Precipitates within olivine phenocrystals in oxidized andesitic scoria from Kasayama volcano, Hagi, Japan

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Mineral precipitates within olivine grains are a sensitive recorder of the oxidation conditions of scoria. The crystallization process of precipitates within olivine phenocrysts in andesitic scoria from Kasayama volcano, Hagi, Yamaguchi Prefecture, Japan was investigated. Electron microprobe analysis and Raman spectroscopy were used for mineral identification and electron back-scattered diffraction to determine the crystallographic orientation of the precipitate minerals and host olivine phenocrysts. The scoria in the interior of the Kasayama scoria cone is red–brown, and the outer surface of the cone is black or black with red–brown tint. The olivine phenocrysts (Fo79–81) within the black scoria lack precipitate minerals, but those in the black scoria with red–brown tint (Fo82–85) contain small amounts of precipitates at their rims, and those in the red–brown scoria (Fo99) contain abundant cryptocrystalline precipitates, including hematite and enstatite. Vermicular rods of hematite and enstatite form symplectite zones on the rims, and symplectite domains in the cores of the phenocrysts. The host olivine and the hematite precipitates have a crystallographic relationship of [100]Ol/[0001]Hem, [010]Ol/[1010]Hem, and [001]Ol/[2130]Hem, which is characteristic of olivine and precipitate minerals generated by high-temperature oxidation. The maximum oxidation temperature is estimated to be >800 °C. High temperature oxidizing conditions may have been maintained in the inner wall of the scoria cone because the scoria that erupted early in the sequence was deposited in the presence of air and was subsequently covered by black scoria making up the outer wall of the cone.

Keywords: Olivine, Precipitates in olivine, Scoria, High temperature oxidation, Kasayama volcano

INTRODUCTION

Porous scoria produced by Strombolian eruptions commonly undergoes post-depositional welding and oxidation (Houghton and Schmincke, 1989). Small-scale Strombolian eruptions at Kasayama volcano, Hagi, Yamaguchi Prefecture, Japan, constructed an andesitic scoria cone, of which the inner wall consists of weakly welded red-brown scoria, and the outer surface comprises porous black scoria (Nagao and Shiba, 2010). The olivine phenocrysts in the red-brown scoria contain abundant Fe-rich opaque precipitates, whereas those in the black scoria lack precipitates (Nagao et al., 1996; Ejima et al., 2012). These observations indicate that olivine is a critical and sensitive mineral for recording oxidation conditions in the scoria.

Nagao et al. (1996) identified magnetite and hematite in opaque precipitates within olivine phenocrysts from the Kasayama scoria. Ejima et al. (2012), in their systematic study of the oxidation state of Fe in olivine phenocrysts from the Kasayama black scoria with red-brown tint, used ⁵⁷Fe Mössbauer spectroscopy to docu-
ment the presence of Fe$^{3+}$ in the olivine crystal structure. However, the occurrence and mineral assemblage of precipitates within olivine phenocrysts in the Kasayama scorias have not been fully described. In this paper, we systematically describe the occurrence of precipitates within olivine phenocrysts in three types of scoria from Kasayama volcano, identify the precipitate minerals, and propose a model for the growth of the symplectic texture of these precipitates during the oxidation process.

**GEOLOGY OF KASAYAMA VOLCANO AND SAMPLE DESCRIPTIONS**

Kasayama volcano, on the coast of the Japan Sea near Hagi in Yamaguchi Prefecture, belongs to the Abu monogenic volcanic group of southwestern Japan (Fig. 1). The volcano consists of basaltic andesite lava flows and subsequent scoria deposits, younger than 0.04 Ma (Kakubuchi et al., 2000). The scoria deposits consist of two nested cones, an outer cone of orthopyroxene–olivine–clinopyroxene andesitic scoria (S1), 300 m across at its base, and an inner cone of clinopyroxene–olivine andesitic scoria (S2), 80 m across at its base with an inner crater of ~30 m across (Fig. 1) (Nagao and Shiba, 2010). The inner wall of the S2 scoria cone is weakly welded and red-brown in color due to intense oxidation. It contains volcanic bombs 10 to 40 cm in length. The outer wall consists of porous black scoria with a weak to strong red-brown tint, hereafter referred to as R-B black scoria, in clasts as large as 10 cm (Nagao et al., 1996; Ejima et al., 2012). The degree of oxidation, as signified by the red-brown tint, is variable. Rare clasts of porous black scoria are found that seemingly have not been subjected to oxidation. Samples of completely black scoria and R-B black scoria were collected from the outer side of the S2 scoria cone (#S04070301–S04070320 and S08032701–S08032710 in Fig. 1), and samples of red-brown scoria were collected from the inner wall (#S07062101–S07062104 and S07062111–S07062114 in Fig. 1).

