Tracht change of groundmass pyroxene crystals in decompression experiments

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Groundmass pyroxene crystals in pumice from the 1914 eruption of Sakurajima in Japan show varied combinations of crystallographic faces (i.e., ‘tracht’). To investigate whether the groundmass pyroxene tracht depends on magma decompression conditions, we performed isothermal single-step decompression experiments on hydrous Sakurajima dacite magma. The magma was held under water-saturated conditions at 920 °C, 120 MPa, and oxygen fugacity conditions no more oxidizing than one log unit above Ni-NiO equilibrium for 24 h. Then, a control experiment was immediately quenched, whereas others were decompressed to final pressures of 20, 10, or 5 MPa and held for 3 h before quenching. Groundmass pyroxenes in the control experiment and that quenched at 20 MPa showed octagonal shapes, whereas those decompressed to lower pressures characteristically had hexagonal shapes. Some pyroxenes in the 20 MPa experiment were hexagonal near plagioclase crystals because plagioclase crystallization locally increased the supersaturation of pyroxene in the melt. We conclude that the tracht of groundmass pyroxenes changes from octagonal to hexagonal as the degree of effective undercooling increases and thus reflects the decompression history of a magma during its ascent in a volcanic conduit.

Keywords: Pyroxene, Crystal habit, Decompression experiment, Sakurajima volcano

INTRODUCTION

Magmas ascending through volcanic conduits are affected by various physicochemical processes that ultimately control eruptive style (e.g., Cassidy et al., 2018). During ascent, magmatic volatiles (e.g., H2O and CO2) exsolve as bubbles, accelerating the ascent of the magma and promoting explosive eruptions, whereas outgassing through the vents and conduit walls reduces explosivity. Melt dehydration via these processes results in phenocryst (>100 µm) overgrowth and the generation of groundmass crystals (typically <30 µm), which affect explosivity by increasing magma viscosity (e.g., Caricchi et al., 2007; Preuße et al., 2016; Mujin and Nakamura, 2020). Furthermore, groundmass crystal textures record magma ascent conditions and eruptive style (e.g., Cashman and Blundy, 2000; Castro and Gardner, 2008; Mujin et al., 2017). Crystal number densities are used for the established analytical methods such as crystal size distributions (CSDs; Marsh, 1998) and water exsolution rate meter (Toramaru et al., 2008).

The premise of these methods is that crystal nucleation rates are positively correlated with the degree of effective undercooling (ΔT_{eff}) induced by dehydration and/or cooling during ascent. However, intense cooling can reduce chemical diffusion rates and hinder crystal nucleation (e.g., Swanson, 1977; Hammer, 2008; Shea and Hammer, 2013). Although theoretically predicted low nucleation rates at the highest ΔT_{eff} (i.e., the bell-shaped relations) have not been well reproduced in decompression experiments (e.g., Mollard et al., 2012; Shea and Hammer, 2013), considerably fast ascent (decompression) rates are assumed to produce pyroclasts containing few groundmass crystals (e.g., Sakurajima volcano, Nakamura, 2006; Redoubt volcano, Wolf and Eichelberger, 1997; Chaitén volcano, Castro and Dingwell, 2009). In these situations, the ascending magma is quenched before the groundmass nucleation rate can reach its peak. Therefore, analytical methods based on crystal number densities alone are probably unreliable, and other indicators such as crystal shape are required to investigate magma dynamics during explosive eruptions.
Previous studies have demonstrated that the aspect ratios and morphologies (e.g., euhedral, hopper, and dendritic) of rock–forming minerals such as plagioclase and pyroxene reflect ΔT_{eff} (e.g., Lofgren, 1974; Hammer and Rutherford, 2002; Shea and Hammer, 2013). In particular, plagioclase has been intensively investigated because it is the dominant phase that crystallizes during decompression. However, variations have been observed in the combinations of crystallographic faces (i.e., ‘tracht’; Suna-gawa, 2005) of groundmass pyroxene crystals in pumice clasts from the 1914 Plinian eruption of Sakurajima volcano, Japan (Fig. 1). In general, groundmass pyroxenes are prismatic (e.g., Castro et al., 2003; Okumura et al., 2022, in press). The combinations of {100}, {010}, and {110} prismatic faces yield octagonal, hexagonal, and parallelogrammatic trachts as shown in Figures 2a and 2b (cf. conference abstracts: Okumura et al., 2019, 2020). The 1914 Sakurajima eruption produced microlite–rich and microlite–poor white pumice clasts (Nakamura, 2006), the former containing octagonal and hexagonal pyroxenes (Fig. 1a) and the latter pyroxenes with parallelogrammatic cross sections (Fig. 1b). The magma batch that formed the microlite–poor pumice is assumed to have experienced faster ascent (Nakamura, 2006); therefore, the tracht of groundmass pyroxenes seems to reflect magma ascent dynamics. Here, we performed decompression experiments on the Sakurajima magma to confirm that pyroxene tracht reflects decompression-induced ΔT_{eff}.

