YOUNGEST TOBA TUFF: WORLD'S LARGEST KNOWN QUATERNARY ERUPTION: ITS PETROLOGY AND IMPACT ON ATMOSPHERE AND CLIMATE*

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EXTENDED ABSTRACT

Introduction

Variously referred to as the Toba caldera, Toba caldera complex, Toba volcanotectonic depression or simply Lake Toba (100 km long, 31 km wide, 450 m deep), this huge volcanic centre in northern Sumatra, Indonesia is the largest resurgent Quaternary caldera on Earth. Over the past 1.2 my, there have been four ash flow tuff eruptions from the caldera complex. The youngest tuff (YTT) erupted at ~74 ka (Ninkovich et al. 1978) expelling an estimated 7 x 10^{15} kg (or 2800 km^3 dense rock equivalent, at 2500 kg m^{-3}) of rhyolitic magma (Rose and Chesner, 1987). Eruption of YTT is responsible for the collapse structure visible today. After this mega eruption, resurgent doming of intracaldera YTT formed Samosir Island, which rises 750 m above Lake Toba. In addition, post-YTT lavas were extruded at 4 sites. YTT consists of an extensive, mostly non-welded outflow sheet with abundant pumice blocks, and covers 20,000 - 30,000 km^2 area.

Petrology of Toba Tuffs

YTT eruption was preceded by 35 km^3 of Haranggoal dacites tuff (HDT, 1.2 Myr BP), the 500 km^3 of Oldest Toba Tuff (OTT, 840 kyr BP) and 60 km^3 of Middle Toba Tuff (MTT, 501 kyr BP) (Chesner and Rose, 1991). Field relations and paleomagnetic signatures indicate that the ash flows originated from calderas alternately situated at the N and S ends of the depression. Magma erupted during successive eruptions subsequent to HDT was compositionally zoned, generally ranging from rhyodacite to rhyolite. Collectively, the YTT, MTT and OTT are referred to as quartz-bearing Toba tuffs and typically contain up to 40 wt% crystals of quartz, sanidine, plagioclase, biotite and hornblende. Minor minerals are magnetite, ilmenite, allanite, zircon and fayalite. They represent crustal melts that became compositionally zoned through extensive crystal fractionation, which occurred at pressures of ~3 kb or depths of 10 km. The magmas were not saturated with water. Much of the crystallization of the quartz-bearing tuffs occurred between 700° and 760 °C, but HDT erupted at higher temperature of 817 °C.

Although similar in composition and mineralogy, the OTT, MTT and YTT can be distinguished by subtle variations in their mineralogy, whole-rock and glass compositions. Mechanical mixing of distinct pumice composition indicates that multiple compositional layers were tapped simultaneously during the eruptions. Low-energy ring fractures were responsible for the emplacement of OTT, MTT and YTT, which resulted in dense welding of all units, except for the top of the youngest unit, and thick accumulations of rhyodacitic magma in the collapsing calderas (Chesner, 1998). Recent seismic tomographic investigations have suggested the presence of two melt regions ('magma reservoirs') between the lake and a depth of 10 km (Masturyono et al. 2001). The tuffs and lavas from these two reservoirs are isotopically distinct. The southern magma reservoir, which tapped OTT, YTT and post-YTT silicic lavas at three widely separated sites are uniform in Nd isotope composition. In northern reservoir magmas (MTT and post YTT eruption at volcano Tandukbenua), εNd is almost one unit lower, and $^{87}Sr/^{86}Sr$ is 0.00015 higher than in rocks from the Southern reservoir. Differences in composition between rocks associated with the two magma reservoirs have also been recognized in some trace elements like Rb, Ba, Ce, Y, Zr, T, Th etc.

