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The Toba Caldera Complex

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A B S T R A C T

The Toba Caldera in Indonesia is one of the most remarkable volcanic features formed during Quaternary geologic time. Its rich history of research for over a century has yielded important information on the physical volcanology of silicic calderas and super-eruptions, geochemical evolution of silicic magma bodies, and geophysical imaging of active sub-volcanic systems. During the past 1.3 my, the Toba area has erupted intermediate composition lavas, followed by intermediate pyroclastics, three quartz-bearing silicic tuffs, and most recently, intermediate to silicic lavas. This pattern represents the incremental assembly and periodic eruption of a crustal magma body of batholithic proportions. The apparent migration of activity to the west, may have implications for the next? Toba super-eruption.

1. Introduction

During the past 30 years, the Toba Caldera and its paroxysmal eruption 74,000 years ago have gained scientific notoriety for several reasons. Viewed from space, the caldera is one of the most striking volcanic craters on Earth, measuring 100 × 30 km. The steep-walled caldera contains Lake Toba, the largest volcanic lake on the planet. Erupting at least 2800 km^3 of magma in a single event 74,000 years ago, it ranks as the largest volcanic eruption of the Quaternary geologic period, qualifying as an 8.8 magnitude eruption. A vast portion of North Sumatra was drowned in ignimbrite that extended from coast to coast, an extensive ash deposit blanketed large portions of Southeast Asia including the entire subcontinent of India, and an aerosol cloud and dust cloud probably encompassed the Earth. The effects of this cataclysmic eruption would have included complete annihilation of both flora and fauna in North Sumatra by the ignimbrite, significant effects on flora and fauna by ash fall in Southeast Asia, and possibly regional to global temperature change and its associated environmental impacts.

The geologic history and origin of the Toba Caldera has captured the attention of several researchers for well over a century since the first accounts of the “liparitic” Toba tuffs and geologic map by Wing Easton (1894, 1896). Subsequent field reconnaissance missions by Volz (1909), Klein (1917), and others contributed to the early characterization of the volcanic rocks of the Toba area. Extensive field work by van Bemmelen (1929, 1939, 1949, 1970) would lead to several important publications on the volcanic origin of Lake Toba, and inspired other contemporary studies by Westerveld (1947), and Verstappen (1961, 1973). Modern volcanological studies began at Toba with its characterization as a “resurgent cauldron” by Smith and Bailey (1968), geophysical, stratigraphic, and geochemical research directed by Susumu Nishimura (Yokoyama et al., 1980), and a major mapping effort that resulted in the publication of 1:250,000 scale geologic maps (Aldiss et al., 1982) and an associated interpretation of the origin of Lake Toba (Aldiss and Ghazali, 1984). Another pulse of Toba research took place in the 1980’s led by George Walker and his students, Mary Caress and Michael Knight, who focused on physical volcanology and paleomagnetism, while Bill Rose and his student Craig Chesner concentrated on the petrology of the Toba tuffs. These studies collectively established a stratigraphic framework (Knight et al., 1986; Chesner and Rose, 1991) and chronology for the deposits associated with the formation of the Toba Caldera Complex: Youngest Toba Tuff (YTT) 0.074 Ma, Middle Toba Tuff (MTT) 0.501 Ma, Oldest Toba Tuff (OTT) 0.840 Ma, and Haranggaol Dacite Tuff (HDT) 1.2 Ma (Nishimura et al., 1977; Diehl et al., 1987; Chesner et al., 1991). This contemporary stratigraphic analysis provided essential context for subsequent petrologic studies and geochemical fingerprinting of the distal Toba ashes. Since then, many researchers have contributed to the petrologic knowledge of the Toba system and its silicic magma bodies by studying the geochemistry and isotope geology of its rocks, minerals, melts, and distal ashes. A major branch of Toba research has also been concerned with the climatic effects of the 74 ka eruption, the largest volcanic eruption experienced by the modern human race.

The most recent field studies at Toba have focused mostly on seismic tomography of the Toba magma chamber, volcanism since the last caldera-forming eruption, and bathymetric mapping of the caldera floor. A seismic reflection profiling study of the sub-

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lacustrine portion of the caldera is scheduled to begin in 2012. Although considerable progress has been made in understanding the caldera complex, its magma bodies, and the effects of its largest eruption, there is still more to be learned from this incredible volcanic, atmospheric, and biospheric laboratory. The goal of this review is to summarize the physical volcanology, petrology, and geophysical research that have been conducted to date, report some additional findings, and provide context to the exciting research presented in this volume.

2. Tectonic setting

Toba is located in the North Sumatra province of the island of Sumatra in western Indonesia, within the Barisan Mountains (Fig. 1). These mountains comprise the backbone of Sumatra and at Toba consist mostly of Permo-Carboniferous metamorphic rocks, Miocene sedimentary rocks, and Quaternary volcanics (Aldiss et al., 1982). Subduction of the Indian-Australian plate beneath the continental Eurasian (Sundaland) plate at a rate between 5.2 and 5.8 cm/year down the Sunda Trench (Prawirodirdjo et al., 1997) has resulted in an active volcanic arc that follows the NW trend of Sumatra. According to Sakaguchi et al. (2006), the crust ranges from 29 to 40 km thick beneath Toba. The depth to the Benioff Zone in the vicinity of Toba is approximately 125 km (Fauzi et al., 1996) indicating a subduction angle of about 30°. Oblique subduction at about 45° has resulted in two significant faults that are parallel to and lie between the trench and volcanic arc. The vertical Sumatran (Semangko) Fault marks the boundary between the Eurasian (Sundaland) plate and the majority of the volcanic arc to the northeast with a forearc basin to the southwest, while the Mentawai Fault (site of the 9.0 M 2004 mega-quake and resultant tsunami, Lay et al., 2005) separates the forearc basin from a forearc accretionary ridge complex further southwest. The entire forearc sliver between the trench and the Sumatran Fault is decoupled and moves northwestward. According to McCarthy and Elders (1997), dextral displacement along the Sumatran Fault has been about 150 km with estimated annual slip rates of 2.3 cm/year near Toba (Bellier and Sebrier, 1995). Gasparon and Varne (1995) suggest that eastern Sumatra, north of the Sumatran Fault, may belong to the Central Granitoid Province of the SIBUMASU terrane (Siam, Burma, Malaysia, Sumatra). A conspicuous feature on the Indian-Australian plate is a 2 km high ridge known as the Investigator Ridge Fracture Zone (IFZ) that subducts almost directly beneath Toba. Fauzi et al. (1996) used earthquake hypocenters to determine the geometry of the subducting slab beneath Toba with particular attention to the IFZ. Their results indicated a bend in the slab that coincided with Toba, high seismicity along the subducted portion of the IFZ, but no conclusive evidence of a tear in the slab along the IFZ as previously suggested by Page et al. (1979). Instead, they suggest that the IFZ may focus volatile release into the mantle wedge beneath Toba.

3. Formation of the Toba Caldera Complex

Over the years, three fundamental questions have confronted field researchers at Toba:

1) Did Toba originate as a tectonic depression/graben from which later ignimbrite eruptions occurred (tectonic depression model), or did the eruption of voluminous ignimbrites result in the formation of the depression (volcano-tectonic model)?
2) How many ignimbrites (ash-flow tuffs) erupted from Toba?
3) How and when did Samosir Island form?

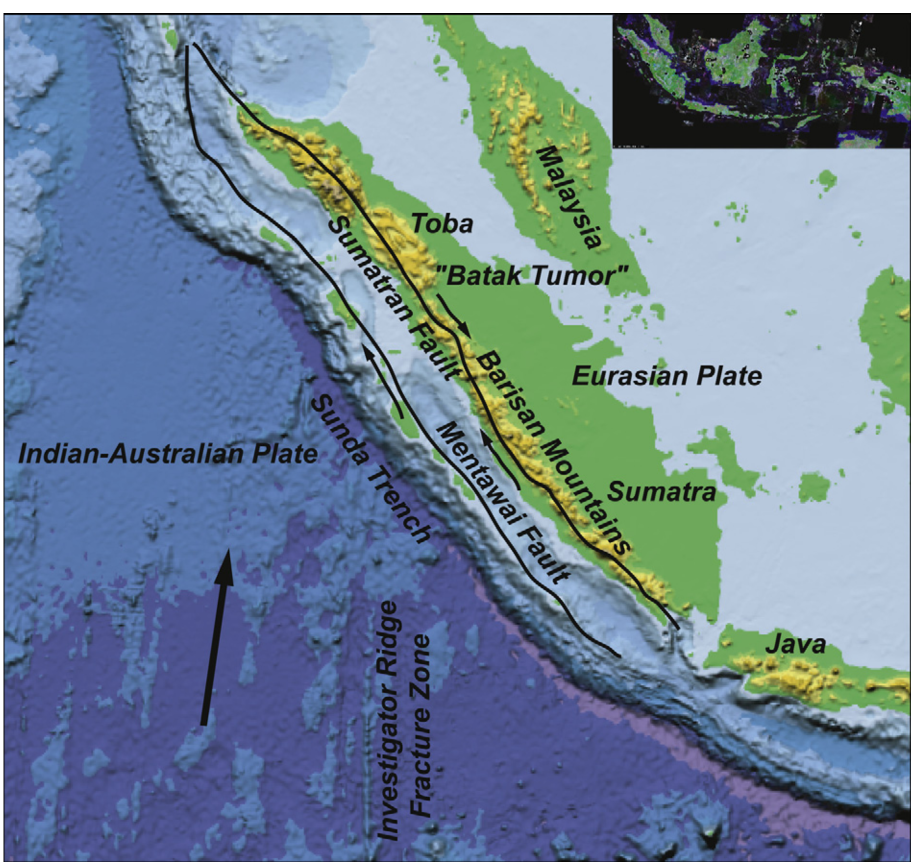

Fig. 1. Tectonic setting and location map (inset) of the Toba Caldera. Tectonic map modified from Simkin et al. (2006).

