Investigating Magma Eruption Dynamics Using Melt Inclusion and Host Mineral Composition

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Abstract –Volcanic rocks are archives of magmatic history. Melt inclusions (MI) in volcanic rocks were commonly used to probe magma composition, but magma's control over variable MI morphology remains poorly understood. This study investigates the morphology of MIs in an anorthoclase megacryst from Mount Erebus, Antarctica. We find that the variation in MI morphology from the core to the rim of the host mineral divides the crystal into five zones and matches with changes in the crystal's growth rate due to pressure change during magma convection. We propose that the morphology of MI is dominated by crystal growth rate which can be linked to magmatic P-T-X conditions in future studies.

Introduction

What is melt inclusion?

Melt inclusion (MI) is a small pocket of melt that is trapped in a crystal due to irregular growing condition[1]. It is formed by sudden increase in crystal growth rate and sealed by low crystal growth rate [1, 2].

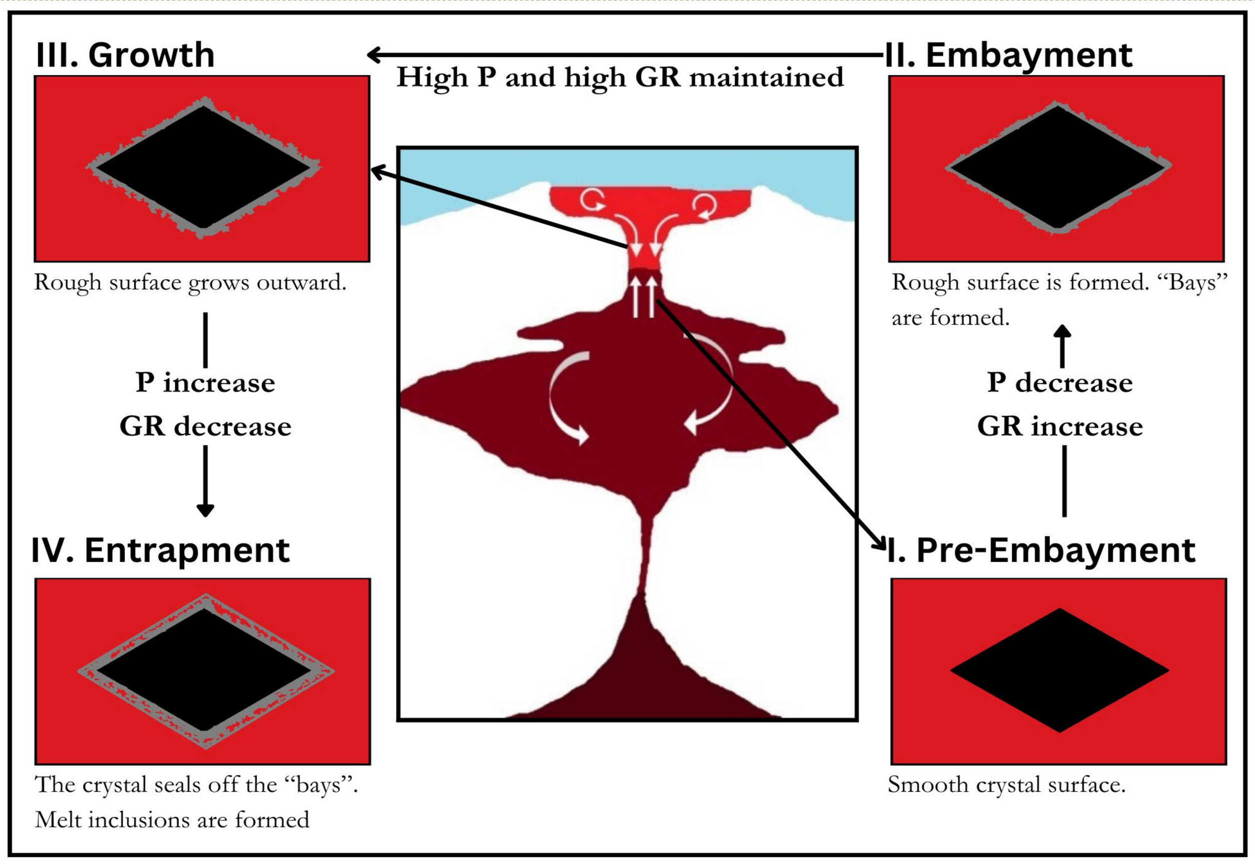

Fig. 1: A schematic diagram showing the formation of MIs in Erebus. Black and grey represent pre-existing and new-grown anorthoclase, respectively.

