Revision 2 to Manuscript # 4638

Gabbroic Shergottite Northwest Africa 6963: an intrusive sample of Mars

Justin Filiberto[1], Juliane Gross[2], Jarek Trela[1,#] and Eric C. Ferré[1]

[1]*Southern Illinois University, Department of Geology, 1259 Lincoln Dr., MC 4324, Carbondale, IL 62901, USA*

[2]*The American Museum of Natural History, Dept. of Earth and Planetary Sciences, Central Park West at 79th Street, New York, NY 10024, USA*

[#]*Now at: Virginia Tech, Department of Geosciences, 4044 Derring Hall (0420), Blacksburg, VA 24061, USA*

ABSTRACT

Meteorite Northwest Africa (NWA) 6963 was classified as a basaltic shergottite based on mineralogy, but here we show that it is a gabbroic rock with a quartz-alkali feldspar intergrowth that represents a late-stage granitic melt. NWA 6963 contains clinopyroxene and maskelynite grains up to 5 mm in length, with minor ferroan olivine, spinel, ilmenite, merrillite, apatite, Fe-sulfides and high-Si glass. NWA 6963 also contains areas of quartz and alkali-feldspar intergrowths up to ~1 mm in size. Based on mineral abundances and textural analysis, we suggest that NWA 6963 is an intrusive rock similar to a terrestrial gabbro. Infiltration of the martian crust by young gabbroic bodies would suggest that estimates of crustal composition, density, and thickness based on the surface chemistry alone would be problematic and the martian crust may be even more heterogenous than is seen from orbit alone. Investigations of

crater walls, where intrusive crustal rocks would be exposed, are needed in order to discover the launch sites of the shergottites and the full heterogeneity of the martian crust.

Keywords: Mars; gabbro; SNC meteorite; shergottite; intrusive; micro-graphic; granite

INTRODUCTION

Martian meteorites are classified, depending on mineralogy, as shergottites, chassignites, nakhlites, and ALH84001 (McSween and Treiman, 1998; Bridges and Warren, 2006). Shergottites represent the largest and most diverse group of martian meteorites and are further subdivided into basaltic, olivine-phyric, and lherzolitic. Basaltic shergottites are dominated by clinopyroxene and plagioclase with no forsteritic olivine (McSween, 1994; Goodrich, 2002; Treiman, 2003; Bridges and Warren, 2006). Those shergottites containing forsteritic olivine are classified as olivine (ol)-phyric shergottites (McSween, 1994; Goodrich, 2002; Treiman, 2003; Bridges and Warren, 2006). Both basaltic and ol-phyric shergottites are thought to be extrusive rocks similar to terrestrial basalts (McSween, 1994; Zuber et al., 2000; Bridges and Warren, 2006; Gross et al., 2011). Lherzolitic shergottites are coarse-grained olivine-pigeonite cumulate rocks and are intrusive in nature (Goodrich, 2002; Bridges and Warren, 2006). Shergottites are also classified based on rare earth element bulk chemistry and isotopic signatures into enriched, intermediate, and depleted categories (Jones, 1989, 2003; Treiman, 2003; Bridges and Warren, 2006; Filiberto et al., 2012). Shergottite NWA 6963 has previously been classified as an enriched basaltic shergottite (Bulletin, 2011; Wilson et al., 2012), but based on mineral abundances, textural analysis, and quartz-alkali feldspar intergrowths, we suggest it represents an intrusive rock similar to a terrestrial gabbro.

SAMPLE AND METHODS

Meteorite Northwest Africa (NWA) 6963 was found at an undisclosed location in Morocco in 2011, represents numerous partly fusion-crusted broken stones that together make up 8-10 kg (Bulletin, 2011), and was classified as a martian shergottite meteorite based on its bulk composition, mineral chemistry and oxygen isotopes (Wilson et al., 2012). For this study we purchased a 1.201 g part slice of the meteorite from Martin Altmann and Stefan Ralew of "Chladni's Heirs", cut and polished a section of it into a thick section, and confirmed that it matched the mineralogy and textural description in the meteoritical bulletin (Bulletin, 2011).

Backscattered electron (BSE) images and X-ray element maps were taken with the Cameca SX100 electron microprobe (EMP) at the American Museum of Natural History (AMNH). The BSE images and X-ray element maps were used to determine the textural characteristics and the modal mineral abundance of this sample using techniques described by Maloy and Treiman (2007).

COMPARISON WITH TERRESTRIAL AND LUNAR GABBROS

Mineralogy

Mineralogically, NWA 6963 is composed of 65 ±5 % pyroxene (25 ±5 % augite and 40 ±5 % pigeonite), 30 ±5 % maskelynite (shocked plagioclase), with minor ferroan olivine, spinel, ilmenite, merrillite, apatite, Fe-sulfides and quartz-alkali feldspar intergrowths, which is similar to many basaltic shergottites (e.g., McSween, 1994; McSween and Treiman, 1998; Bridges and Warren, 2006). The two pyroxenes are in equilibrium and give a high temperature crystallization of ~1250°C and low temperature of ~1000°C calculated from Andersen et al. (1993). Olivine is fayalitic (~Fo_{10}) suggesting that this mineral was a late stage crystallization product.

