Effects of volatile behaviour on dome collapse and resultant pyroclastic surge dynamics: Gunung Merapi 2010 eruption

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Abstract: In 2010, Gunung Merapi (Central Java, Indonesia) generated two violent eruption sequences on 26 October and 5 November culminating in widespread pyroclastic density currents (PDCs) associated with the destruction of lava domes. Tephra from PDC deposits were analysed to examine pre-dome collapse volatile behaviour and evidence of carbonate assimilation. Secondary-ion mass spectroscopy (SIMS) depth profiles of plagioclase phenocrysts reveal that the $^{7}\text{Li}/^{30}\text{Si}$ ratios in 26 October products are higher in the glass compared to the crystal, indicating a build-up of Li in the groundmass not observed in the 5 November samples. Higher Li in the groundmass suggests gas accumulation and rapid development of conduit overpressure in the shallow plumbing system prior to the initial 26 October explosion, which was only captured through the behaviour of quickly diffusing Li and not H$_2$O. Following the explosion-induced decompression, juvenile magma rapidly ascended in great volume to generate extremely destructive PDCs following subsequent dome collapses, particularly on 5 November. Additionally, 26 October tephras contain carbonate grains in the ash component and abundant CO$_2$ within the lava lapilli groundmass, which supports previous studies indicating assimilation of calc-silicate lithologies by the Merapi magma at depth in the plumbing system prior to the onset of 2010 activity.

Supplementary material: Feldspar microlite compositions and SIMS volatile data for the glass measurements are available at http://www.geolsoc.org.uk/SUP18762.

Merapi has remained one of the most active volcanoes in Indonesia throughout the Holocene; radiometric ages suggest a 170 ka record of volcanic activity, with observational records dating back to the 14th century (Gertisser et al. 2011). The eruption record shows regular transitions between explosive and effusive phases, generating both dome-collapse and column-collapse pyroclastic density currents (PDCs) that were often deadly. Merapi activity over the last few decades has been characterized by lava-dome extrusion at variable rates and collapse of domes to produce block-and-ash flows accompanied by pyroclastic surges (Boudon et al. 1993; Andreaastuti et al. 2000; Abdurachman et al. 2000; Siswowidjoyo et al. 1995; Hammer et al. 2000; Newhall et al. 2000; Voight et al. 2000a, b; Schwarzkopf et al. 2001, 2005; Gertisser & Keller 2003a; Charbonnier & Gertisser 2008; Donoghue et al. 2009; Komorovski et al. 2013). A particularly destructive phase occurred in 2006, when repeated block-and-ash flows resulted in surges that overtopped channel margins and destroyed surrounding villages, especially where sabo (‘sand-protection’) dams were present (Charbonnier & Gertisser 2008; Lube et al. 2011). These dams are mitigation constructs meant to decrease the hazards of sediment flows, yet may have actually contributed to the destructive nature of PDCs due to confinement of the available channel and subsequent avulsion of flows (Lube et al. 2011). Such was the case during the 2006 eruption of Merapi.

In October 2010, another intense cycle of activity was preceded by precursory seismicity and inflation of the edifice. Following an initial phreatomagmatic explosion, partial dome collapses were accompanied by explosions which produced numerous PDCs that travelled several kilometres from the edifice and resulted in the deposition of fall tephra in surrounding areas, the destruction of several villages, the evacuation of over 250 000 people and over 350 deaths (Surono et al. 2012). Two events produced particularly large and highly energetic PDCs: one on 26 October and another on 5 November (Cronin et al. 2013). The latter event was particularly large with the widest-spread PDCs known from Merapi in over 100 years, and the production of a high eruption plume (Cronin et al. 2013). This very large 5 November phase involved a considerable gas-driven explosive component (Pallister et al. 2013). Deposits from these PDCs, and intervening ash beds representing smaller surges and ash falls, were sampled from several

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locations that were described by Cronin et al. (2013). These samples were used to carry out a targeted examination of the physical characteristics of tephras recording the observed transition from dome collapse to rapid dome re-growth and explosion-augmented collapse. The sequence of smaller pyroclastic surge, flow and ash-fall deposits provide a detailed record (of almost daily resolution) for individual eruptive events during this heightened cycle of activity.

Detailed petrologic and geochemical analyses have already been performed on samples from several stages of recent Merapi activity. Dome lavas from the 1986–88, 1992–93, 1994 and 1995 effusive periods reveal highly evolved rhyolitic glasses containing 70% crystals with feldspar microlite compositions transitioning from plagioclase at the core to alkali feldspar at the rims (Hammer et al. 2000; Preece et al. 2013). This disequilibrium compositional variation was attributed to degassing of the lava during conduit ascent, and samples show a correlation between dome effusion rate and groundmass microlite content (Hammer et al. 2000). The influence of H2O on the rheological properties of the Merapi magma has therefore already been well documented.

In addition to H2O, the role of CO2 also has a significant effect on magma properties. The low solubility of CO2 in magma at low pressures may influence the vesiculation and degassing dynamics of the magma, as well as the corresponding mineral phase assemblage and crystallization kinetics. Merapi is one of several active volcanoes in the world located above a carbonate platform (e.g. van Bemmelen 1949); consequently, activity at this centre is heavily influenced by magma–carbonate interaction (Chadwick et al. 2007; Deegan et al. 2010, 2011; Troll et al. 2013). Crustal xenoliths have been documented in the volcanic products of Merapi (Camus et al. 2000; Gertisser & Keller 2003b; Chadwick et al. 2007; Troll et al. 2012; van der Zwan et al. 2013), including calc-silicate skarns, although none have been observed in the 2010 products as of yet (Borisova et al. 2013). Deegan et al. (2010) performed experiments to examine the textural, chemical and isotopic effects of magma–carbonate interaction and found that distinct melt compositions were generated. They observed the formation of Ca-rich melt zones locally supersaturated in CO2 and noted the evidence of calc-silicate contamination of the Merapi melt in xenolith-bearing samples. Several calc-silicate minerals are present within these samples, including spurrite (Ca5(SiO4)2 (CO3); Chadwick et al. 2007; Deegan et al. 2010). Experimental studies also indicate that at low pressures exsolution of CO2 from the melt phase of the magma may be especially vigorous (Deegan et al. 2010, 2011), which will significantly influence the mechanisms of fragmentation. All of these factors could affect the rheological properties of the ascending magma, the dynamics of lava dome effusion and the transport properties of PDCs. Quantitative evidence for these upper crustal lithological effects is however lacking.