Co-ignimbrite Ash Fall Deposits of YTT

The pyroclastic flows of youngest Toba eruption generated enormous co-ignimbrite clouds of fine ash, which drifted above both Indian Ocean and South China Sea and deposited as tephra beds. Ninkovich (1979) described an extensive rhyolitic ash horizon, up to 12 cm thick found in deep-sea cores west and north of Sumatra and also Bay of Bengal, and correlated with Youngest Toba eruption based on mineralogy, K-Ar age (73.5 +/- 3 X 10^3 yrs) and oxygen

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isotope stratigraphy. The ash layer occurs at marine oxygen isotope stage (OIS) 5-4 boundary. Rhyolitic ash occurs on land in Malayasia at many localities and has long been attributed to Toba eruption on the basis of proximity, mineralogy and relative age. Williams and Royce (1982) first recognized rhyolitic tephra predating late Pleistocene alluvium occurring in Quaternary sediments of the Son valley, north Central India and later identified as derived from Toba (Rose and Chesner, 1987). At least 1% of the Earth's surface has been estimated covered by Toba ash with thickness of 10 cm or more. Based on the then known dispersal of Toba ash, Rose and Chesner (1987, 1990) estimated a minimum mass of this tephra fall deposit as 2 x 10^{15} kg (a DRE volume of 800 km^3) and opined that this value may be much less than the true value, as the ash fall deposits are most likely to be traced to much greater distances than the known maximum of 3100 km.

Once, more people began looking for it, YTT turend up further afield. Tephra layers, identified as Toba tuff have been reported from many parts of the Indian subcontinent (Middle Sone and Central Narmada Valley Basins, Kukdi, Purna and Tapti Basins, Vamsadhara, Nagavali, Mahanadi and Brahmani River Basins, many river basins of AP etc.) (Acharyya and Basu, 1993). Geochemical fingerprinting of a comprehensive suite of samples, allowing comparison of the Indian samples to those from Toba, Malaysia and more importantly ODP 758 core, located halfway between Sumatra and Sri Lanka that contains Oldest and Middle Toba tephra as well as YTT (Dhen et al. 1991), and fission track dating of two samples of tephra from western India demonstrate that all the presently known Toba tephra occurrences in peninsular India belong to the Youngest Toba eruption (Shane et al. 1995; Westgate et al. 1998).

Nambiar et al. (1996) reported occurrence of late Pleistocene diffused tephra layers in number of deep-sea sediment cores west of Lakshadweep Ridge and based on geochemistry and morphology of glass shards correlated them with YTT (Nambiar and Sukumaran, 2002). The youngest Toba ash was identified in Arabian Sea cores from the upper Indus fan and northeastern Murray Ridge. Based on d^{18} O stratigraphy, Schulz et al. (1998, 2000) estimate ages of ~ 72,400 to 74, 600±5000 yrs BP for the Toba ash in northeast Arabian Sea cores, in good agreement with the ages centred at 74000±2000 yrs BP based on K/Ar, $^{40}Ar/^{39}Ar$ and fission track dating of glass shards from terrestrial outcrops. These sites extend the distance of the Toba ash occurrences to more than 4000 km from the source and the area of the ash blanket to > 4 x 10^6 km^2 (Schulz et al. 1998).

Volcanic glass and pumice fragments found in siliceous abyssal sediments of the Central Indian Ocean Basin (CIOB) south of the equator previously interpreted variously as product of intra-arc volcanism, Krakatau eruption and Indonesian arc volcanism, are found compositionally identical to the fallout deposits of YTT (Pattan et al. 1999). This correlation of CIOB ash with YTT extends the distribution of glass shards 1500 km south of the previously known fallout zone, which provides evidence for bi-hemispheric dispersal of ash from the Toba eruption.

Recently Song et al. (2000) and Buhring et al. (2000), on the basis of geochemical characteristics and oxygen isotope ages reported discovery of YTT in South China Sea Basin (SCSB), which indicates an extended dispersal of glass shards over 1800 km northeast of the Toba caldera, a direction opposite to what was previously conceived. The dispersal of the ash cloud in both western and eastern directions from the source indicates two contrasting wind directions and points to eruption during Northern Hemisphere summer monsoon season when south-westerly winds prevail at low-to middle tropospheric levels, transporting ash from lower parts of the co-ignimbrite clouds eastward into South China Sea and upper tropospheric easterly winds spread Toba ash across the Indian Ocean.

