

Magnetite T.I. : The Case of the Blue Lava
or
Origin of Surficial Color in the Blue Dragon Lava Flow,
Craters of the Moon, Idaho

By

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Abstract

Basalt flows in Craters of the Moon National Monument (COM) near Arco, ID have a striking blue surficial coating that has been observed only at this location and at Kilauea volcano in Hawaii. While the surface of the basalts is blue, the interior is a grey color commonly associated with basalt flows. Faye and Miller (1973) propose that the surface coloration is due to a siliceous film diffusing reflected blue light from near-surface oxidized titanomagnetite crystals; however, results from this study are consistent with the Chemtob and Rossman (2014) mechanism based on blue Kilauea basalt flows. The latter mechanism involves post-eruption dissolution of the fresh basalt surfaces and precipitation of both a siliceous coating and a separate Fe-Ti oxide-rich coating, the latter being the cause for the blue coloration of the basalts. The elevated Ti^{3+} concentrations of COM basalt surfaces suggest a trend of Ti^{3+} surface enrichment that correlates with the presence of blue on the samples. Additionally, partial dissolution observed in near-surface titanomagnetites suggests a dissolution process that could potentially mobilize the Ti^{3+} and Fe^{3+} subsurface ions, transporting them to the surface via the same mechanism as the Chemtob and Rossman (2014) model. Consequently, the mechanism proposed by Faye and Miller (1973) that currently serves as an explanation for the blue coloration should be dismissed in favor of the Chemtob and Rossman (2014) mechanism that more adequately accounts for the surficial color variation observed in the Craters of the Moon basalts.

Introduction

The lava flows at Craters of the Moon National Monument (COM) near Arco, ID are characterized by their distinctive and widespread blue coloration of the basalt surfaces. A similar coloration is observed on younger lava flows at Kilauea volcano in Hawaii, however the blue in these lavas is not nearly as extensive as that at Craters of the Moon (Chemtob and Rossman, 2014). The mechanism responsible for this surficial coloration has yet to be conclusively identified, yet I believe the model for formation of amorphous silica on the surface of basalts proposed by Chemtob and Rossman (2014) is currently the hypothesis that best accounts for the conditions observed at Craters of the Moon. This model argues for the mobilization and surficial precipitation of amorphous silica and oxidized Fe-Ti oxides, resulting in the blue coating found only on the surfaces of the COM lava flows.

Background

Craters of the Moon National Monument is located in south-central Idaho within the Snake River Plain. The volcanic flows within the park range from roughly 2,000 to 15,000 years in age, although the flows sampled for the purpose of this study are part of the youngest eruptive phase. While absolute dates are not available for all the flows, North Crater and Green Dragon (which has now been re-classified as part of the North Crater flow) represent the oldest of the flows at around 2,300 years old (Kuntz et al., 1982). Blue Dragon's age has been constrained with the highest accuracy of the four flows and is dated at $2,076 \pm 45$ years (Kuntz et al., 2007). The Broken Top flow has not been dated, but lies stratigraphically on top of the others in this study, making it the youngest of the sample set. A NW-SE oriented fissure is found in the Blue

Dragon Flow. The Tree Molds Trail samples are on the western side of the fissure, with every other sample located to the east of the fissure (Kuntz et al., 2007).

Methods

Eleven samples were collected from four flows within Craters of the Moon National Monument (Figure 2.1). Two samples were gathered from both the North Crater and Broken Top flows, while three samples were obtained from the Green Dragon flow and four samples from the Blue Dragon flow. The Blue Dragon flow samples were collected from two different locations within Craters of the Moon. Two samples were obtained from the western side of the flow along the Tree Molds Trail, while an additional two were gathered from the eastern edge of the flow at Huddles Hole. Field samples were predominantly *in situ*, although some samples were found as loose, broken fragments on the surface of the flows. While these samples were not *in situ*, their provenance was within the same flow and were translated a negligible distance (<1 m) from their source.

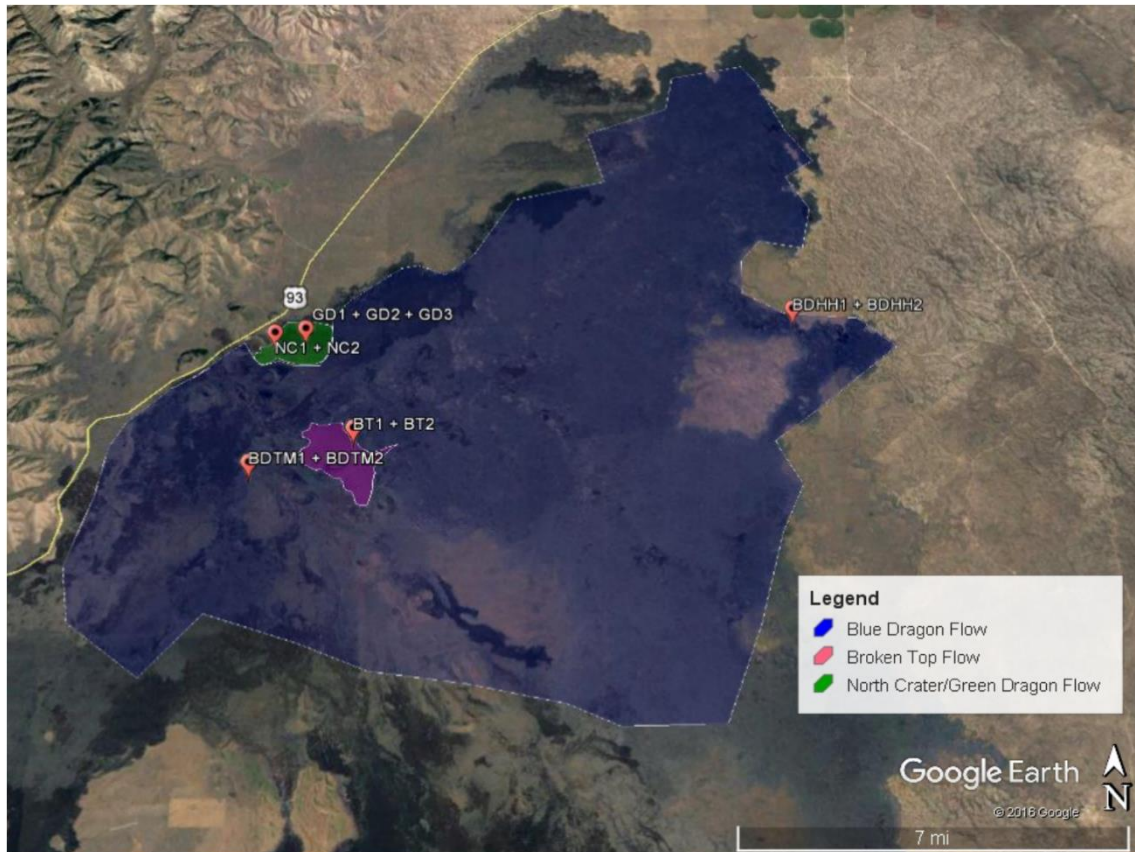


Figure 2.1: Map of Craters of the Moon National Monument with sample locations. Lava flow extents are approximate and meant only as a rough guideline (e.g. Blue Dragon extends farther to the southwest than depicted above).

The analytical methods used in this study were designed around four main hypotheses.

- 1) The blue surficial coloration is due to the surface having high concentrations of Mn while undergoing the weathering process of desert varnish (Perry and Adams, 1978).
- 2) The surface coloration is caused by electron transfer due to the oxidation of titanomagnetites in the surface (Cornell and Schwertmann, 2003).
- 3) Coloration is due to a diffusion of reflected light from oxidized titanomagnetites via a thin siliceous film on the surface of the basalts (Faye and Miller,

1973). 4) The blue surface is a result of dissolution of oxidized titanomagnetites that subsequently precipitate as a distinct coating on the surface (Chemtob and Rossman, 2014).

Thin sections were made from five of the collected samples (Table 2.1). One sample was used from each of the North Crater, Green Dragon, and Broken Top flows, along with one Blue Dragon sample from each collection site. Lava samples were cut both perpendicular and parallel to their surfaces in order to create one thin section that represented a cross-sectional segment of the rock with the surface on one edge, as well as a second thin section that contained only the blue surface. These thin sections were subsequently observed under both transmitted and reflected light microscopes.

Flow	Sample Names	Sample Use
Broken Top	BT1, BT2*	BT1 – SEM, XRD surface powder BT2 – XRD interior powder
Green Dragon	GD1, GD2*, GD3	GD1 – Not Used GD2 – XRD surface powder GD3 – SEM, XRD interior powder
North Crater	NC1 , NC2*	NC1 – SEM, XRD interior and surface powder NC2 – SEM
Blue Dragon (Tree Molds Trail)	BDTM1*, BDTM2	BDTM1 – XRD surface powder BDTM2 – SEM, XRD interior powder
Blue Dragon (Huddles Hole)	BDHH1, BDHH2	BDHH1 – Not Used BDHH2 – SEM, XRD surface and interior powder

Table 2.1: Sample identifications and collection locations.

Bold sample name indicates a sample that was used to make thin sections.

* indicates a sample that was not collected *in situ*.

In addition to thin sections, fragments of the samples were chipped away using hammer and chisel to be examined by scanning electron microscope (SEM). In a similar fashion to the thin sections, chips were taken from each flow; one chip was extracted from the surface and remained unpolished, while the second was removed from within the interior of the sample and

was polished prior to examination in the SEM. These chips were carbon-coated twice in order to ensure a complete coating due to the presence of deep vesicles in many of the samples.

Scanning electron microscope (SEM) imaging and a back-scattered electron (BSE) detector was used to identify mineralogical components such as magnetite crystals as well as other surficial features (e.g., a siliceous film present on each sample). Element maps were generated on the SEM for each flow using the BSE detector. Ten element maps of surface chips for samples BT1, GD3, BDTM2, BDHH2, NC1, and NC2 were collected at random spots on the sample to document the composition of the blue coloration; an additional 10 element maps were produced of the interior chips (excluding NC2) where the blue coloration was not present, for comparison. The resulting 20 element maps were then used to compare compositional variation between the surface and the interior of each sample.

Element maps were generated for two separate North Crater flow surface chips to contrast surficial characteristics in samples from the same flow with varying blue surfaces. The NC1 surface chip was obtained from a portion of the sample that has minimal amounts of blue coloration on the surface. In contrast, the NC2 surface chip is completely blue on the surface (Figure 2.2 showing comparison between NC1 and NC2 chips). Element maps were generated from only the NC1 interior chip and not NC2, as the proximity of the samples (separated on the surface by centimeters) allowed for the use of a single interior chip for comparisons of both surface chips.

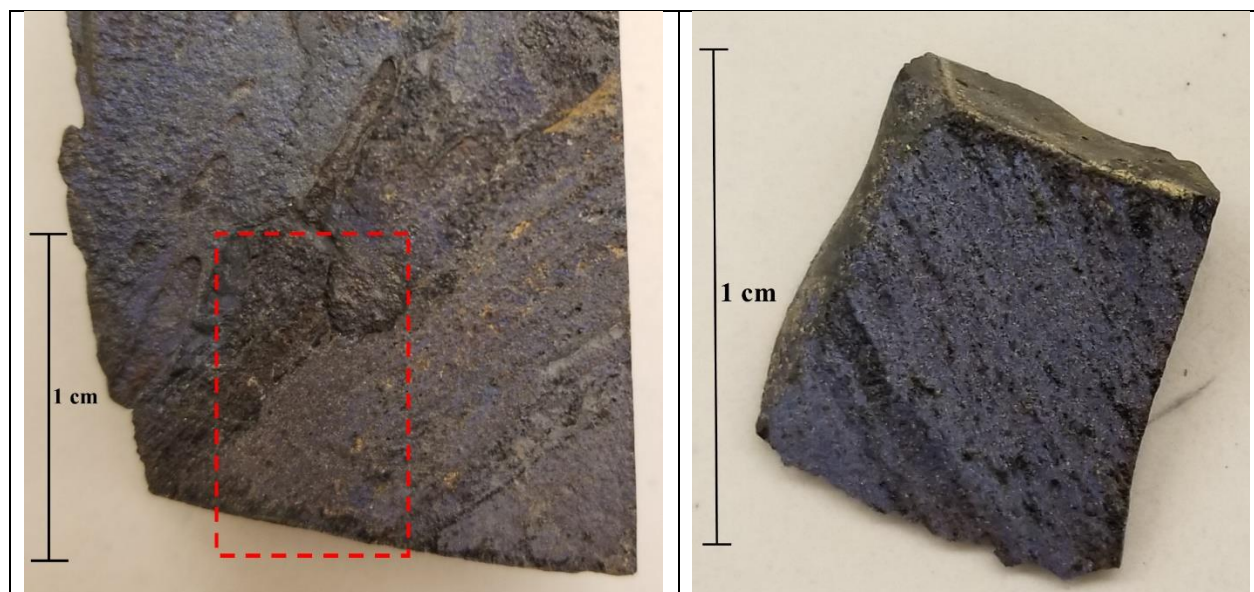


Figure 2.2 North Crater Surface Chip Comparison: (Left) Sample NC1 surface chip (dotted red line) prior to removal. Surface of this chip was minimal blue compared to the surrounding area. (Right) Surface chip of sample NC2 with an almost entirely blue surface.

In addition to the element maps, five SEM images were taken of each surface chip in order to document the presence and extent of the siliceous film. The contrast of each image was then adjusted to accentuate the film's brightness and to darken the surrounding glassy surface. Subsequently, these images were analyzed using the software ImageJ, which was used to generate the area of the sample covered by the siliceous film (National Institutes of Health, <https://imagej.nih.gov/ij/index.html>). The siliceous film area measurements were averaged for each flow sample to generate an approximate extent of coverage for the different flows.

Samples from each flow were also analyzed using X-Ray Diffraction (XRD) (Table 2.1). The non-blue interiors of each sample were powdered using a ball mill and mortar and pestle, while the blue surfaces of the sample were carefully powdered with a diamond-tipped dremel so as not to powder any part of the sample that was not blue. The powders were each placed on a

glass slide in an isopropyl slurry and analyzed using XRD. The resulting scans representing the surface and interior of the samples were then overlain to compare compositional variations between the samples. These peaks were then matched with their corresponding mineral d-spacings.

Results

Field Observations

The first sample collection site is located within the Broken Top flow roughly 1 km north of Crescent Butte near the contact between the Broken Top and Blue Dragon flows. This area is characterized by numerous large (1-2m wide) crevices separating the pahoehoe flows. The first Blue Dragon collection site is along the Tree Molds Trail, roughly 50 m west of the end of the trail. The glassy surface of the flow in this location has been broken away in many areas, revealing a rust-orange oxidized layer of basalt (Figure 3.1). The surface that has not been broken is ropery and iridescent, and it was from one of these faces that the two samples were gathered. The Blue Dragon sample location near Huddles Hole has noticeably different surface features than those seen near the Tree Molds Trail. The Huddles Hole flow has a smoother, less iridescent glassy surface. The Huddles Hole surface is also notably brighter in its blue, whereas the Tree Molds Trail surface has a tarnished, darker coloration.



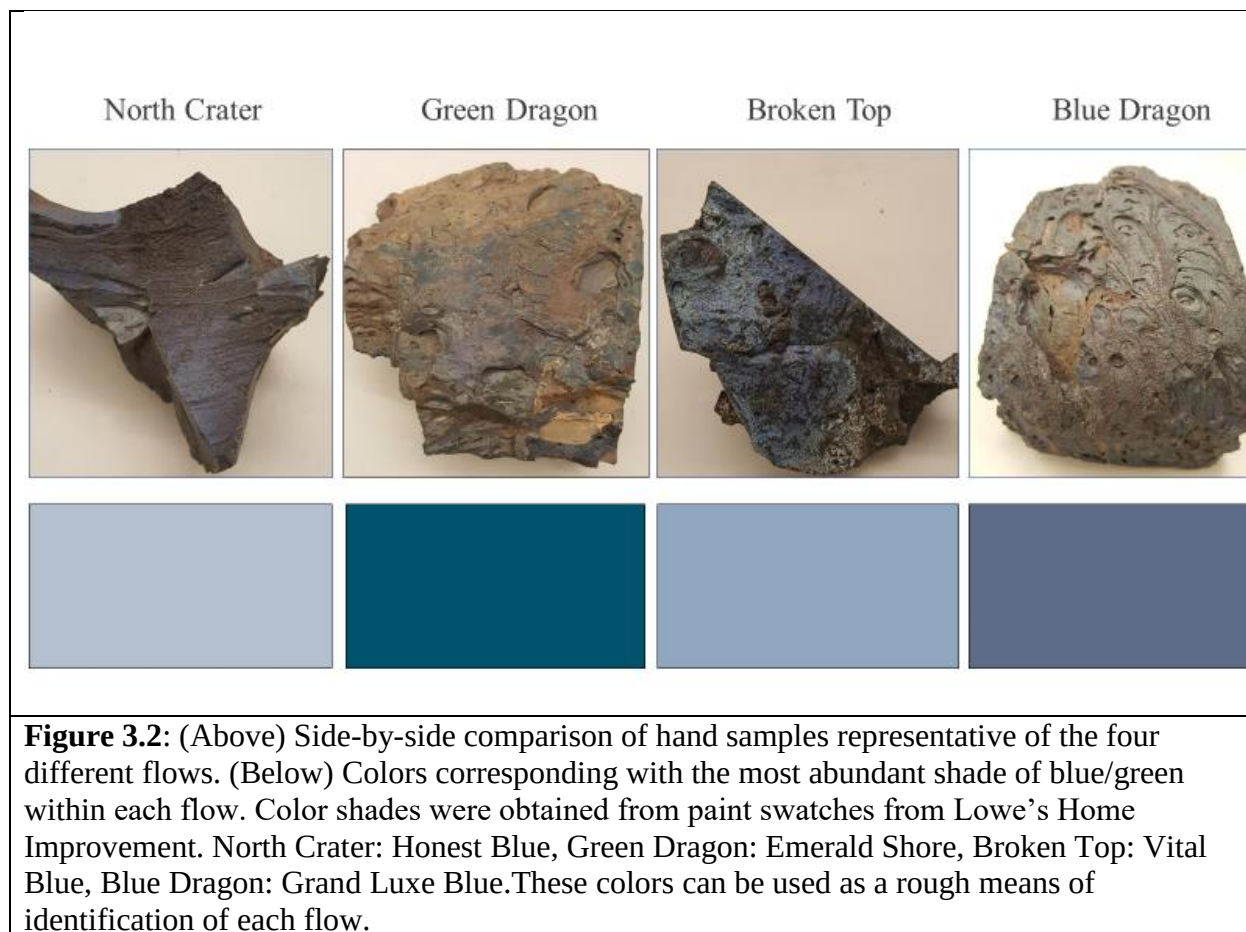
Figure 3.1: Image of the Blue Dragon Tree Molds Trail collection site. Surface of the flow is heavily weathered with many fragments of the blue surface broken off to reveal an orange, oxidized layer beneath. The blue coloration in this area has a dark, tarnished quality.

The Green Dragon flow samples were collected in an area of relatively flat terrain. The flow was identified as the Green Dragon flow based on the noticeable shift in coloration from blue to green. The samples were collected from an intact pahoehoe surface, but a field of jagged a'a' is located several meters to the north of the collection site. The North Crater flow is the bluest of the four flows, with brightly colored patches located just meters apart. The North Crater flow also has the flattest surface of the flows, with an average topographic change of around 1 meter across the flow. Numerous caves of varying size and depth are located beneath the surface of every flow and are a typical flow feature throughout Craters of the Moon.

Physical Descriptions

The appearance of the samples is relatively uniform, save for a few differentiating features such as the shade of blue on the surface. Each sample is aphanitic with a homogenous grey color in the interior and a blue coating on the surface. The samples are dense, without many vesicles; vesicles account for an estimated 20% of the interior volume for most lavas. The Blue Dragon samples are slightly more vesicular due to the presence of large vesicles (3 cm in diameter) compared to the smaller (millimeter scale) vesicles present in the other flow samples. Additionally, samples that were not collected *in situ* have a rusty coloration on the interior indicating iron oxidation. This coloration is not found in samples that were removed from the flows with a hammer, and whose interiors are not visibly weathered.

The blue surface of each sample has a maximum depth of 2 mm, at which point the sample transitions into the ubiquitous grey interior. The blue surface is the most distinguishable variation between the four flows, primarily because the hue varies depending on the flow. The Broken Top surfaces have the lightest shade of blue, followed by North Crater, with Blue Dragon the darkest. Green Dragon's surface has aptly more of a greenish hue and is the most easily distinguishable of the four flows (Figure 3.2). Observations made in the field indicate that the North Crater flow has the most extensive area that is blue of the four flows. The Blue Dragon samples taken from the Tree Molds Trail collection area have a distinct iridescent coating on the surface whereas the other Blue Dragon samples have a tarnished surficial luster. When powdered, the interior of the samples retains its grey coloration; however, when powdered, the originally blue surface of the samples changes to the same rusty brown oxidized color observed in the exposed interiors of some of the samples.



The blue coating exhibits a fluid-like pattern (with drips that appear to flow over surface edges) on many of the samples (Figures 3.3). This “drip” pattern can be observed on every flow, but is not found on every sample. It does not appear to vary in frequency between the different flows.



Figure 3.3: Blue Dragon flow sample (BDHH1). Red arrows point to location of speckled “drip” patterns along edges of sample that may suggest surficial fluid behavior.