Borisova et al. (2013) performed detailed geochemical analyses of the 2010 eruptive products to determine the extent of crustal assimilation and found that incorporation of calc-silicate xenoliths occurred during the 1998 and 2006 eruptive sequences. They also concluded that complete digestion of these xenoliths occurred prior to the 2010 eruption. In the study presented here, we examine the geochemical properties of the 2010 PDC deposits to elucidate the role that volatiles (H2O, CO2, F, Li) play during and between eruptive phases. We use groundmass volatile contents of the juvenile lava and mineralogical analyses of ash to examine the extent of carbonate assimilation in the 2010 surge deposits and address previous findings described by Borisova et al. (2013). Using secondary-ion mass spectroscopy (SIMS) depth-profiling analyses, we examine the behaviour of rapidly diffusing elements (Li and H) within plagioclase phenocrysts during the final stages of conduit ascent and use these data to assess degassing processes prior to the 2010 events. These volatile phases can provide information on degassing processes during the final stages of magma ascent over very short timescales (minutes to hours) and, in some cases, Li can capture variations not captured by H because it diffuses more rapidly (Zhang & Behrens 2000; Richter et al. 2003; Charlier et al. 2012). Examination of groundmass textures in lava lapilli provide evidence for variations in the decompression path during different phases of dome growth; groundmass textures are notably heterogeneous due to the presence of crystalline inclusions, which may also provide information on the assimilation process. For each of the phases described below using the four-phase chronology of Surono et al. (2012) and Pallister et al. (2013), Cronin et al. (2013) identified specific deposits

Fig. 1. Distribution of sedimentary facies of PDC deposits emplaced during the 2010 Gunung Merapi eruption in 26 October (Phase 2) and 5 November (Phase 3). Samples used in this study were retrieved from 6 stratigraphic profiles (4 in the Kinahrejo surge area west of the Kali Gendol channel, white dots; 2 in the Kendil surge area east of Kali Gendol, grey dots) where surge inundations overlapped and where the preservation of the 2010 eruption stratigraphy was most complete.
including those produced by dense valley-focused basal avalanches within the Kali Gendol valley as well as those from expanded PDC currents that spread broadly across the southern slopes (Fig. 1).

Magma intrusion and dome expansion took place during Phase 1 (31 October 2009–26 October 2010), with the last five days showing steam emission and many rockfalls. Phase 2 (26 October–1 November 2010) started with an explosive eruption and sudden dome collapse, producing up to eight PDCs down the Kali Gendol out to 4.9 km (the largest deposit sampled as Unit I; Cronin et al. 2013), along with an extremely violent and mobile surge extending 6.4 km from source (sampled as S1 and K1; Cronin et al. 2013). The surges caused at least 35 fatalities. More than 38 smaller basal avalanches occurred during the days that followed and, on 30 October, an explosive eruption generated an 18 km high plume, destroyed the remaining dome and deposited ash southwards over the sampling area. Phase 3 (1–7 November 2010) began with the rapid effusion of magma and dome regrowth in the SSE-opening crater, accompanied by rockfalls and PDCs out to 4 km from source. Large PDCs were generated on 3–4 November, reaching out to 10 km in the Kali Gendol (sampled as Units II to VII). These also included small surges (sampled as S2–3 and K2). The largest event during this eruption episode occurred in the early hours of 5 November. PDCs reached c. 16 km in Kali Gendol (sampled as Units VIII and IX), and spilled out into adjacent channels. This event also generated the most violent and widespread surge of the sequence, reaching >8 km from source (sampled as K3 and S4). The 26 October and 5 November surges had blast-like dynamics and were augmented by both initial explosive impulse as well as the funnelling effects of the local topography (Cronin et al. 2013). Over 200 people were killed during the 5 November eruption and a large ash plume developed, with ash falling mainly to the west. Ongoing lava extrusion and ash falls occurred during the following two days, with rockfalls as well as column-collapse-generated PDCs in the Kali Gendol (sampled as Units X–XI). The final Phase 4 of the eruption was a waning phase (8–23 November 2010), where dome growth ended by 8 November and the number of explosions and small PDCs decreased sharply for the next few weeks. In summary, the two main sets of samples focused on during this study were from the major climactic events on 26 October (Unit 1, S1, K1) and 5 November (Unit VII–IX, S4, K3). These two events generated the most widespread and deadliest surges (Cronin et al. 2013).

Samples and methods

Samples of the 2010 PDC deposits from the units described above were collected from several
stratigraphically correlated locations on the southern flanks of Merapi during January–February 2011. A total of 37 tephra layers were collected from 6 sampling locations on the southern flank of the Merapi edifice where pyroclastic surges were deposited (Figs 1 & 2). Bulk tephra samples were oven-dried at 60 °C for several days in order to remove adsorbed water before sieving. Table 1 provides identification numbers for all of the samples utilized and indicates which analyses were performed for each sample. Because tephra layers in the stratigraphic sequences were of variable thicknesses and contained various proportions of ash and lapilli, size limitations did not allow us to subject all samples to the same analyses.

**Ash-sized fraction of PDC deposits**

Ash-sized fractions of the PDC samples were sieved from −1.0φ (2 mm) to 5φ (31 μm) increments. The dominant fraction was imaged with the scanning electron microscope (SEM), and a portion was tested for reaction with HCl. The raw, bulk, ash-sized component of 12 samples was examined with a Bruker D8 Advance X-ray diffractometer (XRD) to search for the presence of carbonate minerals. Samples were analysed with CuKα radiation over the range of 5–70° 2θ at each step of 0.02°.

SIMS depth-profiling analyses were used to examine compositional variations in the rims of plagioclasefeldspar phenocrysts. Plagioclase phenocrysts were separated from the 1.0φ (0.5 mm) ash-sized fraction, cleaned and imaged with the Hitachi TM-1000 Tabletop SEM to select the best candidates for SIMS depth-profiling analyses, which displayed euhedral crystal faces covered with a relatively homogenous layer of groundmass glass (for further details of crystal selection see Genareau et al. 2007). For the depth-profiling analyses, selected plagioclase phenocrysts were mounted in indium and a 12.5 kV O₂⁻ primary ion beam operating at a current of 25–35 nA was used to sputter positive secondary ions from the sample held at 5 kV. The primary beam was focused to a diameter of c. 75 μm using aperture illumination (Clement & Compston 1990). A 400 μm field aperture was used to focus secondary ions into the mass spectrometer from the central 15 μm of the sputtered crater and eliminate contributions from the crater walls. Charging was compensated using a normal-incidence electron gun. The spectroscopic routine measured ⁴H, ⁷Li, ¹¹B, ¹⁹F, ²³Na, ²⁷Al, ³⁰Si, ³⁹K, ⁴²Ca, ⁴⁷Ti, ⁵⁴Fe and ⁸⁸Sr over a period of 2–12 hours. Four standards (Stillwater plagioclase, Lake County plagioclase, Amelia albite and Los Posos rhyolite) were also measured using the same analytical conditions. SIMS craters were imaged with the SEM following analysis to determine approximate crater depths.

