

Textural and geochemical studies of the 74 ka Youngest Toba Tuff (YTT), Indonesia: Evidence for eruptions from multiple magma chambers

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Textural and geochemical studies of the 74 ka Youngest Toba Tuff (YTT),

Indonesia: Evidence for eruptions from multiple magma chambers

7万4千年前のトバカルデラ噴火火砕物(YTT)の組織学的及び地球化学的研究：

多重マグマだまりの証拠

岩石循環科学研究分野

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Abstract

The eruption process responsible for the formation of the 74 ka Youngest Toba Tuff (YTT) is still debatable since currently, there are two hypotheses on the magma chamber; one single voluminous chamber or multiple magma chambers. Detailed component analysis of eruption products, comprehensive stratigraphy, mineralogical data, and geochemical signatures of phenocrysts and matrix glass were used to reveal the eruption processes of the YTT super-eruption and to give a constraint to the property of magma chamber. Based on the componentry, mineral assemblages, mineral and glass compositions, and vesicle texture, four distinct pumice types (P1-P4) were identified. The first type (P1) is amphibole-bearing pumice with 77.1 wt % on average of SiO₂ content of glass. This type of pumice is characterized by abundant matrix-vesicles, with plagioclase showing a wide range of anorthite content (from An₂₀ to An₈₀) and disequilibrium texture. The second and third types (P2 and P3) are the most but slightly evolved pumices, with 77.5 and 77.6 wt.% on average of SiO₂ content of glass, respectively. Plagioclases of P2 and P3 pumices commonly have unzoned texture, with low anorthite content (An₃₀ on average). P2 is biotite-bearing, distinctively characterized by abundant pheno-vesicles, while the P3 pumice includes rare pheno-vesicle, skeletal-polyhedral quartz and no biotite. The fourth type of pumice (P4) is quartz- and sanidine-free, shows the less evolved glass composition (76.3 wt.% on average of SiO₂ content of glass), and is characterized by dominant matrix-vesicles and crystal clots of plagioclase, amphibole, pyroxene, and biotite; plagioclase of the P4 pumice shows a hollow texture and high anorthite content (An₅₀₋₆₀). In-situ trace element analysis by LA-ICP-MS for matrix glass of P1, P2, P3 and P4 shows very distinct geochemical signatures, which are clearly correlated with the four pumice types. Plotted on bivariate diagrams of Ba vs. Y,

Sr vs. Y and Ba vs. Sr, the P1 pumice is characterized by relatively medium Ba and Sr (400 – 875 ppm, and 41 – 67 ppm, respectively), but variable Y contents (20 – 53 ppm); the P2 and P3 pumices, on the other hand, show low Ba and Sr (8–136 ppm, and 13 – 37 ppm, respectively) and highly variable Y contents (27 – 77 ppm); and P4 pumice is characterized by relatively high Ba and Sr (1173 – 1340 ppm, and 95 – 124 ppm, respectively), but narrow range of Y contents (21 – 31 ppm). The geochemical signatures of matrix glass compositions of distinct pumice types suggest the occurrence of four distinct magma bodies. The number of fractions of distinct glass shards and pumices (ØGP) with the same geochemical signatures represents the volume fraction of each magma type. From the approximate volume of the magma, 5300 DRE km³ after Costa et al. (2014) and the geographical distributions of each pumice type, it is found that a voluminous P1 (ØGP: 0.61~2554.9 km³), medium P2 (ØGP: 0.28~1162.5 km³), and smallest P4 (ØGP: 0.03~122.7 km³) chambers, located relatively at the northern direction, and small P3 chamber (ØGP: 0.07~309.7 km³) from southern caldera were evacuated during the 74 ka YTT eruption. Eruptions from multiple magma chambers were initiated by a high supersaturation of pheno-vesicle-rich magma (P2 magma), triggering the eruption of P1, P2, P3, and P4 magmas, simultaneously.

Keywords: pumices, distinct magma chamber, the Youngest Toba Tuff (YTT), super eruption

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1. Introduction

The eruption process responsible for the formation of enormous caldera-forming eruption, known as the super eruption, is still debatable. In general, super-eruptions are considered to occur as a result of explosions from very large and long-live magma chambers; examples of these include the case of the Oligocene Lund tuff in the Great Basin of Nevada and Utah (Maughan et al., 2002), Mamaku ignimbrite from Taupo eruption (Milner et al., 2003) and Bishop tuff eruption (Hildreth and Wilson, 2007). However, recent studies suggested a multiple magma chambers model to explain the eruption processes of several super eruptions around the world (Begue et al., 2014; Cooper et al., 2011; Pappalardo et al., 2002; Pabst et al., 2007; Gravley et al., 2007). Multiple magma chambers eruption model build upon detailed studies of eruption products, including melt inclusion in quartz and matrix glass compositions, combined with bulk rock and mineral data (e.g., the Taupo Volcanic Zone eruption; Begue et al., 2014), stratigraphy correlations and component analyses (e.g., the Taupo Volcanic Zone eruption; Gravley et al., 2007), mineral chemistry of plagioclase and Fe-Ti oxide, coupled with trace element signatures of glass shards from all eruptive units (e.g., the Kidnappers super eruption; Cooper et al., 2011), and isotopic analyses (e.g., Campi Flegerei eruption; Pappalardo et al., 2002; Pabst et al., 2007).

As documented in these studies, essential information of eruption process from caldera-forming eruption, both juvenile and non-juvenile materials, can be obtained through detailed componentry analysis of eruption products and a comprehensive stratigraphy (Ross et al., 2021). The texture of crystal and vesicle in juvenile material records the condition of pre-eruptive magma chamber and conduit processes in the generation of the caldera-forming eruption (Suhendro et al., 2021; Simmons et al., 2017;

Vinkler et al., 2012). On the other hand, non-juvenile material, namely lithic fragments, provides information about the evolution of the caldera-forming eruption (Kamata et al., 1993; Simmons et al., 2017; Browne and Gardner, 2004). Therefore, a detailed study of eruptive products is needed to understand the eruption process of large magma bodies.

There is still controversial point for the 74 ka YTT caldera-forming eruption. Chesner (1998, 2012) suggested that all Toba Tuffs (i.e., the 1.2 Ma Harranggaol Dacite Tuff, 800 ka Oldest Toba Tuff, 500 ka Middle Toba Tuff, and 74 ka Youngest Toba Tuff) were produced by the eruption of a large single compositionally zoned magma chamber, based on evidence of chemical zonation associated with past four Toba Tuffs and thermal gradient inferred from coexisting magnetite and ilmenite. On the other hand, several studies focusing on YTT suggest the existence of multiple magma chambers based on geophysics, mineral, glass and melt compositions, and age dating (Vazquez et al., 2004; Pearce et al., 2019; Tierney et al., 2021; Tierney et al., 2019; Matsuryono et al., 2001; Stankiewicz et al., 2010). However, there has been no detailed and comprehensive study of the YTT eruption products, for both juvenile and non-juvenile materials. Therefore, the discussion about the YTT eruption, whether it resulted from one large magma chamber or several magma chambers, is not clear. The goal of this study is to clarify the YTT magma chamber system, identify potential eruption triggers, and reconstruct the eruption history.

In this study, the results of detailed component analysis of juvenile and non-juvenile material of YTT eruption products were presented. Comprehensive stratigraphy was constructed based on variation and abundance of components representing the whole eruption stages that non-welded products are preserved. The mineralogical data, textural analyses, and geochemical signatures of phenocrysts and matrix glass of eruption

products of the 74 ka YTT super eruption were given to infer the existence of multiple magma chambers. Finally, the potential eruption triggers and the reconstruction of eruption history were conferred based on textural analyses and detailed stratigraphy data.

2. The Youngest Toba Tuff (YTT)

Toba Caldera is located in North Sumatra, Indonesia. It has an elongated shape parallel to the great Sumatran fault zone. The Toba volcanic system has erupted a sequence of four major ignimbrites since 1.2 Ma (Chesner and Rose, 1991; Chesner, 1998, 2012). The climax of the eruption of the volcanic sequence produced the Youngest Toba Tuff (YTT) at 74 ka. The YTT eruption produced a large deposit volume (5300 DRE km³), including pyroclastic density current (PDC) and distal ash, as the biggest eruption experienced in quaternary ages (Costa et al., 2014).

The YTT deposit in the proximal area is generally pumice- and crystal-rich (15 - 40 wt.%), and lithic-poor (Chesner, 1991, 2012). The YTT consists of non-welded to welded deposits. Compared to the other pre-YTT deposits, only YTT has non-welded ignimbrite deposits (Chesner and Rose, 1991). Welded pre-YTT ignimbrite was identified by the occurrence of strong fiamme (eutaxitic) texture (Chesner and Rose, 1991; Knight et al., 1986) and the occurrence of pink quartz (Chesner and Rose, 1991), which distinguish it from welded YTT. Knight et al. (1986) showed that the base of YTT deposits is represented by lens-shaped lithic-rich lag breccia associated with grey coarse air fall ash above the Middle Toba Tuff (MTT) deposits in the Harranggaol section (northern caldera).

Glass shards of YTT eruption are commonly found in distal areas such as India, Malaysia, China, and Africa (Chesner and Rose, 1991; Shane et al., 1995; Darren et al., 2017; Pearce., 2019; Smith et al., 2011; Lane et al., 2013). Trace element composition of glass shards from YTT eruption showed more than one population specifically defined

by Ba, Sr, and Y (Fig. 1A; Pearce et al., 2019), which suggests the occurrence of multiple magma chambers (Fig. 1B).

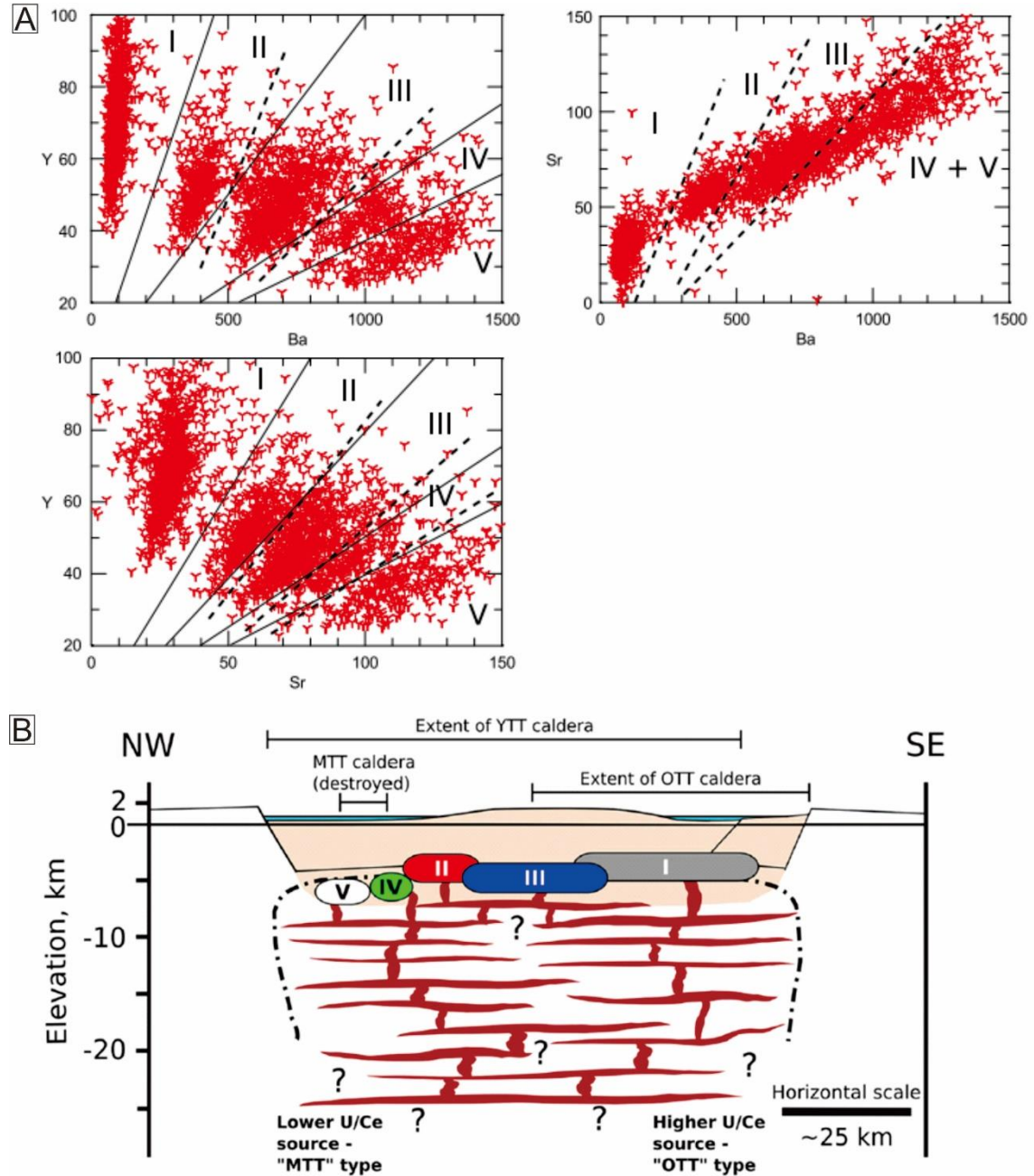


Figure 1. (A) Bivariate plots of Ba vs Y, Sr vs Y, and Ba vs Sr (all as ppm) for 2507 analyses of YTT glass shards defined five distinct populations. (B) Configuration of magma bodies under the YTT caldera at 75 ka. Magma chambers of the different populations trace element populations are labelled I-V (Pearce et al., 2019).

On contrary, several previous studies suggest a compositionally magma zoned model (Fig. 2) for all Toba tuffs including the YTT (Chesner, 1998; Chesner and Luhr, 2010; Chesner, 2012), with the deepest eruption portion of magma body implied by the low silica rocks (40 wt. % crystals), while the high silica rocks (10 wt.% crystals) presumably representative of magma near the chamber roof.

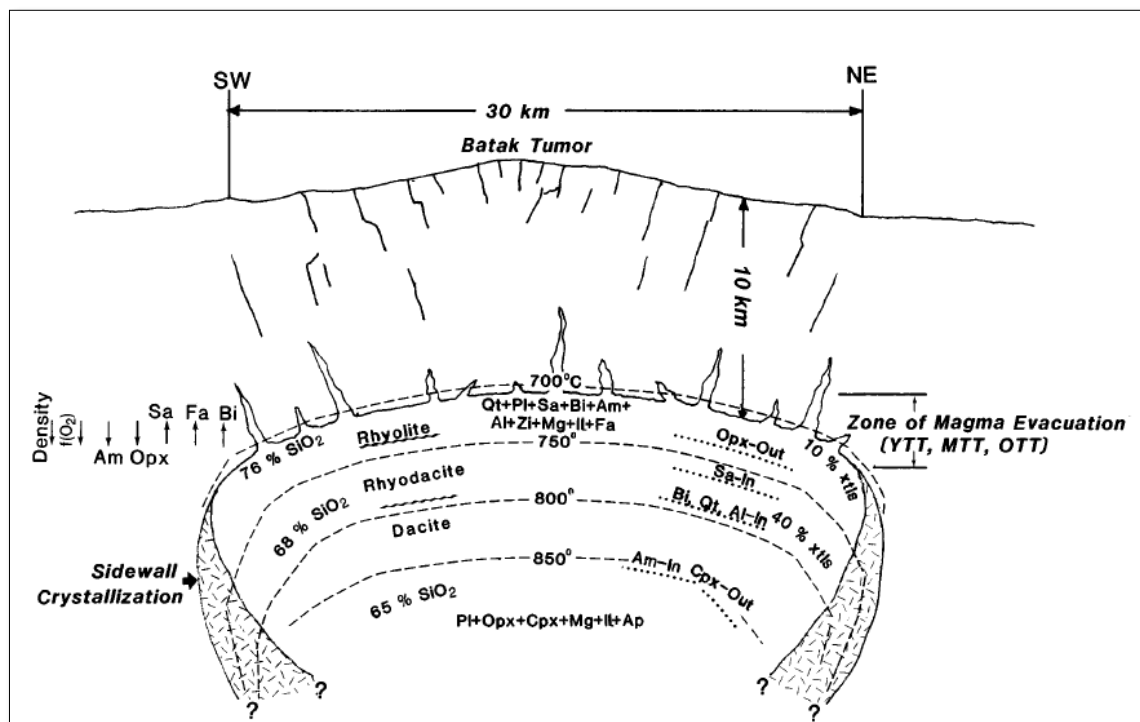


Figure 2. Model of the magma chambers that erupted Toba tuffs, including the Youngest Toba Tuff (YTT), the Middle Toba Tuff (MTT), and the Oldest Toba Tuff (OTT). Qt, quartz; Pl, plagioclase; Sa, sanidine; Bi, biotite; Am, amphibole; Al, allanite; Zr, zircon; Mg, magnetite; Il, ilmenite; Fa, fayalite; Ap, apatite; Opx, orthopyroxene; Cpx, clinopyroxene; xtals, crystals (Chesner, 1998)

3. Methods

3.1. Fieldwork and sampling

During the fieldwork carried out in 2018 and 2020, samples of the non-welded ignimbrite, including pumice and lithic variations were collected. The description of outcrops and sampling at 30 observation points (Fig. 3A) were made to construct the stratigraphy and laboratory analyses. The observation points are distributed in all directions and various distances from the caldera.

3.2. Component analysis

The non-welded YTT samples were sieved using 1 ϕ (1/2 mm) to -6 ϕ (> 64 mm) sieves. Then, the pumice and lithic fragments were rinsed in water and dry in the oven for 24 hours. Pumice and lithic fragments with grain sizes between -2 ϕ (4 mm) to -6 ϕ (> 64 mm) were used to identify the component type. For the component analyses, physical appearances of pumices (i.e., color, mineral associations, and vesicle appearances) were assessed by the naked eye and binocular microscope; while lithic fragments were identified by the rock type. A total of 9175 grains from 19 non-welded samples were used in analyses described in the following subsections.

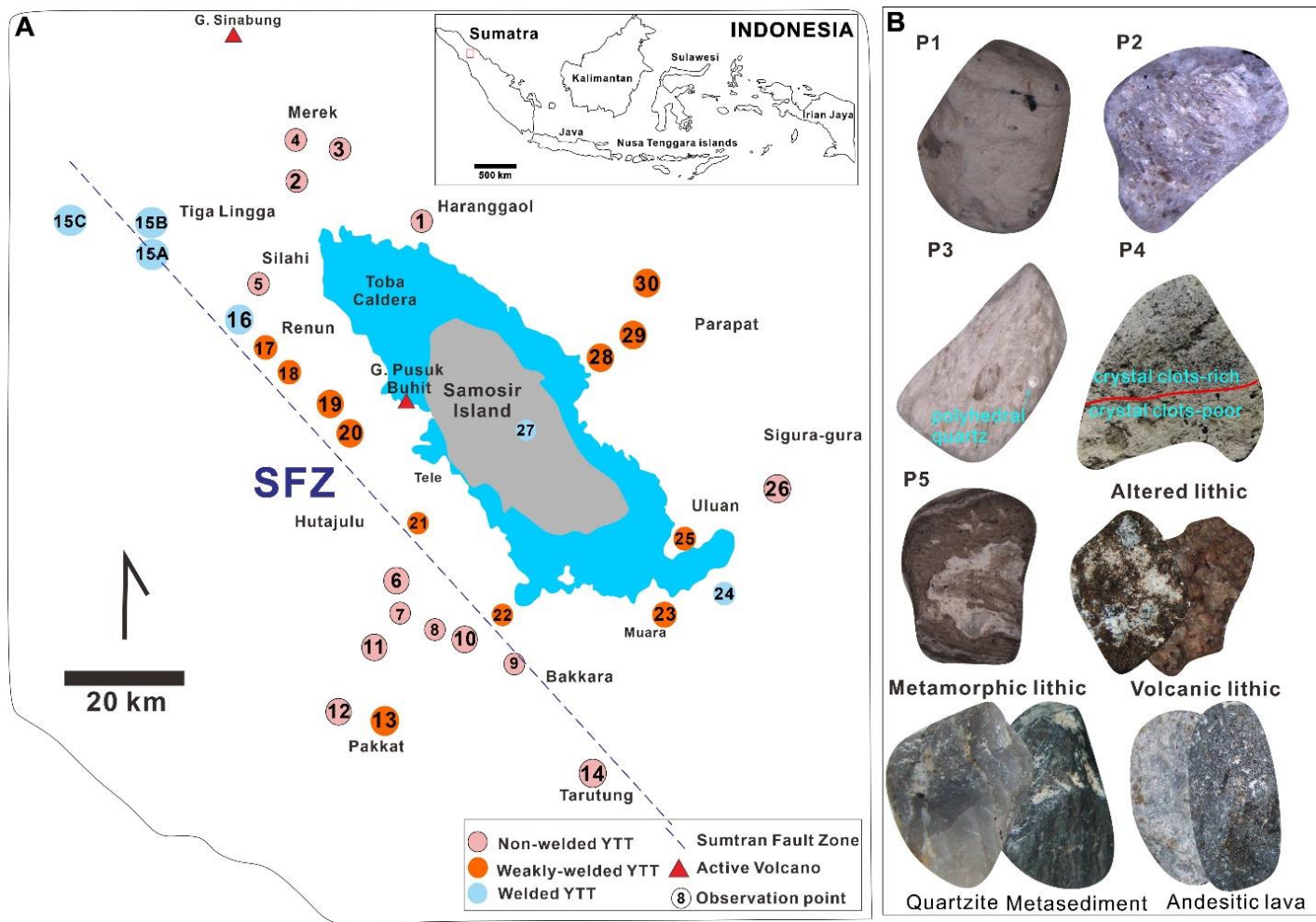


Figure 3. (A) Location map of the sampling and observation points; the location of Toba caldera is highlighted by red square in the inset map. (B) Five distinct pumice types (P1-P5) and the variation of lithic fragments in the Youngest Toba Tuff (YTT) deposit

3.3. Petrography and textural analyses

95 thin sections representing distinct pumice types, which were classified by the component analysis were used for petrography analysis. Observation under an optical microscope for petrographic analysis was conducted to determine the mineral association and crystal texture of each pumice type. The textural analysis of crystal and vesicle for 34 pumices representing distinct populations of pumices was conducted using images taken by a HITACHI TN3030 Scanning Electron Microscope (SEM) at Petrology and Volcanology Laboratory, Kyushu University. High magnification and low magnification backscattered electron images were used to determine textural properties namely pheno-vesicularity, bulk-vesicularity, and crystallinity.

