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From magma ascent to lava extrusion: Cooling history of the Watuadeg pillow lava, Berbah, Yogyakarta, Indonesia

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ABSTRACT. The Watuadeg pillow lava (WPL) is known as one of the most well-studied pillow lava outcrops in Yogyakarta, Indonesia, and its origin has been attributed to the rapid-cooling process of subaqueous lava extrusion. This study provides quantitative evidence of the rapid cooling process of WPL by comparing the size distribution (CSD) and number density (MND) of plagioclase microlites from the core, medial, and marginal (rim) domains of WPL, as microlites represent the syn-eruptive product. We found that the CSD slope significantly increases towards marginal zones, namely 30.4° for the core, 53.4° for the medial, and 228.1° for the rim. CSD slope is inversely proportional to cooling time ($slope = -\frac{1}{Gt}$); thus, by assuming a typical plagioclase microlite growth rate (G) of 1×10^{7} mm/s, it is therefore inferred that the rim experienced the fastest cooling time (±12.1 hours), followed by the medial and core (±52.0 and 91.4 hours, respectively). The increase of MNDs value toward the marginal zones further supports this notion (0.3×10^{15} m^{-3} for the core, 1.4×10^{15} m^{-3} for the medial, and 2.4×10^{15} m^{-3} for the rim), as higher MND with the dominant acicular-spherulitic habit represents a higher degree of undercooling. Our estimation represents the cooling time of magma since it migrated from the reservoir to the surface.

Keywords: Watuadeg · Cooling rates · Crystal size distribution · Microlite number density · Pillow lava.

1 INTRODUCTION

Pillow lava provides crucial information about the paleoenvironment and the history of volcanism, as it generally forms via rapid cooling of subaqueous lava extrusion (Bronto et al., 2002, Staude et al., 2020). However, until the present day, our knowledge of the cooling rate of pillow lava is still lacking, as most previous works dealt with its morphology or petrogenesis (e.g., Bronto et al., 2002, Ardakani et al., 2009, Staude et al., 2020). To shed light on this issue, we attempted to provide the first quantitative approach (in the world) to estimate pillow lava's cooling time using plagioclase microlites from natural samples. Microlites are attributed as syn-eruptive products (formed during magma ascent in the conduit; Toramaru et al., 2008); therefore, quantifying its sizes (crystal size distribution; CSD) and number density (microlite number density; MND) allows us to provide an estimation on the cooling time

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of lava (Higgins, 1996; Higgins, 2006; Morgan, 2006; Noguchi et al., 2008a; Toramaru et al., 2008).

We applied such methods to one of the most well-studied (i.e., the age, stratigraphy, and bulk-rock compositions have been well-constrained) pillow lava outcrops in Yogyakarta, Indonesia, named Watuadeg pillow lava (hereafter abbreviated as WPL). First, we determined the domain of the WPL based on the fracture intensity. Second, we will explain our sampling policy regarding each domain. Finally, we will present our interpretation of the cooling history of pillow lava based on the correlation of CSD and MND data. We argue that the estimated cooling time and resultant microlite textures strongly depend on the contact ratio between water and melt. Namely, the high water-melt ratio in the outer part causes intense fracturing due to rapid cooling of the lava, yielding a typically small microlite size with an acicular-spherulitic habit, resulting in a high MND value. On the other hand, cooling times are low in the region of low melt-water contact ratio (i.e., core), allowing microlites to grow larger via longer crystallization time and obtain prismatic habit, consequently reducing its number densities.