All reported ash beds related to YTT are predominantly composed of glass shards, with some pumice fragments and crystals. Bubble wall shard forms dominate, followed by platy and blocky shards. Quartz and felspars comprise the bulk of crystals, followed by biotite, apatite, and amphibole. All samples display very similar chemistry for major, minor and rare earth elements. They plot within the high silica end of the rhyolite field in TAS diagram. Chondrite-normalized REE profiles of YTT glasses from different tephra beds are remarkably similar, showing steep slope for LREE and a gentle reverse slope for HREE with pronounced negative Eu anomaly.

Reports of the distribution of Toba ash published since 1993 till now show its minimum spread encompassed the northeastern Arabian Sea (64° E), the Indian Ocean, 14° S of equator, northern India and Bangladesh north of the equator and ~113° E in South China Sea. The minimum area of the ash from the eruption, and thus its DRE volume, are thus now substantially larger than previously estimated.

Eruption Parameters: Intensity and Duration

The duration of YTT eruption estimated is 9-14 days (Ninkovich et al. 1979). Applying this to the total YTT volume, Rose and Chesner (1990) computed the average eruption rate at about 8 x 10^{12} g/s Taking the intensity of Toba eruption as 7 1 X 10^9 kg s^{-1}, Woods and Wohletz (1991) estimated the plume height for the YTT cloud as 32±5 km Rampino and Self (1993) considered this to be an under-estimate, suggesting that for peak intensities approaching 10^{10} kg s^{-1}, column heights may have reached 40 km

Impact on the Atmosphere and Climate

Critical for evaluation of Toba's potential climatic impact are estimation of gaseous sulfur yield and the resulting sulphate aerosol loading of the stratosphere Rose and Chesner (1990) estimated gas contents of the YTT magma to have been about 0 05 wt% H_2S and 3 wt% H_2O Scaling the H_2S content to computed eruptive volume, they estimated an eruptive emission of 3 5 x 10^{12} g of H_2S This is equivalent to about 1 x 10^{16} g of sulphate/water aerosol Zielinski et al (1996) estimated the sulphate/water aerosol loading from the volcanic sulphate concentrations recorded at 71 kyr BP in GISP2 ice core as 2 3-4 7 x 10^{12} kg, in reasonable agreement with the earlier estimate based on mineral chemistry However, estimation of sulfur emission by YTT magma, based on extrapolation of experimental data is only around 3 5 x 10^{10} kg (Scaillet et al 1998), which is 2-3 orders of magnitude lower than the previous estimates

Based on scaling up from smaller eruptions and computer models, conservative stratospheric aerosol loading of ~ 1 x 10^{15} g from YTT eruption is predicted to have caused a "volcanic winter" with a global cooling of 3° to 5° C for several years, and regional cooling up to 15° C (Rampino and Self, 1992, 1993) But according to Oppenheimer (2002), the globally averaged surface cooling estimate of 3°-5°C is probably too high , a figure closer to 1° C appears more realistic The eruption occurred during the stage 5a-4 transition of the oxygen isotope record, a time of rapid ice growth and falling sea level Rampino and Self (1992) suggested that the Toba eruption might have greatly accelerated the shift to glacial conditions that was already underway, by inducing perennial snow cover and increased sea-ice extent at sensitive northern latitudes

