CHARACTERIZING THE EFFECTS OF GLACIATION ON THE VOLCANIC SOURCE ROCKS OF THE SAND-E MARS-ANALOG MISSION AND ITS IMPLICATIONS FOR MARS. C. C. Bedford[1, 2], E. B. Rampe[2], M. T. Thorpe[2], R. C. Ewing[3], M. Nachon[3], K. Mason[3], E. Champion[3], L. Berger[3], B. Horgan[4], P. Sinha[4], A. Rudolph[4], E. Reid[5], M. G. A. Lapôtre[6], M. Hasson[6], and P. C. Gray[7], [1]Lunar and Planetary Institute, USRA, Houston, USA (cbedford@lpi.usra.edu), [2]NASA Johnson Space Center, Houston, USA, [3]Texas A&M University, Houston, USA, [4]Purdue University, Lafayette, USA, [5]Mission Control Space Services Ltd., Canada, [6]Stanford University, USA, [7]Duke University, USA.

Introduction: Mars' crust is largely basaltic, and few studies on the Earth have looked at the source-to-sink processes of basaltic volcaniclastic materials. This is particularly true for volcaniclastic materials derived from volcano-ice interactions which are hypothesized to have occurred on Mars [1-3], be a habitable environment for microorganisms [4], and contribute to the global dust inventory [5]. In this study, we seek to characterize the intraglacial and postglacial volcanic source rocks of our Mars analog field site to provide insight on how glaciation could impact volcanic source rocks on Mars.

The SAND-E mission: In July 2019, the SAND-E (Semi-Autonomous Navigation for Detrital Environments) mission investigated the Þórisjökull Mars-analog sedimentary system of SW Iceland. The main science aim of this mission was to investigate the physical and chemical weathering of basaltic sediments in Mars-analog sedimentary systems. The Þórisjökull system is a ~15 km long glacio-fluvio-aeolian sedimentary system that erodes and transports materials from the surrounding intraglacial and post-glacial volcanoes.

Three intraglacial volcanoes (Lítla Björnsfell, Stóra Björnsfell [SB], and the volcanics below Þórisjökull [Th]) are situated at the sediment source and were sampled for the study. In the field, Lítla Björnsfell was divided into two units – Lower [LLB] and Upper [ULB] – based on color differences and contact relationships to a mid-level subaerial flow (designated the Lower Lítla Björnsfell capping flow). These volcanoes are part of the Móberg formation in Iceland which erupted during periods of glaciation in the Pleistocene [6]. The 2019 SAND-E field site also had a postglacial shield volcano, Skjaldbreiður [SKJ]. The intraglacial volcanoes LLB, ULB, and SB consisted of pillow basalt, kubbaberg (cube-jointed) lava, and hyaloclastite tuff, indicative of a subglacial eruption. LLB and SB also had a flat capping unit suggesting that the eruptions penetrated the overlying ice cap.

Methods: Sample preparation for non-tuff samples included sawing the rocks to expose the unaltered interior and remove the weathered exteriors. Geochemical data were then collected using the hand-held Olympus Vanta portable X-ray fluorescence (pXRF) spectrometer. Source-rock endmembers for the non-tuff samples were calculated using a multivariate cluster analysis to test whether any geochemical variation is related to the different morphologies present within the volcanoes, or solely the parent magma.

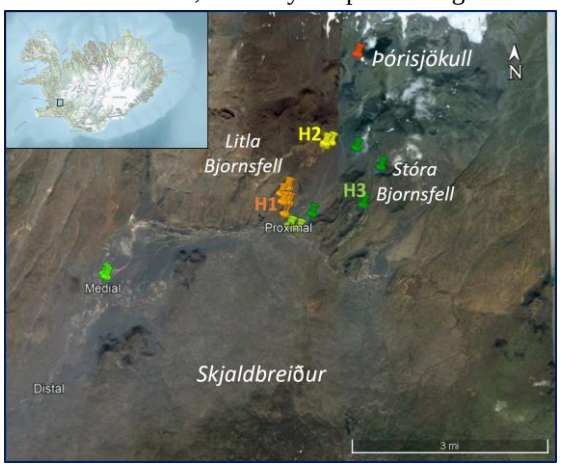

Figure 1: A map showing the field locality with sampling sites and the locations of the SAND-E field investigations. H1 = LLB, H2 = ULB, H3 = SB.

Bulk mineralogical data were acquired at the NASA Johnson Space Center using a Rigaku MiniFlex 6G. Petrographic thin sections of select hand samples were obtained to evaluate petrogenetic relationships among phases in the samples. Thin sections of the hyaloclastite tuff samples were polished and analyzed using the Cameca SX-100 electron microprobe at the NASA Johnson Space Center to investigate geochemical variation associated with the formation of the tuff deposits.

Results: *Pillow, Kubbaberg, and subaerial:* Most pillow, kubbaberg, and subaerial rocks are olivine tholeiites, with the exception of the high-MgO subaerial flow of LLB which is a picrite (MgO 17.7 wt%). The cluster analysis revealed 5 clusters. Cluster 1 has the highest CaO abundances which relates to the highest abundances of pyroxene (33.6 wt%) and included rocks from the LLB subglacial units and the black rocks from Th. Cluster 2 has the most MgO, Ni, Cr, and Co, relating to high olivine abundances (37.0 wt%) and consists of the subaerial capping flow from LLB. Cluster 3 has the most SiO_2, K_2O, and Ba, and the highest abundance of

volcanic glass (15.3 wt%) and derives the pillow and kubbaberg morphologies of ULB. Cluster 4 contains the rocks from SB and SKJ and has the most TiO_2, plagioclase feldspar, and iron oxides, and one of the highest Al_2O_3 and Sr contents. Finally, Cluster 5 has the highest Al_2O_3 and Sr abundances and belongs to the light-toned cobble sampled from the base of Th.