2 Geological Background

Indonesia is situated in an active subduction zone between three plates: Eurasia, Indo-Australia, and Pacific plates (Figure 1a), with an estimated subduction rate of 7–9 cm/year (Brehme et al., 2014; Marliyani et al., 2020). Such active subduction activity forms major trenches, such as the Java, Timor, Sangihe, and Halmahera Trenches (Gertisser et al., 2012, Faral et al., 2022). The Java Trench has been active since the Early Cenozoic (Hall 2002, Smyth et al., 2011), forming subduction-related magmatism-volcanism as indicated by sub-alkaline magma affinities (Setidjadji et al., 2006; see their Fig. 5). During this period, the early stage of volcanisms in Java Island took place in subaqueous (underwater) environment (Smyth et al., 2008), forming abundant pillow lavas. In Central Java, pillow lavas are best preserved in Berbah and Ngawen (Yogyakarta), Bayat (Klaten), and Grindulu River (Pacitan) (Bronto et al., 2002) (Figures 1b and c). Pillow lavas in Berbah and Bayat have relatively similar ages, at approximately 56.3±3.8 and 58.6±3.3 Ma (Hartono 2000; Bronto et al., 2002). While pillow lavas in the Grindulu River are typically younger, ranging from 33.6±9.7 to 42.7±9.8 Ma (Soeria-Atmadja et al., 1994; Bronto et al., 2002). However, such age estimations are still debatable (specifically for Berbah pillow lava), as a recent study by Harijoko et al. (2014) yields significantly younger age (based on the occurrence of Globoquadrina altispira and Globorotalia perpheroronda fossils in the intercalating sedimentary rocks from Semilir Formation), ranging from early to middle Miocene (N5–N10). Moreover, such afore-mentioned pillow lavas are typically basic in compositions (±50–52 wt.% SiO_2, bulk-rock) and have low-K (at most medium-K) magma affinities (Bronto et al., 2002).

3 Methodology

3.1 Sampling

First, we quantitatively determine the structural domain of the Watuadeg pillow lava (WPL). Based on the qualitative observation of fractures (i.e., cooling-induced fractures, which associated with desiccated fracture morphology; see Fig. 13 in Hamada & Toramaru, 2019) (Figure 1d), we found that the WPL can be divided into three domains: core, medial, and marginal (rim) (Figure 2a). The core domain is characterized by the lack abundance of fractures, whereas the rim domain is intensively fractured. A transitional domain between the core and the rim shows an intermediate fracturing (not as fractured as the rim, but more fractured than the core), termed a medial domain. We took one sample from each domain (three, including all domains) for microtextural analyses (see subsection 3.2).

To confirm our qualitative description, we attempted to provide a quantitative-based domain classification by manually digitizing all observed fractures using Corel Draw X7 to obtain the area of fractures (Figure 2b). Subsequently, the total area of fractures on each domain (A_{Fr}) is divided by the domain area (A_c for core, A_m for medial, and A_r for rim) in order to obtain fracture intensity (in area fraction, %) (Figure 2). Our quantitative measurement