Oxygen isotope studies of sediments immediately above YTT layer in a South China Sea (SCS) core suggest that sea-surface temperatures dropped by ~1°C (Song et al 2000), though these could reflect conditions 10s or 100s year after the event Huang et al (2001) also recorded an abrupt 1°C drop in the temperature of SCS immediately above the Toba ash, which lasted for about 1 kyr They implicate the following chain of events polar cooling, expansion of northern hemisphere ice sheets, increasing intensity of the East Asian monsoon, cooling of China and tropical Pacific and reduction of atmospheric water concentration and concluded that such processes could have acted to prolong the short term cooling initiated by the Toba event The highest frequencies of ice-rafted debris in the 95,000 year long record of the North Pacific Ocean were recorded at ~ 72 ka (Kotilainen and Shackleton, 1995) In the Greenland GISP2 ice core, the largest amount of volcanic sulfur in the 110,000-year record occurs at 71±5 ka and is attributed to Toba (Zielinski et al 1996) There also occurs a large ECM spike at this period, which too indicates a volcanic source The massive sulfur peak spans six-seven years, confirming the original estimates of a sulfur aerosol-induced six year volcanic winter proposed by Rampino and Self (1992, 1993) and marks the termination of the interstadial of D-O event 20 This dramatic volcanic event is followed by 1000 years of the absolutely lower ice core oxygen isotope ratios of the last glacial period In other words, for 1000 years immediately following the Toba event, the earth witnessed temperatures relentlessly colder than during the last glacial maximum at 18-21 ka The first 200 years of this stadial event are marked by increased calcium deposition indicating unusually high amounts of wind-blown dust, probably due to decreased vegetation cover and exposure of sediments as sea levels dropped Zeilinski et al (1996) estimated temperature drop of >6°C over Greenland The interstadial portion of D-O event that lasted for ~2000 years following this coldest millennium shows that Toba was not directly responsible for the onset of the last glacial, which occurs in the ice core ~ 68 ka (Zielinski et al 1996), though leaves open the possibility that it is implicated in the ~ 1 kyr cold period prior to interstadial 19 (Oppenheimer, 2002) But inspection of the high-resolution oxygen isotope record of Lang et al (1999) shows that the cold event at 71 ka was consistently coldest for its entire duration, and had the longest duration of all such events in the 110 ka ice core record (Ambrose, 2003) The ice core geochemical record shows that the pattern of enhanced cooling for several centuries after the eruption of Toba does not occur in other stadial events (Zielinski, 2000)

The Vostok ice core from Antarctica shows an aluminum peak, indicating enhanced wind blown dust at ~71 kyr and an increase in non-sea salt sulfur in the core at the stage 5a-4 suggests a possible minor cooling from increased cloud cover of ~0 6° C

Evidence for other atmospheric perturbations arising from the Toba eruption has come to light from further ice core analysis Yang et al (1996) who recorded time resolved concentrations of chloride, nitrate and the ratio of Cl^- to Na^+ in the GISP2 layer found the pulse of aerosol fallout coinciding with depletions of chloride and nitrate and an accompanying low ratio of Cl^- to Na^+ indicating Toba's strong impact on tropospheric chemistry.

Impact on Terrestrial Environment

Rose and Chesner (1990) likened the aftermath of the Toba eruption to an 'enormous fire' covering up to 30000 km^2, arising from the widespread ignition of vegetation. The hot tephra, lava and gases would have exterminated all life in the immediate vicinity of the Toba crater. Gathorne-Hardy and Harcourt-Smith (2003) question the environmental impact, because Mentawi island, located 350 km southwest of Toba, has a primate and termite fauna that was apparently not destroyed by hot debris from the eruption. However, no direct effects should be expected, because this island, as well as rest of Sumatra and Java, was directly upwind of, and thus insulated from the eruption (Ambrose, 2003).

If Tambora, the largest historic eruption (20 km^3 DRE) caused the year without a summer in 1816 and global crop failures and famines (Ramaswamy, 1992), Toba could have been responsible for six years of relentless volcanic winter, substantial lowering of plant biomass and disastrous famine (Rampino and Ambrose, 2003). All aboveground tropical vegetation would have been killed by sudden hard freezes, and a 50% die-off of temperate forests is predicted from hard freezes during the growing season (Rampino and Ambrose, 2000). Long pollen sequences from Java and marine sediments in Indonesia and paleobiogeographic evidence indicate large parts of SE Asia were deforested at this time (Flenley, 1996). Rampino and Ambrose (2000) argued that in oceans, the tephra sedimenting through the water column would have scavenged out nutrients. This effect combined with reduced sunlight reaching sea level, and changes in atmospheric circulation, could have limited surface productivity in the oceans. But it has also been suggested that ash fallout can actually fertilize the oceans by supplying macronutrients and 'bioactive' trace metals (Frogner et al., 2001).