Erebus is an active volcano in Antarctica, that has a permanent phonolitic lava lake [3, 4]. It has anorthoclase megacrysts (width up to 10 cm) with MIs (width up to 600 μm). **Change of pressure** (P) and **growth rate** (GR) during magma convection explain the MI formation in Erebus (Fig.1) [1, 4].

This study proposes a new angle to studying magma dynamics and pre-eruptive history using the **MI morphology**. The study includes two parts:

- **Zoning of the megacryst by MI morphology**. MI morphology parameters focused on this study are **aspect ratio** (AR, i.e. the ratio of major axis to minor axis of fit ellipse) and **area**.
- **Correlation** between **MI morphology** and the **potassium content** ([K]) of the periphery of the MIs, therefore **P**, rate of P change and rate **GR** change of anorthoclase [4].

Objective

1. To invent a way to **zone a crystal efficiently** for **preliminary research** of a crystal.
2. To understand the **controlling factors of MI morphology**.
3. To explore the **potential** of **MI morphology as a lens** of **pre-eruptive magma dynamics**.

Methodology

Fig. 2: Image processing of anorthoclase megacryst to exclude all components apart from MIs.

1. Extracting MI morphologies by image processing - A two-dimensional back-scattered electron (BSE) image of (cross-section perpendicular to c-axis of) the megacryst (20.5 mm × 11 mm) is used (Fig. 2). The morphology data of MIs (Area range: 0.002 to 1 mm^2, n = 687) are extracted by an image processing software, Fiji.
2. Zoning – Similar ellipse is used to zone the crystal according to the sample size, size of the zone and **similarities** of MI morphologies distribution between **neighbouring zones** by Mann-Whitney U-test [5].

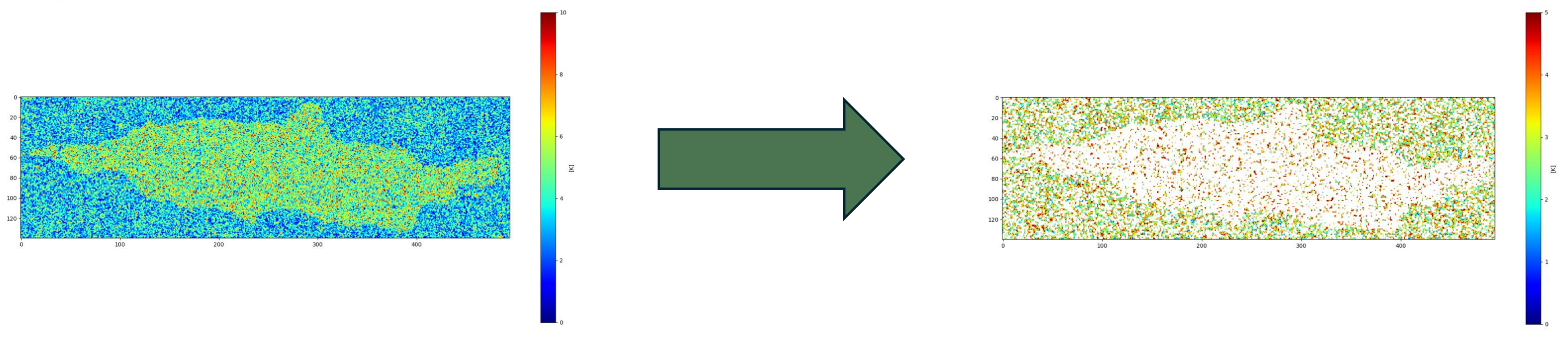

Fig. 3: The way to extract [K] data of the periphery of MIs., where only data with the range of 0 < [K] < 6 are selected.

3. Correlating MI morphology and [K] of the periphery of corresponding MIs – [K] data are collected from BSE elemental maps. Data with the range of 0 < [K] <6 is selected, to eliminate most MI data (Fig. 3). The **K wt%** of Erebus's anorthoclase is directly proportional to its **orthoclase content** (Or%), which is controlled by **P (lower the P, higher the Or%)** [4]. P has a **negative correlation** with the **GR** of anorthoclase [4]. The correlation between MI morphologies and [K] of the periphery of MIs will suggest correlation between MI morphologies, P of magma and GR of anorthoclase.