**DECOMPRESSION EXPERIMENTS**

**Starting material**

We collected white pumice clasts from the 1914 Sakurajima eruption at Kurokami, 4.5 km east of Sakurajima’s southernmost and presently active crater, Minami-dake. We coarsely crushed the pumice, removed phenocrysts under an optical microscope, and collected the groundmass fragments as our starting material. Groundmass crystals consist of orthopyroxene, pigeonite, augite, titanomagnetite, and plagioclase (Nakamura, 2006). As reported in Nakamura (2006), the pumice clasts had almost the same chemical composition of bulk groundmass (i.e., glass and microlites in Table 1), although their groundmass crystallinities were different. Aliquots of 8–10 mg of the starting material and enough water (~ 6 wt%) to achieve water–saturation were loaded into Au capsules (3 mm outer diameter), sealed by welding.

**Experimental procedures**

The capsules were heated in a cold-seal pressure vessel at Tohoku University (Okumura et al., 2021) with a Ni filler rod at 920 °C and 120 MPa for 24 h, then isothermally decompressed to final pressures, P_f, of 5, 10, and 20 MPa in a single step (runs SSD_5, 10, and 20, respectively). Each experiment was held at P_f for 3 h, and then the capsule was quenched by dropping it into a water–cooled zone in the system. To evaluate decompression-induced crystallization, a control experiment was conducted by quenching without any decompression (run EQ_120). During the experiments, the oxygen fugacity of the melt (f_{O_2}, reported in log units relative to Ni–NiO equilibrium as NNO) was assumed to have been maintained at NNO to NNO + 1 (Okumura et al., 2021). The recovered capsules were carefully opened; however, the recovered materials broke into pieces because of their high vesicularity and fragility and lost their positional relations within the capsules. The materials were then mounted in resin for polishing and subsequent analyses.

**ANALYTICAL METHODS**

The polished starting material and run products mounted in
resin were observed using field-emission scanning electron microscopes (FE–SEMs) at Kyoto University. The chemical compositions of glasses were measured using a FE–SEM (JEOL JSM–7001F) coupled with an Oxford Instrument X–Max150 energy dispersive X–ray spectrometer and its associated analytical software ‘AZtec’. Measurements were performed on multiple square regions (~1 × 1 µm²) for 40 s each at an accelerating voltage of 15 kV and a beam current of about 0.35 nA. In some of the run products, plagioclase crystals were observed, and therefore, we analyzed separately the glass near the plagioclases (‘near–Pl’) from that farther than 10 µm from any plagioclase crystal (hereafter, ‘Pl–free’). The average compositions of each sample are reported in Table 1.

Backscattered electron (BSE) images for textural analyses of groundmass pyroxene crystals in the run products were obtained using a FE–SEM (Thermo Fisher Scientific, Helios NanoLab 3G CX) operating at an accelerating voltage of 5 kV, a 6 nm working distance, and 5000× or 6500× magnification (corresponding to regions ~ 30–40 µm on a side). For each sample, more than three regions were selected for random for the analyses. Using ‘ImageJ’ software, we measured the areas of the rectangular regions examined (i.e., the entire image areas) and individual pyroxene cross sections as well as their widths, which we took as the minor axis of the best-fit ellipse. We discriminated pyroxenes from other minerals based on their contrast in BSE images and SEM–EDS maps. In addition, pyroxene crystals smaller than 0.2 µm in width were omitted from further analyses because the spatial resolutions of SEM observations were not enough to investigate their tracht.