The pheno-vesicle and phenocryst were traced manually using mosaic images from 30x images magnifications. The representative matrix-vesicle was traced using 1000x images magnifications. The corrections for vesicle coalesced was made by manually separating the coalesces vesicle. Pheno-vesicle is the large vesicle (> 0.1 mm), representing the pre-existing vesicle in the magma chamber, and matrix-vesicle corresponds to small vesicles (< 0.1 mm), formed by the second nucleation in the conduit during the eruption (Toramaru, 2022). The fractions of phenocrysts (ϕ_{PX}) and pheno-vesicles (ϕ_{PV}) were quantified by dividing the total area of phenocrysts and pheno-vesicles for the total grain area. The total vesicularity of matrix-vesicle (ϕ_{MV}) in grain was obtained by multiplying the representative matrix-vesicularity (ϕ_{mv}) with matrix fraction (ϕ_M) of the total grain area. The representative matrix-vesicularity (ϕ_{mv}) was obtained by dividing the representative matrix vesicle area by the measured matrix area.

The matrix fraction (ϕ_M) was quantified by subtracting the total area by the total fraction of phenocryst and pheno-vesicle.

Definition of textural properties is shown by the equations below.

Pheno-vesicularity

$$\phi_{PV}^* = \frac{\text{Phenovesicle area}}{\text{Total area} - \text{phenocryst area} - \text{matrixvesicle area}} = \frac{\phi_{PV}}{1 - \phi_{PX} - \phi_{MV}} \quad (3.1)$$

Bulk-vesicularity

$$\phi_{BV}^* = \frac{\text{Vesicles area (Pheno+Matrix)}}{\text{Total area} - \text{phenocryst area}} = \frac{\phi_{PV} + \phi_{MV}}{1 - \phi_{PX}} \quad (3.2)$$

Crystallinity

$$\phi_{PX}^\circ = \frac{\text{Phenocryst area}}{\text{Total area} - \text{vesicle area (Pheno+Matrix)}} = \frac{\phi_{PX}}{1 - (\phi_{PV} + \phi_{MV})} \quad (3.3)$$

The number density of the pheno-vesicle and matrix-vesicle was calculated by the following equations.

Pheno-vesicle number density (PVND)

$$\text{PVND} = \frac{N_{pv}}{dp} \times \frac{1}{1 - \phi_{BV}^*} \quad (3.4)$$

Matrix-vesicle number density (MVND)

$$\text{MVND} = \frac{N_{mv}}{dm} \times \frac{1}{1 - \phi_{mv}} \quad (3.5)$$

Where N_{pv} is number density per unit area of pheno-vesicle, dp is the average pheno-vesicle size, ϕ_{BV}^* is bulk vesicularity, N_{mv} is number density per unit area of matrix-

vesicle, and dm is the average matrix-vesicle size, ϕ_{mv} is groundmass or matrix vesicularity.

3.4. Mineral chemistry and glass composition

JEOL JXA 850-F field emission electron microprobe (EPMA) at the Faculty of Science, Kyushu University was used to measure compositions of groundmass glass and crystals (plagioclase, biotite, amphibole, and orthopyroxene). The acceleration voltage was set at 15 kV, with beam current and size of 6 nA and 3 μm , respectively, for plagioclase, biotite, amphibole, and orthopyroxene crystals; while for the groundmass glass, a larger beam diameter of 6 μm was applied to prevent alkali loss (particularly Na).

For the trace element analysis of pumice glass, representative samples from each pumice type were cut perpendicularly to the direction of vesicles elongation, in order to obtain maximum glass thickness. Trace element compositions were determined by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) at Economic Geology Laboratory, Kyushu University, using a 193 NWR (New Wave Research) LA system coupled to an Agilent 7900 ICP-MS. Helium (He; flow rate of 0.8 L/min) and Ar (flow rate of 0.3 L/min) were used as carrier gas and make-up gas, respectively. The analysis was performed using a constant spot diameter of 10 μm (to avoid contamination of glass with crystal due to small glass size), laser energy of 5 J/cm² at a repetition rate of 5 Hz, with a 20 second acquisition time of sample ablation. Si-29 was used as internal standard using SiO₂ concentration determined by EPMA, and the US National Institute of Standards and Technology silicate glass (NIST612) as external standard (e.g., Jochum et al., 2011) for all elements. For analyses of rhyolite glass the minor Si-29 isotope is used as the internal standard as this is abundant in both the NIST612 calibration standard and

in the samples (Pearce et al., 2011). All counting per second (cps) data of analyzed spots were inspected to remove those which showed contamination from the ablation of phenocryst material (i.e., those points which showed anomalously elevated Ca and Sr likely derived from ablated plagioclase).

3.5. Pressure estimation

For the P1, P2, and P3 pumices, consisting of quartz, sanidine, and plagioclase as crystallizing phases, Rhyolite-MELTS computerized program of Gualda and Ghiorso (2014) was used to constrain the crystallization pressure, under the assumption of equilibration between melt, quartz, and two feldspars, i.e., plagioclase and sanidine. The compositions of major elements matrix-glass were used as input and run isobaric simulations at pressures of 25 – 400 MPa, in intervals of 25 MPa, under oxygen fugacity fixed at NNO (nickel-nickel-oxide) (e.g., Gualda and Ghiorso 2014, Beugue, et al., 2014, Pearce et al., 2019). As suggested by Gualda and Ghiorso (2014), the water content in excess of 4 wt.% is relevant for the YTT, the calculations were carried out using 4.9 to 5.7 wt.% H₂O for low- and high- SiO₂ pumices, respectively (e.g., Chesner, 1998).

The presence of orthopyroxene in P1 and P4 pumices allows the application of the orthopyroxene-liquid barometer, specifically global calibration for felsic liquid, from Putirka (2008). The compositions of major elements matrix-glass and orthopyroxene were used as input. The pressure estimation is based on the calibration of Al content and cation fractions in orthopyroxene and glass compositions. Equilibrium between the

orthopyroxene and glass compositions is tested by comparing the observed Fe-Mg exchange coefficient with the constant value which is graphically portrayed in the Rhodes diagram (available on the spreadsheet of orthopyroxene-liquid barometer by Putirka, 2008).

Amphibole occurs as a xenocryst in the YTT magma system (Gardner et al., 2002). The occurrence of amphibole in P1 and P4 pumices allows the application of the amphibole barometer of Ridolfi et al. (2010), a group of formulations that are empirically calibrated for subduction-related volcanoes. By assuming that the amphibole comes from volcanic activity (i.e., not from metamorphic rocks), the pressure estimation from amphibole could lead to a better model of the YTT magma system, specifically the formation depth of the amphibole.

4. Results

4.1.Componentry: juvenile and non-juvenile material

Five distinct types of pumice in juvenile clast were identified based on color, vesicle texture, and mineral assemblage, which were named pumice type P1, P2, P3, P4, and P5 (Fig. 3B). Pumice 1 (72.89% of total component, Table 1) is white pumice characterized by abundant small vesicles with relatively coarse-grain quartz, feldspar, amphibole, biotite, and pyroxene. Pumice 2 (15.8% of total component) is white to greyish in color, characterized by abundant large vesicles, glassy appearances, with relatively small quartz, feldspar, and biotite crystals. Pumice 3 (4.2% of total component) is an immensely white pumice characterized by small vesicles with a unique occurrence of polyhedral quartz. Pumice 4 (0.93% of total component) is white pumice characterized by ubiquitous crystal aggregate consisting of plagioclase, biotite, amphibole, and pyroxene. Pumice 5 (0.57% of total component) is a grey pumice characterized by small vesicles and tiny quartz and feldspar crystals, P5 sometimes also occurs as banded pumice.

Non-juvenile clast namely lithic fragments (5.61% of total component) can be divided into volcanic, metamorphic, and altered lithics (Fig. 3B). Volcanic lithic is the main non-juvenile (49% of total lithic) consisting of lava, andesite, and welded ignimbrite, while metamorphic lithic is subordinate (18% of total lithic) consisting of mainly slate and quartzite. Altered lithic (33% of total lithic) consists of altered igneous and metamorphic lithic.

Table 1. Summary of component analyses of the 74 ka Youngest Toba Tuff. The value in brackets is the proportion in percent

Unit-Region	Location	Pumice type					Lithic type			Total
		P1	P2	P3	P4	P5	Igneous	Metamorphic	Altered	
1-North	1	184(31.03)	293(49.41)	0	0	0	41(6.91)	13(2.19)	62(10.46)	593
	3	343(88.6)	14(3.63)	0	2(0.52)	5(1.3)	14(3.63)	8(2.07)	0	386
	4	376(92.16)	8(1.96)	0	0	2(0.49)	10(2.45)	7(1.72)	5(1.23)	408
	2	793(98.02)	10(1.24)	0	0	6(0.74)	0	0	0	809
	11-L	236(82.23)	20(6.97)	0	0	8(2.79)	12(4.18)	5(1.74)	6(2.09)	287
2-North and South	7-L	385(64.71)	186(31.26)	0	1(0.17)	7(1.18)	6(1.01)	6(1.01)	4(0.67)	595
	7-M	299(57.61)	148(28.52)	0	22(4.24)	1(0.19)	23(4.43)	4(0.77)	22(4.24)	519
	6-A	351(57.45)	211(34.53)	0	2(0.33)	4(0.65)	39(6.38)	4(0.65)	0	611
	6-L	684(86.36)	69(8.71)		0	1(0.13)	15(1.89)	12(1.52)	11(1.39)	792
	6-M	300(50.68)	220(37.16)	0	31(5.24)	1(0.17)	9(1.52)	7(1.18)	24(4.05)	592
	12-L	308(84.38)	31(8.49)	0	5(1.37)	3(0.82)	18(4.93)	0	0	365
	12-M	318(85.71)	25(6.74)	0	2(0.54)	4(1.08)	17(4.58)	5(1.35)	0	371
	14	295(85.76)	29(8.43)	0	0	9(2.62)	9(2.62)	0	2(0.58)	344
3-South	11-M	45(9.30)	33(6.82)	385(79.55)	0	1(0.21)	16(3.31)	4(0.83)	0	484
4 - North and South	2	196(92.45)	6(2.83)	0	2(0.94)	0	1(0.47)	2(0.94)	5(2.36)	212
	8	119(82.64)	0	0	0	0	4(2.78)	10(6.94)	11(7.64)	144
	28	293(74.94)	69(17.65)	0	17(4.35)	0	3(0.77)	4(1.02)	5(1.28)	391
	29	701(87.84)	78(9.77)	0	0	0	7(0.88)	2(0.25)	10(1.25)	798
	36	462(97.47)	0	0	1(0.21)	0	6(1.27)	1(0.21)	4(0.84)	474
Total		6688 (72.89)	1450(15.8)	385(4.2)	85(0.93)	52(0.57)	250(2.72)	94(1.02)	171(1.86)	9175(100)

4.2.Stratigraphy and eruption units

4.2.1 Summary of stratigraphy and units

The ignimbrite deposits of YTT in all observed locations are dominated by P1 and P2 pumices, while P4 and P5 pumices are found in small quantities. The P3 pumice is restricted in the southern region. Based on the occurrence and abundance of juvenile and non-juvenile materials, we divided the YTT stratigraphy into four units.

Unit 1, only found near the north-eastern caldera rim (Fig. 4A), is a massive ignimbrite. The main juvenile is P2 (49% of total components of unit 1, Table 1), while non-juvenile lithic fragment making up 20% of its total component. P1 is a subordinate component of juvenile pumice clasts (31%), while P3 and P4 are absent. The thickness of the unit 1 deposit is approximately 2.5 m. The lithic fragments are mostly dominated by altered lithic and volcanic lithic (53%, 35 % of total lithic component of unit 1, respectively); metamorphic lithic is rare (11% of total lithic component of unit 1).

Unit 2, observed in all directions from caldera (Fig. 4B, C, D, E), is a massive ignimbrite. The main juvenile is P1 (77% on average of total component of unit 2), while the non-juvenile lithic is poor (5%), with subordinate P2 (16%). The lithic component is dominated by fresh volcanic lithic (57% on average of total lithic component of unit 2). In this unit, P4 and P5 were observed as minor components, 1% each of total component. The thickness of unit 2 varies from 7 to 35 m with no correlations with the distance from the caldera rim.

Unit 3 (Fig. 4D, F) is a massive ignimbrite. The main juvenile is P3 (80% of total component of unit 3), distributes only in the south-western area; non-juvenile lithic is

minor in unit 3 (4%), and consists of a typical volcanic lithic, which was not found in other units. The P1 and P2 pumice occur as a minor component (9% and 7%, respectively), and P4 pumice was not found. The thickness of unit 3 is about 2.5 m.

Unit 4 (Fig. 4G) is a massive ignimbrite found in all directions from caldera. In several locations, this unit is followed by a thin stratified oxidized layer (Fig. 4H). The main juvenile is P1 (88% on average of total component of unit 4), P2 is poor (8%), while non-juvenile lithic is also poor (4% on average of total component of unit 4); the lithic component is dominated by altered volcanic lithic (47% on average of total lithic component of unit 4). The P4 pumice was found as a minor component (1%). The thickness of unit 4 varies from 3 to 20 m, the thick deposits were only found in the south direction.



Figure 4. (A, B) Outcrop images of northern deposits. (A) Outcrop image of location 1 showing a P2-rich and lithic-rich ignimbrite of unit 1. (B) Outcrop image of location 2 showing a P1-rich and lithic poor ignimbrite of unit 2. (C, D, E, F, G) Outcrop images of southern deposits. (C) Outcrop image of location 14 showing thick ignimbrite of unit 2. (D) Outcrop image of location 11 shows the contact between units 2 and 3. (E) Outcrop image of the bottom part of location 11 showing P1-rich and lithic-poor ignimbrite of unit 2 (F) Outcrop image of the upper part of location 11 showing P3-rich and lithic-poor ignimbrite of unit 3 (G, H) Outcrop images of location 8 showing extremely P1-rich and lithic poor followed by a thin stratified oxidized layer represent unit 4.

4.2.2 Directional variation of stratigraphy

4.2.2.1 Northern stratigraphy

The northern stratigraphy consists of units 1, 2, and 4 (Fig. 5A), while unit 3 is not found. Unit 1 occurs in the low elevation close to the rim of the northeastern caldera. Unit 2 is mostly found more than 10 km far from the caldera rim, spread in various elevations, while unit 4 is observed at the highest elevation close to the rim of the northwestern caldera.

4.2.2.1 Southern stratigraphy

The southern stratigraphy consists of units 2, 3, and 4 (Fig. 5B), while unit 1 is not found. Units 2 and 4 are spread over various heights. Locally, in the southwest area (Location 11), unit 2 is in direct contact with unit 3 (Figs. 4D, 3B).

4.2.3 Simplified stratigraphy of The Youngest Toba Tuff

Since units 2 and 4 occur both in the northern and southern caldera, a simplified YTT stratigraphy can be constructed by correlating these units. There are systematic changes in pumice and lithic variation along the stratigraphy (Fig. 5C): the lowest stratigraphy (unit 1) is P2- and lithic-rich; the middle stratigraphy (unit 2) is P1-rich and lithic-poor, with the first and minor occurrences of P4 and P5 pumices, locally followed by unit 3 which is mostly rich in P3 pumice; and the highest stratigraphy (unit 4) is extremely P1-rich, P2-, P4- and lithic-poor, with no P3 and P5 pumices. The types and proportions of lithic fragments (Fig. 5D) change with respect to the stratigraphy height; the abundance of volcanic lithic decreases from base to top of the stratigraphy, while altered lithic and metamorphic lithic increase in the opposite direction (Fig. 5D). These

results, particularly regarding the unit 1, are consistent with those reported by Knight et al. (1986) based on descriptions of outcrops in Harrangaol area, which showed that the non-welded YTT deposit was characterized by high lithic content and abundant high vesicular pumice which corresponds to P2 pumice in this study. They showed that the non-welded YTT in Harrangaol area was in contact with the MTT deposit (Fig. 5C). The middle stratigraphy (units 2 and 3) and the highest stratigraphy (unit 4) in this study cover all non-welded YTT deposit distributions presented by Chesner, 1991. In that study, the YTT deposits were distinguished by their differences in the degree of welding. However, there was no detailed characterization of juvenile and non-juvenile material from each non-welded deposit.

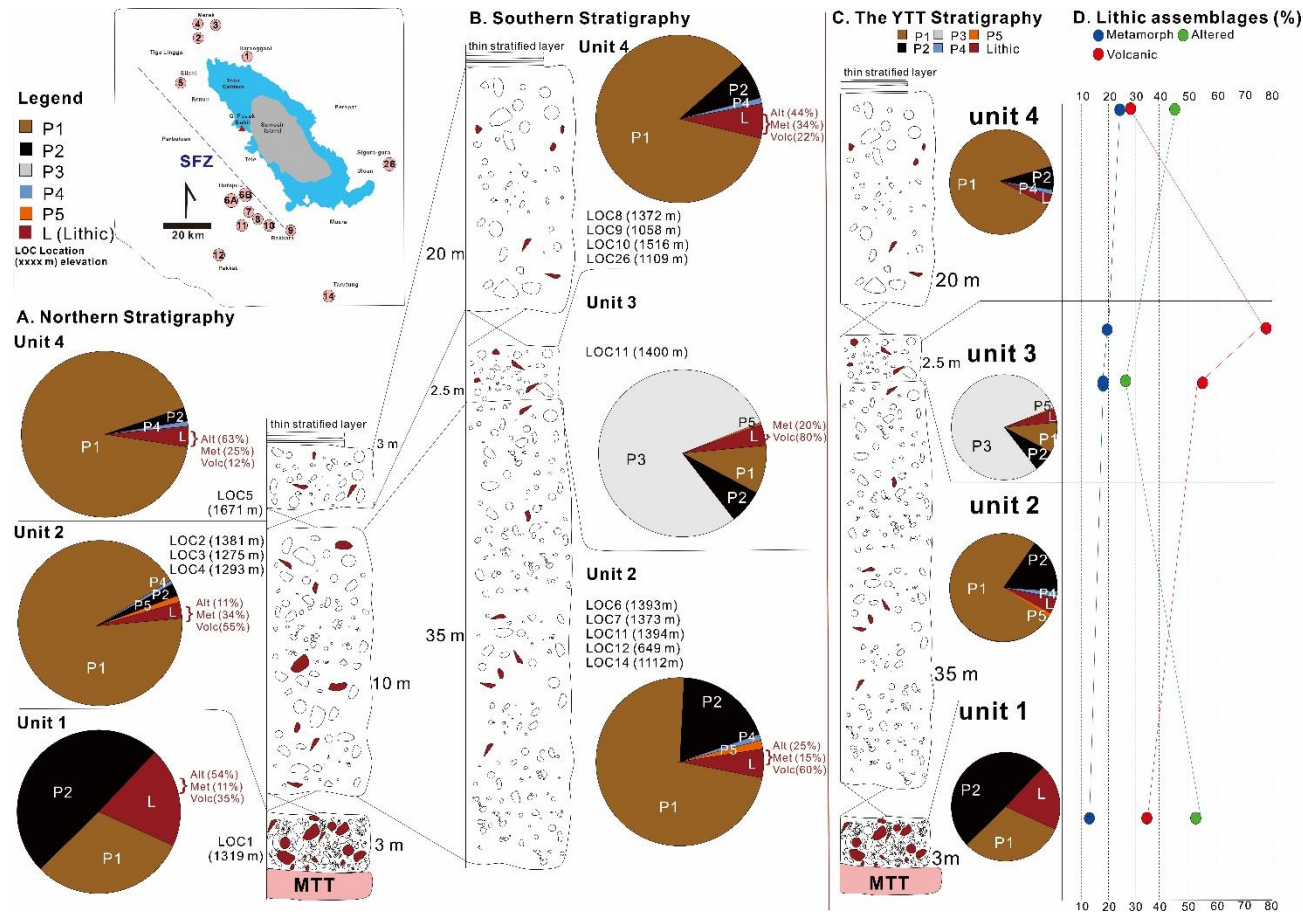


Figure 5. (A) Northern and (B) southern stratigraphy of the 74 ka Youngest Toba Tuff (YTT) eruptions. (C) Simplified stratigraphy made by correlation of units 2 and 4 based on componentry of juvenile and non-juvenile materials. The contact between the Middle Toba Tuff (MTT) and the Youngest Toba Tuff (YTT) deposits in the northern caldera was inferred by the descriptions of Toba tuffs deposits in the Harrangaol section from Knight et al. (1986). (D) Lithic assemblages of 74 ka YTT products with respect to stratigraphy position.

