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## Supplementary Materials for

### **Early oxidation of the martian crust triggered by impacts**

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#### **The PDF file includes:**

Supplementary Text  
Figs. S1 to S14  
References

#### **Other Supplementary Material for this manuscript includes the following:**

(available at [advances.sciencemag.org/cgi/content/full/6/44/eabc4941/DC1](https://advances.sciencemag.org/cgi/content/full/6/44/eabc4941/DC1))

Data files S1 to S5

## Supplementary Text

### Total FeO in melt as an oxygen fugacity indicator for magnetite-saturated mafic magma.

The NWA 7533/7034 meteorites are known to have been affected by thermal resetting, e.g., magnetite-ilmenite pairs in the igneous clasts provide an equilibrium temperature range of 587-706 °C (8). To determine the magmatic oxygen fugacity of these clasts, a new oxybarometer that does not require the minerals to be equilibrated at magmatic temperature is needed. In the following, we show that, for a mafic silicate melt that is saturated in magnetite, its magmatic oxygen fugacity can be directly derived from its chemical composition with an oxybarometer updated after the FeTiMM method from Arató and Audétat (17). Arató and Audétat (17) noticed that the effects of alumina saturation index on TiO<sub>2</sub> solubility were similar to that on magnetite solubility, making the combination of Fe and Ti partitioning between magnetite and melt an oxygen fugacity indicator for silicate melts of basaltic to rhyolitic compositions, even the slowly cooled intrusive rocks like granites (17):

$$\Delta FMQ = \frac{\log\left(D_{FeO_{tot}}^{mgt/melt} / D_{TiO_2}^{mgt/melt}\right) + 0.137 \times AMCCK + 0.102}{0.288 \times AMCCK + 0.054} \quad (1)$$

where  $\Delta FMQ$  is oxygen fugacity in logarithmic deviation relative to the Fayalite-Magnetite-Quartz buffer, and  $D_{FeO_{tot}}^{mgt/melt}$  and  $D_{TiO_2}^{mgt/melt}$  are the partition coefficients of total FeO (FeO<sub>tot</sub>) and TiO<sub>2</sub> between magnetite and melt, respectively.  $AMCCK$  is a melt compositional parameter:

$$AMCCK = X_{Al_2O_3}^{melt} / \left( X_{CaO}^{melt} + X_{Na_2O}^{melt} + X_{K_2O}^{melt} + X_{MgO}^{melt} \right) \quad (2)$$

where  $X_i^j$  stands for the molar proportion of  $i$  in phase  $j$ .

We notice that for experimental melts with MgO  $\geq$  3 wt% in the dataset from Arató and Audétat (17), the partitioning of Ti between magnetite and melt is sensitive to the Mg and Fe contents of the melt (for experimental runs with  $X_{Mg}^{melt} / (X_{Mg}^{melt} + X_{Fe}^{melt}) = 0.284-0.596$  and SiO<sub>2</sub> = 47.56-57.57 wt% in the quenched melts,  $n = 16$ ,  $R^2 = 0.917$ ; fig. S4a):

$$D_{TiO_2}^{mgt/melt} = (-10.2513 \pm 0.8232) \times \frac{X_{Mg}^{melt}}{X_{Mg}^{melt} + X_{Fe}^{melt}} + (7.9212 \pm 0.3914) \quad (3)$$

We are also aware of the definition of  $D_{FeO_{tot}}^{mgt/melt}$ :

$$D_{FeO_{tot}}^{mgt/melt} = \frac{C_{FeO_{tot}}^{mgt}}{C_{FeO_{tot}}^{melt}} \quad (4)$$

where  $C_i^j$  is concentration of  $i$  in phase  $j$ . After, equation 1 can be transformed into:

$$\Delta FMQ = \frac{\log\left[\left(\frac{C_{FeO_{tot}}^{mgt}}{C_{FeO_{tot}}^{melt}}\right) / \left(-10.2513 \times \frac{X_{Mg}^{melt}}{X_{Mg}^{melt} + X_{Fe}^{melt}} + 7.9212\right)\right] + 0.137 \times AMCCK + 0.102}{0.288 \times AMCCK + 0.054} \quad (5)$$

Since the FeO<sub>tot</sub> contents in magnetite from mafic melts ( $C_{FeO_{tot}}^{mgt}$ ) should be 65-75 wt%,  $\Delta FMQ$  in equation 5 would actually be a function of the melt chemical composition ( $C_{FeO_{tot}}^{melt}$ ,  $X_{Mg}^{melt}$ ,

$X_{Fe}^{melt}$  and  $AMCCK$ ). In other words, once the saturation in magnetite is reached, the  $\Delta FMQ$  of a mafic melt can be determined from its major element composition. The effects on  $\Delta FMQ$  from

the uncertainties on  $C_{FeO_{tot}}^{mgt}$ ,  $C_{FeO_{tot}}^{melt}$ ,  $D_{TiO_2}^{mgt/melt}$  and  $AMCNK$  can be quantified with the following partial differential equations:

$$\frac{\partial \Delta FMQ}{\partial C_{FeO_{tot}}^{mgt}} = \frac{1}{C_{FeO_{tot}}^{mgt} \times \ln(10) \times (0.288 \times AMCNK + 0.054)} \quad (6)$$

$$\frac{\partial \Delta FMQ}{\partial C_{FeO_{tot}}^{melt}} = \frac{-1}{C_{FeO_{tot}}^{melt} \times \ln(10) \times (0.288 \times AMCNK + 0.054)} \quad (7)$$

$$\frac{\partial \Delta FMQ}{\partial D_{TiO_2}^{mgt/melt}} = \frac{-1}{D_{TiO_2}^{mgt/melt} \times \ln(10) \times (0.288 \times AMCNK + 0.054)} \quad (8)$$

$$\frac{\partial \Delta FMQ}{\partial AMCNK} = \frac{-0.288 \times \log_{10} \left( \frac{D_{FeO_{tot}}^{mgt/melt}}{D_{TiO_2}^{mgt/melt}} \right) - 0.021978}{(0.288 \times AMCNK + 0.054)^2} \quad (9)$$

After error propagation, the typical uncertainty on the estimated  $\Delta FMQ$  ranges from  $\pm 0.3$ - $0.6$  log unit for  $\Delta FMQ = +0$ - $2$  to  $\pm 0.6$ - $1.0$  log unit for  $\Delta FMQ = +2$ - $5$ , with which the estimated  $\Delta FMQ$  values are consistent with the  $\Delta FMQ$  values derived from magnetite-ilmenite pairs or experimental  $\Delta FMQ$  values (fig. S4b). In the compiled dataset in (17), two runs with high  $SiO_2$  contents of 59.03-59.73 wt% did not follow equation 3, whereas the re-estimated  $D_{TiO_2}^{mgt/melt}$  using equation 3 did return to the  $\Delta FMQ$  values fitting with their experimental  $\Delta FMQ$  values within  $\pm 0.5$  log unit. The application of equation 5 provided  $\Delta FMQ$  values of  $+0.9 \pm 0.3$  and  $+2.4 \pm 0.4$  for samples HEK-14-09 (Hekla volcano, Iceland) and AGU21 (Agung volcano, Sunda Arc), respectively, which have been shown to be oxide-saturated by the Ti isotopic studies in (10) and (11). These two estimated  $\Delta FMQ$  values agree well with those calculated for oceanic island basalts ( $\Delta FMQ = +0.54 \pm 0.83$ , SD) (57) and arc lavas from Sunda Arc ( $\Delta FMQ = +1.7$ - $2.7$ ) (58).

### Furnace melting and crystallization experiments

Based on equation 5, there can be two mechanisms leading to magnetite precipitation (in other words to lower FeO<sub>tot</sub> in melt): (i) a decrease in  $X_{Mg}^{melt} / (X_{Mg}^{melt} + X_{Fe}^{melt})$  when  $\Delta FMQ$  is constant, or (ii) an increase in  $\Delta FMQ$  when  $X_{Mg}^{melt} / (X_{Mg}^{melt} + X_{Fe}^{melt})$  is fixed (fig. S5). For terrestrial lavas, magnetite precipitation is triggered by mechanism (i), whereas the melts equivalent to the NWA 7533 igneous clasts seem to have been controlled by mechanism (ii). While mechanism (i) can be described by melting experiments in Toplis and Carroll (18), and terrestrial magma differentiation, it is necessary to examine mechanism (ii) in the lab. We carried out melting and crystallization experiments at atmospheric pressures. Oxide powders (MgO-Al<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub>-TiO<sub>2</sub>-Cr<sub>2</sub>O<sub>3</sub>-MnO-FeO) and carbonates (NaCO<sub>3</sub>-K<sub>2</sub>CO<sub>3</sub>-CaCO<sub>3</sub>) were weighed out to make  $\approx 1$  g mixture shergottite-like powder. The mixture was ground in an agate mortar to reach homogenization, and aliquots of 50 mg mass were mixed into a viscous slurry and loaded on Pt loops. Since the experiments have been carried out at high  $fO_2$  conditions, the Fe loss due to absorption into Pt wire should be negligible. The samples were heated to 1350 °C at  $\Delta FMQ = -2.9$  to reach a complete melting in a furnace system as described by Sossi *et al.* (59), and a switch of  $\Delta FMQ$  value from  $-2.9$  to  $+2.6$  or  $+6.5$  was conducted while cooling the systems to

