Dynamic deformation of volcanic ejecta from the Toba caldera: Possible relevance to Cretaceous/Tertiary boundary phenomena

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ABSTRACT

Plagioclase and biotite phenocrysts in ignimbrites erupted from the Toba caldera, Sumatra, show microstructures and textures indicative of shock stress levels higher than 10 GPa. Strong dynamic deformation has resulted in intense kinking in biotite and, with increasing shock intensity, the development in plagioclase of planar features, shock mosaicism, incipient recrystallization, and possible partial melting. Microstructures in quartz indicative of strong shock deformation are rare, however, and many shock lamellae, if formed, may have healed during post-shock residence in the hot ignimbrite; they might be preserved in ash falls. Peak shock stresses from explosive silicic volcanism and other endogenous processes may be high and if so would obviate the need for extraterrestrial impacts to produce all dynamically deformed structures, possibly including shock features observed near the Cretaceous/Tertiary boundary.

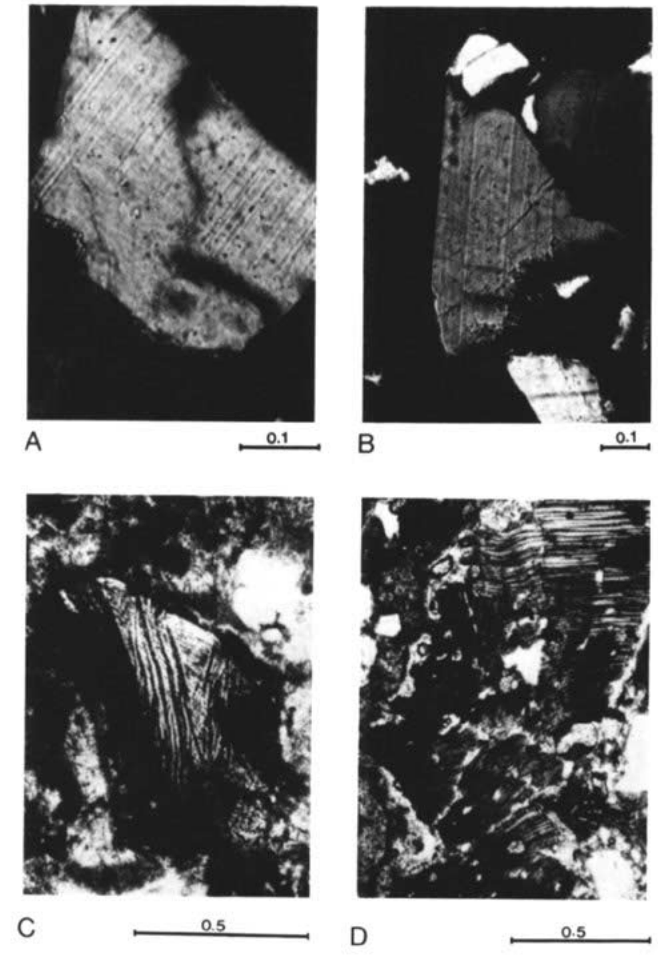

Figure 1. Photomicrographs of shock-produced microstructures in Toba ignimbrites. Scale bars are in millimetres. A and B: Planar features (northeast-trending linear features in A; north-south-trending linear features in B) in quartz grains in specimens T-32 and T-92, respectively; crossed nicols. C and D: Irregularly and highly kinked and fragmented biotite grains in specimens T-94B and 10.680, respectively; plane-polarized light.