4.3 Petrography and textural properties of five distinct YTT pumices

4.3.1 YTT type 1 (P1)

The P1 is dominated by small vesicles (Fig. 6A, G), and the bulk-vesicularity ranges from 50 to 75% (average of 60.6%, Table 2); while the crystallinity ranges from 1 to 36% (average of 18.6%). The average of pheno-vesicularity is 18.6% (Table 2). The mineral assemblage of P1 consists of plagioclase, quartz, biotite, sanidine, amphibole, orthopyroxene, and Fe-Ti oxide (Table 3); most of the phenocrysts are characterized by broken crystals. Crystal clots are common in P1, they occur mainly as a group of plagioclases, a group of plagioclase-quartz-biotite, and a group of amphibole-plagioclase-biotite (Fig. 6K). Plagioclase shows normal zoning (Fig. 7A2) and variable disequilibrium textures, i.e., patchy zoning (Fig. 7A3) and complex texture as a combination of zoning and an intensive hollow texture (Fig. 7A4, A5, B). Decrepitated melt inclusions are common in quartz (Fig. 6M), plagioclase (Fig. 6N), and biotite, and mineral inclusions of zircon and oxide are found mainly in biotite and plagioclase.

4.3.2 YTT type 2 (P2)

The P2 is characterized by abundant large vesicles (Fig. 6B1, 6F), however, small vesicles are still preserved in several grains of pumices (Fig. 6B2); bulk-vesicularity of P2 ranges from 63 to 75% (average of 68.5%, Table 2), while the crystallinity ranges from 1 to 31% (average of 16.4%). The average of pheno-vesicularity is 49.2%. The phenocryst assemblage of P2 consists of plagioclase, sanidine, quartz, biotite, and Fe-Ti oxide; broken crystal and crystal clots of plagioclase-biotite-amphibole are not common. Plagioclase commonly shows unzoned texture (Fig. 7B). Melt and mineral inclusions are rare. Mineral inclusions of zircon and oxide are found only in biotite.

4.3.3 YTT type 3 (P3)

The crystallinity of P3 ranges from 11 - 36% (average of 26.6%) and bulk-vesicularity of 44 - 54% (average of 49.8%, Table 2). The average of pheno-vesicularity is 16.1%. The phenocryst assemblage of P3 consists of plagioclase, sanidine, and quartz. Quartz of P3 pumice shows multiple morphologies namely anhedral, and polyhedral-skeletal; the latter is only found in this type of pumice (Fig. 6C). Plagioclase mainly has unzoned textures (Fig. 7B). Broken crystal and melt inclusion are common. Melt inclusions showing decrepitation features are hosted in quartz and plagioclase. Mineral inclusions of plagioclase, zircon, and titanomagnetite occur mainly in polyhedral-skeletal quartz. Crystal clots occur as a group of plagioclase and plagioclase-skeletal quartz (Fig. 6L).

4.3.4 YTT type 4 (P4)

The crystallinity range of P4 varies from 26 to 36% (average of 31.3%, Table 2), while the bulk-vesicularity ranges from 52 to 65% (average of 58.5%). The average of pheno-vesicularity is 19.6 %. The phenocryst assemblage of P4 consists of plagioclase, biotite, amphibole, orthopyroxene, and Fe-Ti oxide. P4 is characterized by the absence of quartz and sanidine, and the occurrence of ubiquitous crystal clots (Fig. 6D). There are two types of crystal clots that differ in size. The first type is the most common, consisting of small crystal (< 1 mm), mainly as a group of plagioclase, amphibole, biotite, orthopyroxene, and Fe-Ti oxide (Fig. 6I). The second type of clots are rare, dominated by larger size plagioclase (> 1 mm) associated with amphibole, orthopyroxene, and Fe-Ti oxide (Fig. 6J). The presence of these distinct crystal clots characterizes the heterogeneity of P4, which consists of a part characterized by the abundance of type 1 crystal clots and

is relatively rich in pheno-vesicles, while another part characterized by the occurrence of type 2 crystal clots and lack of pheno-vesicles. Plagioclase shows a hollow texture (Fig. 7A6, 7B). Melt inclusions are not common, broken crystal and mineral inclusions are found mainly in plagioclase.

4.3.5 YTT type 5 (P5)

The P5 is characterized by abundant small vesicle (Fig. 6E), and abundant microlite (Fig. 6H); the crystallinity of P5 ranges from 3 to 13% (average of 7.9%, Table 2), while the bulk-vesicularity ranges from 47 to 58% (average of 52.7%). The average of pheno-vesicularity is 12.3 %. The P5 is composed of microphenocryst (i.e., phenocrysts with crystal size less than 1 mm) assemblage consisting of sanidine, plagioclase, quartz, and biotite. All plagioclase experienced unzoned texture (Fig. 7A1, B). Melt inclusions, mineral inclusion, and broken crystals are not common.

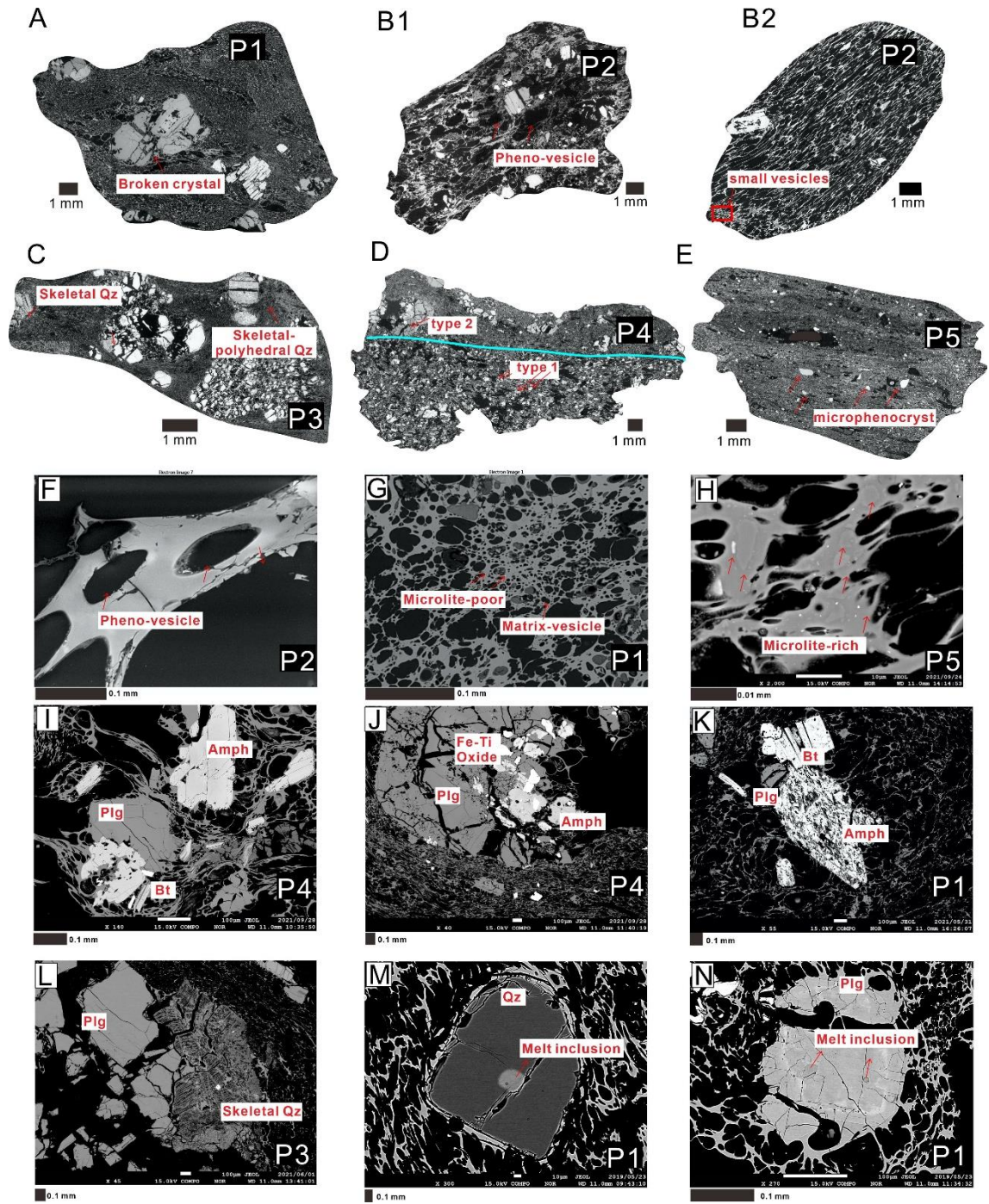


Figure 6. (A-E) A mosaic of representative backscattered electron (BSE) images of five distinct pumice types of the 74 ka Youngest Toba Tuff (YTT) (A: P1; B1-B2: P2; C: P3; D: P4; E: P5). (F, G, H) Vesicle images of P2 (Pheno-vesicle-rich), P1 (matrix-vesicle-rich), and P5 (microlite-rich) pumices. (I-L) crystal clots of YTT: (I) type 1 of P4 (Amph $\pm$ Plg $\pm$ Bt), (J) type 2 of P4 (Plg $\pm$ Amph $\pm$ Fe-Ti Oxide), (K) P1 (Amph $\pm$ Plg $\pm$ Bt), and (L) P3 (Plg $\pm$ skeletal Qz) pumices. (M-N) Decrepitated melt inclusion of P1 pumice: (M) in quartz, (N) in plagioclase.

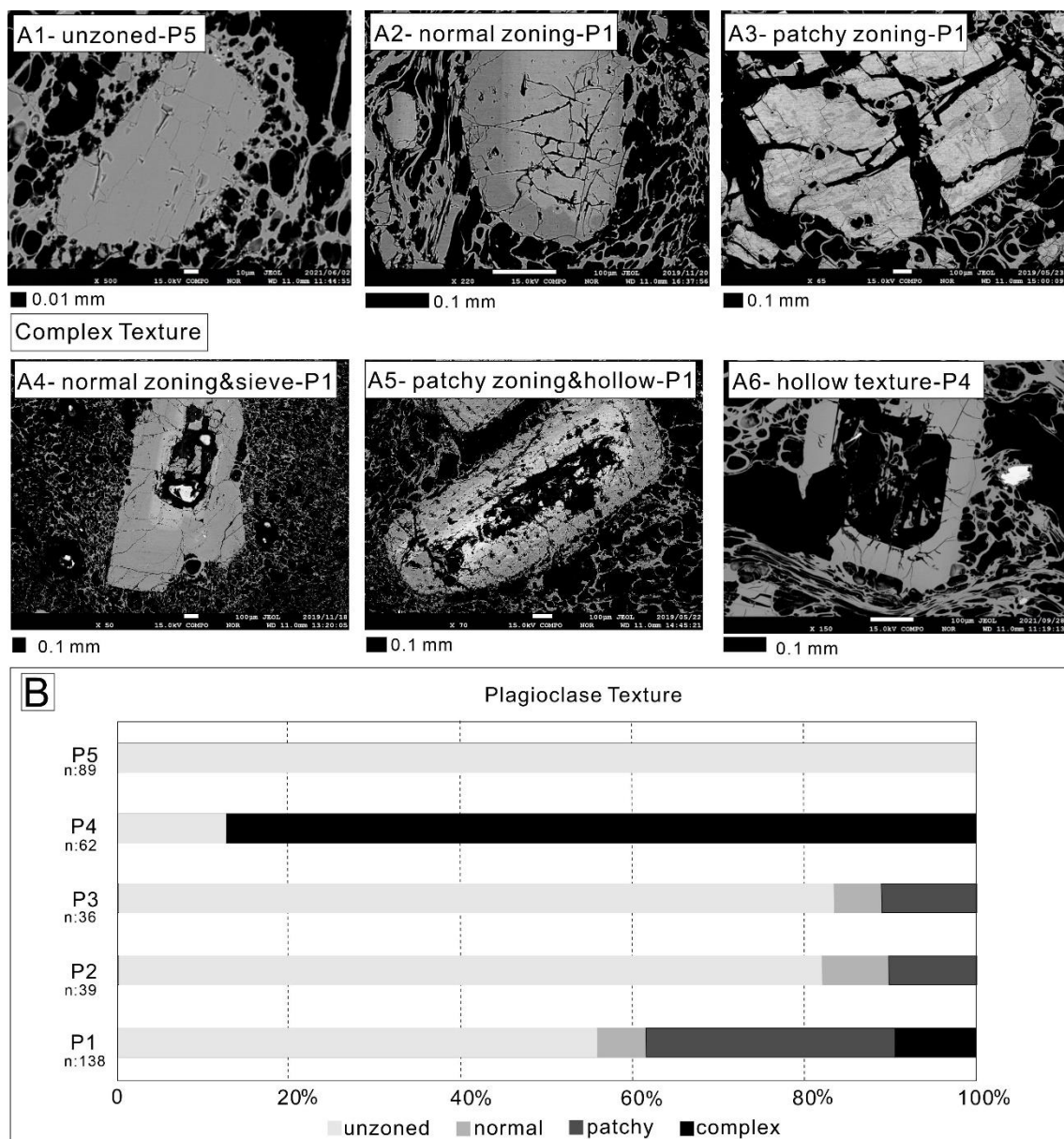


Figure 7. (A1-A6) Variation of plagioclase textures of 74 ka Youngest Toba Tuff (YTT) pumice. (B) Histogram showing the proportion of each plagioclase texture of P1-P5 pumices.

Table 2. Summary of textural analyses of distinct pumice populations of the 74 ka Youngest Toba Tuff.

Pumice type	Sample	ØPV	ØMV	ØPX	Ø _{PV} [*]	Ø _{BV} [*]	Ø _{PX} [°]
P1	P1-1	5.1%	51.3%	4.0%	11.4%	58.6%	9.2%
	P1-2	9.0%	48.9%	15.3%	25.3%	66.8%	36.4%
	P1-3	9.7%	46.8%	6.6%	20.8%	59.8%	15.2%
	P1-4	12.2%	47.3%	8.9%	27.9%	64.1%	22.1%
	P1-5	1.8%	51.3%	5.0%	4.2%	55.8%	10.6%
	P1-6	1.8%	48.5%	14.6%	5.0%	58.7%	29.5%
	P1-7	9.3%	54.3%	4.6%	22.7%	66.2%	12.8%
	P1-8	13.7%	33.3%	7.5%	23.1%	49.7%	14.2%
	P1-9	4.6%	41.5%	17.5%	11.3%	54.9%	32.5%
	P1-10	9.9%	52.9%	8.4%	25.5%	67.6%	22.5%
	P1-11	3.6%	38.0%	16.9%	8.0%	49.3%	28.9%
	P1-12	18.0%	44.4%	5.5%	35.8%	64.9%	14.6%
	P1-13	1.4%	55.2%	4.8%	3.4%	59.3%	10.9%
	P1-14	3.8%	44.9%	14.6%	9.3%	56.3%	28.4%
	P1-15	8.5%	50.1%	0.4%	17.1%	58.8%	1.0%
	P1-16	8.9%	57.3%	1.6%	21.6%	67.1%	4.8%
	P1-17	16.2%	39.4%	12.8%	33.8%	61.4%	28.8%
	P1-18	12.0%	59.1%	5.4%	33.8%	74.5%	18.6%
	P1-19	5.9%	49.6%	5.1%	13.0%	58.2%	11.5%
	Average	8.2%	48.1%	8.4%	18.6%	60.6%	18.6%
P2	P2-1	23.0%	37.7%	10.0%	44.0%	65.0%	25.4%
	P2-2	24.9%	37.4%	7.1%	44.8%	65.1%	18.8%
	P2-3	22.8%	43.4%	0.4%	40.6%	66.4%	1.1%
	P2-4	26.3%	44.3%	8.9%	56.3%	75.0%	30.5%
	P2-5	39.6%	31.2%	3.9%	61.1%	72.1%	13.2%
	P2-6	27.8%	32.9%	7.2%	46.4%	63.3%	18.4%
	P2-7	27.3%	41.2%	1.9%	47.9%	69.2%	5.9%
	P2-8	27.7%	42.0%	5.5%	52.8%	72.1%	18.0%
	Average	27.4%	38.8%	5.6%	49.2%	68.5%	16.4%
P3	P3-1	3.6%	37.5%	6.4%	6.4%	43.7%	10.9%
	P3-2	7.7%	35.2%	20.5%	17.3%	52.0%	35.9%
	P3-3	11.8%	34.6%	17.8%	24.7%	53.8%	33.1%
	Average	7.7%	35.8%	14.9%	16.1%	49.8%	26.6%
P4	P4-1	7.5%	38.3%	14.2%	15.8%	52.2%	26.3%
	P4-2	8.6%	47.3%	16.0%	23.4%	64.9%	36.3%
	Average	8.0%	42.8%	15.1%	19.6%	58.5%	31.3%
P5	P5-1	3.3%	40.6%	7.5%	6.3%	47.1%	13.4%
	P5-2	9.2%	48.5%	1.0%	18.2%	58.2%	2.5%
	Average	6.2%	44.5%	4.3%	12.3%	52.7%	7.9%

Table 3. Summary of petrography of distinct pumice populations of the 74 ka Youngest Toba Tuff. (Plg: plagioclase, Bt: biotite, Sa: sanidine, Qz: quartz, Amph: amphibole, Opx: orthopyroxene, Ox: oxide).

