Searching for Terrestrial Analogues for Mars; Applications for Scanning Electron Microscopy

F. M. Willcocks, N. R. Stephen & S. T. Grimes – University of Plymouth

Earth has seen abundant large-scale basaltic volcanism throughout its geological history, and through orbital and lander space missions this type of volcanism has been identified on Mars. Comparisons between this volcanism on Earth and Mars have been limited because we have a lack of direct samples from the Martian surface, unlike Apollo samples retrieved from our Moon. Martian meteorites are the best samples from the Martian surface that we have available to us on Earth, and they are volcanic in origin – similar to those we find on Earth! Comparing these meteorites to terrestrial volcanic rocks can help us find terrestrial analogues for Martian volcanism, and allows testing of future spacecraft design & function without going off world. Scanning electron microscopy is a powerful tool for this purpose as it is non-destructive and can allow for these comparisons down to microscopic resolution unlike the metre-scale observations made using satellite imagery.



Image courtesy of NASA image library

Terrestrial analogues can be either physical samples or geographical locations, and aim to be chemically and/or physically similar to another planetary body. In this study, the search for analogues continued through petrological and geochemical analyses using non-destructive Scanning Electron Microscopy; basalts from Earth (including a basalt already commercially used by the European Space Agency) and meteorites from Mars were directly compared, to find more accurate terrestrial analogue samples for Martian volcanism. We found that whilst the basalt from the European Space Agency was similar in bulk geochemistry to the Martian meteorites, another sample was much more similar to individual mineral chemistry and petrological observations across these meteorites, and is therefore more analogous to Martian volcanism.

Basaltic Volcanism in our Solar System

Basaltic volcanism has been abundant across Earth's geological history, with intraplate basaltic volcanism producing island arc volcanoes like Hawaii and larger-scale provinces known as flood lavas. Flood lavas can cover millions of cubic kilometres and are generally erupted in less than three million years (Carlson, 1991), forming provinces that can be associated with mass extinction events. These lavas are the product of mantle plumes composed of hot, less dense magma resulting from instability at the base of the mantle and rising, partially melting the shallow lithosphere and causing volcanism. Not only have flood lava eruptions occurred on Earth, evidence of these lavas has also been observed on Mars.

Since the 1960s, when NASA's Mariner 4 mission sent the first close-up images of Mars to us on Earth (Howell, 2012), Martian space exploration has been ever growing, with six space agencies to date successfully sending orbiter and lander spacecraft to Mars (Howell, 2021). The increased accessibility to imagery from the Martian surface allowed for the identification of basaltic volcanism on Mars, occurring at much larger scales to that on Earth (Figure 1). In fact, through satellite imagery from NASA's Thermal Emission Spectrometry (TES) camera aboard the Mars Global Surveyor, scientists have been able to separate the surface of Mars into two lithological groups: Group 1 (basalt) and group 2 (andesite) - both volcanic in nature (Bandfield et al. 2000). More recently however, group 2 has been found to instead comprise of weathered basalt (Wyatt & McSween, 2002). The large shield volcano Olympus Mons is just one example of Martian volcanism and is not only the largest volcano on Mars, but also that we know of in our Solar System! Satellite imagery has allowed for metre-scale observations of Martian flood lavas, comparing stepped features on these lava plains to those of terrestrial flood lavas (Keszthelyi & McEwen, 2007). Mars doesn't have plate tectonics (Carr, 2006) and this - alongside morphological similarities between terrestrial and Martian flood lavas - suggests areas of intraplate volcanism on Earth could host accurate terrestrial analogue samples for Martian volcanism (Hughes et al. 2019).

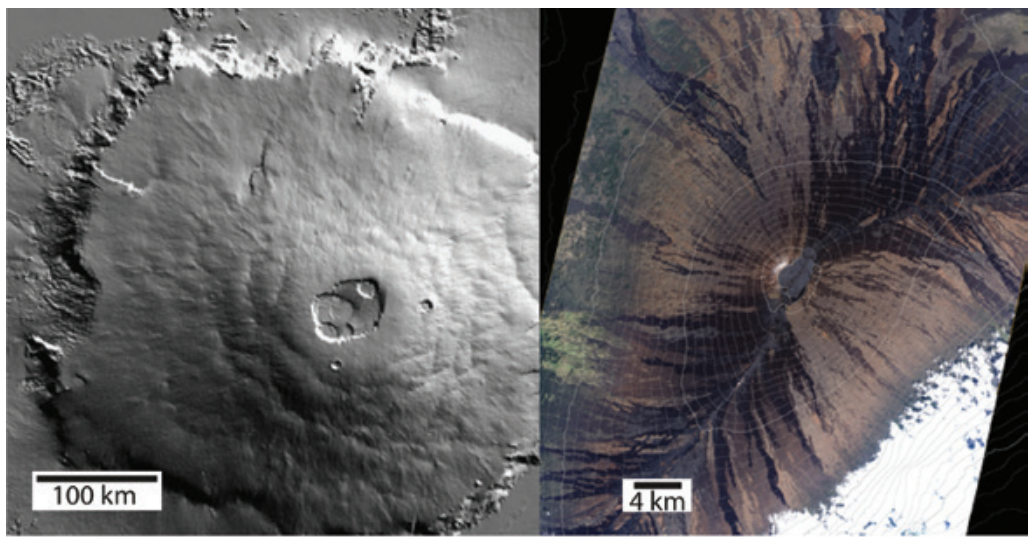


Figure 1. Aerial images displaying the larger scale of (a) Mars' Olympus Mons, Tharsis compared to (b) Earth's Kilauea, Hawaii, (Source: Zimbelman et al., 2015 and NASA Earth Observatory, 2006)