Transmitted and Reflected Light Microscopy

Thin sections of the lavas under transmitted light show consistent mineral modes between each sample's surface and interior. Each sample is very fine grained and aphyric. The largest microlites are plagioclase and are less than 0.5 mm in size. The glass is brown under transmitted light but becomes increasingly opaque with distance from the surface. Mineral modes at the surface under transmitted light are roughly 3% olivine, 25% plagioclase, 10% opaque oxide, and 62% glassy matrix. The mineral modes shift with depth, however, as the plagioclase microlites are more abundant closer to the surface. Farther from the surface, the plagioclase microlites decrease to about 15% abundance as the groundmass increases to 72%. In addition to a change in abundance, the plagioclase microlites are increasingly aligned nearer the surface (Figure 3.4).

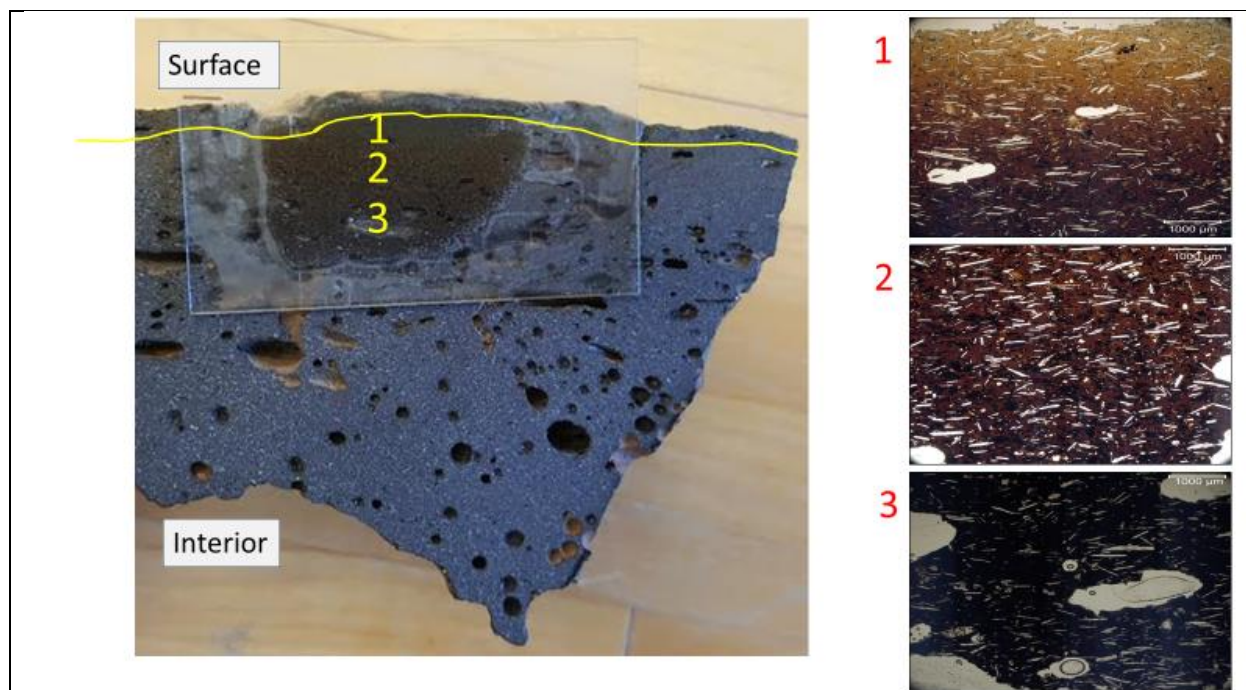


Figure 3.4: (Left) Cross-sectional cut of Broken Top (BT2) hand sample with overlain thin section. Yellow line marks transition zone between 2 mm thick surficial blue color and grey interior. Numbers correspond to the accompanying microscope images. (Right) Three images taken at different sample depths under transmitted light. Plagioclase microlites increase in abundance and alignment near surface while groundmass becomes increasingly opaque with depth.

Magnetite crystals are all roughly 0.25 mm in size. When viewed under reflected light, the magnetite crystals are subhedral, though partly dissolved and embayed. The parts of the crystals adjacent to embayments have a faint blue hue on the inside, similar to the blue color described by Faye and Miller (1973). These authors further described halos around some magnetites, but, in this set of study samples, there is no clear sign of the halo features.

Scanning Electron Microscopy

Samples were observed and analyzed using a Scanning Electron Microscope (SEM) in order to identify key mineralogical features of the rocks such as titanomagnetite and the siliceous coating documented by Faye and Miller (1973) and Chemtob and Rossman (2014). Element maps were generated of the surfaces and interiors of each sample to determine abundance of manganese, titanium, and phosphorus. The interior of the samples extends roughly 2 cm in depth, while the analyzed surfaces account for the top 1 mm of the samples.

Element maps reveal a general trend of higher Ti concentrations in the surfaces compared to the interiors (Figure 3.5). Both Blue Dragon samples (BDTM2/BDHH2) as well as the Green Dragon (GD3) and North Crater (NC2) lava have higher concentrations of Ti on the surface (statistically distinguishable from the interior Ti concentrations with 95% certainty). Broken Top (BT1) also has higher amounts of Ti in the surface material, but those concentrations are not statistically different from those measured in the interior of the samples. Conversely, the minimally blue North Crater sample (NC1) has a lower Ti concentration on the surface compared to the interior (statistically distinguishable from the interior Ti concentrations with 95% certainty).

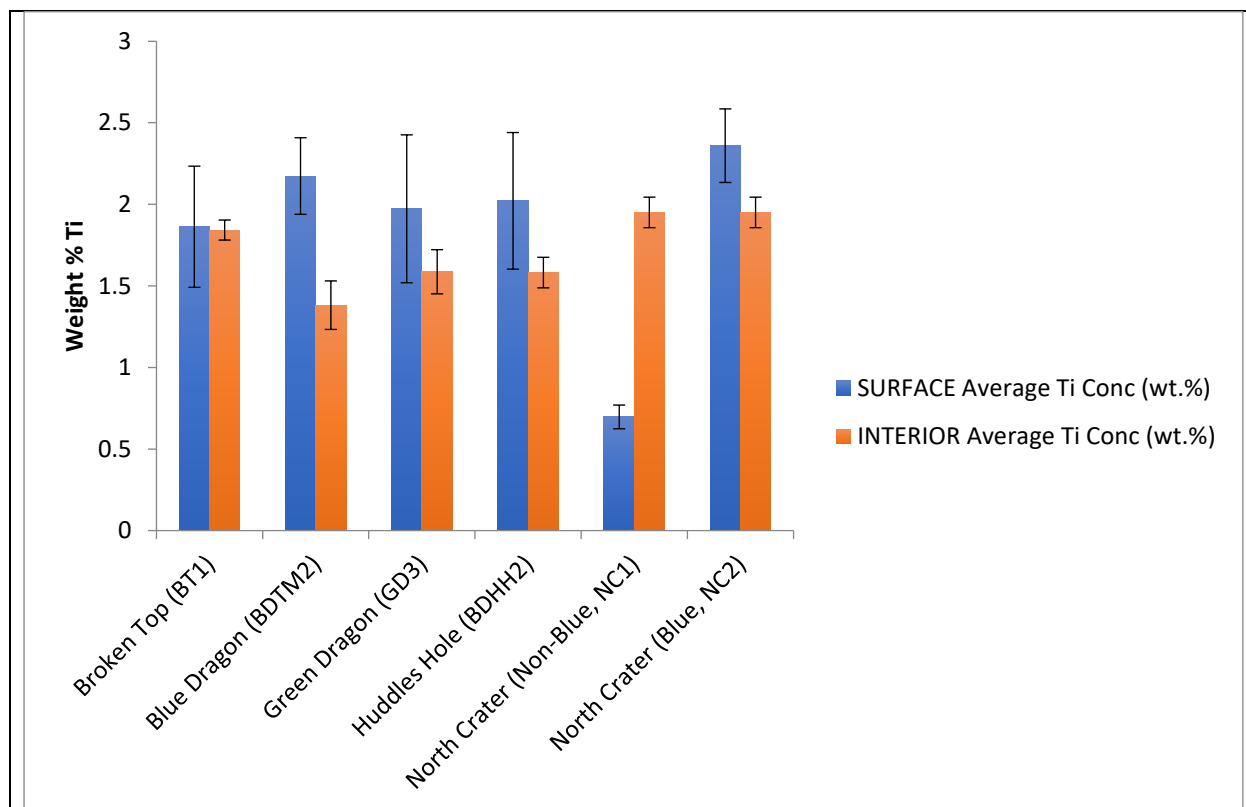
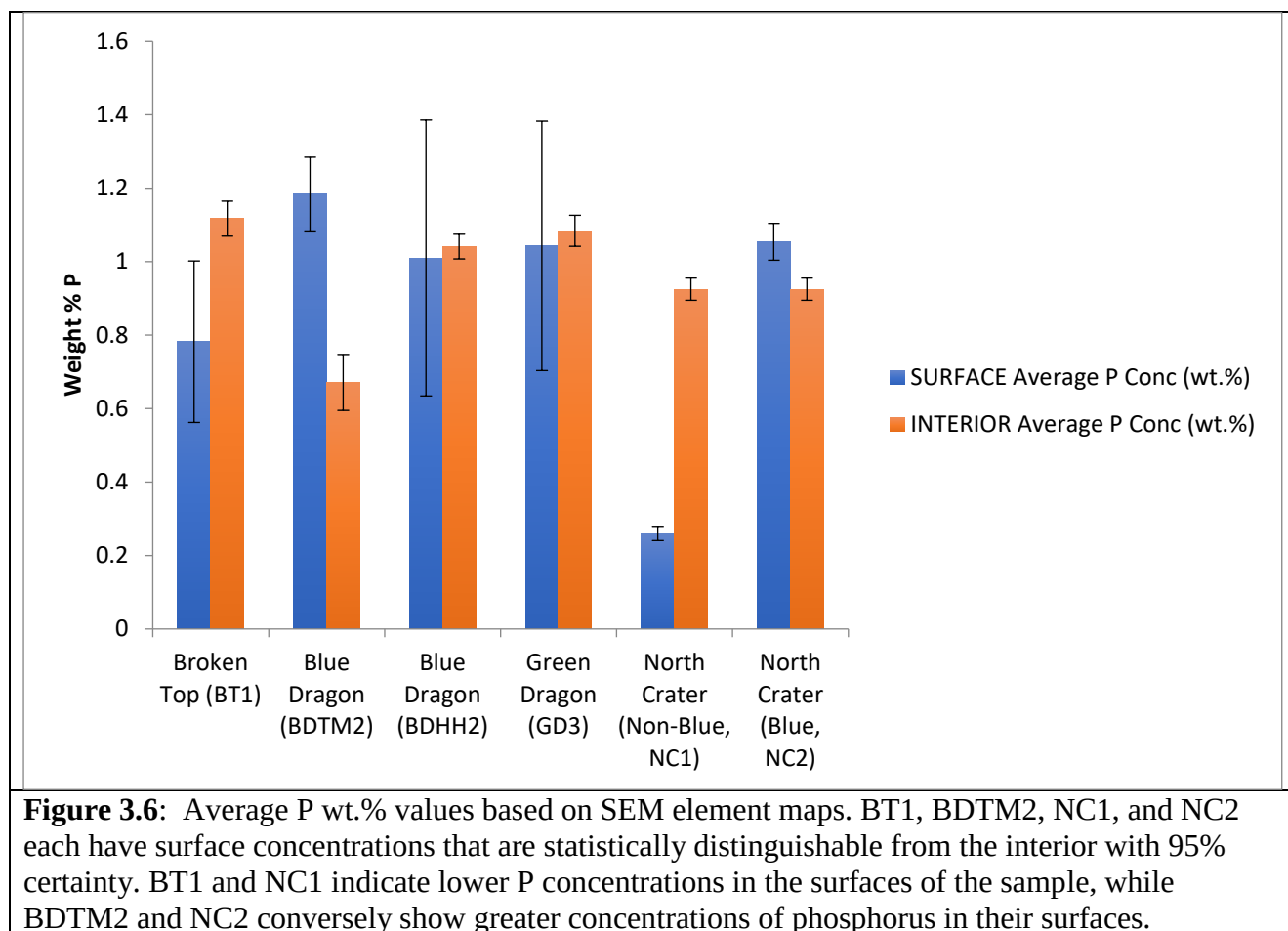


Figure 3.5: Ti wt.% comparison between the surface and interior of six samples. BT1 is the only sample with a surface that is not statistically distinguishable from the interior Ti concentrations with 95% certainty. Each sample with a blue surface has a greater concentration of Ti on the surface compared to the interior of the sample. NC1 is the only sample with less Ti on the surface but does not have a strong blue coloration on its surface.

Phosphorus concentrations obtained from the same area maps do not exhibit as strong a trend as that seen in the Ti concentrations (Figure 3.6). Four of the six samples have lower P concentrations in the surface compared to the interior, although only two of these samples (BT1 and NC1) have surfaces that are significantly distinguishable from the interior concentrations with 95% certainty. The P concentrations in NC2 and BT1 indicate greater amounts of phosphorus in the surface and are also statistically distinguishable with 95% certainty.



The same areas used for titanium and phosphorus mapping were examined for manganese content on the surface, to explore the possibility of a desert varnish being the cause of the blue color (Perry and Adams, 1978). While the generated surface concentrations are greater than that of the interior in some samples, the surface concentration does not exceed 1 wt.% (Figure 3.7).

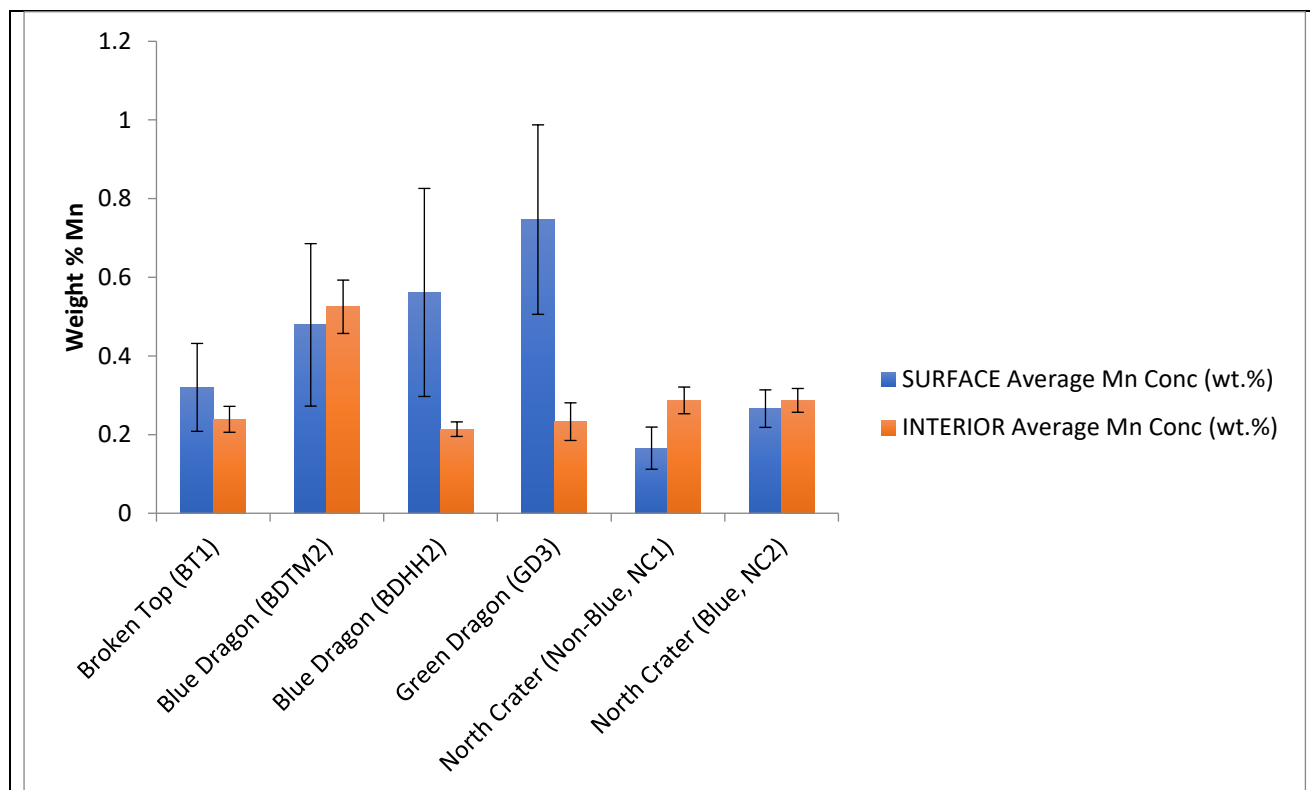


Figure 3.7: Average Mn wt.% values based on SEM element maps. While some samples indicate a higher concentration of Mn at the surface, the largest potential value is around 1% in sample GD3. This is below the 3% needed for a red desert varnish color and well below the amount required for a blue coloration (Perry and Adams, 1978).

Imaging by SEM was also used to locate and identify the siliceous film on the surface of the rocks, which was mentioned by Faye and Miller (1973). This siliceous film exists in all four flows under the SEM, although its areal coverage varies from sample to sample and, in many cases, is indistinguishable from the surrounding glassy surface (Figure 3.8).