**Lapilli-sized fraction of PDC deposits**

Lapilli-sized fractions were separated, cleaned and several clasts > 1 cm were selected to make polished thin sections. Thin sections were analysed under the petrographic microscope, the scanning electron microscope (SEM), the electron microprobe (EMP) and the secondary-ion mass spectrometer (SIMS). Thin sections were imaged with the SEM to roughly assess the groundmass textures between the different phases of dome growth and to image inclusions within the juvenile lava lapilli. A total of 15 thin sections were prepared and, for the textural examination of groundmass microlite contents, 15 images were examined at 1500× magnification from each of 4 sections and the microlites (feldspar, pyroxene and Fe-oxides) were counted. Binary images were used to measure the vesicularity as the percentage of void space relative to total area of the image in 2D.

Thin sections of lava lapilli were analysed with the Jeol JXA-8900 Superprobe to determine groundmass feldspar microlite compositions and obtain X-ray maps of particular elements. For the EMP feldspar analyses, a 15 kV, 40 nA focused beam was used to measure the albite (Ab), anorthite (An) and orthoclase (Or) content in 20–40 individual microlites per section relative to selected mineral standards, in order to differentiate the eruptive phase based upon the feldspar microlite composition. X-ray maps were used to examine the zoning of particular elements in both the phenocryst rims and microlites, and to determine areas of the sample contaminated with epoxy from sectioning.

X-ray element maps were obtained at 1500× on the Superprobe using an accelerating voltage of 12 kV and a dwell time of 12 ms to map an area of 500 × 500 pixels. Maps were obtained of C, Ca, Fe, K, Na and Si abundance, in addition to back-scattered electron images. The analyses outlined above were used primarily to differentiate the 26 October from the 5 November juvenile magma and to supply supporting data for the volatile and inclusion examinations.

SIMS spot analyses were performed to examine volatile contents (H₂O, CO₂, F) of the groundmass glass in the lapilli. A 10 kV, 25 μm rastered Cs⁺ primary ion beam operating at a current of 10 nA was utilized to examine ¹²C, ¹⁸OH, ¹⁸O, ¹⁹F and ²⁸Si. A 150 μm contrast aperture and 100 μm field aperture were used to sputter negative secondary ions from an area c. 8 μm in diameter with the sample held at −5 kV. Samples were held at high vacuum for several hours prior to analysis in order to minimize background H interference.
| Date (Phase) | Stratigraphic sample* | Ash analyses | Lapilli analyses | Thin sections prepared† | SIMS spot analyses | Inclusions present |
|-------------|----------------------|--------------|-----------------|-------------------------|-------------------|------------------|
| | | XRD analysis | XRD confirmation of carbonate | HCl rxn | SIMS depth profiles† | | |
| 5 Nov (Phase3) | 526-1 | | X | X | | |
| | 526-2 | | | | | |
| | 526-3 | | | | | |
| | 526-4 | | | | | |
| | 526-5 | | | | | |
| | 526-6 | | | | | |
| | 526-7 | | | | | |
| | 526-8 | | | | | |
| 26 Oct (Phase2) | 527-1 | | X | | X | |
| | 527-2 | | X | | X | |
| | 527-3 | | X | | X | |
| | 527-4 | | | | | |
| | 527-5 | | | | X | |
| | 527-6 | | | | | |
| 5 Nov (Phase3) | 527-7 | | | X(2) | X(4) | X |
| | 530-1 | | | | X(1) | |
| | 530-2 | | | | | |
| | 530-3 | | | | | |
| | 530-4 | | | | | |
| 5 Nov (Phase3) | 537B-1 | | | X(3) | X(3) | X |
| | 537B-2 | | | | | |
| | 537B-3 | | | | | |
| | 537B-4 | | | | | |
| | 537B-5 | | | | | |
| 26 Oct (Phase2) | 537B-6 | | | X | X | X |
| 5 Nov (Phase3) | 576-1 | | X | X | X(2) | X(1) |
| | 576-2 | | X | X | X(3) | |
| | 576-3 | | X | | | |
| 26 Oct (Phase2) | 576-4 | | X | X | X | |
| 26 Oct (Phase2) | 576-5 | | X | | X | |
| 26 Oct (Phase2) | 576-6 | | X | | X | |
| 5 Nov (Phase3) | 577-1 | | X | X | X(1) | X(2) |
| | 577-2 | | X | X | X(1) | |
| | 577-3 | | X | X | | |
| | 577-4 | | X | X | | |
| 26 Oct (Phase2) | 577-5 | | X | X | | |
| 26 Oct (Phase2) | 577-6 | | X | X | | |

*Location of sample collection site is provided in Figure 1; †Numbers in parentheses indicate the quantity of lapilli or plagioclase phenocrysts that were examined for each sample location.
Table 2. Comparison of textural and geochemical characteristics between 26 October (Phase 2) and 5 November (Phase 3) pyroclastic density current (PDC) deposits

|                      | 26 October (Phase 2) | 5 November (Phase 3) |
|----------------------|----------------------|----------------------|
| **Lapilli analyses** |                      |                      |
| Vesicularity (%)     | 12.7 (5.2)           | 12.6 (3.8)           |
| Groundmass microlite density (mm⁻²) | 5.7 (1.7) × 10³ | 7.6 (0.9) × 10³ |
| Groundmass microlite morphology | Euhedral/tabular | Lath/swallowtail/hopper |
| Feldspar microlite An content (mol%) | 5–40 | 40–70 |
| Feldspar microlite Or Content (mol%) | 5–55 | 1–10* |
| Maximum groundmass H₂O content (wt%) | 0.07 | 0.05 |
| Maximum groundmass F content (ppm) | 284 | 927 |
| **Ash analyses**     |                      |                      |
| An content of phenocryst rims | Decreasing | Decreasing |
| H content from phenocryst to groundmass | Increasing | Increasing |
| Li content from phenocryst to groundmass | Increasing | Decreasing |

*One outlying measurement was removed. Numbers in parentheses represent the standard deviation.

**Results**

Table 2 presents a comparison of the textural and geochemical characteristics observed between the 26 October and 5 November PDC deposits. The microlite textural and geochemical data show clear differences in the lava lapilli (in terms of microlite composition, morphology and number density), and indicate variations in the relative extent of degassing and decompression-induced microlite crystallization between 26 October and 5 November. This information enables the interpretation of the SIMS phenocryst data described in the section ‘Phenocryst rim compositions’. Lapilli-sized fragments of lava are contained within most of the deposits. Lapilli from deposits produced during 26 October of the eruptive sequence (including 26 October widespread surge units) are pale grey lava fragments, rich in feldspar phenocrysts. By contrast, those from the later phases (including the 5 November surge deposits) are darker grey with fewer feldspar phenocrysts. Lava fragments from both phases have similar vesicularities, 12.7 (±3.8)% for 26 October samples and 12.6 (±5.2)% for 5 November, and some lapilli from 5 November contain inclusions of more crystalline material, described in the section ‘Lapilli groundmass textures’. In the majority of samples, the dominant size fraction of the ash component is between 1µ and 2µ. This ash mode is largely composed of free crystals in the 26 October deposits and lava fragments in the 5 November deposits. Some pumice and accidental fragments are also present in most of the samples. The ash component of four total samples from two separate locations displayed reaction to HCl when tested. These were located in the bottom units of the stratigraphic sequence shown in Figure 2 (K1 and S1), and therefore represent samples generated by the main PDC during 26 October.