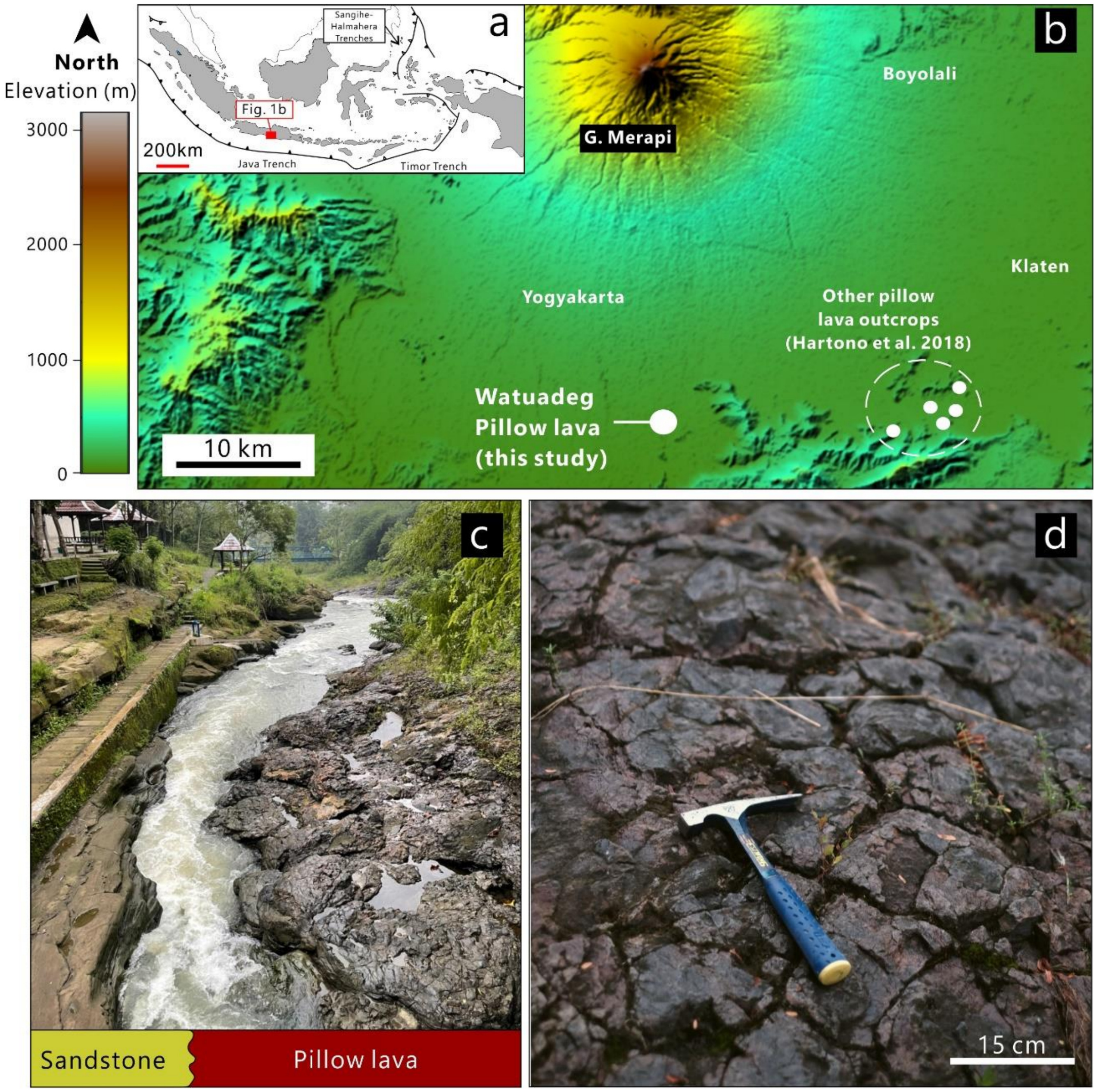

FIGURE 1. (a) Image showing the trench distribution in Indonesia. (b) Map showing the location of pillow lava outcrops around Yogyakarta and Central Java region. The large white circle shows the watuadeg pillow lava (WPL). The digital elevation model (DEM) was obtained from tanahair.indonesia.go.id (open access). (c) Contact between the WPL (righthand side) with sandstone (lefthand side). (d) Close-up view of the WPL, showing desiccated fracture morphology.

