The importance of (Noachian) impact craters as windows to the sub-surface and as potential hosts of life

Schwenzer[1], S. P., Abramov[2], O., Allen[3], C. C., Clifford[1], S., Filiberto[1,4], J., Kring[1], D. A., Lasue[1], J., McGovern[1], P. J., Newsom[5], H. E., Treiman[1], A. H., Wittmann[1], A.

[1]Lunar and Planetary Institute, USRA, 3600 Bay Area Blvd., Houston TX 77058, USA.
[2]Department of Geological Sciences, University of Colorado, 2200 Colorado Ave., Boulder, CO 80309, USA.
[3]ARES, NASA JSC, Mail code: KA, 2101 NASA Road One, Houston, TX, 77058, USA.
[4]Rice University, Department of Earth Science - MS 126, P.O. Box 1892, Houston, TX 77251, USA.
[5]Institute of Meteoritics and Dept. of Earth and Planetary Sciences MSC03-2050, University of New Mexico, Albuquerque NM 87131, USA.

This is LPI contribution #1508.

Synopsis:

Impact craters are important targets for Mars exploration, especially craters of ancient (Noachian) age, which record conditions on Early Mars. They can be used as natural "drill holes" or excavation pits into the subsurface, and so can provide information and samples that would otherwise be inaccessible (e.g., Moore 1977). Impact cratering was the dominant geological process on Early Mars and on the contemporary Earth and Moon (Hartmann and Neukum 2001); investigation of craters will inform our understanding of this geologic process and its effects. Impact craters, early in Mars' history, disturbed and heated its water-bearing crust, and likely initiated long-lived hydrothermal systems (Newsom 1980, Newsom et al. 2001; Abramov and Kring 2005), which created some clement environments for life (Kring 2000a). Also, impact-heat generated lakes may have formed (Newsom et al. 1996). Thus, Noachian impact craters are important exploration targets, providing subsurface access, data on crucial geological processes, and warm, water-rich environments possibly conducive to life.

Introduction:

The last two decades of Mars exploration have yielded crucial new data on its geology and history, one of which is the discovery of water-bearing minerals. Hydrous silicates, such as clays, have been detected from orbit by OMEGA (Bibring et al. 2006) and CRISM (Mustard et al. 2008), while hydrous sulphates have been detected by both orbiters and landers (Arvidson et al. 2007). Thus the NASA goal of "follow the water" has been partially fulfilled, with growing evidence that water was abundant in some places during the Noachian for significant periods of time. The next decade of Mars exploration will focus on understanding Mars as a geologic system, and search for habitable environments and traces of life (MEPAG 2008). The Mars Science Lander (MSL) will carry out the next step of even more sophisticated and detailed investigations on the Martian surface (JPL 2009), followed by the first sample caching activities – alongside with in-depth chemical, mineralogical and petrological characterizations – that will be undertaken by the Mars Astrobiology Explorer-Cacher (MAX-C); Pratt et al. 2009). Sample return remains a long term goal.

The need to learn about Martian water and its fate was driven – at least in part – by the questions about the habitability of the surface and subsurface through time (NRC 2003). Much has been achieved: we now know about the global distribution of near-surface water; we have detected VNIR signatures of hydrous and hydrated minerals; and we have investigated the Martian polar caps (e.g., Bell 2008, Mustard 2009). As is now clear, liquid water was far more abundant on Mars' surface during the Noachian era than at any time since; thus, all current candidate landing sites for MSL are in Noachian terrains: Eberswalde Crater, Gale Crater, Holden Crater, and Mawrth Vallis (Golombek et al. 2009). All these sites contain abundant phyllosilicates, which are key minerals for understanding Noachian aqueous processes. Three of the four target landing sites are in large impact craters, on the rationale that studying the aqueous sediments deposited in the craters, may elucidate Mars' hydrologic history, and could provide evidence of habitable environments, if not life.

However, impact craters are far more than passive depressions that may have hosted fluvial lakes and acted as catchments for aqueous sediments. Impact craters are also (1) the dominant landform of the Noachian, witness to the importance of impacts as a geologic process; (2) natural excavations into the Martian crust providing samples from depths that are otherwise inaccessible; and, (3) former heat sources that may have driven hydrothermal circulation in water- or ice-rich targets – generating and cycling liquid water, causing extensive rock alteration and supplying the necessary source of energy and nutrients required for sustaining habitable environments.