Terrestrial gabbros are typically composed of 30-75% plagioclase, 15-50% clinopyroxene with minor magnetite, amphibole, biotite, chrome-spinel, and olivine and/or quartz (e.g., Carmichael et al., 1974; Hopper and Smith, 1996; O'Driscoll et al., 2008), which is similar to NWA 6963. However, NWA 6963 contains more pyroxene and less plagioclase than typical terrestrial gabbros which is attributed to the difference in chemistry between martian and typical terrestrial magmas and not due to their cooling history (e.g., Dreibus and Wänke, 1985; Wänke and Dreibus, 1988; Treiman et al., 2000; Bridges and Warren, 2006). Martian rocks contain more FeO and less Al_2O_3 than typical terrestrial Mid-Ocean Ridge and Ocean Islands Basalts and have similar chemistry to terrestrial ferropicrites (e.g., Dreibus and Wänke, 1987; Treiman et al., 2000; Filiberto et al., 2006; Filiberto, 2008b), which is reflected in the higher abundance of pyroxene and lower abundance of plagioclase than typical terrestrial gabbros. This observation is consistent with NWA 6963 being a martian gabbroic rock.

Textural description

Meteorite NWA 6963 consists of subhedral clinopyroxene and maskelynite grains up to 5 mm in length with minor ferroan olivine, spinel, ilmenite, merrillite, apatite, Fe-sulfides and quartz-alkali feldspar intergrowths. In contrast, ol-phyric shergottites typically contain large olivine up to several mm in length in a fine grained groundmass (e.g., Goodrich, 2002; Lentz and McSween, 2005; Gross et al., 2011). The pyroxene and maskelynite in NWA 6963 have a subophitic texture with the pyroxenes partly enclosing similar size maskelynite grains (**Fig. 1),** typical for terrestrial gabbroic rocks (e.g., Wager, 1961).

Basaltic shergottites display a range of grain sizes but all contain coarse grained pyroxene and plagioclase set in a fine grained groundmass as shown by crystal size distribution studies (e.g., Lentz and McSween, 2000; Lentz and McSween, 2005). Similar to many basaltic shergottites (e.g., McSween, 1994; Bridges and Warren, 2006; Stephen et al., 2011), the clinopyroxene in NWA 6963 exhibits a strong shape-preferred orientation (Filiberto et al., 2013).

However, unlike the other basaltic and ol-phyric shergottites, NWA 6963 does not contain a fine grained groundmass. Instead it is composed of > 95 % coarse-grained shocked plagioclase and pyroxene with minor minerals that are up to 300 μm in length (**Fig. 2**).

The average grain size (**Fig. 2**) in NWA 6963 (average plagioclase 0.7 ± 0.3 mm and pyroxene 1.1 ± 0.6 mm in NWA 6963) compares with that of pyroxenes and plagioclase in terrestrial (average plagioclase 0.9 ± 0.4 mm and pyroxene 0.9 ± 0.4 mm in a terrestrial layered gabbro of the British Palaeogene igneous province; O'Driscoll et al., 2008) and lunar gabbros (average plagioclase 0.9 ± 0.5 mm and pyroxene 1.7 ± 0.9 mm in lunar gabbro MIL 05035; Joy et al., 2008) rather than with the grain size of martian basaltic or extrusive rocks (average pyroxene 0.3 ± 0.1 mm in NWA 5789; plagioclase was too fine grained to accurately measure in NWA 5789; Gross et al., 2011). Textures of terrestrial gabbros are variable and depend on cooling and crystallization history of the magma (e.g., Blatt et al., 2005). They typically contain subhedral to euhedral plagioclase and pyroxene up to 5 mm in length, with subophitic textures commonly present (Hopper and Smith, 1996; O'Driscoll et al., 2008). Mineral layering and shape-preferred orientation of plagioclase and pyroxene are present in some terrestrial layered mafic sills and indicate magma flow directions during emplacement of the gabbroic body (e.g., Ferré et al., 2002; O'Driscoll et al., 2008; Archanjo et al., 2012). Therefore, based on crystal texture, NWA 6963 resembles terrestrial mafic sills or dikes emplaced, cooled, and crystallized within the martian crust.

Additional comparisons can be made with Apollo and lunar meteorite collections in which gabbroic rocks and clasts are common (e.g., Engel and Engel, 1970; Papike et al., 1998; Joy et al., 2008). For example, the lunar meteorite Miller Range (MIL) 05035 is a coarse grained lunar gabbroic meteorite, and is thought to be part of a stratigraphic column consisting of an upper regolith environment underlain by a coarsening downwards basalt lava flow, ending with a coarse grained gabbro (Joy et al., 2008). MIL 05035 is petrographically and mineralogically similar to NWA 6963 (**Fig. 2**). Both meteorites are coarse grained and consist mainly of pyroxene (MIL 05035: 54-69 vol% pyroxene with grain sizes up to 6 mm; NWA 6963: ~ 65 vol% pyroxene with grain sizes up to 4 mm) and plagioclase (MIL 05035: 17-36 vol% plagioclase with grain sizes up to 4 mm; NWA 6963: ~30 vol% with grain sizes up to 1 mm). Both meteorites contain minor amounts of fayalitic olivine (MIL 05035: $Fo_{1\text{-}11}$; NWA 6963: Fo_9), ilmenite, spinel, FeS, apatite and silica, which represent crystallized products of its residual melt (Joy et al., 2008; Arai et al., 2010). MIL 05035 and NWA 6963 both display intergrowth textures, referred to as symplectic texture in MIL 05035 (Joy et al., 2008). In MIL 05035 this symplectite consists of silica, fayalitic olivine and hedenbergitic pyroxene (Joy et al., 2008); whereas in NWA 6963 quartz and alkali-feldspar form the intergrowth.