Pumice Type	P1 (n:54)	P2 (n:19)	P3 (n:11)	P4 (n:4)	P5 (n:7)
Phases	Plg ± Qz ± Bt ± Sa ± Amph ± Opx ± Ox	Plg ± Sa ± Qz ± Bt ± Ox	Plg ± Sa ± Qz (multiple morphologies: anhedral, polyhedral, skeletal)	Plg ± Amph ± Bt ± Opx ± Ox	Sa ± Plg ± Qz ± Bt
Microscopic textures	Crystal clots: Plg; Plg ± Qz ± Sa; Amph ± Plg ± Bt, broken crystal and broken melt inclusions are very common, mineral inclusions of zircon and oxide are found mainly in biotite and plagioclase	Crystal clots: Plg ± Bt ± Amph (rare), broken crystal and melt inclusions are not common, mineral inclusions of zircon and oxide are found only in biotite	Crystal clots: Plg ± skeletal quartz (rare), broken crystal and melt inclusions are common, mineral inclusions of zircon, Fe-Ti oxide, and plagioclase occur mainly in skeletal- polyhedral quartz	Ubiquitous crystal clots type 1 (size <1mm): Plg; Plg ± Amph ± Px ± Bt ± Ox, and crystal clots type 2 (rare, size >1 mm): Plg ± Amp ± Ox. Melt inclusions are not common. Broken crystal and mineral inclusions are found mainly in plagioclase	Tiny crystal (microphenocryst, less than 1 mm), unzoned crystal. Melt inclusions, mineral inclusion, and broken crystals are rare
Glass texture	Dominated by small vesicle, large vesicles occur near the phenocryst, microlite-poor	Large vesicle is common, microlite-free	Dominated by small vesicle, large vesicles occur near the phenocryst, microlite-free	Dominated by small vesicle, large vesicles occur near the phenocryst, microlite-free	Dominated by small vesicle, large vesicle is rare, microlite-rich
Zoning type	Dominated by unzoned plagioclase. Normal zoning is rare. Patchy zoning and complex texture are common	Dominated by unzoned plagioclase. Normal and patchy zoning are rare	Dominated by unzoned plagioclase. Normal and patchy zoning are rare	Dominated by complex texture (mostly hollow). Unzoned plagioclase is rare	Clear texture (unzoned plagioclase). No zoning texture

4.3.6 Quantitative data of pheno- and matrix-vesicle

In macroscopic (hand specimen) observation, it is clear that the vesicle character of P2 pumice is very different from other pumices in YTT. P2 is characterized by abundant large vesicles, while P1, P3, and P4 are marked by abundant small vesicles. Quantitative data from textural analysis of pheno-vesicle and matrix-vesicle support the qualitative observation. Figure 6 clearly shows the boundary between pheno-vesicle-poor and pheno-vesicle-rich magmas. P2 is characterized by high pheno-vesicle fractions, ranging from 23% to 40%, which represents pheno-vesicle-rich magma. While other pumice types (P1, P3, P4, and P5) have low pheno-vesicle fractions (< 20%), representing pheno-vesicle-poor magma. In addition, P2 pumice consists of a wide range of matrix-vesicle sizes, while P1, P3, and P4 pumices have small matrix-vesicle sizes (Fig. 8B).

Pheno-vesicle-rich magma P2 has typically higher PVND and pheno-vesicularity than P1, P3, and P4 (Fig. 8C-E). Furthermore, P2 clearly shows wider variation and smaller MVND value compared to P1, P2, and P4 (Fig. 8D, E). The plot between PVND and MVND results in two types of correlation, which are correlated to the magma type. The first type is characterized by nearly constant correlation, and corresponds to the pheno-vesicle-rich magma (P2). The second type shows the negative correlation, corresponding to the pheno-vesicle-poor magma (P1, P3, and P4).

MVND data from each magma are then used to estimate the decompression rate using the BND decompression rate meter from Toramaru (2006).

$$\frac{dP}{dt} = a_0 \cdot D \cdot \sigma^2 \cdot P_W^{-1/3} \cdot T^{-1/2} \cdot N^{2/3} = f(C_W, C_{SiO_2}, N)$$

Where, a_0 is a constant ($a_0 = 1 \times 10^{15}$). D is diffusivity of water (m^2/s). σ Is interfacial tension (N/m). P_w is initial saturation pressure (MPa), and T is temperature (K). f is a symbolic expression indicating a function of initial water concentration (C_w), SiO_2 contents (C_{SiO_2}), and bubble number density (N).

Input parameters such as water content were taken from Chesner (1998), using the IR spectroscopic techniques. The water concentrations of 4.9-5.7 wt.% were determined for YTT magma. The pressure and SiO_2 compositions for each magma chamber were taken from the results of this study (Fig. 14 and Table 5, respectively). The results show three order magnitude of magma decompression rate (Fig. 8F, supplementary 1), ranging from 10^6 to 10^8 Pa/s. Specifically, the estimated decompression rates for pheno-vesicle-poor magmas (P1, P3, and P4) are in the same range of 1×10^8 Pa/s to 9×10^8 Pa/s, while for pheno-vesicle-rich magma ranges from 10^6 to 10^8 Pa/s.

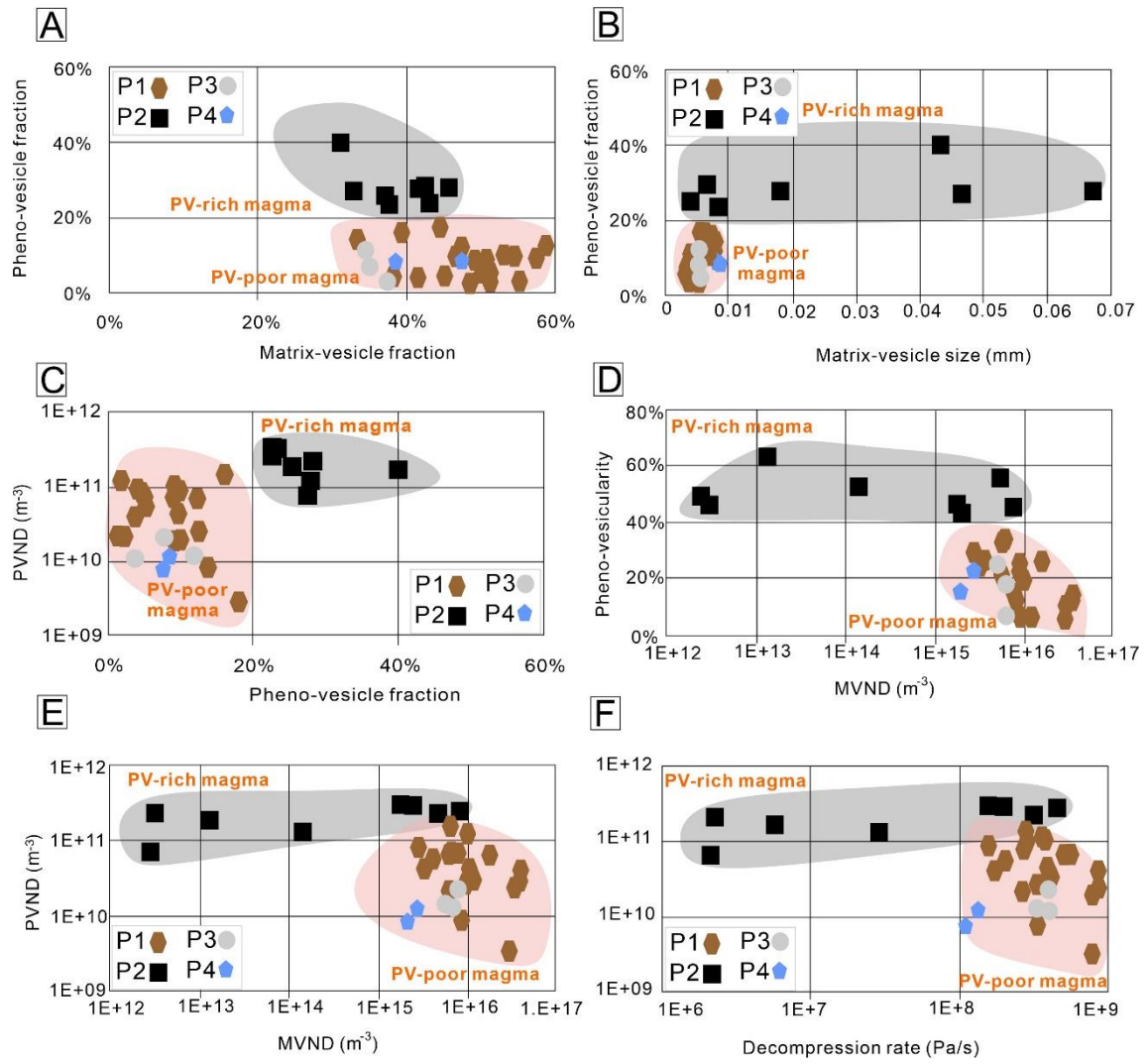


Figure 8. Quantitative textural analysis for pheno-vesicle and matrix-vesicle of the 74 ka YTT pumice. See text for discussion.

4.4 Mineral and glass compositions

The totals of biotite, amphibole, orthopyroxene, and matrix glass composition were mostly > 95%, while plagioclase was > 99% and all were normalized to 100% (Table 4,5). The anorthite values of plagioclase were calculated both from the core and rim. For biotite, amphibole, and orthopyroxene, the ratios between FeO/MgO and selected major elements were used to observe distinct compositional groups.

4.4.1 Plagioclase compositions

Representative plagioclase compositions obtained by EPMA are shown in Table 4. The anorthite (An) contents of plagioclase core compositions are higher in P1 and P4, than those in other pumice types. The An contents of plagioclase core of P1 vary in a wide range, from An₂₀ to An₉₀, and decrease towards the phenocryst rims; while those of P4 are between An₂₀ and An₇₀. On the other hand, plagioclases from P2, P3, and P5 pumices, are characterized mainly by unzoned texture, showed uniform anorthite contents of An₃₀ in average. These compositional features are well depicted in histograms of plagioclase (Fig. 9), which indicates that P2, P3, and P5 pumices have the most evolved plagioclase, followed by slightly evolved P1 plagioclase, while the P4 plagioclase is the less evolved.

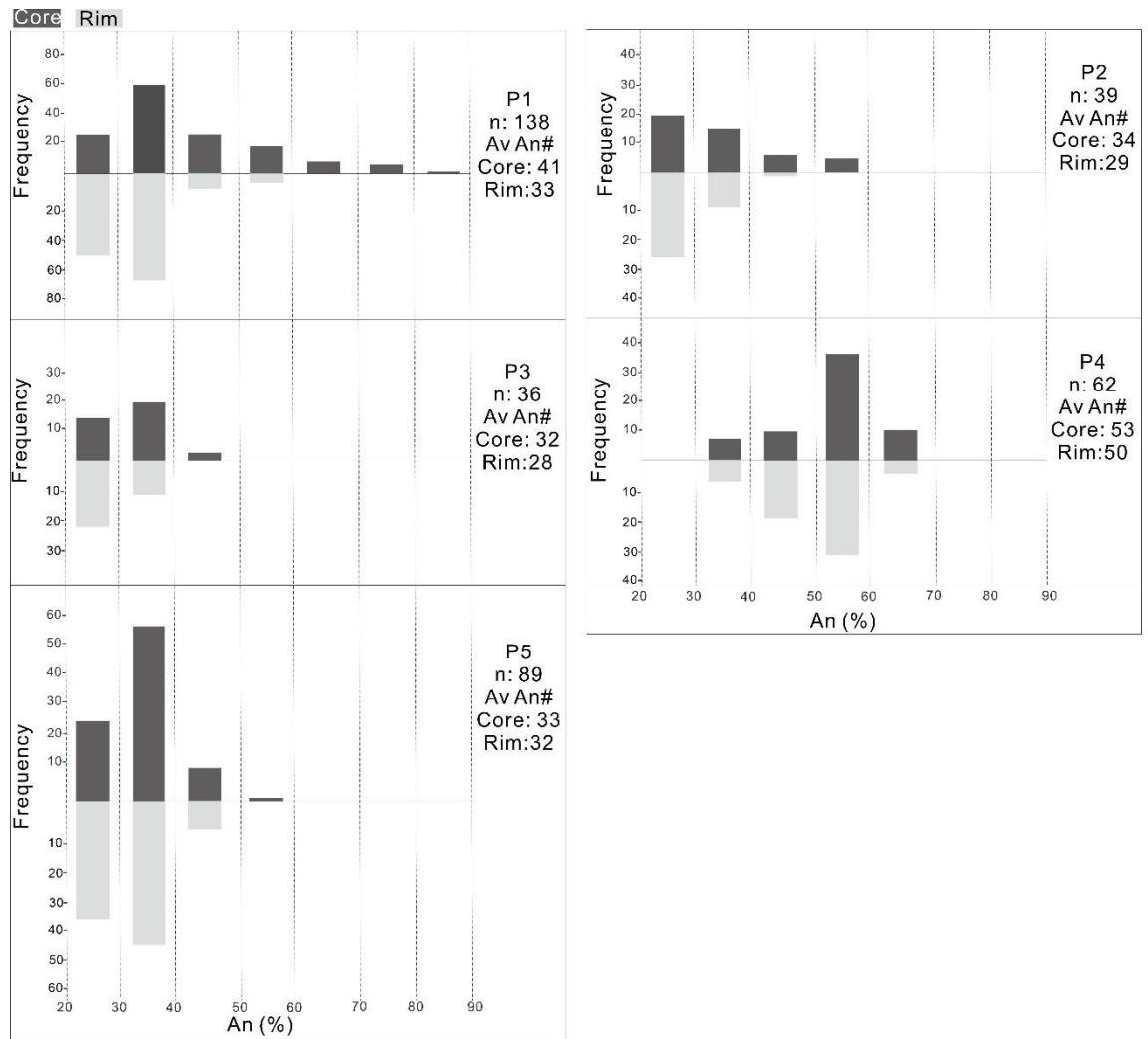


Figure 9. Histograms of plagioclase core and rim compositions from P1-P5 pumices.

4.4.2 Biotite compositions

The EPMA analyses of biotite (Table 4) showed two distinct compositional groups which are correlated with the type of pumice, except the biotite-free P3 pumice (Fig. 10A, B). P4 has narrower ranges of MnO and TiO₂ contents, from 0.1 to 0.3 wt.% and 4 to 4.6 wt.%, respectively, and lower FeO/MgO ratios (1.5-2) compared with other pumice types. The biotite compositions of P1, P2, and P5 are overlying. However, P1 shows wide ranges of MnO and TiO₂ contents, from 0.2 to 0.7 wt.%, and 3.3 to 5.2 wt.%,

respectively, and FeO/MgO ratios of 2.2-3.1. P2 has a narrow range of MnO contents from 0.4 to 0.7 wt.%, and a wide range of TiO₂ contents and FeO/MgO ratios of 3.3-4.6 wt.% and 2.2-2.9 respectively, while P5 has narrow ranges of MnO and TiO₂ contents, from 0.4-0.6 wt.% and 3-3.7 wt.%, respectively, and FeO/MgO ratios of 2.6 -2.9.

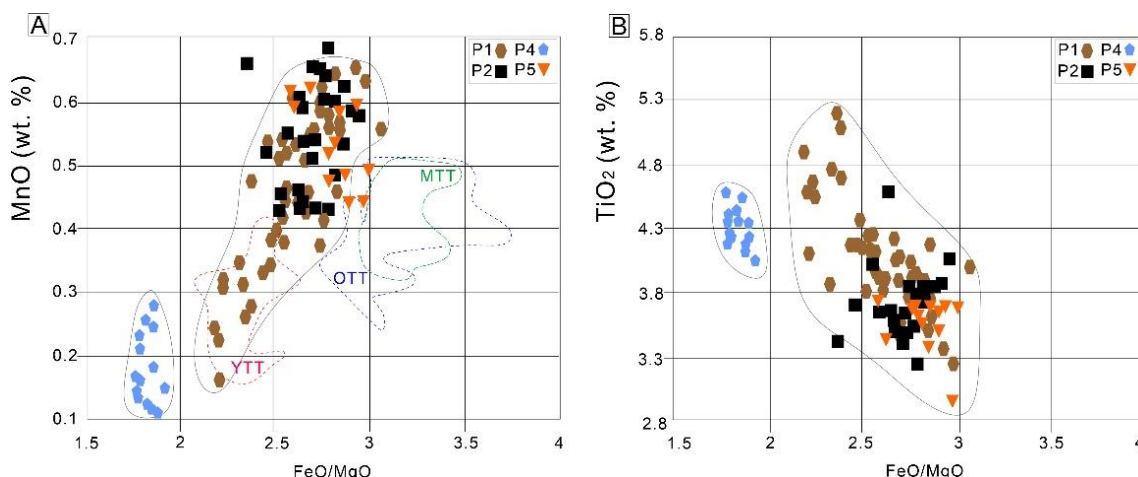


Figure 10. Biotite compositions of P1, P2, P4, and P5 pumices showing two distinct compositional groups. (A) Plots of FeO/MgO ratios versus MnO contents. The polygons outlined by red, blue and green dashed lines are biotite compositional fields of Youngest Toba Tuff (YTT), Oldest Toba Tuff (OTT), and Middle Toba Tuff (MTT), respectively, after Smith et al. (2011). (B) Plots of FeO/MgO versus TiO₂.

4.4.3 Amphibole compositions

Amphibole is present as a single crystal in P1 and P4, and also as part of crystal clots in P1, P2, and P4 pumice. The major element compositions of amphibole (Table 4) showed two distinct compositional groups, which are characterized by the ratio of FeO/MgO and MnO content (Fig. 11A). The first group, consisting of P1 amphibole and amphibole-bearing crystal clots in P2, is characterized by higher FeO/MgO ratios and MnO content, varying from 2.2 to 2.7, and 0.7 to 1.1 wt. %, respectively, with lower TiO₂ content from 1 to 2.1 wt. %, and a narrower range of SiO₂ from 43.2 to 46 wt.%, compared

with amphibole in the second group. The second group, consisting of P4 amphibole and amphibole-bearing crystal clots in P4 and P1, is characterized by wide FeO/MgO ratios, MnO, TiO₂, and SiO₂ varying from 1.2 to 2.2, 0.2 to 0.7 wt.%, 1 to 4 wt.%, and 41 to 46.8 wt. %, respectively.

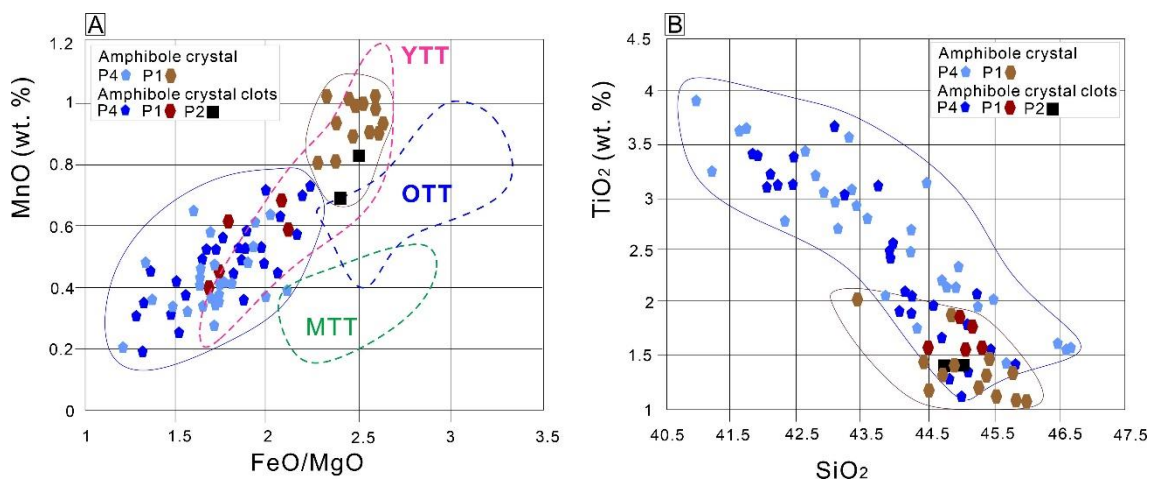


Figure 11. Amphibole compositions of P1, P2, and P4 pumices showing two distinct compositional groups. (A) Plots of FeO/MgO ratios versus MnO contents. The polygons outlined by red, blue and green dashed lines are biotite compositional fields of Youngest Toba Tuff (YTT), Oldest Toba Tuff (OTT), and Middle Toba Tuff (MTT), respectively, after Chesner (1998). (B) Plots of SiO₂ versus TiO₂.

4.4.4 Orthopyroxene compositions

The major element compositions of orthopyroxene (Table 4) showed three distinct compositional groups (Fig. 12). The first group, consisting of P1 orthopyroxene, is characterized by higher FeO/MgO ratios and MnO content, varying from 2.2 to 2.6, and 2.2 to 3.7 wt. %, respectively, with lower Al₂O₃ from 0.3 to 0.5 wt. %, compared to orthopyroxene in P4 pumice. The second group of orthopyroxene occurs in P4 pumice as a single crystal and part of crystal clots and is characterized by moderate FeO/MgO ratios, MnO, and Al₂O₃ contents, varying from 1.3 to 2.1, 0.7 to 1.1 wt. %, and 0.3 to 0.9 wt. %, respectively.

respectively. These two groups have similar compositions to the YTT orthopyroxene which was reported by Pearce, 1998 (Fig. 12A). The third group of orthopyroxene occurs in P4 pumice as a part of crystal clots and is characterized by low FeO/MgO ratios and MnO content, varying from 0.9 to 1.4, and 0.6 to 0.9 wt. %, respectively, with high Al₂O₃ from 0.6 to 1.8 wt. %, which is similar to the compositions of orthopyroxene from the Harranggaol Dacite Tuff (HDT).