**Groundmass microlite compositions**

The major element compositions of feldspar microlites in the lapilli groundmass reveal differences between the lava lapilli that confirm their origin from either the 26 October or 5 November episode of dome growth. Microlites from the 26 October lapilli are more enriched in alkali elements, with An contents <40 mol% on the feldspar ternary plot. However, the majority of 5 November microlites display plagioclase compositions with An contents between 50 and 70 mol% (Table 2; Fig. 3). The 26 October measurements are consistent with previous analyses of the 2006 lava dome (Preece et al. 2013), where alkali-rich microlite rims were attributed to degassing of the magma and shifting of the feldspar liquidus (Nekvasil 1992; Hammer et al. 2000; Preece et al. 2013). However, these results should be considered in light of the inclusion and partial disaggregation of more crystalline material into the juvenile magma, which may have contributed plagioclase microlites that do not reflect ascent conditions. The groundmass microlite measurements are therefore not treated further, but are only used to interpret the ascent dynamics provided by the analysis of volatile element behaviour.

**Groundmass glass compositions**

Groundmass glass compositions in the lava lapilli are very similar between the 26 October and 5 November samples in terms of H₂O content, but noticeably different in terms of CO₂ and F content (Table 2; Fig. 4). Groundmass glass within the 26 October lapilli is enriched in CO₂ relative to the 5 November lapilli, while the 5 November lapilli displays groundmass glass enriched in F relative to the 26 October samples. The 26 October CO₂ contents average 135 000 ppm with a maximum measured
value of 468 000 ppm, while 5 November CO₂ contents are much lower and average 17 886 ppm with a maximum measured value of 59 700 ppm. The 26 October F contents average 40 ppm with a maximum measured value of 284 ppm, whereas 5 November F contents average 421 ppm with a maximum measured value of 927 ppm. Due to the high number densities of microlites in the groundmass, the results of volatile spot analyses in some cases may be an average of both matrix glass and portions of microlite phases; the high F results from the 5 November products however suggest this may be true for only a few of the examined spots (SIMS depth-profiling indicates F below detection limits in the plagioclase, which comprises the majority of the microlite phases).

**Fig. 3.** (a) Feldspar ternary plot displaying the measured compositions of microlites in the groundmass of the examined lava lapilli, which were used to differentiate juvenile lava between 26 October and 5 November of the 2010 eruptive sequence. The 26 October microlites are enriched in alkali elements, consistent with previous analyses of the 2006 lava (Preece et al. 2013), which were interpreted as the result of efficient devolatilization during slower magma ascent. Conversely, 5 November microlites are more An-rich due to more rapid growth at shallow conduit levels. Errors lie within the size of the symbols. (b) Backscattered electron images of the juvenile lava groundmass.

Phenocryst rim compositions

SIMS depth profiles (Genareau et al. 2007, 2009; Genareau & Clarke 2010) were performed on 16 plagioclase phenocrysts (Fig. 5) from the ash-sized fraction of PDC deposits to determine how particular isotopes varied over the last few microns of crystal growth and in the transition from crystal to groundmass. Because samples were not etched or polished, all phenocrysts were coated with some residual groundmass of variable thickness. Textures on phenocryst surfaces were easily distinguishable between 26 October and 5 November samples. Phenocrysts from the 26 October samples displayed well-developed round vesicles preserved in the surface groundmass, while samples from 5 November were coated with more microlites. These textures were consistent with preliminary examinations of ash-grain morphologies for the respective phases. This textural distinction is relevant due to the potential mixing between tephras during density current transport, which may cause phenocrysts from earlier deposits to become entrained in later deposits; this was observed during examination of the tephras.

The boundary between groundmass and phenocrystal surface within the depth profiles was
Fig. 4. SIMS volatile measurements of lava lapilli groundmass glasses reveal (a) low H$_2$O contents in all samples; (b) higher CO$_2$ concentrations in 26 October products relative to 5 November products (the dashed horizontal line indicates the maximum measured value in the 5 November products, which is roughly two orders of magnitude higher than solubility limits allow to be dissolved in the melt); and (c) higher F concentrations in 5 November products relative to 26 October products. Error bars lie within the size of the symbol in some cases.
Fig. 5. Secondary electron images of plagioclase phenocrysts from the 1e (0.5 mm) ash fraction of the PDC deposits, which were depth-profiled using SIMS. Phenocrysts were selected based upon the presence of a flat crystal face covered with a relatively homogenous layer of groundmass, indicating that the outer surface of the phenocryst was in direct contact with the melt phase of the magma at the point of fragmentation.
demarcated by a significant reduction in the count rates of most isotopes, particularly the more volatile elements of $^1H$, $^7Li$, $^{11}B$ and $^{19}F$. In all cases, the $^{11}B/^{30}Si$ and $^{19}F/^{30}Si$ ratios fell below detection limits once the crystal was reached. All depth profiles show that the plagioclase rims were becoming more albitic during the final stages of growth (Fig. 6), consistent with expected compositions forming as a result of either cooling or decompression-induced crystallization in an open-system degassing environment (e.g. Burnham 1979; Sisson & Grove 1993; Moore & Carmichael 1998; Cashman & Blundy 2000). There was no measurable difference in the final An decrease between samples from the 26 October and 5 November lavas, with all analysed crystals decreasing by 3–19 mol% in the final 2 $\mu$m of growth. Precision in the An measurements was c. 2 mol%. Despite similarities in An content between the feldspars, the behaviour of other profiled isotopes was markedly different between the 26 October and 5 November crystals. Proceeding outwards from the crystal into the groundmass, $^1H/^{30}Si$ increases in all examined samples but the $^7Li/^{30}Si$ increases only for the 26 October phenocrysts (Table 2; Fig. 7). In phenocrysts derived from the 5 November deposits, $^7Li/^{30}Si$ either decreases or remains constant in the transition from phenocryst to groundmass (Table 2; Fig. 8).