1100-1250 °C. Oxygen fugacity was buffered by monitoring CO-CO<sub>2</sub> gas mixtures, and at a given temperature, the oxygen fugacity can be estimated with an accuracy of ± 0.05 log unit. An Eurotherm® controller with a thermocouple external to the alumina muffle tube allows the temperature control to be within ± 1 °C (59). For the runs, the cooling rate was set to be 5 °C/h, and the system stayed at the aimed temperature (1100-1250 °C) for 6-10 h to allow sufficient crystallization, after which the melt droplets were dropped into a water tank for quenching. The samples were mounted into epoxy, and measured for major element compositions by SEM at IPGP (data file S5). The results show that oxidation at a given temperature can lower magnetite solubility in mafic melts, and causes magnetite crystallization, thus leading to lower FeOtot contents but higher Mg# values in the melts (fig. S5). Using equation 5, the melts from two runs quenching at 1250 °C and 1150 °C return to  $\Delta FMQ$  values of  $+2.5 \pm 0.8$  and  $+2.3 \pm 0.8$  (fig. S4b), respectively, which fit with the experimental  $\Delta FMQ$  value of  $+2.64 \pm 0.05$ . The melt from a run quenching at 1100 °C and air condition provides  $\Delta FMQ = +5.1 \pm 1.0$ , which is lower than the supposed  $\Delta FMQ$  value when equilibrating with air ( $\sim +6.5$ ). We suspect that equation 3 cannot be exactly extrapolated to  $X_{Mg}^{melt} / (X_{Mg}^{melt} + X_{Fe}^{melt}) > 0.596$  and SiO<sub>2</sub> = 60.6 wt%. For instance, the  $D_{TiO_2}^{mgt/melt}$  value estimated for a melt with  $X_{Mg}^{melt} / (X_{Mg}^{melt} + X_{Fe}^{melt}) = 0.604$  is  $1.73 \pm 0.63$ , which is higher than the measured  $D_{TiO_2}^{mgt/melt}$  value of 0.92 (fig. S4a). Nonetheless, the experiments in this study can confirm that oxidation is a viable mechanism to trigger and forward magnetite crystallization at 1100-1250 °C.

#### Quantifying the effects from oxidation on chemical and Ti isotopic compositions of magmas.

Upon the mechanisms described, equation 3 can be used to estimate the partition coefficients of TiO<sub>2</sub> between magnetite and melt ( $D_{TiO_2}^{mgt/melt}$ ) from the silicate melt composition, and equation 5 provides a link between melt oxygen fugacity and magnetite solubility if considering that  $AMCNK$  is fixed to be 0.35 and magnetite is the only crystallizing phase. Based on an incremental removal of Fe-Ti oxides, we can estimate the remaining Ti fractions ( $f_{Ti}$ ) in the melts experiencing a redox change from  $\Delta FMQ \leq -2.5$  to  $\Delta FMQ = +3-4$  from various starting melts, e.g. the melt with i) Mg# = 45 and FeOtot = 20.5 wt% or ii) Mg# = 35 and FeOtot = 20.5 wt%. While  $f_{Ti}$  after magnetite removal can be quantified, Ti isotopic fractionation factors between different melts and magnetite (usually referred as  $\Delta^{49}Ti_{melt-oxide}$ , i.e., the delta difference on <sup>49</sup>Ti/<sup>47</sup>Ti ratio between the two phases) are less constrained, whereas there have been studies showing that  $\Delta^{49}Ti_{melt-oxide}$  can vary between +0.1‰ and +0.5‰, depending on temperature, melt composition and oxide composition (10, 11, 13-15, 60). After assigning  $\Delta^{49}Ti_{melt-oxide}$  values, the  $\delta^{49}Ti$  of the oxidized melt after oxidation can be calculated following Rayleigh distillation:

$$\delta^{49}Ti_{oxidized\ melt} = \delta^{49}Ti_{parent\ melt} - \Delta^{49}Ti_{melt-oxide} \times \ln(f_{Ti}) \quad (10)$$

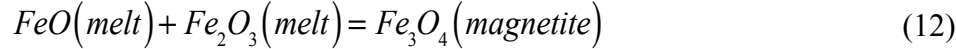
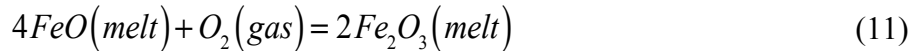
where parent melts can be assumed to have a shergottite-like  $\delta^{49}Ti$  of +0.015‰. Considering that  $\Delta^{49}Ti_{melt-oxide}$  increases with lower temperature and more silicic melt composition (10, 11, 13-15, 60), we can reasonably assign the  $\Delta^{49}Ti_{melt-oxide}$  to be +0.2‰ at Mg# = 45 and to be +0.4‰ at Mg# = 35. Afterwards, we can observe that for parent melts with lower Mg# values, oxidation can result in larger Ti isotopic fractionations in the differentiated melts (Fig. 2 and fig. S6), arising from their higher  $D_{TiO_2}^{mgt/melt}$  and  $\Delta^{49}Ti_{melt-oxide}$  values.



The Ni concentrations in the melt after oxidation can also be estimated with an incremental removal of Fe-Ti oxides after assigning Ni = 1750 ppm and FeO<sub>tot</sub> = 20.5 wt% to the parent melt, as well as  $D_{Ni}^{mgt/melt}$ . The Ni-FeO<sub>tot</sub> systematics of the NWA 7034/7533 igneous clasts can be reproduced by continuous Fe-Ti oxide removal with  $D_{Ni}^{mgt/melt} = 13$  (Fig. 3). While the  $\delta^{49}\text{Ti-Mg\#}$  systematics of the differentiated melts are quite sensitive to the inconsistent  $D_{TiO_2}^{mgt/melt}$  and  $\Delta^{49}\text{Ti}_{\text{melt-oxide}}$  values in parent melts with various Mg# values (or MgO contents), the differentiated melts should follow almost the same oxide-controlled trajectory on the Ni vs. FeO<sub>tot</sub> plot, as soon as these parent melts have been assigned to have the same FeO<sub>tot</sub> contents and Ni concentrations. This explains why the NWA 7533/7034 clasts provide a continuous Ni vs. FeO<sub>tot</sub> pattern (Fig. 3), whereas their distribution seems more scattered on the  $\delta^{49}\text{Ti}$  vs. Mg# plot (Fig. 2). The effects on V and Co in melts can be also quantified following an incremental removal of Fe-Ti oxides.

#### Quantifying oxygen contribution in the melts from the oxidant.

After estimating the  $\Delta FMQ$  values of the silicate melts, the oxygen contribution from the oxidant can be calculated. Note that 10 wt% addition of rocky material from the impactors may alter the oxygen fugacity of the melts by sub log unit, depending on the oxidation state of possible chondritic impactors. While the types of the chondritic impactor are less constrained, we temporarily consider that oxidation of melt can be represented by reaction with free oxygen coming from decomposition of water:



The ferric-ferrous ratio of silicate melt is a function of oxygen fugacity, temperature, pressure and composition as shown by Gaillard *et al.* (61):

$$\ln\left(\frac{X_{\text{Fe}_2\text{O}_3}^{\text{melt}}}{X_{\text{FeO}}^{\text{melt}}}\right) = 0.196 \times \ln(10) \times \left[ \Delta FMQ + \frac{25096 - 0.11 \times (P-1)}{T} - 8.735 \right] + \frac{1.1492 \times 10^4}{T} - 6.675 + \sum d_i X_i^{\text{melt}} \quad (13)$$

where  $T$  is temperature in K,  $P$  is pressure in bar,  $d_i$  is coefficient for  $i$  in melt, and  $X_i^{\text{melt}}$  is molar proportion of  $i$  in melt. The uncertainty on  $X_{\text{Fe}_2\text{O}_3}^{\text{melt}} / X_{\text{FeO}}^{\text{melt}}$  can be estimated from the partial differential equations from equation 13:

$$\frac{\partial \left( \frac{X_{\text{Fe}_2\text{O}_3}^{\text{melt}}}{X_{\text{FeO}}^{\text{melt}}} \right)}{\partial \Delta FMQ} = 0.196 \times \ln(10) \times \frac{X_{\text{Fe}_2\text{O}_3}^{\text{melt}}}{X_{\text{FeO}}^{\text{melt}}} \quad (14)$$

$$\frac{\partial \left( \frac{X_{\text{Fe}_2\text{O}_3}^{\text{melt}}}{X_{\text{FeO}}^{\text{melt}}} \right)}{\partial P} = \frac{-0.02156 \times \ln(10)}{T} \times \frac{X_{\text{Fe}_2\text{O}_3}^{\text{melt}}}{X_{\text{FeO}}^{\text{melt}}} \quad (15)$$

$$\frac{\partial \left( \frac{X_{Fe_2O_3}^{melt}}{X_{FeO}^{melt}} \right)}{\partial T} = \frac{-0.196 \times \ln(10) \times [25096 - 0.11 \times (P-1)] - 1.1492 \times 10^4}{T^2} \times \frac{X_{Fe_2O_3}^{melt}}{X_{FeO}^{melt}} \quad (16)$$