Quartz-Alkali Feldspar Intergrowth

Intergrowths of quartz and alkali-feldspar are common in terrestrial plutonic rocks (e.g., Vogt, 1928; Moorhouse, 1959; Barker, 1970) and hypabyssal rocks such as granophyres (Walraven, 1985), though, these intergrowths are rare in volcanic rocks. NWA 6963 contains areas of quartz and alkali-feldspar intergrowths which can be up to ~1 mm in size. Texturally, quartz and feldspar intergrowths occur as regular arrangements mostly with sharp edges and corners but can also occur irregularly in shape (**Fig. 3**). Phases were identified based on element composition from geochemical maps and EMP data (**Fig 4**). Feldspar within the intergrowth is alkali-feldspar ($Or_{62\text{-}48}Ab_{50\text{-}34}An_{4\text{-}2}$). Minor fayalitic olivine and needles (<1µm) of zircon and ilmenite occur in some intergrowths. We interpret the intergrowth to be igneous in origin and not shock based on a comparison of the mineralogy and textures with shock features in other martian meteorites (e.g., Walton and Spray, 2003; Walton et al., 2012)

A great variety of intergrowths have been repeatedly described in the terrestrial literature and several terms such as graphic granite, micrographic, myrmekitic, and granophyric have been used to describe these textures. Based on the texture and mineral phases (**Fig. 3 and 4)**, we define the intergrowth texture in NWA 6963 as micrographic – a cuneiform, regular intergrowth of quartz and alkali-feldspar that resembles the graphic intergrowth of terrestrial pegmatites but on a microscopic scale. Texturally, such intergrowths in terrestrial samples are suggestive of simultaneous crystallization of quartz and feldspar at the eutectic point (Vogt, 1928; Mehnert, 1968; Barker, 1970). Similar to terrestrial micrographic intergrowths, this suggests that the intergrowths in NWA 6963 formed from a late stage simultaneous eutectic crystallization of quartz and alkali-feldspar. Previously, martian granitic melts have only been found in olivine-hosted melt inclusions in martian meteorites (e.g., Ikeda, 2005). Further, the finding of small pockets of granitic-like melt composition in a gabbroic host in NWA 6963 is consistent with the surface of Mars which is mainly basaltic in composition with only a few possible siliceous areas found from orbit (e.g., Bandfield et al., 2004; Bandfield, 2006; Taylor et al., 2006; McSween et al., 2009; Taylor et al., 2010). Therefore, there may be isolated siliceous bodies within the martian crust that formed from fractional crystallization of a martian basalt such as NWA 6963. Results from experimental fractional crystallization of martian basalts have already shown that martian granitic compositions are plausible (e.g., Minitti and Rutherford, 2000; Whitaker et al., 2005; Nekvasil et al., 2007; Filiberto, 2008a; McCubbin et al., 2008).

IMPLICATIONS

The finding of a martian meteorite that is a gabbro (as opposed to a basalt) should not come as a surprise; on Earth, intrusive rocks are volumetrically 5 times more abundant than extrusive volcanic rocks in oceanic localities, while in continental localities intrusive rocks are 10 times more abundant (Crisp, 1984). Mars does not have plate tectonics with an average crust approximately 50 ± 12 km thick, with estimates as high as 92 km and as low as 3 km (Wieczorek and Zuber, 2004; Taylor and McLennan, 2009). The martian northern lowlands represent a thinner crust (> 30 km), while the southern highlands corresponds to a slightly thicker crust (57 ± 24 km). This is thicker than the average crustal thickness in terrestrial continental regimes (36 km, Cogley, 1984). Therefore, gabbros such as NWA 6963 could make up 5-10 times the volume of the martian crust, compared with extrusive basalts.

However, calculations of the crustal thickness are dependent on knowing the bulk density of the crust and typical values of terrestrial basalts (2.9 - 3.0 x 10^3 kg/m^3) have routinely been used (e.g., Zuber et al., 2000; Taylor and McLennan, 2009). Shergottites typically have a density > 3 x 10^3 kg/m^3 (Coulson et al., 2007), which would reduce the calculated crustal thickness. However, shergottites are approximately 180 my (Jones, 1986; Nyquist et al., 2001; Walton et al., 2008) and may not represent the entire crust but may denote younger magmatism and secondary crustal formation. Infiltration of the martian crust by young gabbroic bodies would suggest that estimates of crustal composition, density, and thickness based on the surface chemistry alone would be problematic and the martian crust may be even more heterogeneous than is seen from orbit alone (e.g., McCubbin et al., 2008).

The martian crust, as seen from orbit, is basaltic in nature with slight variations in bulk chemistry that can be characterized into provinces based on bulk K, Th, and FeO content (Taylor et al., 2006; Taylor et al., 2010). However, the shergottite meteorites have significantly different chemistry than the average martian upper crust (McSween et al., 2003; Filiberto et al., 2006; McSween et al., 2009). Therefore, in places such as Tharsis, and the younger crust of the northern lowlands, the high density of gabbroic bodies, such as NWA 6963, needs to be taken into account when calculating the crustal thickness. In fact, recent models of the martian crust suggest that the density of the lower crust is ~3.4-3.5 x 10^3 kg/m^3 (or greater), which is consistent with the density of shergottites (Coulson et al., 2007) and also consistent with a middle to lower martian crust similar in mineralogy and chemistry to NWA 6963. This might provide an explanation for the so far unsuccessful search for the launch sites of the shergottite martian meteorites (e.g., Hamilton et al., 2003; Lang et al., 2009).