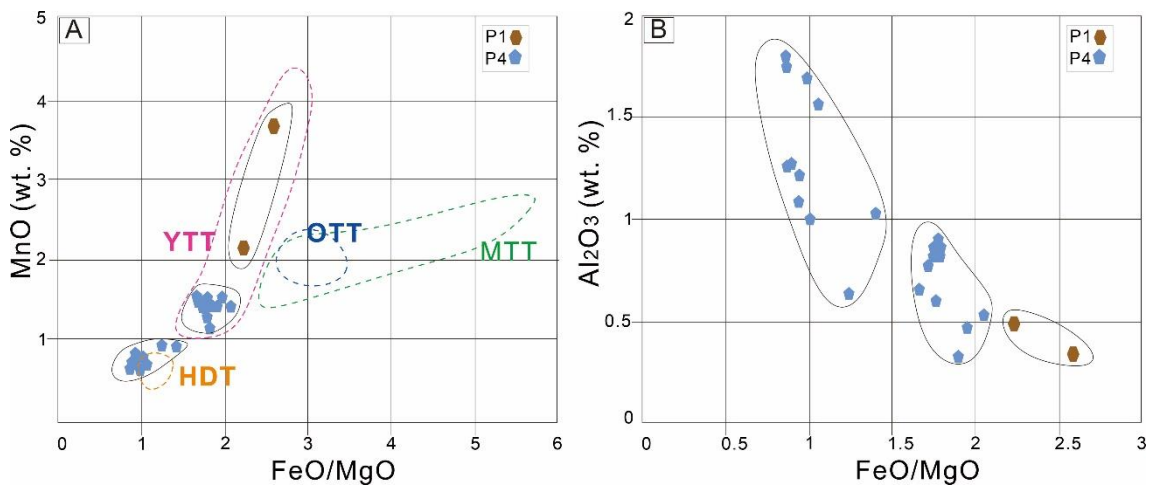


Figure 12. Orthopyroxene compositions of P1 and P4 pumices showing three distinct compositional groups. (A) Plots of FeO/MgO ratios versus MnO contents of orthopyroxene compositions of P1 and P4 pumice showing three distinct compositional groups. The polygons outlined by orange, red, blue and green dashed lines are biotite compositional fields of Harranggaol Dacite Tuff (HDT), Youngest Toba Tuff (YTT), Oldest Toba Tuff (OTT), and Middle Toba Tuff (MTT), respectively, after Chesner (1998). (B) Plots of FeO/MgO versus Al₂O₃.

Table 4. Representative mineral chemistry data of distinct pumice populations of the 74 ka Youngest Toba Tuff.

Sample ID	SiO₂	Al₂O₃	K₂O	CaO	TiO₂	Na₂O	MgO	MnO	FeO	Total	An%	Ab%	Or%	FeO/MgO
Plagioclase crystal														
P11-core	56.07	27.90	0.31	9.76	0.03	5.93	0.02	0.00	0.19	100.24	46.78	51.44	1.78	
P11-rim	60.84	24.23	0.82	5.79	0.01	7.41	0.02	0.06	0.28	99.52	28.69	66.50	4.82	
P12-core	59.50	24.80	0.73	6.88	0.00	7.05	0.00	0.00	0.08	99.03	33.54	62.24	4.21	
P12-rim	60.95	24.62	0.80	6.15	0.00	7.52	0.00	0.00	0.14	100.23	29.71	65.71	4.59	
P13-core	59.83	25.00	0.60	7.89	0.00	7.18	0.02	0.00	0.25	100.80	36.52	60.16	3.32	
P13-rim	61.78	24.46	0.78	5.83	0.06	7.72	0.01	0.06	0.12	100.82	28.12	67.38	4.50	
P14-core	55.17	28.03	0.36	10.55	0.03	5.37	0.03	0.00	0.29	99.84	50.98	46.98	2.04	
P14-rim	56.76	27.20	0.38	10.14	0.04	5.99	0.00	0.04	0.16	100.70	47.32	50.56	2.13	
P15-core	59.47	24.56	0.73	6.27	0.00	7.24	0.00	0.02	0.22	98.53	30.96	64.77	4.28	
P15-rim	60.21	24.36	0.72	6.06	0.07	7.42	0.00	0.04	0.14	99.11	29.81	66.01	4.19	
Biotite crystal														
P1Bt1	35.56	13.11	8.98	0.00	3.35	0.42	8.66	0.65	24.61	95.40				2.84
P1Bt2	35.56	13.35	9.32	0.01	3.79	0.47	9.08	0.43	23.17	95.28				2.55
P2Bt1	35.25	13.15	8.81	0.06	3.67	0.40	8.96	0.62	24.86	95.79				2.78
P2Bt2	36.50	13.46	8.84	0.00	3.69	0.33	8.48	0.57	23.39	95.25				2.76
P4Bt1	35.87	14.54	8.70	0.06	4.08	0.65	10.81	0.17	20.14	95.04				1.86
P4Bt2	36.56	14.79	8.76	0.03	3.90	0.63	10.60	0.14	20.37	95.86				1.92
P5Bt1	35.67	13.64	8.72	0.18	3.52	0.38	8.44	0.57	24.43	95.61				2.89
P5Bt2	36.12	13.90	8.87	0.00	3.27	0.26	7.85	0.44	23.56	94.27				3.00
Amphibole crystal														
P1Amph1	43.63	8.45	0.92	10.38	1.42	1.65	8.73	0.98	22.01	98.21				2.52
P1Amph2	44.58	8.05	0.92	10.72	1.08	1.49	8.39	0.88	21.71	97.88				2.59
P4Amph1	42.23	10.92	0.43	9.99	2.93	2.22	10.39	0.56	18.37	98.02				1.77

P4Amph2	44.47	9.03	0.62	10.24	2.00	1.85	10.41	0.41	18.65	97.78	1.79
Amphibole crystal clots											
P1C- Amph1	43.53	8.72	0.87	10.92	1.54	1.51	9.72	0.58	20.42	97.80	2.10
P1C- Amph2	43.40	8.13	0.76	10.74	1.50	1.34	9.71	0.66	20.04	96.29	2.06
P2C- Amph1	43.74	7.91	1.01	10.61	1.34	1.50	8.94	0.68	21.35	97.17	2.39
P2C- Amph2	43.83	8.39	0.80	10.53	1.36	1.40	8.75	0.82	21.89	97.82	2.50
P4C- Amph1	43.42	8.19	0.78	10.56	1.59	1.47	9.41	0.71	20.99	97.12	2.23
P4C- Amph2	43.25	9.57	0.51	10.42	1.89	1.71	10.37	0.42	18.81	96.96	1.81
Orthopyroxene crystal											
P1Opx1	49.55	0.34	0.00	1.12	0.08	0.06	12.52	3.66	32.41	99.74	2.59
P1Opx2	50.05	0.49	0.06	1.02	0.08	0.05	13.90	2.13	31.01	98.78	2.23
P4Opx1	50.06	0.65	0.00	0.81	0.13	0.00	16.85	1.50	28.11	98.10	1.67
P4Opx2	50.09	0.58	0.00	0.82	0.05	0.00	16.36	1.50	28.99	98.39	1.77
Orthopyroxene crystal clots											
P4C-Opx1	51.99	0.63	0.03	1.67	0.06	0.05	19.93	0.99	24.78	100.13	1.24
P4C-Opx2	52.20	1.21	0.00	1.44	0.19	0.00	22.54	0.82	21.10	99.49	0.94

4.4.5 Glass compositions

The average major and trace element compositions of matrix glass are shown in Table 5. In general, matrix glass of the YTT pumices has a high-silica rhyolite composition, with SiO₂ contents ranging from 76.7 to 77.7 wt.% for P1, 76.8 to 78.5 wt.% for P2, 77 to 78.7 wt.% for P3, and 75.8 to 77.1 wt.% for P4. Binary plots of major element oxides of all pumice types of YTT show no clear trends (Fig.13A-B), except for SiO₂ versus CaO (Fig.13C). The correlation diagram of SiO₂ vs. CaO shows clearly three compositional groups of pumices: the first group, characterized by relatively high CaO contents and lowest SiO₂ contents, is represented by P4 (1.1–1.5 wt.% CaO); the second, group characterized by relatively moderate CaO and SiO₂ contents, is represented mainly by P1 (0.7–1.2 wt.% CaO); and the third group, characterized by lowest CaO contents and relatively higher SiO₂ contents, is represented mainly by P2 and P3 (0.5–0.8 wt.% CaO).

Trace elements analyzed by LA-ICP-MS on matrix glass parts of four pumice types (i.e., P5 pumice type was excluded due to high contents of microlite) included Rb, Sr, Y, Zr, Nb, Ba, Cs, and Hf. Selected element ratios, Sr/Y, Ba/Y, Zr/Y, and Zr/Nb, were used to characterize different pumice populations. Plotted on bivariate diagrams of Ba versus Y (Fig. 13D), Sr versus Y (Fig. 13E), and Ba versus Sr (Fig. 13F), the P1 pumice is characterized by relatively medium Ba and Sr (400 – 875 ppm, and 41 – 67 ppm, respectively), but variable Y contents (20 – 53 ppm); the P2 and P3 pumices, on the other hand, show low Ba and Sr contents (8 –136 ppm, and 13 – 37 ppm, respectively) and highly variable Y contents (27 – 77 ppm); and P4 pumice is characterized by relatively high Ba and Sr (1173 – 1340 ppm, and 95 – 124 ppm, respectively), but a narrow range of Y contents (21 – 31 ppm). Thus, the trace element compositions are clearly correlated

with three pumice populations, which is consistent with the signature in the SiO₂ versus CaO plots. The distinct pumice populations defined by the matrix glass compositions of the four distinct pumices in the proximal area are similar to YTT glass shards compositions in the distal area defined by Pearce et al. (2019; Fig. 13D, E, F). Generally, P1 follows the third population (III), P2 and P3 follow the first population (I), and P4 follows the fifth population (V) defined by Pearce et al. (2019).

Table 5. Average major element and trace element glass compositions of distinct pumice populations of the 74 ka Youngest Toba Tuff.

Major element (wt.%)	P1		P2		P3		P4	
	Av (n:29)	1 σ	Av (n:52)	1 σ	Av (n:41)	1 σ	Av (n:25)	1 σ
SiO ₂	77.13	0.29	77.48	0.36	77.57	0.35	76.31	0.39
TiO ₂	0.05	0.05	0.05	0.04	0.04	0.04	0.12	0.05
Al ₂ O ₃	12.56	0.21	12.34	0.18	12.32	0.22	12.96	0.23
MnO	0.05	0.04	0.07	0.04	0.08	0.04	0.05	0.04
MgO	0.06	0.04	0.04	0.03	0.03	0.03	0.13	0.06
CaO	0.94	0.12	0.69	0.06	0.72	0.06	1.35	0.13
Na ₂ O	3.11	0.12	3.19	0.26	3.09	0.22	3.12	0.12
K ₂ O	5.15	0.24	5.26	0.15	5.29	0.23	4.93	0.14
FeO	0.91	0.14	0.83	0.08	0.84	0.08	1.00	0.14
Trace element (ppm)	Av (n:28)	1 σ	Av (n:86)	1 σ	Av (n:19)	1 σ	Av (n:10)	1 σ
Rb	261.65	64.83	314.8	81.39	318.79	32.65	228.39	14.24
Sr	56.87	5.77	21.85	4.50	21.20	4.09	110.09	9.50
Y	32.87	6.77	45.74	9.12	45.46	5.72	25.41	2.92
Zr	90.30	16.86	76.31	17.4	71.38	12.06	150.11	22.10
Nb	14.89	3.89	19.4	4.52	16.98	7.87	15.35	3.43
Ba	543.25	136.21	79.74	29.38	47.13	19.69	1273.84	62.24
Cs	9.72	4.37	14.48	3.37	11.68	4.00	6.33	2.25
Hf	3.36	2.95	3.10	1.10	2.79	2.44	3.41	1.92
Selected trace element ratios								
Sr/Y	1.73	0.42	0.48	0.13	0.46	0.11	4.33	0.62
Ba/Y	16.53	3.61	1.74	0.63	1.04	0.4	50.13	6.51
Zr/Y	2.75	0.76	1.67	0.36	1.57	0.26	5.91	1.11
Zr/Nb	6.06	1.92	3.93	0.88	4.2	1.86	9.78	3.15

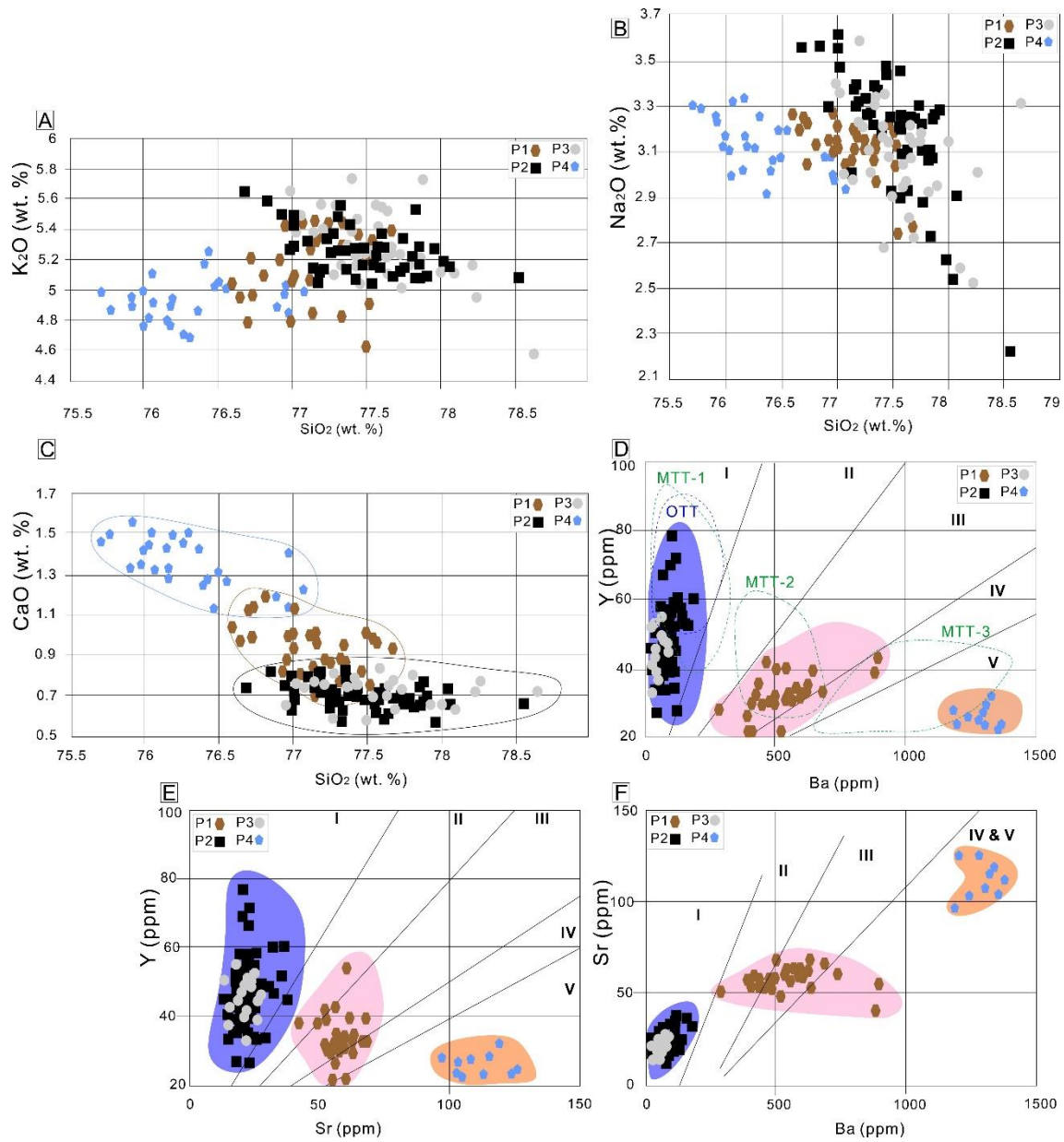


Figure 13. (A-B) Plot of K₂O and Na₂O versus SiO₂ show no clear trends of P1, P2, P3, and P4 glass compositions. (C) Plots of CaO versus SiO₂ defining three distinct populations of P1, P2, P3, and P4 glass compositions. (D) Plots of Ba versus Y (E) Sr versus Y, and (F) Ba versus Sr showing three different populations of glass composition. The roman numerals (I-V) represent five distinct compositions of the Youngest Toba Tuff (YTT) after Pearce et al. (2019), and polygons outlined by blue and green dashed lines indicate the Oldest Toba Tuff (OTT) and Middle Toba Tuff (MTT) glass compositions, respectively, after Pearce et al. (2019).

4.5. Pressure estimation

The glass compositions of P1, P2, and P3 record equilibration of high-silica rhyolite melt with quartz and two feldspars (plagioclase and sanidine) (Table 3), which allow the application of Rhyolite-MELTS (R-MELTS) to constrain the crystallization pressure. Application of quartz + 1 feldspar resulted in wide pressure estimation (Fig. 14A-C), from 95 to 224 MPa (average and standard deviation of pressures: 161 MPa, 36 MPa, respectively) for P1 magma, 94 to 269 MPa (average and standard deviation of pressures: 156 MPa, 61 MPa, respectively) for P2 magma, and 60 to 182 MPa (average and standard deviation of pressures: 108 MPa, 32 MPa, respectively) for P3 magma. In contrast, the application of quartz + 2 feldspars (Fig. 14D-E) resulted in a narrow pressure estimation from 75 to 137 MPa (average and standard deviation of pressures: 115 MPa, 19 MPa, respectively) for P2 magma, and 70 to 138 MPa (average and standard deviation of pressures: 105 MPa, 27 MPa, respectively) for P3 magma. While it resulted only in one data, i.e. 187 MPa, for P1 magma. The average pressures of quartz + 1 feldspar and quartz + 2 feldspars produce values that are not much different, however, based on the abundance of quartz, sanidine, and plagioclase phases in the P1, P2, and P3 (Table 3), the pressures from quartz + 2 feldspars are more reliable for P2 and P3 magmas, and quartz + 1 feldspar for P1 magma.

Pressure estimation by orthopyroxene-liquid barometer, specifically global calibration for felsic liquid (Putirka, 2008) was conducted for P1 and P4. Based on its composition, orthopyroxene is classified into 3 groups (Fig. 12). The calculated pressures for the first group of orthopyroxene in P1 pumice resulted in 121 MPa and 157 MPa, respectively. Meanwhile, the application of the orthopyroxene-liquid barometer resulted in a wide range of pressure, from 129 MPa to 229 MPa (average and standard deviation

of pressures: 194 MPa, 34 MPa, respectively) for the second group of orthopyroxene in P4 magma (Fig. 14F), and 169 MPa to 445 MPa for the third group of orthopyroxene in P4 magma (Fig. 15A). The test of equilibrium between the orthopyroxene and glass compositions is portrayed in the Rhodes diagram (supplementary material 2). The data of the second type of P4 orthopyroxene fall within the dashed curve, while the data of the first type of orthopyroxene in P1 and the third type of orthopyroxene in P4 are outside the curve, which denotes that only the second group of orthopyroxene equilibrated with the glass compositions.

Assuming that the xenocryst of amphibole is volcanic in origin, the amphibole barometer from Ridolfi et al. (2010) was used to better model the YTT magma system. The calculated pressures for amphibole xenocryst (Fig. 15B, C) range from 138 to 200 MPa (average and standard deviation of pressures: 160 MPa, 17 MPa, respectively) for P1, and 162 - 400 MPa (average and standard deviation of pressures: 279 MPa, 66 MPa, respectively) for P4. The pressure estimation of amphibole xenocryst in P4 (Fig. 15C) clearly shows a higher and wider range of pressure compared to the estimated pressure from the orthopyroxene-liquid barometer of the orthopyroxene type 2 in P4 pumice (Fig. 14F).