To oxidize a reduced parent melt containing negligible ferric iron (e.g.,  $\Delta FMQ \leq -2.5$ ), the oxygen contribution from the oxidant in the oxidized melt ( $f_{O-oxidant}^{melt}$ ) can be approximated to:

$$f_{O-oxidant}^{melt} \approx \frac{X_{FeOtot}^{melt} \times \left( \frac{2 \times \frac{X_{Fe_2O_3}^{melt}}{X_{FeO}^{melt}}}{2 \times \frac{X_{Fe_2O_3}^{melt}}{X_{FeO}^{melt}} + 1} \right) \times \frac{1}{2} + (X_{FeOtot}^{parent\ melt} - X_{FeOtot}^{melt}) \times \frac{1}{3}}{\sum \beta_i X_i^{melt}} \quad (17)$$

where  $\beta_i$  represents the oxygen number in oxide  $i$  with molecular formula of  $x_\alpha O_\beta$ . The

uncertainty on  $f_{O-oxidant}^{melt}$  can be estimated from the errors from  $X_{Fe_2O_3}^{melt} / X_{FeO}^{melt}$  and  $X_{FeOtot}^{melt}$ :

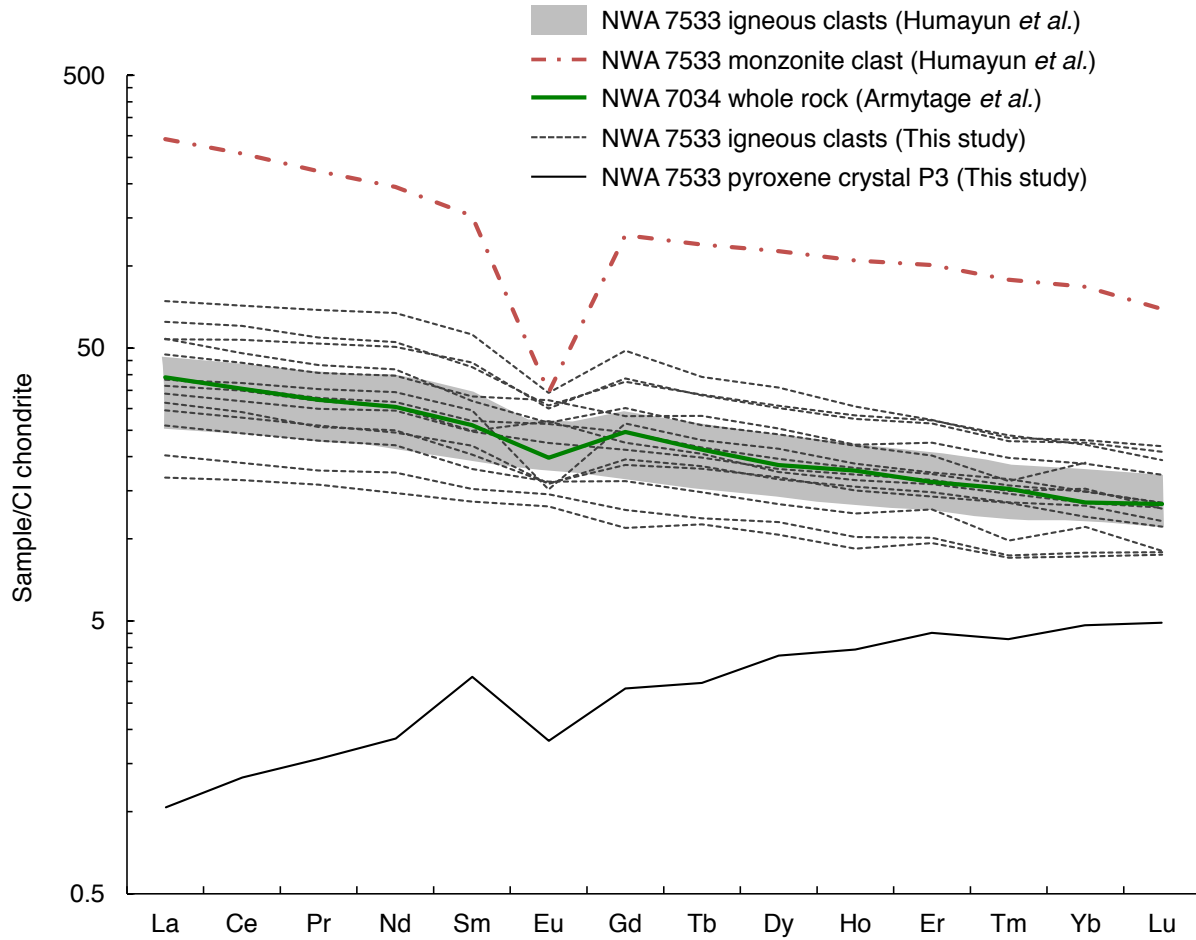
$$\frac{\partial (f_{O-oxidant}^{melt})}{\partial \left( \frac{X_{Fe_2O_3}^{melt}}{X_{FeO}^{melt}} \right)} = \frac{X_{FeOtot}^{melt}}{\left( 2 \times \frac{X_{Fe_2O_3}^{melt}}{X_{FeO}^{melt}} + 1 \right)^2} \times \frac{1}{\sum \beta_i X_i^{melt}} \quad (18)$$

$$\frac{\partial (f_{O-oxidant}^{melt})}{\partial (X_{FeOtot}^{melt})} = \left[ \frac{2 \times \frac{X_{Fe_2O_3}^{melt}}{X_{FeO}^{melt}}}{2 \times \frac{X_{Fe_2O_3}^{melt}}{X_{FeO}^{melt}} + 1} \times \frac{1}{2} - \frac{1}{3} \right] \times \frac{1}{\sum \beta_i X_i^{melt}} \quad (19)$$

Assuming  $FeO_{tot} = 20.5$  wt% for parent melt and a temperature of 1100 °C, integration of the equations above provides  $f_{O-oxidant}^{melt}$  values of  $0.024 \pm 0.006$ ,  $0.026 \pm 0.007$  and  $0.029 \pm 0.008$  for the igneous clasts C16, C7 and C27, respectively. Afterwards, the effects from impact-induced oxidation on the melt  $\Delta^{17}O$  would be dependent on the oxygen contributions from the oxidant (water or perchlorates) and rocky impactor (i.e.,  $f_{O-oxidant}^{melt}$  and  $f_{O-rocky\ impactor}^{melt}$ , respectively):

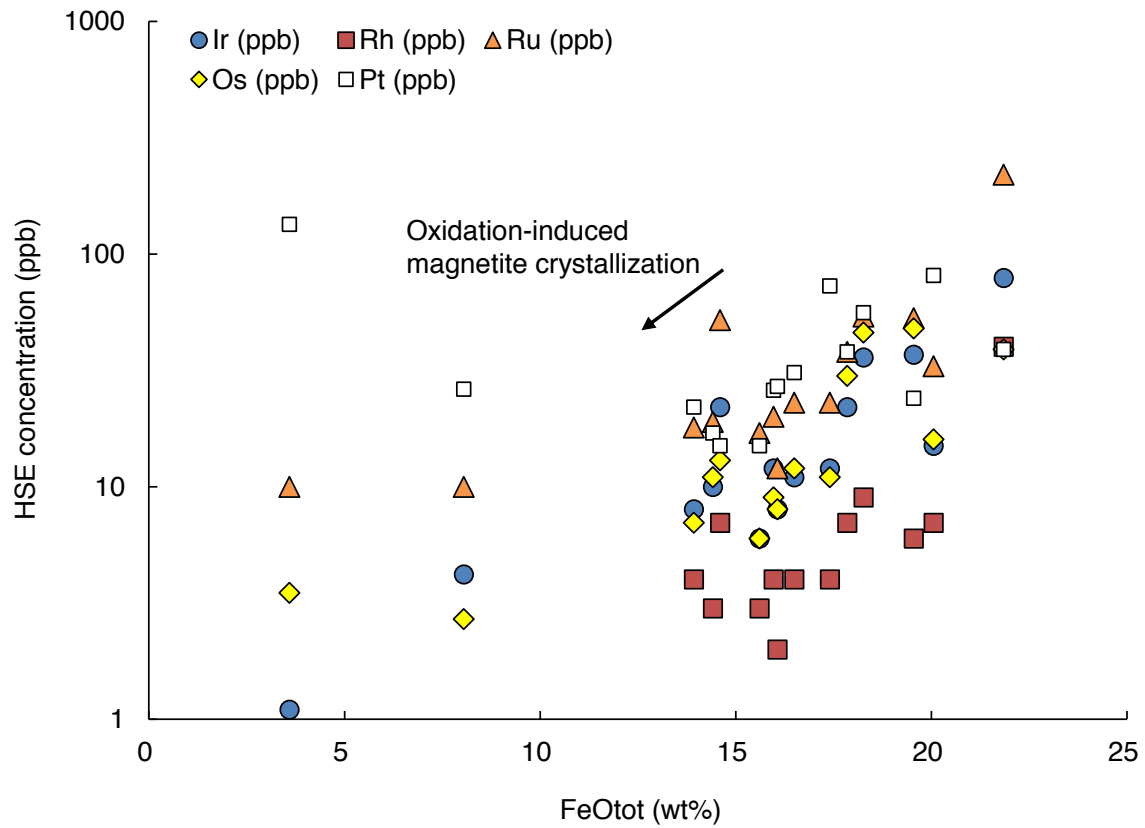
$$\Delta^{17}O_{oxidized\ melt} - \Delta^{17}O_{parent\ melt} \approx \left( \Delta^{17}O_{oxidant} - \Delta^{17}O_{parent\ melt} \right) \times f_{O-oxidant}^{melt} + \left( \Delta^{17}O_{rocky\ impactor} - \Delta^{17}O_{parent\ melt} \right) \times f_{O-rocky\ impactor}^{melt} \quad (20)$$

where  $\Delta^{17}O_i$  is the  $\Delta^{17}O$  value of  $i$ . Once  $f_{O-oxidant}^{melt}$  and  $f_{O-rocky\ impactor}^{melt}$  have been quantified based on oxygen fugacity change and highly siderophile element concentrations, respectively, the effects from oxidation on the  $\Delta^{17}O$  values of oxidized melts would depend on the  $\Delta^{17}O$  differences of oxidant and rocky impactor relative to the reduced parent melt (equation 20).



