EXPLORING MARTIAN IMPACT CRATERS: WHAT THEY CAN REVEAL ABOUT THE SUBSURFACE AND WHY THEY ARE IMPORTANT IN THE SEARCH FOR LIFE.

S. P. Schwenzer[1,8], O. Abramov[2], C. C. Allen[3], S. Clifford[1], J. Filiberto[1,4], D. A. Kring[1], J. Lasue[1,5], P. J. McGovern[1], H. E. Newsom[7], A. Treiman[1], D. T. Vaniman[5], R. C. Wiens[6], A. Wittmann[1]. [1]Lunar and Planetary Institute, USRA, 3600 Bay Area Blvd., Houston TX 77058, USA; schwenzer@lpi.usra.edu; clifford@lpi.usra.edu; kring@lpi.usra.edu; lasue@lpi.usra.edu,; mcgovern@lpi.usra.edu; treiman@lpi.usra.edu; wittmann@lpi.usra.edu;. [2]Department of Geological Sciences, University of Colorado, 2200 Colorado Ave., Boulder, CO 80309, USA; 'Oleg.Abramov@Colorado.edu. [3]ARES, NASA JSC, Mail code: KA, 2101 NASA Road One, Houston, TX, 77058, USA; carlton.c.allen@nasa.gov. [4]Rice University, Department of Earth Science- MS 126, 6100 Main Street, Houston Texas 77005, USA; Justin.Filiberto@rice.edu. [5]Los Alamos National Laboratory, Earth and Environmental Science, EES-14, Mail Stop D-462, Los Alamos, NM 87545, USA, vaniman@lanl.gov.Los; [6]Alamos National Laboratory, Space Science and Applications, ISR-1, Mail Stop D-466, Los Alamos, NM 87545, USA; vaniman@lanl.gov; rwiens@lanl.gov [7]Institute of Meteoritics and Dept. of Earth and Planetary Sciences MSC03-2050, University of New Mexico, Albuquerque NM 87131, USA; newsom@unm.edu. [8]The Open University, Earth and Environmental Sciences, Walton Hall, Milton Keynes, MK7 6AA, UK; s.p.schwenzer@open.ac.uk.

Introduction: During the Noachian period impact cratering was the dominant geological process on Early Mars and the contemporary Earth and Moon [1]. Therefore, impact craters are important targets for Mars exploration. Investigation of these craters will advance our understanding of impact processes and their interaction with the water-bearing Martian crust. Impact craters disturbed and heated this water-bearing crust, and likely initiated long-lived hydrothermal systems [2-4] that may have created (local) clement environments for life [5] and formed secondary minerals [6]. Impact-heat-generated lakes may also have formed [7]. Thus, Noachian impact craters are particularly important exploration targets, providing subsurface access, data on crucial geological processes, and warm, water-rich environments possibly conducive to life. Even if those craters are partially buried by younger geologic deposits, more recent small craters can penetrate those deposits and expose subsurface strata and hydrothermally altered material for study.

Hydrologic aspects and post-impact mineralogy: For habitable conditions, a key ingredient is water. Channel networks [e.g., 8,9], rampart craters [10], and hydrous minerals [e.g., 11,12] provide evidence of a water rich environment and crust in the Noachian. If the early Noachian began warm and wet, theoretical models of atmospheric evolution suggest that such conditions did not persist beyond the end of the late heavy bombardment [8,13]. With the transition to a colder climate, a freezing front developed in the planet's crust, creating a growing cold-trap for both atmospheric and subsurface H_2O – a region known as the cryosphere. Models show that the depth of the cryosphere at that time would vary from about 2 km near the equator up to 6 km near the poles [14]. Below this cryosphere, a briny aquifer is expected, which can connect individual sites of thermal anomalies such as impact craters or volcanoes. A comparably small impact crater of 11.6 km final crater diameter would penetrate this 6 km thick cryopshere [14]. Models of post-formation evolution of larger impact craters [4] indicate that the central region of a 100 km diameter crater reaches temperatures up to 900 °C, melting ice and extracting water from minerals. With time, a hydrothermal system evolves with most intense and longest activity between 300 and 100 °C. Temperatures decline with the isotherms moving inward and down over ~300,000 years [4]. The change in temperature and water flow disturbs the thermochemical state of the pre-impact stratigraphy, causing alteration minerals to form. The main hydrous silicates expected to form from Martian lithologies at intermediate temperatures of ~150 °C are chlorite, smectite (Mg-nontronite) and serpentine [6]. These model results for Martian conditions are supported by observations at terrestrial craters.