**Presence of carbonates**

Testing of the ash-sized tephra component with HCl revealed a reaction indicative of carbonate in four of the samples (Table 1). Gentle bubbling was observed under the binocular microscope in portions of the sample. XRD spectra reveal peaks at intensities and d-spacings indicative of carbonate (calcite and dolomite) minerals (Fig. 9) in 7 of 12 examined samples. Although the proportion within each sample was not directly quantified because we were only seeking confirmation of carbonate presence, the intensity of the dominant carbonate peaks was low relative to more abundant minerals (e.g. plagioclase). This suggests they comprise a small percentage (<5%) of the ash sample, which is supported by the limited nature of the HCl reaction in only 4 of the samples.

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**Fig. 6.** Representative examples of SIMS anorthite (An mol%) depth profiles into 4 of the 16 analysed plagioclase phenocrysts from the ash-sized fraction of PDC deposits. 26 October (Phase 2) crystals are on the left and 5 November (Phase 3) crystals are on the right. All analysed crystals displayed decreasing An trends of 3–19 (±2) mol% in the final 2 $\mu$m of growth, with no observable differences between the two eruptive phases. The dashed vertical line marks the transition from groundmass (gm) to plagioclase. Precision in the An measurements is c. 2 mol%.
Lapilli groundmass textures

The groundmass textures provide a first-order comparison between different magma ascent rates for the two phases of dome growth, and are used to aid interpretation of the volatile data. This precursory treatment of groundmass textures is due to the heterogeneity observed, which indicates disaggregation and partial assimilation of more crystalline inclusions into the juvenile magma. These inclusions, especially dominant within the 5 November lava lapilli, are on the order of 1–3 mm in diameter and are dominated by unzoned, euhedral plagioclase microlites in addition to subhedral Fe-oxides, interstitial anhedral pyroxene and partially vesiculated microlite-free glass (Fig. 10). Boundaries with the juvenile magma are crenulate to lobate and, in some instances, there is evidence of the microlite-rich juvenile melt infiltrating the inclusion boundary for tens of microns and disaggregating some plagioclase crystals (Fig. 10). Portions of these inclusions may therefore have contaminated the juvenile groundmass of the 5 November products as a result of assimilation during magma ascent. Based upon the texture and mineralogy of the inclusions, we classify them as co-magmatic felsic enclaves (according to the terminology of Chadwick et al. 2013).

Discussion

CO₂ values

The CO₂ measurements obtained with SIMS cannot be the result of CO₂ dissolved in the melt, because most of the values lie far above the solubility limit for magmas of this composition at these pressures (e.g. Holloway 1976; Holloway 1981; Holloway &
Blank 1994; Dixon & Stolper 1995; Dixon et al. 1995; Lowenstern 2001; King & Holloway 2002; Newman & Lowenstern 2002; Lesne et al. 2011; Pichavant et al. 2013). CO₂ contents should not exceed 500 ppm for rhyolite melts with the H₂O contents measured (0.5 wt%; e.g. Newman & Lowenstern 2002). The methods utilized in the SIMS spot analyses inhibit the values to be the result of interference with Mg in the samples, since negative secondary C ions were measured using a mass resolving power of 5000 and both methods eliminated possible interference with secondary Mg ions. A matrix effect does exist in terms of high H contents causing an underestimation of the C contents, but all analyses that simultaneously produced anomalously high H and C were discarded. Although products from both 26 October and 5 November contained high CO₂, the amounts measured in the 26 October lapilli were consistently higher, despite similar H₂O and lower F concentrations. Based upon the XRD results which indicate the presence of small amounts of carbonate minerals in the tephra deposits, the high CO₂ values in the 26 October samples are most likely a result of the physical incorporation of carbonate xenoliths into the juvenile magma; the highest measurements stem from the analysis of groundmass glass containing residual portions of this assimilated carbonate material.

Crystallization during magma ascent

X-ray element maps indicate that the Na-enriched rims on the feldspar microlites in the 5 November dome material are c. 2 μm thick. This observation formed the basis of our detailed examination of the final 2 μm of growth in the depth-profiled plagioclase phenocryst rims. All depth-profiled samples showed decreasing An content with no discernable difference between samples from the 26 October and 5 November dome-derived phenocrysts (Fig. 6). The range in An decrease probably reflects the
Fig. 9. One example of X-ray diffraction (XRD) spectra (at 20–50°) from the PDC ash component, showing peaks at appropriate d-spacings and of appropriate magnitudes to indicate the presence of a low proportion (<5%) of calcium carbonate according to the utilized XRD software. Spectra were consistent with the presence of carbonate minerals in 7 of the 12 examined samples. Inset shows the entire spectra from 0–65°.
various positions in the magma at which the different crystals were growing, and this growth may have continued during ascent. The order of magnitude increase in number density of all microlite phases in the 5 November lapilli suggests that this stage of dome growth followed a different decompression path compared to the 26 October dome. The former ascended at a more rapid rate, which resulted in a nucleation-dominated crystallization regime (e.g. Lofgren 1974; Fenn 1977; Kirkpatrick 1981; Swanson et al. 1989; Geschwind & Rutherford 1995; Hammer et al. 1999, 2000; Cashman & Blundy 2000; Hammer & Rutherford 2002; Couch et al. 2003; Clarke et al. 2007; Martel 2012; Preece et al. 2013) and contributed to continuous H2O degassing and Li loss from the melt.

H2O contents of all examined samples are low (<0.5 wt%), indicating extensive degassing of both the 26 October and 5 November lavas. However, F contents of the 5 November lapilli are higher compared to 26 October lapilli. This is likely a result of the comparative amount of degassing and decompression-induced crystallization in the two phases. The 26 October lava was able to ascend and degas efficiently before stalling at shallow levels, as indicated by the H2O and microlite contents in addition to the alkali-rich compositions of the microlites. The 5 November lava also degassed efficiently but ascended more rapidly, resulting in loss of H2O and a greater degree of microlite nucleation and consequently a build-up of F in the residual melt. As the SIMS depth profiles of the plagioclase phenocrysts indicate, F is not present in the feldspars. However, F is compatible in amphibole. The 5 November dome experienced a great deal of decompression-induced crystallization, suggesting that amphibole may have broken down and possibly contributed additional F to the melt phase. The increased groundmass crystallinity occurring at depths (<9 km) outside of the amphibole stability field could therefore result in further F enrichment of the melt.

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Fig. 10. (a–d) Backscattered SEM images of inclusions in juvenile lava lapilli. Several 5 November lava lapilli contain crystalline inclusions (CI) that are dominated by euhedral plagioclase microlites with interstitial anhedral pyroxene in a matrix of microlite-free groundmass glass in the juvenile lava (JL). The margin between the inclusions and juvenile lava is represented by the yellow line and reveals partial disaggregation of the crystalline inclusions (yellow box in c) and infiltration of the microlite-rich juvenile lava groundmass into the periphery of the inclusion for tens of microns (yellow arrow in d).
although evidence of amphibole breakdown was not explicitly sought in this study. Previous studies of melt inclusions from Merapi (Nadeau et al. 2013) suggest that F may partition preferentially into the fluid and, in cases of vapour-brine exsolution, may prefer the brine over the vapour (Aiuppa et al. 2009; Nadeau et al. 2013). The results presented here, which reveal higher F and lower Li in the 5 November products compared to the 26 October products, indicate that F did not behave in a manner similar to Li and remained in the melt rather than exsolving with the fluid.