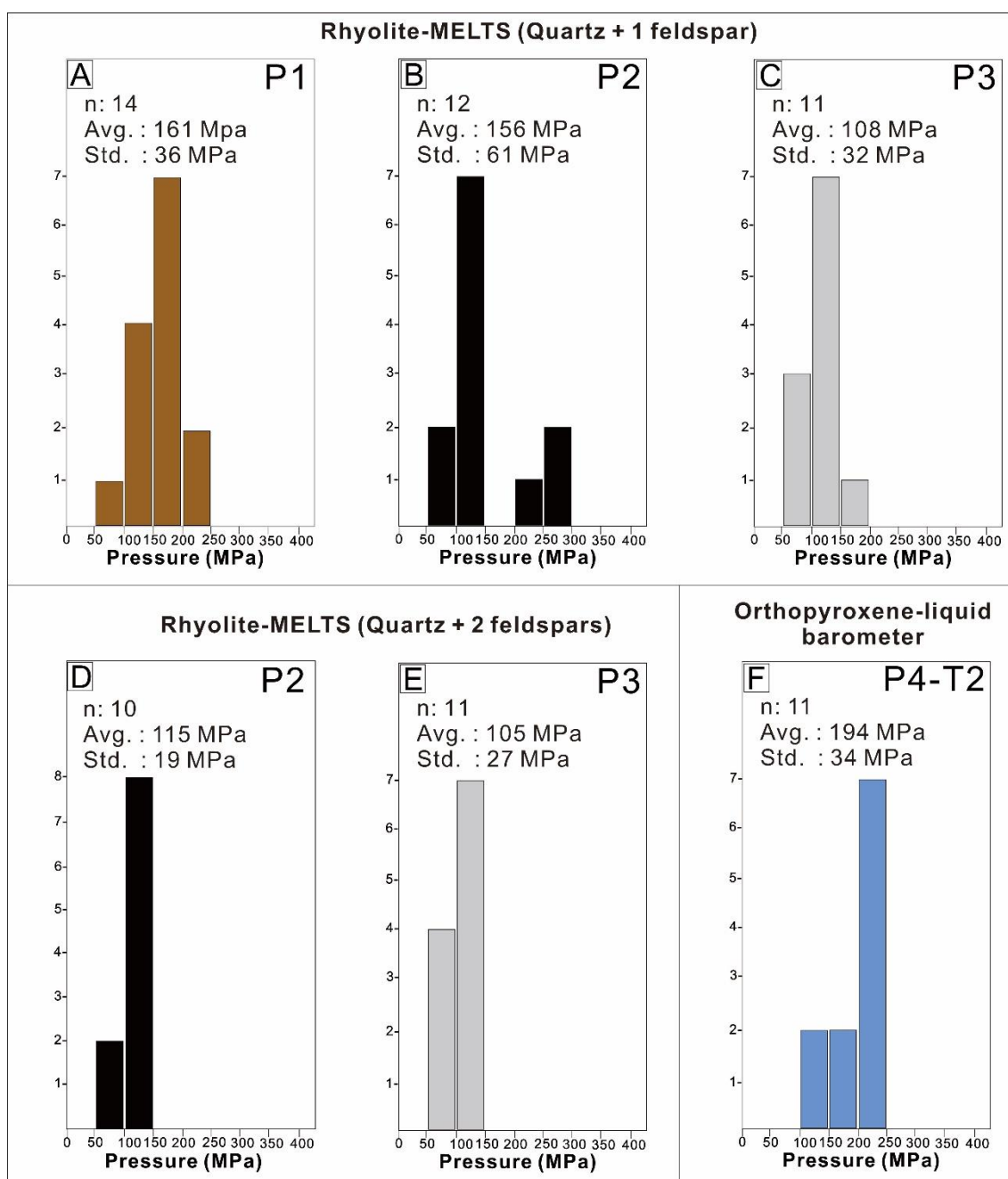


Figure 14. Histograms showing the distribution of estimated pressures calculated using rhyolite-MELTS barometer for P1, P2, and P3 and orthopyroxene-liquid barometer for P4. (A-C) results for the quartz + 1 feldspar using the matrix glass compositions of P1, P2, and P3 pumice, respectively, (D-E) results for the quartz + 2 feldspars using the matrix glass compositions of P2 and P3 pumice, respectively, (F) result for the orthopyroxene-liquid barometer using matrix glass and orthopyroxene compositions of P4 pumice, specifically the compositions of the second group of orthopyroxene.

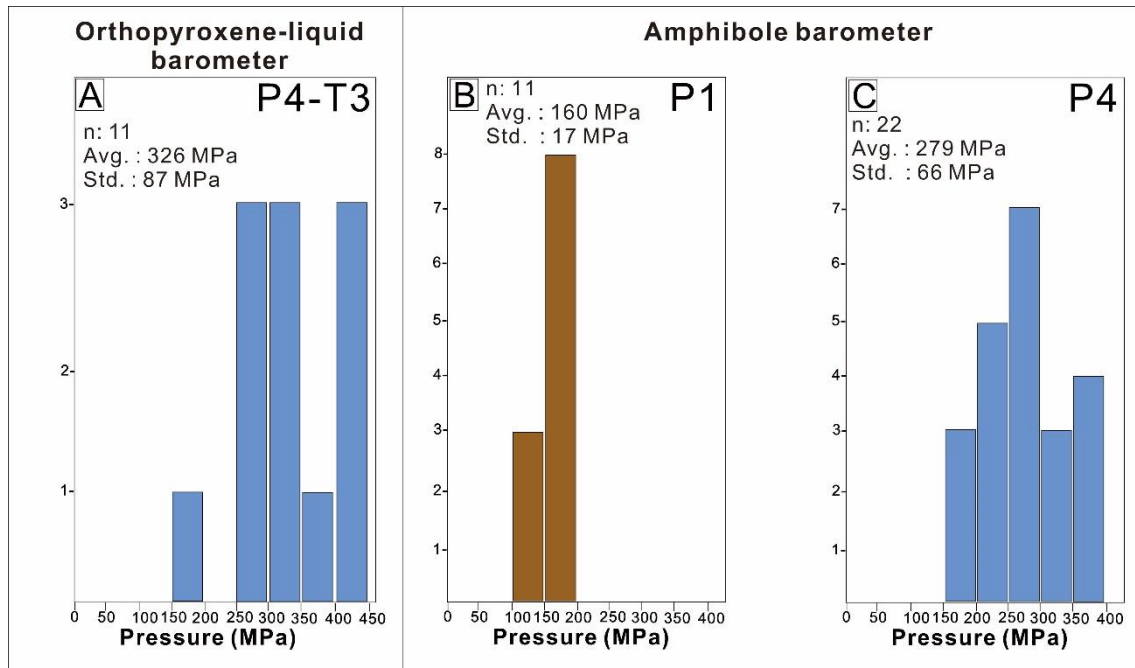


Figure 15. Histograms showing the distribution of estimated pressures calculated using orthopyroxene-liquid barometer and amphibole barometer. (A) result for the orthopyroxene-liquid barometer using matrix glass and orthopyroxene compositions of P4 pumice, specifically the compositions of the third group of orthopyroxene, (B-C) results for the amphibole barometer using the amphibole compositions of P1 and P4 pumice, respectively.

5. Discussion

5.1. Evidences of the 74 ka YTT multiple magma chambers

The proximal non-welded YTT ignimbrite sections allow detailed componentry analyses. Therefore, detailed mineralogical, textural, and geochemical changes of the distinct pumice types along the stratigraphy unit can be recorded. The YTT pumice variations in four eruption units represent the distinct types of magma being evacuated at each eruption phase. In the following subsection several pieces of evidence suggesting that the YTT eruption units did not follow a typical stratified magma chamber model but were evacuated from multiple magma chambers were discussed.

5.1.1. Stratigraphy and chemical compositions

Traditionally, a magmatic system displays a vertical stratification of magma bodies, which is well known as a stratified magma chamber (eg., Suhendro et al., 2021; Kaneko et al., 2007) or compositional zoning magma (eg., Bacon and Druitt, 1988; Milner et al., 2003; Hildreth and Wilson, 2007). The vertical stratification consists of the more mafic and denser material at the bottom of the magma and the more felsic and lower density material at the top (eg., Schmincke, 2004; Bachmann and Huber, 2016; Riehle et al., 1992). When the eruption of a stratified magma chamber occurs, the upper part of the magma chamber, consisting of more evolved magma (SiO_2 -rich), is evacuated first and deposited before the evacuation of the lower part of the magma chamber, composed of less evolved magma (SiO_2 -poor). As the eruption continues, the lower magma chamber will be evacuated and deposited above the previously deposited SiO_2 -rich magma. This results in an inversed stratigraphic sequence in the deposits, consisting of

more evolved materials in the lower units and less evolved materials in upper units of the whole deposits (eg., Schmincke, 2004; Suhendro et al., 2021).

In YTT, the most evolved pumice (P3) was not found in the lower part of the whole deposits in the stratigraphy (Fig. 5C). P3 pumice started occurring in the unit 3. Meanwhile, the least evolved pumice (P4) is found both in the upper stratigraphy (unit 4) and in the middle part of the stratigraphy (unit 2). In addition, distinct pumice types in the same stratigraphic level were found. The occurrence of several pumice types representing distinct chemical compositions throughout the same stratigraphic level suggests simultaneous eruption from multiple magma chambers (e.g., Gravley et al., 2007; Shane et al., 2007; Shane et al., 2008; Begue et al., 2014; Ellis and Wolf, 2012). The distinct chemical compositions of pumice represent different melt regions as part of a complex magma reservoir (e.g., Gravley et al., 2007; Beugue et al., 2014). In the case of 74 ka YTT, the distinct pumice types also have distinct chemical compositions, as clearly showed by the trace element data discussed in the following sections. Thus, the 74 ka YTT caldera-forming eruption is from multiple magma chambers rather than a single stratified magma chamber.

5.1.2. Biotite compositions

Major element compositions of biotite from distinct pumice types show evidence for the involvement of at least two distinct magma types. Biotite in P4 pumice has very distinct compositions (Fig. 10A-B) compared with the biotite from other pumice types. The lower MnO concentration together with the lower ratio of FeO/MgO in P4 biotite may suggest a lower degree of magma differentiation, which is also reflected in the major compositions of P4 magma (Fig. 13A-C, Table 5), and more oxidized conditions (e.g.,

Bell et al., 2017; Abdel-Rahman, 1994) of P4 magma. Melts also may have been oxidized by mixing, assimilation, and degassing during magma ascent (Kelley and Cottrell, 2009; Ueki et al., 2020). Oxide occurs as a phenocryst in P4 pumice (Table 3). In addition, the biotite crystals in P4 pumice host many inclusions of oxide, which may suggest a high degree of oxide fractionation. Furthermore, the occurrence of anomalous crystal clots in P4 may indicate other processes than crystal fractionation, such as mixing (e.g., Forni et al., 2018) and assimilation (e.g., Erdmann et al., 2010; Huber et al., 2011; Reubi and Blundy, 2008).

5.1.3. Trace element matrix glass chemistry

Geochemical signatures of the trace element matrix glass of distinct YTT pumices (Fig. 13D-F) suggest a contrast model for compositional zoning of magma storage; each magma type has independent evolution of trace element compositions, which reflect distinct melt regions with respect to the feldspar fractionation (e.g., Cooper et al., 2011) as explained below. The strong evidence of multiple melt region is indicated by three different trace element populations especially shown by Ba and Sr concentrations: low Ba and Sr (P2 and P3), medium Ba and Sr (P1), and high Ba and Sr (P4).

During the magma crystallization, Sr and Ba are easily incorporated in feldspar phenocrysts as Sr replaces Ca and K in plagioclase and sanidine, respectively, and Ba replaces K only in sanidine, leaving a Sr- and Ba-depleted melt as these phases are crystallized (e.g., Bouseily and Sokkary, 1975). The low Ba and Sr concentrations reflected in P2 and P3 magmas is consistent with the abundant phenocrysts of sanidine and plagioclase in these pumice types. Meanwhile, the P1 pumice is dominated by plagioclase and minor sanidine, which may suggest a relatively lower degree of sanidine

fractionation of P1 magma, compared with P2 and P3 magmas. This is consistent with the medium Ba and Sr contents of P1 magma. On the other hand, the P4 magma is characterized by high concentrations of Ba and Sr, which is consistent with the absence of sanidine.

Although the P2 and P3 magmas are both characterized by low Ba and Sr, the differences in geographical distributions (Table 1), vesicles texture, and the presence and absence of certain phases in P2 and P3 (e.g., presence of skeletal-polyhedral quartz and absence of amphibole+biotite in P3; Table 3), together with different lithic fragments (Fig. 5D) suggest that these magmas came from distinct magma chambers.

5.2. Position of YTT multiple magma chambers

Differences in YTT pumice distributions, glass composition, and mineralogical association may give insight into their position in the crust and the spatial relationship between YTT multiple magma chambers. The depth of magma chamber was calculated using the average of pressures obtained from R-MELTS of Gualda and Ghiorso, (2014) for P1, P2, and P3 magmas, and the orthopyroxene-liquid barometer of Putirka (2008) for P4 magma, assuming upper crust density of 2.7 g cm^{-3} .

5.2.1. Low Ba and Sr magmas (P2 and P3)

The low Ba and Sr magmas in YTT are represented by P2 and P3. The P2 and P3 magmas are characterized by the most but slightly evolved pumices, with 77.5 and 77.6 wt.% on average of SiO_2 content of the glass, respectively, and abundant unzoned plagioclase texture (Fig. 7B). Modelling of crystal fractionation predicts that magma stored in the upper crust, which is highly enriched in plagioclase, is characterized by high

SiO₂ and lower Sr concentrations in the melt compositions (Halliday et al., 1990; Parmigiani et al., 2016). The pressure estimation from quartz + 2 feldspars yields 115 MPa and 105 MPa, corresponding to 4.3 km and 4 km depth for P2 and P3 magmas, respectively. Thus, the P2 and P3 chambers are classified as shallow magma chambers.

P2 and P3 pumice have different geographical distributions. P2 was spread in all caldera directions, and the first occurrence of P2 was in unit 1, which is restricted in the northern region, while P3 is limited only in unit 3 in the southern region (Fig. 5B). Based on the first occurrence and the distribution of P2 and P3, P2 magma might have been accumulated in a relatively northern region. On the other hand, the P3 magma chamber is located relatively in the southern region (Fig. 16).

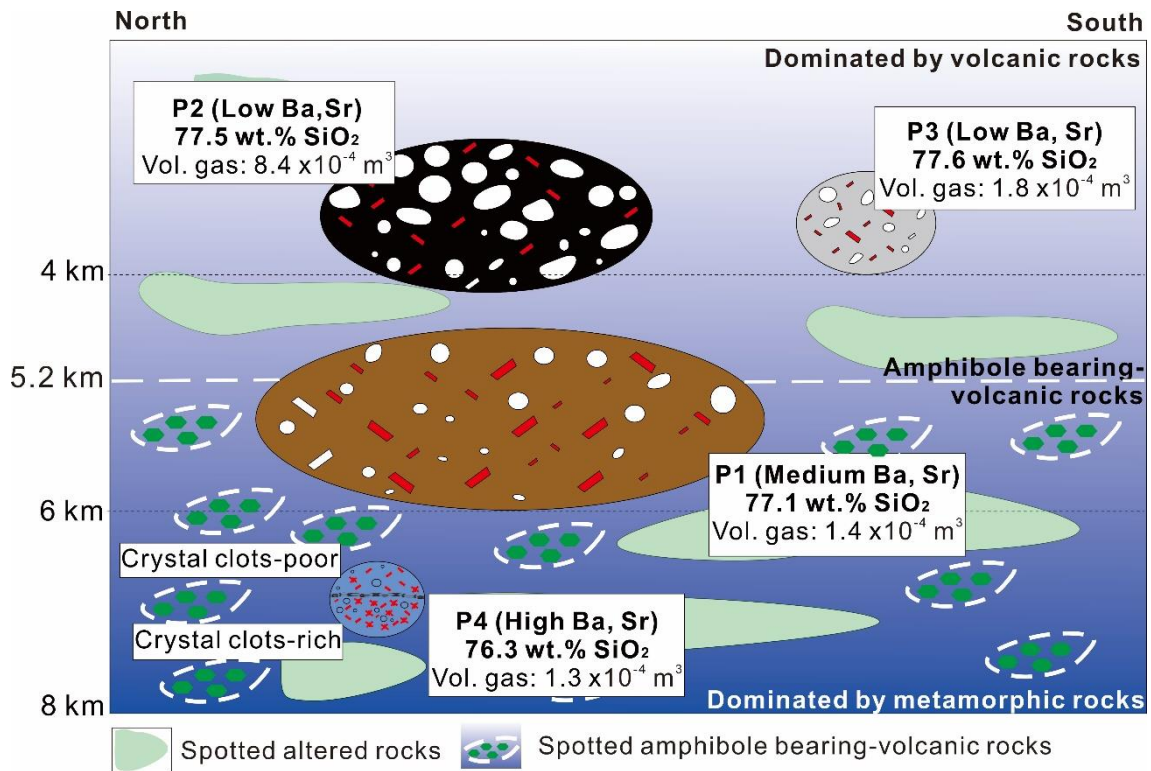


Figure 16. The YTT pre-eruptive magma chambers. Distinct magma bodies are found at different depths and pressure, estimated from the R-MELTS of Gualda and Ghiorso (2014) for P1, P2, and P3 magmas, respectively, and the orthopyroxene-liquid barometer of Putirka (2008) for P4 magma. Volcanic rock and metamorphic rock are illustrated based on the geological profile from geological maps of Toba Caldera (sheets of Pematangsiantar (Clarke et al., 1982) and Sidikalang (Aldiss et al., 1983)), while spotted altered rocks are illustrated based on the presence of altered rocks from the component analysis. The depth of amphibole bearing volcanic rocks was inferred by the results of the amphibole barometer of Ridolfi et al. (2010). See text for discussion.

5.2.2. Medium Ba and Sr magma (P1)

The medium Ba and Sr magma in YTT is represented by P1 magma. P1 magma is more evolved than P4 magma, but less evolved than P2 and P3 magmas (Table 5, Fig. 13A-C). The pressure estimation of P1 magma from quartz + 1 feldspar yielded 161 MPa, equivalent to 6.1 km depth. Together with the P2 pumice, P1 pumice also first occurred in unit 1 in the northern region (Fig. 5A) implying that P1 lies relative to the north, beneath the P2 magma chamber (Fig. 16).

Amphibole is ubiquitous in P1 pumice; it is present as a single crystal and also as a part of crystal clots. However, amphibole in YTT is xenocryst in origin, Ar-Ar age dating of amphibole xenocrysts in YTT pumice yielded an age of about 1.5 Ma (Gardner et al., 2002). Amphibole xenocrysts could be relicts from wall rock and merge in the magma during magma ascent (e.g., Shane et al., 2005; Gansecki et al., 1996). The pressure estimation of amphibole xenocryst using the amphibole barometer from Ridolfi et al. (2014) resulted in a narrow pressure range from 138 to 200 MPa, corresponding to 5.2 – 7.6 km formation depth, which indicates that the amphibole comes from volcanic wall rocks within that range of depth.

The lithic fragment of igneous rock in non-welded YTT ignimbrite consists of lava, andesite, and welded ignimbrite. Amphibole is commonly found in andesite, suggesting that andesite could be one of the sources of amphibole in the YTT magma system. The andesite lithic varies in texture from porphyritic (Fig. 17 A-B) to aphanitic texture (Fig. 17 C-D). Chesner, 2012 mentioned that the oldest volcanic rocks exposed in the caldera walls consist of andesite and basaltic andesite. The K-Ar dating of these rocks yields 1.2 Ma (Yokohama and Hehanussa, 1981). This age is similar to the age of the amphibole xenocryst in YTT pumice. In addition, the geological maps of Toba Caldera, specifically sheets of Pematangsiantar (Clarke et al., 1982) and Sidikalang (Aldiss et al., 1983), show that andesite in Toba comes from various volcanic activities with the age ranging from Pleistocene to Miocene.