Terrestrial Analogues in Space Exploration

Terrestrial analogues can be samples or geographical locations and aim to be chemically and/or physically similar to another planetary body such as the Moon and Mars. These samples can be widely grouped into four different categories: Chemical, biological, geological and mechanical (Foucher et al. 2021). Geological analogues in particular are most widely used across space exploration (Foucher et al. 2021), and aim to be petrologically (similar mineralogy and textures), chemically (similar bulk and individual mineral chemistry) or physically (similar grain size and density) similar to another planetary body (Foucher et al. 2021; ESA, 2021). Having accurate analogue samples means we can test components for future spacecraft that are aiming to interact with another planetary surface, to ensure their functionality can meet mission objectives and sustain future, longer term space missions. An example of how space agencies are doing this is in NASA's Mars Yard designed by NASA's Mars Technology Programme (Karl et al. 2021) where robotic prototypes that will be used in research and flight projects for future Mars missions (such as the Perseverance rover) are tested in terrain that model the Martian surface (NASA Science, 2020). Geological analogue samples can also aid in the understanding of another planetary body's formation through comparisons of known features from terrestrial samples to observations of satellite and meteorite data. In this study, we looked for geological terrestrial analogue samples for the Martian surface. This was carried out by comparing terrestrial samples to Martian meteorites.

Martian Meteorites

A meteorite is a solid, natural object that has landed on Earth's surface after travelling through space and surviving atmospheric entry (Alexander, 2021). Meteorites are broadly grouped into two categories: Chondrites (non-differentiated) and Achondrites (differentiated), with primitive achondrites falling between these two groups (Hibiya et al. 2018). Martian meteorites are achondrites as Mars is differentiated into a core, mantle and crust (Witze, 2021). We can tell a meteorite is from Mars because trapped glasses within these meteorites contain the same concentrations of noble gas isotopes that have been recorded in Mars' atmosphere by NASA's Viking 1 and 2 missions (McSween Jr, 2015).

Martian meteorites are more representative of the geology future spacecraft might face on the Martian surface compared to surface data. This is because of the lack of andesite compositions within the Martian meteorite collection unlike what has previously been observed by surface observations (Bandfield et al. 2000) and the direct origin of these samples. The lack of directly returned samples from Mars means these meteorites are the only direct samples that we have available to us on Earth, therefore, are incredibly useful when looking for terrestrial analogue samples.

There are five groups of Martian meteorites separated by their mineralogy and textures: Shergottites, nakhlites, chassignites, orthopyroxenites (ALH 84001), and polymict breccias. Shergottites can generally be subdivided into three subgroups: Olivine-phyric, basaltic and poikilitic. Olivine-phyric and basaltic shergottites are volcanic in origin and are most similar to basalt lavas on Earth (Filiberto et al. 2014); these differ to poikilitic shergottites that are intrusive (i.e. not erupted at the surface) in origin. The similarity of olivine-phyric and basaltic shergottites to basalts on Earth meant these meteorites were the main focus of this study. Shergottites are the most abundant Martian meteorite on Earth to date, and so are most representative of Martian volcanism.