**Li behaviour**

The behaviour of Li, as revealed in the SIMS depth profiles, indicates that the measured ion ratios are potentially the result of both degassing and diffusion in the shallow plumbing system. Previous depth-profiling studies (Genareau et al. 2009; Genareau & Clarke 2010) suggest that Li may indicate the onset of volatile degassing in an ascending magma if Li is assumed to partition preferentially into the fluid phase (Webster et al. 1989). Li will therefore show progressively decreasing concentrations in the rims of plagioclase phenocrysts growing as a result of decompression-induced crystallization in a devolatilizing magma. The SIMS depth-profiling results in this study reveal decreasing or constant $^{7}\text{Li}/^{30}\text{Si}$ ion ratios within the final microns of plagioclase phenocrysts for all of the examined samples regardless of eruptive phase, suggesting that Li was either diffusing out of the crystal during the final stages of ascent or that the final microns of phenocryst growth occurred adjacent to a progressively Li-depleted melt. However, it is the Li behaviour in the *groundmass* on the surfaces of phenocrysts that indicates changes in the degassing state of the system between 26 October and 5 November of the 2010 Merapi eruption. The build-up of Li in the 26 October groundmass glass shows that exsolving volatiles, likely originating from a deeper magma source, were accumulating in the shallow conduit system and contributed to the development of system overpressure (e.g. Berlo et al. 2004) immediately prior to the initial 26 October explosion. Conversely, depth profiles of the 5 November crystals reveal a more efficient loss of Li from the melt, due to its higher (2–3 times) diffusion rate compared with H$_2$O (Zhang & Behrens 2000; Richter et al. 2003; Charlier et al. 2012). Coupled with the increased microlite crystallization and melt F enrichment of 5 November, this indicates efficient volatile degassing during magma ascent, causing the Li to escape more rapidly. The shift from protracted volatile accumulation to efficient volatile escape between 26 October and 5 November of the 2010 eruption was too rapid to be constrained through slower-diffusing elements such as Ca and Na. Even H$_2$O was not able to escape the melt as rapidly as Li; the final moments of volatile exsolution during ascent of the 5 November lava dome can therefore only be geochemically observed through the behaviour of Li.

**Carbonate assimilation**

We provide the findings outlined above as supporting evidence for the previous work of Borisova et al. (2013), which interpreted the geochemical analyses of 2010 Merapi products as an indication of complete assimilation of calc-silicate inclusions. The results presented here also suggest that calc-silicate assimilation was in its final stages during 26 October and proceeded to completion with the onset of the 5 November magma ascent and lava effusion. This interpretation is based upon comparison between data derived from the 26 October and 5 November PDC deposits, summarized below.

- **26 October:** (1) reaction of ash samples in the lowermost layers of two stratigraphic sequences with HCl; (2) spatially variable and extremely high (far beyond reasonable melt solubility levels) CO$_2$ measurements in the lapilli groundmass glass; and (3) peaks in XRD spectra at d-spacings indicative of carbonate minerals within ash samples derived from lower layers of the stratigraphic sequences.
- **5 November:** (1) spatially variable and high (but lower than those for 26 October samples) CO$_2$ measurements in the lapilli groundmass glass; (2) peaks in XRD spectra at d-spacings indicative of carbonate minerals within ash samples derived from upper layers of the stratigraphic sequences, although this may result from remobilization of lower layers where carbonate preservation appears to be higher; and (3) observed partial disaggregation of crystalline inclusions derived from the magma storage zone, which lies above the depth at which calc-silicate xenoliths were incorporated into the 2006 juvenile magma.

Since carbonate assimilation is occurring at depth (>10 km) in the plumbing system as suggested by previous studies (e.g. Chadwick et al. 2007; Troll et al. 2012; Borisova et al. 2013), some portions of incorporated inclusions of this material would be efficiently disaggregated due to the interaction with higher-temperature (>1000 °C; Costa et al. 2013) juvenile magma. Relict fragments of carbonate have been found in calc-silicate xenoliths from previous eruptive episodes at Merapi (Deegan et al. 2010; Troll et al. 2012); the disassociation (essentially, melting) of carbonate therefore resulted in spatially variable and high levels of CO$_2$. 
throughout the melt phase of the juvenile magma. Any existing remnants of these inclusions that survived ascent through the conduit were later disaggregated during PDC transport, resulting in ash-sized fragments of carbonate in very limited portions of the tephra as indicated by both the XRD spectra and HCl reaction. This evidence for carbonate minerals is more prevalent in lower layers of the stratigraphic sequences than in upper layers. We interpret this as a relatively higher degree of preservation for carbonate remnants in the earlier stage of eruption and the likely remobilization of 26 October products into upper layers of the sequences (derived from 5 November) during PDC transport.

Conclusions

The 2010 eruptive events at Gunung Merapi began with an explosion, contrary to typical behaviour at Merapi. This explosion also generated one of the most energetic pyroclastic surges seen at the volcano for over 150 years. The 26 October 2010 explosion destabilized the 2006 dome material that resided in the conduit, clearing the way for ascent of juvenile magma which subsequently went on to generate a series of explosions, culminating in the largest and most violent surge-producing event on 5 November 2010. The combined geochemical and textural analyses of PDC deposits from these two main eruptive events (and intermediate events) during the 2010 episode provide information on the relative roles of carbonate assimilation and volatile behaviour in the transition from 26 October to 5 November of the eruptive sequence. Calc-silicate xenoliths incorporated into the magma during the eruptive events of 1998 and 2006 were assimilated at the onset of 2010 activity, and any relict carbonates (Deegan et al. 2010; Troll et al. 2012) within these inclusions that remained during magma ascent resulted in the presence of carbonate grains in tephra samples deposited during the 2010 PDCs. SIMS depth profiles of plagioclase phenocrysts within the ash-sized fraction of the surge deposits reveal a build-up of Li in the groundmass of the 26 October lava dome that did not occur in the later 5 November lava. This suggests a stage of protracted gas accumulation in the shallow plumbing system that contributed to the overpressure generated prior to the initial explosion of 26 October. The initial explosion cleared the pre-existing 2006 lava from the conduit, making way for the rapid ascent of the 2010 magma. Groundmass textures within the subsequent climactic 5 November lapilli show that a rapid decompression occurred, promoting a greater degree of undercooling and a crystallization regime dominated by nucleation over growth. The increased microlite abundance in the groundmass, in addition to a higher F content and an efficient loss of Li from the melt, indicates efficient and rapid volatile loss during 5 November dome growth, which allowed the effusion of a significant volume of lava in a short period of time (c. 10 days). This sequence of events resulted in the increased volume, longer run-out distance and greater overall destruction of the resulting PDCs following the 5 November dome collapse.

