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Meteorite fusion crust variability

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Abstract–Two assumptions commonly employed in meteorite interpretation are that fusion crust compositions represent the bulk-rock chemistry of the interior meteorite and that the vesicles within the fusion crust result from the release of implanted solar wind volatiles. Electron microprobe analyses of thin sections from lunar meteorite Miller Range (MIL) 05035 and eucrite Bates Nunataks (BTN) 00300 were performed to determine if the chemical compositions of the fusion crust varied and/or represented the published bulk rock composition.

It was determined that fusion crust compositions are significantly influenced by the incorporation of fragments from the substrate, and by the composition and grain size of those minerals. Because of compositional heterogeneities throughout the meteorite, one cannot assume that fusion crust composition represents the bulk rock composition. If the compositional variability within the fusion crust and mineralogical differences among thin sections goes unnoticed, then the perceived composition and petrogenetic models of formation will be incorrect.

The formation of vesicles within these fusion crusts were also compared to current theories attributing vesicles to a solar wind origin. Previous work from the STONE-5 experiment, where terrestrial rocks were exposed on the exterior of a spacecraft heatshield, produced a vesicular fusion crust without prolonged exposure to solar wind suggesting that the high temperatures experienced by a meteorite during passage through the Earth's atmosphere are sufficient to cause boiling of the melt. Therefore, the assumption that all vesicles found within a fusion crust are due to the release of implanted volatiles of solar wind may not be justified.

INTRODUCTION

Meteorites are rocks that have traveled through space and survived the descent through the atmosphere to land on the surface of the Earth (Papike 1998; Norton 2002). They come in a wide variety of types and compositions and are the only physical samples that we have from the asteroid belt, Mars, and in many cases, unexplored locations of the Moon. Despite these differences, many studies make the same assumptions when characterizing and cataloging meteorites. We have explored two of these prevalent assumptions that may yield flawed interpretations: 1) fusion crust compositions represent the bulk rock chemistry of the interior meteorite and 2) the vesicles within the fusion crust result from the release of implanted solar wind volatiles.

One of the unique features of meteorites found on Earth is the presence of a fusion crust (Fig. 1). As a meteoroid passes through the atmosphere, frictional heating causes its outer surface to melt, and while in its liquid state, the molten material flows and is ablated from the surface of the meteorite. In many cases, this melt is heated to high enough temperatures to vaporize portions of the melt, volatilizing elements/oxides from the melt of the minerals in the rock (Genge and Grady 1999; Brandstätter et al. 2008), thus forming vesicles of various sizes in the fusion crust glass. Different degrees of mixing occur as the melt begins to flow over the surface, resulting in flow banding of various colors and compositions. Nevertheless, not all minerals are completely melted at the surface and incompletely digested solid fragments can be incorporated into the melt. Ultimately, the decreasing velocity of the meteorite results in the quenching of the melt film on the surface and the preservation of a fusion crust.

Fusion Crusts and Vesicles

The ability to experimentally reproduce the conditions that a meteorite experiences as it passes through the atmosphere was accomplished by the STONE-5 experiment (Brandstätter et al. 2008), which mounted terrestrial rocks of a known origin, mineralogy, texture, and composition on the