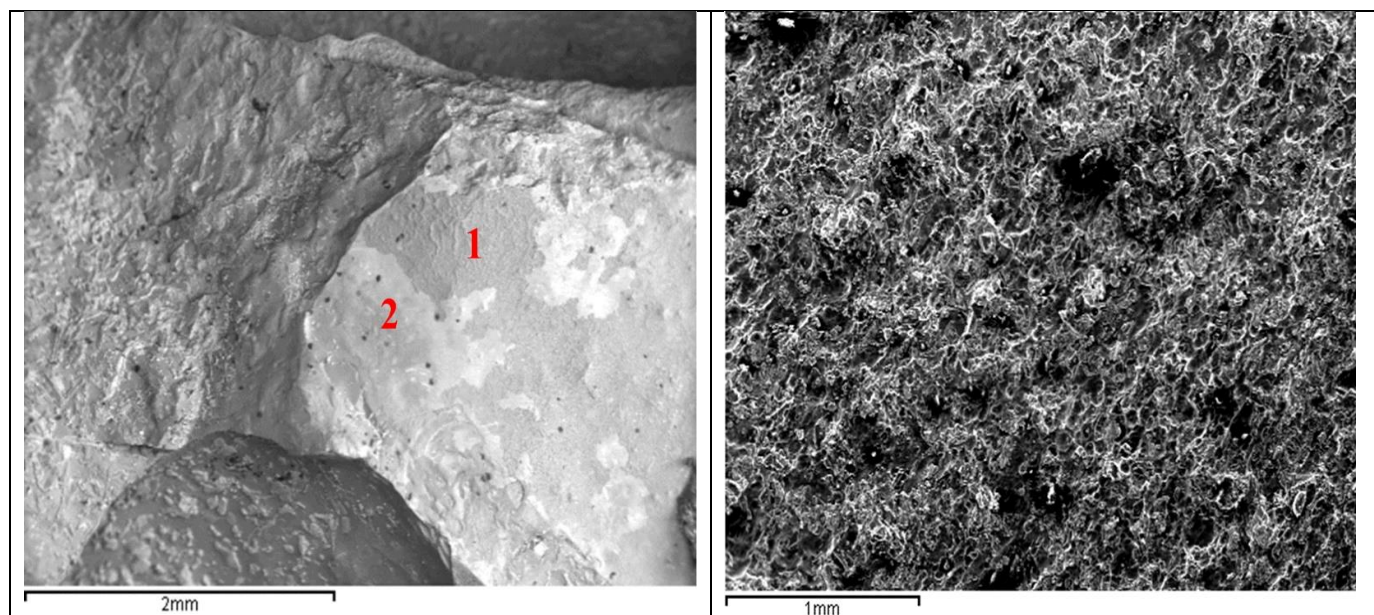
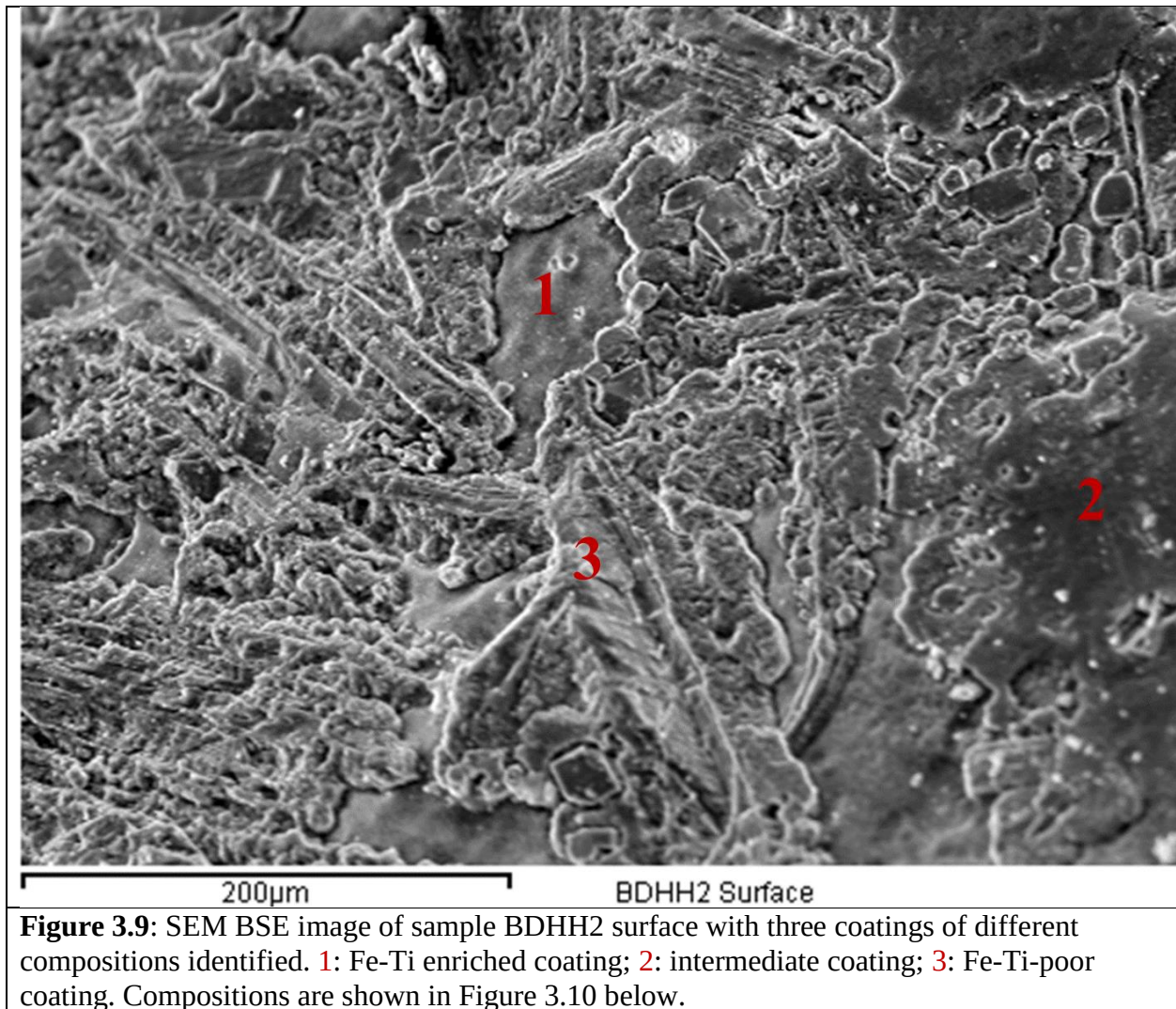
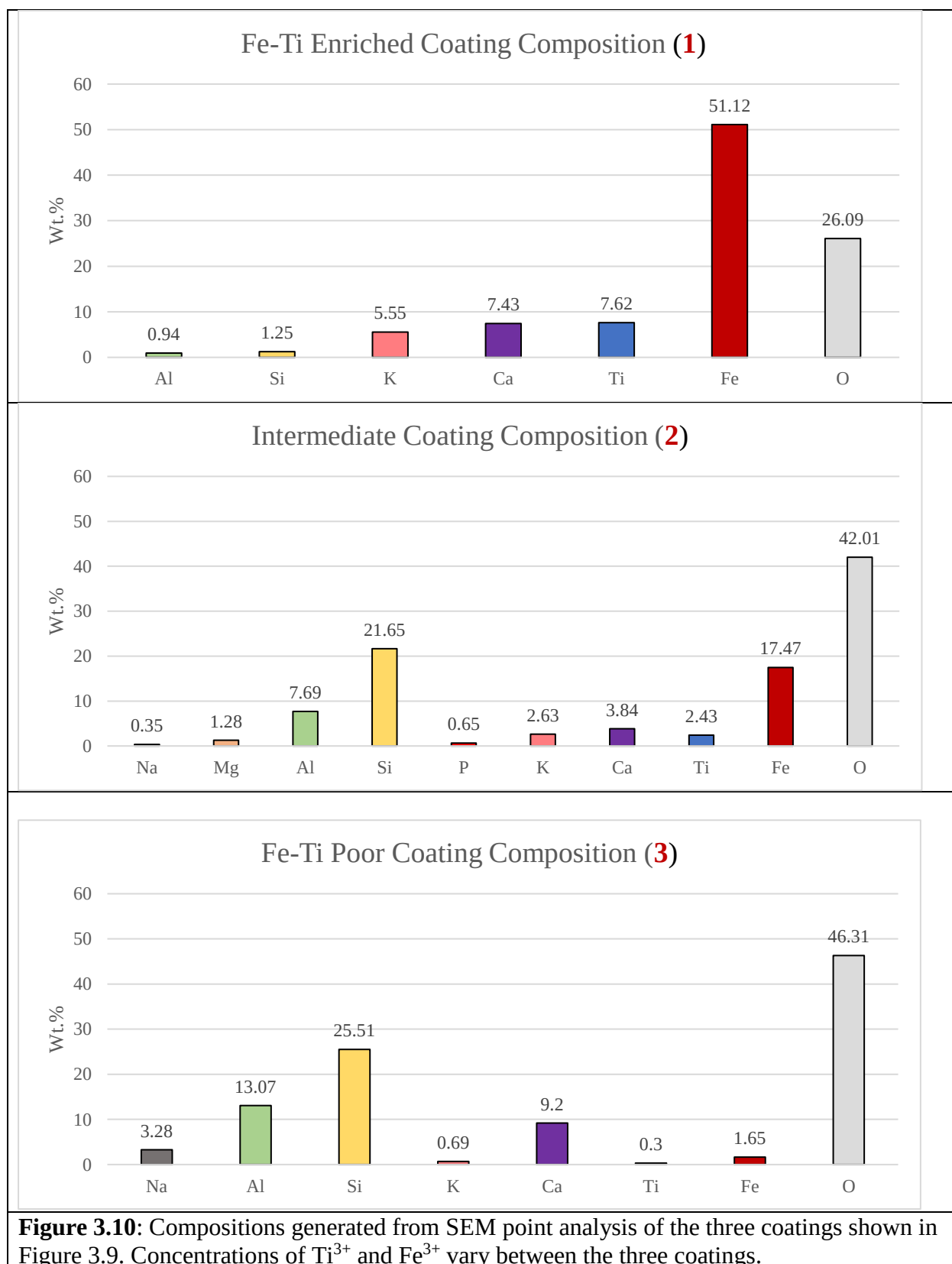


Figure 3.8: Comparison of surficial coatings on two separate surface samples. (Left) SEM BSE image of Blue Dragon flow (BDTM2) surface. **1** indicates a glassy surface (darker contrast, ridged texture). **2** marks the post-eruption silica coating (lighter contrast, smooth texture). (Right) SEM BSE image of North Crater flow (NC2) surface. Surficial coating is relatively indistinguishable from glassy basalt surface at this scale.

In samples where the silica coating is easily distinguishable, such as BDTM2, it appears as a fluid-like coating with a higher relief and brighter contrast than the surrounding glass. Point analyses across each sample yielded varying compositions of the coating (Figures 3.9 and 3.10). In some areas the coating is Fe- and Ti-rich; however, the coating in different locations on the same sample surface is Fe- and Ti-poor with increased concentrations of Al, Na, and Ca. The variation in compositions suggest some degree of cation-transporting surface alteration similar to that proposed by Chemtob and Rossman (2014).





X-Ray Diffraction Analysis

X-ray diffraction (XRD) analyses were used to document mineralogical differences between the surface and interior of the basalts. A consistent characteristic of each XRD scan is the relatively low count frequency for each d-spacings value, particularly for the surface samples. These low values (<1000 counts/s) are the result of the predominance of amorphous material or glass in the samples. While the lower peak counts do reduce the overall resolution of the scans, it is still possible to compare the surface and interior.

In each sample, there is a distinct difference between the powdered surface and interior XRD spectra. Surface scans in each sample exhibit a substantial reduction of a peak corresponding to olivine and magnetite. While the olivine/magnetite peak is reduced in size, the plagioclase peaks, predominantly the ones for anorthite, have similar heights in both the surface and interior samples, suggesting that plagioclase is preserved while abundances of magnetite and olivine have been reduced in the surfaces of the samples (Figure 3.11).

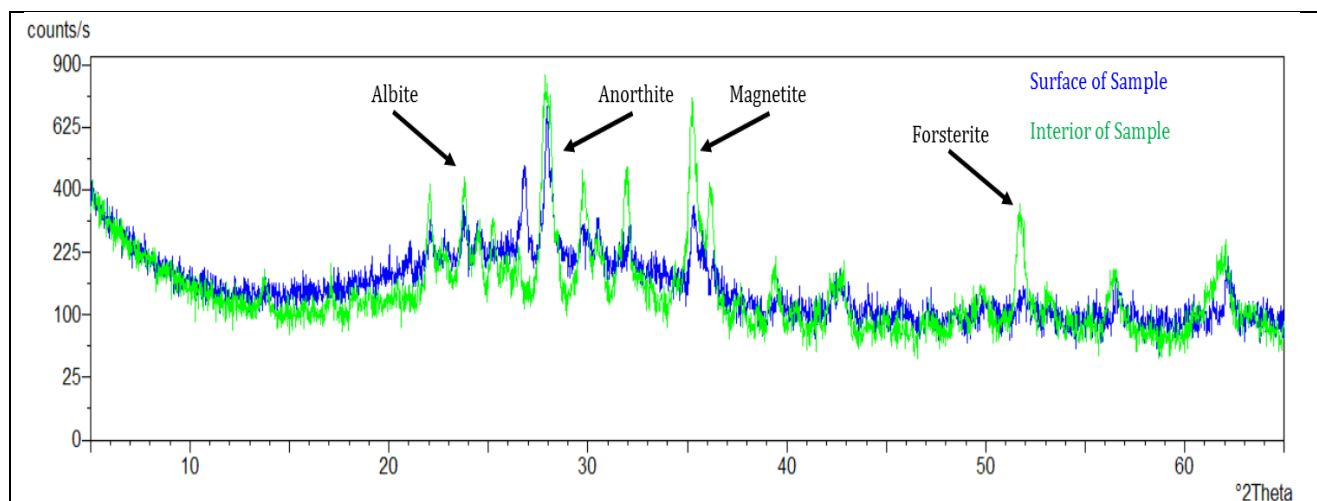


Figure 3.11: Overlay of two XRD spectra of Blue Dragon (BDTM2) powders. The blue spectra shows surface composition while green corresponds to the basaltic interior. There is a noticeable reduction in magnetite and olivine peaks in the surface, although plagioclase remains relatively unchanged.

An anomalous peak was observed in the surface scan of the BDTM2 sample but was not definitively identified. It is possible this peak corresponds to a mineralogical component of the siliceous film present on the surface.

Discussion

The primary focus of this study is to determine the cause of the wide-spread blue coloration in the basalt at Craters of the Moon National Monument. Additional questions include trying to understand why the blue color is simply a surface phenomenon, as well as why the only reported occurrences are at Craters of the Moon and at Kilauea volcano in Hawaii. Below, I explore several hypotheses to address these research questions.

Desert Varnish

The first hypothesis to explain the blue coloration on the COM basalts is the concentration of manganese in the surface material, which has been shown to cause a blue-ish color known as the desert varnish weathering phenomenon. In 1978, Randall Perry and John B. Adams documented alternating layers of dark and light coloration on the micron scale in rocks in arid climates in the western U.S. The darker, blue-black surficial layers were attributed to manganese-rich rock compositions. They found that weathered surfaces containing around 20 wt.% Mn have a dark, opaque varnish while surfaces with ~3 wt.% Mn appear red. Blue hues similar to what is seen at Craters of the Moon are observed in surfaces with Mn content in the upper half of this compositional range.

The SEM maps of the surface of a Blue Dragon sample indicate an average manganese concentration of $0.5 \pm 0.2\%$ ($n = 10$, $1 = 0.2\%$). Thus, the manganese content of the Craters of

the Moon basalts is well below that needed for a blue coloration due to desert varnish (Perry and Adams, 1978). Additionally, Perry and Adams (1978) reported a botryoidal geometry of the surfaces of their samples under SEM. No such textural features were found during SEM imaging, providing further evidence to support rejecting the desert varnish hypothesis for COM.

Electron Charge-Transfer

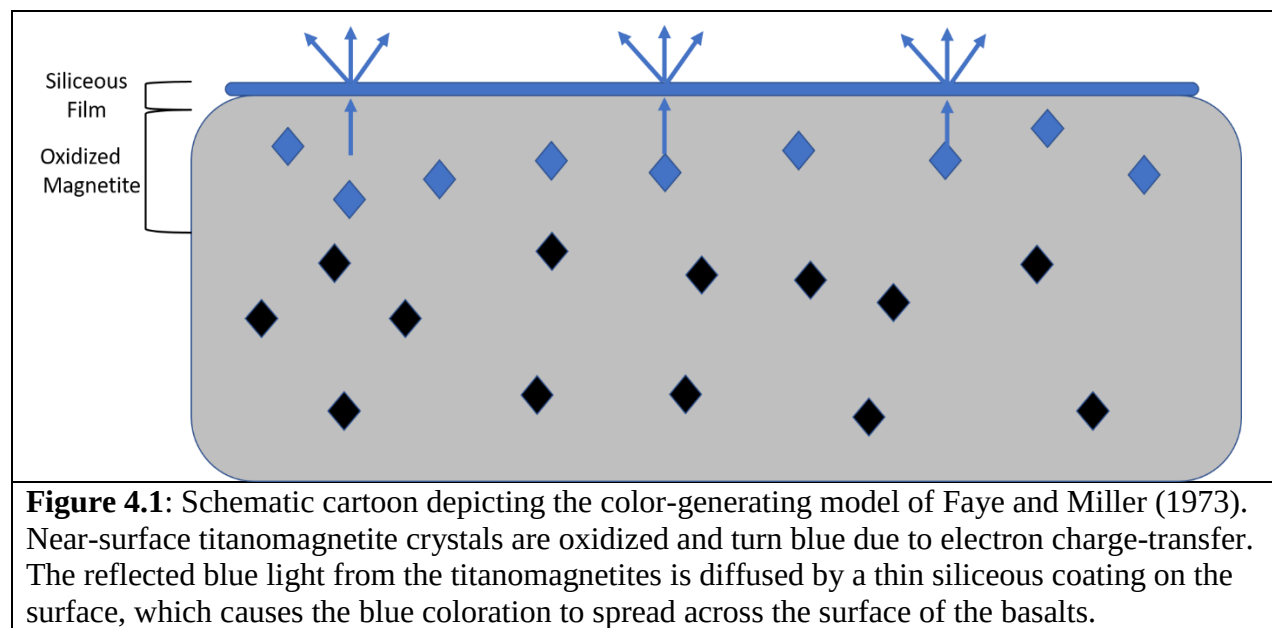
Another potential explanation for the blue coloration of the Craters of the Moon basalts is the oxidation of titanomagnetite crystals near the surface. The electron transfer process between Fe^{2+} oxidizing to Fe^{3+} while Ti^{4+} is reduced to Ti^{3+} causes light to be absorbed in the yellow (570 nm) wavelength. The resulting reflected light therefore is blue (475 nm). The process proposed here is similar to the reason that sapphires containing trace amounts of iron and titanium in the corundum matrix are blue. My SEM results, which indicate the presence of Ti in the COM basalt surfaces, suggest that this explanation is potentially feasible for the blue basalts.

Among the five COM samples that showed statistically significant (95%) differences between the surfaces and the interiors in terms of titanium, four (GD3, BDTM2, BDHH2, and NC2) have higher concentrations of titanium in the surface than within the interior of the rocks. If the surface material were oxidized, it could generate conditions appropriate for charge-transfer blue coloration. Sample NC1 contradicts this trend, however, with a higher concentration of Ti in the interior compared to the surface. The inverse relationship between Ti concentrations in sample NC1 provide further evidence supporting a titanomagnetite-drive surface coloration because this particular sample did not have much blue on its surface. If higher surface Ti concentration correlates with the blue color, a lower surface Ti concentration in a non-blue sample might be expected.

While elevated Ti content in the blue surface suggests a causal relationship between Ti and coloration, near-surface oxidation of titanomagnetite does not fully explain the existence of a blue surface. Even though oxidized titanomagnetite crystals reflect blue light, one major complication is that oxidation of titanomagnetite crystals would only turn the individual crystals blue, and would not generate a ubiquitous blue surface. Oxidation of the titanomagnetite crystals alone would not be enough to cause the widespread coating along the surface that is present in all COM samples.

Faye and Miller (1973) Hypothesis

Gordon Faye and Roy Miller propose a solution to the blue basalt problem in their 1973 study of Blue Dragon basalt samples. They suggest the presence of a thin siliceous film on the surface of the basalts that serves to diffuse the light reflected off the oxidized titanomagnetites, resulting in a blue coating rather than individual specks of blue magnetite (Figure 4.1). My SEM analysis confirms that a siliceous film is present on the surface of every flow in this study. While the film varies in extent of coverage between the different flows, it is detectable on every flow.



Chemtob and Rossman (2014) Model

While the Faye and Miller (1973) hypothesis accounts for the amorphous silica on the surface and oxidized blue titanomagnetite, it does not address the widespread variation in the color of the Craters of the Moon flows, including the Green Dragon flow's coloration. A 2014 study by Chemtob and Rossman provides a more detailed mechanism for the generation of the blue color of some basalt flows at Kilauea, which also invokes a silica coating. The Chemtob and Rossman (2014) model proposes two distinct post-eruption surficial coatings, one of which is similar to the siliceous film discussed by Faye and Miller (1973) whereas the other is a second Ti-Fe oxide-rich layer, which is associated with bright coloration in the surface (Figure 4.2).

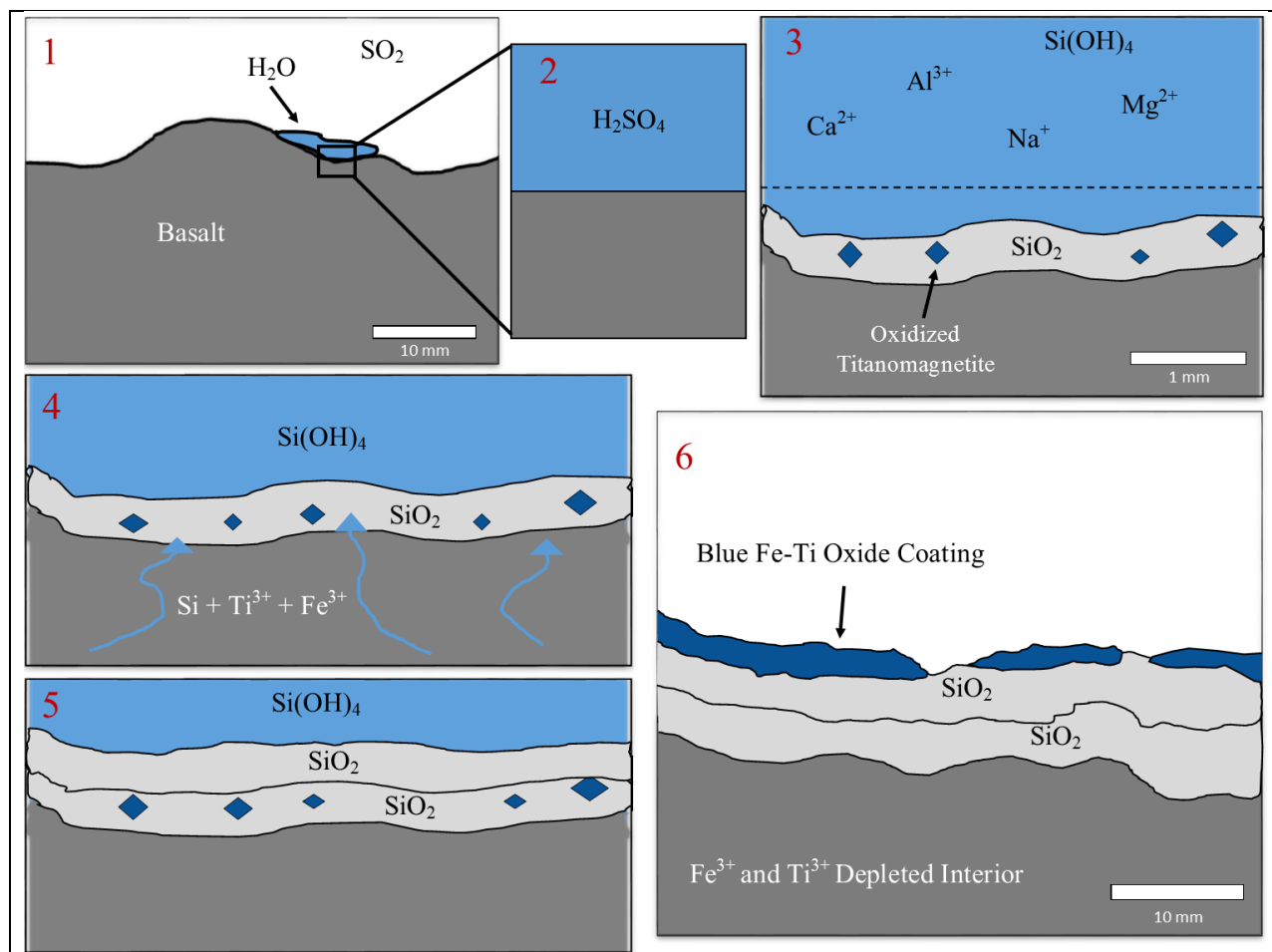


Figure 4.3: Amended cartoon schematic of the Chemtob and Rossman (2014) silica coating model. 1) Water interacts with surface of fresh basalt in presence of volcanic vapors (SO_2). 2) Surface fluids become acidified (H_2SO_4). 3) Acidic fluids dissolve Ca^{2+} , Al^{3+} , Mg^{2+} , Fe^{3+} , and Ti^{3+} . The more soluble cations are removed via runoff while Fe^{3+} , Ti^{3+} , and silica precipitate on the surface. 4) Hot, silica-bearing fluids transport additional Fe^{3+} and Ti^{3+} ions to the surface. 5) Transported Fe and Ti precipitate with silica onto the surface. 6) Over time continued precipitation of Fe^{3+} and Ti^{3+} forms a blue Fe-Ti oxide coating atop the amorphous silica.