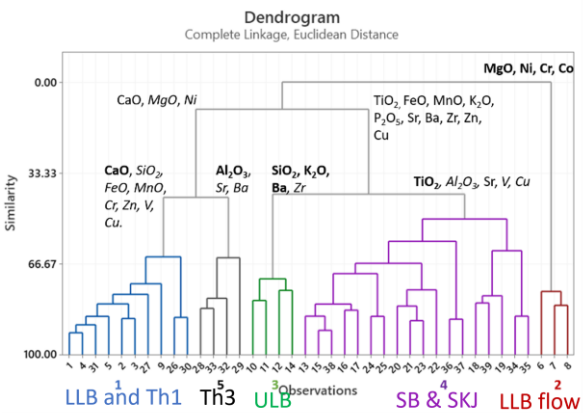

Figure 2: Dendrogram displaying the clustering results of the pillow, kubbaberg, and subaerial morphologies.

Table 1: Average mineralogy of the main clusters C1 shown in Fig. 1. Red represents high relative abundances and blue represents low abundances.

	C1	C2	C3	C4
Feldspar	43.9	37.8	41.0	51.8
Pyroxene	33.6	23.7	29.4	29.1
Olivine	13.9	37.0	14.3	16.3
Fe-oxides	0.5	0.8	0.1	1.7
Ilmenite	0.0	0.7	0.0	0.0
Amorphous	8.1	0.0	15.3	1.1
Total	100.0	100.0	100.0	100.0

Hyaloclastite tuff: Hyaloclastite tuff deposits compose the majority of the intraglacial volcanoes and contain a mixture of palagonite cement, tachylite clasts (opaque volcanic glass), reworked and brecciated pillow/kubbaberg clasts, and sideromelane (transparent volcanic glass) clasts. The degree of crystallinity of these deposits, palagonitization, grain size, and the ratio of tachylite and/or brecciated pillow to sideromelane varies with height in the volcanic mounds, with the uppermost units of ULB having the highest abundance of sideromelane (>90 wt% X-ray amorphous), finest grain size, and the most weakly cemented. One aspect all tuff deposits have in common is that they are geochemically enriched in TiO_2 and FeO_T and depleted in CaO relative to the other morphologies in their volcanoes. Phyllosilicates were not widespread in the hyaloclastite tuff samples but were detected in the SB sample.

Conclusions: The clustering results revealed that compositional variation relates to the individual volcanic units, not morphology, showing that there is no significant geochemical variation between the subglacial pillow or kubbaberg morphologies, and the subaerial flows. The main distinguishing factor between subaerial flows and subglacial pillow and kubbaberg morphologies relates to the degree of crystallinity. Subglacial units had an X-ray amorphous component, were more finely crystalline, and exhibited quench textures in thin section compared to the crystalline subaerial flow deposits that are likely derived from intraglacial capping units or postglacial volcanoes.

The only morphology that can be distinguished using geochemistry is the altered hyaloclastite tuff with ~1.5x higher TiO_2 and FeO_T values. Hyaloclastite tuff deposits also have the highest X-ray amorphous abundance.

Glaciation and deglaciation are also the causes of geochemical variation between the different volcanoes themselves [7-10]. Previous studies have shown that incompatible trace element depletion coupled with high SiO_2, CaO, and low FeO_T abundances, such as those found in LLB and Th likely relates to low-pressure peridotite melting during deglaciation [10]. Deglaciation also triggers decompression melting of the underlying mantle, which facilitates the transportation of dense, picritic melts [8-10], such as those which are present in the LLB capping unit. As such, LLB and Th are likely the oldest volcanics in the area relating to the onset of deglaciation during the last glacial maximum. ULB, SB and SKJ have similar incompatible element abundances, with SB and SKJ possessing very similar petrologic properties. As such, these likely formed later when the effects of the initial onset of deglaciation had passed.

Our results show that the best way to identify the products of volcano-ice interaction on Mars is to combine the detection of an X-ray amorphous component with an image analysis of the unit and high TiO_2 values with bulk geochemical data. As FeO_T can also partition into basaltic minerals, this is not a reliable indicator.

References: [1] Martínez-Alonso S. et al. (2011) doi:10.1016/j.icarus.2011.01.004. [2] Ghatan G. J. and Head J. W. (2002) doi:10.1029/2001JE001519 [3] Ackiss et al. (2018) doi:10.1016/j.icarus.2018.03.026 [4] Cousins C. R. et al. (2013) doi:10.1016/j.jvolgeores.2013.02.009 [5] Bishop J. L. et al. (2002) doi:10.1144/GSL.SP.2002.202.01.19 [6] Jakobsson S. P. and Gudmundsson M. T. (2008) *Jökull* no. 58 pp179-196. [7] Maclennan J. et al. (2002) doi:10.1029/2001GC000282. [8] Sinton J. et al. (2005) doi:10.129/2005GC001021. [9] Andrew R. E. B. and Gudmundsson A. (2007) doi: 10.1016/j.jvolgeores.2007.08.011. [10] Eason D. E. et al. (2015) doi:10.1007/s00445-015-0916-0.