Ground truth on Earth and Mars: On Earth, there are few large, complex impact craters and impact basins that can be studied for their post-impact effects. Two prominent examples are Sudbury and Chixculub, for which post-impact hydrothermal hydrology was calculated using the same model that was applied to Mars [15,16]. Mineralogic information for both craters comes from detailed investigations (e.g., Chicxulub [17-19], and Sudbury [20]). In both cases, diverse hydrothermal mineral assemblages are observed that display a succession from high to lower temperatures and host rock dependence. Typically, clay minerals are key components in alteration of impact crater lithologies [21]. Transferring this knowledge to Mars is not straightforward because information from Mars is not at the same level of detail as for Earth. However, several discoveries of hydrous silicates, especially nontronite and chlorite in central peaks and terrace zones of complex Noachian craters on Mars, point at the potential of finding fossil hydrothermal systems and their alteration products. Currently the best examples come from an ~40 km diameter crater in Nili Fossae (17°N, 72°E) for which 15 % smectite and 20 % pumpellyite in a plagioclase and pyroxene bearing rock are deduced from the spectra [22]; a 25 km crater west of Nili Fossae (20°N, 66°E) where analcime and chlorite/smectite have been found in the central uplift [12]; and an ~60 km diameter crater in Cimmeria Terra (32°S, 141°E) where chlorite and either Al-phyllosilicate or hydrous silica have beend detected in the central uplift [23].

Impact craters and life: All craters with evidence of phyllosilicate in their central peaks are in Noachian terrains. Not only was the Noachian the period with water activity, the impact frequency was also very high during the Late Heavy Bombardment (e.g., [24]). This, in turn, may have caused extremely inhospitable conditions as a result of repeated sterilization of the surface (e.g., [25]). At the same time, an abundance of surface and subsurface habitats may have been created in the form of impact crater lakes (e.g., [7,26,27]) and impact-induced hydrothermal systems (e.g., [2,28]) driven by impact-deposited heat, providing an incubator for organisms able to thrive in hot subsurface hydrothermal fluids [29,30]. While hydrology and mineralogy of post-impact systems are independent of surface temperature, connection of the individual sites by a deep aquifer may have been critical for the emergence and resilience of life under cold surface conditions.

Exploring impact craters: The Martian crust, in general, and impact-generated strata, in particular, are divers and inhomogeneous both laterally and vertically. To take the depth-dimension into account, many proposed Mars landers have payloads that include drills or excavation tools, but no spacecraft instruments are currently capable of accessing deeper than a decimeter or so. However, natural excavation by smaller craters at sites of interest will allow access to the subsurface.

Gale crater and MSL. To illustrate this exploration strategy, we chose ~150 km Gale crater in Elysium Planitia (4.49ºS, 137.42ºE), which is also one of the proposed landing sites for MSL. Gale has a complex history that begins with the deposition of the target lithologies and continues with the impact and its aftermath, followed by sedimentation and erosion, including one or more crater lakes [26,31,32]. Small craters have hit all zones of the crater including the crater ejecta, crater terrace zone, crater floor and the central mound, and, thus, excavated pre-impact target rocks, impact strata, and post-impact sediments [14]. If MSL lands in Gale, a succession of instruments can be used to investigate fresh, less dust-covered young craters that expose strata of interest. Those instruments include the Mars Descent Imager to map the projected driving path upon landing, the imaging and analysis techniques on MSL's mast, which can operate from a distance; and finally, small craters and their ejecta can be contact sol targets where the rover stops to analyse the rocks with its detailed mineralogic instrument suite. Each site will most likely display a variety of rocks. For example, a subsequent impactor producing a crater into crater floor material could have excavated lake sediments and melt sheet material. Each site can provide options for geologic investigation and enhances opportunities to discover fossil habitats and any remnants of their potential inhabitants.