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References

ADURACHMAN, E. K., BOURDIER, J.-L., & VOIGHT, B. 2000. Nuees ardentes of 22 November 1994 at Merapi volcano, Java, Indonesia. Journal of Volcanology and Geothermal Research, 100, 345–361.
AIUPPA, A., BAKER, D. R., & WEBSTER, J. D. 2009. Halogens in volcanic systems. Chemical Geology, 263, 1–18.
ANDREASTUTI, S. D., ALLOWAY, B. V., & SMITH, I. E. M. 2000. A detailed tephrostratigraphic framework at Merapi Volcano, Central Java, Indonesia: implications for eruption prediction and hazard assessment. Journal of Volcanology and Geothermal Research, 100, 51–67.
BERLO, K., BLUNDY, J., TURNER, S., CASHMAN, K., HAWKESWORTH, C. & BLACK, S. 2004. Geochemical precursors to volcanic activity at Mount St. Helens, USA. Science, 306, 1167–1169.
BORISOVA, A., MARTEL, C., ET AL. 2013. Highly explosive 2010 Merapi eruption: evidence for shallow-level crustal assimilation and hybrid fluid. Journal of Volcanology and Geothermal Research, 261, 193–208.
BOUDON, G., CAMUS, G., GOURGAUD, A. & Lajoie, J. 1993. The nuee-ardente deposits of Merapi volcano Central Java, Indonesia: stratigraphy, textural characteristics, and transport mechanisms. Bulletin of Volcanology, 55, 327–342.
BURNHAM, C. W. 1979. The importance of volatile constituents. In: YODER, H. S. (ed.) The Evolution of the Igneous Rocks: Fiftieth Anniversary Perspectives. Princeton University Press, Princeton, 439–482.
Deegan, F. M., Troll, V. R., Freda, C., Misti, V. & Chadwick, J. P. 2011. Fast and furious: crustal CO₂ release at Merapi volcano, Indonesia. Geology Today, 27, 63–64.

Dixon, J. E. & Stolper, E. M. 1995. An experimental study of water and carbon dioxide solubilities in mid-ocean ridge basaltic liquids. Part II: applications to degassing. Journal of Petrology, 36, 1633–1646.

Dixon, J. E., Stolper, E. M. & Holloway, J. R. 1995. An experimental study of water and carbon dioxide solubilities in mid-ocean ridge basaltic liquids. Part I: calibration and solubility models. Journal of Petrology, 36, 1607–1631.

Donoghue, E., Troll, V. R., Schwarzkopf, L. M., Clayton, G. & Goodhue, R. 2009. Organic block coatings in block-and-ash flow deposits at Merapi Volcano, central Java. Geological Magazine, 146, 113–120.

Fenn, P. M. 1977. The nucleation and growth of alkali feldspars from hydros melts. Canadian Mineralogist, 15, 135–161.

Genareau, K. & Clarke, A. B. 2010. In situ measurements of plagioclase growth using SIMS depth profiles of ⁷Li/⁶⁷Sr: a means to acquire crystallization rates during short duration decompression events. American Mineralogist, 95, 592–601.

Genareau, K., Hervig, R. L. & Clarke, A. B. 2007. Geochemical variations in late-stage growth of volcanic phenocrysts revealed by SIMS depth-profiling. American Mineralogist, 92, 1374–1382.

Genareau, K., Clarke, A. B. & Hervig, R. L. 2009. New insights into explosive volcanic eruptions: connecting crystal-scale chemical changes with conduit-scale dynamics. Geology, 37, 367–370.

Gertisser, R. & Keller, J. 2003a. Temporal variations in magma composition at Merapi Volcano (Central Java, Indonesia): magmatic cycles during the past 2000 years of explosive activity. Journal of Volcanology and Geothermal Research, 123, 1–23.

Gertisser, R. & Keller, J. 2003b. Trace element and Sr, Nd, Pb and O isotope variations in medium-K and high-K volcanic rocks from Merapi Volcano, Central Java, Indonesia: evidence for the involvement of subducted sediments in Sunda Arc magma genesis. Journal of Petrology, 44, 457–489.

Gertisser, R., Charbonnier, S. J. et al. 2011. Merapi (Java, Indonesia): anatomy of a killer volcano. Geology Today, 27, 57–62.

Geshwind, C. H. & Rutherford, M. J. 1995. Crystallization of microlites during magma ascent: the fluid mechanics of 1980–1986 eruptions at Mount St. Helens. Bulletin of Volcanology, 57, 356–370.

Hammer, J. E. & Rutherford, M. J. 2002. An experimental study of the kinetics of decompression-induced crystallization in silicic melt. Journal of Geophysical Research, 107, 148–227.

Hammer, J. E., Cashman, K. V., Hoblitt, R. P. & Newman, S. 1999. Degassing and microlite crystallization during pre-climactic events of the 1991 eruption of Mt. Pinatubo, Philippines. Bulletin of Volcanology, 60, 355–380, http://dx.doi.org/10.1007/s004450050238

Hammer, J. E., Cashman, K. V. & Voight, B. 2000. Magma processes revealed by textural and compositional insights from experimental petrology. Journal of Petrology, 51, 1027–1051.
trends in Merapi dome lavas. *Journal of Volcanology and Geothermal Research*, **100**, 165–192.

HOLLOWAY, J. R. 1976. Fluids in the evolution of granitic magmas: consequences of finite CO₂ solubility. *Geological Society of America Bulletin*, **87**, 1513–1518.

HOLLOWAY, J. R. 1981. Volatile interactions in magmas. In: NEWTON, R. C., NAVROTSKY, A. & WOOD, B. J. (ed.) *Thermodynamics of Minerals and Melts*, 273–293. Springer Verlag, New York.

HOLLOWAY, J. R. & BLANK, J. G. 1994. Application of experimental results to COH species in natural melts. *Reviews in Mineralogy and Geochemistry*, **30**, 187–209.

KING, P. L. & HOLLOWAY, J. R. 2002. CO₂ solubility and speciation in intermediate (andesitic) melts: the role of H₂O and composition. *Geochemica et Cosmochimica Acta*, **66**, 1627–1640.

KIRKPATRICK, R. J. 1981. Kinetics of crystallization of igneous rocks. *Reviews in Mineralogy*, **8**, 321–395.

KOMOROVSKI, J.-C., JENKINS, S. E., et al. 2013. Paroxysmal dome explosion during the Merapi 2010 eruption: processes and facies relationships of associated high-energy pyroclastic density currents. *Journal of Volcanology and Geothermal Research*, **261**, 260–294.