Zoning of Megacryst

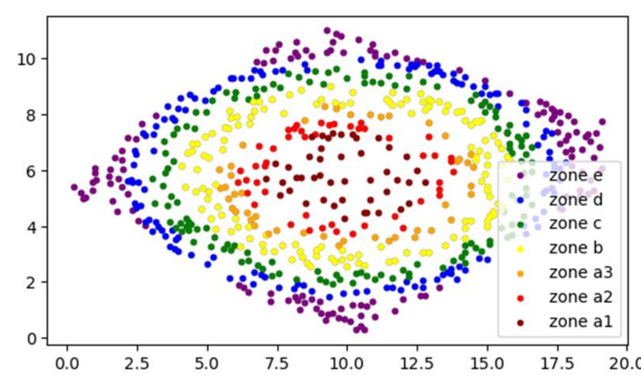

Fig. 4 (left): Zoning of the megacryst.

- **7 zones** are established based on the mentioned criteria (Fig. 4).
- By the similarities of AR and Area of different zones (Fig. 5 & 6), we find out that:
  - ➢ Zones d and e, and zone a2 and a3 are nearly identical.
  - ➢ Zones a1, c, d and e have similar.
  - ➢ Zones b and c are different..
- We suggest that zones with similar MI morphology parameters undergo similar magmatic processes.

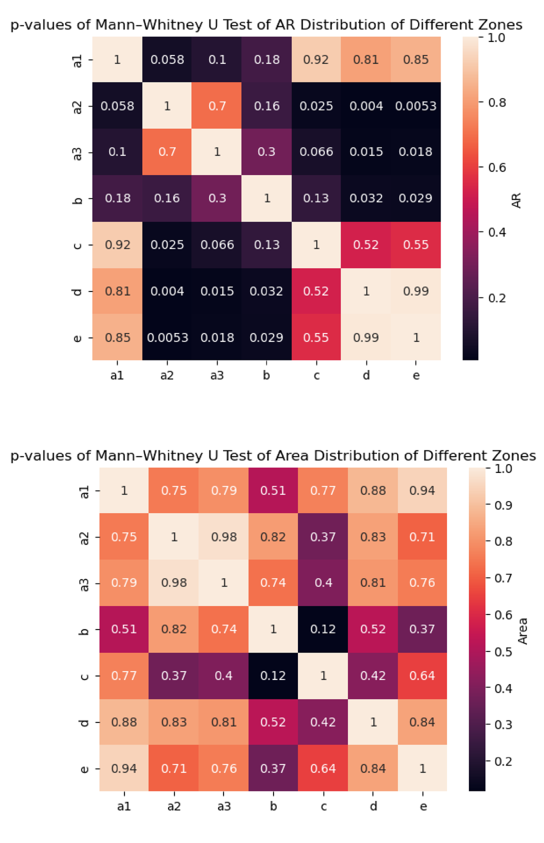

Fig. 5 (upper) & Fig. 6 (lower): p-values of Mann-Whitney U Test of AR and Area distribution between different zones.

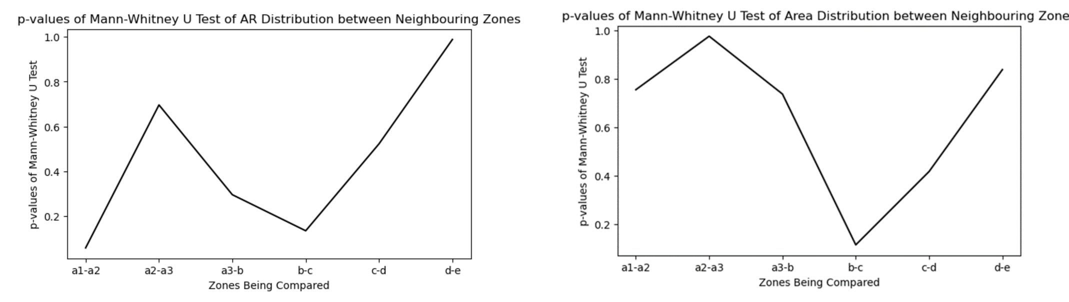

Fig. 7 (left) & Fig. 8 (right): p-values of Mann-Whitney U Test of AR and Area distribution between different zones.