(1) Impact cratering as the dominant geologic process of the Noachian

Noachian terrains are the oldest and most heavily cratered on the Martian surface (Hartmann and Neukum 2001), with crater densities comparable to those of the ancient lunar and Mercurian highlands. Many researchers have postulated a spike in the impact cratering rate at ~ 3.9 Ga, which has significant implications for solar system dynamics and the persistence of life. Like dating Apollo lunar samples (LPI 2009) to learn about the Moon's cratering record, absolute dating of craters in Noachian terrains will further our understanding of Mars' basin forming events and their chronological context. This, in turn, will allow calibrating the crater count ages with radiometric ages. Consequently, these results will provide insight into the succession and duration of Mars' geologic events. Comparing this to the lunar records (e.g., Cohen et al. 2000), can answer questions on the early history of the terrestrial planets: their initial evolution and when and where they may have hosted hospitable environments. Most of the information needed to understand the early habitability of the solar system can only be retrieved from Mars, because the early history of the Earth has been largely obliterated by later geologic activity; the Moon never contained significant amounts of water; and Venus took a different evolutionary path whose evidence has been lost by a recent global resurfacing event.

On Mars, impact craters were frequent in the Noachian. The shorter the duration of the Late Heavy Bombardment (LHB), the greater the likelihood that crustal heating and resurfacing by impact events once exceeded that of volcanic activity. In addition to localized heating of the crust, impact cratering, as a geologic process, has a variety of other physical effects, such as excavating, overturning and fracturing the crust, as well as producing extensive topographic changes (e.g., the global dichotomy, Utopia, and Hellas). Thus, characteristics such as the porosity and permeability of the subsurface, as well as the number and distribution of sedimentary catchments on the surface are changed. Assuming water was present, impact-generated hydrothermal systems (see (3)), impact-triggered outflow channels (Brakenridge et al. 1985), and mineralogical changes (see (3)) would have resulted. Studies of terrestrial craters have shown that impacts wreak havoc in the direct and distant vicinity of the impact site (Kring 2007) and can cause global environmental effects (Kring 2000a, Segura et al. 2002).

On top of their impact cratering record, the Noachian terrains are also home to the abundant phyllosilicates identified from orbit (Bibring et al. 2006, Mustard et al. 2008). Therefore, studying the process that shaped the phyllosilicate-bearing terrains is a fundamental task when attempting to understand Noachian Mars as a geologic and potentially ecologic system.

(2) Impact craters are natural excavations into Mars' subsurface

Much of Mars' interesting science (e.g., groundwater, weathering profiles) lies beneath its surface, and thus is inaccessible to most remote sensing and surface exploration methods. Many proposed Mars landers have included drills or excavation tools, but none beyond simple 'back-hoes' have flown; more capable systems are heavy, complex, and power-hungry, leaving no spacecraft instruments currently capable of accessing deeper than a decimeter or so.

Impact craters provide natural access to the Martian subsurface – with no additional costs in spacecraft weight, complexity, and power. The formation and evolution of small impact craters is well understood from analyses of artificial impact and explosion sites (Moore 1967, 1977), impact cratering experiments (Stöffler et al. 1975), and terrestrial impact craters, especially the well-preserved Meteor Crater in Arizona (Shoemaker 1960, Kring 2007a). Impact craters excavate material from the subsurface, expose a geologic section of the target, and deposit samples of these rocks as ejecta near the crater therefore allowing access to rock that was formerly in the subsurface. Moreover, the ejecta is sorted by depth – the deepest material deposited closest to the crater rim. Experience with sampling of ejecta blankets on the

Moon was gained during the Apollo missions (Moore 1977); investigations of Martian ejecta blankets were undertaken by the MERs (Squyres et al. 2004, 2008). Furthermore, impact excavation has been proposed as a natural excavation process even for the search for the evidence of life (Cockell and Barlow 2002).

Crater walls are important, because they expose rocks in their natural context and sequence, and are accessible to 'remote' in situ instruments like the ChemCam on MSL or Raman spectrometry. However, crater walls may be steep and strongly brecciated, and thus difficult to access for contact investigations. Impact ejecta, while not in place, can be accessed and analyzed readily by a rover. The exploration strategy therefore would be to document and analyze the rocks in the crater walls to understand the local stratigraphy. Then, the rover can analyze fragments in the ejecta blanket, and link them to particular layers in the crater walls.

(3) Impact-deposited heat can drive hydrothermal systems

On present day Mars, permanent liquid water is unstable at the surface, but water ice has been detected in the subsurface (e.g., Carr 2006, Bell 2008). In Mars' early history, the geologic record contains evidence for liquid surface water. However, whether the Martian climate was ever warm and hospitable and how long such clement conditions may have lasted is still unknown (Carr 2006). Therefore, (volcanic) hydrothermal systems are considered important places for the search of life MEPAG ND-SAG (2008, p. 14–15): they provide a long-lived source of warm to hot water, and maintain a water flow that can transport chemical species. Moreover, the mineral reactions caused by the flow of hot water/brine can be harvested as source of energy by microorganisms. Furthermore, phylogenetic studies support the idea that life on Earth originated in warm to hot environments, because the tree of life originates from thermophile ancestors (Pace 1997). All the arguments in favor of volcanic hydrothermal systems hold true for impact-generated hydrothermal systems, too. During the period of LHB impact cratering may have been the dominant thermal process, controlling the surface and subsurface conditions of Noachian Mars.