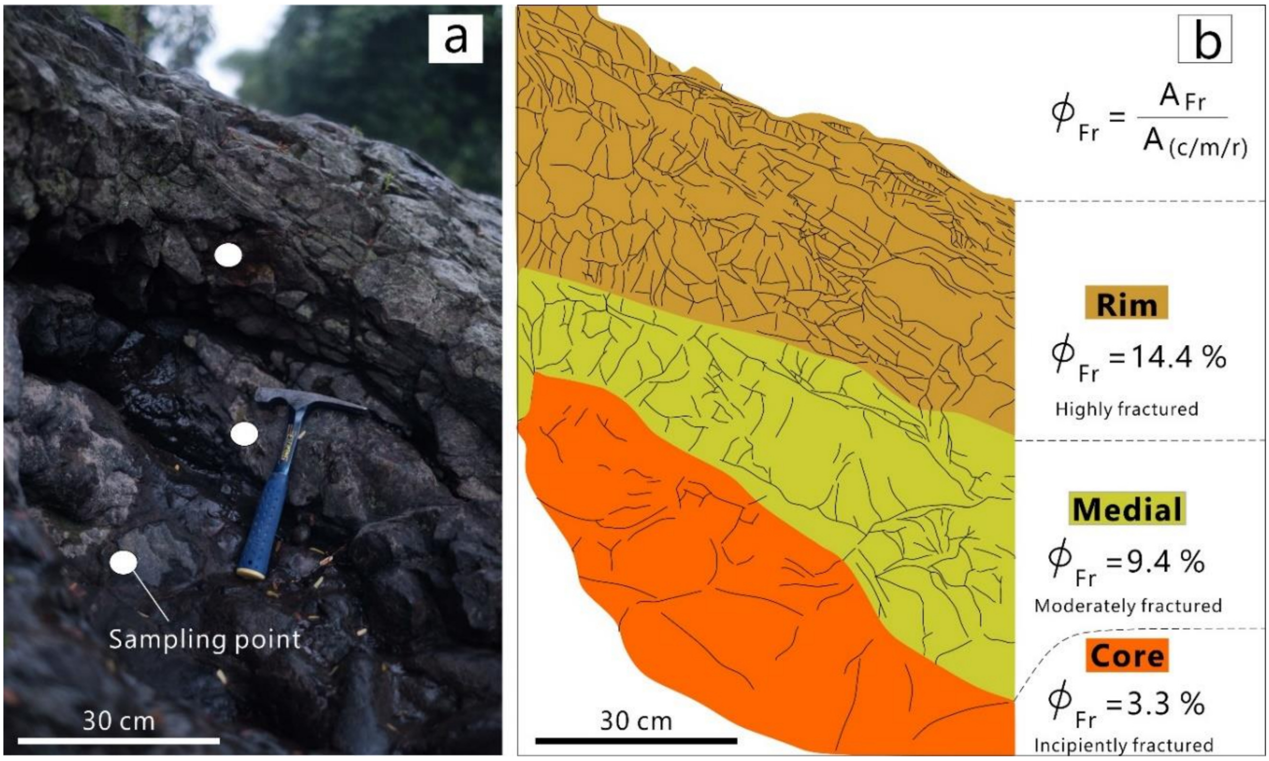

FIGURE 2. Based on the qualitative (a) and quantitative (b) descriptions of fracture intensity, the WPL is divided into three domains: core, medial, and rim. Samples were taken from each domain to see the systematic changes in microlites.

agrees well with the qualitative description, as the core represents the lowest fracture intensity (3.3 %), followed by the medial and rim (9.4 % and 14.4 %, respectively) (Figure 2). This implies that our sampling positions have been representative enough for the following microtextural analyses.

3.2 Microtextural analyses: Crystal size distribution and microlite number density

A total of 3 (three) thin section samples (each domain is represented by 1 thin section) were made for microtextural analyses, including crystal size distribution (CSD) and microlite number density (MND). Since we dealt with microlites (a small-sized crystals that formed during an eruption via undercooling; Toramaru et al., 2008), the digitation for CSD and MND requires the largest magnification in order to represent the most detailed image of plagioclase microlites (Figure 3). Subsequently, the digitized plagioclase microlites were processed by CSD-corrections software (Higgins, 2006) in order to obtain the size distribution. The input parameter of the crystal aspect ratio in the CSD-correction software was obtained from the CSDslice program (Morgan, 2006). ImageJ also processed the digitized plagioclase microlites to obtain some textural properties (e.g., average size, number, and volume fraction) (Figure 4). We used three images with similar magnification for each domain for statistical purposes. The values from the three images were averaged to obtain the most representative values for microtextural analyses. Finally, CSD slope and MND were obtained from the following equations:

$$\text{CSD slope} = -\frac{1}{Gt} \tag{1}$$

$$\text{MND}\,(N_v) = \frac{N_{am}}{d_m} \tag{2}$$

where G is the typical growth rate of plagioclase microlites (at most 10^7 mm/s; Cashman, 1993; Higgins, 1996), t is the residence time (or cooling time) of magma since it migrated from the reservoir to the surface, N_{am} is the number of microlites per unit area, and d_m is the average microlite diameter.