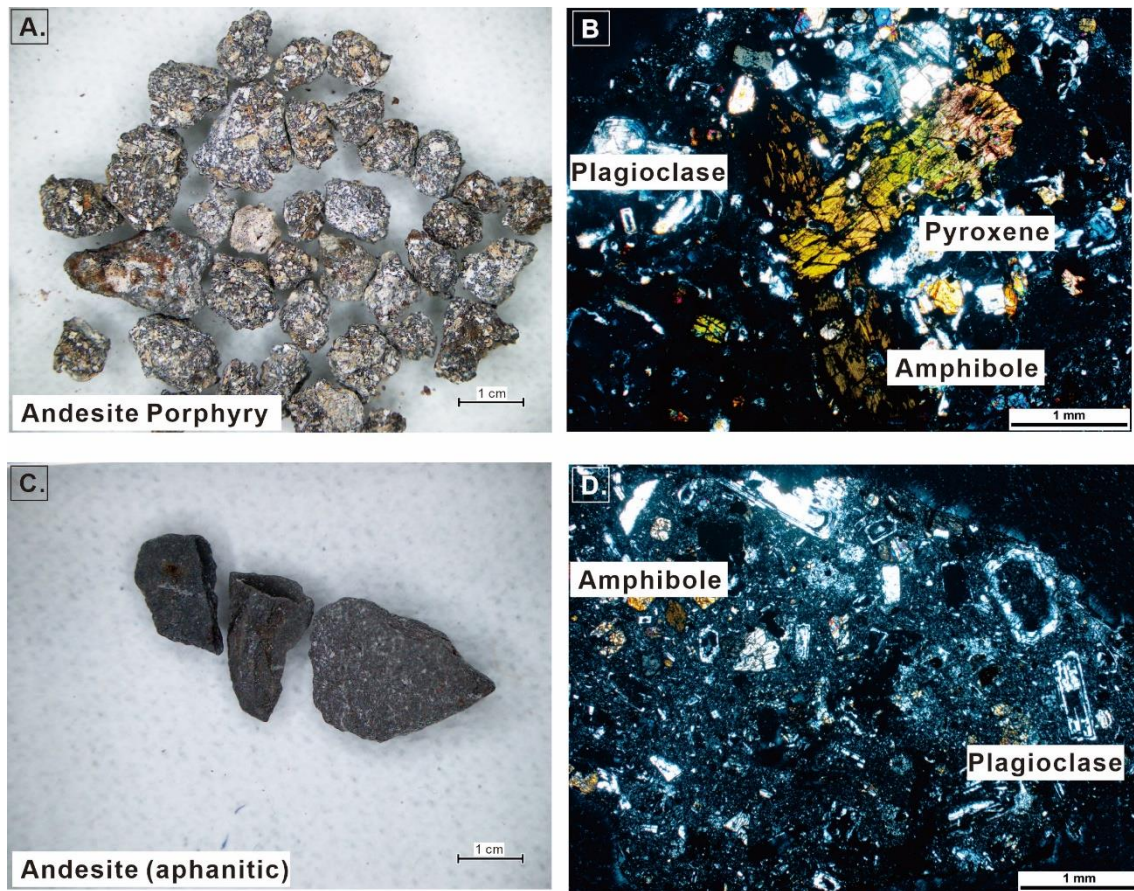


Figure 17. The fragment of andesite in non-welded YTT (A) Lithic fragment of andesite porphyry in non-welded YTT ignimbrite, (B) thin section image of andesite porphyry. (C) Lithic fragment of andesite in non-welded YTT ignimbrite, (D) thin section image of andesite showing aphanitic texture.

5.2.3. High Ba and Sr magma (P4)

High Ba and Sr magma is reflected in least evolved P4 magma, which is free of quartz and sanidine. P4 magma is heterogeneous, which is clearly illustrated by the sharp boundary between the two domains in the pumices of this type (Fig. 6D). The first domain is a crystal clots- and a pheno-vesicle-rich region, and the second domain is a crystal clots- and a pheno-vesicle-poor region. The heterogeneity of P4 magma indicates the occurrence of layered magma chamber. However, in the most cases of layered magma in large silicic system, the heterogeneity is caused by chemically distinct magmas (e.g.,

Shane et al., 2007; Kaneko et al., 2007; Smith et al., 2005). Contrastingly, no chemical distinction between the two parts of P4 magma. The layering of magma in P4 may indicate the melt extraction from crystal mush (e.g., Beugue et al., 2014; Ellis et al., 2014, Girard and Stix, 2009).

The first occurrence of P4 pumice was in unit 2 in the northern region as a minor component, associated with the P1 and P2 pumices (Fig. 5A), indicating that P4 is also located relative to the north. Test of equilibrium using Rhodes diagram (supplementary material 2) indicates that the second group of orthopyroxene in P4 pumice is phenocryst, while the third group of orthopyroxene is probably xenocryst in origin. The pressure estimation of the second group of P4 magma from the orthopyroxene-liquid barometer of Putirka (2008) yielded 194 MPa, which is equivalent to a depth of 7.3 km, suggesting that P4 was the deepest chamber of the YTT magma system (Fig. 16).

Similar to P1, amphibole is also ubiquitous in P4 pumice. However, the composition of amphibole crystals in P4 and P1 pumices is different (Fig. 11). The pressure estimation of amphibole xenocryst in P4 resulted in a wide pressure range from 162 to 400 MPa, or equal to 6.1 – 15.1 km formation depth, which indicates that the amphibole xenocryst in P1 and P4 probably came from different volcanic rocks at various depths, and merged during magma ascent (e.g., Shane et al., 2005; Gansecki et al., 1996).

5.3. Volume of distinct YTT magmas

The number of fractions of glass shards and pumices ($\emptyset$ GP) with identical trace element signatures can be used to estimate the volume fraction of each magma type. The available data on the proportion of YTT glass shards in the distal area from Pearce et al. (2019) and our componentry data were combined to calculate the $\emptyset$ GP fraction. Pearce et al. (2019) found five types of magma based on the trace element compositions, namely PI, PII, PIII, PIV, and PV. Low Ba and Sr (PI), medium Ba and Sr (PIII), and high Ba and Sr (PV) magma in Pearce et al. (2019) are highly correlated with P2 and P3 pumices, P1, and P4 pumices, respectively (Fig. 13D-F). In this study, pure pumice correlated with PII and PIV magma was not found, but it is likely that the compositions of PII and PIV magmas were recorded in some P1 pumice (Fig. 13E-F). In addition, no matrix-glass chemistry analysis was conducted on P5 pumice due to abundant microlite (Fig. 6H). To quantify the fraction of pumice ($\emptyset$ P) and glass shard ($\emptyset$ G), the proportion of pumice and glass shard were normalized to 100 % (Table 6), excluding the proportion of P5 for each pumice fraction, and the proportion of PII and PIV after Pearce et al. (2019) for the glass shard fraction. The approximate volume of the magma chamber was calculated from the 4161 DRE km³, excluding 1139 km³ from the unfound populations in this study (PII and PIV after Pearce et al., 2019) of 5300 km³ of total YTT magma after Costa et al. (2014).

Low Ba and Sr magma is represented by two different types of pumices which come from different chambers, namely P2 and P3 magma. Pearce et al. (2019) reported that there was only one chamber of low Ba and Sr magma because their study was based solely on distinct trace element compositions of glass shards without characterization of the pyroclast (i.e., color, mineralogy, mineral chemistry, and textural). In fact, the low Ba

and Sr glass shard composition found in the distal area could have come from two low Ba and Sr magma chambers (P2 and P3 magmas). The glass shard fraction in the distal region representing two different magmas was calculated by assuming that the pumice fraction in the proximal area is equal to the glass shard fraction in the distal region. The fractions of P2 and P3 pumices in the proximal area are 0.169 and 0.045, respectively. Meanwhile, the total fraction of low Ba and Sr glass shard in the distal area is 0.494, resulting in the fractions of glass shard of 0.39, and 0.104 for P2 and P3 magma, respectively (Table 6). Given these values, the ØGP of P2 is 0.279 (1162.5 km²), and ØGP 0.074 (309.7 km³) for P3.

Table 6. The volume of each magma chamber estimated by the fractions (ØGP) of distinct glass shards after Pearce et al. (2019) and pumices from this study with the same trace element signatures. Magma volume is calculated from the 5300 km³ estimate for DRE of the Youngest Toba Tuff (YTT) after Costa et al. (2014), excluding the unfound glass populations in this study (PII and PIV after Pearce et al. (2019)).

Trace element population	ØP (Proximal pumices)		ØG (Distal glass shards)		ØGP	Volume (km ³)
	This study	Normalized	Pearce et al., 2019	Normalized		
Low Ba, Sr	0.16 (P2)	0.169	0.366 (PI)	0.390	0.279	1162.5 (P2)
	0.04 (P3)	0.045		0.104	0.074	309.7 (P3)
Medium Ba, Sr	0.73 (P1)	0.777	0.331 (PIII)	0.451	0.614	2554.9 (P1)
High Ba, Sr	0.01 (P4)	0.009	0.037 (PV)	0.05	0.030	122.7 (P4)

Medium Ba and Sr together with high Ba and Sr magmas are represented by P1 and P4 pumices, respectively. P1 pumice is the most dominant pumice in the proximal area. In contrast, P4 is the minor component. The fractions of P1 and P4 pumices in the proximal area are 0.777 and 0.009, respectively. Meanwhile, the glass shard fractions of

medium Ba and Sr magma and high Ba and Sr magma in the distal region are 0.451 and 0.05, respectively. Given these values, the ØGP of P1 is 0.614 (2554.9 km²), and the ØGP of P4 is 0.03 (122.7 km³).

The most common method for estimating the volumes of distinct magma chambers based on total erupted magma is to use the proportions of distinct juvenile types (e.g., Cooper et al., 2011; Pearce et al., 2019). However, error estimation from the standard deviation of sample distribution cannot be used due to the nature of pyroclastic density current (PDC). PDCs can be distributed and deposited anywhere, depending on the geographical morphology and location of magma and vents which rejects the assumption that the same type of pumices is expected to have the same proportions in PDC deposits in the different locations in the proximal region. In addition, for the case of the 74 ka YTT, there are several factors that contribute to the uncertainty of the estimated volume, including:

1. The 74 ka YTT ignimbrite consists of both non-welded and welded deposits (Fig. 1A). The welding process modifies the texture of the crystals and vesicles which would make the identification of pumice type, especially P2 pumice, impossible by macroscopic observation. Thus, the fraction of distinct pumice types can only be calculated from the componentry data of the non-welded samples.
2. Glass shards in the distal region are believed to be co-ignimbrite plume material transported by wind (Pearce et al., 2019; Lane et al., 2013). The currently available proportions of chemically distinct glass shards data, both from drill core and surface data, are generally concentrated in southwest regions such as India, the Arabian Sea, and Malaysia (Pearce et al., 2019). Furthermore, previous researchers reported that YTT glass

shards also were distributed to the northwest region like China, and west direction for example at Lake Malawi, Africa (Rose and Chesner, 1990; Lane et al., 2013, Matthews et al., 2012). Moreover, based on isopach map modeling from Costa et al., 2014 showed that YTT ash was widespread in various other areas that had never been studied.

5.4. Volume of gas in YTT magma chambers

The volume of gas recorded in pumice after fragmentation in the atmosphere is expressed as pheno-vesicularity. Assuming an ideal gas equation state, the average pheno-vesicularity data was used to calculate the volume of gas in the magma chamber at a given pressure. The pheno-vesicularity (ϕ_{PV}^*) recorded in pumice after fragmentation occurs at atmospheric pressure; it is equivalent to the volume of gas in the pumice divided by the total melt and gas volume. With these assumptions, the volume of gas in the magma chamber (V_C) can be calculated using the following equations:

$$P_a V_g = P_c V_C \quad (5.1)$$

$$\phi_{PV}^* = \frac{V_g}{(1 + V_g)} \quad (5.2)$$

$$\phi_{PV}^* + \phi_{PV}^* V_g = V_g \quad (5.3)$$

$$V_g = \frac{\phi_{PV}^*}{(1 - \phi_{PV}^*)} \quad (5.4)$$

$$V_C = \frac{P_a V_g}{P_c} \quad (5.5)$$

Where P_a and P_c are the atmospheric pressure (0.1 MPa) and the average of pressures of each magma chamber, respectively. ϕ_{PV}^* is the average pheno-vesicularity (phenocryst and matrix-vesicle free) from the textural analysis (Equation 3.1). V_g is the volume fraction of gas in the pumice at atmospheric pressure. Equation 5.1. is an

isothermal condition equation state, this equation provides an approach to see how the pressure and volume of gases in magma are related. Simply, the lower the pressure, the bigger the gas volume, and vice versa. When magma is deep in the crust, pressure on it from all the overlying rock (confining pressure) is high. As magma rises up to the surface, the pressure is progressively decreased. Equation 5.2 is the transformation of the volume fraction of total gas in pumice with the total melt and gas at atmospheric conditions; one (1) refers to the total melt volume in cubic meters. Equation 5.3 is the transformation of equation 5.2. Equation 5.4 is the transformation of equation 5.3, the V_g represents the cubic meter of gas within the melt volume of 1 cubic meter. Equation 5.5 is the substitution of the first equation.

Input parameters and calculated volume of gas in each magma chamber can be seen in Table 7. P2 magma has the most abundant gas in the chamber ($8.4 \times 10^{-4} \text{ m}^3$) within the melt volume of 1 cubic meter, while P1, P3, and P4 magmas are relatively gas-poor ($< 2 \times 10^{-4} \text{ m}^3$). The abundant amount of gas in the P2 magma chamber is responsible for a very distinct vesicle texture of P2 compared to other YTT pumices.

Table 7. Input parameters and calculated volume of gas (V_c) in each magma chamber. The calculation of gas volume in magma chamber is based on the assumption of an ideal gas equation state. The average pheno-vesicularity of each magma chamber was derived from textural data (Table 2), average pressures estimation (P_c) from R-MELTS of Gualda and Ghiorso (2014) for P1, P2, and P3 magmas, and orthopyroxene-liquid barometer of Putirka (2008) for P4 magma (section 4.5).

Type	Average ϕ_{PV}^*	V_g (m^3)	P atm (MPa)	P chamber (MPa)	V_c (m^3)
P1	18.58%	0.23	0.1	161	1.4×10^{-4}
P2	49.24%	0.97	0.1	115	8.4×10^{-4}
P3	16.15%	0.19	0.1	105	1.8×10^{-4}
P4	19.60%	0.24	0.1	194	1.3×10^{-4}

5.5. Eruption mechanism of the 74 ka YTT super eruption

5.5.1. The initial eruption triggers

The lowest stratigraphy of the 74 ka YTT is represented by unit 1 in the northern region, specifically in the Haranggaol area (Fig. 5C). This unit is suggested to be the initial phase of the eruption characterized by abundant P2 pumice and lithic, and subordinate P1 pumice. The vesicle texture of P2 pumice (Fig. 6F, Table 2) rich in pheno-vesicle (49.2 % on average of pheno-vesicularity) suggests magma chamber overpressure (e.g., Toramaru, 2022; Suhendro et al., 2022; Hupper and Woods, 2002), leading to the evacuation of mostly P2 magma in the initial phase.

Unit 1 as the initial phase is also supported by Knight et al. (1986) findings that in the Haranggaol area, the MTT deposit was in contact with the YTT deposit with similar characteristics to unit 1 (rich in pumice with large vesicles and lithic). Moreover, the eruption ages of YTT derived from U-Th and (U-Th)/He age dating of zircon (Mucek et al., 2017) showed a slightly older eruption age for the northern region (79.5 ± 5.5 ka) than the eruption of YTT in the south (78.1 ± 5.8 ka) which implies that the 74 ka Toba eruption began from a vent located in the northern part of the caldera (Fig. 18A).

5.5.2. Multiple magma chambers eruption

Overpressure of magma chamber causes a fissure in surrounding rocks and triggers the eruption (Tait et al., 1989, Toramaru, 2022, Suhendro et al., 2022) leading to the formation of volcanic vents, as implied by the abundance of lithic in the early phase of caldera-forming eruption (e.g., Vinkler et al., 2012; Simmons et al., 2017; Pittari et al., 2008). The altered and volcanic lithic in unit 1 (Fig. 5D) indicates vent derived of pre-

volcanic rocks including erosion of lithic from depths near the bottom part of the P2 magma chamber and roof of the P1 magma chamber (Fig. 18A).

The vertically adjacent position of the magma chambers (Fig. 16) facilitates the formation of two types of conduits during the eruption. The first type is the conduit that evacuated one type of magma and the second type is the hybrid conduit that evacuated the different magma types, simultaneously. P2 is the most abundant component in the lowest stratigraphy of the whole deposits (unit 1), while P1 is subordinate (Fig. 5C). P2 magma was intensively evacuated by the first type of conduit in the initial phase, while P1 magma was evacuated by the hybrid conduit, which formed due to the rupture of P2 magma (Fig. 18A).

Since P2 is the second voluminous chamber (Table 6), the eruption of P2 magma triggered other magma chambers to erupt simultaneously with the development of a new and wider conduit in the middle phase, represented by the variation of lithic and pumice in the units 2 and 3. The development of new and wider conduit could have enhanced the formation of various wall-rock fractures indicated by the increasing proportion of fresh volcanic lithic in the middle phase of the eruption (Fig. 5D).

The early middle phase corresponds to the eruptions of P1, P2, and P4 magmas, depositing the unit 2 in all caldera directions (Fig. 18B). As time passes, the eruption continues to evacuate P3 magma locally in the southern region (Fig. 18C). The other magma chambers also reached their critical condition to erupt due to the proximity of each chamber. In addition, the occurrence of ubiquitous crystal fractures in YTT phenocryst (Fig. 6A), polyhedral-skeletal quartz in P3 pumice (Fig. 6C), and complex plagioclase texture in P4 pumice (Fig. 7A6) indicate strong undercooling due to sudden

disequilibrium (e.g., Barbee et al., 2020; Giacomoni et al., 2014) in consequence of the simultaneous magma chambers eruption. Similar simultaneously multiple eruptions from distinct magma chambers were reported in other super eruptions such as the 1 Ma Kidnappers (Cooper et al., 2011) and 240 ka Taupo eruption (Gravley et al., 2007).

The abundance of P1 pumice in the middle stage (Fig. 5C) indicates that the eruption of P1 magma was dominant in this phase. Nonetheless, P4 magma also erupted, but due to the relatively deeper position of the chamber most likely some amount of magma could not be erupted but instead sank due to massive caldera collapse (e.g., Simmons et al., 2017). The final phase of the eruption was marked by the evacuation of mostly remaining P1 magma (Fig. 18D) and evacuation of altered lithic (Fig. 5D), which indicates the deeper evacuation of magma as the final phase of YTT caldera-forming eruption.

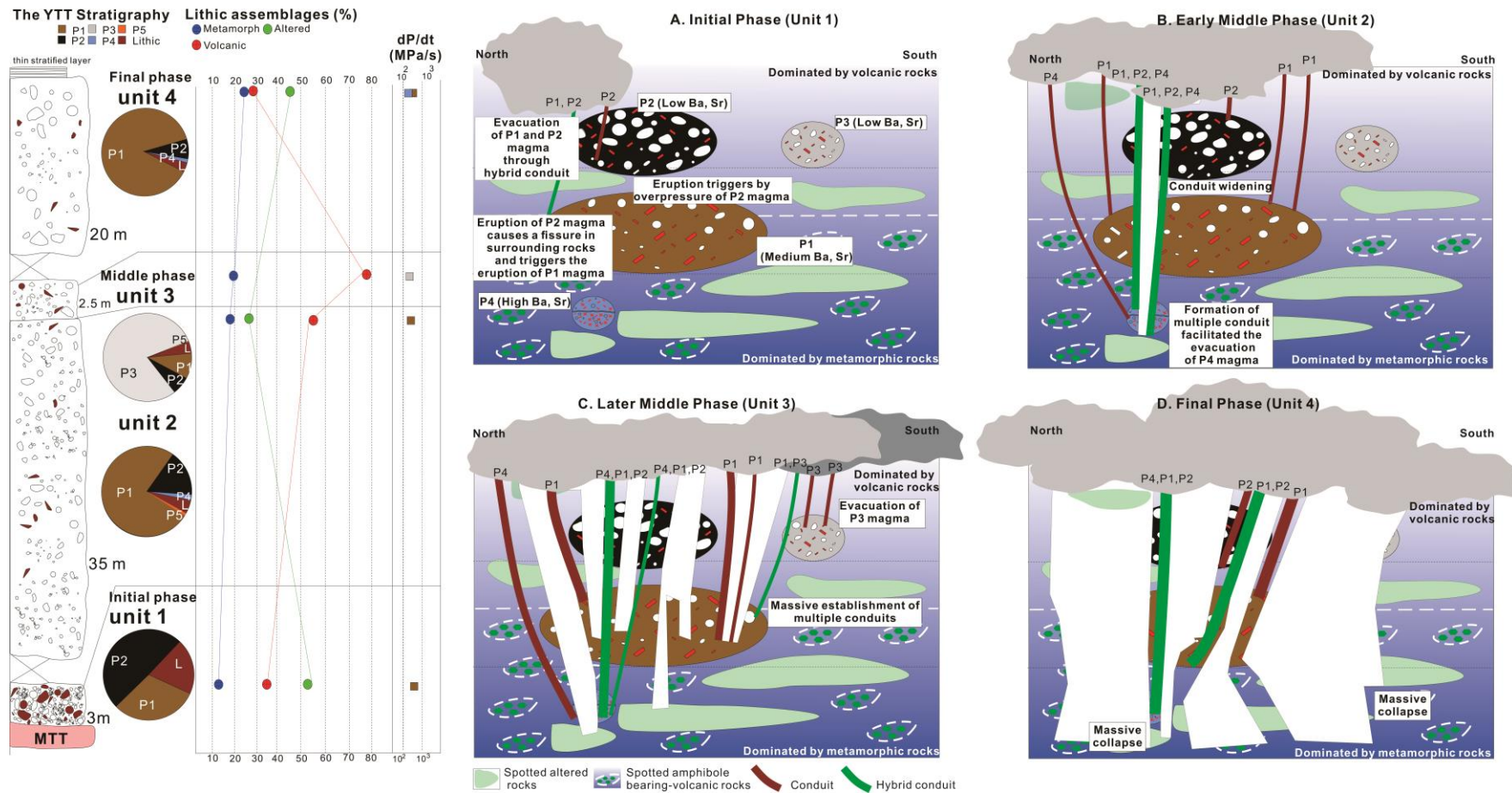


Figure 18. Schematic diagrams showing the (A) the initial phase (B) early middle phase, (C) later middle phases, and (D) final phases of the 74 ka Youngest Toba Tuff magma system. Vertical and horizontal scales are approximate only, to be consistent with the estimated volumes erupted of the respective magma types. See text for discussion.