The Chemtob and Rossman (2014) model has two main phases. The first occurs within one year after eruption of the flow, while the second develops in the years following the initial eruption. The initial phase is short-lived, and involves the formation of the amorphous silica layer. In the first days, or even hours, following the eruption, rainfall or water vapor interacts with sulfuric volcanic vapors resulting in an acidic surface fluid (Figure 4.2; Steps 1 and 2). This fluid dissolves the unaltered basaltic surface of the flow. During dissolution, more soluble

cations (Ca^{2+} , Al^{3+} , Na^{+} , Mg^{2+}) are dissolved and subsequently removed from the glassy surface by runoff (Figure 4.2; Step 3). Iron, phosphorus, and titanium ions, being less soluble than the ions listed above, while dissolved in the aqueous fluid, precipitate with the amorphous silica, rather than being transported away from the lava surface (Chemtob and Rossman, 2014).

In addition to the *in situ* dissolution of material from the lava flow surface, Chemtob and Rossman (2014) propose that near-surface Ti-Fe oxides are mobilized by hot silica-bearing fluids inside the flow and brought to the surface via hydrothermal circulation (Figure 4.2; Step 4). When these fluids reach the surface and begin to evaporate, additional silica, P, and Ti-Fe oxides are precipitated onto the lava's surface (Figure 4.2; Step 5). The second, longer phase of the Chemtob and Rossman (2014) model predicts that the accumulation of silica and Ti-Fe oxides on the flow top from internal hydrothermal fluid circulation slowly thickens the amorphous silica coating, along with deposition of iron and titanium ions on the surface (Figure 4.2; Step 6). Ultimately, the lava flow is covered by a double layer of amorphous silica, the lower one depleted in mobile cations and the upper one rich in Ti-Fe oxides (Chemtob and Rossman, 2014).

The Chemtob and Rossman (2014) hypothesis explains many of the characteristics observed in the Craters of the Moon basalts. Titanium and phosphorus concentrations in the samples are elevated on the COM lava surfaces compared to their interiors (Figure 4.2; Steps 3-5). Elevated phosphorus levels serve as a means of corroborating the mobility of Ti^{3+} toward the surface as phosphorus undergoes the same mobilization process (Chemtob and Rossman, 2014). The phosphorus content of this study's samples obtained from SEM element maps does not, however, suggest a trend phosphorus enrichment or depletion in the basalts (Figure 3.6). While phosphorus concentrations in COM lava surfaces do not support the Chemtob and Rossman

(2014) model, concentrations of Ca^{2+} and Na^{+} in the lavas are lower in the siliceous surface layer, supporting the notion they were removed during dissolution. Variations in the concentration of Fe^{3+} and Ti^{3+} observed within the surface coating of COM lavas also serve as an indication of mobility of the two cations within the surface, as the cations are heterogeneously dispersed by the surface fluids (Figure 3.9) (Chemtob and Rossman, 2014).

The clear trend of Ti-enrichment in the surface of blue COM samples provides additional evidence in support of the Chemtob and Rossman (2014) model (Figure 3.5). The dissolution and mobilization of subsurface Ti^{4+} cations result in the subsequent enrichment of the cations in the surface. This enrichment is observed in every SEM sample except for NC1, which does not have a blue surface. Further evidence to support the Chemtob and Rossman (2014) model is seen in the relationship between the blueness of the North Crater flow and its relatively flat topography. The flat morphology of the North Crater flow is consistent with Chemtob and Rossman's (2014) proposal of a preferential accumulation of surface fluids in flows with a flatter flow-top morphology.

The Chemtob and Rossman (2014) model is also consistent with the glassy nature of the COM lavas (Figure 3.4). The exceptionally glassy surfaces of these basalts increase the potential rate of dissolution of the surface by a fluid, is likely to result in a widespread silica coating. Furthermore, titanomagnetite crystals observed under reflected light are subhedral and partially dissolved, indicating interaction with hydrothermal fluids within the basalts. The drip-like features observed on the edges of every flow also suggest the presence of surficial fluids (Figure 3.3). Additional evidence suggesting a texturally dependent coloration is observed in the powdering of the blue surfaces of the samples. The powdered surface is not blue but rather a rusty, orange coloration similar to that of the exposed interior, suggesting that the textural

arrangement of the titanomagnetites affects their color. The textural arrangement of the Fe-Ti oxide coating on the surface of the flows may result in reflection of blue light; however, when this arrangement is disturbed (e.g. powdering the surface), the blue coloration is replaced by a more common rusty orange color.

Finally, the surfaces of the COM lavas are exceptionally hard (e.g., a diamond-tipped dremel was needed to powder the surfaces). The surfaces of the fresh blue basalts found by Chemtob and Rossman (2014) are much more fragile than in comparison, suggesting that the surficial hardness of COM lavas may be caused by case hardening as the amorphous silica coatings undergo longer (relative to the decade-scale ages of the Kilauea flows) periods of weathering. Given that the Chemtob and Rossman (2014) model is consistent with the COM lava flow data and accounts for the variation in coloration of the flows, this model is my preferred explanation of the atypical blue basalt surfaces found in Craters of the Moon National Monument.

Conclusion

The data obtained in this study suggest a complex origin of the blue coloration observed in lava flows at Craters of the Moon National Monument. The Chemtob and Rossman (2014) model for the gradual formation of a surficial silica coating in Kilauea lava flows is potentially applicable to the COM lavas as well. While the blue color originates from the oxidation of titanomagnetite crystals, the wide coverage of blue can be attributed to the dissolution and mobilization of these crystals, which subsequently precipitate as a surficial film, via hydrothermal fluids. This surficial Fe-Ti oxide layer preserves the blueness of the titanomagnetites while spreading the coloration across a broader surface area. Ultimately, the

current coloration present in Craters of the Moon lavas is likely a result of the accumulation of an oxidized titanomagnetite-rich coating caused by a hydrothermal alteration of the surfaces of the basalts.

The fact that this surface phenomenon has been observed only at Craters of the Moon and Kilauea suggests that a specific set of conditions must be met in order for the blue surficial coating to form. Furthermore, the extent of blue surface coatings on Kilauea flows is far less than that of Craters of the Moon. While composition of the basalts must be a factor if the blue originates from titanomagnetite oxidation, it is likely that climate is also a dominant controlling factor. Given the arid climate at Craters of the Moon (average of 10.49 inches of annual precipitation), the blue coating may have been better preserved than at Kilauea, which has an average annual precipitation of 68.62 inches (U.S. Climate Data, <http://www.usclimatedata.com>). Additionally, the relative abundance and compositional variances of steam (e.g. pH levels) during the coating formation may also play a role in the differences between Kilauea and COM. With these assumptions, it is possible that regional climate and water properties have a major role in forming and preserving surficial phenomena in fresh basalt flows.

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Table A1: SEM Element Map Data of Sample BT1 Surface

Map 1					Map 2					Map 3				
Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula
Na K	1.93	1.84	2.6	Na2O	Na K	1.72	1.65	2.32	Na2O	Na K	1.48	1.42	2	Na2O
Mg K	1.37	1.24	2.28	MgO	Mg K	1.48	1.34	2.45	MgO	Mg K	1.52	1.38	2.52	MgO
Al K	8.23	6.7	15.55	Al2O3	Al K	8.14	6.65	15.38	Al2O3	Al K	7.71	6.31	14.58	Al2O3
Si K	25.42	19.87	54.37	SiO2	Si K	25.07	19.69	53.64	SiO2	Si K	25.54	20.06	54.63	SiO2
P K	0.84	0.6	1.93	P2O5	P K	0.93	0.66	2.13	P2O5	P K	0.89	0.63	2.03	P2O5
S K	0.23	0.16	0.57	SO3	S K	0.19	0.13	0.47	SO3	S K	0.27	0.18	0.67	SO3
Cl K					Cl K	0.25	0.15	0		Cl K	0.24	0.15	0	
K K	1.61	0.9	1.93	K2O	K K	1.68	0.94	2.02	K2O	K K	1.66	0.94	2	K2O
Ca K	3.6	1.97	5.04	CaO	Ca K	3.72	2.05	5.21	CaO	Ca K	3.5	1.92	4.89	CaO
Ti K	2.16	0.99	3.61	TiO2	Ti K	2.06	0.95	3.43	TiO2	Ti K	2.01	0.93	3.35	TiO2
Mn K					Mn K					Mn K	0.21	0.09	0.28	MnO
Fe K	9.42	3.7	12.12	FeO	Fe K	9.87	3.9	12.69	FeO	Fe K	9.96	3.93	12.81	FeO
Mo L					Mo L					Mo L				
O	45.19	62.02			O	44.9	61.88			O	45.01	62.06		
Totals	100				Totals	100				Totals	100			

Map 4					Map 5					Map 6				
Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula
Na K	0.98	0.92	1.32	Na2O	Na K	1.09	1.05	1.47	Na2O	Na K	1.23	1.16	1.66	Na2O
Mg K	1.74	1.55	2.89	MgO	Mg K	1.68	1.53	2.79	MgO	Mg K	1.6	1.42	2.66	MgO
Al K	6.78	5.43	12.8	Al2O3	Al K	7.14	5.85	13.49	Al2O3	Al K	7.95	6.36	15.01	Al2O3
Si K	29.87	23	63.9	SiO2	Si K	26.31	20.73	56.29	SiO2	Si K	28.07	21.6	60.05	SiO2
P K	0.32	0.22	0.72	P2O5	P K	0.68	0.49	1.57	P2O5	P K	0.57	0.39	1.3	P2O5
S K					S K	0.28	0.19	0.7	SO3	S K	0.26	0.18	0.66	SO3
Cl K	0.57	0.35	0		Cl K	0.27	0.17	0		Cl K				
K K	1.66	0.92	2	K2O	K K	1.49	0.84	1.79	K2O	K K	1.44	0.79	1.73	K2O
Ca K	2.36	1.28	3.31	CaO	Ca K	2.97	1.64	4.16	CaO	Ca K	2.89	1.56	4.04	CaO
Ti K	1.05	0.47	1.75	TiO2	Ti K	1.56	0.72	2.61	TiO2	Ti K	1.61	0.72	2.68	TiO2
Mn K					Mn K					Mn K				
Fe K	6.87	2.66	8.84	FeO	Fe K	11.55	4.58	14.86	FeO	Fe K	7.94	3.07	10.21	FeO
Mo L	1.27	0.29	1.9	MoO3	Mo L					Mo L				
O	46.54	62.91			O	44.96	62.2			O	46.45	62.74		
Totals	100				Totals	100				Totals	100			

Map 7					Map 8					Map 9				
Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula
Na K	2.37	2.31	3.2	Na2O	Na K	1.93	1.88	2.6	Na2O	Na K	1.57	1.52	2.11	Na2O
Mg K	1.39	1.28	2.3	MgO	Mg K	1.36	1.25	2.25	MgO	Mg K	1.6	1.47	2.66	MgO
Al K	7.8	6.46	14.74	Al2O3	Al K	8.14	6.75	15.38	Al2O3	Al K	7.65	6.33	14.45	Al2O3
Si K	23.78	18.93	50.88	SiO2	Si K	23.62	18.81	50.53	SiO2	Si K	24.29	19.31	51.97	SiO2
P K	0.95	0.69	2.18	P2O5	P K	1.07	0.77	2.44	P2O5	P K	0.88	0.63	2.02	P2O5
					S K					S K	0.33	0.23	0.82	SO3
Cl K	0.37	0.24	0		Cl K	0.41	0.26	0		Cl K	0.36	0.23	0	
K K	1.86	1.06	2.24	K2O	K K	1.91	1.09	2.3	K2O	K K	1.74	0.99	2.09	K2O
Ca K	4.21	2.35	5.89	CaO	Ca K	3.94	2.2	5.51	CaO	Ca K	3.4	1.89	4.76	CaO
Ti K	2.13	0.99	3.55	TiO2	Ti K	2.28	1.07	3.81	TiO2	Ti K	2.01	0.94	3.36	TiO2
Mn K	0.23	0.09	0.3	MnO	Mn K	0.29	0.12	0.37	MnO	Mn K	0.47	0.19	0.6	MnO
Fe K	11.16	4.47	14.35	FeO	Fe K	11.18	4.48	14.39	FeO	Fe K	11.52	4.6	14.82	FeO
					Mo L					Mo L				
O	43.75	61.13			O	43.87	61.33			O	44.2	61.67		
Totals	100				Totals	100				Totals	100			

Map 10				
Element	Weight%	Atomic%	Compd%	Formula
Na K	1.11	1.08	1.5	Na2O
Mg K	1.75	1.61	2.9	MgO
Al K	7.04	5.85	13.31	Al2O3
Si K	25.05	19.99	53.6	SiO2
P K	0.69	0.5	1.58	P2O5
S K	0.3	0.21	0.76	SO3
Cl K	0.22	0.14	0	
K K	1.47	0.84	1.77	K2O
Ca K	2.85	1.59	3.99	CaO
Ti K	1.76	0.82	2.93	TiO2
Mn K	0.4	0.16	0.52	MnO
Fe K	13.16	5.28	16.93	FeO
Mo L				
O	44.19	61.91		
Totals	100			

Table A2: SEM Element Map Data of Sample BT1 Interior

Map 1					Map 2					Map 3				
Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula
Na K	3.48	3.4	4.69	Na2O	Na K	3.61	3.53	4.87	Na2O	Na K	3.66	3.58	4.93	Na2O
Mg K	1.72	1.59	2.86	MgO	Mg K	1.73	1.6	2.86	MgO	Mg K	1.71	1.58	2.83	MgO
Al K	7.02	5.83	13.26	Al2O3	Al K	6.93	5.77	13.08	Al2O3	Al K	6.93	5.77	13.1	Al2O3
Si K	22.83	18.23	48.83	SiO2	Si K	22.62	18.11	48.39	SiO2	Si K	22.7	18.16	48.56	SiO2
P K	1.18	0.86	2.71	P2O5	P K	1.14	0.82	2.6	P2O5	P K	1.11	0.8	2.54	P2O5
Cl K	0.26	0.16	0		Cl K	0.28	0.18	0		Cl K	0.28	0.18	0	
K K	1.63	0.94	1.96	K2O	K K	1.66	0.95	2	K2O	K K	1.56	0.9	1.88	K2O
Ca K	5.62	3.15	7.87	CaO	Ca K	5.51	3.09	7.7	CaO	Ca K	5.5	3.09	7.7	CaO
Ti K	1.78	0.83	2.97	TiO2	Ti K	1.9	0.89	3.17	TiO2	Ti K	1.9	0.89	3.17	TiO2
Mn K	0.2	0.08	0.26	MnO	Mn K	0.22	0.09	0.28	MnO	Mn K	0.26	0.11	0.34	MnO
Fe K	11.14	4.47	14.33	FeO	Fe K	11.46	4.62	14.75	FeO	Fe K	11.4	4.59	14.67	FeO
O	43.14	60.47			O	42.95	60.35			O	42.98	60.36		
Totals	100				Totals	100				Totals	100			

Map 4					Map 5					Map 6				
Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula
Na K	3.79	3.7	5.1	Na2O	Na K	3.79	3.7	5.11	Na2O	Na K	3.65	3.56	4.92	Na2O
Mg K	1.73	1.6	2.87	MgO	Mg K	1.69	1.56	2.8	MgO	Mg K	1.71	1.57	2.83	MgO
Al K	7.02	5.84	13.26	Al2O3	Al K	6.92	5.75	13.08	Al2O3	Al K	7.03	5.84	13.29	Al2O3
Si K	22.65	18.11	48.46	SiO2	Si K	22.89	18.27	48.98	SiO2	Si K	22.83	18.22	48.83	SiO2
P K	1.08	0.79	2.48	P2O5	P K	1.11	0.81	2.55	P2O5	P K	1.12	0.81	2.57	P2O5
Cl K	0.25	0.16	0		Cl K	0.26	0.16	0		Cl K	0.27	0.17	0	
K K	1.58	0.91	1.91	K2O	K K	1.67	0.96	2.01	K2O	K K	1.61	0.93	1.95	K2O
Ca K	5.49	3.07	7.68	CaO	Ca K	5.51	3.08	7.71	CaO	Ca K	5.47	3.06	7.65	CaO
Ti K	1.8	0.84	3	TiO2	Ti K	1.82	0.85	3.03	TiO2	Ti K	1.94	0.91	3.24	TiO2
Mn K	0.24	0.1	0.3	MnO	Mn K	0.3	0.12	0.39	MnO	Mn K	0.21	0.09	0.28	MnO
Fe K	11.41	4.59	14.68	FeO	Fe K	10.95	4.39	14.09	FeO	Fe K	11.02	4.42	14.18	FeO
O	42.96	60.3			O	43.09	60.36			O	43.13	60.43		
Totals	100				Totals	100				Totals	100			

Map 7					Map 8					Map 9				
Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula
Na K	3.59	3.5	4.84	Na2O	Na K	3.55	3.47	4.79	Na2O	Na K	3.64	3.56	4.91	Na2O
Mg K	1.67	1.54	2.76	MgO	Mg K	1.78	1.64	2.95	MgO	Mg K	1.79	1.66	2.97	MgO
Al K	7.03	5.84	13.27	Al2O3	Al K	7.15	5.96	13.52	Al2O3	Al K	6.97	5.8	13.17	Al2O3
Si K	22.86	18.27	48.91	SiO2	Si K	22.62	18.09	48.39	SiO2	Si K	22.71	18.17	48.59	SiO2
P K	1.07	0.77	2.45	P2O5	P K	1.08	0.78	2.48	P2O5	P K	1.07	0.78	2.46	P2O5
Cl K	0.21	0.13	0		Cl K	0.3	0.19	0		Cl K	0.28	0.18	0	
K K	1.65	0.95	1.98	K2O	K K	1.54	0.88	1.85	K2O	K K	1.61	0.92	1.94	K2O
Ca K	5.52	3.09	7.73	CaO	Ca K	5.55	3.11	7.77	CaO	Ca K	5.41	3.03	7.56	CaO
Ti K	1.81	0.85	3.02	TiO2	Ti K	1.76	0.82	2.93	TiO2	Ti K	1.82	0.85	3.04	TiO2
Mn K	0.21	0.09	0.27	MnO	Mn K	0.24	0.1	0.31	MnO	Mn K	0.27	0.11	0.34	MnO
Fe K	11.31	4.55	14.55	FeO	Fe K	11.44	4.6	14.72	FeO	Fe K	11.46	4.61	14.74	FeO
O	43.07	60.42			O	42.99	60.35			O	42.97	60.34		
Totals	100				Totals	100				Totals	100			

Map 10				
Element	Weight%	Atomic%	Compd%	Formula
Na K	3.48	3.39	4.68	Na2O
Mg K	1.74	1.61	2.89	MgO
Al K	7.02	5.83	13.26	Al2O3
Si K	22.77	18.18	48.71	SiO2
P K	1.21	0.88	2.77	P2O5
Cl K	0.25	0.16	0	
K K	1.66	0.95	2	K2O
Ca K	5.59	3.13	7.82	CaO
Ti K	1.9	0.89	3.16	TiO2
Mn K				
Fe K	11.23	4.51	14.44	FeO
O	43.16	60.48		
Totals	100			

Table A3: SEM Element Map Data of Sample BDTM2 Surface

Map 1					Map 2					Map 3				
Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula
Na K	1.69	1.67	2.27	Na2O	Na K	1.67	1.65	2.25	Na2O	Na K	1.76	1.72	2.38	Na2O
Mg K	1.31	1.22	2.17	MgO	Mg K	1.31	1.22	2.17	MgO	Mg K	1.5	1.38	2.49	MgO
Al K	8.3	6.99	15.67	Al2O3	Al K	8.3	6.99	15.68	Al2O3	Al K	8.86	7.35	16.74	Al2O3
Si K	22.05	17.85	47.18	SiO2	Si K	22.09	17.88	47.26	SiO2	Si K	23.12	18.43	49.46	SiO2
P K	1.21	0.89	2.78	P2O5	P K	1.19	0.87	2.72	P2O5	P K	1.12	0.81	2.57	P2O5
S K	0.14	0.1	0.34	SO3	S K	0.15	0.1	0.37	SO3	S K	0.17	0.12	0.43	SO3
Cl K	0.29	0.19	0		Cl K	0.3	0.19	0		Cl K	0.28	0.17	0	
K K	1.73	1.01	2.09	K2O	K K	1.72	1	2.07	K2O	K K	1.56	0.9	1.88	K2O
Ca K	2.86	1.62	4	CaO	Ca K	2.81	1.6	3.94	CaO	Ca K	2.31	1.29	3.23	CaO
Ti K	2.46	1.17	4.1	TiO2	Ti K	2.46	1.16	4.1	TiO2	Ti K	2.1	0.98	3.5	TiO2
Mn K	0.55	0.23	0.72	MnO	Mn K	0.53	0.22	0.69	MnO	Mn K	0.96	0.39	1.24	MnO
Fe K	14.29	5.82	18.39	FeO	Fe K	14.35	5.84	18.47	FeO	Fe K	12.28	4.92	15.79	FeO
Cu K					Cu K					Cu K				
O	43.12	61.26			O	43.12	61.27			O	43.97	61.53		
Totals	100				Totals	100				Totals	100			