**EXPERIMENTAL METHODS**

The samples selected for petrographic and analytical studies are one black scoria sample (#S08032710; Fig. 2A), six R-B black scoria samples (#S08032701–S08032707) (Fig. 2B), and five red-brown scoria samples (#S07062101–S07062103, S07062111, and S07062112; Fig. 2C). One thin section was prepared from each selected sample.

The chemical composition and elemental distribution within minerals in the thin sections were determined by JEOL JXA–8800M and JXA–8530F electron microprobe analyzers (EMPA) at Shimane University, operated at an accelerating voltage of 15 kV, with 20 nA beam current and 1 µm beam diameter. The standard materials used were natural forsterite for Si(Si$K\alpha$1) and Mg(Mg$K\alpha$1), and synthetic oxides Fe$_2$O$_3$ for Fe(Fe$K\alpha$1), Ca$_3$V$_2$O$_8$ for Ca(Ca$K\alpha$1), TiO$_2$ for Ti(Ti$K\alpha$1), Al$_2$O$_3$ for Al(Al$K\alpha$1), etc.
Cr$_2$O$_3$ for Cr(Cr$_{K\alpha}$), MnO for Mn(Mn$_{K\alpha}$), and NiO for Ni(Ni$_{K\alpha}$). The ZAF method was used for data correction.

Raman spectra were measured with an NRS–5100 laser Raman spectrometer, equipped with a microscope with a focal spot size of 2 μm, at the National Institute of Advanced Industrial Science and Technology (AIST), Japan. Excitation was performed using 532 nm line of a solid-state laser with an output power of 20 mW.

RESULTS

Petrography

In thin section, under plane-polarized light, olivine phenocrysts in the black scoria samples are euhedral to subhedral, 0.2–1 mm long, and generally fractured. They contain inclusions of primary chromite and magnetite (Figs. 3A and 4A), but other impurities are not observed. Clinopyroxene phenocrysts are almost colorless, euhedral to anhedral in form and ~ 0.1–1 mm across (Fig. 3A). The groundmass exhibits intersertal texture, and consists of rounded and colorless clinopyroxene, euhedral plagioclase laths 0.01–0.6 mm long, fresh volcanic glass, and small amounts of opaque minerals. Quartz xenocrysts ~ 5 mm long also occur, as described by Nagao et al. (1996).

The R–B black scoria differs from the black scoria in that the olivine phenocrysts have small amounts of precipitates, consisting of hematite and enstatite, in their rims (Fig. 3B), and in the areas surrounding euhedral to subhedral inclusions of Cr–bearing magnetite (Figs. 4D–4F).

The red–brown scoria differs from the black scoria in that the olivine phenocrysts contain abundant precipitates (Fig. 3C). The precipitates consist of hematite and enstatite on the rims and along fractures of the olivine phenocrysts (Figs. 4G–4I), and in the areas surrounding euhedral to subhedral inclusions of Cr–bearing magnetite and Cr–bearing magnesioferrite (Figs. 4J–4L). Among these precipitates, the hematite around the Cr–bearing magnesioferrite is rich in Cr, but other occurrences of hematite are not rich in Cr. Clinopyroxene phenocrysts in the red–brown scoria are lemon–yellow with darker rims, and the clinopyroxene in the groundmass is also dark lemon–yellow.

Texture and morphology of symplectic precipitates within olivine phenocrysts

At a micrometer scale, the precipitates within olivine phenocrysts from the red–brown scoria have a symplectic texture and morphology (Figs. 5A–5D). The phenocrysts...
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precipitates consist of vermicular rods of hematite and connected blobs of enstatite. In the core of the olivine phenocrysts, the precipitates form symplectic aggregates of hematite and enstatite (Fig. 5B) or are arranged perpendicular to the $a$-axis of olivine (Figs. 5C and 6). The symplectic precipitates consist of vermicular rods of hematite and connected enstatite (Figs. 5D–5E). Precipitates around chromite grains show a radial texture (Figs. 5B and 5D). The hematite precipitates range in size from a few micrometers to less than a micrometer, and they are covered by enstatite (Fig. 5E).