FIGURE 3. Representative cross-polarized (X) thin-section images of the core, medial, and rim domains. Note the microlite differences (in terms of size, habit, and number density) between each domain.

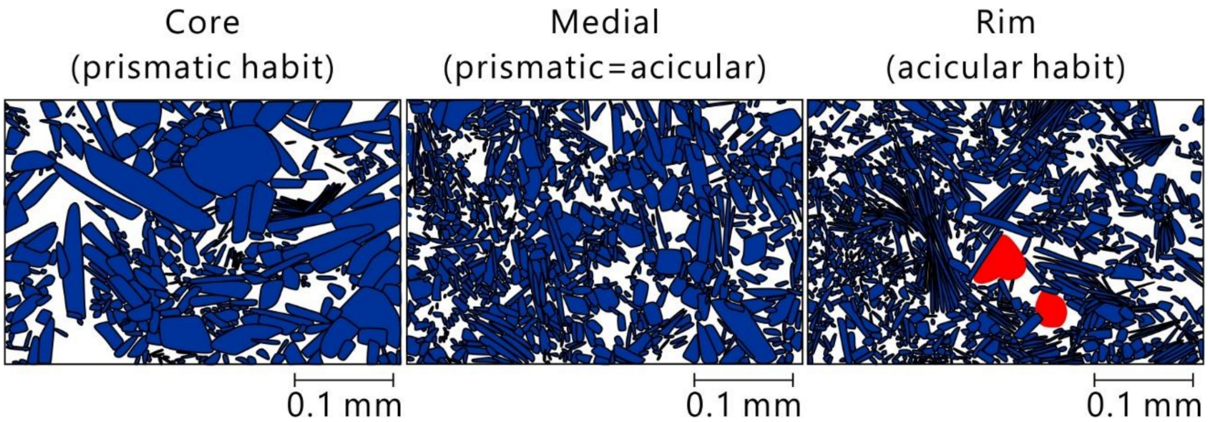

FIGURE 4. Digitized plagioclase microlites for microtextural analyses. Blue denotes plagioclase, and red represents vesicles.

4 RESULTS AND DISCUSSION

Many studies have shown that the nucleation and growth of microlites are strongly controlled by initial melt temperature, compositions, and water content (e.g., Cashman & Blundy, 2000; Couch et al., 2003; Toramaru 2019; Suhendro et al., 2021). However, the Watuadeg pillow lava is known to have nearly-identical bulk-rock compositions 49.9–51.1 wt.% SiO_2; see Fig. 9 of Bronto et al., (2002). This implies that; although all domains (core, medial, and rim) exhibit distinctive textural characteristics of plagioclase microlites (i.e., size and number density), the homogeneity of rock compositions suggests they likely erupted at similar temperature and water content conditions. Therefore, in this case, initial melt temperature, compositions, and water content are found to have no role in controlling the extent of microlite crystallization. Instead, we tend to suggest that an external process, such as the contact ratio between water (m_w) and melt (m_m) as the most important factor in controlling microlite size and number density (Wohletz & McQueen, 1984), where a higher contact ratio between water and melt would yield faster cooling rates and vice versa. This is shown by the systematic increase of CSD slope from the core towards the rim, particularly 30.4° for the core, 53.4° for the medial, and 228.1° for the rim (Figure 5a, b). Such increment of the slope is also accompanied by a decrease in maximum crystal size, an increase in microlite number density (MND) (Figure 5c), and changes in microlite habit (Figure 4). Plagioclase microlites in the core domain exceed 0.5 mm with a relatively low MND value (0.3×10^{15} mm^{-3}) and prismatic habit. While plagioclase microlites in the medial and rim only reach up to 0.3 mm and 0.1 mm, resulting in a typically high MNDs value (1.4×10^{15} m^{-3} and 2.4×10^{15} m^{-3}), respectively, with a predominantly acicular-spherulitic habit (Figures 4 and 5). Small aspect ratio crystals (e.g., acicular-spherulitic) represent a small average diameter (Preece et al. 2016), and the average diameter is inversely proportional to the number density (Equation 2), suggesting that the acicular-spherulitic-dominated and high MND samples are attributed to the high nucleation rate condition (nucleation-dominated regime) as a result of rapid undercooling. By contrast, predominantly prismatic microlite crystals with low MND value imply a growth-dominated regime as a result of slow undercooling (Lofgren, 1974; Hammer et al., 2000; Sable et al., 2006; Szramek et al., 2006; Preece et al., 2016).