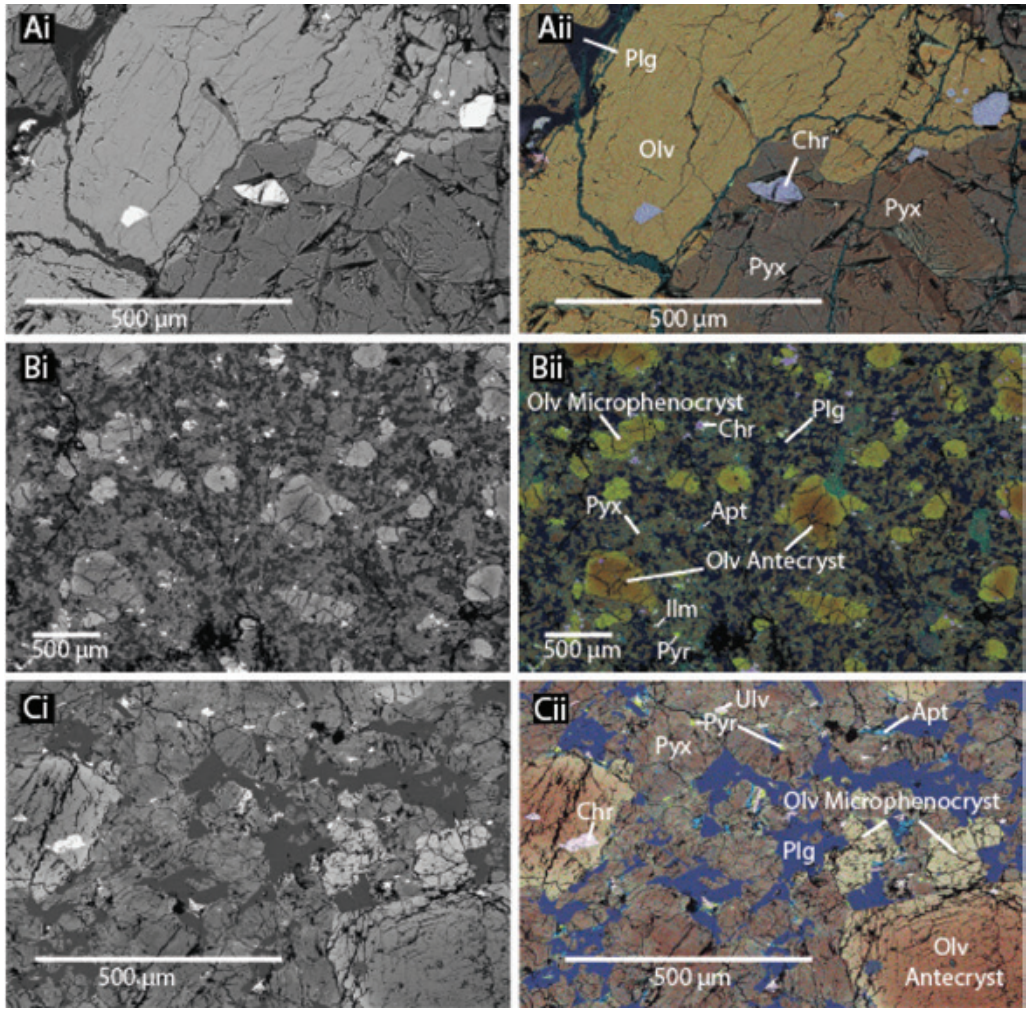


Figure 2 - Ai) BSE image of NWA 7397, Aii) EDS image of NWA 7397 displaying olivine (olv), pyroxene (pyx), plagioclase (plg) and chromite (chr) in a non-poikilitic texture. Bi) BSE image of NWA 1110, Bii) EDS image of NWA 1110 displaying zoned olivine antecrysts and unzoned olivine micro-phenocrysts surrounded by pyroxene and plagioclase. Chromite, apatite (apt), ilmenite (ilm) and pyrrhotite (pyr) are present in the groundmass, Ci) BSE image of Tissint, Cii) EDS image of Tissint displaying zoned olivine antecrysts and unzoned olivine micro-phenocrysts, surrounded by pyroxene and plagioclase. Chromite is present as inclusions in olivine antecrysts, and in the groundmass alongside ulvöspinel (ulv), pyrrhotite and apatite. All EDS images follow the same key: red = Mg, green = Fe, teal = Ca, dark blue = Al, purple = Cr, blue = P, yellow = S, pink = Ti

Methodology

When picking which terrestrial lavas to use it was important to find samples that formed in a similar geological setting to the volcanism on Mars. The lack of plate tectonics on Mars meant samples of intraplate volcanic origin were chosen. Two samples from Hawaii (H-001 and H-002) and an analogue sample already commercially used by ESA (ESA01-A) were chosen. One sample from New Mexico (NM-001) that formed in an intra-rift setting was also selected for a broader comparison. When choosing Martian meteorites, two olivine-phyric Shergottites (NWA 1110 and Tissint) were selected and one poikilitic Shergottite (NWA 7397) for wider comparison.

Scanning Electron Microscopy-Energy Dispersive Spectroscopy (SEM-EDS) was the chosen analytical technique for this study as it is non-destructive and allows for the same, high-resolution observations of petrology and major element geochemistry across terrestrial and extra-terrestrial samples. Data was collected using the JEOL-7001F field emission SEM equipped with an Oxford Instruments 50 mm^2 X-Max EDS detector and Oxford Instrument's AZtec software. Greyscale Backscatter Electron (BSE) images and EDS X-ray element maps were collected using 9 nA probe current, 20 KeV acceleration voltage at 10 mm working distance.

Results & Discussion

The Martian Meteorites

NWA 7397 consisted of olivine, distinct grains of unzoned pyroxene and unzoned plagioclase within a non-poikilitic texture (Figure 2Ai & 2Aii). Pyroxene and plagioclase were intergrown which suggests they crystallised together. NWA 1110 (Figure 2Bi & 2Bii) and Tissint (Figure 2Ci & 2Cii), however, displayed olivine antecrysts and olivine micro-phenocrysts. Antecrysts are crystals that crystallised earlier in the magma chamber before remaining there until they are re-introduced into the melt (Balta et al. 2015). These often have an irregular, corroded shape (Shearer et al. 2008) which is different to the regular shape often displayed by phenocrysts. Both NWA 1110 and Tissint displayed inclusions of chromite in their antecrysts, as well as ulvöspinel around antecrysts and in the groundmass. Tissint also had ilmenite and apatite present in the groundmass. Both NWA 1110 and Tissint had a groundmass composed of unzoned plagioclase and zoned pyroxene that was finer in than the olivine micro-phenocrysts, suggesting it cooled faster (Papike et al. 2009). NWA 1110 and Tissint displayed finer grain sizes compared to NWA 7397, likely due to their extrusive origin.