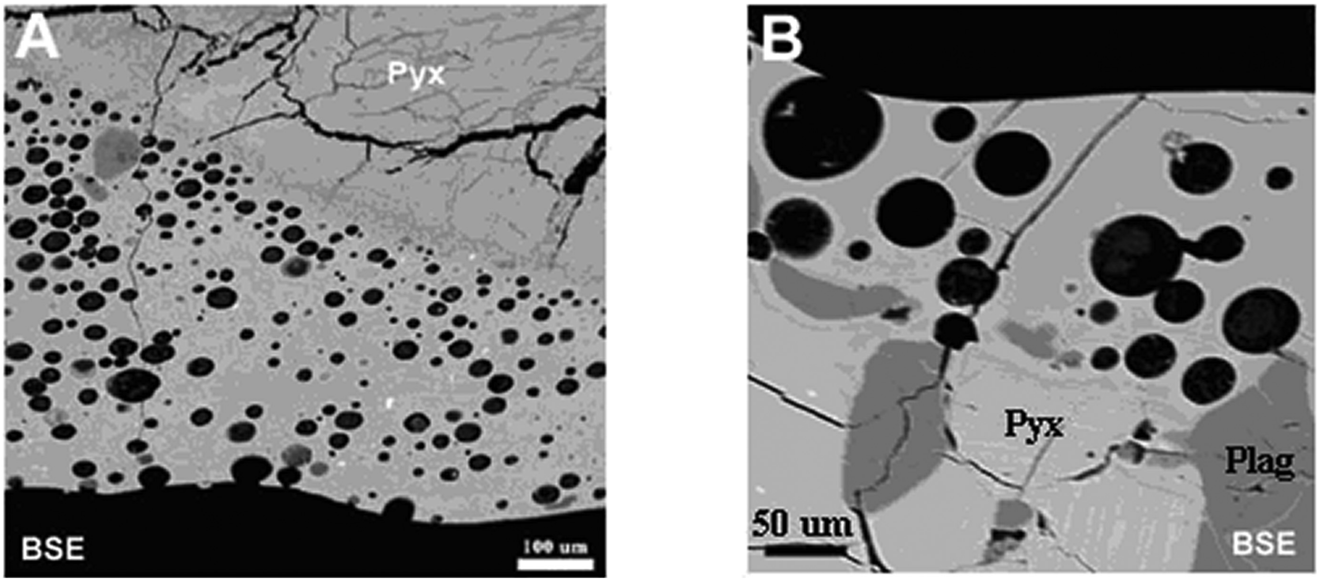

Fig. 1. Backscattered electron (BSE) images of MIL 05035, 40 (A) and BTN 00300, 26 (B) fusion crusts. Abundant vesicles can be found within the fusion crust of each type of meteorite. Heterogeneity of fusion crust composition can be seen as different shades of gray to white in these images.

heat shield of a FOTON-M2 capsule. The melting and destruction of the heat shield as it descended through the atmosphere influenced the fusion crust composition in some places through partial mixing, creating a heterogeneous diabase-silica melt. Significant features recognized in the fusion crust of a dolerite (diabase) sample consisted of vesicles, inclusions of silica fibers from the heat shield, and chemical compositions ranging from silica-rich to basaltic.

Korotev (2005) stated that the formation of vesicular fusion crusts on meteorites of lunar regolith breccias resulted from the release of implanted solar wind. Similar conclusions were drawn on a lunar mare basalt meteorite LaPaz Icefield (LAP) 02224 (Joy et al. 2006) and on two achondrites, Graves Nunataks (GRA) 06128 and 06129 (Zeigler et al. 2008), despite the differing compositions, textures, and rock types of these meteorites. By disregarding the textural differences of the meteorites, these studies did not account for the ability of solar wind to be retained at the surface of a crystalline rock or throughout a breccia. In this study, the generation of fusion crust vesicles cannot be attributed to the implantation of solar wind, but most likely resulted from the loss of volatile elements by evaporation and degassing as suggested by Genge and Grady (1999) for chondrites and achondrites. Lunar breccias, on the other hand, are made up of grains which were exposed at the surface of the Moon and collected abundant solar wind volatiles on their surfaces (Basu and Molinaroli 2001) and although solar wind implantation for a "gardened" lunar regolith breccia may be a reasonable contributor of vesicle-forming gases within a fusion crust, a fully crystalline rock would not retain any solar wind in its interior. The only solar wind that may be present on the surface of such a meteorite would be in the outer 10–20 nm. Since the original surface of all meteorites is removed during the descent through the atmosphere, all solar wind gases within the outer few tens of nm would be the first components to vaporize and would not be preserved as vesicles within the fusion crust. Therefore, vesicles found within the fusion crusts of crystalline meteorites must form as a result of vaporization of the melt itself. This process is similar to the formation of Hi-Al, Si-poor (HASP) glass that occurs in lunar soil, resulting through selective volatilization of elements and oxide components (Naney et al. 1976; Vaniman 1990).