Assuming a typical growth rate of plagioclase microlites as 10^7 mm/s (Cashman, 1993; Higgins, 1996), the cooling time of plagioclase microlites in the WPL core, medial, and rim are expected to be ± 91.3 hours, 52 hours, and 12.2 hours, respectively (Table 1). Despite this finding, it is important to note that microlites are syn-eruptive products (Noguchi et al., 2008a; Toramaru et al., 2008); hence, these values are not a direct estimation of lava cooling time when it made contact with water (i.e., during the formation of pillow lava structure). Instead, the calculated time represents the cooling time of magma since it migrated from the reservoir to the surface (Figure 6).

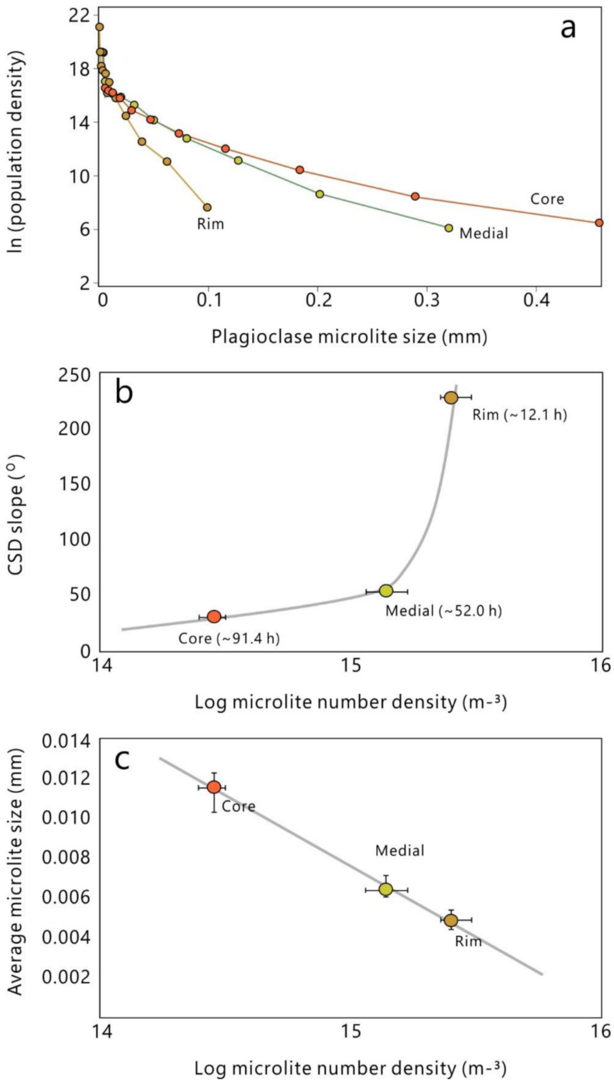

FIGURE 5. (a) Correlation between average microlite size and microlite number density, (b) crystal size distribution of plagioclase microlites in the core, medial, and rim domains, (c) correlation between CSD slope with microlite number density.

5 CONCLUSION

This is the first study that confirms the interpretation of the rapid cooling process in pillow lava. The outer part (rim) experienced the fastest cooling time due to the high water: melt contact ratio, allowing the preservation of original microlite sizes and number density since the magma ascent. By contrast, the medial and core experienced slower cooling time than the rim due to the relatively low water: melt contact ratio, facilitating microlites to grow into larger sizes and reducing their number densities.