NWA 7397, NWA 1110 and Tissint are all tholeiitic in composition plotting in the basalt/trachy-basalt regions on a TAS diagram. This suggests that for a terrestrial sample to make an accurate analogue they should also be tholeiitic in composition, plotting within these regions. Olivine antecrysts in NWA 1110 and Tissint displayed Mg-rich centres that become Fe-rich towards the rims. In both samples, the olivine micro-phenocrysts surrounding these antecrysts were Fe-rich and similar in composition to the antecryst rims. Olivine in NWA 7397 was un-zoned and Fe-rich similar to olivine micro-phenocrysts in NWA 1110 and Tissint. Pyroxene in NWA 1110 and Tissint displayed zoning of two different compositions; pigeonite and augite. In NWA 7397 however, pyroxene didn't show zoning and instead displayed distinct grains of pigeonite and augite. On average plagioclase across NWA 7397 is composed of An_{52}. Plagioclase compositions within NWA 1110 are similar to those of NWA 7397, averaging at $An_{53.}$ Compositions in Tissint display anorthite compositions at a much higher average of $An_{64.}$

H-001

H-001 was collected on the flanks of Kilauea in 2017 and is associated with the Eastern Rift Zone (ERZ), forming in an intraplate environment. H-001 had abundant gas bubbles (vesicles) and displayed a porphyritic texture of rare plagioclase, pyroxene and olivine micro-phenocrysts in a glassy groundmass (Figure 3Ai & Aii). There was an absence of accessory minerals across the sample. H-001 had a finer grain size than H-002 suggesting it crystallised quicker (Haldar & Tišljar, 2014). The glassy groundmass, absence of accessory phases and scarcity of olivine and plagioclase across H-001 is very different to NWA 1110, NWA 7397 and Tissint. This indicates H-001 would not make a good petrological analogue for Martian volcanism.

H-001 is a tholeiitic basalt and was analogous to the bulk geochemistry of the Martian shergottites in this study. Olivine in H-001 was unzoned and displayed Mg-rich compositions. When compared to the Martian meteorites, olivine in H-001 was most similar to the Mg-rich cores of antecrysts in NWA 1110 and Tissint. This indicates that H-001 could make an accurate geological analogue for individual olivine compositions in olivine-phyric shergottites, however it is not analogous to poikilitic shergottite NWA 7397. Pyroxene in H-001 was augite in composition, similar to NWA 7397, NWA 1110 and Tissint. Despite this, pyroxene compositions in H-001 were limited with no pigeonite present across the sample. Overall, pyroxene in H-001 was analogous to Martian shergottites in this study but was not a perfect match. Plagioclase in H-001

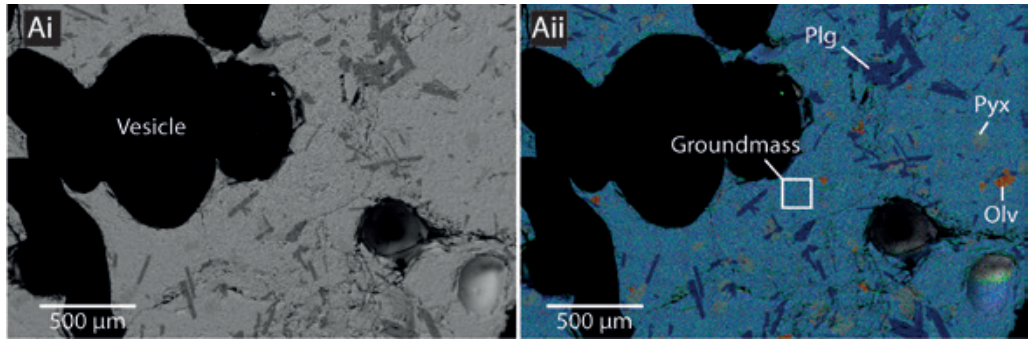


Figure 3 - Ai) BSE image of H-001 displaying the presence of vesicles, Aii) EDS image of H-001 displaying olivine, pyroxene and plagioclase micro-phenocrysts surrounded by a glassy groundmass. Key: red = Mg, green = Fe, teal = Ca, dark blue = Al.

displays compositions reaching an average of An_{69}. Whilst the average composition is similar to plagioclase in Tissint, the range of anorthite content in H-001 reaches much higher concentrations than NWA 7397, NWA 1110 and Tissint. This indicates it is not the most analogous sample to the Martian shergottites compared to other terrestrial samples analysed.

H-002

H-002 was sampled from the flanks of Kilauea in 2013 and is associated with the ERZ, forming in an intraplate environment. The sample has abundant vesicles and is a porphyritic basalt with olivine and plagioclase macro- and micro-phenocrysts (Figure 4Ai & Aii). The sample has a fine-grained plagioclase and high-Ca pyroxene groundmass indicative of fast cooling (Haldar & Tišljar, 2014). Olivine macro-phenocrysts contain inclusions of chromite. When compared to the Martian shergottites in this study, the presence of olivine macro-phenocrysts and their inclusion of chromite was similar to NWA 1110 and Tissint. Despite this, the abundance of vesicles and size of plagioclase relative to olivine differed greatly. This suggests that whilst there are some similarities between H-002 NWA 1110 and Tissint, H-002 is not the best analogue for these shergottites. Textures shown by H-002 were also very different to NWA 7397.