Mineral chemistry

Table 1 lists representative EMPA data from the cores and rims of olivine phenocrysts in the three different scoria classes, and Table 2 lists the compositions of chromite, Cr-bearing magnetite, Cr-bearing magnesioferrite, and Cr-bearing hematite within the olivine phenocrysts. Quantitative data could not be obtained for the hematite and enstatite in the precipitates because they were smaller than 1 μm.

The chemical compositions of olivine phenocrysts in the black scoria are Fo 79.6–80.8 in the cores and Fo 78.7–80.7 in the rims, indicating normal zoning. However, in the R–B black scoria, the Fo content of the olivine phenocrysts depends on the volume of precipitates and is higher in the rims (Fo 84.0–85.2) than in the cores (Fo 82.1–84.0). In the red-brown scoria, which contains considerable amounts of precipitate, the Fo content of the olivine phenocrysts reaches Fo 98.8–98.9. The compositions of the enstatite rims on the olivine phenocrysts in the red-brown scoria are En 90.7–91.6 Fs 4.6–6.3 Wo 2.0–2.3.

The compositions of the clinopyroxene phenocrysts are diopside to augite (Wo 41.8–45.3 En 43.6–47.2 Fs 8.6–11.3) in the black scoria, augite (Wo 41.8–44.3 En 44.0–47.7 Fs 8.8–14.7) in the R–B black scoria, and augite (Wo 38.9–44.3 En 43.1–51.0 Fs 7.5–12.3) in the red–brown scoria.

End-member compositions of primary chromite and Cr-rich magnetite in the olivine phenocrysts from the black, R–B black, and red-brown scorias are FeCr$_2$O$_4$(Chr):MgAl$_2$O$_4$(Sp):MgFe$_2$O$_4$(Mfr):Fe$_3$O$_4$(Mag):TiFe$_2$O$_4$(Usp) = 45.0:21.0:18.5:12.7:2.9, 35.7:11.8:23.6:27.7:1.3, and 32.9:7.4:28.2:30.4:1.1, respectively, as calculated from the atomic ratios in Table 2. Therefore, the Chr component of primary chromite decreases with increasing volume of precipitate because of oxidation, and the Mfr and Mag components increase. Cr-rich magnetite inclusions in the olivine phenocrysts in the R–B black and red-brown scorias (Table 2) are considered to have originated as chromite.
Figure 4. Back-scattered electron images (BEI) and element distribution maps. (A), (B), and (C): BEI, Mg distribution, and Fe distribution of an olivine phenocryst in the black scoria, respectively. (D), (E), and (F): BEI, Mg, and Fe distributions of an olivine phenocryst in the R-B black scoria. (G), (H), and (I): BEI, Mg, and Fe distributions of an olivine phenocryst in the red-brown scoria. (J), (K), and (L): Cr, Mg, and Fe distributions of precipitates in an olivine phenocryst in the red-brown scoria. Chr, chromite; Cr-Hem, Cr-bearing hematite; Cr-Mag, Cr-bearing magnetite; En, enstatite; Hem, hematite; Mag, magnetite; Mfr, magnesioferrite; Ol, olivine; Pre, precipitate minerals. Color version is available online from http://doi.org/10.2465/jmps.161219.
Mineral identification by Raman spectroscopy

The peaks in the Raman spectra of the symplectic precipitates (Fig. 7A) and the outermost rim mineral (Fig. 7B) in olivine phenocrysts from the red-brown scoria are assigned to hematite and enstatite, based on the Raman data in the RRUFF database. Reference numbers of Raman data in RRUFF are R050644, R060744, and R060630 for enstatite and R040024 for hematite.

Crystallographic orientations of precipitates and host olivine phenocryst

Representative results of the EBSD analysis, presented in Figure 8, show the relationship between crystallographic axes of host olivine (space group $Pbnm$) and hematite precipitate (space group $R3c$). The projection of the [000$\bar{1}$] axis of hematite aligns precisely with the [100] axis of olivine, and in portions of the hematite, [1010] and [2130] are parallel to [010] and [001] of the host olivine, respectively: $[100]_{\text{Ol}}// [000\bar{1}]_{\text{Hem}}$, $[010]_{\text{Ol}}// [10\bar{1}0]_{\text{Hem}}$, and $[001]_{\text{Ol}}// [2130]_{\text{Hem}}$. Thus, the host olivine and hematite precipitates have a crystallographic relationship in which the $c$-axis of hematite in the symplectic precipitates is parallel to the $a$-axis of the host olivine.