The habitability of an environment depends critically on temperature, chemistry (nutrients and hazardous compounds), and the availability of water and energy. Moreover, the fractured nature of impact-metamorphosed rocks, the newly formed minerals and the increased surface area of minerals are just some features necessary for the creation of habitable environments (Cockell et al. 2005). This suggests that if life prevailed on Early Mars, impact craters would have been an abundant, contemporary feature that could have harbored life beyond a potential clement period with permanent liquid water on the surface.

Moreover, an impact delivers a huge amount of energy, which scales with the mass and the square of the velocity of the impactor – and much of it is turned into heat. This creates a powerful heat source in the center of the crater capable of generating intense hydrothermal activity. Hydrocode simulations for two large terrestrial craters (Abramov and Kring 2004, 2007) have provided insights into the temperature and fluid flow regimes of impact structures. Applied to Mars (Abramov and Kring 2005) the following scenario is expected to evolve in a complex crater of 100 km diameter: Shortly after the impact, rocks in the subsurface of the innermost part of the crater are up to 900 °C hot; temperatures decline with distance from the center. The water flow is mainly inwards at this point with a major upwelling zone along the hottest inner part. With time, the temperature decreases, and the diversity of water flow regimes increases. Several convection cells evolve in the area between the innermost part and the outer crater rim (Fig. 1). This activity could have been significantly increased by impactors large enough to break through the subsurface cryosphere (with a thickness estimated from 2 km at the equator to 5 km at the pole) and reach the underground liquid water reservoirs.

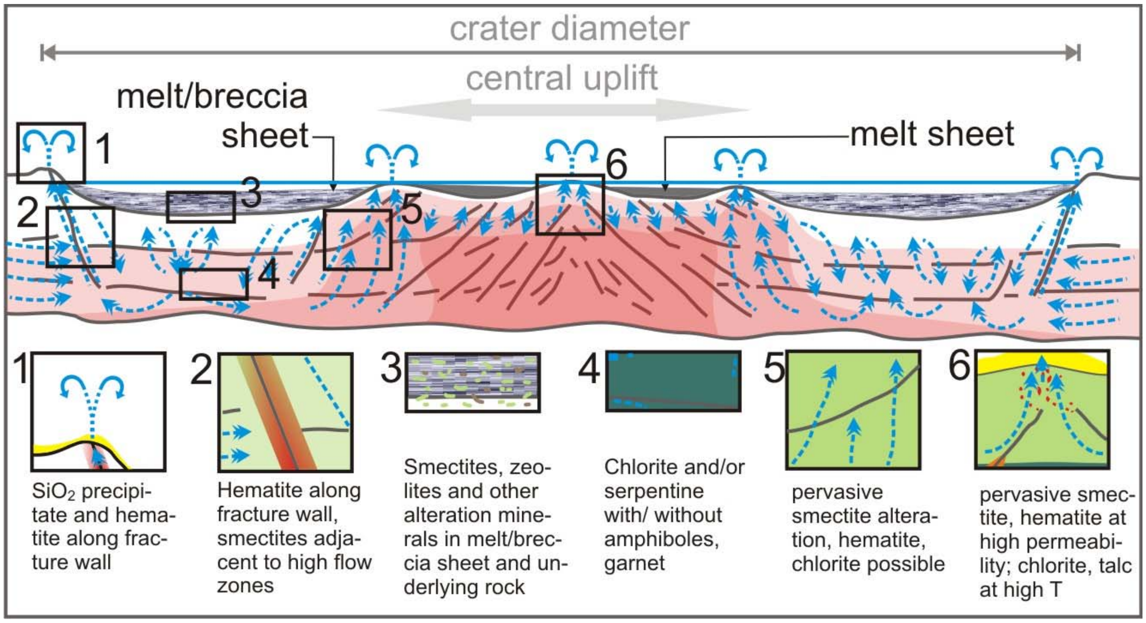

Figure 1. Schematic cross section of a complex Martian impact crater about 4000 years after the impact. Temperature distribution, water flow and alteration minerals are shown for the different settings possible as impact aftermath. The main mass of the water will be at temperatures between ambient and 200 °C.

