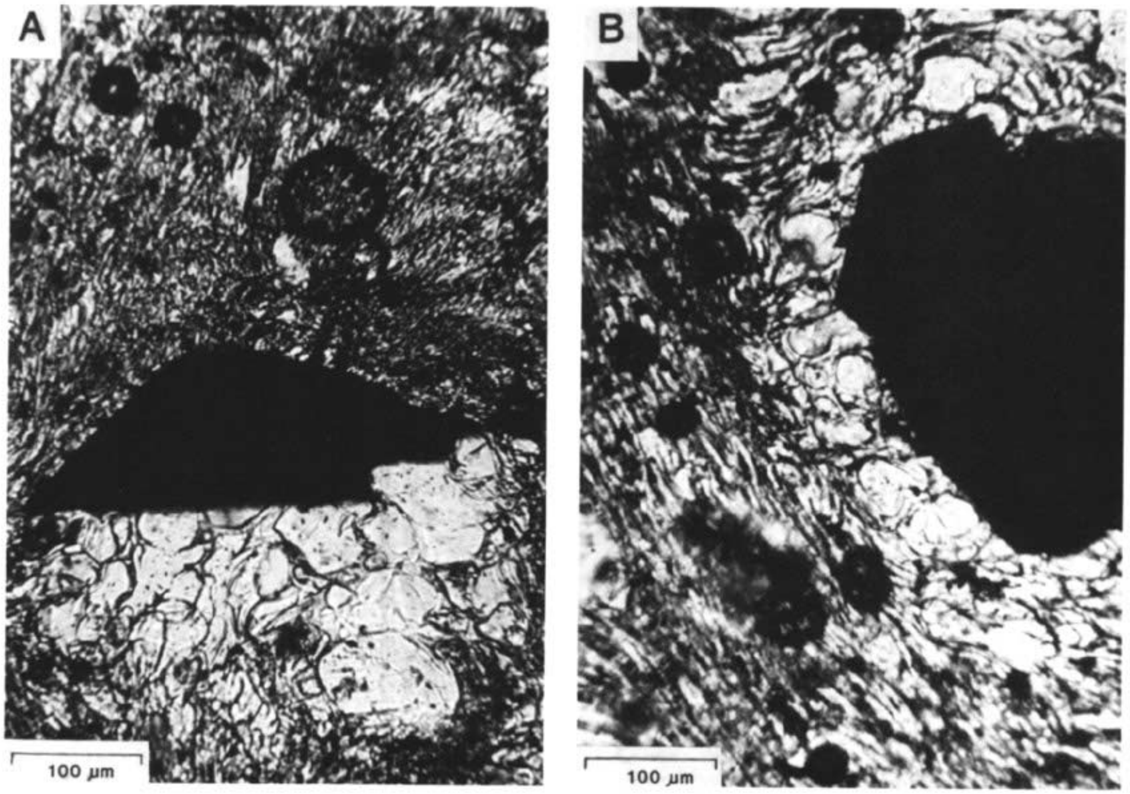

**Figure 5. Concentration of spherical-shaped vesicles in shadow zones behind a phenocryst (A), and surrounding a phenocryst (B).**

In order to refine this estimate, more data points are necessary. The ash is known to cover the eastern Indian Ocean with a thickness of about 10 cm, and it occurs in India in a fluvial sequence. Considering the absence of any significant changes in size and shape, it is conceivable that the ash might occur in Central Asia, the Middle East, and beyond. More distance ash localities should be sought, and the Antarctic ice cores should be examined for the Toba ash.

We have also calculated the ignimbrite volume from the youngest Toba eruption by assuming an outflow sheet area of 20000 km$^2$, an intracaldera area of 2500 km$^2$, and average thicknesses of 80 and 400 m, respectively. We arrived at a total ignimbrite volume of >2000 km$^3$ DRE for this eruption. By combining the ignimbrite volume and ash volume, we have calculated the total volume of the youngest Toba tuff to be at least 2800 km$^3$ DRE, but it may conceivably be much larger because the extent of the ash blanket is unknown.

As Walker (1972) and Sparks and Walker (1977) have shown, ignimbrites tend to concentrate crystals because during their turbulent emplacement, ash composed mostly of glass is preferentially lost. We can use this reasoning to estimate the volume of coignimbrite ash through least-squares mixing calculations. By determining the amount of ash that needs to be mixed with the ignimbrite matrix in order to obtain the average pumice composition of a sampling site, we have calculated the volume of glass that has elutriated during ignimbrite emplacement. Such calculations show that between 6% and 81% of glass has been lost from individual areas of the outflow sheet. An average of seven sites indicates that approximately 37% of the volume of the ignimbrite was elutriated as glass upon eruption and emplacement. This translates to about 750 km$^3$ of ash composed entirely of glass for an on-land ignimbrite volume of 2000 km$^3$. This is a minimum estimate because it does not include crystals, which are invariably part of the ash. Ninkovich (1979) reported that crystals are always less than 10% of the ash. If 5% crystals is assumed, the volume of ash elutriated from the ignimbrite is raised to 840 km$^3$ DRE.

## COIGNIMBRITE ASH

Various lines of evidence suggest that the Toba ash may be entirely of coignimbrite origin. Field evidence for this is the lack of any significant Plinian-fall deposits underlying the ignimbrite, suggesting there was no large Plinian column before eruption of the ash flows.

By examining the ash closely and characterizing its shape, we have shown that the widely dispersed Toba ash is composed almost entirely of bubble-wall shards. These shards have very high drag coefficients, which greatly reduce the height of the eruption column necessary for their dispersal. A high Plinian column is therefore not required to disperse the ash so widely.

The volume of elutriated ash estimated from mixing calculations is the same as that calculated by the integrated-volume technique. This suggests that the entire ash-fall volume could have been elutriated off the top of the moving ignimbrite during its emplacement and convected upward into the atmosphere.

## CONCLUSIONS

1. The new volume estimate for the youngest Toba tuff is at least 2800 km$^3$ of DRE magma. This number includes an estimate of about 800 km$^3$ of widely dispersed ash.

2. Bubble-wall shards disperse preferentially and widely because of high drag coefficients related to their shapes.

3. High crystal content in the Toba magma may generate a greater proportion of bubble-wall shards, which appear to form in pressure shadows near phenocrysts.

4. The Toba eruption may not have had a Plinian phase prior to the large ignimbrite, and the distal ash may be entirely of coignimbrite origin.

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