INTRODUCTION

Alvarez et al. (1980) have argued that massive biological changes at the Cretaceous/Tertiary (K/T) boundary, at 65 Ma, were probably caused by impact of a 10-km-diameter asteroid. Part of the resulting ejecta reached the stratosphere and considerably reduced the amount of sunlight reaching Earth for several years. A brief cessation of photosynthesis resulted in widespread floral and faunal extinction. The primary evidence cited for this cataclysmic event rests on anomalously high concentrations of platinum-group metals, especially iridium, in marine clays near the K/T boundary at several localities around the globe. Although the 200-km-diameter crater that would have resulted from such an event has not yet been found, support for the impact hypothesis has come from the discovery by Bohor et al. (1984, 1985) of shock lamellae in 15 quartz grains at or near the K/T boundary near Brownie Butte in east-central Montana and in 10 grains at the Pontedazzo site in Umbria, Italy. Possible occurrences of shocked quartz at the boundary in other areas are listed by Bohor et al. (1985), and closely spaced microfractures, attributed to <10 GPa shock stresses, have been observed by Izett and Pillmore (1985) at nine sites in the Raton Basin, New Mexico and Colorado, as well as at 25 cm *below* the K/T boundary at Brownie Butte.

To date, the best-documented data for shocked quartz at the K/T boundary are those for Brownie Butte, where 61 intersecting sets dominantly parallel to the rhombohedra $\underline{\omega}$ $(10\bar{1}3)$ and $\underline{\pi}$ $(10\bar{1}2)$ are observed, and for Pontedazzo, where 46 sets dominantly parallel to $\underline{\omega}$ and with a subordinate set parallel to Υ $(04\bar{4}1)$ occur. Such planar features, first observed in quartz at the Clearwater Lake impactite, Canada (McIntyre, 1962), and observed since in many cryptoexplosion structures (Short and Bunch, 1968), have been described in detail (e.g., Carter, 1965, 1968a, 1968b; Bunch,

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1968; Chao, 1968; Engelhardt et al., 1968; Robertson et al., 1968). These microstructures, which first appeared in quartz in granodiorite that had undergone peak shock pressures of 6 GPa during the Hardhat nuclear explosion (Short, 1968a), are abundant in orthoquartzite and granodiorite shocked in the pressure range 7–40 GPa in high explosive and chemical implosion experiments (Short, 1968b) and were induced in quartz single crystals shock-loaded with a 20-mm powder gun to pressures greater than 10 GPa (Horz, 1968). They may occur in single or multiple sets (Short, 1968a; Carter, 1968b), the number of sets apparently increasing with increasing shock intensity (Short, 1968b). The lamellar structures are composed of short-range order (glassy) material induced during small shear displacements, are unquestionably of dynamic origin, and apparently require deviatoric stresses greater than 5 GPa, about two orders of magnitude higher than average lithospheric tectonic stresses.

Since publication of the Alvarez et al. (1980) impact hypothesis, many articles and symposia have appeared that discuss, among other phenomena, climatic and photosynthetic effects of such an ejected global dust cloud (e.g., Reid, 1981; Kent, 1981), the effects of sedimentation and bioturbation on elemental redistributions (e.g., review by Officer and Drake, 1985), and floral and faunal changes at the K/T boundary (e.g., Axelrod, 1981; Officer and Drake, 1983; Smit and Romein, 1985; McLean, 1985). Many of these discussions have attempted to establish that the geologic record indicates a transitional period of biological changes over a time span of 10^4 to 10^5 yr rather than an instantaneous event. This viewpoint also appears to be supported strongly by apparent significant differences in ages of the marine and continental K/T boundaries (e.g., McLean, 1985). A peak in volcanic activity at about 65 Ma (near the time of eruption of the basalts of the Deccan Traps, India) seems to be the most reasonable alternative (e.g., Officer and Drake, 1985; McLean, 1985; Officer et al., 1985; H. R. Nasland, C. B. Officer, and G. B. Johnson, in prep.) and could account, by a large number of environmental changes, for the selective extinctions observed, as well as for the iridium anomaly. However, evidence for strong shock deformation, although extensively researched for cryptoexplosion structures during the 1960s and for returned lunar samples in the early 1970s, has not been searched for or obtained for volcanic explosions or eruptions, to our knowledge. The obvious place to begin such an investigation is to examine rock samples from the most violent type of volcanic eruptions, those occurring at silicic calderas. The last Toba eruption in Sumatra, which occurred 75000 yr ago, may have been one of the largest eruptions of this type on Earth; thus, its deposits are primary candidates for this preliminary study.