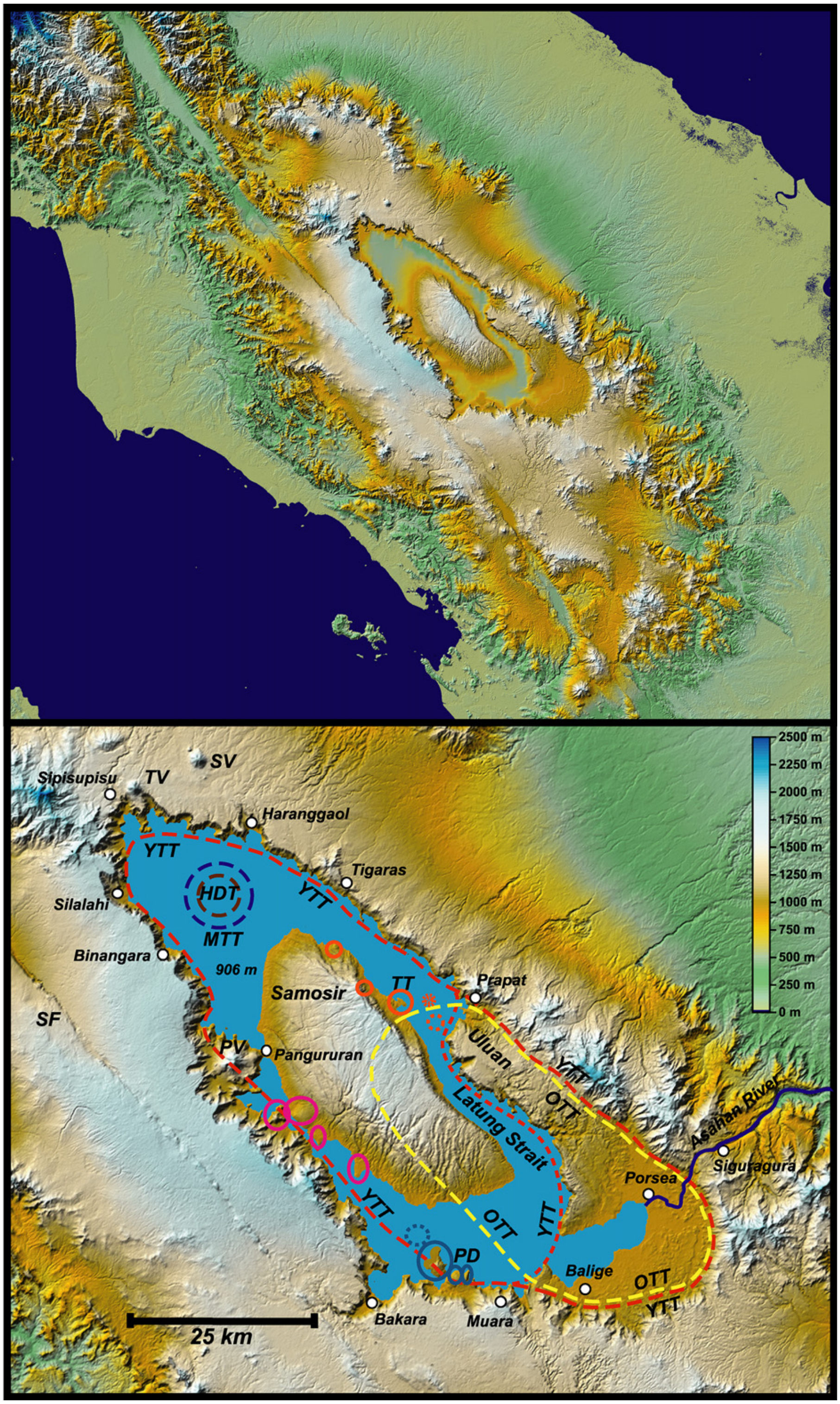

Fig. 2. Toba Caldera Complex location map plotted on base DEM image. Caldera locations indicated by dashed lines where HDT = brown, OTT = yellow, MTT = dark blue, and YTT = red. Inner YTT collapse fault is shown with short red dashes. Samosir lava domes are outlined by orange circles and Pardepur lava domes are light blue. Dotted orange and light blue circles are sub-lacustrine lava domes, identified by bathymetry, that belong to the Samosir and Pardepur lava dome groups respectively. Orange asterisk is possibly an area of sub-lacustrine hydrothermal activity associated with another Samosir lava dome. Pink ovals are areas of recent uplift that may be underlain by hypabyssal intrusions. Abbreviations are: PV = Pusikbukit volcano, PD = Pardepur lava domes, TT = Tuk–Tuk lava domes, TV = Tandukbenua volcano, SV = Singgalang volcano, SF = Sumatran Fault. Towns are indicated in white (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Prior to modern theories of silicic caldera formation and evolution, it is easy to understand why most of the early researchers supported the tectonic depression model. It simply was unimaginable that such an enormous feature as Toba could form as the result of one or more ignimbrite eruptions. The tectonic depression model, first expressed by Wing Easton (1894, 1896) persisted with modifications for nearly a century by subsequent researchers including Volz (1909), Westerveld (1947), Verstappen (1961, 1973), and Nishimura et al. (1984). Only one early researcher, van Bemmelen (1929, 1939, 1949, 1970) championed a volcanic origin by maintaining that "no investigator, who has set eyes on the imposing precipitous escarpments surrounding the Toba cauldron (many hundreds of metres high and plunging down 400–500 m to the floor of this sink), will ever contend that this trough existed already before the outburst." Since 1984, with a greater understanding of silicic calderas at hand, all subsequent researchers have been in favor of a volcanic or volcano-tectonic origin for Toba including Aldiss and Ghazali (1984), Knight et al. (1986), Chesner and Rose (1991), and Bellier and Sebrier (1994). The most recent study used SPOT imagery to support a model whereby pull-apart or step-over tectonics associated with the Sumatra Fault has controlled the location of the ignimbrite eruptions. Although most field researchers recognized more than one ignimbrite in the steep slopes surrounding Lake Toba, or in deeply incised valleys outside of the depression, some maintained that the present depression formed mostly as the result of a single eruption (Van Bemmelen, 1939; Aldiss and Ghazali, 1984; Chesner and Rose, 1991), while others suggested a piecemeal origin.

Another issue that has received considerable attention over the years is the origin of Samosir Island. Van Bemmelen (1939) described its origin as a resurgent dome long before Smith and Bailey's classic paper on resurgent calderas. Noting its thick veneer of diatomaceous lake sediments, its westward dips, eastern fault scarp, and that the maximum possible lake level was well below its highest elevations, Van Bemmelen concluded that it was uplifted after eruption of the ignimbrites, and that the Uluan peninsula resurged at this time as well. Many workers resisted this concept, and even those that accepted it debated the timing of the uplift. It wasn't until radiometric dating of the welded ignimbrites exposed in the eastern fault scarp revealed that these tuffs were 73 ka (Chesner et al., 1991) and that some of the lake sediments were as young as 33 ka (Chesner et al., 2000), that uplift of the Samosir (and possibly Uluan) resurgent dome became widely accepted as one of the most recent events to occur at Lake Toba.

The model presented here for the formation and evolution of the Toba Caldera Complex (Fig. 2), utilizes the contributions of many researchers who have sought to explain the origin of the "kesselbruch" (basin generated by collapse along arcuate faults) for the past 117 years. It is based upon the identification, distribution, geochemistry, and geochronology of 4 separate ignimbrites, pre- and post-caldera volcanics, caldera-fill sediments, and recent bathymetric surveying. Some elements of this evolutionary sequence are not endorsed by all researchers, and in keeping with its long history of study, controversy still exists.

3.1. Pre-Caldera andesites

The oldest volcanic rocks exposed in the walls of the caldera are found in the northern portion of the caldera and consist of a thick sequence of 2-pyroxene andesites ($SiO_2 = 57$ wt. %) and basaltic andesites (Fig. 3A). These rocks outcrop at lake level from the Haranggaol area to near Sipisupisu where they are up to 500 m thick and consist of interbedded lavas that dip to the northeast. One sample has a K–Ar age of 1.3 Ma (Yokoyama and Hehanussa, 1981). Van Bemmelen (1970) described similar rocks exposed in the northwestern escarpment between Silalahi and Binangara that dip to the SSE and are up to 800 m in total thickness. However, samples collected at lake level in this area are welded tuffs and appear to belong to the overlying HDT. An andesitic breccia has also been described by van der Marel (1948a) at the base of the escarpment in the northern portion of Samosir Island. Chesner and Rose (1991) interpreted these intermediate rocks to represent a large strato-volcano, centered over the northern portion of the present caldera that typified volcanic edifices of Sumatra's main volcanic arc. Exposures of other pre-caldera volcanic rocks are sparse, including some highly altered andesitic breccias near the southern caldera margin east of Muara, two small exposures of andesite and diorite along the southernmost shore of Samosir Island, and andesite lavas along the lake shore north of the opening to the Bakara embayment. Pre-caldera andesites have also been mapped by Aldiss et al. (1982) at lake level east of the opening to Bakara Bay, and exposures in the west caldera wall just south of Pusikbukit volcano.

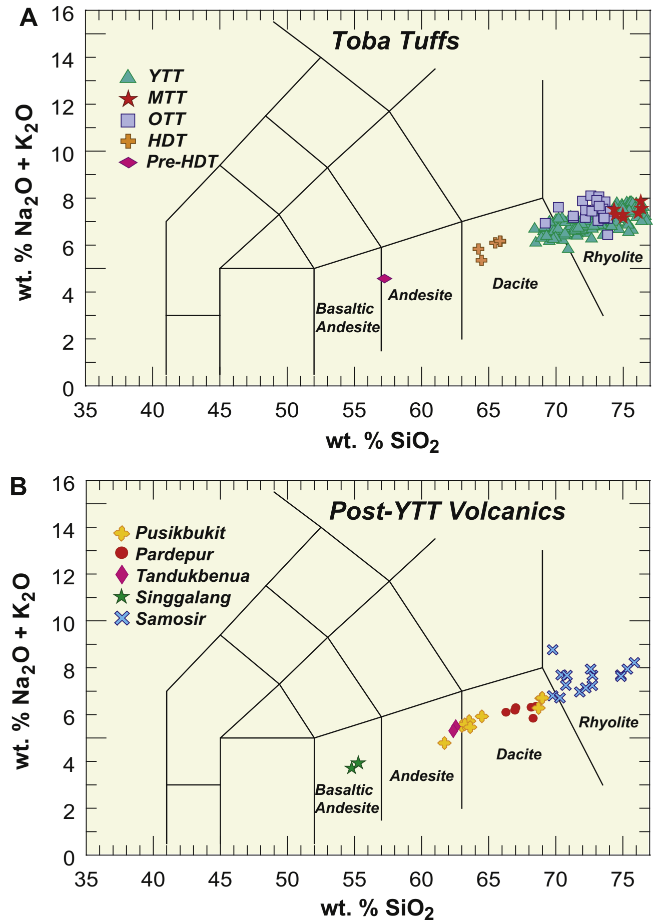

Fig. 3. Bulk rock chemistry of the Toba tuffs (A) and post-YTT volcanics (B) plotted on total alkalis vs. SiO_2 volcanic rock classification from LeBas et al. (1986).

3.2. Haranggaol Dacite Tuff

The onset of explosive volcanism at Toba is marked by exposures of the densely welded Haranggaol Dacite Tuff in the northern caldera walls above the sequence of andesitic lavas. The HDT has a distinctive "streaky" appearance in outcrop due to abundant parallel white structures that stand out against the grey matrix of the tuff. This parataxitic texture consists of highly elongated (up to 1 m in length), spindle shaped, slightly vesicular, glassy domains that represent stretched pumices. Such linear fabric is consistent with an origin during post-emplacement secondary flow (Wolff and Wright, 1981), and thus the HDT is interpreted as a rheomorphic tuff (Knight et al., 1986). The HDT is up to 100 m thick in the caldera wall near Haranggaol and on the rim between Haranggaol and Tigaras, and commonly exhibits columnar joints. It has also been identified in the northwestern scarp at lake level near Binangara, where it may be several 100's m thick. Based upon limited thickness and distribution data, Chesner and Rose (1991) estimated that the tuff has a dense-rock-equivalent (DRE) volume of ~35 km. They interpreted the HDT to represent a Crater Lake-type caldera eruption from the large pre-caldera stratovolcano that had previously erupted the underlying andesitic lavas (Fig. 2). The only known date for the HDT is a fission track age of 1.2 Ma by Nishimura et al. (1977). Phenocrysts consist of plagioclase, orthopyroxene, and clinopyroxene, and its bulk rock composition (63–66 wt. % SiO_2) indicates that the HDT is dacitic (Fig. 3A). Eruptive temperature determined using Fe–Ti oxides is 847 °C with a $fO_2 = 10^{-12.5}$ (Chesner, 1998). An initial $^{87}Sr/^{86}Sr$ ratio for the HDT is 0.71363 (Fig. 4). The strong crustal signature of the HDT and the conformable older andesitic lavas indicates that a deviation from typical magmatic evolution of mantle derived melts was underway at Toba at this time.