Fusion Crusts and Bulk Compositions

The bulk chemical composition of a rock permits its classification and is an essential piece of data with which to construct its petrogenesis. Although it is difficult to determine exactly where meteorites come from, many are believed to be from the asteroid belt in the solar system based on their chemical and physical similarities. Previously, it was assumed that the bulk composition of a meteorite could be approximated from an analysis of its fusion crust and that the average of a few fusion crust analyses represents the bulk composition of the meteorite (e.g., Korotev et al. 1996; Genge and Grady 1999; Gnos et al. 2002; Day et al. 2006). Although some cases show this can provide an acceptable approximation of the bulk rock composition (Genge and Grady 1999; Gnos 2002), other samples, even those combining several analyses, may not adequately represent the significant compositional variation within some fusion crusts, let alone the composition of the entire rock.

In order to explore this premise, the abundant fusion crust that is preserved on the lunar meteorite Miller Range

(MIL) 05035, thin sections 6 and 40, was analyzed with an electron microprobe (EMP) and compared to published bulk rock compositions (Joy et al. 2007; Liu et al. 2009). These particular meteorite sections were chosen because they have significant fusion crust glass on their perimeters. Additional analyses were performed on the thin fusion crust of the eucrite meteorite, BTN 00300, thin section 26, to determine if fine-grained meteorites show similar variability within their fusion crusts.

METHODS

Polished thin sections of lunar meteorite MIL 05035, 6 and 40, and BTN 00300, 26, were examined and digitally mapped with a petrographic microscope, in both reflected and transmitted light, in order to identify mineral assemblages and their textural relationships. Compositional analyses were performed with a Cameca SX-50 electron microprobe to determine the composition of the fusion crust and adjacent mineral substrate. Compositional analyses were obtained with an accelerating potential of 15 keV, 10 nA beam, and a spot size of 5 µm. To examine the relationship between mineral substrate and adjacent fusion crust compositions, a series of transects at 10 µm steps were performed. Additional analyses were performed throughout the fusion crust to explore internal variability of the glass.

MINERALOGY AND PETROLOGY

Lunar meteorite MIL 05035 is a 142.2 g unbrecciated, low-Ti mare basalt found during the 2005–2006 Antarctic Search for Meteorites (ANSMET) field season (Antarctic Meteorite Newsletter 2006). Meteorite thin sections used in this study (6 and 40) consist of ~66%, coarse clinopyroxene and ~29% shocked plagioclase feldspar (maskelynite). The remaining ~5% consist of: a) interstitial minerals such as fayalite, troilite, and ulvöspinel, which are intergrown with ilmenite, and tridymite; b) Fe-rich pyroxene assemblages that include symplectic intergrowths of olivine, tridymite, and ferroaugite; and c) mesostasis composed of K-rich glass, fayalitic olivine, merrillite, baddeleyite, and tridymite (Liu et al. 2007).

The fractured nature of the pyroxenes and the transformation of the plagioclase crystals into maskelynite are indicative of shock-pressure (French 1998), most likely experienced during excavation of this rock from the lunar surface. Within MIL 05035, anhedral clinopyroxene grains range from 3–8 mm in size, have a composition of $Wo_{11–43}$ $En_{2–44}$ (Arai et al. 2007; Joy et al. 2007; Liu et al. 2007), and typically exhibit twinning and exsolution lamellae. The subhedral maskelynite grains, (up to 1.5 mm long), show compositional zoning that ranges from $An_{95–76}$ (Arai et al. 2007; Joy et al. 2007; Liu et al. 2007). Some crystals along the external surface, adjacent to the fusion crust, have partially crystallized as fine-grained, feathery plagioclase dendrites. The opaque assemblages are made up of ilmenite, ulvöspinel, and troilite, with one large ilmenite and one large ulvöspinel comprising the bulk of the opaques in 05035, 40. The areas with a symplectic texture contain small crystals (~5–10 µm) of anhedral SiO_2, fayalite, and pyroxene (Wo_{40} En_9). Samples 05035, 6 is approximately 1.0 cm × 1.5 cm and 05035, 40 is approximately 0.9 cm × 0.9 cm in size. The fusion crust is highly vesicular and varies in thickness from <0.1 mm to ~0.6 mm, and covers about 16% and greater than 50% of their respective perimeters.