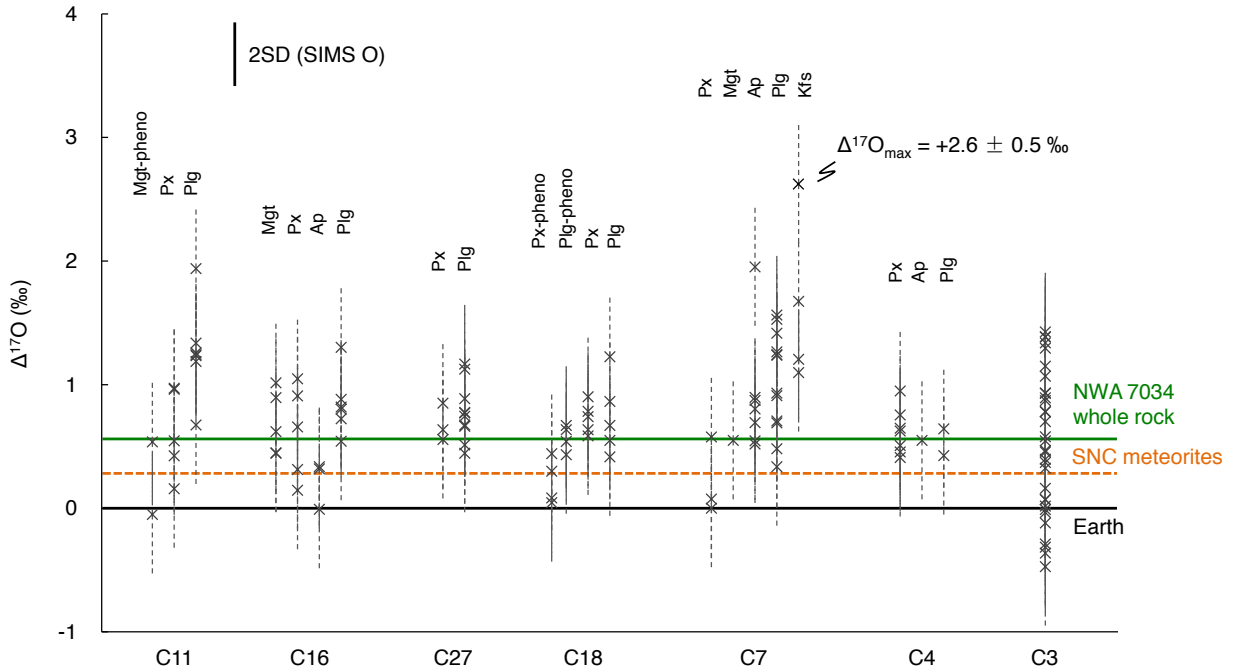
**Fig. S1.**

Rare earth element abundances of the NWA 7533/7034 igneous clasts after a normalization onto CI chondrite values (39). Data of the NWA 7533 igneous clasts with a unique monzonite clast (3) and whole rock NWA 7034 meteorite (31) are also shown.



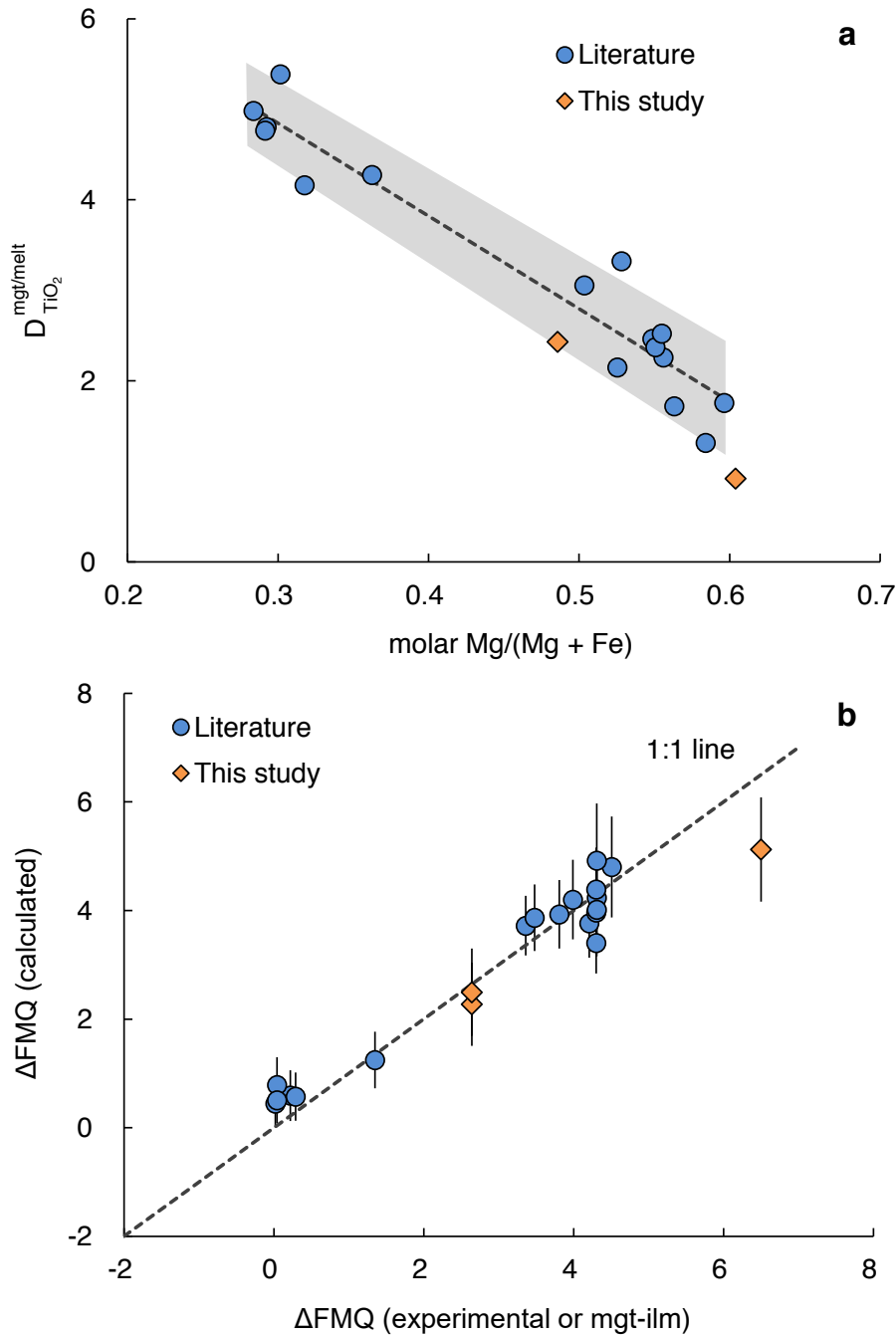
**Fig. S2.**

Highly siderophile element (HSE) abundances and FeO<sub>tot</sub> contents of the NWA 7533 clasts obtained by laser ablation measurements in Humayun *et al.* (3).