3.3. Oldest Toba Tuff

The first of the 3 quartz-bearing Toba tuffs (ignimbrites) is exposed mostly at lake level along the western scarp of the Uluan peninsula, and in the walls of the southern and western portions of the caldera. The only places it has been identified outside the present caldera are in the deeply incised Asahan River canyon and in a fault block north of the lake. This densely welded rhyolite tuff contains quartz, sanidine, plagioclase, biotite, amphibole, and occasional orthopyroxene, with accessory amounts of allanite, zircon, magnetite, and ilmenite (the same assemblage as all the quartz-bearing Toba tuffs). The OTT can be distinguished in the field from younger welded Toba tuffs by its typically pink quartz, and its reverse polarity. A few exposures described by Chesner (1988) may possibly represent unwelded OTT, but this association has not been proven. Chesner (1998) demonstrated that it is compositionally zoned from 69 to 74 wt. % SiO_2 (Fig. 3A) and, in one locality, has fiamme with SiO_2 contents ranging between 61 and 74 wt. %. The OTT erupted at temperatures between 704 and 759 °C, with fO_2 of −16 to −14 log units, had 2.0–5.5 wt. % dissolved water, and <125 ppm CO_2 (Chesner, 1998; Chesner and Luhr, 2010). Initial

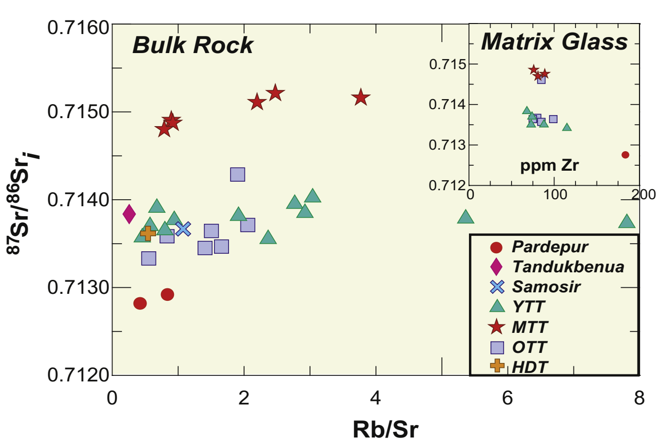

Fig. 4. Initial $^{87}Sr/^{86}Sr$ vs. Rb/Sr for bulk rocks and Zr for matrix glasses (inset). Isotopic ratios determined at the Open University and reported in Chesner (1988).

$^{87}Sr/^{86}Sr$ ratios range between 0.71333–0.71429 (Fig. 4); Wark et al. (2000) report εNd = −9.9‰ for the OTT.

The OTT has been dated using $^{40}Ar/^{39}Ar$ at 840 ka (Diehl et al., 1987). Based upon its distribution, a source in the southern portion of the present caldera is suggested. Caress (1985) and Knight et al. (1986) interpret the southeastern topographic margin of the present caldera to coincide with a portion of an OTT caldera, now known as the Porsea Caldera (Fig. 2). Beyond this presumed segment of caldera boundary, the location of the OTT caldera is speculative, although distribution of the subsequent MTT (next section) suggests that the pre-caldera stratovolcano to the north, and its small HDT caldera, remained intact after the OTT eruption. Although caldera size and overall tuff distribution are poorly constrained, Knight et al. (1986) estimated a DRE volume of about 500 km^3 for the OTT ignimbrite. OTT ash has, however, been identified in deep sea cores in the Indian Ocean and South China Sea (Dehn et al., 1991; Lee et al., 2004; Pattan et al., 2010), and an additional 1800 km^3 of ash boost its estimated DRE volume to ~2300 km^3 (Pattan et al., 2010).

3.4. Middle Toba Tuff

In the northern walls of the caldera between Haranggaol and Silalahi, a quartz-bearing welded Toba tuff of limited extent overlies the HDT. This unit, known as the MTT, is very distinctive in the field, demonstrating well-defined eutaxitic texture. Its light gray top with black glassy fiamme grades into a vitrophyric, columnar jointed base. Limited geographic distribution at only a few exposures in the northern caldera walls, where the tuff is up to 180 m thick, allow a minimum DRE volume estimate of ~60 km^3 for the MTT ignimbrite (Chesner and Rose, 1991). Based upon similar distribution to the underlying andesites and HDT, the MTT is also presumed to have been erupted from the pre-caldera stratovolcano in northern Toba (Fig. 2), perhaps enlarging the HDT caldera. However, like the surmised HDT caldera, no remnants of an MTT caldera have been identified. Sanidine from the MTT has been dated by $^{40}Ar/^{39}Ar$ at 501 ka (Chesner et al., 1991).

Chesner (1998) determined that the MTT is a reversely zoned rhyolite tuff with SiO_2 contents ranging from 72 wt. % SiO_2 near its base to 76 wt. % SiO_2 at its top (Fig. 3A). Eruptive temperatures were 743–751 °C, $fO_2 = 10^{-15}$, and dissolved H_2O and CO_2 were 2.0–5.5 wt. % and <90 ppm respectively. Strontium isotopic ratios are the highest of all the Toba tuffs ranging from 0.71470 to 0.71521 (Fig. 4); Wark et al. (2000) report εNd = −10.8‰ for the MTT. Although the MTT has the same mineralogy and general chemistry as the other quartz-bearing Toba tuffs, it can be distinguished from them by its whole rock and mineral chemistry as well as its isotopic ratios. Dehn et al. (1991) tentatively identified MTT ash in deep sea cores from the Indian Ocean, although nothing in the field geology suggests that the MTT eruption was any larger than a Crater-Lake type eruption, and significant distal ash or pumice fall is unlikely.

3.5. The Youngest Toba Tuff eruption

Continued emplacement of silicic magma bodies into the upper crust for nearly 1 my, eventually assembled a continuous, batholith-sized magma body, delineated by an area of regional doming that van Bemmelen (1939) referred to as the *Batak Tumor* (Figs. 1,2). At 74 ka foundering of the roof of this shallow magma body formed the feature visible today that is commonly referred to as the Toba Caldera. The collapse feature is elongate parallel to the volcanic front, measures about 100 × 30 km, covers about 2270 km^2, and encompasses all previous calderas (MTT, OTT, and HDT) and most of the presumed stratovolcano in the north. Lake Toba covers about $^2/_3$ of the caldera floor and is up to 500 m deep.

From lake bottom to caldera rim, total relief ranges from about 900 to 1700 m.

The topographic margin of the caldera is interpreted to be the recessed expression of a ring fracture fault that encircled the caldera. Piston-like caldera collapse along a ring fracture is suggested by the steep slopes and high relief of the caldera walls. In the southeastern portion of the caldera, partial collapse occurred along the caldera bounding ring fracture while additional collapse occurred along a second arcuate fault that coincides with the steep western face of the Uluan peninsula. Coincident with caldera collapse, ~2000 km^3 (DRE) of compositionally zoned rhyolitic to rhyodacitic magma erupted as ignimbrites. Some of these mobile pyroclastic flows escaped the caldera and descended the slopes of the Batak Tumor towards both coastlines of Sumatra while others were trapped in the collapsing caldera where they accumulated to great thicknesses. When the eruption was over, a steep walled, flat floored caldera, about 2 km deep, would have existed. Below the caldera rim but perched well above its floor, the Uluan block would have been the only topographic feature visible above the caldera's flat floor. Beneath the caldera floor, ignimbrite, over 600 m thick in places, welded and began to cool.

The tuffs deposited by this colossal eruption are collectively known as the YTT and consist of thick intra-caldera fill tuffs, an extensive outflow sheet, and a distal ash. Intracaldera tuffs are exposed in 2 main areas of the caldera. Between Prapat and Porsea ("Prapat Graben") exposures of the YTT are usually <100 m thick and the tuff is non-welded to incipiently welded. However, in the eastern scarp of Samosir Island up to 600 m of densely welded YTT tuff is exposed. This portion of the YTT is thought to represent thick ponding within the main portion of the YTT caldera bounded by the caldera structural margin to the west and northeast, and by the Uluan peninsula to the east.

According to the map of Aldiss et al. (1982), the YTT outflow sheet covers ~20,000 km^2. Considering the area of the caldera and that the tuffs are likely to have entered both the Indian Ocean and the Straits of Malacca, up to 30,000 km^2 of northern Sumatra may have been inundated by ignimbrite. Most of the outflow sheet consists of non-welded ignimbrite, but in areas where it exceeds 100 m in thickness, it can be incipiently to densely welded. Locations where the outflow sheet is known to be welded include the Asahan Valley, the western caldera walls, and deeply incised areas east and west of the caldera. Rose and Chesner (1987) have estimated that approximately 1000 km^3 of DRE tuff exists as caldera fill and another 1000 km^3 exists as outflow. The significance of these voluminous ash-flow tuffs has been formally recognized in Spanish linguistics where 'toba' is the word for 'tuff'.

Although the base of the YTT is rarely exposed, at the few exposures where it can be seen there is no evidence of a plinian fall deposit. A bedded ash containing accretionary lapilli has been noted at the base of the YTT on the Uluan block near Prapat, and may be the only evidence of pre-ignimbrite fall from the eruption. Thus, it seems unlikely that the YTT ignimbrites were generated by collapsing plinian eruption columns, but instead were emplaced by immediate fountain collapse at the onset of the eruption, similar to the volcano-tectonic depression ignimbrite eruptions of the Altiplano-Puna Volcanic Complex, Central Andes (de Silva et al., 2006). Knight et al. (1986) interpreted the magnetic anisotropy of welded YTT to indicate 2 distinct vent areas for the YTT. A grain size analysis study of the non-welded YTT by Caress (1985) supported this interpretation and also indicates a linear vent system within the present Latung Strait. Based upon distribution of early erupted high-Si pumices and late erupted low-Si pumices as well as overall tuff distribution patterns, an eruption model consisting of numerous active ring fracture segments around the entire caldera is also possible (Chesner and Rose, 1991; Chesner, 1998).

In addition to the great volumes of YTT outflow sheet and intracaldera tuffs, significant YTT ash fall is recorded from deep sea cores in the northern Indian Ocean, Arabian Sea, South China Sea, and at terrestrial locations on the Malaysian Peninsula and the Indian sub-continent (Ninkovich et al., 1978a; Ninkovich, 1979; Stauffer et al., 1980; Rose and Chesner, 1987; Dehn et al., 1991; Acharyya and Basu, 1993; Shane et al., 1995; Westgate et al., 1998; Pattan et al., 1999; Bühring et al., 2000; Lee et al., 2004; Raj, 2008). Based upon the known thicknesses and distribution of the ash fall, as well as glass loss calculations from the ignimbrite, Rose and Chesner (1987) estimated that an additional 800 km^3 (DRE) of YTT consisted of distal ash. Since their calculation, the YTT ash has been discovered in several additional localities, and the total volume of ash is probably in excess of 800 km^3. The lack of proximal plinian pumice fall deposits led Rose and Chesner (1987) to conclude the YTT ash was entirely of co-ignimbrite origin. Thus, an ash cloud of enormous areal extent would have been generated by elutriated ash convecting into the atmosphere during emplacement of the vast ignimbrite sheet. Furthermore, ignimbrite is likely to have entered the sea along both coasts of Sumatra, generating significant ash plumes at the eastern and western margins of the 30,000 km^2 ignimbrite surface. The co-ignimbrite model can account for the observed distribution and thickness of the YTT ash without the high plinian columns (50–80 km) suggested by Ninkovich et al. (1978b). In the same study, an eruption duration estimate of 9–14 days was made based upon the style of graded beds in the deep sea YTT ash layer. Combining the DRE volume estimates of the ignimbrite (2000 km^3) and the co-ignimbrite ash (>800 km^3), at least 2800 km^3 of magma was erupted during the YTT event, possibly in just a few weeks.

3.6. *Petrology of the Youngest Toba Tuff*

Mineralogy, geochemistry, and isotopic analyses of the YTT received considerable attention once the stratigraphic framework for the eruptive units was established by Knight et al. (1986) and Chesner and Rose (1991). Bulk rock chemistry of individual pumice blocks from the YTT (Chesner, 1998) indicated eruption of a compositionally zoned silicic magma chamber that ranged from 68 to 77% SiO_2 (Fig. 3A). Compositions of individual pumice blocks from the same exposures record simultaneous eruption of rhyolite and rhyodacite across compositional boundaries. The geographic distribution of exposures consisting of predominantly high or low-SiO_2 rocks indicates that most of the YTT outflow sheet consists of high-SiO_2 rocks, while low-SiO_2 rocks are confined within the caldera and its rim, suggesting that caldera collapse coincided with eruption of the low-SiO_2 magma. Crystallinity ranged from about 12 to 40 wt. % with higher contents in the lower SiO_2 rocks. The crystal rich YTT magma contained phenocrysts of quartz, sanidine, plagioclase, biotite, and amphibole, with accessory amounts of orthopyroxene, allanite, zircon, magnetite, and ilmenite. Occasionally, fayalite, and inclusions of apatite and pyrrhotite were also noted. Chesner (1998) interpreted that the zonation had developed from crystal fractionation of the phenocrystic mineral assemblage. Although similar in composition and mineralogy, the 3 quartz-bearing Toba Tuffs (YTT, MTT, and OTT) can be distinguished using their combined bulk rock and mineral chemistries. The variety of mineralogy allowed estimation of intensive parameters via several techniques and indicated eruptive temperatures of 701–780 °C, fO_2 ranges of −16 to −14 log units, and total pressures of 3 kb. An experimental petrology study by Gardner et al. (2002) indicated that amphibole was not a stable phase in the Toba magmas and therefore it is entirely of xenocrystic origin. Dating of mineral separates indicated that all amphibole and some plagioclase were introduced into the magma as xenocrysts from source rocks as old as 1.5 Ma. Because Chesner's total pressure estimate of 3 kb was based on the amphibole geobarometer, they concluded that it was invalid and that the YTT magma equilibrated at pressures of 1.0–1.5 kb prior to eruption.