Eucrite BTN 00300 is a 124.6 g unbrecciated basaltic achondrite of the eucrite group found by ANSMET in 2000 (Antarctic Meteorite Newsletter 2001). Primarily, it is composed of fine-grained (average grain size of ~20 µm) anhedral to subhedral pyroxene ($Wo_{7–35}$ $En_{37–44}$) and plagioclase ($An_{87}Or_{0.5}$) (Meteoritical Bulletin, http://tin.er.usgs.gov/meteor/metbull.php?code=4958). The plagioclase in this sample has not undergone sufficient shock to transform it to maskelynite. Thin section 26 is approximately 1.5 cm long × 0.7 cm wide and has a fusion crust that varies in thickness from approximately 0.05 mm to 0.2 mm and contains varying amounts of vesicles along 50% of its perimeter. Crystal substrates, adjacent to the fusion crust, have been partially melted.

DISCUSSION

Lunar meteorite MIL 05035, 40 has a preserved fusion crust over half of its outer surface, and contains an area where this crust is up to 0.6 mm thick. The abundance of fusion crust in the analyzed thin section has provided an excellent opportunity to examine the textural and compositional relationship of this glass to minerals that make up its substrate (considered to be the crystal adjacent to the fusion crust in the thin section). Several traverses were performed from the mineral substrate to the outer edge of the fusion crust (Fig. 2), of which three will be discussed here. These include two from shocked maskelynite (plagioclase) and one from a coarse-grained pyroxene. The traverses through the fusion crust adjacent to the plagioclase indicated two trends: 1) the fusion crust composition gradually transitions from a plagioclase to a pyroxene composition and 2) the fusion crust composition rapidly transitions from a plagioclase to a pyroxene composition. The fusion crust adjacent to the pyroxene-crystal substrate maintains a dominantly pyroxene composition, indicating no significant mixing has occurred. Together these trends suggest that some compositional mixing occurs, but the fusion crust does not become homogenized, and the coarse-grained minerals can significantly influence fusion crust composition.

In order to explore the connection between grain size and fusion crust composition, we analyzed the fine-grained eucrite BTN 00300, 26, which has a thin fusion crust around

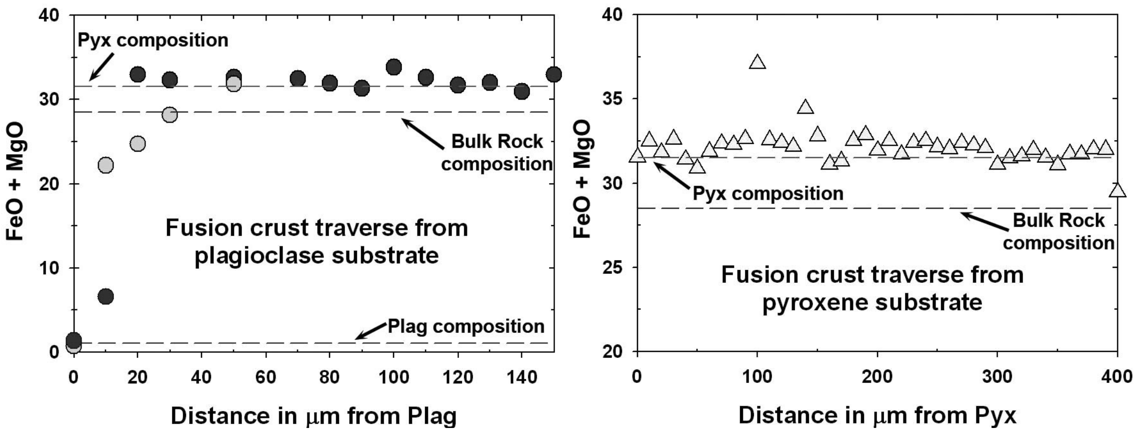

Fig. 2. EMP traverses from plagioclase (left) and pyroxene (right) substrate into and across the adjacent fusion crust of MIL 05035. Two different plagioclase traverses (left) have been included to indicate variability of the fusion crust adjacent to plagioclase. The fusion crust maintains a pyroxene-dominated composition. Bulk rock composition from Joy et al. (2007).