Spectral data from orbital missions has been used to study the mineralogy of the martian surface at young volcanic provinces in the Tharsis region (Lang et al. 2009) and global crust (Hamilton et al. 2003) to identify the launch site for the shergottite meteorites, but did not analyze any region that had meteorite-like compositions. However, when considering that NWA 6963, and possibly other basaltic shergottites, represent intrusive and not extrusive rocks, their launch sites may simply not be exposed on the surface with an aerial footprint large enough to be identified from orbit. Instead, investigations of crater walls, where intrusive crustal rocks would be exposed, may be needed in order to discover the launch sites of the shergottites and the full heterogeneity of the martian crust.

ACKNOWLEDGMENTS

We are grateful to reviewers G. Jeffrey Taylor and Molly McCanta, and associate editor Jessica Larsen for helpful reviews of this paper. This work was supported by NASA MFR grant #NNX13AG35G to J. Filiberto and J. Gross

FIGURE CAPTIONS

Fig. 1. Backscattered electron image (BSE) of the mineral texture in NWA 6963. The dark gray color represents maskelynite, and the lighter gray color is pyroxene. Light gray and white colors represent chromite and iron sulfides. Maskelynite and pyroxene show a subophitic texture, with the pyroxenes partly enclosing similar size maskelynite grains.

Fig. 2. Comparison between gabbros from Mars, Moon and Earth and an ol-phyric basalt from Mars. BSE images of martian gabbro NWA 6963 (a), martian olivine-phyric basalt NWA 5789 (Gross et al., 2011) (b), lunar gabbro MIL 05035 (two slides) (Joy et al., 2008) (c) and a terrestrial gabbro (thin section image in polarized light) (d) from the layered gabbros of the British Palaeogene igneous province (O'Driscoll et al., 2008). Note that NWA 6963 and the terrestrial gabbro show strong orientation of the mineral grains. For comparison olivine-phyric shergottite NWA 5789 has olivine megacrysts set in a very fine grained matrix. Ol = olivine; Pyx = pyroxene; Plag = plagioclase.

Fig. 3. BSE image of the quartz-feldspar intergrowth in NWA 6963 (a). Close up of the intergrowth structure. Dark gray represents quartz, lighter gray represents feldspar. The bright colors in (b) represent ilmenite, ±zircon, ±fayalitic olivine. Pyx = pyroxene; Plag = plagioclase; Fsp = feldspar; Qtz = quartz; Ilm = ilmenite.

Figure 4. Element maps of the quartz-feldspar intergrowths in NWA 6963.

REFERENCES CITED

Andersen, D. J., Lindsley, D. H., and Davidson, P. M., 1993, QUIlF: A Pascal Program to Assess Equilibria among Fe-Mg-Mn-Ti oxides, Pyroxenes, Olivine, and Quartz: Computers and Geosciences, v. 19, no. 9, p. 1333-1350.

Arai, T., Ray Hawke, B., Giguere, T. A., Misawa, K., Miyamoto, M., and Kojima, H., 2010, Antarctic lunar meteorites Yamato-793169, Asuka-881757, MIL 05035, and MET 01210 (YAMM): Launch pairing and possible cryptomare origin: Geochimica et Cosmochimica Acta, v. 74, no. 7, p. 2231-2248.

Archanjo, C., Campanha, G. C., Salazar, C., and Launeau, P., 2012, Using AMS combined with mineral shape preferred orientation analysis to understand the emplacement fabrics of the Apiaí gabbro-norite (Ribeira Belt, SE Brazil): International Journal of Earth Sciences, v. 101, no. 3, p. 731-745.

Bandfield, J. L., 2006, Extended surface exposures of granitoid compositions in Syrtis Major, Mars: Geophysical Research Letters, v. 33, no. 6.

Bandfield, J. L., Hamilton, V. E., Christensen, P. R., and McSween, H. Y., 2004, Identification of quartzofeldspathic materials on Mars: Journal of Geophysical Research-Planets, v. 109, no. E10.

Barker, D. S., 1970, Compositions of granophyre, myrmekite, and graphic granite: Geological Society of America Bulletin, v. 81, no. 11, p. 3339-3350.

Blatt, H., Tracy, R., and Owens, B., 2005, Petrology: igneous, sedimentary, and metamorphic, WH Freeman.

Bridges, J. C., and Warren, P. H., 2006, The SNC meteorites: basaltic igneous processes on Mars: Journal of the Geological Society, v. 163, no. 2, p. 229-251.

Bulletin, M., 2011, Meteoritical Bulletin: Meteoritics & Planetary Science.

Carmichael, I. S., Turner, F. J., and Verhoogen, J., 1974, Igneous petrology, McGraw-Hill New York.

Cogley, J. G., 1984, Continental margins and the extent and number of the continents: Reviews of Geophysics, v. 22, no. 2, p. 101-122.

Coulson, I. M., Beech, M., and Nie, W., 2007, Physical properties of Martian meteorites: Porosity and density measurements: Meteoritics & Planetary Science, v. 42, no. 12, p. 2043-2054.

Crisp, J. A., 1984, Rates of magma emplacement and volcanic output: Journal of Volcanology and Geothermal Research, v. 20, no. 3–4, p. 177-211.