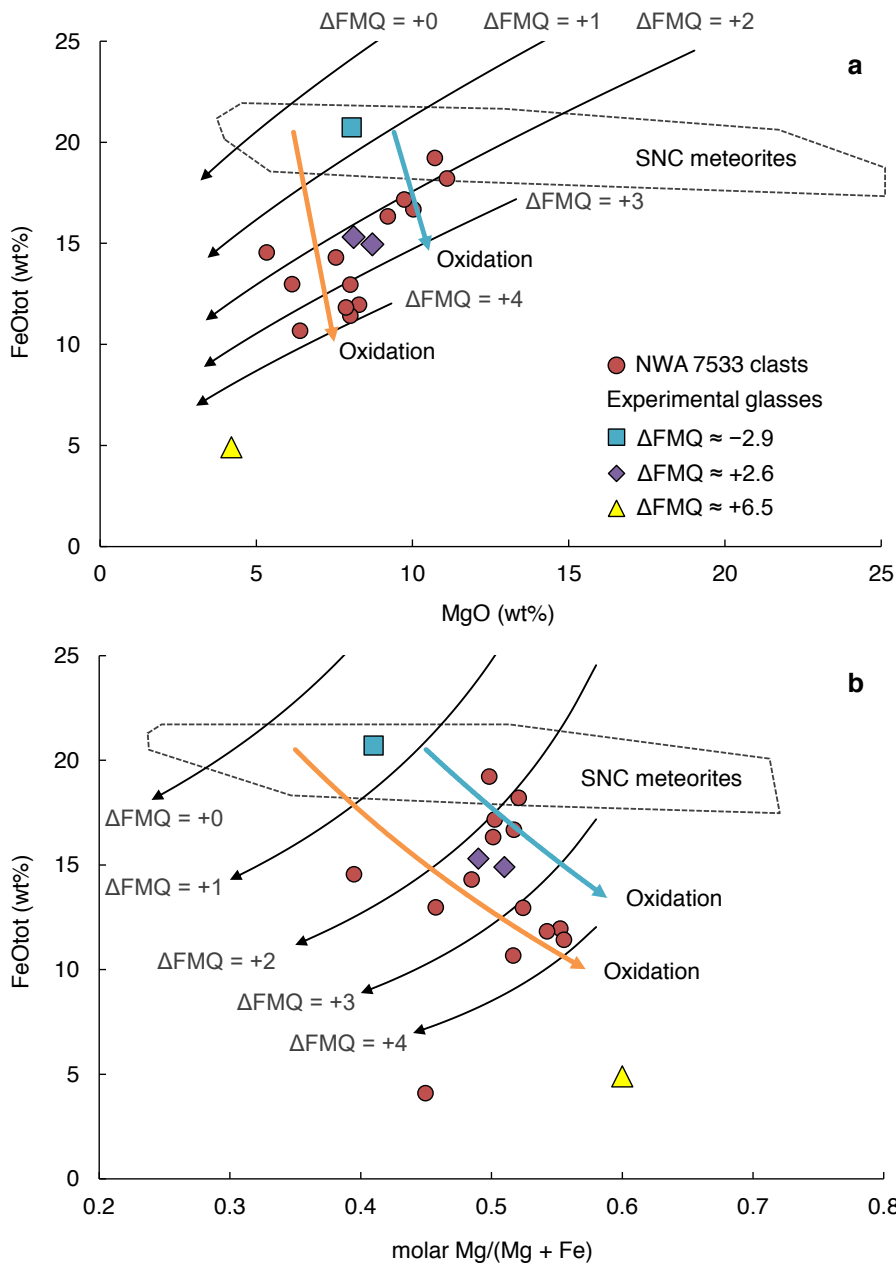
**Fig. S3.**

*In situ* triple O isotopic results on seven NWA 7533/7034 igneous clasts obtained by SIMS measurements in this study. The values for whole rock NWA 7034 meteorite (4), SNC meteorites (41) and the Earth are also shown.



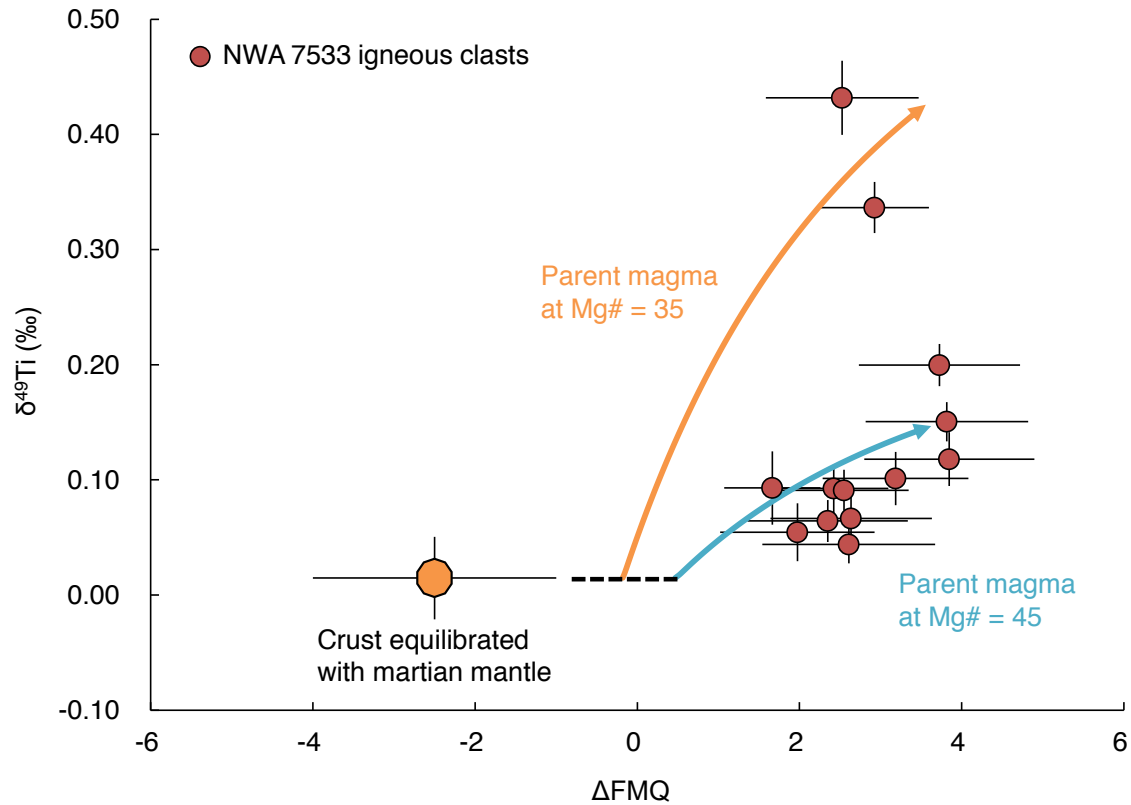
**Fig. S4.**

(a) Plot showing the correlation between  $D_{\text{TiO}_2}^{\text{mgt/melt}}$  and melt Mg# in 16 experimental runs from the compilation in Arató and Audétat (17), except for two runs with high  $\text{SiO}_2$  contents of 59.03-59.73 wt%. (b) Plot comparing the  $\Delta\text{FMQ}$  values calculated from the oxybarometer updated after Arató and Audétat (17) with the values from experimental settings or those estimated using magnetite-ilmenite pairs (17). Results from the experimental runs in this study are also shown.



**Fig. S5.**

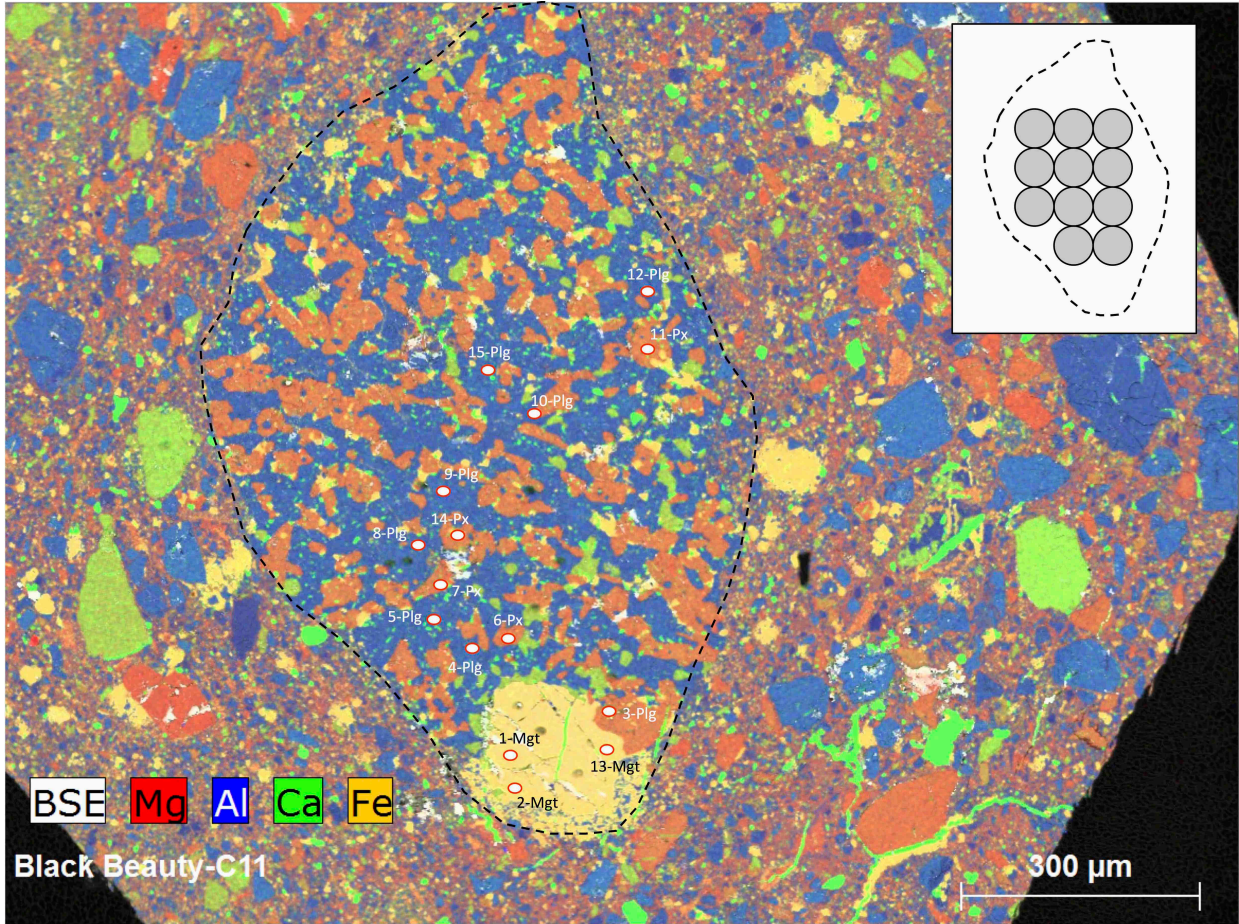
Plots of FeO<sub>tot</sub> versus MgO (**a**) and FeO<sub>tot</sub> versus molar Mg/(Mg + Fe) (**b**) for the NWA 7533 clasts and experimental glass samples at ΔFMQ values of -2.9, +2.6 and +6.5 from the furnace experiments in this study. The black curves show the compositional variations predicted by equation 5 for oxide-saturated silicate melts at ΔFMQ values of +0, +1, +2, +3 and +4, assuming the AMCNK value fixed to be 0.35. The two colored trajectories with arrow represent the effects from oxide removal, caused by oxidation of the basaltic shergottite-like melts (FeO<sub>tot</sub> = 20.5 wt%) at Mg# values of 35 (the orange) and 45 (the blue).