~50% of the outer surface of this thin section. We would expect that as grain size decreases, fusion crust composition would become more homogeneous. Three traverses from the mineral substrate through the fusion crust were performed at different locations to see if the same trends recognized in MIL 05035 could be seen in a fine-grained sample. Since a bulk rock composition for this meteorite is currently unavailable, we were unable to compare the fusion crust composition to that of the bulk rock. However, compositional variability is also observed within the fusion crust of this meteorite (Fig. 3). Three distinct compositions exist, indicating that mixing has not occurred.

To further explore the compositional variations within the fusion crust, Figure 4 shows a plot of (FeO + MgO) (pyroxene components) versus Al_2O_3 (plagioclase/maskelynite) for MIL 05035. The fusion crust compositions adjacent to plagioclase and pyroxene substrates range between these two end-members, while compositions adjacent to symplectite significantly favor the pyroxene end-member. The cluster of points near 7% Al_2O_3 and 31% (FeO + MgO) is not unusual in a sample that consists primarily of pyroxene. These analyses suggest that mixing prior to quenching has occurred, but to different degrees. Comparison between the average of 170 analyses taken throughout the fusion crust with the bulk rock compositions of Joy et al. (2007) and Liu et al. (2009) are shown in Table 2. Although it might suggest that this average satisfactorily represents the bulk rock composition, significant implications must be addressed. The average composition of the fusion crust of MIL 05035 is deficient in SiO_2, MgO, SO_2, and Cr_2O_3, and contains excessive FeO, TiO_2, Al_2O_3, Na_2O, MnO, and K_2O, relative to the bulk rock compositions. If we use the average fusion crust values and the compositions from Joy et al. (2007) and Liu et al. (2009), the bulk rock has a Mg# = 40.2 and 37.8 respectively, and the averaged fusion crust composition has an Mg# = 31.9, which would have significant ramifications for petrogenetic modeling. This average should not be considered as a satisfactory representation of the bulk rock due to the significant variance associated with the amounts of MgO and Al_2O_3 present. But if it was assumed to be a representative value, what is the likelihood that only a few analyses would adequately sample the compositional variability of the fusion crust and produce a similar result with the significant variability recognized in MgO and Al_2O_3?

This work demonstrates that the composition of the fusion crust varies with respect to the substrate mineralogy. Mixing occurs, but is incapable of homogenizing the entire fusion crust, at least within the crust that remains. It is entirely possible that the outermost portions of the melt, which were ablated away, may have had a more representative whole rock composition; however, the fusion crust present is rather inhomogeneous in composition.

Several authors (e.g., Korotev et al. 1996; Gnos et al. 2002; Day et al. 2006) have used the average of a few fusion-crust analyses to approximate the bulk composition of the meteorite. Indeed, this may produce an acceptable compositional value depending on the accuracy that is needed. However, considerable care should be taken in applying such principles. As this present study has demonstrated, the compositional variability within the fusion crust of a single thin section may not reflect the bulk rock from which it originated. The incorporation of locally present, low abundance constituents into the melt can produce anomalously high concentrations in the fusion crust; that is, variations due to partial mixing of the melt can bias analyses. Gleason et al. (1997) recognized that small variations in data sets had the potential to significantly affect geochemical models of Martian basalts. Similar caution should be exercised when determining a "close enough" composition from any fusion crust and suggesting that it represents the bulk rock composition. The average of even high numbers of EMP analyses of a fusion crust may indicate an apparent high degree of precision, but whether or not those analyses accurately represent the bulk composition is another question. It may be an interesting composition to have if nothing else is