References: [1] Hartmann W.K., Neukum G. (2001) *Space Sci. Rev.*, 96, 165–194. [2] Newsom H.E. (1980) *Icarus*, 44, 207–216. [3] Newsom H.E. et al. (2001) *Astrobiology* 1, 71–88. [4] Abramov O., Kring D.A. (2005) *J. Geophys. Res. 110*, doi: 10.1029/2005JE002453. [5] Kring D.A. (2000) *GSA today 10(8)*, 1–7. [6] Schwenzer S.P., Kring. D.A. (2009) *Geology* 37, 1091–1094. [7] Newsom H.E. et al. (1996) *J. Geophys. Res*., 101, 14,951–14,955. [8] Carr M.H. (1999) *J. Geophys. Res.* 104, 21897–21909. [9] Carr M.H. (2006) The Surface of Mars. Cambridge. [10] Reiss D. et al. (2006) *MAPS* 41, 1437–1452. [11] Bibring J.-P. et al. (2005) *Science* 307, 1576–1581. [12] Ehlmann B.L. et al. (2009) *J. Geophys. Res.* 114, doi: 10.1029/2009JE003339. [13] Haberle R. M. et al. (1994) *Icarus* 109, 102–120. [14] Schwenzer, S.P. et al. The importance and exploration of Noachian impact craters as windows into the subsurface and as potential habitats for early Martian life, in prep. for Icarus by the authors of this abstract. [15] Abramov O., Kring D.A. (2004) *J. Geophys. Res.*, 109, doi: 10.1029/2003JE002213. [16] Abramov O., Kring D.A. (2007) *MAPS*, 42, 93–112. [17] Hecht L.et al. (2004) *MAPS*, 39: 1169–1186. [18] Zürcher L., Kring D.A. (2004) *MAPS*, 39: 1199–1221. [19] Zurcher L.et al. (2005) In: Kenkmann T. et al. Large Meteorite Impacts III, Geological Society of America, Special Paper 384: 223–238. [20] Ames D.E.et al. (2006) In: C. Cockellet al. Biological Processes Associated with Impact Events, p. 55–100. [21] Naumov M.V. (2005) *Geofluids*, 5: 165–184. [22] Poulet F. et al. (2008) *Icarus* 195, 106–130. [23] Wray J.J. et al. (2009) *Geology* 37, 1043–1046. [24] Strom R.G. et al. (2005) *Science* 309, 1847–1849. [25] Sleep N.H., Zahnle K. (1998) *J. Geophys. Res*. 103, 28529–28544. [26] Cabrol N.A. et al. (1999) *Icarus* 139, 235–245. [27] Newsom, H.E. in prep. Heated lakes on Mars. In: Cabrol, N. (ed.): Lakes on Mars, in preparation; Cambridge Press. [28] Zahnle K.J., Sleep N.H. (1997). Impacts and the early evolution of life. In Comets and the Origin and Evolution of Life, 175–208, Springer-Verlag, New York. [29] Maher K.A., Stevenson D.J. (1988) *Nature* 331, 612–614. [30] Chyba C.F. (1993) *Geochim. Cosmochim. Acta* 57, 3351–3358. [31] Malin M.C., Edgett, K.S. (2000) *Science* 290, 1927–1937. [32] Milliken, R.E. et al. (2009) *LPSC* XL, #1479.