Dreibus, G., and Wänke, H., 1985, Mars, a Volatile-Rich Planet: Meteoritics, v. 20, no. 2, p. 367-381.

-, 1987, Volatiles on Earth and Mars - a Comparison: Icarus, v. 71, no. 2, p. 225-240.

Engel, A., and Engel, C. G., 1970, Lunar rock compositions and some interpretations: Geochimica et Cosmochimica Acta Supplement, v. 1, p. 1081.

Ferré, E. C., Bordarier, C., and Marsh, J. S., 2002, Magma flow inferred from AMS fabrics in a layered mafic sill, Insizwa, South Africa: Tectonophysics, v. 354, no. 1–2, p. 1-23.

Filiberto, J., 2008a, Experimental Constraints on the Parental Liquid of the Chassigny Meteorite: A Possible Link between the Chassigny Meteorite and a Gusev Basalt.: Geochimica et Cosmochimica Acta, v. 72, no. 2, p. 690-701.

-, 2008b, Similarities between the shergottites and terrestrial ferropicrites: Icarus, v. 197, no. 1, p. 52-59.

Filiberto, J., Chin, E., Day, J. M. D., Franchi, I. A., Greenwood, R. C., Gross, J., Penniston-Dorland, S. C., Schwenzer, S. P., and Treiman, A. H., 2012, Geochemistry of intermediate olivine-phyric shergottite Northwest Africa 6234, with similarities to basaltic shergottite Northwest Africa 480 and olivine-phyric shergottite Northwest Africa 2990: Meteoritics & Planetary Science, v. 47, no. 8, p. 1256-1273.

Filiberto, J., Gross, J., Trela, J., and Ferré, E., 2013, Constraints on Fabric-Forming Mechanisms in Shergottite NWA 6963: Results from Mineralogy and Shape-Preferred Orientation: Lunar and Planetary Science Conference, p. abstract # 2124.

Filiberto, J., Nekvasil, H., and Lindsley, D. H., 2006, The Mars/Earth dichotomy in Mg/Si and Al/Si ratios: Is it real?: American Mineralogist, v. 91, p. 471-474.

Goodrich, C. A., 2002, Olivine-phyric martian basalts: A new type of shergottite: Meteoritics & Planetary Science, v. 37, p. 31-34.

Gross, J., Treiman, A. H., Filiberto, J., and Herd, C. D. K., 2011, Primitive olivine-phyric shergottite NWA 5789: Petrography, mineral chemistry, and cooling history imply a magma similar to Yamato-980459: Meteoritics & Planetary Science, v. 46, no. 1, p. 116-133.

Hamilton, V. E., Christensen, P. R., McSween, H. Y., and Bandfield, J. L., 2003, Searching for the source regions of martian meteorites using MGS TES: Integrating martian meteorites into the global distribution of igneous materials on Mars: Meteoritics & Planetary Science, v. 38, no. 6, p. 871-885.

Hopper, D. J., and Smith, I. E., 1996, Petrology of the gabbro and sheeted basaltic intrusives at North Cape, New Zealand: New Zealand Journal of Geology and Geophysics, v. 39, no. 3, p. 389-402.

Ikeda, Y., 2005, Magmatic inclusions in martian meteorites: Antarct. Meteorite Res., v. 18, p. 170-187.

Jones, J., Isotopic relationships among the shergottites, the nakhlites and Chassigny, *in* Proceedings Lunar and Planetary Science Conference Proceedings1989, Volume 19, p. 465-474.

-, 2003, Constraints on the structure of the martian interior determined from the chemical and isotopic systematics of SNC meteorites: Meteoritics & Planetary Science, v. 38, no. 12, p. 1807-1814.

Jones, J. H., 1986, A discussion of isotopic systematics and mineral zoning in the shergottites: Evidence for a 180 m.y. igneous crystallization age: Geochimica et Cosmochimica Acta, v. 50, no. 6, p. 969-977.

Joy, K. H., Crawford, I. A., Anand, M., Greenwood, R. C., Franchi, I. A., and Russell, S. S., 2008, The petrology and geochemistry of Miller Range 05035: A new lunar gabbroic meteorite: Geochimica et Cosmochimica Acta, v. 72, no. 15, p. 3822-3844.

Lang, N. P., Tornabene, L. L., McSween Jr, H. Y., and Christensen, P. R., 2009, Tharsis-sourced relatively dust-free lavas and their possible relationship to Martian meteorites: Journal of Volcanology and Geothermal Research, v. 185, no. 1-2, p. 103-115.

Lentz, R. C. F., and McSween, H. Y., 2000, Crystallization of the basaltic shergottites: Insights from crystal size distribution (CSD) analysis of pyroxenes: Meteoritics & Planetary Science, v. 35, no. 5, p. 919-927.

Lentz, R. C. F., and McSween, H. Y., 2005, A textural examination of the Yamato 980459 and Los Angeles shergottites using crystal size distribution analysis: Antarctic Meteorite Research, v. 18, p. 66.

Maloy, A. K., and Treiman, A. H., 2007, Evaluation of image classification routines for determining modal mineralogy of rocks from X-ray maps: American Mineralogist, v. 92, no. 11-12, p. 1781.

McCubbin, F. M., Nekvasil, H., Harrington, A. D., Elardo, S. M., and Lindsley, D. H., 2008, Compositional diversity and stratification of the Martian crust: Inferences from crystallization experiments on the picrobasalt Humphrey from Gusev Crater, Mars,: Journal of Geophysical Research, v. 113, no. E11013, p. doi:10.1029/2008JE003165.