Figure 6 shows that the extension direction of the symplectite precipitate, which crystallized at the latest stage from the host olivine, is nearly perpendicular to...
DISCUSSION

The precipitates in olivine phenocrysts in the Kasayama oxidized scoria are similar to those previously described in oxidized lavas by Ejima et al. (2013). Precipitates consisting of vermicular rods and radial ribs of hematite, typical of the Kasayama red-brown scoria, as well as the precipitate assemblage of hematite and enstatite, are characteristically generated by oxidation at subsolidus temperatures (Haggerty and Baker, 1967; Blondes et al., 2012; Ejima et al., 2013). Well-defined crystallographic relationships between host olivine and precipitate hematite crystals have been reported previously in oxidized olivine containing precipitates elsewhere (Champness, 1970; Kohlstedt and Vander, 1975; McKernan and Carter, 1989; Hwang et al., 2008; Blondes et al., 2012; Ejima et al., 2015). It has been attributed to the similarity of the closest packing scheme of oxygens on the (100), (010), and (001) planes (especially the (001) plane) in olivine and precipitate minerals (Fig. 3 in Champness, 1970; Fig. 13 in Ejima et al., 2015).

However, the olivine phenocrysts in the scoria tend to have a euhedral morphology and are less variable in shape than those in lava described by Haggerty and Baker (1967) and Ejima et al. (2013, 2015). This feature is also documented in oxidized scoria of the Otsukayama scoria cone on Daikon-jima Island, Shimane Prefecture (Ejima and Akasaka, 2016), and the Kometsuka scoria cone at Aso volcano, Kumamoto Prefecture (Ejima, 2015). The difference in olivine morphology between oxidized scoria and lava can be attributed to the differences in the crystallization process of the phenocrysts. Conversely, the volume of the precipitates is smaller in the red-brown scoria than in the red-brown lava from Kasayama. This difference may be attributed to the total Fe content of olivine phenocrysts, which are 17–19 wt% in black scoria (Table 1) and 23–31 wt% in black lava from Kasayama (Ejima et al., 2013).

The results of our study suggest the following high-temperature oxidation process in olivine phenocrysts from the Kasayama scoria:

1. Primary euhedral olivine phenocrysts containing primary chromite, crystallized from magma, with normal zoning from Fo79.6–80.8 at the core to Fo78.7–80.7 at the rim (Fig. 9A).
2. After the eruption of lava and scoria, high-temperature oxidation occurred in the inner wall of the Kasayama scoria cone. Small amounts of symplectic precipitates consisting of hematite and enstatite crystallized at the margins of the olivine phenocrysts. Primary chromite oxidized to Cr-rich magnesioferrite and Cr-rich magnetite, and Cr released from the chromite diffused into the precipitate minerals (Fig. 9B). The Fo contents increased in both the cores (Fo82.1–84.0) and rims (Fo84.0–85.2) of altered olivine phenocrysts, reversing the gradient in Fo content within the primary phenocrysts.
3. With continued or repeated oxidation at high temperatures, enstatite and vermicular rods and radial ribs of hematite crystallized on the rims and in clusters perpendicular to the a-axis of the host olivine, and a thin outer layer of enstatite was formed (Fig. 9C). The remaining primary chromite changed to Cr-bearing magnesioferrite and Cr-bearing hematite. Olivine compositions became extremely Mg-rich (Fo99).