Map 4					Map 5					Map 6				
Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula
Na K	1.82	1.77	2.45	Na2O	Na K	1.89	1.85	2.54	Na2O	Na K	1.96	1.94	2.64	Na2O
Mg K	1.49	1.36	2.47	MgO	Mg K	1.49	1.39	2.48	MgO	Mg K	1.36	1.27	2.26	MgO
Al K	8.38	6.92	15.83	Al2O3	Al K	8.52	7.12	16.1	Al2O3	Al K	8.51	7.18	16.07	Al2O3
Si K	23.92	18.98	51.17	SiO2	Si K	22.38	17.98	47.88	SiO2	Si K	21.45	17.38	45.88	SiO2
P K	1.1	0.79	2.51	P2O5	P K	1.26	0.92	2.9	P2O5	P K	1.23	0.91	2.82	P2O5
S K	0.16	0.11	0.4	SO3	S K	0.15	0.11	0.38	SO3	S K	0.17	0.12	0.42	SO3
Cl K	0.28	0.18	0		Cl K	0.35	0.22	0		Cl K	0.41	0.26	0	
K K	1.74	0.99	2.1	K2O	K K	1.74	1	2.09	K2O	K K	1.71	0.99	2.06	K2O
Ca K	2.59	1.44	3.63	CaO	Ca K	2.76	1.55	3.86	CaO	Ca K	2.82	1.6	3.95	CaO
Ti K	2	0.93	3.34	TiO2	Ti K	2.13	1	3.55	TiO2	Ti K	2.55	1.21	4.26	TiO2
Mn K	0.36	0.14	0.46	MnO	Mn K	0.6	0.25	0.77	MnO	Mn K	0.49	0.2	0.64	MnO
Fe K	11.93	4.76	15.35	FeO	Fe K	13.29	5.37	17.1	FeO	Fe K	14.46	5.89	18.6	FeO
Cu K					Cu K					Cu K				
O	44.22	61.61			O	43.44	61.24			O	42.88	61.03		
Totals	100				Totals	100				Totals	100			

Map 7					Map 8					Map 9				
Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula
Na K	2.37	2.3	3.2	Na2O	Na K	1.93	1.88	2.6	Na2O	Na K	1.47	1.44	1.98	Na2O
Mg K	1.44	1.32	2.39	MgO	Mg K	1.43	1.32	2.38	MgO	Mg K	1.42	1.31	2.35	MgO
Al K	8.45	6.99	15.96	Al2O3	Al K	8.43	6.99	15.93	Al2O3	Al K	8.35	6.94	15.78	Al2O3
Si K	23.45	18.63	50.16	SiO2	Si K	23.55	18.75	50.38	SiO2	Si K	23.51	18.79	50.3	SiO2
P K	1.01	0.73	2.31	P2O5	P K	1.34	0.97	3.08	P2O5	P K	1.28	0.93	2.94	P2O5
S K	0.18	0.12	0.44	SO3	S K	0	0	0		S K	0.15	0.1	0.36	SO3
Cl K	0.43	0.27	0		Cl K	0.31	0.2	0		Cl K	0.16	0.1	0	
K K	1.65	0.94	1.98	K2O	K K	1.65	0.95	1.99	K2O	K K	1.59	0.91	1.92	K2O
Ca K	2.84	1.58	3.97	CaO	Ca K	2.32	1.29	3.24	CaO	Ca K	2.3	1.29	3.22	CaO
Ti K	2.12	0.99	3.53	TiO2	Ti K	2	0.93	3.33	TiO2	Ti K	2.08	0.98	3.47	TiO2
Mn K	0.21	0.08	0.27	MnO	Mn K	0.41	0.17	0.54	MnO	Mn K	0.33	0.13	0.43	MnO
Fe K	11.93	4.77	15.34	FeO	Fe K	12.6	5.05	16.21	FeO	Fe K	12.37	4.97	15.91	FeO
Cu K					Cu K					Cu K	0.93	0.33	1.16	CuO
O	43.93	61.28			O	44.01	61.51			O	44.05	61.78		
Totals	100				Totals	100				Totals	100			

Map 10				
Element	Weight%	Atomic%	Compd%	Formula
Na K	1.95	1.88	2.63	Na2O
Mg K	1.47	1.34	2.44	MgO
Al K	8.11	6.67	15.33	Al2O3
Si K	24.65	19.46	52.72	SiO2
P K	1.1	0.79	2.51	P2O5
S K	0.2	0.14	0.5	SO3
Cl K	0.4	0.25	0	
K K	1.63	0.92	1.96	K2O
Ca K	2.23	1.23	3.12	CaO
Ti K	1.84	0.85	3.07	TiO2
Mn K	0.35	0.14	0.45	MnO
Fe K	11.55	4.59	14.86	FeO
Cu K				
O	44.52	61.73		
Totals	100			

Table A4: SEM Element Map Data of Sample BDTM2 Interior

Map 1					Map 2					Map 3				
Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula
Na K	1.35	1.4	1.82	Na2O	Na K	1.27	1.32	1.71	Na2O	Na K	1.52	1.61	2.04	Na2O
Mg K	2.22	2.18	3.69	MgO	Mg K	2.26	2.22	3.75	MgO	Mg K	2.22	2.24	3.68	MgO
Al K	8.84	7.82	16.7	Al2O3	Al K	8.88	7.86	16.78	Al2O3	Al K	8.45	7.67	15.97	Al2O3
Si K	17.62	14.97	37.69	SiO2	Si K	17.43	14.82	37.29	SiO2	Si K	15.69	13.67	33.56	SiO2
P K	0.65	0.5	1.49	P2O5	P K	0.74	0.57	1.7	P2O5	P K	0.75	0.59	1.72	P2O5
Cl K	0.35	0.23	0		Cl K	0.34	0.23	0		Cl K	0.38	0.26	0	
K K	1.46	0.89	1.76	K2O	K K	1.44	0.88	1.73	K2O	K K	1.29	0.81	1.55	K2O
Ca K	3.73	2.22	5.21	CaO	Ca K	3.77	2.25	5.28	CaO	Ca K	3.09	1.89	4.33	CaO
Ti K	1.41	0.7	2.35	TiO2	Ti K	1.43	0.71	2.39	TiO2	Ti K	1.32	0.67	2.2	TiO2
Mn K	0.56	0.24	0.72	MnO	Mn K	0.58	0.25	0.75	MnO	Mn K	0.62	0.28	0.8	MnO
Fe K	21.93	9.37	28.22	FeO	Fe K	21.98	9.4	28.28	FeO	Fe K	26.24	11.5	33.75	FeO
Cu K					Cu K					Cu K				
O	39.88	59.47			O	39.87	59.5			O	38.43	58.8		
Totals	100				Totals	100				Totals	100			

Map 4					Map 5					Map 6				
Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula
Na K	1.33	1.42	1.79	Na2O	Na K	2.42	2.5	3.26	Na2O	Na K	1.75	1.82	2.36	Na2O
Mg K	2.42	2.44	4.01	MgO	Mg K	2	1.96	3.32	MgO	Mg K	2.22	2.18	3.68	MgO
Al K	7.72	7.02	14.58	Al2O3	Al K	6.96	6.13	13.14	Al2O3	Al K	7.85	6.95	14.84	Al2O3
Si K	15.86	13.86	33.93	SiO2	Si K	18.89	15.98	40.4	SiO2	Si K	18.22	15.48	38.97	SiO2
P K	0.73	0.58	1.68	P2O5	P K	0.74	0.57	1.7	P2O5	P K	0.64	0.49	1.47	P2O5
Cl K	0.27	0.19	0		Cl K	0.4	0.26	0		Cl K	0.36	0.24	0	
K K	1.42	0.89	1.71	K2O	K K	2.13	1.29	2.56	K2O	K K	1.71	1.04	2.06	K2O
Ca K	3.61	2.21	5.04	CaO	Ca K	3.64	2.16	5.09	CaO	Ca K	3.45	2.06	4.83	CaO
Ti K	1.45	0.74	2.42	TiO2	Ti K	1.67	0.83	2.78	TiO2	Ti K	1.43	0.71	2.39	TiO2
Mn K	0.62	0.28	0.8	MnO	Mn K	0.48	0.21	0.62	MnO	Mn K	0.52	0.23	0.68	MnO
Fe K	26.24	11.53	33.75	FeO	Fe K	20.77	8.84	26.72	FeO	Fe K	22.04	9.42	28.36	FeO
Cu K					Cu K					Cu K				
O	38.33	58.82			O	39.91	59.28			O	39.79	59.37		
Totals	100				Totals	100				Totals	100			

Map 7					Map 8					Map 9				
Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula
Na K	1.48	1.57	2	Na2O	Na K	1.29	1.44	1.74	Na2O	Na K	2.27	2.37	3.06	Na2O
Mg K	2.36	2.36	3.91	MgO	Mg K	2	2.11	3.31	MgO	Mg K	2.04	2.01	3.38	MgO
Al K	7.67	6.91	14.5	Al2O3	Al K	7.28	6.92	13.76	Al2O3	Al K	7.79	6.92	14.72	Al2O3
Si K	16.99	14.71	36.35	SiO2	Si K	14.52	13.25	31.06	SiO2	Si K	17.82	15.19	38.11	SiO2
P K	0.56	0.44	1.27	P2O5	P K	0.54	0.45	1.24	P2O5	P K	0.65	0.5	1.49	P2O5
Cl K	0.29	0.2	0		Cl K	0.27	0.19	0		Cl K	0.41	0.28	0	
K K	1.5	0.93	1.81	K2O	K K	1.18	0.78	1.42	K2O	K K	1.38	0.85	1.67	K2O
Ca K	3.65	2.21	5.1	CaO	Ca K	2.55	1.63	3.57	CaO	Ca K	3.78	2.26	5.29	CaO
Ti K	1.35	0.68	2.25	TiO2	Ti K	1.09	0.59	1.82	TiO2	Ti K	1.26	0.63	2.1	TiO2
Mn K	0.49	0.22	0.63	MnO	Mn K	0.42	0.2	0.55	MnO	Mn K	0.46	0.2	0.59	MnO
Fe K	23.76	10.34	30.56	FeO	Fe K	18.38	8.44	23.64	FeO	Fe K	22.68	9.72	29.17	FeO
Cu K	1.07	0.41	1.34	CuO	Cu K	14.07	5.68	17.62	CuO	Cu K				
O	38.85	59.03			O	36.4	58.33			O	39.46	59.08		
Totals	100				Totals	100				Totals	100			

Map 10				
Element	Weight%	Atomic%	Compd%	Formula
Na K	2.03	2.07	2.74	Na2O
Mg K	2.13	2.06	3.53	MgO
Al K	8.65	7.53	16.35	Al2O3
Si K	18.81	15.72	40.25	SiO2
P K	0.71	0.54	1.63	P2O5
Cl K	0.38	0.25	0	
K K	1.54	0.92	1.85	K2O
Ca K	3.82	2.24	5.34	CaO
Ti K	1.41	0.69	2.36	TiO2
Mn K	0.5	0.21	0.64	MnO
Fe K	19.37	8.14	24.92	FeO
Cu K				
O	40.64	59.62		
Totals	100			

Table A5: SEM Element Map Data of Sample BDHH2 Surface

Map 1					Map 2					Map 3				
Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula
Na K	1.9	1.94	2.56	Na2O	Na K	1.87	1.92	2.52	Na2O	Na K	1.79	1.87	2.41	Na2O
Mg K	1.08	1.04	1.79	MgO	Mg K	1.33	1.29	2.21	MgO	Mg K	1.32	1.31	2.19	MgO
Al K	7.63	6.64	14.41	Al2O3	Al K	7.45	6.52	14.07	Al2O3	Al K	7.27	6.48	13.74	Al2O3
Si K	19.35	16.18	41.39	SiO2	Si K	18.88	15.89	40.39	SiO2	Si K	17.37	14.88	37.16	SiO2
P K	1.51	1.15	3.47	P2O5	P K	1.25	0.95	2.87	P2O5	P K	1.6	1.25	3.68	P2O5
S K					S K	0.21	0.15	0.52	SO3	S K				
Cl K	0.28	0.18	0		Cl K	0.38	0.25	0		Cl K	0.27	0.18	0	
K K	1.72	1.03	2.07	K2O	K K	1.58	0.96	1.91	K2O	K K	1.47	0.9	1.77	K2O
Ca K	3.33	1.95	4.66	CaO	Ca K	3.36	1.98	4.69	CaO	Ca K	3.35	2.01	4.69	CaO
Ti K	2.57	1.26	4.28	TiO2	Ti K	2.38	1.18	3.97	TiO2	Ti K	2.52	1.26	4.2	TiO2
Mn K	0.4	0.17	0.51	MnO	Mn K	0.72	0.31	0.93	MnO	Mn K	1.03	0.45	1.34	MnO
Fe K	19.11	8.04	24.58	FeO	Fe K	19.85	8.4	25.54	FeO	Fe K	22.2	9.56	28.56	FeO
O	41.14	60.41			O	40.74	60.18			O	39.8	59.84		
Totals	100				Totals	100				Totals	100			

Map 4					Map 5					Map 6				
Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula
Na K	1.22	1.21	1.64	Na2O	Na K	1.31	1.3	1.76	Na2O	Na K	1.57	1.54	2.12	Na2O
Mg K	1.42	1.34	2.36	MgO	Mg K	1.38	1.3	2.29	MgO	Mg K	1.3	1.21	2.16	MgO
Al K	6.86	5.81	12.96	Al2O3	Al K	7.15	6.06	13.51	Al2O3	Al K	7.8	6.53	14.73	Al2O3
Si K	23.31	18.98	49.87	SiO2	Si K	22.84	18.6	48.85	SiO2	Si K	23.13	18.6	49.48	SiO2
P K	0.8	0.59	1.84	P2O5	P K	0.99	0.73	2.26	P2O5	P K	1.19	0.87	2.72	P2O5
S K	0.28	0.2	0.71	SO3	S K	0.24	0.17	0.59	SO3	S K	0.26	0.18	0.65	SO3
Cl K	0.22	0.14	0		Cl K	0.28	0.18	0		Cl K	0.21	0.13	0	
K K	1.76	1.03	2.12	K2O	K K	1.79	1.05	2.16	K2O	K K	1.84	1.06	2.21	K2O
Ca K	2.9	1.65	4.06	CaO	Ca K	2.98	1.7	4.17	CaO	Ca K	3.07	1.73	4.29	CaO
Ti K	1.99	0.95	3.32	TiO2	Ti K	2.06	0.98	3.43	TiO2	Ti K	2.02	0.95	3.37	TiO2
Mn K	0.63	0.26	0.81	MnO	Mn K	0.56	0.23	0.72	MnO	Mn K	0.33	0.14	0.43	MnO
Fe K	15.63	6.4	20.1	FeO	Fe K	15.52	6.35	19.96	FeO	Fe K	13.7	5.54	17.62	FeO
O	42.99	61.44			O	42.91	61.35			O	43.58	61.52		
Totals	100				Totals	100				Totals	100			

Map 7					Map 8					Map 9				
Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula
Na K	1.34	1.27	1.8	Na2O	Na K	1.36	1.29	1.83	Na2O	Na K	1.46	1.4	1.97	Na2O
Mg K	1.4	1.26	2.31	MgO	Mg K	1.47	1.32	2.43	MgO	Mg K	1.4	1.26	2.32	MgO
Al K	6.87	5.57	12.98	Al2O3	Al K	7.32	5.91	13.83	Al2O3	Al K	7.45	6.06	14.08	Al2O3
Si K	27.82	21.66	59.51	SiO2	Si K	27.88	21.62	59.64	SiO2	Si K	26.77	20.93	57.26	SiO2
P K	0.64	0.45	1.47	P2O5	P K	0.52	0.36	1.19	P2O5	P K	0.61	0.43	1.4	P2O5
S K	0.34	0.23	0.85	SO3	S K	0.39	0.27	0.98	SO3	S K	0.37	0.25	0.92	SO3
Cl K	0.31	0.19	0		Cl K	0.34	0.21	0		Cl K	0.27	0.16	0	
K K	1.75	0.98	2.11	K2O	K K	1.59	0.89	1.92	K2O	K K	1.74	0.98	2.1	K2O
Ca K	2.56	1.4	3.58	CaO	Ca K	2.63	1.43	3.68	CaO	Ca K	2.8	1.53	3.92	CaO
Ti K	1.48	0.68	2.47	TiO2	Ti K	1.38	0.63	2.3	TiO2	Ti K	1.62	0.74	2.7	TiO2
Mn K					Mn K					Mn K				
Fe K	9.81	3.84	12.61	FeO	Fe K	9.21	3.59	11.85	FeO	Fe K	10.15	3.99	13.06	FeO
O	45.7	62.47			O	45.91	62.49			O	45.36	62.25		
Totals	100				Totals	100				Totals	100			

Map 10				
Element	Weight%	Atomic%	Compd%	Formula
Na K	1.76	1.72	2.37	Na2O
Mg K	1.22	1.13	2.02	MgO
Al K	7.82	6.53	14.78	Al2O3
Si K	23.56	18.88	50.4	SiO2
P K	0.99	0.72	2.27	P2O5
S K	0.2	0.14	0.5	SO3
Cl K	0.32	0.2	0	
K K	1.91	1.1	2.3	K2O
Ca K	3.15	1.77	4.41	CaO
Ti K	2.2	1.04	3.67	TiO2
Mn K	0.26	0.11	0.33	MnO
Fe K	12.91	5.2	16.61	FeO
O	43.69	61.46		
Totals	100			

Table A6: SEM Element Map Data of Sample BDHH2 Interior

Map 1					Map 2					Map 3				
Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula
Na K	3.43	3.33	4.63	Na2O	Na K	3.42	3.32	4.61	Na2O	Na K	3.35	3.25	4.52	Na2O
Mg K	1.71	1.57	2.84	MgO	Mg K	1.74	1.6	2.89	MgO	Mg K	1.82	1.67	3.02	MgO
Al K	6.94	5.74	13.12	Al2O3	Al K	6.99	5.78	13.22	Al2O3	Al K	6.89	5.7	13.02	Al2O3
Si K	23.81	18.91	50.94	SiO2	Si K	23.76	18.86	50.82	SiO2	Si K	23.82	18.92	50.96	SiO2
P K	1.03	0.74	2.35	P2O5	P K	1.03	0.74	2.36	P2O5	P K	1.01	0.73	2.32	P2O5
Cl K	0.27	0.17	0		Cl K	0.26	0.17	0		Cl K	0.21	0.13	0	
K K	1.76	1	2.12	K2O	K K	1.75	1	2.1	K2O	K K	1.69	0.96	2.03	K2O
Ca K	5.09	2.83	7.12	CaO	Ca K	5.02	2.79	7.03	CaO	Ca K	5.01	2.79	7.01	CaO
Ti K	1.57	0.73	2.62	TiO2	Ti K	1.61	0.75	2.69	TiO2	Ti K	1.61	0.75	2.68	TiO2
Mn K	0.21	0.08	0.27	MnO	Mn K	0.21	0.08	0.27	MnO	Mn K	0.18	0.07	0.23	MnO
Fe K	10.68	4.26	13.74	FeO	Fe K	10.69	4.27	13.75	FeO	Fe K	10.87	4.34	13.99	FeO
O	43.51	60.64			O	43.51	60.64			O	43.53	60.68		
Totals	100				Totals	100				Totals	100			

Map 4					Map 5					Map 6				
Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula
Na K	3.39	3.29	4.57	Na2O	Na K	3.44	3.33	4.63	Na2O	Na K	3.38	3.27	4.55	Na2O
Mg K	1.71	1.57	2.84	MgO	Mg K	1.76	1.62	2.92	MgO	Mg K	1.66	1.52	2.75	MgO
Al K	6.85	5.67	12.93	Al2O3	Al K	6.87	5.68	12.99	Al2O3	Al K	7.13	5.89	13.47	Al2O3
Si K	23.83	18.94	50.97	SiO2	Si K	23.87	18.94	51.06	SiO2	Si K	23.85	18.92	51.01	SiO2
P K	0.98	0.71	2.25	P2O5	P K	1.03	0.74	2.35	P2O5	P K	1.03	0.74	2.36	P2O5
Cl K	0.25	0.16	0		Cl K	0.21	0.13	0		Cl K	0.19	0.12	0	
K K	1.73	0.99	2.08	K2O	K K	1.64	0.93	1.98	K2O	K K	1.67	0.95	2.02	K2O
Ca K	5.07	2.83	7.1	CaO	Ca K	5	2.78	6.99	CaO	Ca K	5	2.78	7	CaO
Ti K	1.57	0.73	2.62	TiO2	Ti K	1.67	0.78	2.78	TiO2	Ti K	1.53	0.71	2.55	TiO2
Mn K	0.24	0.1	0.31	MnO	Mn K	0.2	0.08	0.26	MnO	Mn K	0.23	0.09	0.3	MnO
Fe K	10.93	4.37	14.06	FeO	Fe K	10.75	4.29	13.82	FeO	Fe K	10.73	4.28	13.8	FeO
O	43.44	60.64			O	43.57	60.7			O	43.6	60.72		
Totals	100				Totals	100				Totals	100			

Map 7					Map 8					Map 9				
Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula
Na K	3.44	3.33	4.63	Na2O	Na K	3.43	3.32	4.63	Na2O	Na K	3.49	3.38	4.71	Na2O
Mg K	1.7	1.56	2.83	MgO	Mg K	1.76	1.61	2.92	MgO	Mg K	1.78	1.63	2.95	MgO
Al K	7.05	5.82	13.32	Al2O3	Al K	7.13	5.88	13.47	Al2O3	Al K	7.06	5.82	13.33	Al2O3
Si K	23.74	18.84	50.79	SiO2	Si K	23.84	18.88	51	SiO2	Si K	23.79	18.85	50.88	SiO2
P K	1.07	0.77	2.45	P2O5	P K	1.07	0.77	2.44	P2O5	P K	1.07	0.77	2.45	P2O5
Cl K	0.21	0.13	0		Cl K	0.27	0.17	0		Cl K				
K K	1.7	0.97	2.05	K2O	K K	1.64	0.93	1.97	K2O	K K	1.79	1.02	2.16	K2O
Ca K	4.98	2.77	6.96	CaO	Ca K	5.02	2.79	7.03	CaO	Ca K	5.01	2.78	7	CaO
Ti K	1.62	0.75	2.69	TiO2	Ti K	1.59	0.74	2.65	TiO2	Ti K	1.52	0.71	2.54	TiO2
Mn K					Mn K					Mn K	0.22	0.09	0.29	MnO
Fe K	10.94	4.37	14.07	FeO	Fe K	10.59	4.22	13.62	FeO	Fe K	10.63	4.24	13.68	FeO
O	43.56	60.69			O	43.67	60.7			O	43.64	60.71		
Totals	100				Totals	100				Totals	100			