Beddoe-Stephens et al. (1983) conducted the first melt inclusion study of Toba rocks although their descriptive and analytical work was performed before the modern stratigraphic relationships had been established. A recent study of melt inclusions in quartz phenocrysts (Chesner and Luhr, 2010) indicated dissolved H_2O contents between 4.0 and 5.5 wt. %, CO_2 contents of 20–175 ppm, and gas saturation pressures of 1.1–1.4 kb. A major finding of this study revealed that all melt inclusions, regardless of their host rock bulk composition were high-SiO_2 rhyolites, and that the most evolved composition melt inclusions were found in quartz crystals erupted from low-SiO_2 magma. Unusually large euhedral quartz crystals (up to 2 cm in diameter) are common in Toba pumices. Their large and abundant negative crystal melt inclusions (up to 200 μm), highly resorbed edges, and cathodoluminescent zoning are suggestive of long crystallization histories. Thus, Chesner and Luhr (2010) concluded that the compositional zonation of the YTT magma body originated mostly by removal and accumulation of phenocrysts from upper portions of the magma body into its lower portions, from a high-SiO_2 parental magma. Although major element chemistry and compatible trace element geochemistry supported this conclusion, enriched incompatible trace element concentrations in melt inclusions relative to matrix glass from both low and high-SiO_2 samples required a different explanation. Even though Thomas et al. (2003) concluded that boundary layer processes did not affect the trace element compositions of melt inclusions from YTT zircon, allanite, plagioclase, and quartz, Chesner and Luhr maintained that the role of diffusional boundary effects on incompatible trace elements of Toba quartz-hosted melt inclusions should not be dismissed.

The melt inclusion study also provided a long overdue determination of the dissolved S contents of the YTT magma. Previously, the only estimate of dissolved S had been made by Rose and Chesner (1990) from the composition of pyrrhotite inclusions in magnetite. Those results suggested that about 10^{16} g of H_2SO_4 may have been emitted to the atmosphere during the YTT eruption. Scaillet et al. (1998) questioned this estimate based upon the low solubility and diffusivity of S in low temperature silicic melts, and called for further evaluation of the S content of the YTT melt. Oppenheimer's (2002) review of the YTT eruption reiterated the need for refined S data and led to Chesner and Luhr's (2010) melt inclusion study. Sulfur contents (6–32 ppm) determined by microprobe analysis of YTT melt inclusions indicated that only 10^{14} g of H_2SO_4 could have been supplied to the atmosphere from S dissolved in the YTT magma, far less than the earlier calculation. When considering the climatic effects of this lower estimate, global cooling directly related to H_2SO_4 would have been more similar to that associated with the 1815 Tambora eruption instead of the volcanic winters predicted by the higher quantities from previous estimates. However, the atmospheric effects of the large quantities of H_2O and halogens ($\sim 10^{15}$ g each of Cl and F), suggested from melt inclusions need further investigation.

Allanite in the YTT has drawn the attention of several workers since it was first described as a characteristic mineral of the Toba tuffs by Druif (1934) who referred to it as "orthite". Marel (1948b) recognized that allanite and zircon were present in soils derived from weathering of the YTT, and their abundances (comprising up to 80% of the heavy mineral fraction) were related to the extent of weathering. Chesner and Ettlinger (1989) analyzed this REE bearing member of the epidote group and determined the structural formula for the Toba allanites. Their work showed that allanite compositions varied with bulk rock chemistry and that fractionation of 0.052% modal fractionation could explain the observed variations in La, Ce, and Sm of the bulk rock suite. They also concluded that allanite crystallization is controlled by magma temperature, crystallizing only from magma below 800 °C, and does not require high abundances of REE's. Hoshino et al. (2010) determined the structural formula of allanite from a welded YTT sample and maintained that oxidation and dehydrogenation during welding had produced the first known naturally occurring oxy-allanite. Vazquez and Reid (2004) performed rim to core analyses of several allanite crystals from the YTT, showing that they were oscillatory zoned. Coupling their compositional data with spot ion-probe $^{238}U/^{230}Th$ age dates supports a model of magma accumulation in the YTT magma chamber that lasted at least 150 ky.

Isotopic studies of the YTT offered further insights into magma generation and evolution at Toba. Initial $^{87}Sr/^{86}Sr$ ratios of the YTT range from 0.71355–0.71402, and show isotopic zonation with the most silicic rocks having the highest Sr ratios (Fig. 4); $\varepsilon Nd = -9.9‰$ has been reported by Wark et al. (2000) for the YTT. All post-caldera rocks analyzed within and just outside the caldera have similar ratios. These ratios are very different than those reported for the mantle derived mafic and intermediate rocks that typify the Sunda arc (0.7038–0.7059; Whitford, 1975). The 80 Ma Hatapang granite, about 45 km southeast of Toba, has a similarly high $^{87}Sr/^{86}Sr$ ratio of 0.7150 (Clarke and Beddoe-Stephens, 1987) which led Gasparon and Varne (1995) to infer that an S-type granitoid basement terrane underlies Toba and is part of the SIBUMASU terrane. Chesner (1998) interpreted these high ratios to indicate that crustal anatexis of radiogenic source rocks generated the Toba magmas, which then underwent further crystal fractionation in shallow magma chambers. Wark et al. (2000) disagree, suggesting that the Toba primary magmas were radiogenic mafic melts that evolved to silicic compositions by AFC (assimilation-fractional crystallization) processes. Because over 85% assimilation of a hypothetical radiogenic crust ($^{87}Sr/^{86}Sr = 0.7300$) into mantle derived mafic melts is required to generate the Toba Sr isotopic signature (Chesner, 1988), all radiogenic magmas at Toba, regardless of their composition, should be considered the product of crustal melting. Chesner (1988) also analyzed $^{18}O/^{16}O$ and showed that most YTT rocks have $\delta^{18}O = +8.7–10.3‰$, while quartz separates are +9.4–9.8 (most are +9.6), and plagioclase ranges between +8.1 and 8.3‰. The consistency of oxygen isotopic ratios of quartz separates among all units (OTT $\delta^{18}O = +9.5–9.7‰$, MTT $\delta^{18}O = +9.5–9.6‰$) and post-YTT rocks ($\delta^{18}O = +9.5‰$) indicate that the Toba magma bodies did not undergo interaction with meteoric waters between or after eruptions (Hildreth et al., 1984).

Collectively, petrologic studies conducted at Toba are consistent with the rhyolite-mush model presented by Hildreth and Wilson (2007) and compositionally zoned magma chamber dynamics reviewed by Bachmann and Bergantz (2008). Applied to Toba, their models suggest that the quartz-bearing Toba tuffs and calderas represent the surface expression of a large granitoid batholith that episodically provides monotonous composition melts to shallow magma reservoirs. Crystal fractionation in the sub-volcanic magma chamber for at least 150 ky results in compositional zoning whereby the magma near the roof of the chamber becomes more evolved than the original melt, while the magma at deeper levels appears less evolved due to the accumulation of crystals. Eventually, water saturation and roof-magma density contrasts lead to roof failure/caldera collapse and ignimbrite eruption in a manner similar to the thermo-mechanical ignimbrite eruption model described by de Silva et al. (2006). Subsequently, degassed remnant magmas from the shallow system may erupt as ring fracture lava domes, or new melts from the deeper batholith can recharge the system causing renewed uplift and/or volcanism. Eventually, after an interval of up to 765 ky (the interval between the large volume

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eruptions at Toba OTT – YTT), or as few as 340 ky (the repose between OTT and MTT) the process can repeat itself.

4. Post YTT activity

Since the YTT eruption 74,000 years ago, significant changes have taken place within the caldera. The post-YTT modification starting point is envisioned to be an ~2 km deep, steep walled caldera, with a flat floor covered by a thick accumulation of welded YTT. The caldera floor was at a maximum elevation of 400 m asl, but was more likely considerably lower, perhaps approaching sea level. Only the Uluan block and Porsea embayment would have had higher elevations within the outer bounding caldera collapse scarp.

4.1. Lake filling

Almost immediately after the eruption, while the thick caldera fill tuffs were cooling, Lake Toba began to fill with water. Using current precipitation rates (2100 mm/year) and evaporation rates (1350 mm/year), the lake may have filled at least 750 mm/year. At these rates, it could have reached its overflow level of 1160 m near Porsea, in about 1500 years. Considering the contribution of truncated aquifers and a few areas of surface runoff into the caldera, it may have filled even faster. A distinct high-water-mark (1160 m) lake terrace formed at the lake's outlet in the Asahan valley (Terrace I of Verstappen, 1961). This terrace can be traced on the eastern caldera wall to Prapat and occurs in a few places on the southern wall between the Asahan River outlet and Balige. Terrace I also occurs on the eastward dipping slopes on the west side of the Uluan peninsula. A second prominent terrace occurs at 1050 m and is best exposed in the low lying areas on the east side of the Uluan block between Prapat and Porsea (Terrace II of Verstappen, 1961). Terrace II can be correlated to the top of the OTT exposed in the Asahan valley. These lake terraces developed in the Prapat graben because this is the only area where non-welded YTT occurs inside the caldera. Notably, there are no reports of the 1160 and 1050 m lake terraces in the unconsolidated sediments that cover Samosir Island. After about 150 m of further incision into the OTT, lake level has now been stabilized at 906 m (more-or-less) by the Asahan hydroelectric dams.

4.2. Lacustrine sedimentation

Coincident with the filling, overflowing, and lowering of lake level, the sub-lacustrine caldera floor experienced significant modifications. Sedimentation into the lake was a major process that would have included landslides from the steep unstable caldera walls accompanied by fluvial sedimentation from high gradient streams with small catchment areas that flowed between the caldera rim and the lake. These processes would have deposited slide blocks and coarse breccias at the base of the ring fault and small wedges of coarse sediments at the mouths of streams. Sedimentation in the interior of the lake would have been dominated by silt and clay size volcaniclastic sediments rich in diatoms. Lake sediments cover all of Samosir Island (except for the eastern scarp), the low-lying areas between Porsea and Balige, most of southern Uluan, and other isolated locations on Uluan as well. Because they are best exposed on Samosir Island, where they are up to 100 m thick, these sediments are known as the Samosir Formation. Although few detailed descriptions of the lake sediments exist, they have been generally described as a fining upwards sequence of debris flows, volcanic breccias, and conglomerates, covered by at least 30 m of laminated tuffaceous sand and silt, diatomaceous clay, nearly pure diatomites, and volcanic ash (Ruttner, 1935; Marel, 1947; van Bemmelen, 1970; Yokoyama and Hehanussa, 1981). Identification of an exposure of pre-caldera andesite directly beneath lake sediments on southern Samosir demonstrates that an occasional basement high may have protruded through the thick YTT caldera fill.