The estimation of oxidation temperature is not easy because the assemblage of precipitate minerals depends not only on temperature but also on the grain size of the

![Image of BEI and upper hemisphere equal-area projections showing the orientation of a host olivine phenocryst in relation to symplectic precipitates, which crystallized in the latest stage of cooling. Ol, olivine; Pre, precipitate minerals; V, void.](image-url)
## Table 1. Chemical compositions of olivine phenocrysts in the Kasayama scoria showing the minimum and maximum Fo contents

|                | Black scoria (# S08032710) | Black scoria with red-brown tint (# S08032702) | Red-brown scoria (# S07062111) |
|----------------|-----------------------------|-----------------------------------------------|--------------------------------|
|                | Core                        | Rim                                           | Core                          | Rim                          | Core                        | Rim                          |
|                | Min. Fo | Max. Fo | Min. Fo | Max. Fo | Min. Fo | Max. Fo | Min. Fo | Max. Fo | Min. Fo | Max. Fo |
| SiO₂           | 40.39   | 40.57   | 40.06   | 40.55   | 40.73   | 41.01   | 40.93   | 40.96   | 42.74   | 43.12   |
| TiO₂           | -       | -       | 0.09    | -       | -       | -       | -       | -       | -       | -       |
| FeO<sup>3+</sup> | 18.15   | 17.09   | 18.79   | 17.41   | 16.08   | 14.12   | 14.24   | 13.14   | 0.93    | 0.76    |
| NiO            | 0.22    | 0.25    | 0.20    | 0.38    | 0.18    | 0.27    | 0.28    | 0.20    | -       | 0.04    |
| MnO            | 0.25    | 0.20    | 0.23    | 0.23    | 0.25    | 0.32    | 0.26    | 0.22    | 0.24    | 0.26    |
| MgO            | 41.22   | 41.97   | 40.41   | 42.62   | 43.00   | 44.10   | 44.17   | 44.65   | 56.94   | 56.98   |
| CaO            | 0.20    | 0.17    | 0.20    | 0.16    | 0.18    | 0.17    | 0.14    | 0.20    | 0.08    | 0.05    |
| Total          | 100.43  | 100.25  | 99.89   | 101.35  | 100.42  | 99.99   | 100.02  | 99.54   | 100.93  | 101.21  |

Cations per 4 oxygens

| Si  | 1.022 | 1.023 | 1.022 | 1.015 | 1.021 | 1.024 | 1.022 | 1.022 | 0.997 | 1.002 |
| Ti  | -     | -     | 0.002 | -     | -     | -     | -     | 0.003 | -     | -     |
| Fe  | 0.384 | 0.361 | 0.401 | 0.364 | 0.337 | 0.295 | 0.297 | 0.274 | 0.018 | 0.015 |
| Ni  | 0.005 | 0.005 | 0.004 | 0.008 | 0.004 | 0.005 | 0.006 | 0.004 | -     | 0.004 |
| Mn  | 0.005 | 0.004 | 0.005 | 0.005 | 0.005 | 0.007 | 0.005 | 0.005 | 0.005 | 0.005 |
| Mg  | 1.556 | 1.578 | 1.537 | 1.590 | 1.607 | 1.641 | 1.644 | 1.661 | 1.980 | 1.974 |
| Ca  | 0.005 | 0.005 | 0.005 | 0.004 | 0.005 | 0.005 | 0.004 | 0.005 | 0.002 | 0.001 |
| Total | 2.977 | 2.976 | 2.976 | 2.986 | 2.979 | 2.977 | 2.978 | 2.974 | 3.002 | 2.998 |

Fo 79.6 80.8 78.7 80.7 82.1 84.0 84.0 85.2 98.8 98.9

* Total Fe as FeO.

## Table 2. Representative chemical compositions of primary chromite, Cr-bearing magnetite, magnesioferrite, and hematite in olivine<sup>*</sup>

|                | Black scoria (# S08032710) | Black scoria with red-brown tint (# S08032702) | Red-brown scoria (# S07062111) |
|----------------|-----------------------------|-----------------------------------------------|--------------------------------|
|                | Chromite                    | Cr-bearing magnetite                           | Cr-bearing magnetite              | Cr-bearing magnesioferrite    | Cr-bearing hematite          |
| TiO₂           | 3.53                        | 1.70                                          | 0.42                            | -                             | -                             |
| Cr₂O₃          | 32.52                       | 25.15                                         | 23.57                           | 24.17                         | 20.66                         |
| Al₂O₃          | 10.20                       | 5.59                                          | 3.55                            | 6.54                          | 3.47                          |
| Fe₂O₃<sup>**</sup> | 23.63                      | 38.01                                         | 44.14                           | 42.64                         | 71.07                         |
| FeO<sup>**</sup> | 21.34                       | 21.56                                         | 20.59                           | -                             | -                             |
| NiO            | 0.07                        | 0.19                                          | 0.35                            | 0.44                          | -                             |
| MnO            | 0.36                        | 0.40                                          | 0.68                            | 0.48                          | 0.29                          |
| MgO            | 7.57                        | 6.62                                          | 6.76                            | 25.13                         | 6.31                          |
| Total          | 99.22                       | 99.20                                         | 100.06                          | 99.40                         | 101.80                        |

** Recalculated values based on the structural formula for chromite and magnetite; total Fe as Fe₂O₃ for magnesioferrite and hematite.