H-002 displays a calc-alkaline composition different to the tholeiitic compositions displayed by the Martian shergottites in this study, and so isn't the best analogue for their bulk geochemistry. Olivine macro-phenocrysts in H-002 were weakly zoned, displaying Mg-rich centres that become Fe-rich towards the rims. Olivine micro-phenocrysts are most similar in composition to the Fe-rich rims of the olivine macro-phenocrysts. Both olivine macro- and micro-phenocrysts in H-002 are most similar to core compositions of olivine antecrysts in NWA 1110 and Tissint, but are not similar to those in NWA 7397, suggesting it is an accurate analogue for olivine-phyric shergottites in this study. Plagioclase across

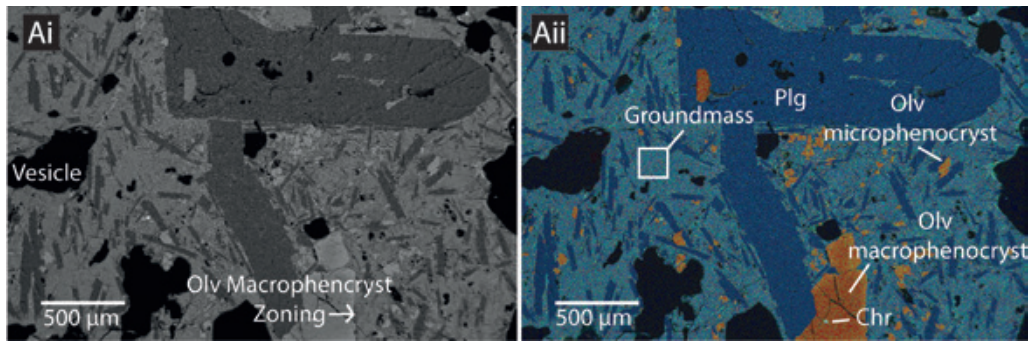


Figure 4 - Ai) BSE image of H-002 displaying the presence of vesicles, Aii) EDS image of H-002 displaying a porphyritic texture of plagioclase and zoned olivine macro-phenocrysts, unzoned olivine and plagioclase micro-phenocrysts surrounded by a very fine groundmass of pyroxene and plagioclase. Chromite was present in some olivine macro-phenocrysts. Key: red = Mg, green = Fe, teal = Ca, dark blue = Al, purple = Cr.

Hawaii 2 had an average composition of An_{61}. These compositions are more similar to Tissint than those in H-001 and overlap with plagioclase compositions in NWA 7397 and NWA 1110. This indicates that H-002 is a more accurate analogue for plagioclase in the Martian shergottites than H-001.

ESA01-A

ESA01-A is the product of the intraplate volcanism that produced the North Atlantic Igneous Province. ESA01-A is aphyric in texture and displayed no vesicles unlike H-001 and H-002. The sample contains olivine and a groundmass of intergrown ilmenite, ulvöspinel, zoned plagioclase and pyroxene (Figure 5Ai & Aii). ESA01-A was coarser in grain size compared to H-001 and H-002 suggesting it crystallised relatively slower than these samples. The coarser groundmass of ESA01-A was more representative of the Martian shergottites in this study than H-001 and H-002, however, the intergrown ilmenite and ulvöspinel, and lack of olivine macro-phenocrysts across ESA01-A differs greatly to NWA 1110 and Tissint. Plagioclase zoning that is abundant in ESA01-A is also absent across all Martian shergottites in this study. Overall, ESA01-A is not petrologically the most representative sample for NWA 7397, NWA 1110 or Tissint.

ESA01-A is a tholeiitic basalt and was analogous to the bulk geochemistry of the Martian shergottites. Olivine compositions of ESA01-A are Fe-rich and are most analogous to olivine micro-phenocrysts in NWA 1110 and Tissint. Additionally, ESA01-A is the only terrestrial sample that is analogous to olivine in NWA 7397. This indicates that ESA01-A is an accurate analogue for olivine compositions in the olivine-phyric and poikilitic shergottites in this study. Pyroxene in ESA01-A is diopside in composition, differing greatly to NWA 7397, NWA 1110 and Tissint. This indicates that ESA01-A is not an accurate analogue for individual pyroxene compositions across the Martian shergottites in this study. Additionally, the zoning of plagioclase across ESA01-A is extensive, resulting in plagioclase compositions ranging from Na-rich to Ca-rich plagioclase (An_{16-100}), averaging at An_{55}. This is very different to the Martian shergottites in this study and suggests that ESA01-A is the least accurate analogue for plagioclase compositions within NWA 7397, NWA 1110 and Tissint in this study.