5.5.3. Magma decompression rate of the 74 ka YTT eruption

The plots in Fig. 8E show a negative correlation between MVND and PVND and a higher MVND for pheno-vesicle-poor magma. While pheno-vesicle-rich magma is characterized by relatively lower MVND. The lower the PVND in pheno-vesicle-poor magma (P1, P3, and P4) results in a higher decompression rate due to the effective formation of matrix-vesicle. Furthermore, in the pheno-vesicle-rich magma (P2), the high PVND value prevents the second nucleation, resulting in relatively lower decompression. Toramaru (2014) explained that the presence of pheno-vesicle prevents the formation of matrix-vesicle by the second nucleation due to the increase in total surface area and depletion of gases in the melt.

The negative correlation between PVND and decompression rate of pheno-vesicle-poor magma is also shown in other silicic calderas, for example in Maninjau (Suhendro et al., 2022). The 52 ka Maninjau caldera-forming eruption produced crystal poor white rhyolite pumice. From the vesicle texture, the pumices were classified into two categories namely transparent white pumice (TWP) and non-transparent white pumice (NTWP) pumice (Suhendro et al., 2022). From the vesicle texture, the transparent pumice has a similar characteristic to the P2 pumice in this study, while the NTWP pumice looks like P1 pumice. However, at 52 ka Maninjau caldera-forming eruption, pheno-vesicle-rich pumice and pheno-vesicle-poor pumice were produced by the same magma chamber, namely the white magma chamber; the pheno-vesicle-rich pumice represent the upper magma, while the pheno-vesicle-poor pumice came from the lower magma chamber. In contrast with the 74 ka YTT magma system, the pheno-vesicle-rich and pheno-vesicle-poor magma represent different magma bodies (Fig. 16).

Suhendro et al., 2022 showed that the MVND value of pheno-vesicle-rich magma could not be used as an index of magma decompression because matrix-vesicle nucleation was hindered by the abundance of pheno-vesicles. Therefore, the dynamics of magma decompression rate from the initial phase to the final phase of YTT eruption were only presented by the decompression rate estimation of pheno-bubble poor magma. The decompression rate showed relatively same value through the eruption phases, i.e. $> 10^2$ MPa/s (Fig. 18). Furthermore, the magma decompression rate of the 74 ka YTT eruption is higher than other crystal-rich rhyolite eruptions (Fig. 19). A high decompression rate leads to strong fragmentation of the melt within the conduit producing very explosive eruption during the 74 ka YTT eruption.

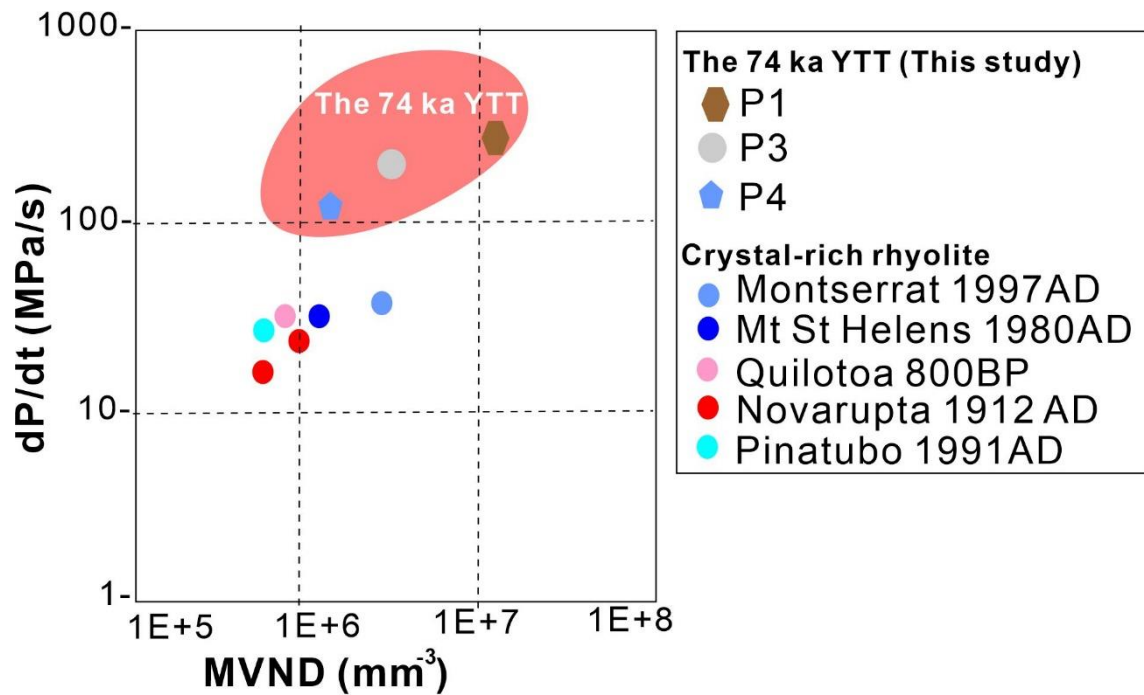


Figure 19. The use of MVND to estimate decompression rate from pyroclast. The magma decompression rate values were obtained using a homogenous nucleation assumption. The decompression rate estimation of the 74 ka YTT eruption is higher than other crystal-rich rhyolite eruptions (data from crystal-rich rhyolite were taken from Shea, 2017).

5.5.4. Conduit mixing

The major element compositions of P1 overlap with those of P2, P3, and P4 magmas (Fig. 13A-C). In addition, the trace element study conducted by Pearce et al. (2019) reported the presence of hybrid pumice containing two compositions in some YTT pumices, mostly a combination of medium Ba and Sr and high Ba and Sr compositions, and some combinations of compositions medium Ba and Sr and low Ba and Sr. The overlapping of magma compositions and the occurrence of hybrid pumice indicate syn-eruptive conduit mixing, which facilitated the evacuation of different magma types simultaneously (e.g., Wada, 1992; Blake and Campbell, 1986; Collins et al., 2000). Koyaguchi, (1975) proposed that conduit mixing can occur during a sudden decompression, which also results in the formation of many fractures that act as pathways for magma to rise to the surface, such a way that magma can overturn turbulently and mix in the conduit.

The conduit mixing may also be responsible for the occurrence of xenocryst in P1, P2, and P4 pumices. Xenocrysts in P1, P2, P4 pumices were likely incorporated from the conduit wall due to conduit mixing during the eruption. Crystal transfer from different frameworks due to conduit mixing also occurs in other eruptions such as during the 27 ka Oruanui eruption from Taupo Volcanic Zone (Allan et al., 2012), the 13.4 Ma Gran Canaria Ignimbrite (Sumner and Wolf, 2003), and the 2001-2007 eruption of Soufrière Hills volcano, Montserrat (Humphreys et al., 2009).

5.6. Comparison with other eruptions of multiple magma chambers

Eruptions of multiple magma chambers were also reported for several caldera-forming eruptions around the world (Table 8). Table 8 summarizes the main evidence, characteristics, and potential eruption triggers of multiple magma chambers around the world. In general, multiple magma chambers are revealed by the presence of distinct juveniles with different chemical compositions (Gravley et al., 2007; Beugue et al., 2014; Cooper et al., 2011; Reuby and Nichols, 2005; Papalardo et al., 2002; Pabst et al., 2007). Moreover, multiple magma chamber systems have a wide range of chemical compositions, from andesite to rhyolite, indicating that multiple magma chambers occur regardless of magma composition.

Multiple magma chambers system around the world occurs at a relatively shallow depth (< 7.5 km; Table 8), which indicates that the shallow region is more favourable for hosting multiple magma chambers. This is because, at shallower depths (above the brittle-ductile transition), several fractures are formed in crust due to its brittle behaviour (e.g. Parisio et al., 2019), providing thus favourable conditions for magma migration and accumulation. In addition, the occurrence of pheno-vesicle rich magma in the 74 ka YTT and 52 ka Maninjau magma system is associated with the vertical position of distinct magma bodies, whereby the pheno-vesicle rich magma is placed in the shallowest position. The vertical position and the brittle condition in the shallow regions may facilitate the migration of volatiles from a deeper magma chamber to a shallower magma chamber.

Caldera-forming eruptions are caused by internal and external triggers. Internal triggers occur due to overpressure and mafic recharge, while external triggers are caused by tectonic activity (Cashman and Giordano, 2014). Both internal and external triggers

could facilitate eruptions of multiple magma chambers (Table 8). The juvenile materials of the 74 ka YTT eruption and other calderas in Sumatra (i.e. Maninjau and Ranau) consist of pheno-vesicle-rich pumice. Pheno-vesicle-rich pumice, both from YTT and Maninjau, are abundant in the lower stratigraphy indicating overpressure in the early phase of the eruption. Meanwhile, when compared to other eruptions which produce extremely high silica rhyolite (i.e. Mamaku ignimbrite and Ohakuri ignimbrite from Taupo Volcanic Zone), the initial eruption was triggered by tectonic activity. The Taupo Volcanic Zone is indeed located in the extension zone. However, by the vertical position of multiple magma chambers in very active tectonic regions, it is very possible for volatile accumulation in the shallowest chambers as happened in the 74 ka YTT and 52 ka Maninjau. However, it should be underlined that detailed component studies of the eruption products were overlooked in many other studies. Thus, it is possible that volcanic eruptions previously assumed to be only a result of tectonic events can also be caused by magma chamber overpressure or a combination of internal and external triggers.

This study showed that the voluminous ignimbrite product of the caldera-forming eruption that usually looks homogeneous is actually composed of diverse variations of juvenile and non-juvenile materials. In addition, this study highlighted the importance of componentry analysis to build comprehensive stratigraphy, clarify magma chamber systems, identify initial eruption triggers, and reconstruct the eruption history.

Table 8. Multiple magma chambers system around the world

Eruption center	Evidences	Characteristics	Eruption triggers	References
The 74 ka Youngest Toba Tuff eruption, Indonesia	Five distinct pumice populations (P1, P2, P3, P4, and P5), major and trace element compositions of matrix glass, trace element of distal glass shards, mineral chemistry data, and geophysics data	Crystal-poor to crystal-rich (mush) rhyolite magma, vertical position of distinct magma chambers, maximal depth: 7.3 km, the occurrence of pheno-vesicle-rich pumice (sub-ordinate).	Overpressure of pheno-vesicle-rich magma	This study; Pearce et al., 2019; Tierney et al., 2021; Masturyono et al., 2001; Stankiewicz et al., 2010
The 52 ka Maninjau eruption, Indonesia	Four distinct pumice populations, namely: Non-transparent white pumice (NTWP), transparent white pumice (TWP), light grey pumice (LG), and dark grey pumice (DG), mineral chemistry, and major element glass compositions	Crystal-poor to crystal-rich rhyolite magma, vertical position of distinct magma chambers, maximal depth: 6.6 km, the occurrence of pheno-vesicle-rich pumice (common)	Overpressure of pheno-vesicle-rich magma	Suhendro, 2021 (doctoral dissertation)
The 33 ka Ranau eruption, Indonesia	Three distinct pumice populations (A, B, and C), mineral chemistry, and whole rock major and trace element compositions of pumice	Crystal-poor dacite, crystal-poor to crystal rich rhyolite magma, vertical position of distinct magma chambers, maximal depth: 7 km, the occurrence of pheno-vesicle-rich pumice (very rare)	-	Gunawan, 2019 (master thesis)

The 29 ka and 20 ka Batur eruption, Indonesia	Distinct major element and trace element compositions of Ubud ignimbrite and Gunungkawi ignimbrite	Andesite to dacite magma, vertical position of distinct magma chambers, maximal depth: 5.3 km	Overpressure and mafic recharge	Reubi and Nichols, 2005
The 1 Ma kidnappers eruption, Taupo Volcanic Zone, New Zealand	Three distinct populations of major and trace element compositions of glass shards	Rhyolite magma, three independent melt bodies are found at approximately same depth, maximal depth: 6.5 km	Tectonic	Cooper et al., 2011
The paired Mamaku and Ohakuri eruption, Taupo Volcanic Zone, New Zealand	Major and trace element compositions of matrix-glass and quartz hosted melt inclusion	Crystal-poor to crystal-rich (mush) rhyolite magma, vertical position of distinct magma chambers, maximal depth: 5 km	Tectonic	Beugue et al., 2014; Gravley et al., 2007
The 37 ka Campanian Ignimbrite eruptions, Campi Flegrei caldera, Italy	Major, trace element, and radiogenic isotope (Sr, Pb, and Nd) data	Evolved phonolitic magma, vertical position of distinct magma chambers, maximal depth: 5 km	Mafic recharge (mixing) and magma chamber coalescence	Papalardo et al., 2002; Pabst et al., 2007
The 12 ka Neapolitan Yellow Tuff eruptions, Campi Flegrei caldera, Italy	Major, trace element, and radiogenic isotope (Sr, Pb, and Nd) data	Evolved trachytic magma, vertical position of distinct magma chambers, maximal depth: 5 km	Mafic recharge (mixing) and magma chamber coalescence	Papalardo et al., 2002; Pabst et al., 2007

6. Conclusion

YTT pumice (74 % of the total component) consists of 5 different types (P1, P2, P3, P4, and P5). P1 is the most abundant juvenile, P2 is subordinate, and P3, P4, and P5 were found as minor components. Lithic fragment (6 % of total component) consists of volcanic, metamorphic, and altered lithic. Based on the component analysis, YTT stratigraphy consists of 4 eruption units of ignimbrite (unit 1, unit 2, unit 3, and unit 4).

The classification of pumice types by the human eyes correlates with different internal structures (mineralogy and vesicles), and geochemical signatures. Major and trace element glass compositions of P1-P4 pumices suggest that there were at least four pre-eruptive magma chambers prior to the 74 ka YTT super eruption, namely P1, P2, P3, and P4.

The medium Ba and Sr (P1) is the most voluminous magma chamber (2554.9 km³). The P1 pumice is dominated by plagioclase and minor sanidine. The pressure estimation of P1 magma is 161 MPa. The low Ba and Sr magmas are represented by P2 and P3. Although same in trace element compositions, they are different in geographical distributions, vesicle texture, mineralogical association, and lithic fragments. P2 is the second voluminous magma chamber (1162.5 km³), while P3 is a small magma chamber (309.7 km³). P2 and P3 magmas have abundant phenocryst of plagioclase and sanidine. The pressure estimation of P2 and P3 magmas is 115 MPa and 105 MPa, respectively. The high Ba and Sr (P4) is the smallest magma chamber (122.7 km³). The P4 pumice is free from quartz and sanidine. The sharp boundary between crystal clots- and pheno-vesicle region with crystal-clots- and a pheno-vesicle poor region indicates the occurrence of the layered magma chamber. The pressure estimation of P4 magma is 194 MPa.

Based on the distribution of distinct pumice types and pressure estimation, it is found that P1, P2, and P4 are located in the northern region, P4 is the deepest chamber (7.3 km), P1 is located in moderate depth (6.1 km), and P2 is the shallow chamber (4.3 km). While P3 is the shallowest chamber located in the southern region (4 km).

Eruptions from multiple magma chambers were initiated by a high supersaturation of pheno-vesicle-rich magma (P2 magma), triggering the eruption of P1, P2, P3, and P4 magmas simultaneously. The vertically adjacent position of the magma chambers facilitates the formation of a hybrid conduit leading to the conduit mixing. The decompression rate showed relatively the same value from the initial phase to the final phase of the eruption ($> 10^2$ MPa/s) which was responsible for a very explosive eruption during the 74 ka YTT eruption.

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Supplementary 1.

Data for decompression rate estimation and PVND of four distinct 74 ka YTT magma

Sample	D m ² /s	Σ N/m	Pw MPa	T K	MVND m ⁻³	dP/dt Pa/s	PVND m ⁻³
P1-1	1.22E-11	1.35E-01	161	1073.77	3.84E+16	9.61E+08	3.75E+10
P1-2	1.22E-11	1.35E-01	161	1073.77	4.04E+15	2.14E+08	5.10E+10
P1-3	1.22E-11	1.35E-01	161	1073.77	9.83E+15	3.87E+08	1.00E+11
P1-4	1.22E-11	1.35E-01	161	1073.77	2.89E+15	1.71E+08	8.92E+10
P1-5	1.22E-11	1.35E-01	161	1073.77	1.15E+16	4.30E+08	2.56E+10
P1-6	1.22E-11	1.35E-01	161	1073.77	8.93E+15	3.63E+08	2.16E+10
P1-7	1.22E-11	1.35E-01	161	1073.77	9.83E+15	3.87E+08	1.11E+11
P1-8	1.22E-11	1.35E-01	161	1073.77	3.19E+15	1.83E+08	3.93E+10
P1-9	1.22E-11	1.35E-01	161	1073.77	8.70E+15	3.57E+08	7.93E+09
P1-10	1.22E-11	1.35E-01	161	1073.77	1.67E+16	5.51E+08	6.38E+10
P1-11	1.22E-11	1.35E-01	161	1073.77	3.33E+16	8.74E+08	1.84E+10
P1-12	1.22E-11	1.35E-01	161	1073.77	6.59E+15	2.97E+08	8.04E+10
P1-13	1.22E-11	1.35E-01	161	1073.77	3.03E+16	8.21E+08	3.02E+09
P1-14	1.22E-11	1.35E-01	161	1073.77	3.78E+16	9.51E+08	2.19E+10
P1-15	1.22E-11	1.35E-01	161	1073.77	1.06E+16	4.07E+08	3.68E+10
P1-16	1.22E-11	1.35E-01	161	1073.77	6.06E+15	2.81E+08	1.80E+10
P1-17	1.22E-11	1.35E-01	161	1073.77	6.13E+15	2.83E+08	6.55E+10
P1-18	1.22E-11	1.35E-01	161	1073.77	6.39E+15	2.91E+08	1.31E+11
P1-19	1.22E-11	1.35E-01	161	1073.77	1.56E+16	5.26E+08	6.27E+10
P2-1	1.06E-11	1.58E-01	115	1069.75	1.93E+15	1.74E+08	2.48E+11
P2-2	1.06E-11	1.58E-01	115	1069.75	8.55E+15	4.69E+08	2.07E+11
P2-3	1.06E-11	1.58E-01	115	1069.75	2.39E+15	2.01E+08	2.39E+11
P2-4	1.06E-11	1.58E-01	115	1069.75	4.91E+15	3.52E+08	1.68E+11
P2-5	1.06E-11	1.58E-01	115	1069.75	1.25E+13	6.06E+06	1.61E+11
P2-6	1.06E-11	1.58E-01	115	1069.75	3.17E+12	2.42E+06	2.04E+11
P2-7	1.06E-11	1.58E-01	115	1069.75	2.87E+12	2.27E+06	6.70E+10
P2-8	1.06E-11	1.58E-01	115	1069.75	1.38E+14	3.00E+07	1.08E+11
P3-1	1.03E-11	1.64E-01	105	1068.72	6.77E+15	4.29E+08	1.09E+10
P3-2	1.03E-11	1.64E-01	105	1068.72	7.08E+15	4.42E+08	2.06E+10
P3-3	1.03E-11	1.64E-01	105	1068.72	5.47E+15	3.72E+08	1.19E+10
P4-1	1.42E-11	1.20E-01	194	1083.31	2.08E+15	1.21E+08	7.52E+09
P4-2	1.42E-11	1.20E-01	194	1083.31	2.84E+15	1.49E+08	1.12E+10

Supplementary 2.

Rhodes diagram portrays the equilibrium between the orthopyroxene and liquid compositions using partition coefficient (K_D) of experimental data ($K_D(\text{Fe-Mg})^{\text{opx-liq}} = 0.29 \pm 0.06$) from Putirka, 2008.