With BSE images at higher magnifications (<50000×), each pyroxene cross section could be classified into several tracht types: octagonal, heptagonal, hexagonal, pentagonal, or parallelogrammatic tracht based on the number of faces between a pair of parallel faces (Figs. 2b–2e). For example, the octagonal and hexagonal trachts have three and two faces between a pair of parallel faces, respectively, and the heptagonal tracht has the properties of octagonal on one side and hexagonal on the other side (Fig. 2c). Pyroxenes that were difficult to classify as having a particular tracht were classified as ‘other’. If cross sections were incomplete (e.g., chipped), we classified them based on the remaining parts; however, those having no pairs of parallel faces were classified as ‘other’ (Fig. 2d). The intermediate tracht, such as heptagonal, could only be identified when the cross section had all constituent faces (Fig. 2c). In addition, when cross sections were slightly rounded, we checked the existence of flat faces in the amplified images (Fig. 2e). Finally, we acquired the size distributions of pyroxene cross sections in each tracht group in intervals of 0.4 µm above crystal width of 0.2 µm (i.e., 0.2–0.6 µm, 0.6–1.0 µm, etc.) and plotted the area number density of crystal cross sections (Nₘ) in each interval and tracht group against crystal width.

### RESULTS

Table 1 shows glass compositions of the starting material and run products. The groundmass of EQ_120 contained low–Ca pyroxene, high–Ca pyroxene, titanomagnetite,
near glass compositions tended to be more evolved in the 10 but ubiquitously in SSD_5. As shown in Table 1, the crystals showed dendritic chain morphologies (Figs. 3c and 3e); they crystallized locally in SSD_20 and SSD_10, which is consistent with pyroxenes in our samples, the numerical model of Higgins (1994) calculated that the probability of a cross section consisting of only prismatic faces is less than 55–80% (Fig. 2 in Higgins 1994). In addition, small crystals were more difficult to classify than large ones (Fig. 4) due to the spatial resolution of FE-SEM and the relatively large effect of shape rounding. From the above, the large proportion of ‘other’ in the acquired data is to some extent statistically unavoidable. Given that the proportion of particular trachts (i.e., octagonal, heptagonal, and hexagonal) was independent of the location within the sample, the ‘other’ crystals probably have the particular trachts in the same proportion as those identified. Therefore, the proportion of ‘other’ does not affect the following discussions.

Figure 3. BSE images of groundmass in run products from experiments (a) EQ_120, (b) and (c) SSD_20, (d) SSD_10, and (e) SSD_5. (c) and (e) include plagioclase crystals.

Groundmass pyroxene crystals were largely faceted and ubiquitous and had no obvious lineation in all run products. They exhibited different trachts according to the run products (Fig. 3, Table 2). All pyroxene cross sections were octagonal in EQ_120 (Fig. 3a) as were most in SSD_20 (Fig. 3b), although some near plagioclases were hexagonal and heptagonal (Fig. 3c). In contrast, hexagonal and heptagonal pyroxenes appeared in both near-Pl and Pl-free regions in SSD_10 (Fig. 3d) and SSD_5 (Fig. 3e). We note that these trends did not depend on the analyzed regions in the samples. Pyroxenes with parallelogrammatic tracht observed in Sakurajima pumice (Fig. 1b) were not produced in our experiments (Table 2).

Figure 4 shows the size distributions of pyroxene cross sections of each tracht in each experiment. Octagonal crystals spanned broad size ranges whereas hexagonal and heptagonal crystals were relatively small in all decompression experiments except SSD_5 (Figs. 4b–4d). In SSD_5, the number density of octagonal crystals was lower than that in EQ_120, whereas hexagonal and heptagonal crystals spanned a broad size range and were more abundant than octagonal ones (Fig. 4e).