NM-001

NM-001 was analysed for a wider comparison as it formed in an environment differing from H-001, H-002 and ESA01-A. NM-001 is a product of intraplate volcanism associated with the Rio Grande Rift in New Mexico; the formation of this rift zone has been associated with the subduction of the Farallon plate (Ricketts et al. 2016), producing an intra-rift tectonic setting. This setting is not analogous to what is expected on Mars. NM-001 contained vesicles and displayed a distinct texture of olivine macro-phenocrysts and olivine micro-phenocrysts. Olivine macro-phenocrysts also contained small inclusions of chromite. These were surrounded by plagioclase laths and a microcrystalline and glassy groundmass of olivine, plagioclase and pyroxene (Figure 6Ai & Aii). NM-001 displayed evidence of magma mixing with zoning present in olivine macro-phenocrysts, and olivine reaction rims around plagioclase laths. The fine, glassy nature of the groundmass indicates crystallisation was relatively quick, similar to H-001 and H-002. When compared to Martian shergottites in this study, the texture of zoned olivine macro-phenocrysts and unzoned olivine micro-phenocrysts across NM-001 was strikingly similar to the texture of zoned olivine antecrysts and un-zoned olivine micro-phenocrysts in NWA 1110 and Tissint. The inclusion of spinel in olivine macro-phenocrysts and abundance of plagioclase in NM-001 is also similar to NWA 110 and Tissint. Whilst the Martian shergottites didn't display evidence for magma mixing like NM-001, NM-001 is most petrologically similar to olivine-phyric shergottites in this study.

NM-001 displays a calc-alkaline composition different to the tholeiitic compositions displayed by the Martian shergottites in this study, and is not analogous to their bulk geochemistry. Olivine macro-

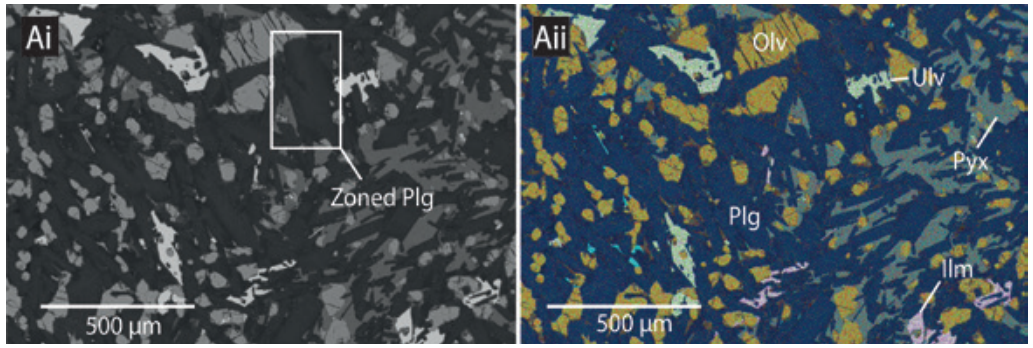


Figure 5 - Ai) BSE image of ESA01-A displaying strongly zoned plagioclase, Aii) EDS image of ESA01-A displaying an aphyric texture of olivine, and intergrown plagioclase, pyroxene, ulvöspinel and ilmenite. Key: red = Mg, green = Fe, teal = Ca, dark blue = Al, purple = Cr, pink = Ti.

phenocrysts in NM-001 displayed a similar trend in zoning of Mg-rich centres and Fe-rich rims also seen in NWA 1110 and Tissint. The macro-phenocryst rims in NM-001 were also similar to the surrounding Fe-rich olivine micro-phenocrysts. Whilst the zoning patterns are similar, all olivine compositions in NM-001 are most analogous to olivine antecrysts in NWA 1110 and Tissint. This suggests NM-001 is an accurate analogue for olivine-phyric shergottites in this study. Across the terrestrial samples, NM-001 displays the largest range of pyroxene compositions with an abundance of hedenbergite and presence of augite and pigeonite. Hedenbergite is not present in the Martian shergottites, however, the inclusion of augite and pigeonite in NM-001 is similar to NWA 7397, NWA 1110 and Tissint. Overall, NM-001 is analogous to individual pyroxene compositions across Martian meteorites in this study, but is not a perfect match. Plagioclase compositions in NM-001 have an average of An_{56}. This average is very similar to those observed in NWA 7397 and NWA 1110, indicating NM-001 is an accurate analogue for plagioclase compositions in Martian shergottites in this study.

Conclusion

Large scale basaltic volcanism has been abundant in the geological history of Earth and Mars, and on Mars is often observed at metre scales through satellite imagery. Martian meteorites are the closest samples we have from the Martian surface available to us on Earth, and can provide an insight into the volcanic processes Mars has experienced at much higher resolution. With the preparations for future Martian space travel underway, the importance of testing spacecraft designs is ever growing and accurate geological terrestrial analogue samples are useful for this. The comparison of petrology (mineralogy and textures) and geochemistry (bulk and individual mineral compositions) in terrestrial intraplate basalts to Martian meteorites allows us to search for more of these analogues, and aid the technological developments of spacecraft ready for these missions. SEM-EDS is a useful tool to search for these analogues as it allows for the same, non-destructive data collection on both terrestrial and Martian samples.