- Comparing the p-values of the selected parameters between neighbouring zones (Fig. 7 & 8), both parameters agree that **Zone a2** and **a3**, and **Zone d** and **e** can be considered as the **same** zones respectively, while **Zone b** and **c** are **very different** from one another. Thus, this crystal is divided as five zones.
- This demonstrates a way to zone a crystal, whether MI morphologies have relationship with magma evolution will be discussed.

Correlation between MI Morphologies and [K]

- Fig. 9 shows that **AR** and **Mean [K]** have a **substantial negative correlation**.
- This implies that mean P affects the AR, **more time** the crystal being in **low P** (**high GR**) after the start of embayment, **higher** the **Mean [K]** and **less elongated** MIs.

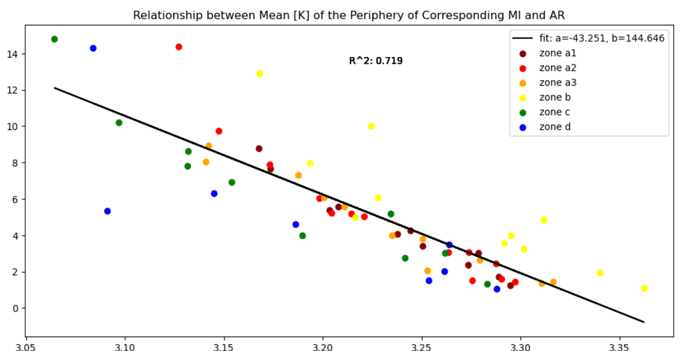

Fig. 9: Relationship between Mean [K] of the periphery of MIs and AR of MIs.

What does Std [K]/Minor mean?

As MI grows along the direction of its minor axis, one suggests that the length of minor axis has a positive relationship with the growing period. Thus, Std [K]/Minor is used as a proxy to show the rates of change of Or%, P and GR.

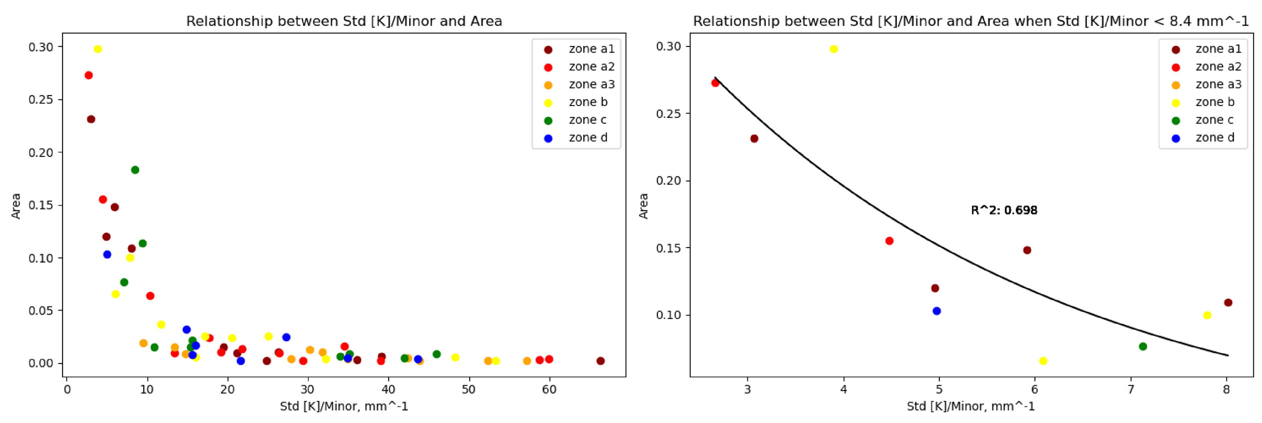

Fig. 10a (left): Relationship between std [K]/Minor of the periphery of MIs and Area of MIs; Fig. 10b (right): Relationship between Std [K]/Minor of the periphery of MIs and Area of MIs when Std [K]/Minor < 8.4 mm^{-1}.

- In Fig. 10a, two different trends are seen. All MIs with Std [K]/Minor ≥ 8.4 mm^{-1} have roughly the same area (0.002-0.005 mm^2), while those with **Std [K]/Minor < 8.4 mm^{-1}** have distinctive **substantial negative relationship** with Area (Fig. 10b).
- Considering MIs with Std [K]/Minor < 8.4 mm^{-1} (Fig. 10b), MIs with large Area are explained by long major axis and/or long minor axis. Long minor axis is caused by **low rate of P change** after embayment and **high crystal GR for a long time** before seal-off [2]. The formation of long major axis is yet to be discovered.