**Fig. S6.**

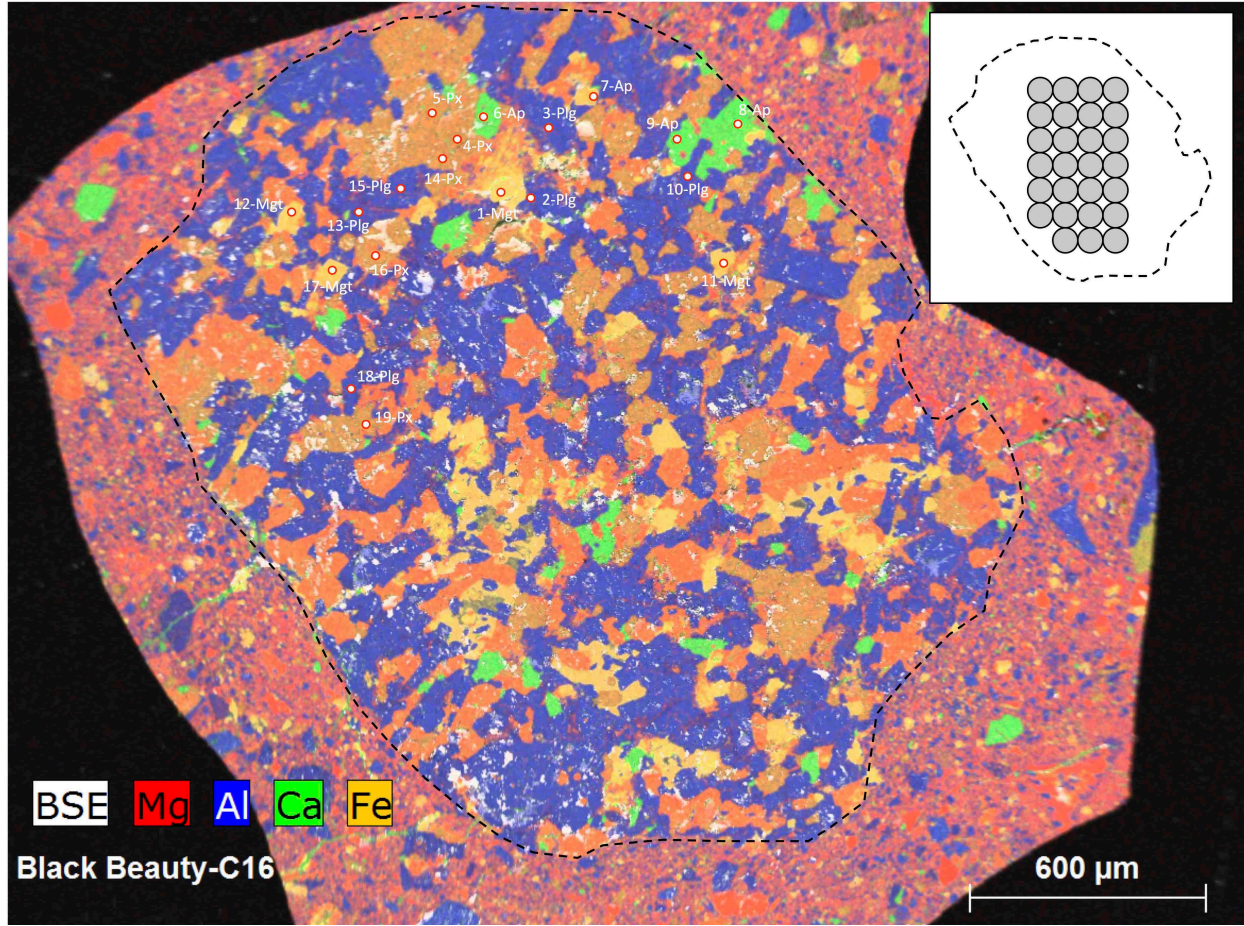
Plot of  $\delta^{49}\text{Ti}$  versus  $\Delta\text{FMQ}$  for the NWA 7533 clasts. The crust at equilibrium with martian mantle is considered to have a  $\delta^{49}\text{Ti}$  value of  $+0.015 \pm 0.036\text{‰}$  based on the Ti isotopic results from shergottites in this study, and an average  $\Delta\text{FMQ}$  value of  $-2.5 \pm 1.5$  (6). The two colored trajectories with arrow represent the effects from oxide removal, caused by oxidation of the basaltic shergottite-like melts ( $\text{FeO}_{\text{tot}} = 20.5 \text{ wt\%}$ ) at Mg# values of 35 (the orange) and 45 (the blue).





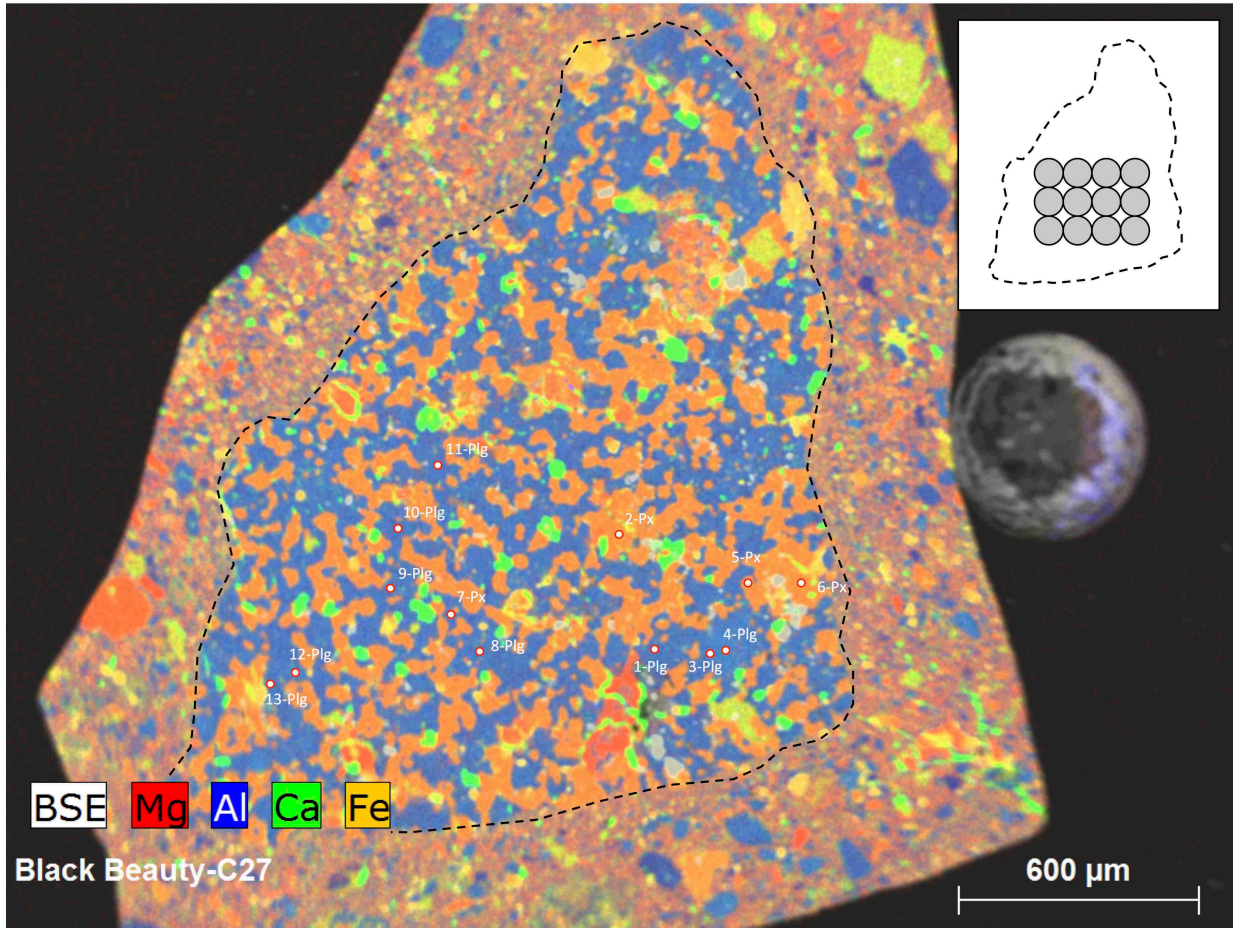
**Fig. S7.**

Chemical map with SIMS (~15 μm) and laser ablation (~160 μm in the inset) spots for clast C11.