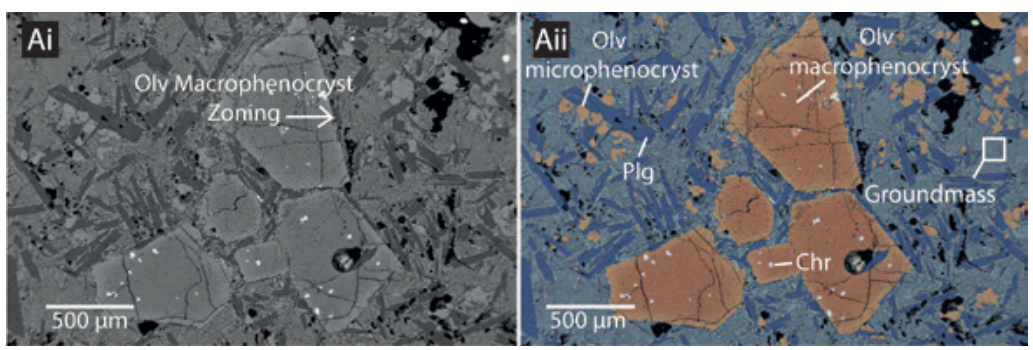


Figure 6 - Ai) BSE image of NM-001 displaying small vesicles and zoning of olivine macro-phenocrysts, Aii) EDS image of NM-001 showing a porphyritic texture of zoned olivine macro-phenocrysts and unzoned olivine micro-phenocrysts, surrounded by plagioclase laths and a fine-grained pyroxene, plagioclase groundmass. Chromite is present in olivine macro-phenocrysts. Key: red = Mg, green = Fe, teal = Ca, dark blue = Al, purple = Cr.

In this study, NM-001 was most petrologically similar to olivine-phyric shergottites displaying a texture of olivine macro-phenocrysts and olivine micro-phenocrysts alike the olivine antecrysts and olivine micro-phenocrysts in NWA 1110 and Tissint. None of the terrestrial samples were analogous to NWA 7397, likely due to their extrusive origin relative to the intrusive origin of poikilitic shergottites.

H-001 and ESA01-A were both tholeiitic in composition and displayed the most similar bulk geochemistry to NWA 7397, NWA 1110 and Tissint. This means these samples were the most accurate analogues for bulk geochemistry for Martian shergottites in this study.

ESA01-A was the only sample that displayed olivine compositions analogous to poikilitic shergottite NWA 7397 and olivine micro-phenocrysts in NWA 1110 and Tissint. H-001, H-002 and NM-001 were analogous to olivine antecrysts in both NWA 1110 and Tissint, suggesting that all terrestrial samples are accurate analogues for individual olivine compositions in Martian shergottites in this study.

NM-001 and H-001 were most analogous to individual pyroxene compositions in Martian shergottites in this study, with NM-001 displaying a wider range of compositions including augite and pigeonite, whilst H-001 exhibited a more limited range but of augite compositions like those seen in NWA 7397, NWA 1110 and Tissint.

Finally, both NM-001 and H-002 displayed similar plagioclase compositions to Martian Shergottites in this study, with NM-001 more similar to NWA 1110 and NWA 7397 whilst H-002 is most similar to Tissint.

From this study it is clear that no terrestrial sample analysed was a perfect match for the Martian meteorites. We did however find that of all the samples analysed, NM-001 is the best match for the shergottites analysed in this study, in particular for olivine-phyric shergottites - even more so than commercial analogue ESA01-A. The similarity of NM-001 compared to ESA01-A for these meteorites in this study indicates that we should also be looking for terrestrial analogues outside of strictly intraplate settings, particularly in intra-rift tectonic settings. Shergottites are the most abundant Martian meteorite that we have on Earth, and the similarity of these to NM-001 suggest NM-001 is the most representative analogue for Martian volcanism in this study.

Acknowledgments

Thank you to Plymouth Electron Microscopy Centre for facilitating this study including all the technicians for their help when using the instruments.

Biography of the Author

Francesca has recently completed a ResM in Planetary Geological Sciences at the University of Plymouth and is currently working as a technician at Plymouth Electron Microscopy Centre.



References

Alexander, C, M, O'D. (2021), 'Meteorite', available at < https://www.britannica.com/science/meteorite >, (Accessed: 01/09/2021)

Balta, J. B., Sanborn, M. E., Udry, A., Wadwha, M., McSween Jr, H.Y. (2015), 'Petrology and trace element geochemistry of Tissint, the newest shergottite fall', *Meteoritics & Planetary Science*, **50**, 63-85

Bandfield, J. L., Hamilton, V. E., Christensen, P. R. (2000), 'A global view of Martian surface compositions from MGS-TES', Science, 1626-1630

Carlson, R.W. (1991), 'Physical and Chemical Evidence on the Cause and Source Characteristics of Flood Basalt Volcanism', *Australian Journal of Earth Sciences,* **38**, 525-544

Carr, M. (2006), 'Volcanism' in *Carr. M., 'The Surface of Mars',* Cambridge University Press, Chapter 3, 43-47

ESA (2021), 'ESA²C Collection', Available at < https://sacf.esa.int/sacf-home/esa2c-collection/ >, (Accessed: 13/01/21)

Filiberto, J., Trela, J., Gross, J., Ferre, E. C. (2014), 'Gabbroic Shergottite Northwest Africa 6963: An intrusive sample of Mars', *American Mineralogist,* **99**, 601-606