4.3. Resurgence

The most noticeable post-caldera feature within the Toba caldera is Samosir Island with its highest point at 1630 m. Its upper surface dips gently to the west (5–8°), while its eastern edge consists of a series of parallel fault scarps with considerable displacement. Van Bemmelen (1939) was the first geologist to conclude that Samosir had risen to its present position from well below lake level by demonstrating that its regional westward tilt, en echelon faulted eastern margin, absence of lake terraces, and thick accumulation of diatomaceous lake sediments were consistent with resurgence (Fig. 5). Smith and Bailey (1968) regarded Samosir Island and the Uluan Peninsula as a classic example of a resurgent dome. They cited the flared pattern of faults in northern Samosir and the occurrence of lava domes along the eastern scarp as additional evidence to support van Bemmelen's resurgence model. It is now known to have overall dimensions of 60 × 20 km and been uplifted at least 1100 m to its present position. A single ^{14}C date (33,090 ± 570, Illinois State Geological Survey, Chesner et al., 2000) on organic-rich lake sediments collected near the highest elevations on Samosir, indicate that about 33,000 years ago Samosir Island was still beneath lake level. Thus, resurgent rates of at least 1.8 cm/year are required to account for the displacement to its present position from a lake level of ~1000 m 33,000 years ago. If resurgence has been ongoing for the past 74 ky, an average uplift rate of 1.5 cm/year is required. Because it is unclear when resurgence began and ended, the actual rates are likely to have been higher.

Across the Latung Strait, lies the Uluan peninsula (Sibolangit peninsula) which appears to be a semi-symmetrical counterpart to Samosir Island with its steep western scarp and 10–15° eastward dips. Van Bemmelen (1939) and Smith and Bailey (1968) considered Uluan and Samosir to represent 2 half domes separated by a deep sector graben, the Latung Strait. An evaluation of fault patterns on Samosir by Aldiss and Ghazali (1984) supported an origin by tensional rifting across an area of uplift for the Latung Strait. Based upon the updoming of lake terraces I and II of at least 160 m and possibly 250 m (Verstappen, 1961), Chesner and Rose (1991) agreed that Uluan has resurged as well, but not nearly as much as Samosir. Uluan appears to have resurged along the reactivated inner collapse scarp of the YTT caldera. The resurgence that uplifted Uluan was not confined to that half dome, but included the eastern topographic caldera margin, uplifting its lake terraces about 100 m more than those on Uluan. Minimum uplift rates are 0.3 cm/year for the Uluan block and 0.5 cm/year for eastern caldera wall, based upon uplift indicated by the warped lake terraces.

4.4. Samosir lava domes

Besides resurgence, other notable activity since the YTT eruption includes the eruption of several lava domes and small to moderate size volcanic centers (Fig. 2). Within the caldera, post-YTT volcanism is concentrated in two general areas, the southwestern ring fracture and along the northern portion of the Samosir fault. On northeastern Samosir Island, 3 separate areas of lava dome emplacement have been identified at or near lake level. At the Tuk–Tuk peninsula several overlapping lava domes were erupted along 3 faults paralleling the main Samosir fault scarp. Two additional areas of lava dome extrusion occur at the base of the main fault further north. Because none of these exposures is covered with much (if any) lacustrine sediments, they were presumed to be

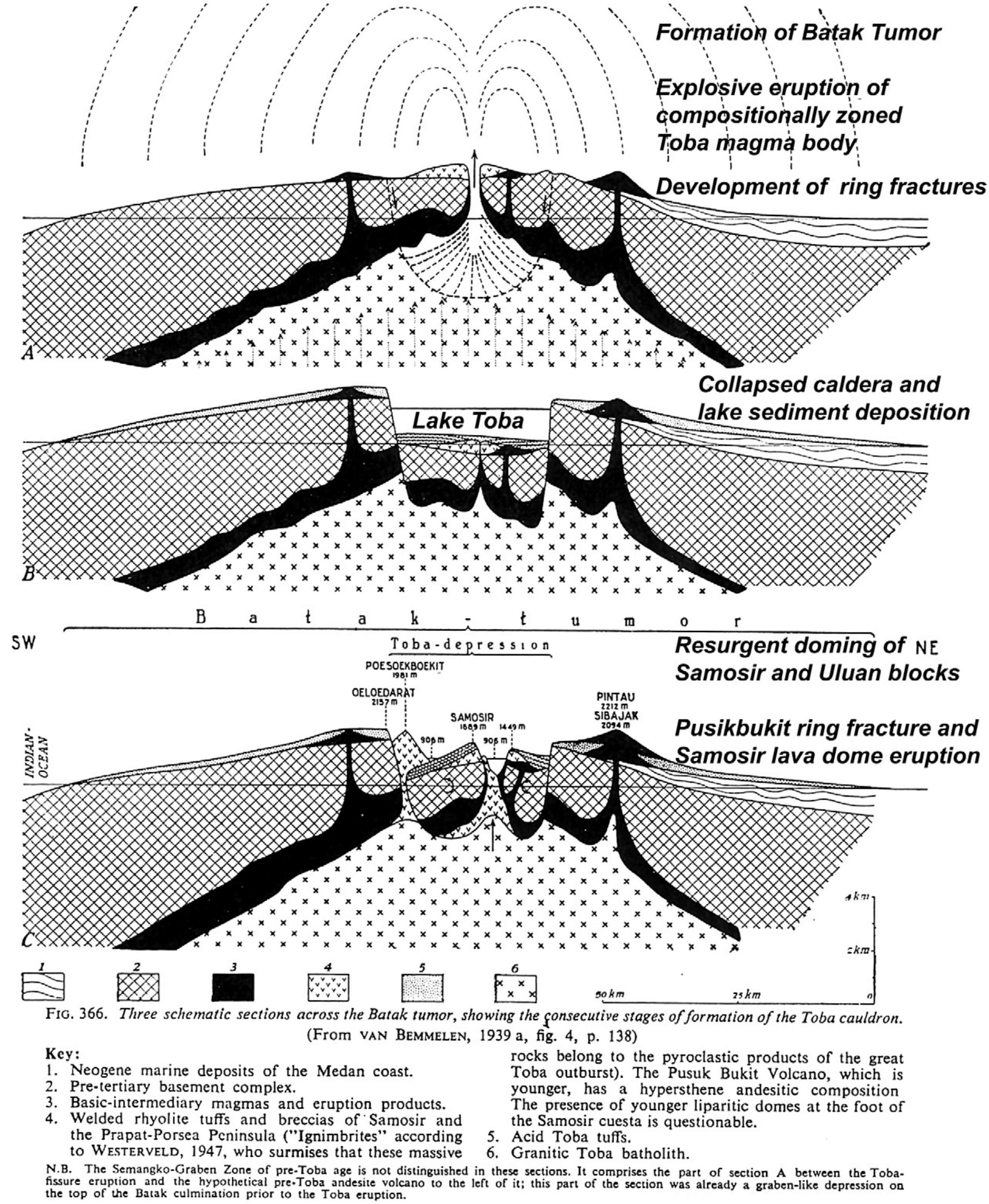

Fig. 5. Van Bemmelen's (1939) original depiction of caldera formation and resurgent doming at Toba. Annotations have been added in bold italics.

relatively young. A possible subaqueous lava dome has also been identified from bathymetry about 5 km southeast of the Tuk–Tuk peninsula. All of the Samosir lava domes are rhyolitic and resemble the YTT in composition (69–76 wt. % SiO_2, Fig. 3B), mineralogy, and Sr isotopic ratios (0.71367, Fig. 4). This led Chesner et al. (1996) to suggest that they represented remnant YTT magma that was possibly erupted during resurgence. Sanidine from all 13 of these lava domes have been dated by $^{40}Ar/^{39}Ar$ (W. McIntosh, personal communication 1999; Chesner et al., 2000), and enigmatically have ages that are indistinguishable from the YTT (75–77 ka). Although their ages may suggest that they represent vents for the YTT, their location and thin to absent sedimentary veneer are inconsistent with this interpretation. Alternatively, the Samosir lava domes may consist of remnant YTT magma that had crystallized sanidine phenocrysts shortly before the YTT eruption and was later remobilized and erupted during resurgence.

4.5. Pusikbukit Volcano

The other location of intracaldera volcanism is along the southwestern ring fracture between Pusikbukit volcano and Pardepur Island (Fig. 2). Pusikbukit volcano rises over 1000 m above the lake to an elevation of 1982 m, almost 200 m above the western caldera wall. This composite volcano consists mostly of 2 pyroxene andesite (61–65 wt. % SiO_2) and a few hornblende dacite lava flows (68–69 wt. % SiO_2, Fig. 3B). Based upon their geomorphic expression, the dacitic lavas are the youngest. No historic eruptions have been recorded at Pusikbukit, but an active solfatera is present on its northeastern flank. The andesites exhibit ubiquitous petrographic evidence of magma mixing including basaltic xenoliths and blebs, spongy and boxy cellular plagioclase, spongy cellular orthopyroxene, reacted amphibole, presence of quartz, and banded groundmass of different color and crystallinity. Chesner and Hester (1996) have interpreted the andesites to represent mixes between remnant YTT magma and mafic melts. The dacites are not on fractionation trends with the andesites, nor do they appear to be mixes between the andesites and YTT rhyolite. Instead, they are quite similar to dacitic rocks erupted along the southwest ring fracture at Pardepur Island. Wark et al. (2000) report $^{87}Sr/^{86}Sr$ ratios of 0.7146–0.7168 for the Pusikbukit andesites, 0.7151 for the dacites, and εNd values of −11 and −10.2‰ respectively. The strong crustal signature of the rocks erupted at Pusikbukit that overlap with the isotopic ratios for the Toba tuffs, indicates that Pusikbukit volcano may be the surface expression of magma recharge into the Toba system.

4.6. Pardepur lava domes

About 35 km southeast of Pusikbukit volcano, Pardepur Island and 2 domal areas onshore to the south, are more typical ring fracture lava domes (Fig. 2). Each appears to be a monogenetic exogenous low lava dome. All are subaerial and Pardepur Island appears to be the youngest, displaying a well-defined coulee that flowed to the north. Their lack of sedimentary cover and youthful surface expressions suggest that they are quite young, although no fumarolic or hot spring activity is known. The Pardepur lava domes contain plagioclase, orthopyroxene and amphibole phenocrysts and have a limited compositional range between 66 and 69% SiO_2 (Fig. 3B), and a $^{87}Sr/^{86}Sr$ ratio of 0.71281 (Fig. 4). Rafted giant pumice blocks sampled from lake sediments on southern Uluan have similar compositions and Sr ratios (0.71291, Fig. 4) and are thought to have formed by subaqueous lava dome eruptions from the Pardepur lava domes (Chesner and Rose, 1991). These rocks, along with the most recent dacites erupted at Pusikbukit are interpreted to represent recent influx of new magma into Toba's sub-volcanic system. Bathymetry has also identified a likely lava dome about 3 km northwest of Pardepur Island, along the southwest ring fracture (Fig. 2). Further north, three areas along the western shore of Samosir Island are conspicuously updomed. The northernmost area (Pintubatu) has active hot springs and fumaroles and is intensely hydrothermally altered. Across the narrow channel to the west is an area with recently eroded radial drainages suggestive of uplift. Along the lake shore beneath this recently uplifted area, hot springs and altered/mineralized (realgar and orpiment) basement rock were noted. Although no volcanic rocks are exposed at any of these areas, the presence of hypabyssal intrusions (cryptodomes) is strongly suggested.

4.7. Tandukbenua and Singgalang volcanoes

Two small andesitic centers are located outside the topographic margin of the caldera to the north. Tandukbenua volcano is located just a few kilometers north of the caldera near Sipisupisu while Singgalang volcano lies to the northeast, about 8 km from Lake Toba. Both cones rise about 500 m above the YTT outflow sheet and appear to have formed since the YTT eruption. Singgalang, the more vegetated and eroded cone is older than Tandukbenua, and according to Aldiss and Ghazali (1984), may even pre-date the YTT. A 2-pyroxene andesite lava sample from Tandukbenua contains 62 wt. % SiO_2 (Fig. 3B) and has a $^{87}Sr/^{86}Sr$ ratio of 0.71384 (Fig. 4), while basaltic andesite lavas from Singgalang have 54–56 wt. % SiO_2 (Fig. 3B). Wark et al. (2000) reported basaltic andesites and dacites occur at Tandukbenua as well with $^{87}Sr/^{86}Sr$ and εNd values of 0.7128–0.7140 and −10.4 to −10.8‰ respectively. Like Pusikbukit andesites, the Tandukbenua rocks have petrographic evidence indicating that its magmas are mixes between mafic and silicic components which includes; mafic inclusions, boxy and spongy cellular plagioclase, reacted amphibole and biotite, and quartz. In contrast, the Singgalang basaltic andesites exhibit no disequilibrium textures. The contrasting compositions and petrography between Tandukbenua and Singgalang may help delineate the extent of the YTT magma body to the north, or, should Singgalang pre-date the YTT, provide additional constraints on pre-YTT mafic magmas. Nevertheless, the strong crustal signature of both mafic and intermediate rocks at Tandukbenua indicates that it is not a normal arc-related volcano like those found further north and south of Toba in Sumatra (Gasparon, 2005).