LESNE, P., SCAILLET, B., PICHAVANT, M. & BENY, J. M. 2011. The carbon dioxide solubility in alkali basalts: an experimental study. *Contributions to Mineralogy and Petrology*, **162**, 153–168.

LOFGREN, G. 1974. An experimental study of plagioclase crystal morphology: isothermal crystallization. *American Journal of Science*, **274**, 243–273.

LOWENSTERN, J. B. 2001. Carbon dioxide in magmas and implications for hydrothermal systems. *Mineralium Deposita*, **36**, 490–502.

LUBE, G., CRONIN, S. J., THOURET, J.-C. & SURONO, 2011. Kinematic characteristics of pyroclastic density currents at Merapi and controls on their avulsions from natural and engineered channels. *Geological Society of America Bulletin*, **123**, 1127–1140.

MARTEL, C. 2012. Eruption dynamics inferred from microlite crystallization experiments: application to Plinian and dome-forming eruptions of Mt. Pelée (Martinique, Lesser Antilles). *Journal of Petrology*, **53**, 699–725.

MOORE, G. & CARMICHAEL, I. S. E. 1998. The hydrous phase equilibria (to 3 kbar) of an andesite and basaltic andesite from western Mexico: constraints on water content and conditions of phenocryst growth. *Contributions to Mineralogy and Petrology*, **130**, 304–319.

NADEAU, O., WILLIAMS-JONES, A. E. & STIX, J. 2013. Magmatic–hydrothermal evolution and devolatilization beneath Merapi volcano, Indonesia. *Journal of Volcanology and Geothermal Research*, **261**, 50–68, http://dx.doi.org/10.1016/j.jvolgeores.2013.04.006

NEKVASIL, H. 1992. Ternary feldspar crystallization in high temperature felsic magma. *American Mineralogist*, **77**, 592–604.

NEWHALL, C. G., BRONTO, S. et al. 2000. 10 000 years of explosive eruptions of Merapi volcano, Central Java: archaeological and modern implications. *Journal of Volcanology and Geothermal Research*, **100**, 9–50.

NEWMAN, S. & LOWENSTERN, J. B. 2002. *VolatileCalc*: a silicate melt–H₂O–CO₂ solution model written in Visual Basic for excel. *Computers & Geosciences*, **28**, 597–604.

PALLISTER, J. S., SCHNEIDER, D. J. ET AL. 2013. Merapi 2010 eruption—Chronology and extrusion rates monitored with satellite radar and used in eruption forecasting. *Journal of Volcanology and Geothermal Research*, **261**, 144–152.

PICHAVANT, M., CARLO, I. D., ROTOLE, S. G., SCAILLET, B., BURGISSE, A., LE GALL, N. & MARTEL, C. 2013. Generation of CO₂-rich melts during basalt magma ascent and degassing. *Contributions to Mineralogy and Petrology*, **166**, 545–561.

PREECE, K., BARCLAY, J., GERTISER, R. & HERD, R. A. 2013. Textural and micro-petrological variations in the eruptive products of the 2006 dome-forming eruption of Merapi volcano, Indonesia: implications for sub-surface processes. *Journal of Volcanology and Geothermal Research*, **261**, 98–120.

RICHTER, F. M., DAVIS, A. M., DEPAULO, D. J. & WATSON, E. B. 2003. Isotope fractionation by chemical diffusion between molten basalt and rhyolite. *Geochemica et Cosmochimica Acta*, **67**, 3905–3923.

SCHWARZKOPF, L. M., SCHMINCKE, H.-U. & TROLL, V. R. 2001. Pseudotachylite on impact marks of block surfaces in block-and-ash flows at Merapi volcano, Central Java, Indonesia. *Geologische Rundschau*, **90**, 769–775.

SCHWARZKOPF, L. M., SCHMINCKE, H.-U. & CRONIN, S. J. 2005. A conceptual model for block-and-ash flow basalt avalanche transport and deposition, based on deposit architecture of 1998 and 1994 Merapi flows. *Journal of Volcanology and Geothermal Research*, **139**, 117–134.

SISSON, T. W. & GROVE, T. L. 1993. Experimental investigations of the role of H₂O in calc-alkaline differentiation and subduction zone magmatism. *Contributions to Mineralogy and Petrology*, **113**, 143–166.

SISOWIDJOYO, S., SURYO, I. & YOKOVAYA, I. 1995. Magma eruption rates of Merapi volcano, Central Java, Indonesia during one century (1890–1992). *Bulletin of Volcanology*, **57**, 111–116.

SURONO, JOUSSET, P. ET AL. 2012. The 2010 explosive eruption of Java’s Merapi volcano - a ‘100-year’ event. *Journal of Volcanology and Geothermal Research*, **241–242**, 121–135.

SWANSON, S. E., NANEY, M. T., WESTRICH, H. R. & EICHELBERGER, J. C. 1989. Crystallography history of Obsidian Dome, Inyo Domes, California. *Bulletin of Volcanology*, **51**, 161–176.

TROLL, V. R., HILTON, D. R. ET AL. 2012. Crustal CO₂ liberation during the 2006 eruption and earthquake events at Merapi volcano, Indonesia. *Geophysical Research Letters*, **39**, L11302.

TROLL, V. R., DEEGAN, F. M., ET AL. 2013. Magmatic differentiation processes at Merapi Volcano: inclusion petrology and oxygen isotopes. *Journal of Volcanology and Geothermal Research*, **261**, 38–49.

VAN BEMMELEN, R. 1949. *The Geology of Indonesia*. Martinus Nijhoff, The Hague.

VAN DER ZWAN, F. M., CHADWICK, J. P. & TROLL, V. R. 2013. Textural history of recent basaltic-andesites and plutonic inclusions from Merapi volcano. *Contributions to Mineralogy and Petrology*, **166**, 43–63.
Voight, B., Constantine, E. K., Siswowidjoyo, S. & Torley, T. 2000a. Historical eruptions of Merapi volcano, Central Java, Indonesia, 1768–1998. Journal of Volcanology and Geothermal Research, 100, 69–138.

Voight, B., Sukyar, R. & Wirakusumah, A. D. 2000b. Introduction to the special issue on Merapi volcano. Journal of Volcanology and Geothermal Research, 100, 1–8.

Webster, J. D., Holloway, J. R. & Hervig, R. L. 1989. Partitioning of lithophile trace elements between H2O and H2O + CO2 fluids and topaz rhyolite melt. Economic Geology and the Bulletin of the Society of Economic Geologists, 84, 116–134.

Zhang, Y. & Behrens, H. 2000. H2O diffusion in rhyolitic melts and glasses. Chemical Geology, 169, 243–262.