TABLE 1. Textural parameters of plagioclase microlites.

	N_a (m^{-2})	Avg. microlite d (mm)	Avg. microlite fraction (%)	N_v (m^{-3})	CSD Slope (°)	Estimated cooling time (hours)
Rim	1.2×10^{13}	0.0048	21.1	2.5×10^{15}	228.1	12.1
Medial	8.9×10^{12}	0.0064	34.5	1.4×10^{15}	53.4	52.0
Core	3.3×10^{12}	0.0115	49.3	2.8×10^{14}	30.1	91.4

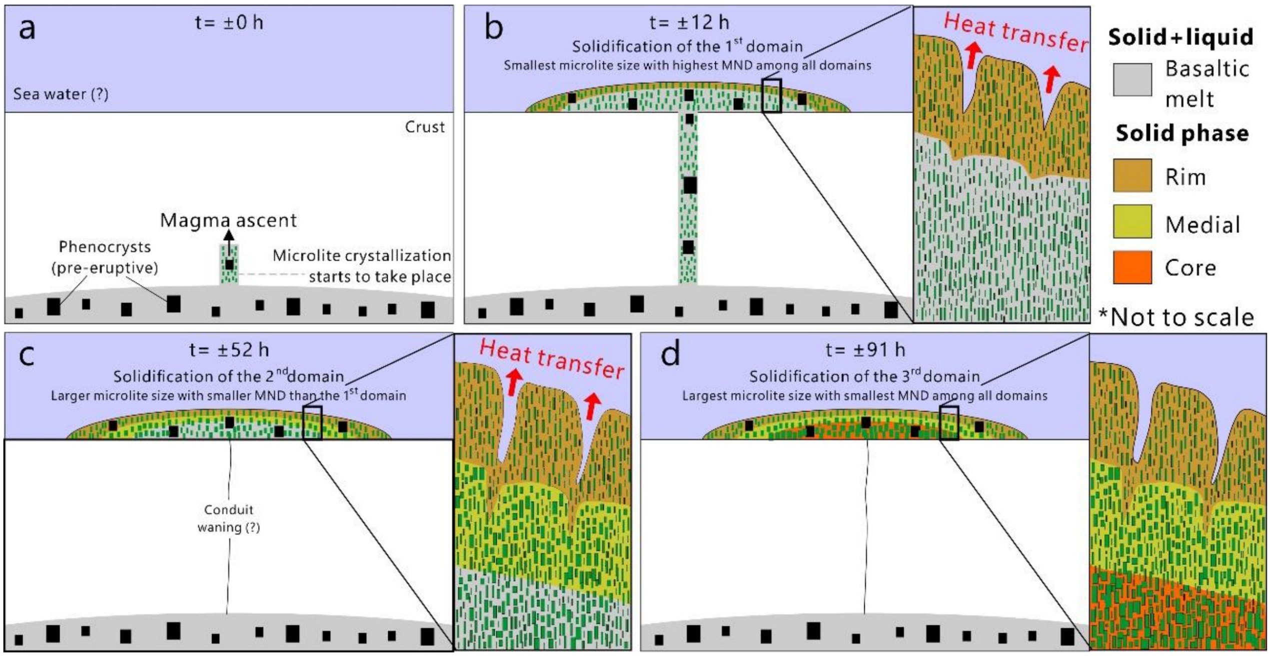

FIGURE 6. Cartoon showing the formation process of the core, medial, and rim domains (light brown, light green, and orange color, respectively) in the WPL. (a) Microlite crystallization starts to take place during magma ascent. (b) The outer part (rim) experienced the fastest cooling rate (±12 h since magma ascent) due to a high degree of undercooling, yielding typically small microlite sizes (high MND values) with acicular-spherulitic habit. (c, d) Whereas the inner part (medial and core) experienced a slower cooling rate (±52 and 91 h since magma ascent, respectively), allowing the extensive growth of microlites (into larger size), thus reducing its relative number density and changing its habit into more prismatic shape.

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