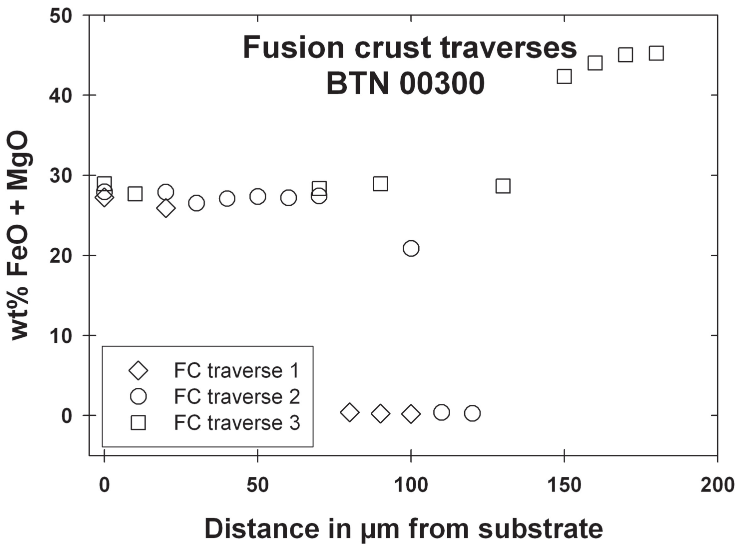

Fig. 3. BTN 00300 fusion crust (FC) analyses. The three fusion crust traverses indicate that composition does not change gradually with distance from the substrate and suggest that significant mixing has not occurred. No bulk rock composition is currently available for this sample.

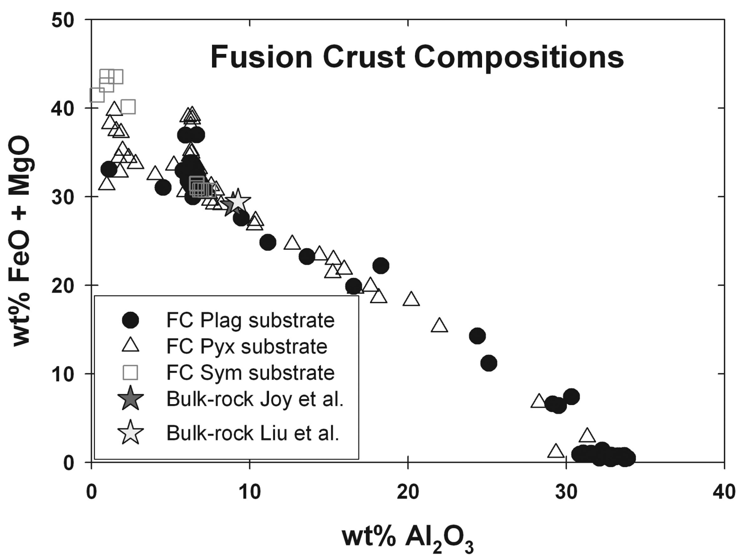

Fig. 4. EMP analyses of MIL 05035 indicating fusion crust compositional variations versus the bulk rock compositions from Joy et al. (2007) and Liu et al. (2009). FC = fusion crust, Plag = plagioclase, Pyx = pyroxene, Sym = symplectite. The cluster of points around 7% Al_2O_3 and 31% (FeO + MgO) would be expected, since pyroxene is the most abundant mineral in this sample.

available, but caution should always to be applied with its use and significance.

SUMMARY

Through the examination of the preserved fusion crust in thin sections from MIL 05035 and BTN 00300, we have observed that a fusion crust can have significant heterogeneity. This confirms similar determinations by our group. Substrate compositions, fragments incorporated into the melt, and grain size often have considerable influence over the adjacent fusion crust composition. The mixing that has occurred before these melts quenched appears to have been incapable of homogenization, resulting in a variety of compositions throughout the fusion crust. This study has demonstrated that the use of a few EMP fusion crust analyses to determine the bulk composition of a meteorite must be used with extreme caution. A few fusion crust analyses which are averaged to approximate the bulk rock composition may not adequately represent the variability of the fusion crust, let alone the entire meteorite.

The composition, texture, and lithology of the meteorite

Table 1. EMP data from selected fusion crust analyses of MIL 05035 and BTN 00300. For MIL 05035, Plag* (plagioclase), Pyx* (pyroxene), and Sym* (symplectite) indicate the substrate adjacent to the fusion-crust analysis. For BTN 00300, FC 1 represents selected analyses from traverse #1 within the fusion crust, FC 2 = traverse #2, FC 3 = traverse #3.