Foucher, F., Hickman-Lewis, K., Hutzler, A., Joy, K. H., Folco, L., Bridges, J. C., Wozniakiewicz, P., Martínez-Frías, J., Debaille, V., Zolensky, M., Yano, H., Bost, N., Ferrière, L., Lee, M., Michalski, J., Schroeven-Deceuninck, H., Kminek, G., Viso, M., Russell, S., Smith, C., Zipfel, J., Westall. (2021), 'Definition and use of functional analogues in planetary exploration', *Planetary and Space Science*, **197**, 105162

Haldar, S. K. & Tišljar, J. (2014), 'Chapter 4 – Igenous Rocks', in *Haldar, S. K. & Tišljar, J. 'Introduction to Mineralogy and Petrology'*, Elsevier, 93-120

Hibiya, Y., Archer, G. J., Tanaka, R., Sanborn, M. E., Sato, Y., Lizuka, T., Ozawa, K., Walker, R. J., Yamaguchi, A., Yin, Q-Z., Nakamura, T., Irving, A. J. (2018), 'The origin of the unique achondrite Northwest Africa 6704: Constraints from petrology, chemistry and Re-Os, O and Ti isotope systematics', *Geochimica et Cosmochimica Acta*, **245**, 597-627

Howell, E. (2012), 'Mariner 4: First Spacecraft to Mars', available at < https://www.space.com/18787-mariner-4.html > (Accessed: 03/12/21)

Howell, E. (2021), 'A brief history of Mars missions', available at < https://www.space.com/13558-historic-mars-missions.html > (Accessed: 03/12/21)

Hughes, S.S., Haberle, C.W., Nawotniak, S.E.K., Sehlke, A., Garry, W.B., Elphic, R.C., Payler, S.J., Stevens, A.H., Cockell, C.S., Brady, A.L., Heldmann, J.L., Lim, D.S.S. (2019), 'Basaltic Terrains in Idaho and Hawai'i as Planetary Analogs for Mars Geology and Astrobiology', *Astrobiology*, **19(3)**, 260-283

Karl, D., Cannon, K. M., Gurlo, A. (2021), 'Review of Space Resources Processing of Mars Missions: Martian simulants, regolith bonding concepts and additive manufacturing', *Open Ceramics*, 100216

Keszthelyi, L. & McEwen, A. (2007), 'Comparison of flood lavas on Earth and Mars', in Chapman, M., '*The Geology of Mars: Evidence from Earth-Based Analogs*', Cambridge University Press, Chapter 5, 126-145

McSween, Jr, H.Y. (2015), 'Petrology on Mars', *American Mineralogist,* **100**, 2380-2395

NASA Science: Mars Exploration Program (2020), 'Test Rover Moves to Mars Yard', Available at < https://mars.nasa.gov/resources/25245/test-rover-moves-to-mars-yard/ >, (Accessed: 13/01/21)

NASA Earth Observatory (2006), 'Mauna Loa Oberservatory', available at < https://earthobservatory.nasa.gov/images/43182/mauna-loa-observatory >, (Accessed: 10/12/21)

Papike, J. J., Karner, J. M., Shearer, C. K., Burger, P. V. (2009), 'Silicate mineralogy of Martian meteorites', *Geochimica et Cosmochimica Acta,* **73**, 7443-7485

Ricketts, J. W., Kelley, S. A., Karlstrom, K. E., Schmandt, B., Donahue, M. S., van Wijk, J. (2016), 'Synchronous opening of the Rio Grande rift along its entire length at 25-10 Ma supported by apatite (U-Th)/He and fission-track thermochronology, and evaluation of possible driving mechanisms', GSA Bulletin, 128, 397-424

Shearer, C. K., Burger, P.V., Papike, J. J., Borg, L. E., Irving, A. J., Herd, C. (2008), 'Petrogenic linkages among Martian basalts: Implications based on trace element chemistry of olivine', *Meteoritics & Planetary Science,* **43**, 1241-1258

Witze, A. (2021), 'First peek inside Mars reveals a crust with cake-like layers', *Nature,* **589**, 13

Wyatt, M. B. & McSween Jr, H. Y. (2002), 'Spectral evidence for weathered basalt as an alternative to andesite in the northern lowlands of Mars', *Nature*, 417, 263-266

Zimbelman, J. R., Garry, W. B., Bleacher, J. E., Crown, D.A. (2015), 'Volcanism on Mars', in *Sigurdsson, H. 'The Encyclopedia of Volcanoes (Second Edition)',* Elservier, Chapter 41, 717-728

BRUKER



ANALYZERS FOR ELECTRON MICROSCOPY

The right angle for better analysis

Bruker's unique range of analytical tools for electron microscopes gives researchers the ability to analyze the composition and structure of materials in great detail. Their range, including EDS for SEM and TEM, WDS, EBSD and micro-XRF on SEM, provides the most comprehensive compositional and structural analysis of materials available. In addition, the full integration of each tool with ESPRIT software allows data obtained across these complementary measurement techniques to be easily combined – allowing researchers to see the whole picture and get the best results.

For more information please visit www.bruker.com/xflash7

Innovation with Integrity