McSween, H. Y., 1994, What We Have Learned About Mars from SNC Meteorites: Meteoritics, v. 29, no. 6, p. 757-779.

McSween, H. Y., Grove, T. L., and Wyatt, M. B., 2003, Constraints on the composition and petrogenesis of the Martian crust: Journal of Geophysical Research-Planets, v. 108, no. E12.

McSween, H. Y., Taylor, G. J., and Wyatt, M. B., 2009, Elemental Composition of the Martian Crust: Science, v. 324, no. 5928, p. 736-739.

McSween, H. Y., and Treiman, A. H., 1998, Martian Meteorites, *in* Papike, J. J., ed., Reviews in Mineralogy, Volume 36, Mineralogical Society of America, p. 6-01-06-40.

Mehnert, K. R., 1968, Migmatites and the origin of granitic rocks, Elsevier Amsterdam.

Minitti, M. E., and Rutherford, M. J., 2000, Genesis of the Mars Pathfinder "sulfur-free" rock from SNC parental liquids: Geochimica et Cosmochimica Acta, v. 64, no. 14, p. 2535-2547.

Moorhouse, W. W., 1959, The study of rocks in thin section.

Nekvasil, H., Filiberto, J., McCubbin, F. M., and Lindsley, D. H., 2007, Alkalic parental magmas for the chassignites?: Meteoritics & Planetary Science, v. 42, no. 6, p. 979-992.

Nyquist, L. E., Bogard, D. D., Shih, C. Y., Greshake, A., Stöffler, D., and Eugster, O., 2001, Ages and Geologic Histories of Martian Meteorites: Space Science Reviews, v. 96, no. 1, p. 105-164.

O'Driscoll, B., Stevenson, C. T. E., and Troll, V. R., 2008, Mineral Lamination Development in Layered Gabbros of the British Palaeogene Igneous Province: A Combined Anisotropy of Magnetic Susceptibility, Quantitative Textural and Mineral Chemistry Study: Journal of Petrology, v. 49, no. 6, p. 1187-1221.

Papike, J. J., Ryder, G., and Shearer, C. K., 1998, Lunar Samples, *in* Papike, J. J., ed., Reviews in Mineralogy, Volume 36, Mineralogical Society of America, p. 5-01-05-234.

Stephen, N., Benedix, G., Bland, P., Berlin, J., Salge, T., and Goran, D., EBSD analysis of the Shergottite Meteorites: New developments within the technique and their implication on what we know about the preferred orientation of Martian minerals, *in* Proceedings AGU Fall Meeting Abstracts2011, Volume 1, p. 1709.

Taylor, G. J., Boynton, W. V., Brückner, J., Wänke, H., Dreibus, G., Kerry, K., Keller, J., Reedy, R., Evans, L., Starr, R., Squyres, S., Karunatillake, S., Gasnault, O., Maurice, S., d'Uston, C., Englert, P., Dohm, J., Baker, V., Hamara, D., Janes, D., Sprague, A., Kim, K., and Drake, D., 2006, Bulk composition and early differentiation of Mars: Journal of Geophysical Research, v. 111, no. E03S10, p. doi:10.1029/2005JE002645.

Taylor, G. J., Martel, L. M. V., Karunatillake, S., Gasnault, O., and Boynton, W. V., 2010, Mapping Mars geochemically: Geology, v. 38, no. 2, p. 183-186.

Taylor, S. R., and McLennan, S. M., 2009, Planetary crusts: their composition, origin and evolution, Cambridge University Press Cambridge.

Treiman, A. H., 2003, Chemical compositions of martian basalts (shergottites): Some inferences on basalt formation, mantle metasomatism, and differentiation in Mars: Meteoritics & Planetary Science, v. 38, no. 12, p. 1849-1864.

Treiman, A. H., Gleason, J. D., and Bogard, D. D., 2000, The SNC meteorites are from Mars: Planetary and Space Science, v. 48, no. 12-14, p. 1213-1230.

Vogt, J., 1928, On the graphic granite: K. Norske Vidensk Selkabs. Förh. Bd. l, p. 67.

Wager, L., 1961, A note on the origin of ophitic texture in the chilled olivine gabbro of the Skaergaard intrusion: Geological Magazine, v. 98, no. 5, p. 353-366.

Walraven, F., 1985, Genetic aspects of the granophyric rocks of the Bushveld Complex: Economic Geology, v. 80, no. 4, p. 1166-1180.

Walton, E. L., Irving, A. J., Bunch, T. E., and Herd, C. D. K., 2012, Northwest Africa 4797: A strongly shocked ultramafic poikilitic shergottite related to compositionally intermediate Martian meteorites: Meteoritics & Planetary Science, p. in press.

Walton, E. L., Kelley, S. P., and Herd, C. D. K., 2008, Isotopic and petrographic evidence for young Martian basalts: Geochimica et Cosmochimica Acta, v. 72, no. 23, p. 5819-5837.

Walton, E. L., and Spray, J. G., 2003, Mineralogy, microtexture, and composition of shock-induced melt pockets in the Los Angeles basaltic shergottite: Meteoritics & Planetary Science, v. 38, no. 12, p. 1865-1875.

Wänke, H., and Dreibus, G., 1988, Chemical-Composition and Accretion History of Terrestrial Planets: Philosophical Transactions of the Royal Society of London Series a-Mathematical Physical and Engineering Sciences, v. 325, no. 1587, p. 545-557.