MIL 05035	Plag*	Plag*	Plag*	Plag*	Plag*	Plag*	Pyx*	Pyx*
P_2O_5	<0.03	0.04	0.09	0.06	<0.03	0.05	<0.03	<0.03
SiO_2	47.8	49.7	47.1	47.1	45.5	45.3	47.2	51.2
SO_2	<0.03	<0.03	<0.03	0.06	0.26	0.10	<0.03	<0.03
TiO_2	0.06	0.04	1.37	1.44	0.63	2.05	0.04	1.01
Al_2O_3	31.1	30.9	6.64	11.2	25.1	13.7	32.3	1.97
V_2O_3	0.07	<0.03	<0.03	0.04	0.05	<0.03	0.04	0.04
Cr_2O_3	0.06	0.05	0.28	0.25	0.08	0.21	<0.03	0.46
MgO	<0.03	0.05	6.30	6.60	2.03	4.54	0.05	12.8
CaO	17.1	16.6	11.6	12.5	15.4	12.2	17.8	10.6
MnO	<0.03	0.05	0.44	0.36	0.17	0.32	0.06	0.34
FeO	1.02	0.86	24.8	18.2	9.16	18.7	0.69	22.4
Na_2O	1.49	1.65	0.28	0.30	0.43	0.34	1.35	0.05
K_2O	0.20	0.22	0.05	0.08	0.07	0.07	0.06	<0.03
Total	98.9	100.2	99.0	98.2	98.9	97.6	99.6	100.9

MIL 05035	Pyx*	Pyx*	Pyx*	Pyx*	Sym*	Sym*	Sym*	Sym*
P_2O_5	<0.03	0.05	0.04	<0.03	0.03	0.04	0.04	0.04
SiO_2	50.5	46.0	45.4	45.5	45.3	47.0	46.0	45.8
SO_2	0.10	<0.03	0.06	<0.03	0.05	<0.03	0.13	0.11
TiO_2	0.93	2.48	2.53	0.87	0.67	0.57	0.59	0.82
Al_2O_3	2.79	7.87	7.56	15.3	1.54	0.97	0.98	2.32
V_2O_3	<0.03	<0.03	<0.03	<0.03	0.05	0.04	<0.03	0.05
Cr_2O_3	0.64	0.36	0.30	0.05	0.08	0.06	0.08	0.07
MgO	14.0	6.47	6.65	4.03	3.00	3.03	3.75	4.66
CaO	10.7	11.2	11.5	13.1	7.61	7.63	8.14	9.00
MnO	0.47	0.34	0.41	0.23	0.57	0.51	0.64	0.65
FeO	19.7	24.2	24.6	18.9	40.5	39.6	39.8	35.5
Na_2O	0.08	0.23	0.21	0.43	0.06	0.05	0.10	0.15
K_2O	<0.03	0.07	<0.03	0.06	0.05	<0.03	0.05	<0.03
Total	99.9	99.3	99.3	98.5	99.5	99.5	100.3	99.2

MIL 05035	Sym*	Sym*		BTN 00300	FC 1	FC 1	FC 1	FC 1
P_2O_5	0.03	0.05		P_2O_5	na	na	na	na
SiO_2	45.7	45.9		SiO_2	49.0	48.2	45.0	44.1
SO_2	0.09	<0.03		SO_2	<0.03	0.05	<0.03	<0.03
TiO_2	1.76	1.82		TiO_2	0.65	0.60	<0.03	<0.03
Al_2O_3	7.18	7.40		Al_2O_3	11.7	12.7	34.7	34.5
V_2O_3	<0.03	0.04		V_2O_3	na	na	na	na
Cr_2O_3	0.19	0.21		Cr_2O_3	0.12	0.16	<0.03	<0.03
MgO	6.86	6.61		MgO	7.45	7.11	0.03	0.03
CaO	11.5	11.4		CaO	9.32	9.37	17.8	18.1
MnO	0.47	0.43		MnO	0.63	0.50	<0.03	<0.03
FeO	23.8	24.1		FeO	19.8	18.8	0.21	0.18
Na_2O	0.22	0.21		Na_2O	0.39	0.37	1.05	1.13
K_2O	0.07	0.06		K_2O	0.04	0.03	0.08	0.05
Total	97.9	98.2		Total	99.1	97.9	98.9	98.1