4.8. Bathymetry

Until recently, the sub-lacustrine detail of the caldera and its features were essentially unknown because the only bathymetric map of the lake was antiquated and of poor resolution (Stehn, 1939). In 2005 and 2008 about 90 separate transect lines over nearly 600 km of lake bottom were surveyed with single-beam sonar. The resultant high resolution bathymetric map (Fig. 6) and lake–bottom profiles (Fig. 7) have provided valuable data concerning caldera formation and evolution that was previously unavailable. Bathymetry reveals that most of the 400–1200 m steep caldera walls extend uninterrupted another 400–500 m below lake level. Collapse mega-blocks are common features at the base of the ring fracture fault. The deepest parts of the lake are found along a segment of the northeastern ring fracture, south of Haranggaol. Here, depths of 500 m were recorded in a narrow band at the base of the fault, about 0.5 km from the shoreline. Previously reported depths up to 529 m by Stehn (1939) could not be substantiated. The shallowest portions of the lake are found in Porsea Bay where profiles indicate the presence of a drowned valley leading to the Asahan River outlet. Because the valley cuts the Uluan collapse scarp, and its floor is below the level of the lake outlet, it must have existed prior to downdropping of the Uluan block during the YTT eruption.

The bathymetric map also shows that the overall size of the Samosir resurgent dome is ~60 × 20 km and that it retains its asymmetrical shape below the water line with gentle westward slopes that merge into the western ring fracture. Its steeper eastern face descends to depths of about 425 m, but is not nearly as steep as the subaqueous extensions of the outer caldera collapse scarp and the west face of Uluan peninsula. The Latung Strait (Fig. 7, profiles 16, 17, 26–28) has an asymmetrical profile with steep eastern slopes that resemble the abrupt caldera ring fracture, consistent with interpretation that Uluan's western face owes its origin mostly to collapse during the YTT eruption. Beyond the Samosir resurgent dome, featureless plains are found at depths of 450–490 m and dominate the large open regions of the northern and southern portions of the lake. The constancy of the lake bottom profiles and depths in these areas and within the Latung Strait point towards a virtually flat pre-resurgent caldera floor across the entire caldera,

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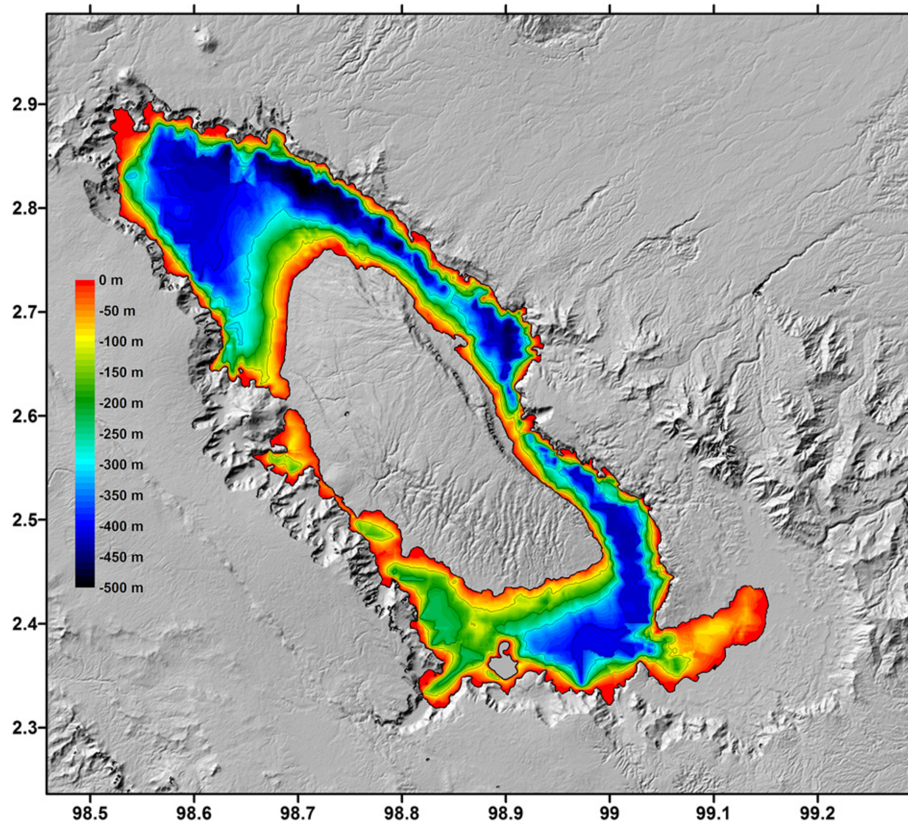

Fig. 6. Bathymetric map of Lake Toba. Depth is represented by isochromes; 100 m contour lines are plotted for reference. Data was gridded using the kriging method and map was generated using *Surfer*® from Golden Software.

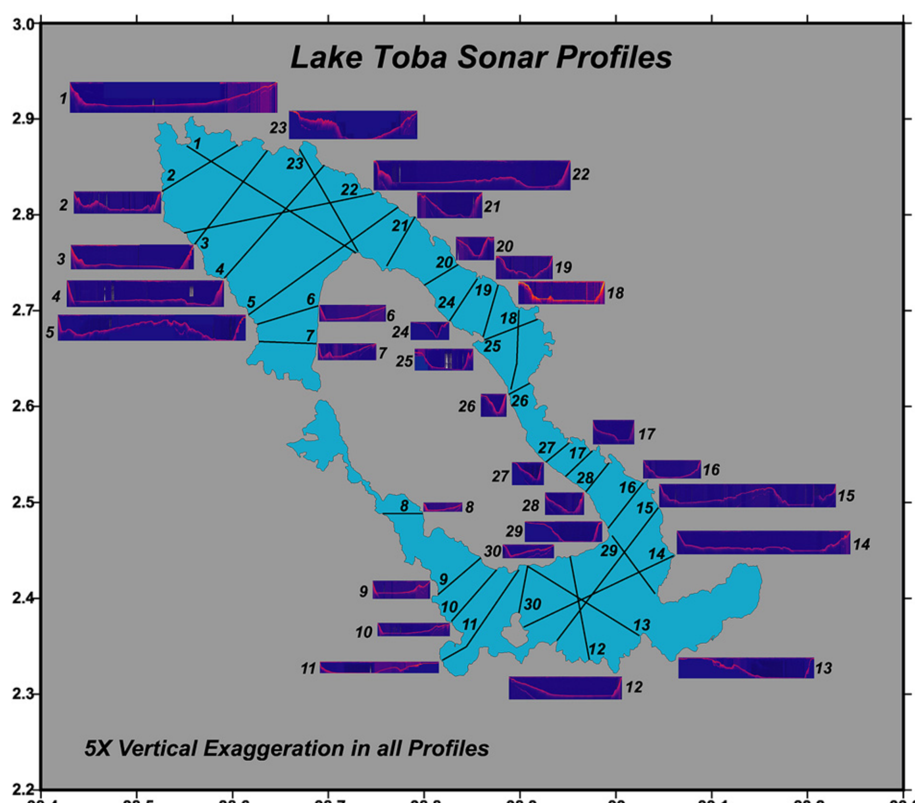

Fig. 7. Sonar profiles along selected transect lines. Profiles generated using *Sonar Log Viewer v. 2.1.2*© from Lowrance®. Vertical exaggeration = 5× in all profiles; no horizontal exaggeration.

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with the exception of the perched Uluan block. Thus, bathymetry supports the concept of a contiguous YTT caldera, and the model of two separate YTT calderas suggested by Knight et al. (1986) is unsubstantiated. Because lava and tuff distributions in the northern caldera walls imply the existence of a former stratovolcano and the likelihood of HDT and MTT calderas, but no bathymetric evidence exists for these features, this portion of the Toba's geologic history is presumed to be completely buried beneath intracaldera YTT and lake sediments.

Other local features revealed by the survey include a post-caldera collapse debris avalanche (identified by its classic hummocky topography) that originated in the Haranggaol scallop (Fig. 7, profile 23), a submerged ring fracture lava dome northwest of Pardepur Island (Fig. 7, profile 11), extensions of Samosir fault scarps to the north and south, and additional fault scarps and a lava dome (Fig. 7, profile 18) on the east face of the Samosir resurgent dome. An unusual area of sonar signal-loss about 3 km east of the Tuk–Tuk peninsula could possibly indicate an area of hydrothermal activity and be associated with another lava dome (Fig. 7, profile 25). The bathymetric map and profiles will be especially useful in guiding an upcoming seismic reflection profiling study at Toba.

5. The present state

5.1. Geophysical evidence for magma bodies

Unlike the majority of Sumatra, northern Sumatra has two regional areas of low Bouger gravity, one centered on Lake Toba, and another of even lower gravity to the northwest of Toba (Milsom and Walker, 2005). In detail, the Toba gravity contours mimic the outline of the caldera and closely follow the shape of Samosir Island, with a minimum of −75 mGal over the southwest portion of Samosir Island. Nishimura (1981) and Nishimura et al. (1984) interpreted another area of low gravity near Porsea to represent the location of a 20 km diameter caldera within the Toba depression. Masturyono et al. (2001) evaluated the possible causes for the Toba gravity anomaly and concluded that it can be explained either by thick accumulation of low density tuff within the caldera or by warm low density crust at depth. Accordingly, the Toba anomaly may be due in part to the existence of a large partially crystallized granitic batholith beneath the caldera.

Studies using arrival times of local seismic events recorded during a 4 month interval in 1995 indicate seismic sources in two main areas beneath Toba (Masturyono et al., 2001; Koulakov et al., 2009) (Fig. 8). One cluster of events occurred about 15–30 km below and to the west of Pusikbukit volcano and is suggested to represent the border of a mid-crustal magma body. A second area of seismicity, located 120–140 km directly beneath Toba, is interpreted to occur within the subducted slab and may be related to melting processes.