* SiO₂, CaO, Na₂O, and K₂O were under the detection limit and are not shown.

Cations per 4 oxygens

| Ti  | 0.090 | 0.045 | 0.011 | -     | -     |
| Cr  | 0.870 | 0.699 | 0.660 | 0.602 | 0.105 |
| Al  | 0.407 | 0.231 | 0.148 | 0.243 | 0.419 |
| Fe³⁺ | 0.602 | 1.005 | 1.176 | 1.010 | 1.373 |
| Fe²⁺ | 0.603 | 0.633 | 0.609 | -     | -     |
| Ni  | -     | 0.007 | 0.010 | 0.011 | -     |
| Mn  | 0.010 | 0.012 | 0.020 | 0.013 | 0.011 |
| Mg  | 0.382 | 0.347 | 0.357 | 1.180 | 0.137 |
| Total | 2.964 | 2.979 | 2.991 | 3.059 | 2.045 |

Cations per 3 oxygens

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olivine and the duration of heating (Haggerty and Baker, 1967). However, annealing experiments summarized by Koltermann (1962) indicate that olivine breaks down to an assemblage of forsterite + cristobalite + enstatite + magnetite at 1100 °C, to cristobalite + forsterite + enstatite + hematite at 1080 °C, and to forsterite + SiO2–glass + hematite at 820 °C. Haggerty and Baker (1967) obtained the assemblage forsterite + enstatite + hematite + magnetite by heating olivine to temperatures >820 °C. Therefore, we estimate that the precipitates within olivine phenocrysts in the Kasayama scoria crystallized at temperatures >800 °C, as the case of the Kasayama lava (Ejima et al., 2013).

Such temperature conditions in the presence of air may have been maintained in the inner wall of the Kasayama scoria cone because the scorias deposited early in the sequence were covered by rapidly cooled black sco-

Figure 7. Raman spectra of precipitates in olivine grains from red-brown scoria (#S07062111) at locations shown by spots. Peaks are identified from the RRUFF database. (A) Precipitate domain within olivine phenocryst. (B) Outer rim of olivine phenocryst. En, enstatite; Hem, hematite; Ol, olivine; Pre, precipitate minerals; Spl, spinel. Color version is available online from http://doi.org/10.2465/jmps.161219.
rias that built up the outer wall. The scorias of the outer wall were also oxidized in the presence of heat from the inner wall and precipitates subsequently crystallized in olivine phenocrysts in the R–B black scorias.

CONCLUSIONS

Scoria in the inner wall of the S2 scoria cone of Kasayama volcano is red–brown and weakly welded, whereas black and R–B black scoria occur on the outer wall of the cone. Olivine phenocrysts within the black scoria lack precipitate minerals, but those in the R–B black scoria contain small amounts of precipitates at their rims, and those in the red–brown scoria contain abundant crypto-crystalline precipitates including hematite and enstatite. The Fo contents of the olivine phenocrysts correlate with the volume of precipitates present. The host olivine and hematite precipitate have crystallographic relationships of [100]$_{Ol}$//[-001]$_{Hem}$, [010]$_{Ol}$//[1010]$_{Hem}$, and [001]$_{Ol}$//[-2130]$_{Hem}$. Though oxidation of Fe$^{2+}$-bearing olivine and nucleation of hematite preferentially occur from the rim and along dislocations and fractures, our observations suggest that mineral inclusions such as primary chromite, which is oxidized rapidly, also can be highly reactive sites for olivine oxidation. These precipitates appear to have crystallized at temperatures >800 °C. Such high temperature oxidizing conditions in the presence of air could be maintained in the inner wall of the scoria cone because the scorias erupted and deposited early in the sequence were covered by rapidly cooled black scorias ejected by a later eruption. Thus, the scorias of the inner wall were oxidized more strongly than those of the outer wall.

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SUPPLEMENTARY MATERIALS

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