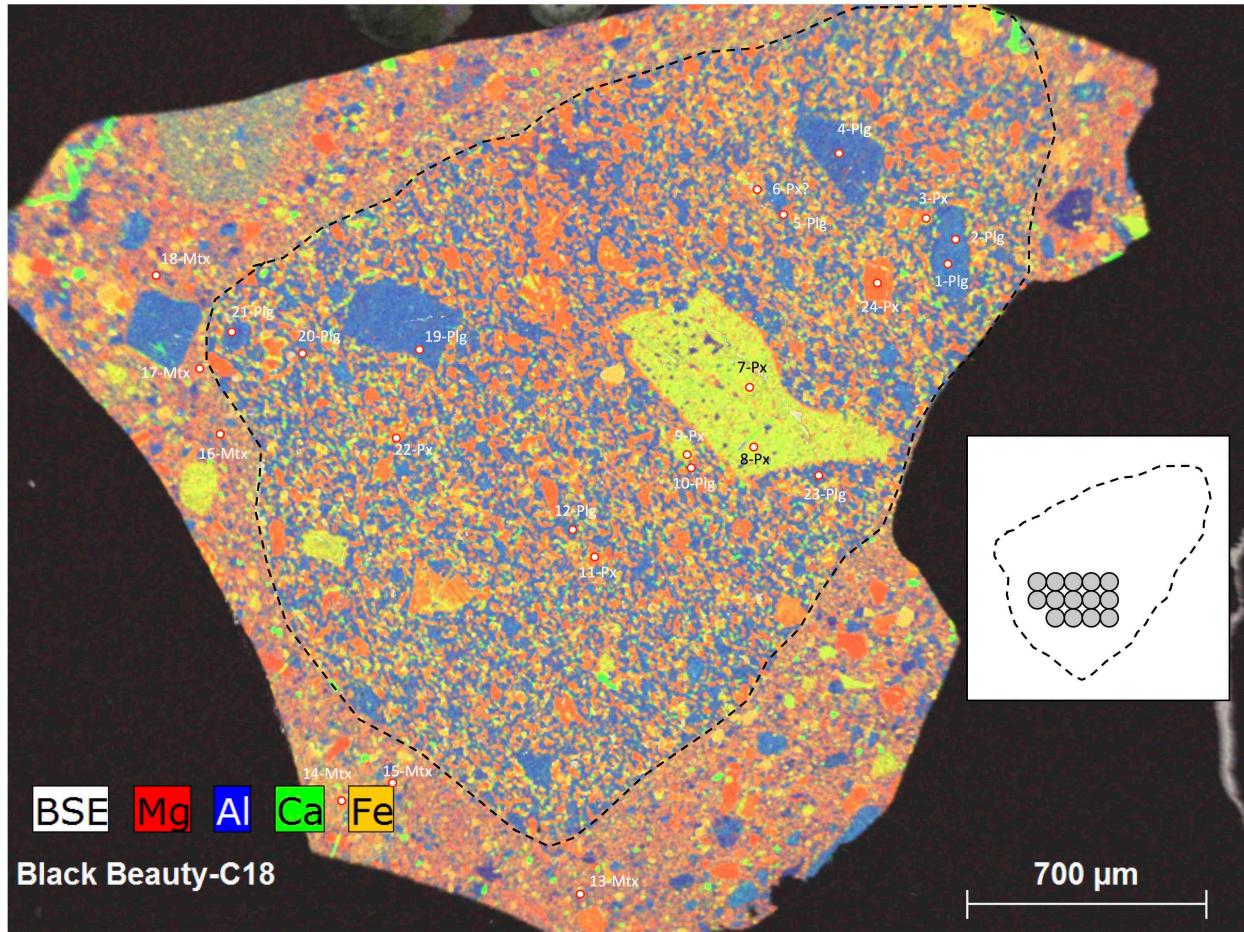
**Fig. S8.**  
Chemical map with SIMS (~15 μm) and laser ablation (~160 μm in the inset) spots for clast C16.





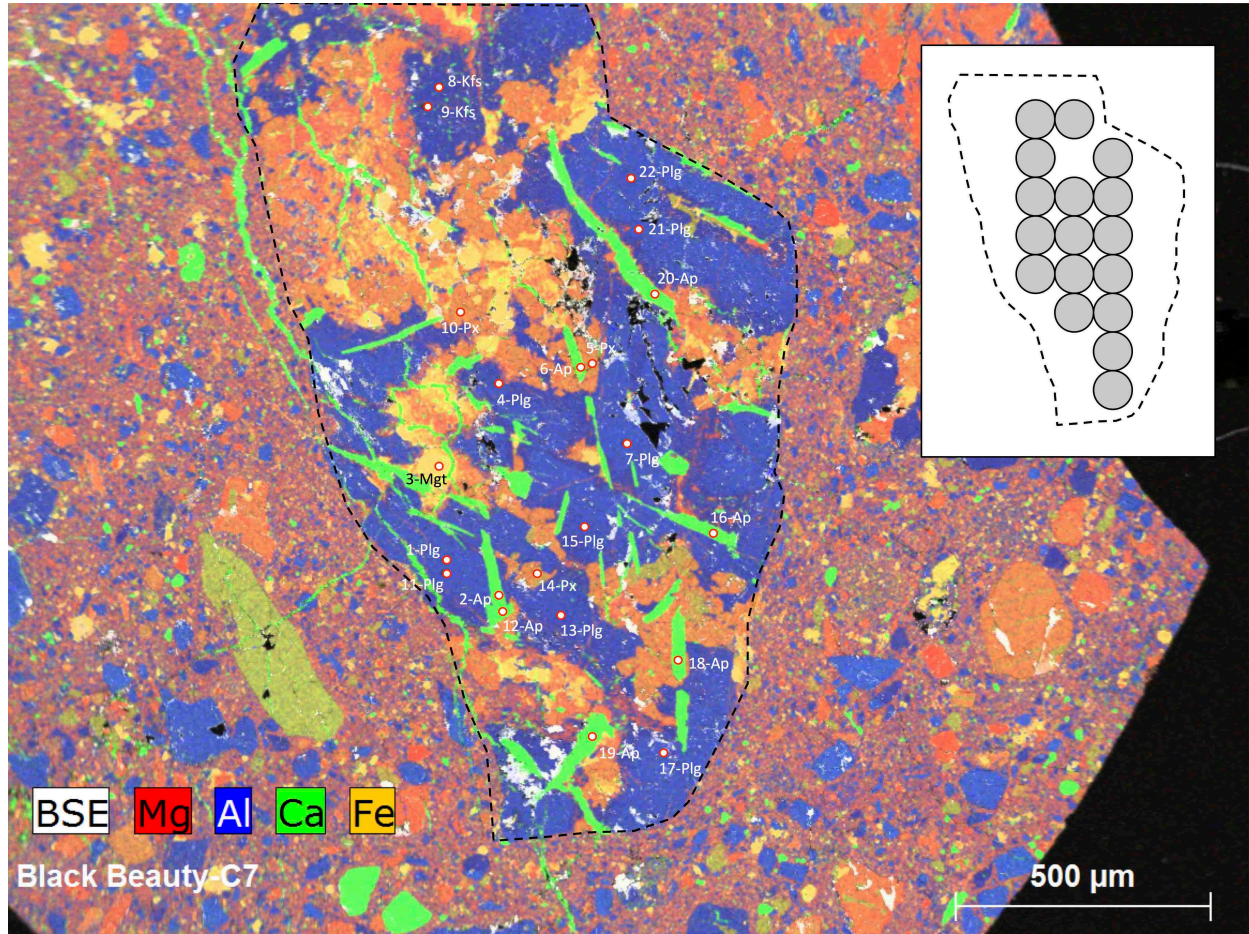
**Fig. S9.**

Chemical map with SIMS (~15 μm) and laser ablation (~160 μm in the inset) spots for clast C27.