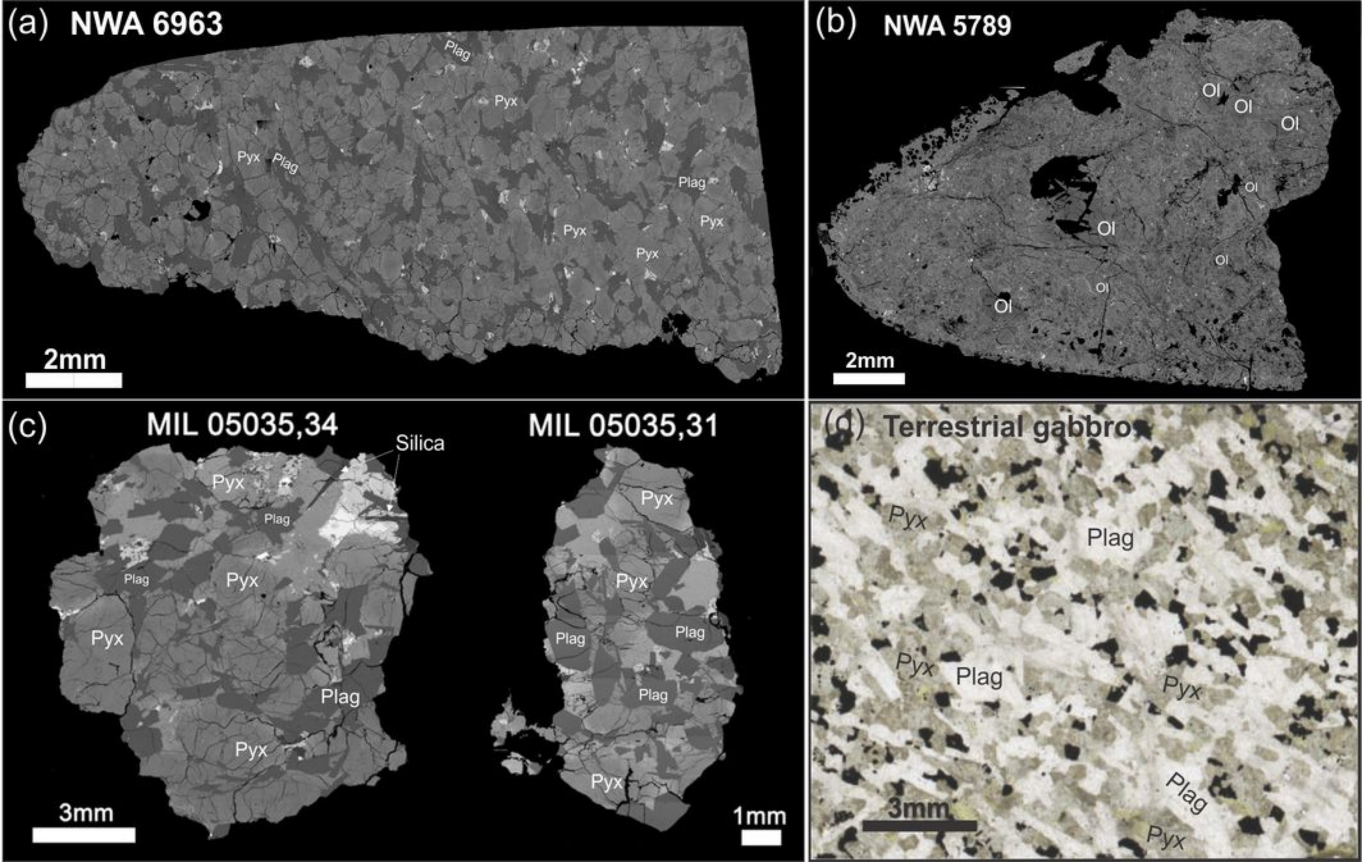
Whitaker, M., Nekvasil, H., and Lindsley, D. H., 2005, Potential Magmatic Diversity On Mars.: Lunar and Planetary Science, v. XXXVI, p. Abstract # 1440.