Map 10				
Element	Weight%	Atomic%	Compd%	Formula
Na K	3.46	3.36	4.67	Na2O
Mg K	1.72	1.57	2.85	MgO
Al K	7.09	5.85	13.4	Al2O3
Si K	23.77	18.85	50.86	SiO2
P K	1.09	0.78	2.5	P2O5
Cl K	0.17	0.11	0	
K K	1.76	1	2.12	K2O
Ca K	5.03	2.79	7.03	CaO
Ti K	1.53	0.71	2.55	TiO2
Mn K	0.22	0.09	0.28	MnO
Fe K	10.54	4.2	13.56	FeO
O	43.61	60.69		
Totals	100			

Table A7: SEM Element Map Data of Sample GD3 Surface

Map 1					Map 2					Map 3				
Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula
Na K	1.76	1.74	2.37	Na ₂ O	Na K	1.64	1.61	2.21	Na ₂ O	Na K	1.54	1.53	2.08	Na ₂ O
Mg K	1.57	1.46	2.6	MgO	Mg K	1.63	1.52	2.7	MgO	Mg K	1.55	1.45	2.57	MgO
Al K	9.32	7.83	17.61	Al ₂ O ₃	Al K	8.72	7.3	16.48	Al ₂ O ₃	Al K	7.18	6.07	13.56	Al ₂ O ₃
Si K	21.11	17.04	45.15	SiO ₂	Si K	21.92	17.62	46.89	SiO ₂	Si K	22.48	18.27	48.1	SiO ₂
P K	1.59	1.16	3.64	P ₂ O ₅	P K	1.41	1.02	3.22	P ₂ O ₅	P K	1.09	0.8	2.5	P ₂ O ₅
S K					S K	0.33	0.23	0.83	SO ₃	S K	0.49	0.35	1.22	SO ₃
Cl K	0.2	0.13	0		Cl K	0.31	0.2	0		Cl K	0.45	0.29	0	
K K	1.63	0.94	1.96	K ₂ O	K K	1.55	0.9	1.87	K ₂ O	K K	1.62	0.94	1.95	K ₂ O
Ca K	2.73	1.54	3.81	CaO	Ca K	2.56	1.45	3.59	CaO	Ca K	2.7	1.54	3.77	CaO
Ti K	2.16	1.02	3.6	TiO ₂	Ti K	1.89	0.89	3.15	TiO ₂	Ti K	1.94	0.92	3.24	TiO ₂
Mn K	0.84	0.35	1.09	MnO	Mn K	1.18	0.48	1.52	MnO	Mn K	0.69	0.29	0.89	MnO
Fe K	13.97	5.67	17.97	FeO	Fe K	13.4	5.42	17.23	FeO	Fe K	15.28	6.24	19.66	FeO
O	43.14	61.12			O	43.46	61.36			O	42.98	61.3		
Totals	100				Totals	100				Totals	100			

Map 4					Map 5					Map 6				
Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula
Na K	1.63	1.59	2.2	Na ₂ O	Na K	1.71	1.73	2.31	Na ₂ O	Na K	1.79	1.79	2.41	Na ₂ O
Mg K	1.38	1.27	2.28	MgO	Mg K	1.29	1.23	2.14	MgO	Mg K	1.48	1.4	2.45	MgO
Al K	6.91	5.75	13.06	Al ₂ O ₃	Al K	7.75	6.66	14.65	Al ₂ O ₃	Al K	8.17	6.98	15.44	Al ₂ O ₃
Si K	24.71	19.75	52.87	SiO ₂	Si K	20.11	16.6	43.02	SiO ₂	Si K	20.49	16.81	43.84	SiO ₂
P K	0.74	0.54	1.69	P ₂ O ₅	P K	1.36	1.02	3.11	P ₂ O ₅	P K	1.2	0.89	2.74	P ₂ O ₅
S K	0.58	0.4	1.44	SO ₃	S K	0.34	0.25	0.85	SO ₃	S K	0.36	0.26	0.9	SO ₃
Cl K	0.29	0.18	0		Cl K	0.54	0.35	0		Cl K	0.38	0.25	0	
K K	1.77	1.02	2.14	K ₂ O	K K	1.61	0.95	1.93	K ₂ O	K K	1.77	1.04	2.13	K ₂ O
Ca K	2.71	1.52	3.79	CaO	Ca K	3.01	1.74	4.22	CaO	Ca K	2.96	1.7	4.15	CaO
Ti K	1.54	0.72	2.57	TiO ₂	Ti K	2.89	1.4	4.82	TiO ₂	Ti K	2.34	1.13	3.9	TiO ₂
Mn K	0.57	0.23	0.73	MnO	Mn K	0.51	0.21	0.66	MnO	Mn K	0.69	0.29	0.89	MnO
Fe K	13.16	5.29	16.93	FeO	Fe K	16.92	7.02	21.76	FeO	Fe K	16.16	6.67	20.79	FeO
O	44.01	61.74			O	41.97	60.83			O	42.23	60.81		
Totals	100				Totals	100				Totals	100			

Map 7					Map 8					Map 9				
Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula
Na K	1.42	1.38	1.92	Na2O	Na K	1.79	1.78	2.41	Na2O	Na K	1.56	1.54	2.1	Na2O
Mg K	1.39	1.27	2.3	MgO	Mg K	1.38	1.29	2.28	MgO	Mg K	1.67	1.55	2.76	MgO
Al K	7.31	6.05	13.82	Al2O3	Al K	8.55	7.23	16.15	Al2O3	Al K	6.76	5.67	12.77	Al2O3
Si K	24.05	19.11	51.44	SiO2	Si K	21.3	17.32	45.57	SiO2	Si K	24.09	19.42	51.53	SiO2
P K	0.95	0.69	2.18	P2O5	P K	0.78	0.57	1.79	P2O5	P K	0.6	0.44	1.37	P2O5
S K	1.1	0.76	2.74	SO3	S K	0.7	0.5	1.75	SO3	S K	0.67	0.47	1.66	SO3
Cl K	0.42	0.27	0		Cl K	0.52	0.33	0		Cl K				
K K	1.81	1.03	2.18	K2O	K K	1.7	0.99	2.05	K2O	K K	1.53	0.89	1.85	K2O
Ca K	2.65	1.48	3.71	CaO	Ca K	2.56	1.46	3.58	CaO	Ca K	2.23	1.26	3.12	CaO
Ti K	1.98	0.92	3.31	TiO2	Ti K	2.13	1.02	3.56	TiO2	Ti K	1.31	0.62	2.18	TiO2
Mn K					Mn K					Mn K				
Fe K	12.43	4.97	15.99	FeO	Fe K	15.8	6.46	20.33	FeO	Fe K	16.06	6.51	20.66	FeO
O	44.49	62.07			O	42.78	61.05			O	43.54	61.63		
Totals	100				Totals	100				Totals	100			

Map 10				
Element	Weight%	Atomic%	Compd%	Formula
Na K	1.54	1.47	2.07	Na2O
Mg K	1.55	1.4	2.57	MgO
Al K	7.96	6.47	15.03	Al2O3
Si K	26.23	20.49	56.11	SiO2
P K	0.71	0.51	1.64	P2O5
S K	0.42	0.28	1.04	SO3
Cl K	0.47	0.29	0	
K K	1.68	0.94	2.02	K2O
Ca K	2.39	1.31	3.34	CaO
Ti K	1.55	0.71	2.58	TiO2
Mn K				
Fe K	10.2	4.01	13.12	FeO
O	45.31	62.13		
Totals	100			

Table A8: SEM Element Map Data of Sample GD3 Interior

Map 1					Map 2					Map 3				
Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula
Na K	3.45	3.34	4.65	Na2O	Na K	3.41	3.29	4.59	Na2O	Na K	3.61	3.51	4.87	Na2O
Mg K	1.79	1.64	2.96	MgO	Mg K	1.65	1.51	2.74	MgO	Mg K	1.61	1.48	2.67	MgO
Al K	7.22	5.96	13.64	Al2O3	Al K	7.67	6.31	14.5	Al2O3	Al K	7.35	6.09	13.89	Al2O3
Si K	23.65	18.75	50.6	SiO2	Si K	23.84	18.84	50.99	SiO2	Si K	23.18	18.45	49.58	SiO2
P K	1.12	0.8	2.56	P2O5	P K	1.01	0.72	2.3	P2O5	P K	1.13	0.81	2.58	P2O5
Cl K					Cl K					Cl K				
K K	1.63	0.93	1.96	K2O	K K	1.68	0.95	2.03	K2O	K K	1.62	0.92	1.95	K2O
Ca K	4.88	2.71	6.82	CaO	Ca K	4.59	2.54	6.42	CaO	Ca K	4.82	2.69	6.74	CaO
Ti K	1.59	0.74	2.65	TiO2	Ti K	1.53	0.71	2.55	TiO2	Ti K	1.6	0.75	2.67	TiO2
Mn K					Mn K	0.33	0.13	0.42	MnO	Mn K	0.25	0.1	0.32	MnO
Fe K	11	4.38	14.15	FeO	Fe K	10.46	4.16	13.45	FeO	Fe K	11.46	4.59	14.74	FeO
O	43.68	60.77			O	43.84	60.83			O	43.39	60.62		
Totals	100				Totals	100				Totals	100			

Map 4					Map 5					Map 6				
Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula
Na K	3.6	3.48	4.85	Na2O	Na K	3.66	3.55	4.94	Na2O	Na K	3.45	3.38	4.66	Na2O
Mg K	1.64	1.5	2.72	MgO	Mg K	1.67	1.53	2.77	MgO	Mg K	1.75	1.62	2.9	MgO
Al K	7.22	5.95	13.64	Al2O3	Al K	6.98	5.76	13.19	Al2O3	Al K	6.8	5.66	12.85	Al2O3
Si K	23.85	18.88	51.02	SiO2	Si K	23.68	18.78	50.65	SiO2	Si K	23.11	18.49	49.43	SiO2
P K	1.07	0.77	2.45	P2O5	P K	1.13	0.81	2.59	P2O5	P K	1.07	0.77	2.44	P2O5
Cl K					Cl K	0.27	0.17	0		Cl K	0.18	0.11	0	
K K	1.64	0.93	1.98	K2O	K K	1.72	0.98	2.07	K2O	K K	1.67	0.96	2.01	K2O
Ca K	4.9	2.72	6.86	CaO	Ca K	4.99	2.77	6.98	CaO	Ca K	4.7	2.64	6.58	CaO
Ti K	1.5	0.69	2.49	TiO2	Ti K	1.61	0.75	2.68	TiO2	Ti K	1.93	0.9	3.22	TiO2
Mn K					Mn K					Mn K	0.2	0.08	0.25	MnO
Fe K	10.87	4.33	13.99	FeO	Fe K	10.79	4.3	13.88	FeO	Fe K	12.03	4.84	15.48	FeO
O	43.71	60.75			O	43.52	60.6			O	43.12	60.55		
Totals	100				Totals	100				Totals	100			

Map 7					Map 8					Map 9				
Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula
Na K	3.6	3.49	4.85	Na2O	Na K	4.21	4.08	5.68	Na2O	Na K	4	3.87	5.4	Na2O
Mg K	1.7	1.56	2.83	MgO	Mg K	1.74	1.59	2.88	MgO	Mg K	1.77	1.62	2.93	MgO
Al K	6.86	5.67	12.96	Al2O3	Al K	6.8	5.61	12.85	Al2O3	Al K	6.93	5.71	13.09	Al2O3
Si K	23.78	18.88	50.88	SiO2	Si K	23.64	18.73	50.58	SiO2	Si K	23.78	18.83	50.87	SiO2
P K	1.1	0.79	2.53	P2O5	P K	1.1	0.79	2.53	P2O5	P K	1.02	0.73	2.33	P2O5
Cl K	0.31	0.19	0		Cl K	0.57	0.36	0		Cl K	0.45	0.28	0	
K K	1.73	0.98	2.08	K2O	K K	1.84	1.05	2.22	K2O	K K	1.78	1.01	2.15	K2O
Ca K	4.89	2.72	6.84	CaO	Ca K	4.84	2.69	6.77	CaO	Ca K	4.83	2.68	6.76	CaO
Ti K	1.62	0.75	2.7	TiO2	Ti K	1.45	0.68	2.43	TiO2	Ti K	1.46	0.68	2.43	TiO2
Mn K	0.21	0.09	0.27	MnO	Mn K	0.21	0.09	0.28	MnO	Mn K	0.19	0.08	0.24	MnO
Fe K	10.69	4.27	13.76	FeO	Fe K	10.27	4.09	13.22	FeO	Fe K	10.36	4.13	13.33	FeO
O	43.51	60.61			O	43.3	60.24			O	43.42	60.37		
Totals	100				Totals	100				Totals	100			

Map 10				
Element	Weight%	Atomic%	Compd%	Formula
Na K	3.55	3.43	4.78	Na2O
Mg K	1.67	1.53	2.77	MgO
Al K	7.06	5.82	13.33	Al2O3
Si K	23.89	18.92	51.11	SiO2
P K	1.09	0.78	2.5	P2O5
Cl K	0.21	0.13	0	
K K	1.75	1	2.11	K2O
Ca K	4.85	2.69	6.79	CaO
Ti K	1.58	0.74	2.64	TiO2
Mn K	0.24	0.1	0.32	MnO
Fe K	10.45	4.16	13.44	FeO
O	43.65	60.7		
Totals	100			

Table A9: SEM Element Map Data of Sample NC1 Surface

Map 1					Map 2					Map 3				
Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula
C K	19.34	26.46	70.87	CO2	C K	21.45	28.48	78.59	CO2	C K	18.58	25.77	68.09	CO2
Na K	0.69	0.49	0.93	Na2O	Na K	0.54	0.37	0.73	Na2O	Na K	0.75	0.55	1.02	Na2O
Mg K	0.31	0.21	0.51	MgO	Mg K	0.27	0.18	0.45	MgO	Mg K	0.39	0.27	0.65	MgO
Al K	2.26	1.37	4.26	Al2O3	Al K	1.94	1.15	3.66	Al2O3	Al K	2.36	1.45	4.45	Al2O3
Si K	6.04	3.53	12.92	SiO2	Si K	4.16	2.36	8.9	SiO2	Si K	6.4	3.8	13.7	SiO2
P K	0.28	0.15	0.64	P2O5	P K					P K	0.3	0.16	0.69	P2O5
S K					S K					S K				
Cl K					Cl K					Cl K	0.15	0.07	0	
K K	0.57	0.24	0.69	K2O	K K	0.49	0.2	0.59	K2O	K K	0.68	0.29	0.82	K2O
Ca K	0.9	0.37	1.26	CaO	Ca K	0.71	0.28	1	CaO	Ca K	1.04	0.43	1.46	CaO
Ti K	0.72	0.25	1.19	TiO2	Ti K	0.54	0.18	0.89	TiO2	Ti K	0.8	0.28	1.33	TiO2
Mn K	0.28	0.09	0.37	MnO	Mn K					Mn K	0.18	0.05	0.23	MnO
Fe K	4.94	1.45	6.35	FeO	Fe K	4.04	1.15	5.2	FeO	Fe K	5.75	1.71	7.4	FeO
O	63.67	65.39			O	65.87	65.65			O	62.6	65.16		
Totals	100				Totals	100				Totals	100			

Map 4					Map 5					Map 6				
Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula
C K	18.56	25.64	68.01	CO2	C K	18.54	25.54	67.92	CO2	C K	18.4	25.41	67.44	CO2
Na K	0.78	0.56	1.05	Na2O	Na K	0.85	0.61	1.14	Na2O	Na K	1	0.72	1.35	Na2O
Mg K	0.43	0.29	0.71	MgO	Mg K	0.44	0.3	0.72	MgO	Mg K	0.38	0.26	0.63	MgO
Al K	2.12	1.3	4	Al2O3	Al K	2.33	1.43	4.4	Al2O3	Al K	2.14	1.32	4.05	Al2O3
Si K	7.06	4.17	15.1	SiO2	Si K	7.28	4.29	15.58	SiO2	Si K	7.53	4.44	16.1	SiO2
P K	0.25	0.13	0.57	P2O5	P K	0.26	0.14	0.6	P2O5	P K	0.24	0.13	0.54	P2O5
S K	0.13	0.07	0.32	SO3	S K	0.08	0.04	0.21	SO3	S K	0.09	0.05	0.23	SO3
Cl K	0.15	0.07	0		Cl K	0.09	0.04	0		Cl K	0.07	0.03	0	
K K	0.68	0.29	0.82	K2O	K K	0.7	0.3	0.84	K2O	K K	0.79	0.33	0.95	K2O
Ca K	1	0.41	1.39	CaO	Ca K	1.02	0.42	1.43	CaO	Ca K	1.07	0.44	1.5	CaO
Ti K	0.66	0.23	1.11	TiO2	Ti K	0.7	0.24	1.17	TiO2	Ti K	0.67	0.23	1.12	TiO2
Mn K	0.19	0.06	0.25	MnO	Mn K	0.13	0.04	0.17	MnO	Mn K	0.11	0.03	0.14	MnO
Fe K	5.08	1.51	6.53	FeO	Fe K	4.45	1.32	5.72	FeO	Fe K	4.57	1.36	5.88	FeO
O	62.93	65.27			O	63.13	65.29			O	62.93	65.24		
Totals	100				Totals	100				Totals	100			

Map 7					Map 8					Map 9				
Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula
C K	18.54	25.65	67.94	CO2	C K	18.61	25.66	68.19	CO2	C K	18.94	26	69.39	CO2
Na K	0.84	0.61	1.14	Na2O	Na K	1.02	0.74	1.38	Na2O	Na K	0.91	0.65	1.22	Na2O
Mg K	0.45	0.31	0.74	MgO	Mg K	0.48	0.33	0.79	MgO	Mg K	0.44	0.3	0.74	MgO
Al K	2.23	1.37	4.21	Al2O3	Al K	2.26	1.39	4.27	Al2O3	Al K	2.17	1.33	4.11	Al2O3
Si K	6.92	4.1	14.81	SiO2	Si K	6.95	4.1	14.86	SiO2	Si K	6.65	3.91	14.23	SiO2
P K	0.24	0.13	0.55	P2O5	P K	0.26	0.14	0.6	P2O5	P K	0.25	0.14	0.58	P2O5
S K					S K					S K				
Cl K	0.09	0.04	0		Cl K	0.09	0.04	0		Cl K	0.1	0.04	0	
K K	0.72	0.3	0.86	K2O	K K	0.65	0.28	0.78	K2O	K K	0.65	0.27	0.78	K2O
Ca K	1	0.42	1.41	CaO	Ca K	1.18	0.49	1.65	CaO	Ca K	1.1	0.45	1.53	CaO
Ti K	0.79	0.27	1.32	TiO2	Ti K	0.71	0.24	1.18	TiO2	Ti K	0.67	0.23	1.12	TiO2
Mn K	0.13	0.04	0.16	MnO	Mn K	0.11	0.03	0.14	MnO	Mn K	0.18	0.05	0.23	MnO
Fe K	5.26	1.57	6.77	FeO	Fe K	4.7	1.39	6.05	FeO	Fe K	4.64	1.37	5.96	FeO
O	62.79	65.2			O	62.98	65.18			O	63.3	65.25		
Totals	100				Totals	100				Totals	100			

Map 10				
Element	Weight%	Atomic%	Compd%	Formula
C K	18.4	25.44	67.42	CO2
Na K	0.87	0.63	1.17	Na2O
Mg K	0.44	0.3	0.74	MgO
Al K	2.27	1.4	4.29	Al2O3
Si K	7.29	4.31	15.59	SiO2
P K	0.26	0.14	0.6	P2O5
S K	0.09	0.05	0.23	SO3
Cl K	0.13	0.06	0	
K K	0.68	0.29	0.82	K2O
Ca K	1.03	0.43	1.45	CaO
Ti K	0.71	0.25	1.18	TiO2
Mn K	0.18	0.05	0.23	MnO
Fe K	4.79	1.42	6.16	FeO
O	62.86	65.24		
Totals	100			

Table A10: SEM Element Map Data of Sample NC1 Interior

Map 1					Map 2					Map 3				
Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula
Na K	3.06	3.05	4.13	Na2O	Na K	2.95	2.95	3.98	Na2O	Na K	2.82	2.83	3.8	Na2O
Mg K	1.34	1.26	2.22	MgO	Mg K	1.43	1.36	2.38	MgO	Mg K	1.45	1.38	2.41	MgO
Al K	7.27	6.17	13.74	Al2O3	Al K	6.53	5.56	12.34	Al2O3	Al K	6.19	5.3	11.7	Al2O3
Si K	21.44	17.47	45.86	SiO2	Si K	21.48	17.57	45.96	SiO2	Si K	21.26	17.48	45.48	SiO2
P K	0.95	0.7	2.17	P2O5	P K	0.93	0.69	2.13	P2O5	P K	0.95	0.71	2.19	P2O5
S K					S K	0.18	0.13	0.46	SO3	S K	0.15	0.11	0.38	SO3
Cl K	0.23	0.15	0		Cl K	0.31	0.2	0		Cl K	0.2	0.13	0	
K K	1.96	1.15	2.37	K2O	K K	1.95	1.14	2.34	K2O	K K	1.93	1.14	2.33	K2O
Ca K	5.7	3.25	7.97	CaO	Ca K	5.76	3.3	8.06	CaO	Ca K	6.01	3.46	8.4	CaO
Ti K	1.86	0.89	3.1	TiO2	Ti K	1.88	0.9	3.13	TiO2	Ti K	2.04	0.98	3.41	TiO2
Mn K	0.26	0.11	0.33	MnO	Mn K	0.25	0.1	0.32	MnO	Mn K	0.29	0.12	0.37	MnO
Fe K	13.89	5.69	17.87	FeO	Fe K	14.46	5.95	18.6	FeO	Fe K	15.02	6.21	19.33	FeO
Cu K					Cu K					Cu K				
O	42.04	60.12			O	41.89	60.15			O	41.68	60.14		
Totals	100				Totals	100				Totals	100			