BTN 00300	FC 2	FC 2	FC 2	FC 2	FC 3	FC 3	FC 3	FC 3
P_2O_5	na	na	na	na	na	na	na	na
SiO_2	47.1	48.2	46.4	45.6	47.6	47.3	48.9	49.3
SO_2	0.05	0.08	<0.03	<0.03	<0.03	<0.03	<0.03	0.32
TiO_2	0.68	0.70	0.37	<0.03	0.70	0.63	0.35	0.32
Al_2O_2	10.9	11.4	20.1	34.7	10.8	10.6	0.26	0.37
V_2O_2	na	na	na	na	na	na	na	na
Cr_2O_2	0.19	0.21	0.13	<0.03	0.20	0.13	0.15	0.18
MgO	7.26	6.96	5.70	0.05	7.23	7.49	12.0	11.6
CaO	9.76	9.83	10.9	18.0	9.55	9.06	3.24	2.83
MnO	0.62	0.61	0.47	<0.03	0.61	0.65	0.98	0.97
FeO	20.6	19.5	15.2	0.33	20.4	20.9	33.1	33.7
Na_2O	0.39	0.42	0.54	1.16	0.41	0.38	<0.03	<0.03
K_2O	0.03	<0.03	<0.03	0.06	<0.03	0.03	0.04	<0.03
Total	97.6	97.9	99.8	99.9	97.5	97.2	99.0	99.6

na = not analyzed.

Table 2. Comparison of the bulk rock compositions of Joy et al. (2007), Liu et al. (2009) and the average of 170 EMP fusion crust analyses from MIL 05035. *Joy et al. (2007) data were originally listed with a standard deviation of 2σ, but were modified here to maintain consistency; na = not analyzed.

	Fusion crust		Reconstructed		Bulk rock	
	This study	1σ error	Liu et al.	1σ error	Joy et al.	1σ error*
SiO_2	45.5	1.70	47.0	1.80	48.4	0.14
TiO_2	1.99	0.94	1.44	0.57	0.90	0.01
Al_2O_3	9.61	7.94	9.26	0.29	8.85	0.04
Cr_2O_3	0.30	0.28	0.33	0.07	0.30	0.01
MgO	5.83	2.39	7.44	0.82	7.79	0.03
CaO	11.9	2.16	11.8	0.40	12.1	0.10
MnO	0.36	0.13	0.32	0.03	0.33	0.02
FeO	22.5	8.05	22.0	1.90	20.7	0.10
Na_2O	0.32	0.35	0.26	0.03	0.21	0.01
K_2O	0.05	0.06	0.03	0.03	0.01	0.01
P_2O_5	0.05	0.03	0.05	0.01	0.02	0.01
SO_2	0.05	0.05	0.11	0.05	na	
Total	98.5		100		99.3	
Mg#	31.6		37.8		40.2	

are all significant influences on the retention capacity of solar wind implanted volatiles. Regolith breccias contain solar wind volatiles throughout their interiors, but crystalline rocks will only retain those volatiles on the outer few tens of nanometers of their surfaces. The rapid removal of surface material when a meteorite enters the Earth's atmosphere should remove all solar wind volatiles from the crystalline rock prior to the formation of a fusion crust. Therefore, the vesicles which are present in the fusion crusts of crystalline rocks form as a result of volatilization of minerals and/or elements which make up the rock and are not the result of solar wind implantation. Indeed, it is only the outermost portion (millimeters) of the meteorite that is really raised to high temperatures; which raises the question: just how much does escaping solar wind contribute to the bubbles in the fusion crust? The bubble/vesicle texture of lunar regolith breccia meteorites do not appear significantly different from those of wholly crystalline rocks.

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