**DISCUSSION**

As shown in Figure 4, more than half of the analyzed cross sections were classified as ‘other’ in almost all run products because their shapes were difficult to classify as the particular trachts. The classification as ‘other’ is mainly due to the relative position of the crystal to the polished surface of the sample: some crystals intersected the polished surface at their edges and corners or were oriented roughly parallel to the surface, which yielded the cross sections with insufficient prismatic faces for the classification. For a rectangular body with a 3D aspect ratio of 1:1:2–10, which is consistent with pyroxenes in our samples, the numerical model of Higgins (1994) calculated that the probability of a cross section consisting of only prismatic faces is less than 55–80% (Fig. 2 in Higgins 1994). In addition, small crystals were more difficult to classify than large ones (Fig. 4) due to the spatial resolution of FE-SEM and the relatively large effect of shape rounding. From the above, the large proportion of ‘other’ in the acquired data is to some extent statistically unavoidable. Given that the proportion of particular trachts (i.e., octagonal, heptagonal, and hexagonal) was independent of the location within the sample, the ‘other’ crystals probably have the particular trachs in the same proportion as those identified. Therefore, the proportion of ‘other’ does not affect the following discussions.

The tracht-specific CSDs (Fig. 4) reflect the temporal evolution of crystal textures during the experiments. The wide size range of octagonal crystals originates from crystallization during equilibration at 120 MPa before decompression (Fig. 4a). The small sizes of hexagonal and heptagonal pyroxenes in all decompression experiments except SSD_5 (Figs. 4b–4d) suggest that they formed while the experiments were held at P_f after decompression. The broader size range of hexagonal and heptagonal pyroxenes in SSD_5 (Fig. 4e) is probably due to their overgrowth on pre-existing octagonal crystals, consistent with compositional zonings observed in the pyroxenes (Figs. 3d and 3e). Therefore, decompression-induced crystallization in Pl-free regions of SSD_20 characteristically produces octagonal pyroxenes, whereas that in SSD_10, SSD_5, and near-Pl regions of SSD_20 characteristically produces hexagonal and heptagonal pyroxenes. The heptagonal tracht is probably an intermediate form in the transition from octagonal to hexagonal. These tracht changes are thus associated with two factors: the magnitude of decompression and the existence of plagioclase.
The decrease in $P_f$ caused the tracht of pyroxenes to change from octagonal to hexagonal, even in Pl–free regions of the run products (Figs. 4b and 4d). Since the extent of decompression in fluences $\Delta T_{ef}$, it is plausible that these changes resulted from crystallization kinetics depending on $\Delta T_{ef}$. Sekine et al. (1979) performed phase equilibrium experiments on groundmass from the 1914 Sakurajima pumice under water–saturated conditions at $f_{O_2}$ of NNO buffer. Using their estimates of pyroxene liquidus temperatures (915–930, 1000–1015, 1030–1040, and 1050–1060 °C at 120, 20, 10, and 5 MPa, respectively), we calculated $\Delta T_{ef}$ for our run products as the liquidus temperature at the experimental pressure minus the experimental temperature (920 °C). We obtained $\Delta T_{ef} = 0$–10, 80–95, 110–120, and 130–140 °C in experiments EQ_120, SSD_20, SSD_10, and SSD_5, respectively. These results indicate that larger $\Delta T_{ef}$ generated hexagonal pyroxenes, and the threshold value for producing octagonal versus hexagonal pyroxenes was around $\Delta T_{ef} = 90–110$ °C in our experiments.

The change in melt composition due to plagioclase crystallization (Table 1) probably also affected the tracht of nearby pyroxenes (Figs. 3c and 4c). As explained in Mujin et al. (2017) and shown in our results, the liquidus volume of plagioclase increases with decreasing water pressure compared to that of pyroxene, and their cotectic boundary shifts toward pyroxene. This favors plagioclase crystallization, which causes the evolution of melt and a resultant increase in $\Delta T_{ef}$ for pyroxene (Fig. 12b in Mujin et al., 2017).