Map 4					Map 5					Map 6				
Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula
Na K	2.93	2.95	3.95	Na2O	Na K	2.78	2.81	3.74	Na2O	Na K	2.92	2.93	3.94	Na2O
Mg K	1.4	1.34	2.33	MgO	Mg K	1.4	1.34	2.32	MgO	Mg K	1.44	1.37	2.4	MgO
Al K	6.1	5.23	11.53	Al2O3	Al K	5.92	5.11	11.19	Al2O3	Al K	6.13	5.24	11.58	Al2O3
Si K	21.42	17.64	45.82	SiO2	Si K	20.95	17.36	44.83	SiO2	Si K	21.57	17.73	46.15	SiO2
P K	0.86	0.64	1.98	P2O5	P K	0.97	0.73	2.22	P2O5	P K	0.92	0.69	2.11	P2O5
S K					S K					S K				
Cl K	0.25	0.16	0		Cl K	0.26	0.17	0		Cl K	0.29	0.19	0	
K K	1.99	1.18	2.4	K2O	K K	2.01	1.2	2.43	K2O	K K	2.05	1.21	2.47	K2O
Ca K	5.93	3.42	8.3	CaO	Ca K	5.98	3.47	8.37	CaO	Ca K	5.82	3.35	8.15	CaO
Ti K	2.02	0.97	3.37	TiO2	Ti K	2.15	1.04	3.58	TiO2	Ti K	1.96	0.94	3.27	TiO2
Mn K	0.28	0.12	0.36	MnO	Mn K	0.37	0.16	0.48	MnO	Mn K	0.29	0.12	0.38	MnO
Fe K	15.33	6.35	19.72	FeO	Fe K	16.01	6.67	20.59	FeO	Fe K	14.97	6.19	19.26	FeO
Cu K					Cu K					Cu K				
O	41.48	59.99			O	41.2	59.94			O	41.62	60.03		
Totals	100				Totals	100				Totals	100			

Map 7					Map 8					Map 9				
Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula	Element	Weight%	Atomic%	Compd%	Formula
Na K	3.04	3.06	4.09	Na2O	Na K	3.16	3.17	4.25	Na2O	Na K	3.14	3.14	4.23	Na2O
Mg K	1.38	1.31	2.29	MgO	Mg K	1.49	1.41	2.47	MgO	Mg K	1.4	1.33	2.32	MgO
Al K	6.15	5.27	11.61	Al2O3	Al K	6.32	5.41	11.94	Al2O3	Al K	6.23	5.32	11.78	Al2O3
Si K	21.3	17.56	45.58	SiO2	Si K	21.37	17.58	45.72	SiO2	Si K	21.61	17.72	46.23	SiO2
P K	0.9	0.67	2.07	P2O5	P K	0.92	0.68	2.1	P2O5	P K	0.93	0.69	2.13	P2O5
S K					S K					S K				
Cl K	0.34	0.22	0		Cl K	0.43	0.28	0		Cl K	0.39	0.25	0	
K K	2.02	1.19	2.43	K2O	K K	1.9	1.12	2.28	K2O	K K	2	1.18	2.41	K2O
Ca K	5.86	3.38	8.2	CaO	Ca K	5.49	3.16	7.68	CaO	Ca K	5.88	3.38	8.22	CaO
Ti K	1.92	0.93	3.21	TiO2	Ti K	1.89	0.91	3.16	TiO2	Ti K	1.86	0.9	3.11	TiO2
Mn K	0.3	0.13	0.39	MnO	Mn K	0.26	0.11	0.33	MnO	Mn K	0.3	0.12	0.38	MnO
Fe K	15.39	6.38	19.8	FeO	Fe K	13.88	5.74	17.85	FeO	Fe K	14.62	6.03	18.8	FeO
Cu K					Cu K	1.43	0.52	1.79	CuO	Cu K				
O	41.4	59.89			O	41.48	59.9			O	41.65	59.95		
Totals	100				Totals	100				Totals	100			

Map 10				
Element	Weight%	Atomic%	Compd%	Formula
Na K	3.17	3.16	4.27	Na2O
Mg K	1.45	1.37	2.41	MgO
Al K	6.3	5.36	11.9	Al2O3
Si K	21.82	17.84	46.68	SiO2
P K	0.92	0.68	2.1	P2O5
S K				
Cl K	0.38	0.25	0	
K K	1.92	1.13	2.32	K2O
Ca K	5.71	3.27	7.99	CaO
Ti K	1.93	0.92	3.21	TiO2
Mn K	0.27	0.11	0.35	MnO
Fe K	14.29	5.87	18.39	FeO
Cu K				
O	41.84	60.03		
Totals	100			

Table A11: SEM Element Map Data of Sample NC2 Surface

Map 1			Map 2			Map 3		
Element	Weight%	Atomic%	Element	Weight%	Atomic%	Element	Weight%	Atomic%
O K	53.87	71.02	O K	54.03	71.19	O K	54.85	71.69
Na K	1.52	1.4	Na K	1.52	1.4	Na K	1.44	1.31
Mg K	0.98	0.85	Mg K	1.03	0.89	Mg K	0.93	0.8
Al K	6.67	5.21	Al K	6.23	4.87	Al K	6.45	5
Si K	17.28	12.98	Si K	17.57	13.19	Si K	17.69	13.17
P K	1.1	0.75	P K	1.02	0.7	P K	1.08	0.73
S K			S K			S K		
Cl K	0.19	0.11	Cl K	0.14	0.08	Cl K		
K K	1.48	0.8	K K	1.54	0.83	K K	1.54	0.82
Ca K	2.31	1.22	Ca K	2.18	1.15	Ca K	2.26	1.18
Ti K	2.46	1.08	Ti K	2.24	0.99	Ti K	2.43	1.06
Mn K	0.3	0.12	Mn K	0.28	0.11	Mn K	0.22	0.08
Fe K	11.84	4.47	Fe K	12.21	4.61	Fe K	11.1	4.16
Totals	100		Totals	100		Totals	100	

Map 4			Map 5			Map 6		
Element	Weight%	Atomic%	Element	Weight%	Atomic%	Element	Weight%	Atomic%
O K	55.25	72.11	O K	54.18	71.29	O K	54.13	71.28
Na K	1.44	1.31	Na K	1.41	1.29	Na K	1.49	1.37
Mg K	1.02	0.87	Mg K	0.98	0.85	Mg K	0.92	0.8
Al K	6.34	4.9	Al K	6.32	4.93	Al K	6.54	5.11
Si K	17.08	12.7	Si K	17.68	13.25	Si K	17.27	12.95
P K	1.09	0.73	P K	1.01	0.69	P K	1.07	0.73
S K			S K			S K		
Cl K	0.13	0.08	Cl K	0.13	0.08	Cl K	0.16	0.1
K K	1.44	0.77	K K	1.52	0.82	K K	1.47	0.79
Ca K	2.25	1.17	Ca K	2.24	1.18	Ca K	2.19	1.15
Ti K	2.14	0.93	Ti K	2.49	1.1	Ti K	2.63	1.16
Mn K	0.32	0.12	Mn K	0.23	0.09	Mn K	0.27	0.1
Fe K	11.51	4.3	Fe K	11.8	4.45	Fe K	11.85	4.47
Totals	100		Totals	100		Totals	100	

Map 7			Map 8			Map 9			Map 10		
Element	Weight%	Atomic%	Element	Weight%	Atomic%	Element	Weight%	Atomic%	Element	Weight%	Atomic%
O K	53.64	70.81	O K	53.05	69.89	O K	53.98	70.99	O K	53.73	70.62
Na K	1.65	1.52	Na K	1.51	1.38	Na K	1.63	1.49	Na K	1.58	1.45
Mg K	0.91	0.79	Mg K	1.03	0.9	Mg K	1.04	0.9	Mg K	0.9	0.78
Al K	6.62	5.18	Al K	6.29	4.91	Al K	6.06	4.72	Al K	6.68	5.21
Si K	17.4	13.08	Si K	19.79	14.85	Si K	18.1	13.56	Si K	18.27	13.68
P K	1.09	0.74	P K	0.96	0.65	P K	1.01	0.68	P K	1.11	0.76
S K			S K	0.17	0.11	S K	0.14	0.09	S K		
Cl K	0.26	0.16	Cl K	0.45	0.26	Cl K	0.27	0.16	Cl K	0.24	0.14
K K	1.56	0.84	K K	1.71	0.92	K K	1.61	0.87	K K	1.55	0.84
Ca K	2.28	1.2	Ca K	2.14	1.13	Ca K	2.12	1.11	Ca K	2.54	1.33
Ti K	2.57	1.13	Ti K	1.97	0.87	Ti K	2.12	0.93	Ti K	2.55	1.12
Mn K	0.23	0.09	Mn K	0.35	0.13	Mn K	0.26	0.1	Mn K	0.2	0.08
Fe K	11.8	4.46	Fe K	10.59	4	Fe K	11.67	4.39	Fe K	10.64	4.01
Totals	100		Totals	100		Totals	100		Totals	100	

Table A12: SEM Phosphorus Concentrations

	Average P wt.%	STDEV	%RSD	Pooled STDEV Squared	Pooled STDEV	Calculated T Value	Tabulated T Value
BT1							
Surface	0.78	0.22	28.11	0.03	0.16	4.71	2.1
Interior	1.12	0.05	4.26				
BDTM2							
Surface	1.18	0.10	8.48	0.01	0.09	-12.88	2.1
Interior	0.67	0.08	11.34				
BDHH2							
Surface	1.01	0.38	37.19	0.07	0.27	0.26	2.1
Interior	1.04	0.03	3.22				
GD3							
Surface	1.04	0.34	32.56	0.06	0.24	0.38	2.1
Interior	1.08	0.04	3.89				
NC1							
Surface	0.26	0.02	7.45	0.00	0.03	58.51	2.1
Interior	0.93	0.03	3.27				
NC2							
Surface	1.05	0.05	4.76	0.00	0.04	-6.96	2.1
Interior (NC1)	0.93	0.03	3.27				

Table A13: SEM Manganese Concentrations

	Average Mn wt.%	STDEV	%RSD	Pooled STDEV Squared	Pooled STDEV	Calculated T Value	Tabulated T Value
BT1							
Surface	0.32	0.11	34.94	0.01	0.08	-2.20	2.1
Interior	0.24	0.03	13.80				
BDTM2							
Surface	0.48	0.21	43.12	0.02	0.15	0.67	2.1
Interior	0.53	0.07	12.93				
BDHH2							
Surface	0.56	0.26	47.12	0.04	0.19	-4.15	2.1
Interior	0.21	0.02	8.64				
GD3							
Surface	0.75	0.24	32.26	0.03	0.17	-6.62	2.1
Interior	0.23	0.05	20.55				
NC1							
Surface	0.17	0.05	32.40	0.00	0.04	6.05	2.1
Interior	0.29	0.03	11.85				
NC2							
Surface	0.27	0.05	17.92	0.00	0.04	1.18	2.1
Interior (NC1)	0.29	0.03	3.27				

Table A14: SEM Titanium Concentrations

	Average Ti wt.%	STDEV	%RSD	Pooled STDEV Squared	Pooled STDEV	Calculated T Value	Tabulated T Value
BT1							
Surface	1.86	0.37	19.95	0.07	0.27	-0.17	2.10
Interior	1.84	0.06	3.34				
BDTM2							
Surface	2.17	0.23	10.80	0.04	0.20	-9.01	2.10
Interior	1.38	0.15	10.75				
BDHH2							
Surface	2.02	0.42	20.71	0.09	0.30	-3.30	2.10
Interior	1.58	0.09	5.93				
GD3							
Surface	1.97	0.45	22.97	0.11	0.33	-2.58	2.10
Interior	1.59	0.14	8.54				
NC1							
Surface	0.70	0.07	10.44	0.01	0.08	33.42	2.10
Interior	1.95	0.09	4.80				
NC2							
Surface	2.36	0.23	9.55	0.03	0.17	-5.30	2.10
Interior (NC1)	1.95	0.09	4.80				

Table A15: ImageJ Film Coverage Percentages

Sample	Image	% Coverage of Film	Average % Coverage	STDEV	%RSD
BT1	1	7.6			
	2	18.6			
	3	5.5			
	4	11.6			
	5	10.7	10.8	5.0	46.2
BDTM2	1	10.2			
	2	35.4			
	3	45.0			
	4	25.8			
	5	7.9	24.9	16.0	64.3
GD3	1	7.4			
	2	1.8			
	3	2.5			
	4	20.8			
	5	5.8	7.7	7.7	100.3
NC1	1	4.6			
	2	4.9			
	3	2.0			
	4	1.5			

Table A16: SEM Point Analysis Compositions of Surface Coatings in BT1

Intermediate Coating	Element	Weight%	Atomic%	Compd%	Formula
	Mg K	0.79	0.78	1.31	MgO
	Al K	6.08	5.44	11.48	Al ₂ O ₃
	Si K	19.09	16.43	40.85	SiO ₂
	P K	0.85	0.66	1.95	P ₂ O ₅
	K K	2.76	1.71	3.32	K ₂ O
	Ca K	3.3	1.99	4.61	CaO
	Ti K	5.41	2.73	9.03	TiO ₂
	Fe K	21.34	9.24	27.45	FeO
	O	40.38	61.01		
	Totals	100			
Fe-Ti Coating	Element	Weight%	Atomic%	Compd%	Formula
	Na K	2.31	2.52	3.11	Na ₂ O
	Mg K	0.99	1.03	1.65	MgO
	Al K	7.72	7.18	14.58	Al ₂ O ₃
	Si K	12.77	11.42	27.32	SiO ₂
	Ca K	4.71	2.95	6.59	CaO
	Ti K	8.32	4.36	13.87	TiO ₂
	Fe K	25.56	11.49	32.88	FeO
	O	37.63	59.05		
	Totals	100			

Table A17: SEM Point Analysis Compositions of Surface Coatings in BDHH2

Fe-Ti Coating						Intermediate Coating					
	Element	Weight%	Atomic%	Compd%	Formula		Element	Weight%	Atomic%	Compd%	Formula
	Al K	0.94	1.12	1.77	Al ₂ O ₃		Na K	0.35	0.35	0.47	Na ₂ O
	Si K	1.25	1.43	2.68	SiO ₂		Mg K	1.28	1.22	2.12	MgO
	K K	5.55	4.56	6.69	K ₂ O		Al K	7.69	6.63	14.53	Al ₂ O ₃
	Ca K	7.43	5.96	10.4	CaO		Si K	21.65	17.94	46.31	SiO ₂
	Ti K	7.62	5.11	12.7	TiO ₂		P K	0.65	0.49	1.48	P ₂ O ₅
	Fe K	51.12	29.41	65.76	FeO		K K	2.63	1.57	3.17	K ₂ O
	O	26.09	52.41				Ca K	3.84	2.23	5.38	CaO
	Totals	100					Ti K	2.43	1.18	4.06	TiO ₂
							Fe K	17.47	7.28	22.48	FeO
							O	42.01	61.1		
							Totals	100			

Fe-Ti Poor Coating					
	Element	Weight%	Atomic%	Compd%	Formula
	Na K	3.28	3.02	4.42	Na ₂ O
	Al K	13.07	10.28	24.69	Al ₂ O ₃
	Si K	25.51	19.27	54.56	SiO ₂
	K K	0.69	0.38	0.84	K ₂ O
	Ca K	9.2	4.87	12.87	CaO
	Ti K	0.3	0.13	0.5	TiO ₂
	Fe K	1.65	0.63	2.12	FeO
	O	46.31	61.42		
	Totals	100			

Figure A1: XRD Spectra of Surface and Interior of Broken Top Flow

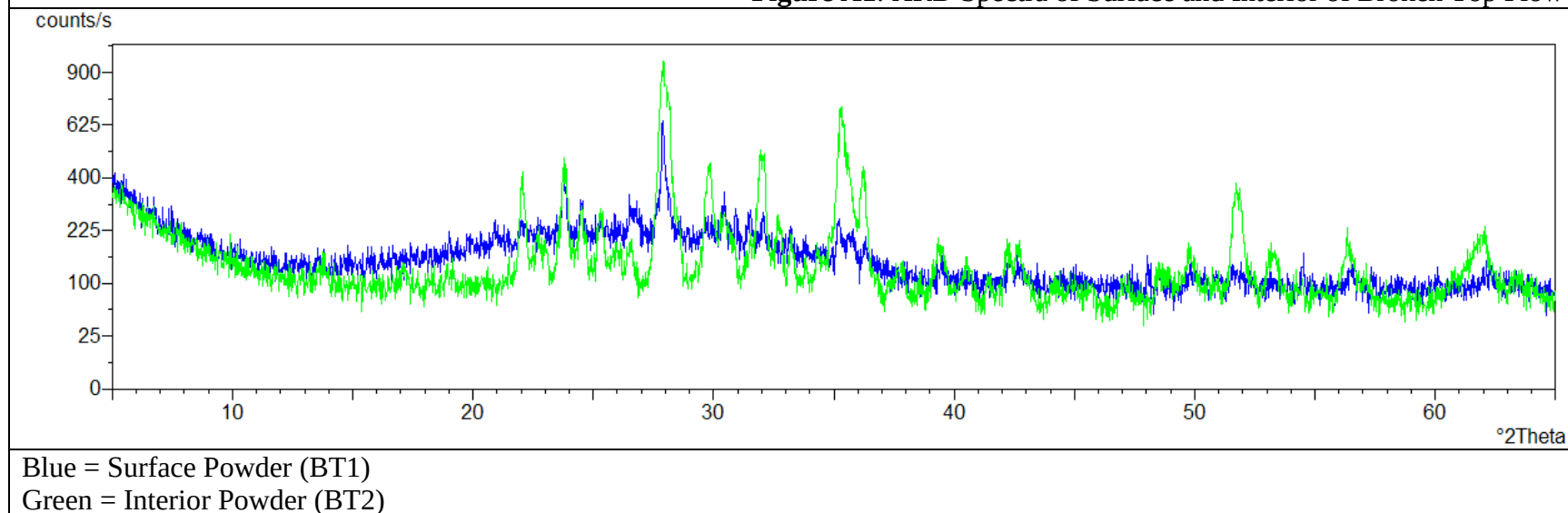
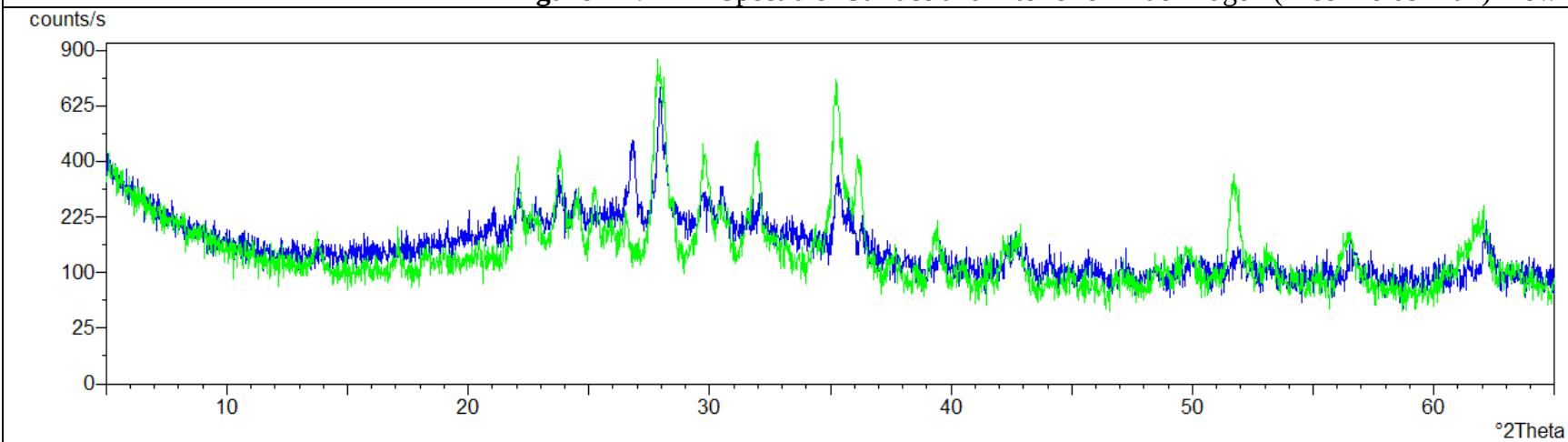
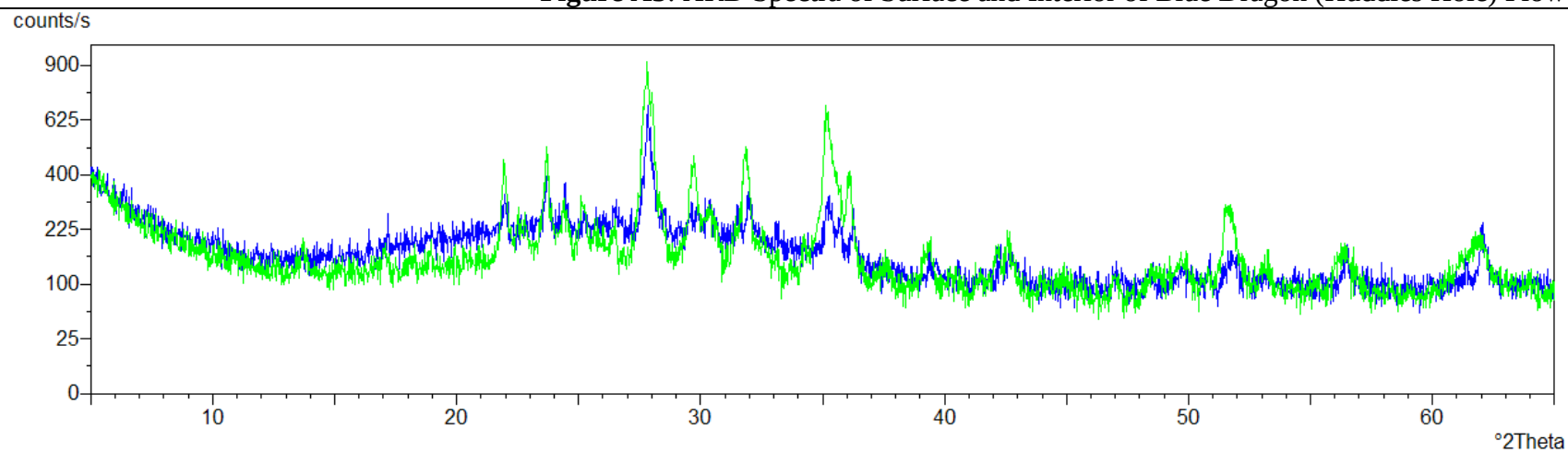