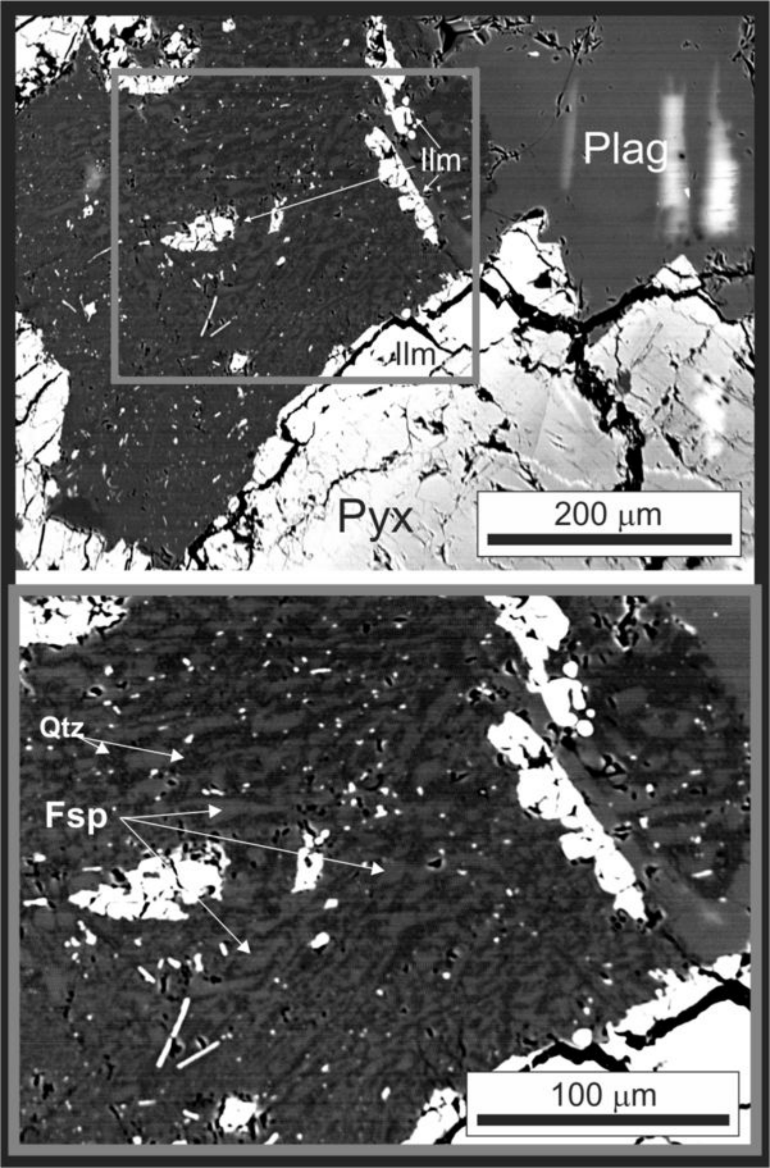
Wieczorek, M. A., and Zuber, M. T., 2004, Thickness of the Martian crust: Improved constraints from geoid-to-topography ratios: Journal of Geophysical Research: Planets, v. 109, no. E1, p. 10.1029/2003je002153.

Wilson, N., Agee, C., and Sharp, Z., 2012, New Martian Shergottite NWA 6963: Lunar and Planetary Science Conference v. 43, p. Abstract #1696.

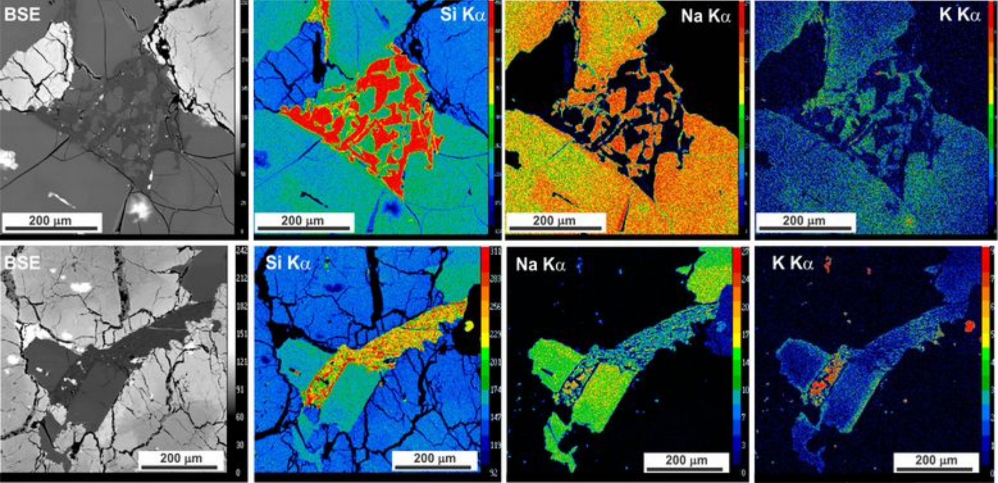
Zuber, M. T., Solomon, S. C., Phillips, R. J., Smith, D. E., Tyler, G. L., Aharonson, O., Balmino, G., Banerdt, W. B., Head, J. W., Johnson, C. L., Lemoine, F. G., McGovern, P. J., Neumann, G. A., Rowlands, D. D., and Zhong, S., 2000, Internal Structure and Early Thermal Evolution of Mars from Mars Global Surveyor Topography and Gravity: Science, v. 287, no. 5459, p. 1788-1793.

Pyx
Ox
Plag
Pyx
Plag
Intergrowth
Pyx
Ox
FeS
FeS
Intergrowth
Plag
Pyx
1mm
Plag
FeS
Ox
Pyx
Plag
Pyx
Ox
Plag
Pyx
Plag
0.5mm
Pyx
Pyx
Plag
FeS
FeS
Ox
Ox
Pyx
Plag
Pyx
Plag
0.5mm


(a) NWA 6963
Plag
Pyx
Pyx
Plag
Plag
Pyx
Pyx
Pyx
2mm
(b) NWA 5789
Ol
Ol
Ol
Ol
Ol
Ol
Ol
Ol
2mm
(c) MIL 05035,34
MIL 05035,31
Silica
Pyx
Plag
Plag
Pyx
Pyx
Plag
Pyx
Pyx
Pyx
Plag
Plag
Plag
Pyx
3mm
1mm
(d) Terrestrial gabbros
Pyx
Plag
Pyx
Plag
Pyx
Plag
Pyx
3mm



Ilm
Plag
Ilm
Pyx
200 µm
Qtz
Fsp
100 µm


BSE
Si Kα
Na Kα
K Kα
200 µm
BSE
Si Kα
Na Kα
K Kα
200 µm