In conclusion, pyroxene tracht reflects the effects of both decompression and melt evolution on $\Delta T_{ef}$. Given the trend that the number of prismatic faces decreases with increasing $\Delta T_{ef}$ (i.e., octagonal to hexagonal), we can predict that a further $\Delta T_{ef}$ would produce the parallelogrammatic tracht observed in the 1914 Sakurajima pumice (Fig. 1b). Further research is needed to experimentally reproduce the parallelogrammatic tracht and to investigate the effects on the tracht of experimental conditions such as the magnitude of decompression, the degree of crystallization, and the presence of seed crystals or pre-existing crystal nuclei in the melt before decompression.

### Table 2. Tracht analyses of run products

| Sample      | Analyzed area (µm²) | φ_Px (area%) | Octagon | Heptagon | Hexagon | Pentagon | Parallelogram | Other |
|-------------|---------------------|--------------|---------|----------|---------|----------|---------------|-------|
| EQ_120 (Pl–free) | 5724                | 1.7          | 40      | 0        | 0       | 0        | 0             | 46    |
| SSD_20 (Pl–free)  | 3387                | 3.6          | 67      | 2        | 1       | 0        | 0             | 84    |
| SSD_10 (near–Pl)        | 2032                | 4.2          | 21      | 8        | 18      | 0        | 0             | 66    |
| SSD_5 (near–Pl)         | 2710                | 5.5          | 22      | 9        | 17      | 0        | 0             | 26    |

**Figure 4.** CSDs of pyroxenes with respect to tracht. The logarithm of $N_a$ (the area number density of crystal cross sections) is plotted against crystal width for each size interval. The total number of crystals analyzed ($n$) and the proportion of crystals in each tracht are shown at top-right in each panel.

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### CONCLUDING REMARKS

We confirmed that the tracht of groundmass pyroxene crystals changes as a function of $\Delta T_{ef}$. In contrast, plagioclase shows no obvious change in morphology. Therefore, the pyroxene tracht records a range of $\Delta T_{ef}$ that differs from that inferred from plagioclase textures. In addition, tracht information is available even when pyroclasts contain few crystals because they have been quenched too rapidly to allow sufficient crystal nucleation. We conclude that pyroxene tracht is a promising indicator of magma ascent history and can be used to investigate magma ascent dynamics during explosive eruptions.

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REFERENCES

Caricchi, L., Burlini, L., Ulmer, P., Gerya, T., et al. (2007) Non-Newtonian rheology of crystal-bearing magmas and implications for magma ascent dynamics. Earth and Planetary Science Letters, 264, 402-419.

Cashman, K. and Blundy, J. (2000) Degassing and crystallization of ascending andesite and dacite. Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences, 358, 1487-1513.

Cassidy, M., Manga, M., Cashman, K. and Bachmann, O. (2018) Controls on explosive-effusive volcanic eruption styles. Nature Communications, 9: 2839. doi: 10.1038/s41467-018-05293-3.

Castro, J.M., Cashman, K.V. and Manga, M. (2003) A technique for measuring 3D crystal-size distributions of prismatic microlites in obsidian. American Mineralogist, 88, 1230-1240.

Castro, J.M. and Gardner, J.E. (2008) Did magma ascent rate control the explosive-effusive transition at the Inyo volcanic chain, California? Geology, 36, 279-282.

Castro, J.M. and Dingwell, D.B. (2009) Rapid ascent of rhyolitic magma at Chaitén volcano, Chile. Nature, 461, 780-783.

Hammer, J.E. (2008) Experimental studies of the kinetics and energetics of magma crystallization. In Minerals, Inclusions And Volcanic Processes (Putirka, K.D. and Teply, F.J. III Eds.). Reviews in Mineralogy and Geochemistry, 69, Mineralogical Society of America, Washington, D.C., 9-60.