Seismic tomography studies by Stankiewicz et al. (2010), Koulakov et al. (2009), Sakaguchi et al. (2006), and Masturyono et al. (2001) all have indicated the presence of magma or partly molten portions of the upper crust beneath Toba. The most recent study based on 4 months of ambient seismic noise in 2008, indicates a region about 75 × 30 × 15 km (length-width-depth) or 34,000 km^3 that attenuates seismic waves. This region is located mostly beneath Lake Toba, is sharply bounded to the east by the Latung scarp and northeast caldera wall, but extends beyond the caldera margin to the west, especially at depths between ∼2 and 5 km. The most distinct low velocity area occurs beneath Samosir Island and extends to at least 15 km depth where it coincides almost exactly with the outline of Samosir Island. Masturyono et al. (2001), using 3-D P-wave velocities, seismicity, and gravity data concluded that a large magma reservoir resides in the upper 10 km of crust beneath the southern $^2/_3$ of the caldera, and a smaller reservoir can be identified beneath the north end of the lake. The larger region narrows at depth to the northwest until it becomes highly focused and extends into the mantle beneath Pusikbukit volcano. Sakaguchi et al. (2006) using a receiver function method to

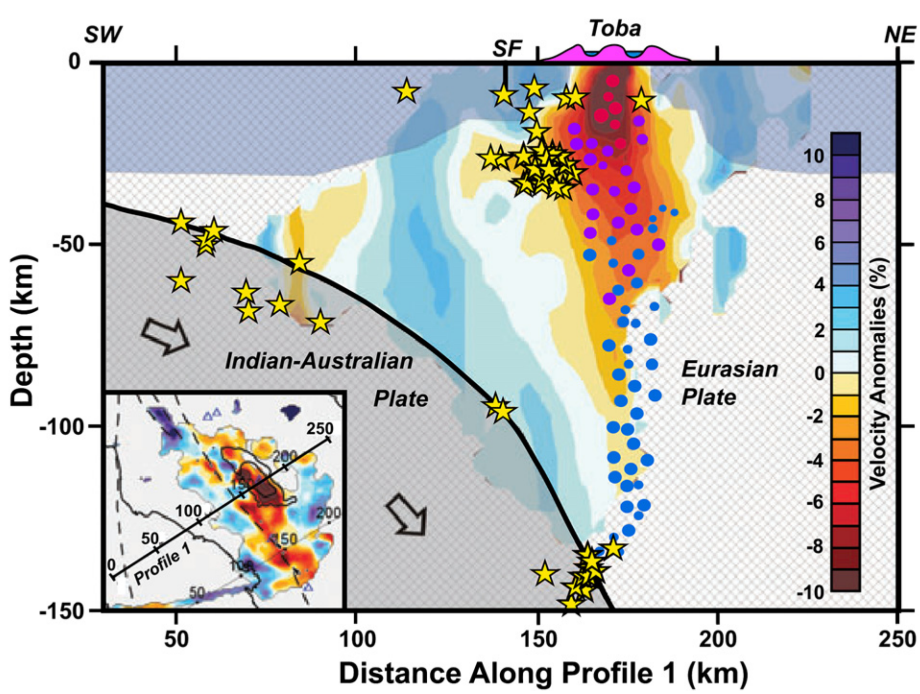

Fig. 8. SW-NE seismic tomography cross-section through the Toba area showing P-wave seismic velocity anomalies (modified from Koulakov et al., 2009). Location of cross-section line is indicated as line 1 on inset map. Yellow stars indicate the locations of seismic events from January to May 1995. Colored dots represent ascending fluids and melts. SF = Sumatran Fault (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

interpret the 1995 seismic data, identified a continuous magma reservoir with a few zones of more focused lower velocities beginning at 8–14 km beneath the caldera. This study also identified an oval zone of thickened crust, centered beneath the eastern caldera margin near Prapat, and coinciding with the location of the subducted Investigator Ridge Fracture Zone, that they interpreted as a possible area of basaltic underplating. Koulakov et al.'s (2009) evaluation of the same seismic data yielded higher resolutions suggestive of magma chambers at 15 km beneath Toba and possibly extending to 5 km, and low velocity regions extending all the way to the subducted slab. However, they assert that the anomalous regions are no different than a cross-arc region of "normal volcanism" south of Toba and at other normal volcanic arcs, and therefore argue that there is no evidence to suggest that a super-volcano scale magma chamber presently exists beneath Toba.

5.2. Geologic evidence for recent unrest

Although no historic eruptions have occurred within the caldera, Pusikbukit volcano and Pardepur Island are morphologically young volcanic features that formed along the southwestern ring fracture. Pusikbukit, a polygenetic cone with some youthful appearing lava flows and an active solfatera on its eastern flank, should be regarded as a possible site for future lava flow eruptions. Pardepur Island and its nearby subaerial and subaqueous lava domes have formed from monogenetic ring fracture eruptions and none of these areas is known to have active thermal features. Between the Pardepur lava domes and Pusikbukit, hypabyssal cryptodome intrusions are suggested by domed lake sediments, of which the Pintubatu area is the most recent intrusion as evidenced by its fumaroles and hot springs. Other areas of hot spring activity have been noted along the narrow straits between Samosir and the western caldera wall. In view of the history and current activity of the southwestern ring fracture, future lava dome or cryptodome emplacement in this area is likely. Outside the caldera, the Tandukbenua volcano, and possibly the older Singgalang cone, could also be the sites of future eruptions.

Recently, there has been no strong evidence to suggest that Samosir Island continues to resurge. Should evidence of emerging shorelines or increased seismicity be detected, it would not be surprising considering that ~600 m of resurgence has taken place in the last 33 ky. Aldiss and Ghazali (1984) noted that a semi-oval bulge could be defined by the 1500 m contour in the tuff plateau west of the caldera. Here, the YTT surface gradually rises above the caldera rim for several kilometers before cresting and descending towards the Indian Ocean. Several lines of evidence led them to conclude that the area was uplifted since the YTT eruption. This area is clearly visible on the digital elevation model (DEM) image (Fig. 2) which shows that it is similar in size and shape to Samosir Island. It is tempting to suggest that this domal area could mark a northwesterly progression of magma bodies from the OTT Porsea caldera, to the inner YTT collapse scarp along the west face of the Uluan peninsula, to a future caldera encompassing the domed up area and centered around the southwestern ring fracture. Indeed, this area corresponds to the most recent volcanic activity at Toba, is the most seismically active portion of the Toba area, and is a region where seismic velocity anomalies extend beyond the present topographic margin of the caldera.

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References

Acharyya, S.K., Basu, P.K., 1993. Toba ash on the Indian subcontinent and its implications for correlation of late Pleistocene alluvium. Quaternary Research 40, 10–19.

Aldiss, D.T., Ghazali, S.A., 1984. The regional geology and evolution of the Toba volcano-tectonic depression, Indonesia. Journal of the Geological Society, London 141, 487–500.

Aldiss, D.T., Whandoyo, R., Ghazali, S.A., Kusyono, 1982. Geology of the Sidikalang Quadrangle, northern Sumatra (1:250,000 sheets NA 47-5, 47-6). Geological Research and Development Centre. Bandung, Indonesia.

Bühring, C., Sarnthein, M., Leg 184 Shipboard Scientific Party, 2000. Toba ash layers in the South China Sea: evidence of contrasting wind directions during eruption ca. 74 ka. Geology 28, 275–278.

Bachmann, O., Bergantz, G.W., 2008. Deciphering magma chamber dynamics from styles of compositional zoning in large silicic ash flow sheets. In: Reviews in Mineralogy and Geochemistry, Minerals, Inclusions and Volcanic Processes, vol. 69, pp. 651–674.

Beddoe-Stephens, B., Aspden, J.A., Shepherd, T.J., 1983. Glass inclusions and melt compositions of the Toba Tuffs, Northern Sumatra. Contributions to Mineralogy and Petrology 83, 278–287.

Bellier, O., Sebrier, M., 1994. Relationship between tectonism and volcanism along the Great Sumatran Fault Zone deduced by SPOT image analyses. Tectonophysics 233, 215–231.

Bellier, O., Sebrier, M., 1995. Is the slip rate variation on the Great Sumatran Fault Zone accompanied by fore-arc stretching? Geophysical Research Letters 22, 1969–1972.

Caress, M.E., 1985. Volcanology of the youngest Toba Tuff, Sumatra [M.S. Thesis]. Monoa, University of Hawaii, p. 150.

Chesner, C.A., 1988. The Toba Tuff and Caldera Complex, Sumatra, Indonesia: Insights into Magma Bodies and Eruptions. Ph.D. Thesis, Michigan Technological University, Houghton, p. 428.

Chesner, C.A., 1998. Petrogenesis of the Toba Tuffs, Sumatra, Indonesia. Journal of Petrology 39, 397–438.

Chesner, C.A., Ettlinger, A.D., 1989. Composition of volcanic allanite from the Toba Tuffs, Sumatra, Indonesia. American Mineralogist 74, 750–758.

Chesner, C.A., Hester, J.C., 1996. Pusikbukit volcano: a post-caldera composite volcano in the toba caldera, Sumatra, Indonesia. Geological Society of America Abstracts with Programs 28, 32.

Chesner, C.A., Luhr, J.F., 2010. A melt inclusion study of the Toba Tuffs, Sumatra, Indonesia. Journal of Volcanology and Geothermal Research 197, 259–278.

Chesner, C.A., Rose, W.I., 1991. Stratigraphy of the Toba Tuffs and evolution of the Toba Caldera Complex, Sumatra, Indonesia. Bulletin of Volcanology 53, 343–356.

Chesner, C.A., Rose, W.I., Deino, A., Drake, R., 1991. Eruptive history of Earth's largest Quaternary caldera (Toba, Indonesia) clarified. Geology 19, 200–203.

Chesner, C.A., Sporleder, B.A., Bohnenstiehl, D.R., Dolan, M.T., 1996. Post-caldera lavas at the Toba Caldera, Sumatra, Indonesia. Geological Society of America Abstracts with Programs 28, 32.

Chesner, C.A., Boroughs, S.P., Storm, L.C., McIntosh, W.C., 2000. Constraints on resurgence at the Toba Caldera, Sumatra, Indonesia. Geological Society of America Abstracts with Programs 3, 502.

Clarke, M.C.G., Beddoe-Stephens, B., 1987. Geochemistry, mineralogy and plate tectonic setting of a Late Cretaceous Sn–W granite from Sumatra, Indonesia. Mineralogical Magazine 51, 371–387.

Dehn, J., Farrell, J.W., Schmincke, H.-U., 1991. Neogene tephrochronology from Site 758 on northern Ninetyeast Ridge: Indonesian arc volcanism of the past 5 ma. Proceedings Ocean Drilling Program, Scientific Results 121, 273–295.

de Silva, S., Zandt, G., Trumbull, R., Viramonte, J.G., Salas, G., Jimenez, N., 2006. Large ignimbrite eruptions and volcano-tectonic depressions in the Central Andes: a thermomechanical perspective. Special Publications. In: Troise, C., de Natale, G., Kilburn, C.R.J. (Eds.), Mechanisms of Activity and Unrest at Large Calderas, vol. 269. Geological Society, London, pp. 47–63.

Diehl, J.F., Onstott, T.C., Chesner, C.A., Knight, M.D., 1987. No short reversals of Brunhes age recorded in the Toba tuffs, north Sumatra, Indonesia. Geophysical Research Letters 14, 753–756.

Druif, J.H., 1934. De Bodem van Deli, II; Mineralogische onderzoekingen van de bodem van Deli, vol. 32. Bulletin van het Deli Proefstation. 195.

Fauzi, McCaffrey, R., Wark, D., Sunaryo, Prih Haryadi, P.Y., 1996. Lateral variation in slab orientation beneath Toba Caldera, northern Sumatra. Geophysical Research Letters 23, 443–446.