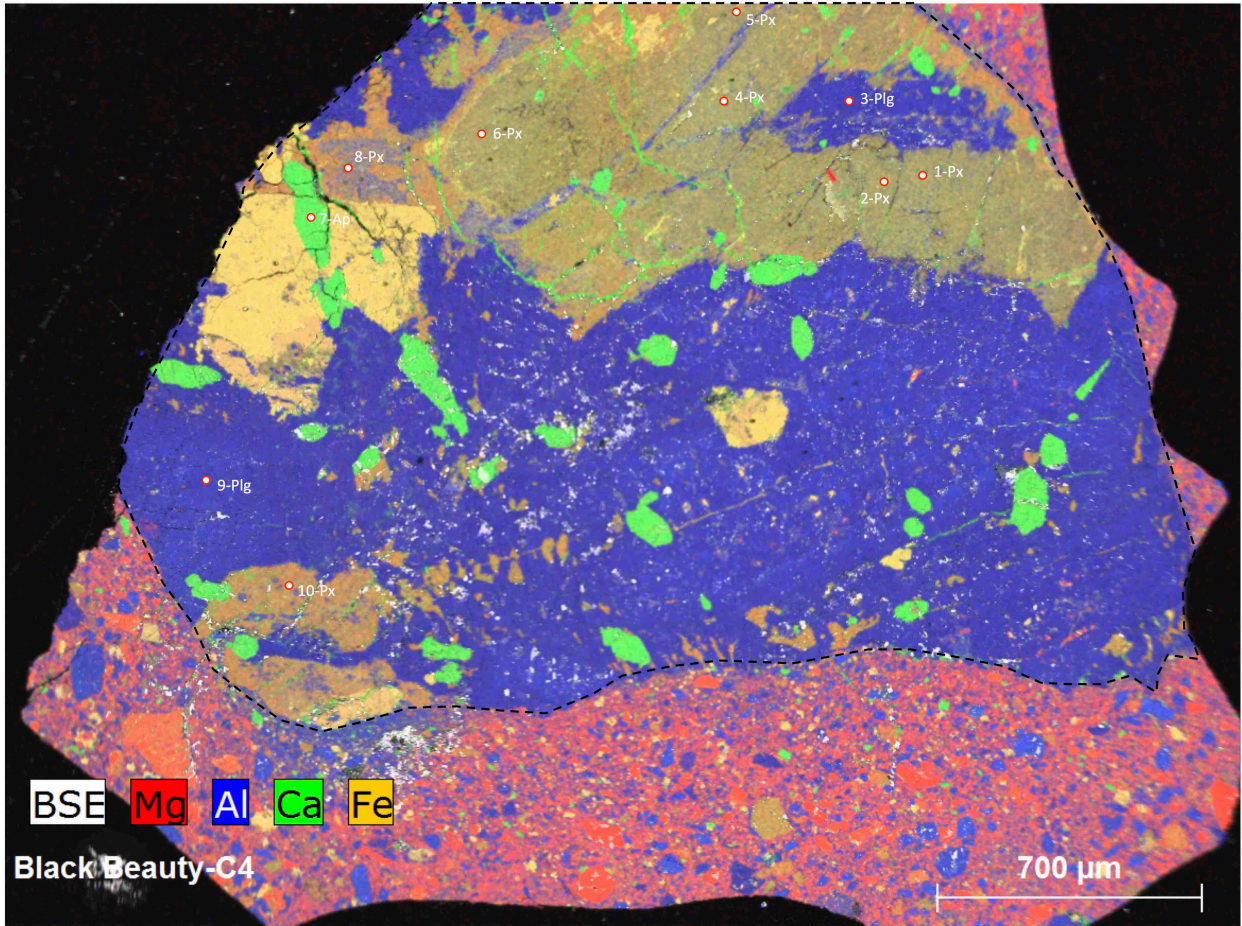


**Fig. S10.**  
Chemical map with SIMS (~15 μm) and laser ablation (~160 μm in the inset) spots for clast C18.



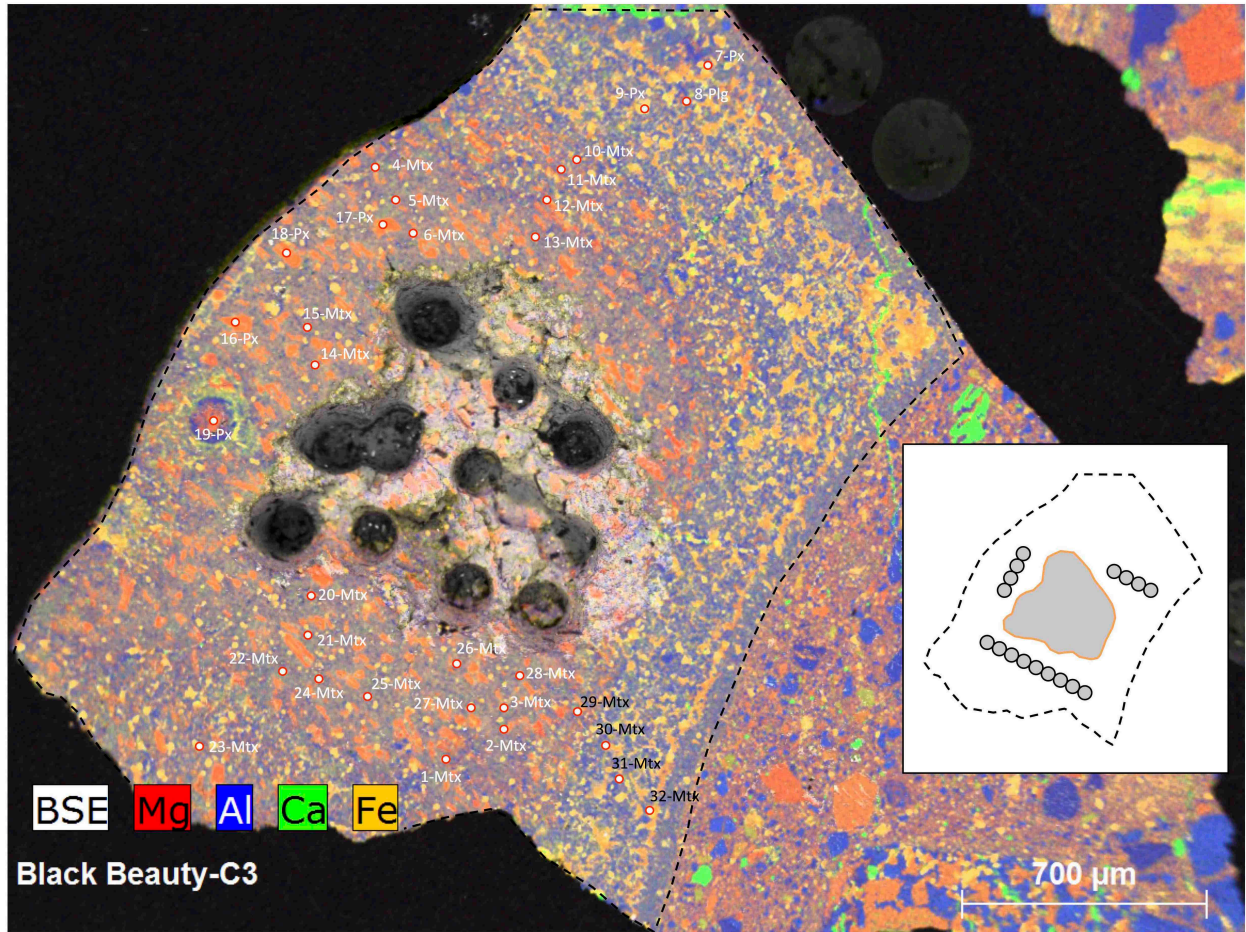


**Fig. S11.**  
 Chemical map with SIMS (~15 µm) and laser ablation (~160 µm in the inset) spots for clast C7.



**Fig. S12.**  
Chemical map with SIMS (~15 μm) spots for clast C4.





**Fig. S13.**  
Chemical map with SIMS (~15 μm) and laser ablation (~160 μm in the inset) spots for clast C3.



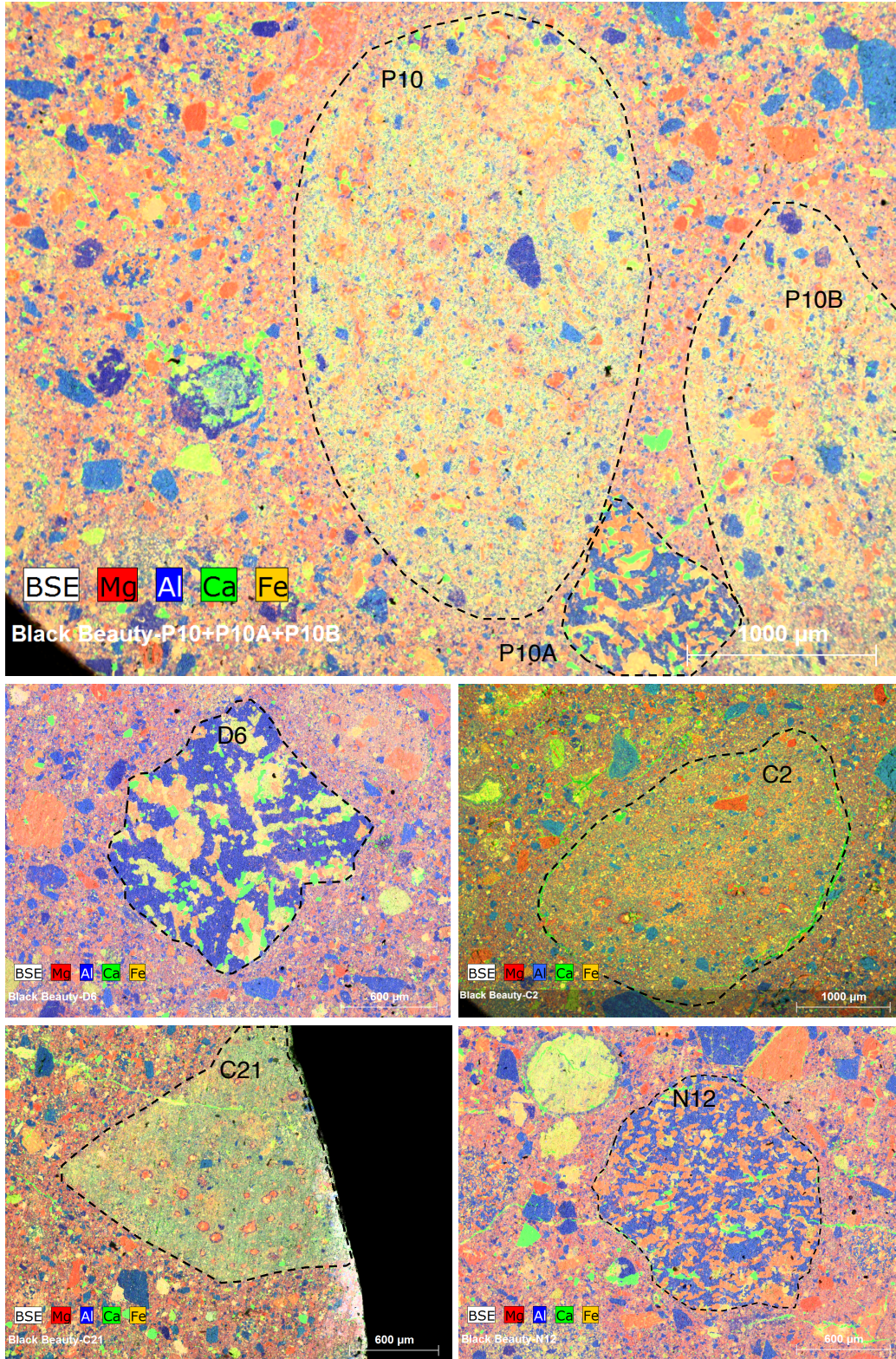


Fig. S14.  
Chemical maps for clasts D6, C21, P10, P10A, P10B, C2 and N12.



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