TOBA VOLCANISM

The Toba caldera in northern Sumatra was first described as a volcano-tectonic depression by Bemmelen (1939) and has since been studied by Smith and Bailey (1962, 1968) and others. Toba lies along a destructive plate margin and is about 100 × 30 km, elongated in a northwest-southeast direction parallel to the active volcanic front in Sumatra. In areal extent, the Toba caldera is more than 50 times greater than Krakatoa and in volume it is about 400 times greater (Kent, 1981). A prominent ash horizon associated with the youngest Toba eruption occurs in deep-sea cores in the Indian Ocean (Ninkovich et al., 1978b) and on land in Malaysia and elsewhere.

At least three major eruptions have occurred at Toba (Knight et al., 1984), the latest at 0.075 Ma (Ninkovich et al., 1978a). Ignimbrites associated with these eruptions are all calc-alkaline rhyolites (68% to 76% SiO_2; Chesner, 1985), are mineralogically and lithologically similar, and are distinguished primarily by magnetic polarity and chemical composition. Exposed sections through the ignimbrites consist of thick sequences of crystal-rich, poorly sorted, massively bedded welded tuffs overlain by nonwelded pyroclastic flow deposits. All Toba rocks contain quartz, plagioclase (Ab_{69}–Ab_{54}), sanidine, biotite, amphibole, orthopyroxene, magnetite, ilmenite, allanite, zircon, and apatite. Samples used in this analysis are part of a large suite being employed in a major petrological/geochemical study of Toba deposits by C. A. Chesner and W. I. Rose (in prep.).

DEFORMATION MICROSTRUCTURES

For our preliminary analysis, we have used research polarizing microscope and universal stage techniques to examine thin sections at 13 welded ignimbrites at or from within 20 km of the caldera, one sample (10.680) from a drill core, two pumice samples, and one welded ash collected inside the caldera. Although quartz is abundant in most of these specimens, it is typically only fractured, and planar features of the type shown in Figures 1A and 1B were observed in single sets in only 24 (<<1%) grains in nine sections of the welded ignimbrites and in the welded ash. Orientations of the planar features with respect to the *c* axis are shown in Figure 2, and although they are not significant statistically, these orientations correspond approximately with those (107 sets) observed by Bohor et al. (1984, 1985) and observed in other extensive studies of shocked quartz discussed above.

Local occurrences of highly and irregularly kinked and fragmented biotite crystals, such as those shown in Figures 1C and 1D, are also good indicators of shock deformation during the Toba explosion. Biotite kinking of this type has been observed in granodiorite shocked by the Hardhat nuclear explosion (Cummings, 1968; Short, 1968a), in high explosive and chemical implosion experiments in the shock stress range 7–40 GPa (Short, 1968b), and in many natural impactites (e.g., Bunch, 1968; Chao, 1968; Short and Bunch, 1968). Biotites that have been heavily shocked are oxidized and converted to fine aggregates of magnetite at their boundaries; they have reduced pleochroism and birefringence near their centers (Chao, 1968) and have anomalous interference figures (Cummings, 1968). These shock-metamorphic