Impact on Humans

The climatic effects of volcanic eruptions can have severe consequences for human populations. Virtually all studies of the genetic structure of living human populations that have analysed the history of past population size, have identified a significant late Pleistocene human population bottleneck – a dramatic reduction, followed by expansion from a very small population size in Africa approximately 70 kyrs ago. The highest estimates of effective population size during the bottleneck are about 10,000 reproductive females (Sherry et al. 1997), and Harpending et al. (1993) provided estimates as low as 500-3000 females. Famine caused by the Toba super-eruption and volcanic winter provides a plausible hypothesis for late Pleistocene human population bottlenecks (Ambrose, 1998, 2003), though according to Gathorne-Hardy and Harcourt-Smith (2003), it is unlikely that Toba super-eruption caused a human, animal or plant population bottleneck. Six years of volcanic winter, followed by 1000 years of the coldest, driest climate of the late Quaternary may have caused low primary productivity and famine, and thus could have decimated most Modern man's populations, especially outside of isolated tropical refugia (Ambrose, 1998). Many local human populations at higher latitudes and in the path of the ash fallout may have been completely eliminated. Release from the bottleneck could have occurred either at the end of the hypercold phase, coinciding with D-O event interstadial 19 around 70 ka, or 10,000 years later, at the transition from cold oxygen isotope stage 4 to warmer stage 3, as late as 60 ka. In this climate-induced bottleneck scenario (Volcanic Winter/Weak Garden of Eden Model proposed by Ambrose, 1998) the surviving populations would have expanded simultaneously when favorable climates returned. The largest populations surviving from this catastrophe should have been found in the largest tropical refugia, and thus in equtorial Africa. High genetic diversity in modern Africans may thus reflect a less severe bottleneck rather than earlier population growth.

Volcanic winter and the instant Ice Age may help resolve the central but unstated paradox of the recent African origin of humankind: if we are all so recently "Out of Africa", why do we not all look more African? Because the volcanic winter and consequent environmental changes would have reduced populations to levels low enough for founder effects, genetic drift and local adaptations to produce rapid population differentiation, causing the peoples of the world look so different today. In other words, Toba may have caused modern human races to differentiate abruptly only 70, 000 years ago, rather than gradually over one million years (Ambrose, 1998).

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ANNOUNCEMENT

Geological Society of India

Annual General Meeting – 2004

and

National Seminar on Deltas of India

The Annual General Meeting (AGM) of the Geological Society of India for 2004 will be held at the invitation of the Department of Geology, Andhra University during 2-4 November 2004, at Visakhapatnam A national seminar on 'Deltas of India' with special emphasis on the natural resources of deltas (oil and natural gas) will be held concurrently, organized by the Department of Geology, Andhra University Scientists interested in participating in the national seminar may please contact Prof K L V Ramana Rao, Head of the Department of Geology, Andhra University, Visakhapatnam - 530 003, **Phone:** (0891) 2754871 Ext 243, (0891) 2734883, **Email:** lvrkoya@yahoo com

During the Annual Convention, it is customary to hold a session for presentation of results of recent and ongoing research, especially by younger researchers, who are requested to contact Shri S V Srikantia, Secretary, Geological Society of India, No 63, 12th Cross, Gavipuram, PB No 1922, Bangalore-560 019 **Email:** gsocind@bgl vsnl net in, **Telefax:** 080-26613352, **Phone:** 080-26522943

A.U. GEOLOGY DEPARTMENT ALUMNI MEET

During the National Seminar on Deltas of India (2-4 November 2004) it is envisaged to hold a meeting of the Alumni of the Geology Department of the Andhra University at Visakhapatnam during one of the evenings Former students of the Department are requested to send updated addresses (including telephone number and Email address) of their own and other alumni known to them to Prof K L V Ramana Rao, HOD, Department of Geology, Andhra University, Visakhapatnam-530 003, **Email:** lvrkoya@yahoo com