Figure A2: XRD Spectra of Surface and Interior of Blue Dragon (Tree Molds Trail) Flow



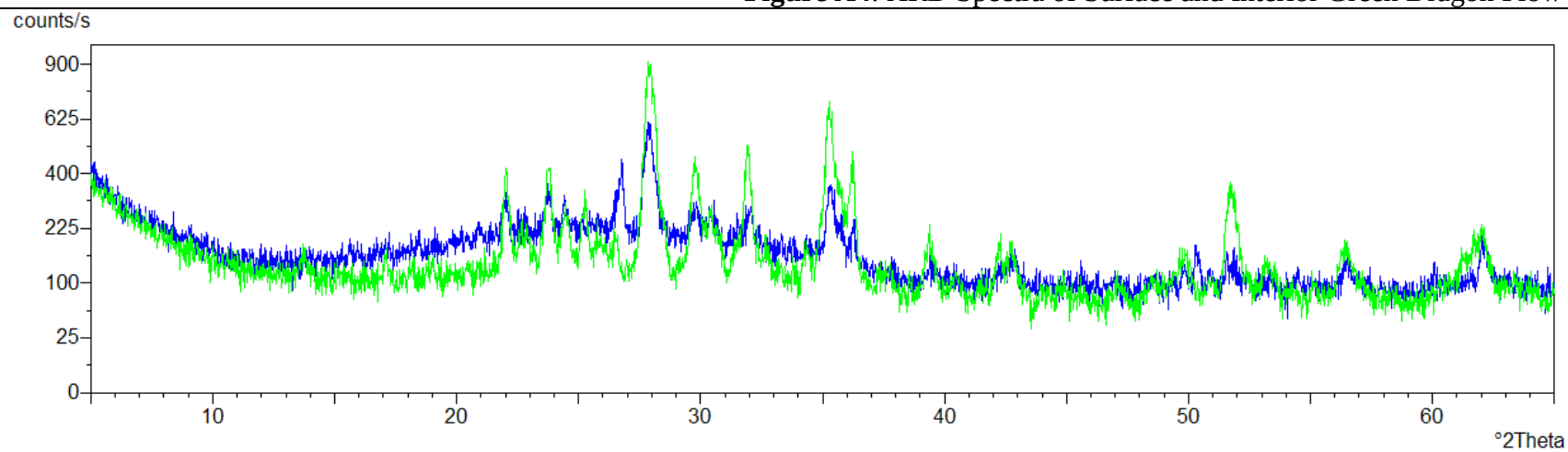
Blue = Surface Powder (BDTM1)
Green = Interior Powder (BDTM2)

Figure A3: XRD Spectra of Surface and Interior of Blue Dragon (Huddles Hole) Flow



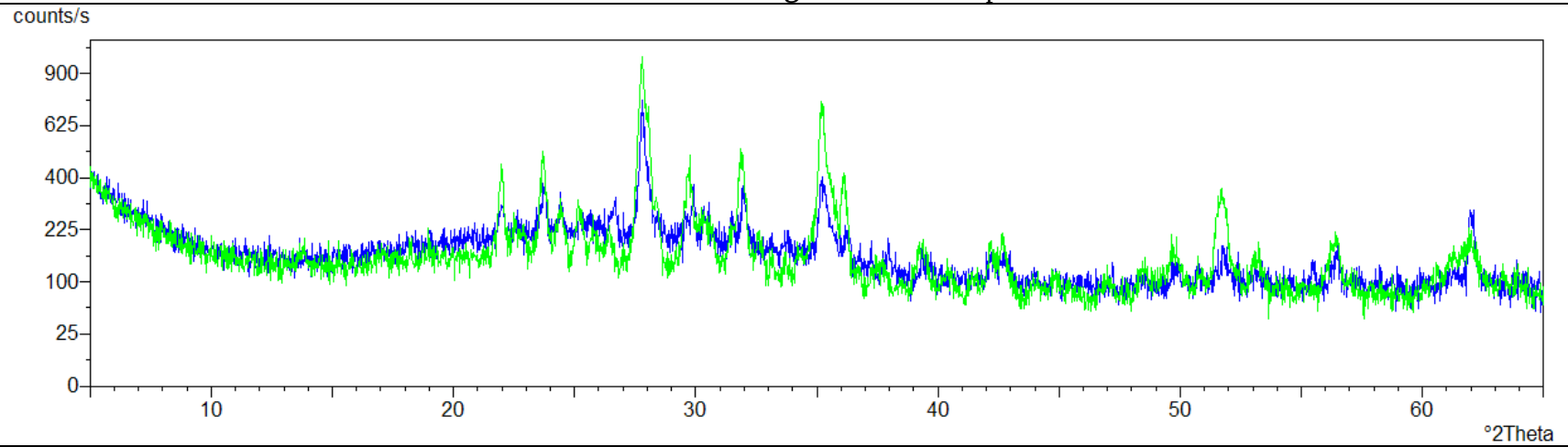
Blue = Surface Powder (BDHH2)
Green = Interior Powder (BDHH2)

Figure A4: XRD Spectra of Surface and Interior Green Dragon Flow



Blue = Surface Powder (GD2)
Green = Interior Powder (GD3)

Figure A5: XRD Spectra of Surface and Interior North Crater Flow



Blue = Surface Powder (NC1)
Green = Interior Powder (NC1)

Figure A6: SEM BSE Image of Surface of Sample BT1



2mm

Figure A7: SEM BSE Image of Surface of Sample BDTM2

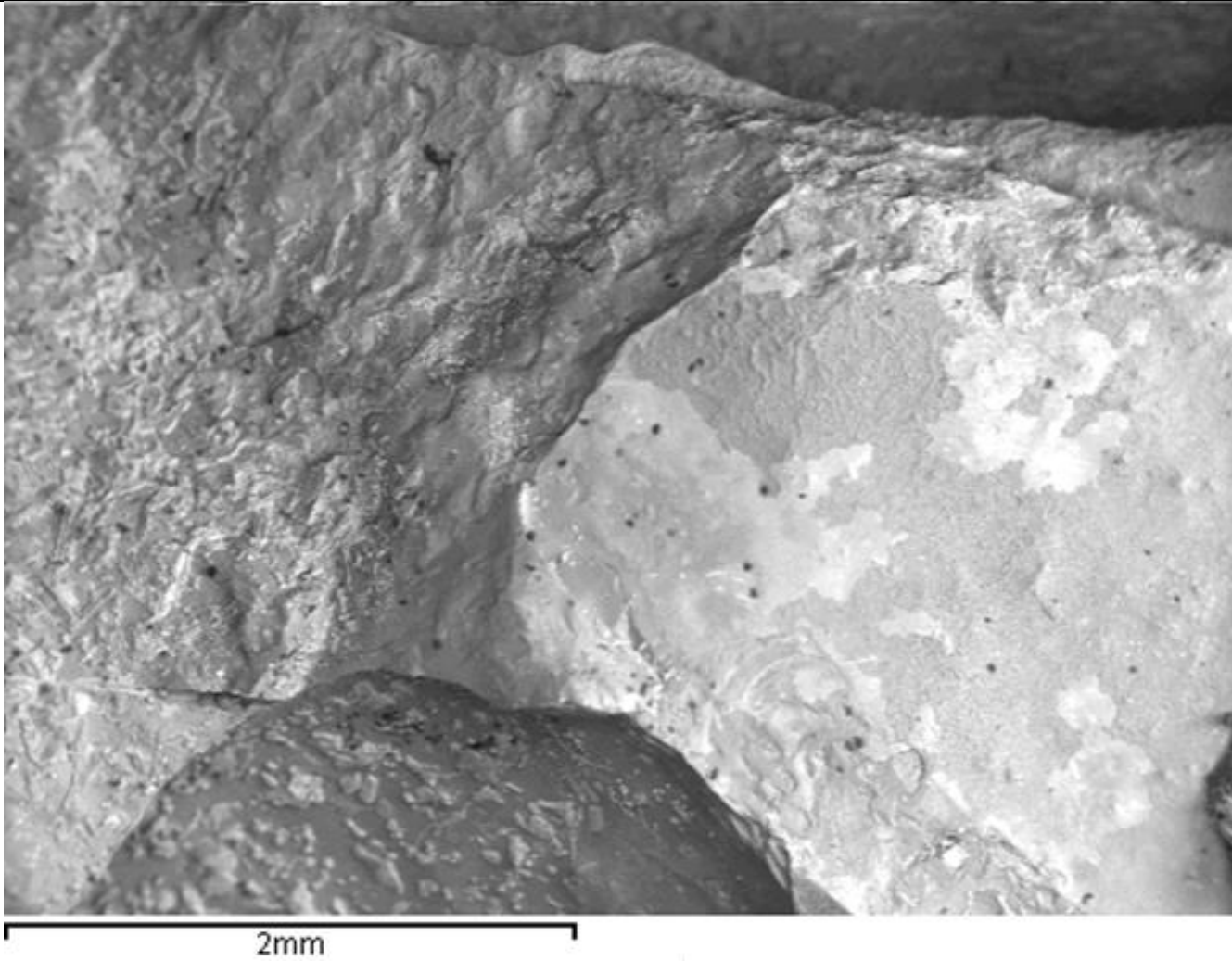


Figure A8: SEM BSE Image of Surface of Sample BDHH2

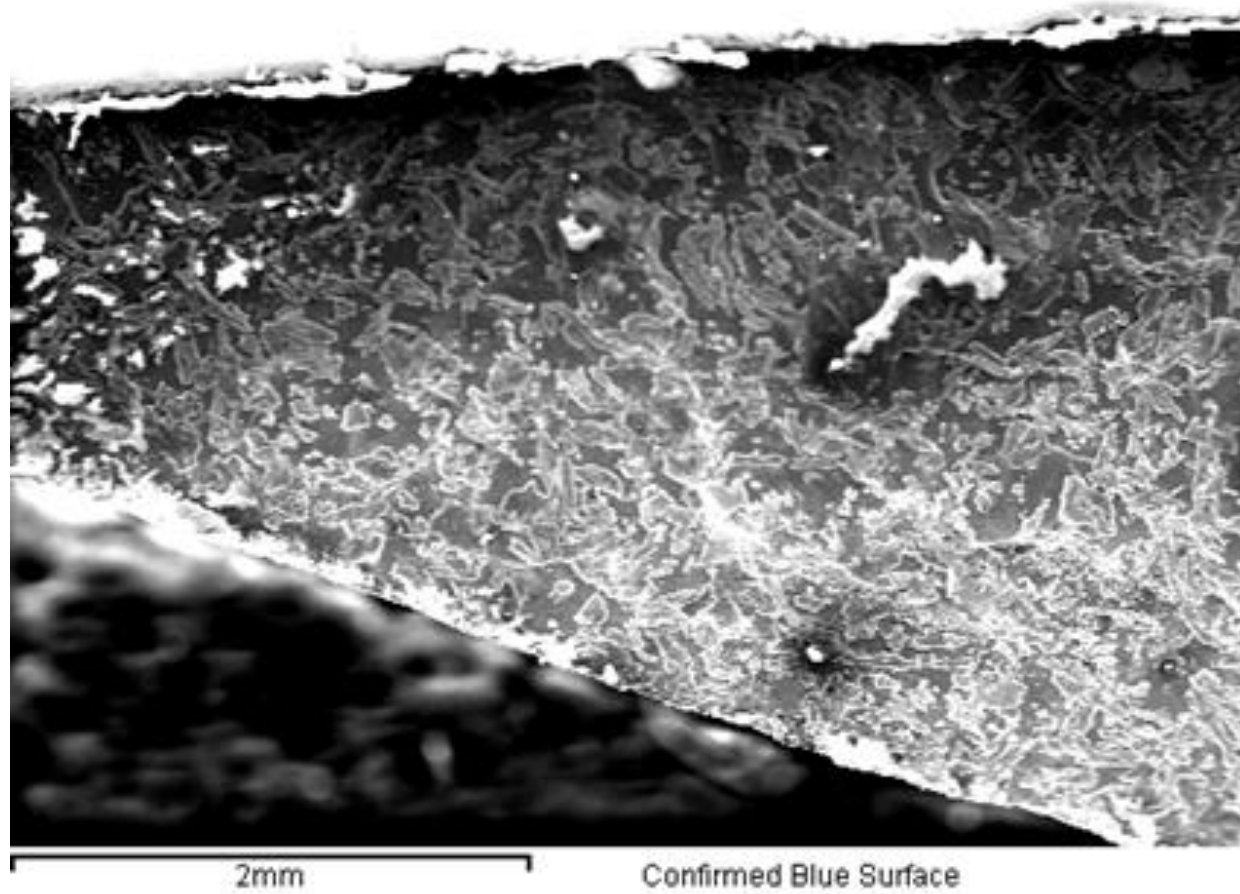


Figure A9: SEM BSE Image of Surface of Sample GD3

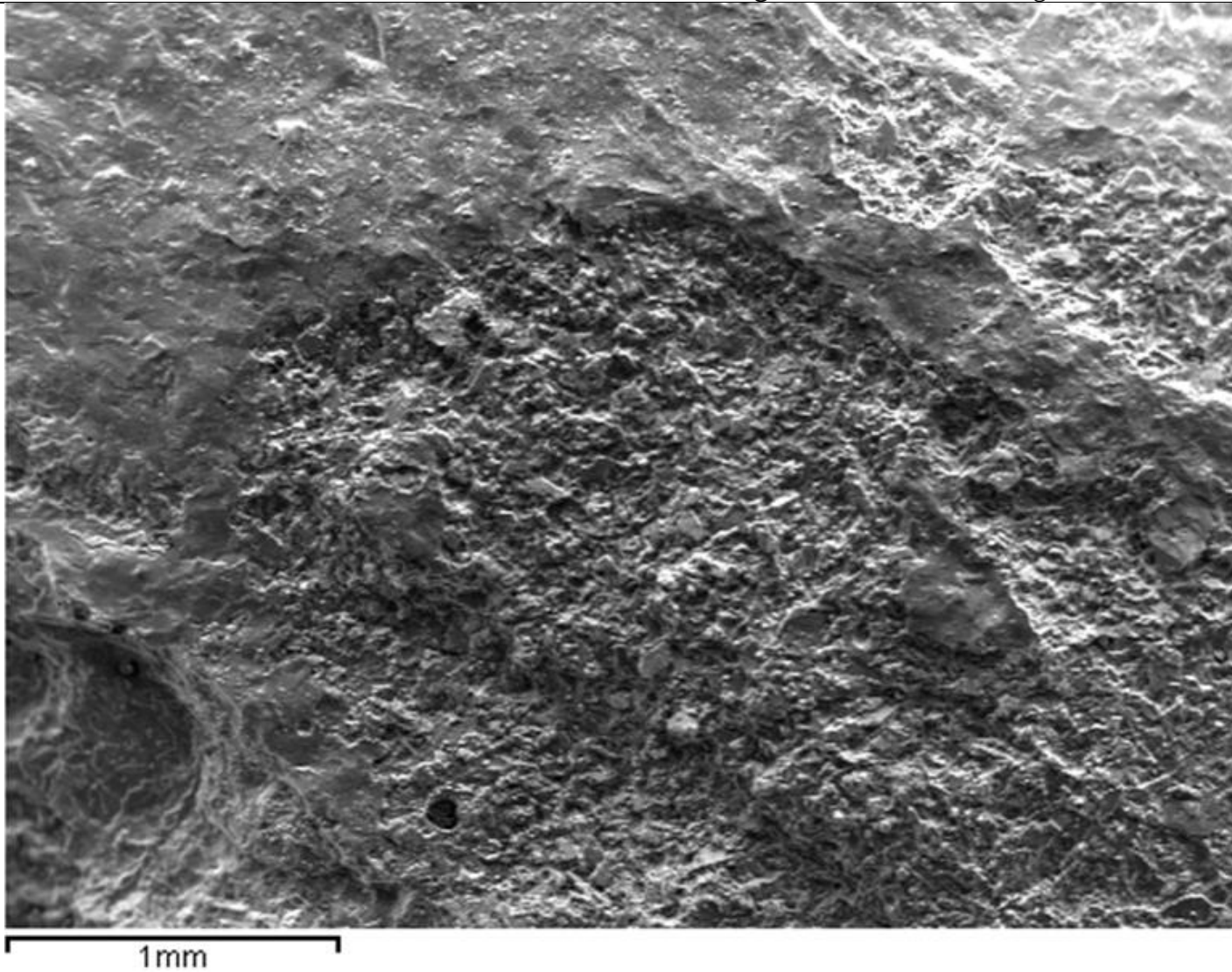


Figure A10: SEM BSE Image of Surface of Sample NC1

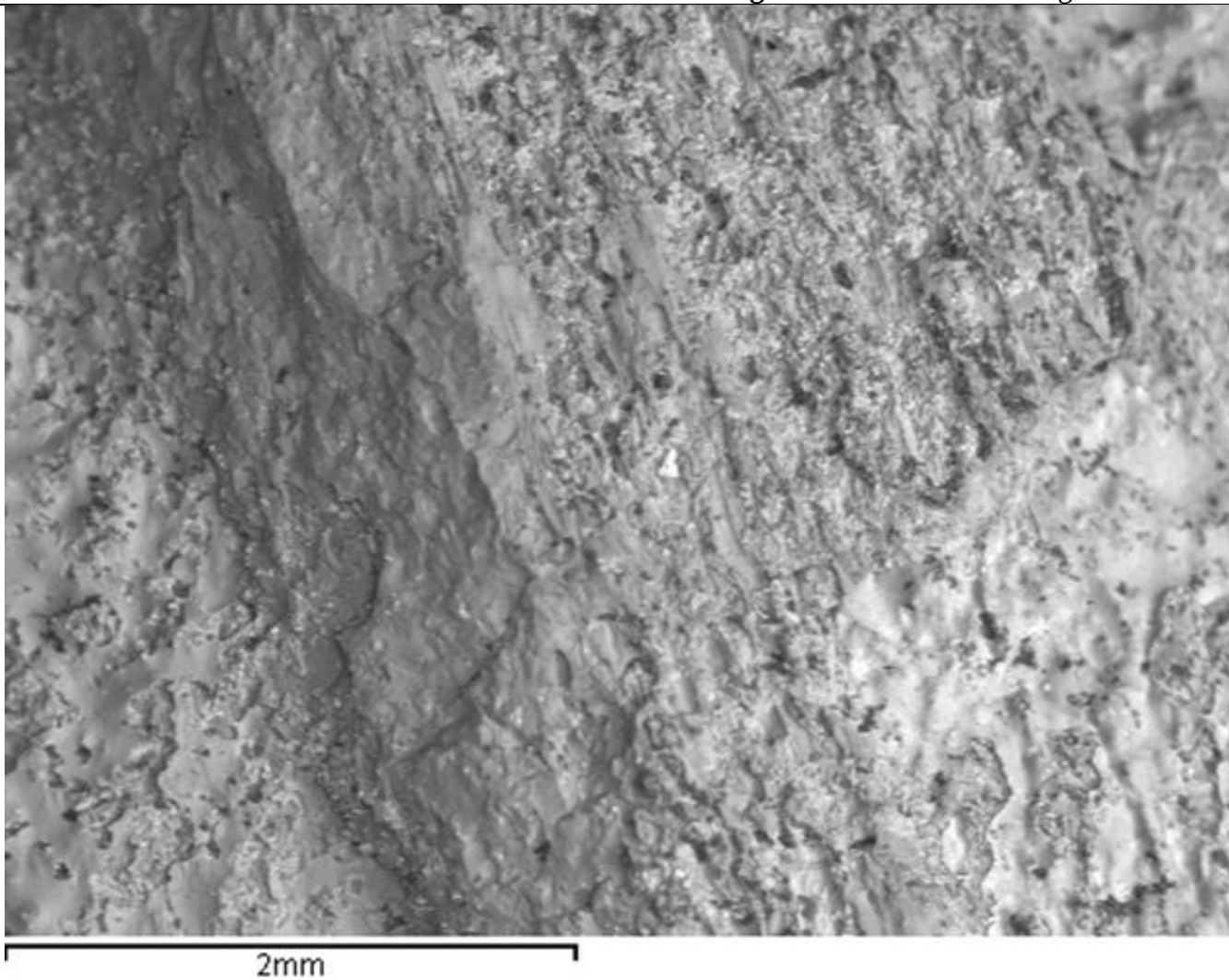


Figure A11: SEM Image of Surface of Sample NC2