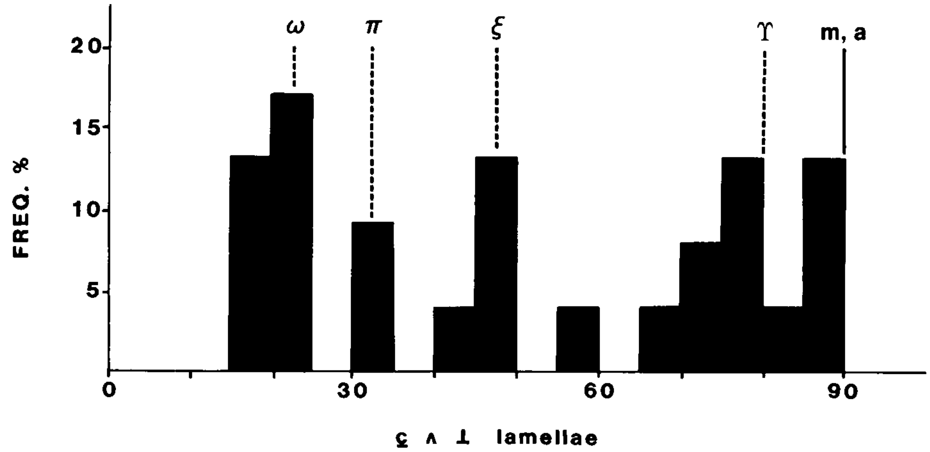

Figure 2. Histogram showing orientation with respect to c axis of 24 sets of planar features in 17 Toba sections studied. Quartz crystal forms indicated are ω ($10\bar{1}3$), π ($10\bar{1}2$), ξ ($11\bar{2}2$), Υ ($04\bar{4}1$), and m,a (1010).

changes are observed in some of the deformed biotites in the Toba specimens; especially pronounced are the grain-boundary magnetite aggregates.

The foregoing observations on deformed quartz and biotite, although highly suggestive, do not by themselves provide firm evidence for strong shock deformation during the Toba eruption. However, when considered together with the more widespread and better-documented deformation of plagioclase, there is little question that strong shock deformation has occurred. Planar features, analogous in most respects to those in quartz, are more abundant in plagioclase than in quartz in the Toba specimens examined, but their orientations have not yet been measured. Planar features in plagioclase have also been observed at some K/T sites (Bohor et al., 1985) in impactites (e.g., Bunch, 1968; Robertson et al., 1968), and in the Hardhat explosion (Short, 1968a, 1968b). They first appear at somewhat higher shock stress levels than are required for their development in quartz (Chao, 1968; Short, 1968b).

At still higher shock stress levels, a mosaic or chaotic subgrain texture develops in shocked silicates (e.g., Stoffler, 1972). These textures in plagioclase in impactites and experiments are commonly accompanied with increasing shock stress by decreases in refractive index and birefringence and by partial recrystallization and partial to total conversion to glass (e.g., Chao, 1968; Bunch, 1968; Short and Bunch, 1968; Robertson et al., 1968; Short, 1968b). A similar progression has been observed for naturally and experimentally shocked olivine (Carter et al., 1968). Examples of shock mosaicism are prodigious in all Toba samples studied when account is taken of the heterogeneities expected of shock deformations. Examples of this type of deformation are shown in Figure 3. In Figure 3A, typical mosaic structures of quartz showing very irregular, patchy extinction differ appreciably from the generally smooth, regular, optically homogeneous subgrain structure in recovered tectonically deformed quartz (e.g., Carter, 1976). This chaotic substructure is also shown in a plagioclase crystal in Figure 3B; incipient recrystallization, probably annealing following peak shock stresses (Carter et al., 1968), is observed near the center of the grain. Twin bands (east-west) in the plagioclase crystal of Figure 3C are distorted by the shock mosaic extinction zones in the crystal. The extinction zones or subgrains in this crystal and as shown in Figure 3D are somewhat more regular than the zones developed in shock experiments and in impactites, probably as a result of some annealing recovery during postshock residence in the hot ignimbrite. Microstructures of this type have not been observed in tectonically deformed plagioclase, to our knowledge. Subgrain development during dynamic recovery takes place by dislocation creep, which is highly unlikely for the plagioclase in the Toba tectonic environment.

DISCUSSION AND CONCLUSIONS

Violent silicic volcanic explosions apparently are capable of producing high local shock stress concentrations that in the Toba ignimbrite are best manifested in shock mosaicism of plagioclase presumably in the wall rock of the caldera. The fact that microstructures in quartz are rare, however, poses an enigma that may be related to the structural and physical environment of the erupting volcano. Temperatures (based on Fe-Ti oxide data; C. A. Chesner, in prep.) at the time of the eruption were near 700 °C as compared to near-ambient temperatures for most rocks shocked experimentally and those subjected to extraterrestrial impact. Accordingly, differences in the nature and development of microstructures produced by shock deformation at a given stress level are expected in the two settings, and healing and/or annealing may be expected in shocked materials contained within an ignimbrite flow. Some of the evidence for shock, such as perhaps shock lamellae in quartz, may be obliterated by healing during postshock residence times at high temperature, whereas more resilient microstructures in other minerals, such as plagioclase and biotite, may be altered somewhat but preserved. Alternatively, shock lamellae may not form readily in preheated shocked quartz crystals (T. Ahrens, 1985, personal commun.). If these assertions are correct, then microstructures from the Toba ignimbrites cannot explain the postulated global occurrence of shocked quartz at the K/T boundary.