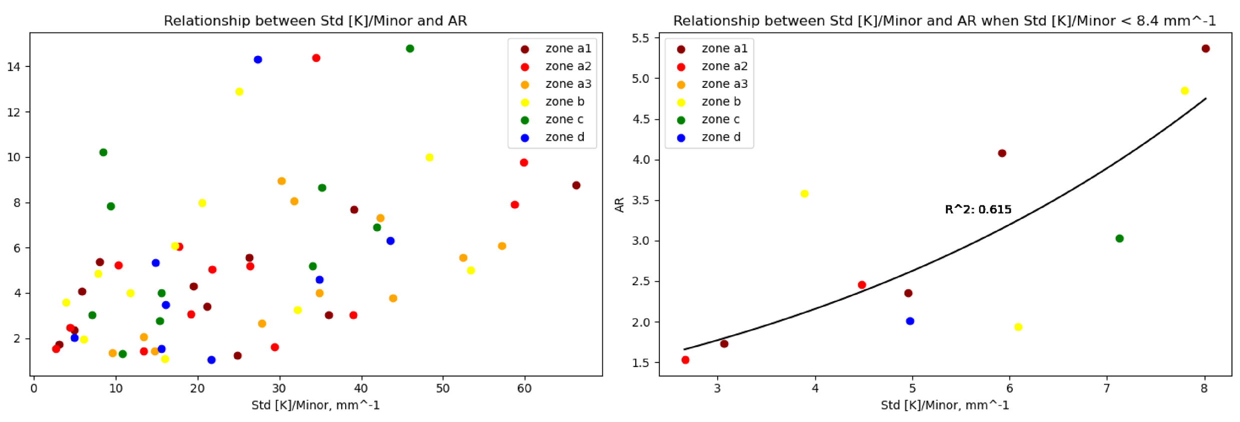

Fig. 11a (left): Relationship between Std [K]/Minor of the periphery of MIs and AR of MIs; Fig. 11b (right): Relationship between Std [K]/Minor of the periphery of MIs and AR of MIs when Std [K]/Minor < 8.4 mm^{-1} (Area > 0.05 mm^2).

- No correlation between AR and Std [K]/Minor (Fig. 11a). But data with **Std [K]/Minor < 8.4 mm^{-1}** has a **moderate correlation** (Fig. 11b).
- For those MIs, **lower the rate of P change** after embayment, a **longer period of high GR**, **less elongated** the crystal [2].
- MIs with Std [K]/Minor < 8.4 mm^{-1} follow both correlations with AR and Area, respectively. Thus, **large MIs** (Area > 0.05 mm^2) from all zones **follow both relationships**.
- Small MIs (**Area ≤ 0.05 mm^2**) have **no clear correlation**. This can be explained by the **disequilibrium** between the crystal and the melt due to abrupt GR drop and seal-off after embayment.

Implications

Zoning
- Zoning by MI morphology is an efficient way to **divide a crystal** with complex zoning.
- This method is used for **preliminary research of a crystal**.
- It indicates **major episodes of magmatic activities** with information about **supersaturation**.
- It is helpful for researchers to decide the **area of interest** within a crystal.
- Different numbers of zones can be selected, depending on the study purpose.

Marker
- For MIs with Area > 0.05 mm^2, **large** and **less elongated MIs** are indicators of **sudden drop of P**, followed by **prolonged period of low P**, before they seal off due to high pressure.
- MI morphology acts as a **marker of major magmatic events**, such as magma ascent, or even **past eruption events**.

Monitor
- As MI morphology is related to rate of P change and magma ascent rate, it is treated as **pulse monitor of volcanoes**.
- Pattern of pulse is useful to the studies of **magma convection**, **plumbing system dynamics** and **eruption frequency**.

Screener
- The **compositions** of some host crystal and MIs are **altered**.
- **Mean [K] and Std [K]** can be **inferred** by MI morphology, which can **verify** the **legitimacy** of the **composition analysis** of crystal and MI.
- **Simulation of the initial distribution of [K]** at their peripheries, their **Or%**, **P** and **GR** is plausible. Information that was lost can be regained.

Further Studies

- Forward modelling can be done to estimate the average magma ascent rate of different zones. This will provide another insight in rate of pressure change and MI morphologies.
- Detail study on the length of major axis shall be performed with Or% of around MIs being surveyed.

Key References
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