Gardner, J.E., Layer, P.W., Rutherford, M.J., 2002. Phenocrysts versus xenocrysts in the youngest Toba Tuff: iImplications for the petrogenesis of 2800 km^3 of magma. Geology 30, 347–350.
Gasparon, M., 2005. Quaternary Volcanicity. In: Barber, A.J., Crow, M.J., Milsom, J.S. (Eds.), Sumatra: Geology, Resources and Tectonic Evolution, Geological Society Memoir No. 31. The Geological Society, London, pp. 120–130.
Gasparon, M., Varne, R., 1995. Sumatran granitoids and their relationship to Southeast Asian terranes. Tectonophysics 251, 277–299.
Hildreth, W., Wilson, C.J.N., 2007. Compositional zoning of the Bishop Tuff. Journal of Petrology 48, 951–999.
Hildreth, W., Christiansen, R.L., O'Neil, J.R., 1984. Catastrophic isotopic modification of rhyolitic magma at times of caldera subsidence, Yellowstone Plateau volcanic field. Journal of Geophysical Research 89 (B10), 8339–8369.
Hoshino, M., Kimata, M., Chesner, C.A., Nishida, N., Shimizu, M., Akasaka, T., 2010. Crystal chemistry of volcanic allanites indicative of naturally induced oxidation-dehydrogenation. Mineralogy and Petrology 99, 133–141.
Klein, W.C., 1917. De Oostoever van het Toba-meer in Noord-Sumatra. Jaarb. Van het Mijnwezen in Ned. Oost-Indie 46, 136–187.
Knight, M.D., Walker, G.L., Ellwood, B.B., Diehl, J.F., 1986. Stratigraphy, paleomagnetism, and magnetic fabric of the Toba tuffs: constraints on the sources and eruptive styles. Journal of Geophysical Research 91, 355–382.
Koulakov, I., Yudistira, T., Luehr, B.G., Wandono, 2009. P, S velocity and Vp/Vs ratio beneath the Toba caldera complex (Northern Sumatra) from local earthquake tomography. Geophysical Journal International 177, 1121–1139.
Lay, T., Kanamori, H., Ammon, C.J., Nettles, M., Ward, S.N., Aster, R.C., Beck, S.L., Bilek, S.L., Brudzinski, M.R., Butler, R., DeShon, H.R., Ekstrom, G., Satake, K., Sipkin, S., 2005. The great Sumatra-Andaman earthquake of 26 December 2004. Science 308, 1127–1133.
LeBas, M.J., LeMaitre, R.W., Streckeisen, A., Zanettin, B., IUGS Subcommittee on the Systematics of Igneous Rocks, 1986. A chemical classification of volcanic rocks based on the total Alkali-Silica diagram. Journal of Petrology 27, 745–750.
Lee, M.Y., Chen, C.H., Wei, K.Y., Iizuka, Y., Carey, S., 2004. First Toba supereruption revival. Geology 32, 61–64.
Marel, H.W., van der, 1947. Diatomaceous deposits at Lake Toba. Journal of Sedimentary Petrology 17-3, 129–134.
Marel, H.W., van der, 1948a. Het Tobameer. Geol. En Mijnb 10, 80–89.
Marel, H.W., van der, 1948b. Volcanic glass, allanite and zircon as characteristic minerals of the Toba rhyolite at Sumatra's East Coast. Journal of Sedimentary Petrology 18, 24–29.
Masturyono, McCaffrey, R., Wark, D.A., Roecker, S.W., Fauzi, Ibrahim, G., Sukhyar, 2001. Distribution of magma beneath Toba caldera complex, north Sumatra, Indonesia, constrained by three-dimensional P wave velocities, seismicity, and gravity data. Geochemistry Geophysics Geosystems 2, 1014,. doi:10.1029/2000GC000096.
McCarthy, A.J., Elders, C.F., 1997. Cenozoic deformation in Sumatra: oblique subduction and the development of the Sumatran Fault System. Special Publications. In: Fraser, A.J., Matthews, S.J. (Eds.), Petroleum Geology of Southeast Asia, vol. 126. Geological Society, London, pp. 355–363.
Milsom, J.S., Walker, A.S.D., 2005. The gravity field. In: Barber, A.J., Crow, M.J., Milsom, J.S. (Eds.), Sumatra: Geology, Resources and Tectonic Evolution, Geological Society Memoir No. 31. The Geological Society, London, pp. 16–23.
Ninkovich, D., 1979. Distribution, age and chemical composition of tephra layers in deep-sea sediments off western Indonesia. Journal of Volcanology and Geothermal Research 5, 67–86.
Ninkovich, D., Shackleton, N.J., Abdel-Monem, A.A., Obradovich, J.D., Izett, G., 1978a. K–Ar age of the late Pleistocene eruption of Toba, north Sumatra. Nature 276, 574–577.
Ninkovich, D., Sparks, R.S.J., Ledbetter, M.T., 1978b. The exceptional magnitude and intensity of the Toba eruption, Sumatra: an example of the use of deep-sea tephra layers as a geological tool. Bulletin of Volcanologique 41, 286–298.
Nishimura, S., 1981. The Development of Neo-tectonics in Sumatra, Indonesia. In: Paleolimnology Lake Biwa Japan Pleistocene, vol. 5, pp. 151–176.
Nishimura, S., Abe, E., Yokoyama, T., Wirasantosa, S., Dharma, 1977. Danau Toba–The outline of Lake Toba, North Sumatra, Indonesia. In: Paleolimnology Lake Biwa Japan Pleistocene, vol. 5, pp. 313–332.
Nishimura, S., Abe, E., Nishida, J., Yokoyama, T., Dharma, A., Hehanussa, P., Hehuwat, F., 1984. A gravity and volcanostratigraphic interpretation of the Lake Toba region, North Sumatra, Indonesia. Tectonophysics 109, 253–272.
Oppenheimer, C., 2002. Limited global change due to largest known Quaternary eruption, Toba ~74 kyr BP? Quaternary Science Review 21, 1593–1609.
Page, B.G.N., Bennett, J.D., Cameron, N.R., Bridge, D.McC., Jeffery, D.H., Keats, W., Thaib, J., 1979. A review of the main structural and magmatic features of Northern Sumatra. Journal of the Geological Society of London 136, 569–579.
Pattan, J.N., Shane, P., Banakar, V.K., 1999. New occurrence of youngest Toba tuff in abyssal sediments of the central Indian Basin. Marine Geology 155, 243–248.
Pattan, J.N., Prasad, M.S., Babu, E.V.S.S.K., 2010. Correlation of the oldest Toba Tuff to sediments in the central Indian Ocean Basin. Journal of Earth Systems Science 119, 531–539.
Prawirodirdjo, J., Bock, Y., McCaffrey, R., Genrich, J., Calais, E., Stevens, C., Puntodewo, S.S., Subarya, C., Rais, J., 1997. Geodectic observations of interseismic strain segmentation at the Sumatra subduction zone. Geophysical Research Letters 24, 2601–2604.
Raj, R., 2008. Occurrence of volcanic ash in the Quaternary alluvial deposits, lower Narmada basin, western India. Journal of Earth Systems Science 117, 1–8.
Rose, W.I., Chesner, C.A., 1987. Dispersal of ash in the great Toba eruption, 75 ka. Geology 15, 913–917.
Rose, W.I., Chesner, C.A., 1990. Worldwide dispersal of ash and gases from Earth's largest known eruption: Toba, Sumatra 75 Ka. Global and Planetary Change 3, 269–275.
Ruttner, F., 1935. Kieselgur and andere lakustrische Sedimente im Tobagebiet; Ein Beitrag zur Geschichte de Tobasees in Nordsumatra Archiv fur Hydrobiologie, Suppl Bd. XIII "tropische Binnengewasser" V, 399–461.
Sakaguchi, K., Gilbert, H., Zandt, G., 2006. Converted wave imaging of the Toba Caldera, Indonesia. Geophysical Research Letters 33, L20305. doi:10.1029/2006GL027397.
Scaillet, B., Clemente, B., Evans, B.W., Pichavant, M., 1998. Redox control of sulfur degassing in silicic magmas. Journal of Geophysical Research 103, 23,937–23,949.
Shane, P., Westgate, J., Williams, M., Korisettar, R., 1995. New geochemical evidence for the youngest Toba tuff in India. Quaternary Research 44, 200–204.
Simkin, T., Tilling, R.I., Vogt, P.R., Kirby, S.H., Kimberly, P., Stewart, D.B., 2006. This Dynamic Planet: World Map of Volcanoes, Earthquakes, Impact Craters, and Plate Tectonics. Smithsonian Institution, U.S. Geological Survey, U.S. Naval Research Laboratory, Institute of Earth Sciences Jaume Almera, Spanish National Research Council.
Smith, R.L., Bailey, R.A., 1968. Resurgent cauldrons. In: Coats, R.R., Hay, R.L., Anderson, C.A. (Eds.), Studies in Volcanology, vol. 116. Geological Society of America, Memoir, pp. 613–662.
Stankiewicz, J., Ryberg, T., Haberland, C., Fauzi, Natawidjaja, D., 2010. Lake Toba volcano magma chamber imaged by ambient seismic noise tomography. Geophysical Research Letters 37, L17306. doi:10.1029/2010GL044211.
Stauffer, P.H., Nishimura, S., Batchelor, B.C., 1980. Volcanic ash in Malaya from a catastrophic eruption of Toba, Sumatra, 30,000 years ago. In: Nishimura, S. (Ed.), Physical Geology of Indonesian Island Arcs. Kyoto University.
Stehn, Ch.E., 1939. De nieuwe dieptekaart van het Tobameer (Noord-Sumatra) van Drost en Bekkering, De Ingenieur in Nederlandsch-Indie; IV "De Mijningenieur 121–126.
Thomas, J.B., Bodnar, R.J., Shimizu, N., Chesner, C.A., 2003. Melt inclusions in zircon. In: ZirconHanchar, J.M., Hoskin, P.W.O. (Eds.), Reviews in Mineralogy and Geochemistry, vol. 53, pp. 63–87.
Van Bemmelen, R.W., 1929. The origin of Lake Toba (North Sumatra). Proceedings of the 4th Pacific Science Congress 2A Batavia, 115–124.
Van Bemmelen, R.W., 1939. The volcano-tectonic origin of Lake Toba (North Sumatra). De Ingenieur in Nederlandsch Indie 6-9, 126–140.
Van Bemmelen, R.W., 1949. The geology of Indonesia. In: Nijhoff, Martinus (Ed.), General Geology of Indonesia and Adjacent Archipelagos 1A. Government Printing Office, The Hague, p. 732.
Van Bemmelen, R.W., 1970. The Geology of Indonesia. In: Nijhoff, Martinus (Ed.), General Geology of Indonesia and Adjacent Archipelagos 1A, second ed. Government Printing Office, The Hague, p. 732.
Vazquez, J.A., Reid, M.R., 2004. Probing the accumulation history of the voluminous Toba magma. Science 305, 991–994.
Verstappen, H.T., 1961. Some volcano-tectonic depressions of Sumatra, their origin and mode of development. Kon. Ned. Acad. Wetensche. Proc., Ser. B 64, 428–443.
Verstappen, H.T., 1973. In: Wollters-Nordhoff (Ed.), A Geomorphological Reconnaissance of Sumatra and Adjacent Islands (Indonesia) Groningen.
Volz, W., 1909. Nord-Sumatra, Bd I; Die Bataklander 395.
Wark, D.A., Masturyono, M., McCaffrey, R., Farmer, G.L., Rani, M., Sukhyar, R., 2000. Plumbing of the Toba magma system; petrologic and geophysical evidence of two shallow reservoirs and their mantle roots. Eos Transactions American Geophysical Union 81–48, 1387.
Westerveld, J., 1947. On the origin of the acid volcanic rocks around Lake Toba, North Sumatra. Verhandelingen der Koninklijke Nederlandsche Akademie van Wetenschappen, AFD. Natuurkunde 43, 1–52.
Westgate, J.A., Shane, P.A.R., Pearce, N.J.G., Perkins, W.T., Korisettar, R., Chesner, C.A., Williams, M.A.J., Acharyya, S.K., 1998. All Toba tephra occurrences across peninsular India belong to the 75 ka eruption. Quaternary Research 50, 107–112.
Whitford, D.J., 1975. Strontium isotopic studies of the volcanic rocks of the Sunda arc, Indonesia, and their petrogenetic implications. Geochimica et Cosmochimica Acta 39, 1287–1302.
Wing Easton, N., 1894. Een geologische verkenning in de Toba-landen, Jaarb. Van het Mijnwezen in Ned. Oost-Indie 23, 99–164.
Wing Easton, N., 1896. Der Toba-See; Ein Beitrag zur Geologie von Nord-Sumatra, Zeitschr. D. Deutsche geol. Gesellsch 48, 435–467.
Wolff, J.A., Wright, J.V., 1981. Rheomorphism of welded tuffs. Journal of Volcanology and Geothermal Research 10, 13–34.
Yokoyama, T., Hehanussa, P.E., 1981. The age of "Old Toba Tuff" and some problems on the geohistory of Lake Toba, Sumatra, Indonesia. Paleolimnology of Lake Biwa and the Japanese Pleistocene 9, 177–186.
Yokoyama, T., Nishimura, S., Abe, E., Otofuji, Y., Ikeda, T., Suparka, S., Dharma, A., 1980. Volcano-, magneto and chrono-stratigraphy and the geologic structure of Danau Toba, Sumatra, Indonesia. In: Nishimura, S. (Ed.). Physical geology of Indonesian island arcs, Kyoto, pp. 122–143.

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