Hammer, J.E. and Rutherford, M.J. (2002) An experimental study of the kinetics of decompression-induced crystallization in silicic melt. Journal of Geophysical Research, 107, doi: 10.1029/2001JB000281.

Higgins, M.D. (1994) Numerical modeling of crystal shapes in thin sections: estimation of crystal habit and true size. American Mineralogist, 79, 113-119.

Lofgren, G. (1974) An experimental study of plagioclase crystal morphology: isothermal crystallization. American Journal of Science, 274, 243-273.

Marsh, B.D. (1998) On the interpretation of crystal size distributions in magmatic systems. Journal of Petrology, 39, 553-599.

Mollard, E., Martel, C. and Bourdier, J.L. (2012) Decompression-induced crystallization in hydrated silica-rich melts: empirical models of experimental plagioclase nucleation and growth kinetics. Journal of Petrology, 53, 1743-1766.

Mujin, M., Nakamura, M. and Miyake, A. (2017) Eruption style and crystal size distributions: Crystallization of groundmass nanolites in the 2011 Shinmoedake eruption. American Mineralogist, 102, 2367-2380.

Nakamura, K. (2006) Textures of plagioclase microline and vesicles within volcanic products of the 1914-1915 eruption of Sakurajima Volcano, Kyushu, Japan. Journal of Mineralogical and Petrological Sciences, 101, 178-198.

Okumura, S., Ishihashi, H., Itoh, S., Suzumura, A., et al. (2021) Decompression experiments for sulfur-bearing hydrous rhyolite magma: Redox evolution during magma decompression. American Mineralogist, 106, 216-225.

Okumura, S.H., Mujin, M., Tsuchiyama, A., Shimobayashi, N. and Miyake, A. (2019) Crystal Size Distributions based on crystal habit of groundmass pyroxene crystals in the ejecta of the Shinmoedake 2011 eruption. Abstracts Japan Geoscience Union Meeting 2019, SCG52-04.

Okumura, S.H., Tsuchiyama, A. and Miyake, A. (2020) Habit and parallel intergrowth texture of the groundmass pyroxene in the pumice from the 1914 Plinian eruption at the Sakurajima volcano. The Abstracts 2020 Online Annual Meeting of Japan Association of Mineralogical Sciences, S1-05 (in Japanese).

Okumura, S.H., Mujin, M., Tsuchiyama, A. and Miyake, A. (2022) 3D crystal size distributions of pyroxene nanolites from nano X-ray computed tomography: Improved correction of crystal size distributions from CSDCorrections for magma ascent dynamics in conduits. American Mineralogist, in press. doi: 10.2138/am-2022-8039.

Preece, K., Gertisser, R., Barclay, J., Charbonnier, S.J., et al. (2016). Transitions between explosive and effusive phases during the cataclysmic 2010 eruption of Merapi volcano, Java, Indonesia. Bulletin of Volcanology, 78: 54, doi: 10.1007/s00445-016-1046-z.

Sekine, T., Katsura, T. and Aramaki, S. (1979) Water saturated phase relations of some andesites with application to the estimation of the initial temperature and water pressure at the time of eruption. Geochimica et Cosmochimica Acta, 43, 1367-1376.

Shea, T. and Hammer, J.E. (2013) Kinetics of cooling- and decompression-induced crystallization in hydrous mafic-intermediate magmas. Journal of Volcanology and Geothermal Research, 260, 127-145.

Sunagawa, I. (2005) Crystals: Growth, Morphology, and Perfection. pp. 295, Cambridge University Press, New York.

Swanson, S.E. (1977) Relation of nucleation and crystal-growth rate to the development of granitic textures. American Mineralogist, 62, 966-978.

Toramaru, A., Noguchi, S., Oyoshihara, S. and Tsune, A. (2008) MND (microlite number density) water exsolution rate meter. Journal of Volcanology and Geothermal Research, 175, 156-167.

Wolf, K.J. and Eichelberger, J.C. (1997) Syneruptive mixing, degassing, and crystallization at Redoubt Volcano, eruption of December, 1989 to May 1990. Journal of Volcanology and Geothermal Research, 75, 19-37.

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