However, silicic eruptions larger than Toba may have occurred in the past (Smith, 1979). The eruption column for the youngest Toba eruption was estimated to have exceeded heights of 50 km (Ninkovich et al., 1978b); rapid cooling of small shocked quartz grains in the column might well preserve the microstructures, if formed. In this hypothesis, shocked quartz might occur in ash falls associated with large silicic volcanic eruptions. This possibility should be investigated thoroughly for Toba ash

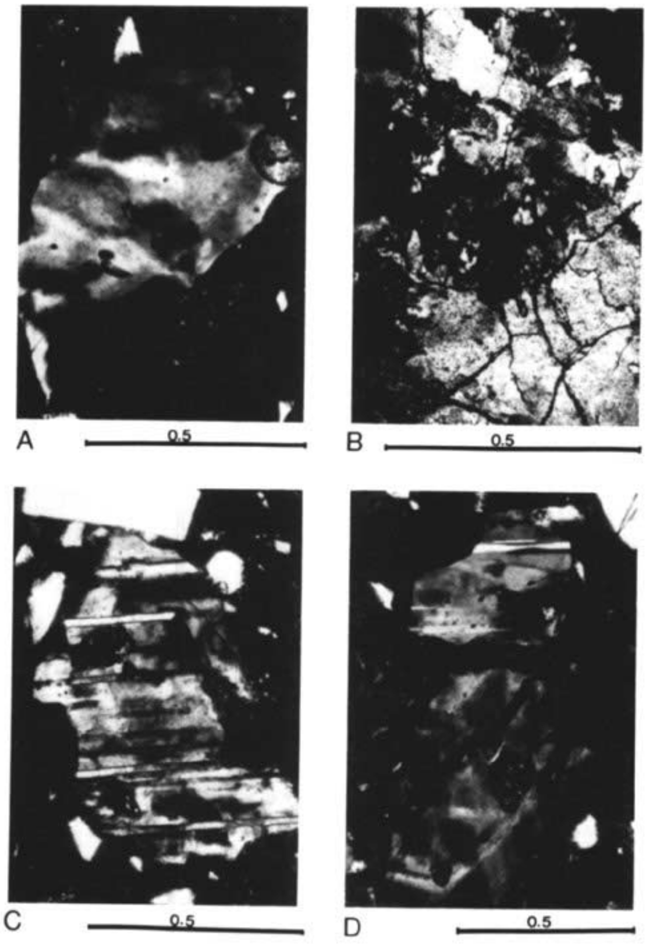

Figure 3. Photomicrographs showing shock-mosaic texture in quartz and plagioclase of Toba ignimbrites; crossed nicols. Scale bars are in millimetres. A: Mosaic structure in quartz grain in section T-94B. B: Strong mosaicism and incipient recrystallization (small white grains in center) in plagioclase in specimen 10.680. C and D: Partially recovered mosaic structure in plagioclase in specimens T-65 and T-94B, respectively.

along with the search for large calderas and impact craters that formed about 65 Ma.

Because of the differences in initial temperatures between impactites, experiments, and volcanic processes, it is difficult to estimate peak shock stress during the Toba explosion. If, however, the shock stresses are near those required to produce shock mosaicism in plagioclase at initial ambient temperatures, then local shock stress concentrations appreciably greater than 10 GPa are indicated. Endogenous processes producing similar high shock stress levels at considerable depths appear to be required to explain shock metamorphism of the Vredefort structure, South Africa (Lilly, 1981; Schreyer, 1983).

Thus, it appears that shock stresses of large magnitude can be produced by internal processes and do not require impacts of extraterrestrial objects. Clearly, the matter of internal shock deformation merits further investigation that we hope will be stimulated by the preliminary results presented here.

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