The lifetime of this system is calculated to be 290,000 years (Abramov and Kring 2005); a 30 km diameter crater would be hydrothermally active for 30,000 years, while basin sized events can have lifetimes reaching the million year range (Abramov and Kring 2005). The change in temperature in concert with the – locally vigorous – water flow alters the physico-chemical conditions in the subsurface of the impact site. Consequentially, alteration minerals will form. Serpentine and chlorite are expected to be most abundant, where the permeability is low. The smectitic clay nontronite is the main mineral in more permeable parts of the host rock (Schwenzer and Kring in press, Fig. 1). Interestingly, nontronite was the first hydrous sheet silicate detected from the Martian orbit (Bibring et al. 2005). While hydrous (sheet) silicates (chlorite, nontronite) are very abundant on Noachian terrains, they are absent on younger terrains (Bibring et al. 2006, Mustard et al. 2008). Their ubiquity in the Noachian suggests that they may have been formed by a variety of geologic processes, but two factors make impact craters a likely source for such minerals: (1) The LHB overprinted the early Martian surface. Frequent impact craters cover the surface to the extent that crater saturation limit may have been reached (Hartmann and Neukum 2001); the surface thereby was deeply gardened (Hartmann and Neukum 2001) and impact-generated hydrothermal systems reached down to several kilometers (Abramov and Kring 2005). (2) Signatures of hydrous minerals have been found in the rims and central peaks of large, Noachian craters (e.g., Poulet et al. 2008, Ehlmann et al. 2008) providing potential ground-truth of the formation of these phases by impact-generated hydrothermal systems.

For the survival of life, impacts – as known from terrestrial cases – have to be considered as devastating and beneficial. As much as the Chicxulub impact caused a mass extinction at the K-T-boundary allowing a different flora and fauna to evolve afterwards (Kring 2000a, 2007), the LHB could have been a bottleneck for any existing life on Earth (Kring 2000a, Cockell 2006) resulting in the tree of life starting with thermophiles. If life existed on Mars, the same principles may apply, with impact-generated hydrothermal systems providing niches for life in a variety of temperature zones (Abramov and Kring 2005) that evolve over time. The systems are long lasting (Abramov and Kring 2005); and craters are abundant if not dominant (Hartmann and Neukum 2001). The alteration mineral assemblages contain a variety of sheet silicates (Schwenzer and Kring in press) that could have helped catalyzing the first steps towards life (Brack 2006). Those mineral reactions are furthermore capable of delivering nutrients and energy to support biomass (Varnes et al. 2003). Impact crater lakes can provide connections to deep aquifers and represent habitable Petri dishes where life could potentially evolve in situ or flourish (Newsom 1980, Newsom et al. 1996, Cockell 2006;). Investigating impact craters as sites for long-lasting (hot) water activity would therefore provide insights into the hydrological, mineralogical, and potential biological evolution of Early Mars.

Summary and exploration strategy

The investigation of large, Noachian impact craters will address fundamental questions regarding the geology, geologic evolution and habitability of Early Mars – including three of four MEPAG goals (MEPAG 2008):

- *I. Determine, if life ever arose on Mars:* Noachian-age impact craters, as well as the younger craters superposed on them, are natural scars that excavate the subsurface. Understanding the thermal, hydrological, and mineralogical history of these ancient craters will provide valuable insights into the nature of the Early Martian environment and its most important geologic process.
- *III. Determine the evolution of the surface and interior of Mars:* The formation of outcrops and the excavation of material from up to tens of kilometers depth give access to subsurface strata and their chemical, petrologic and mineralogic record. This alone makes impact craters on Noachian surfaces a superb approach to the study of the Martian crust. Moreover, impact cratering itself is an extraordinarily important process on Early Mars. Calibrating the Martian impact crater history by direct radiometric dating will put constraints on the geologic history of the entire planet.
- *IV. Prepare for human exploration:* Crater walls and ejecta blankets are unique in-situ-investigation–safe-sampling sites for human exploration. Also, large impact craters that exhibit evidence of past hydrothermal activity are excellent targets for ore deposits and other mineralogical resources, such as zeolites and clays (e.g., water and gas treatment), hydrothermal (ore) deposits (metal or energy resources) and as construction materials.

Proposed exploration strategy: The suitability of potential future landing sites, like Eberswalde, Gale, and Holden Craters, can be evaluated in the context of the above science goals. Smaller, superposed craters can provide important information about their hosts, investigated initially by an examination of the available HiRISE, HRSC, CRISM, OMEGA and other remote sensing data. Superposed craters on the larger impact's crater rim and central peak are the ones most likely to reveal evidence of hydrated silicates indicative of an impact-generated hydrothermal origin. The ones on the crater floor may unravel melt sheet mineralogy, which should express itself in mafic minerals; or they may provide outcrops of the sedimentary crater fill, depending on which material they hit and how large (i.e., deep) they are in relation to the sedimentary and impact generated strata. Therefore, an initial orbital investigation of the small craters in the large Noachian craters, yields a first-order expertise of their geological setting. Once on the ground with rover-based instrumentation, the exploration of the small craters should start with mapping the stratigraphy in the crater walls. Where direct access to crater walls is limited by the steepness of slopes or other local obstacles and hazards, investigations will require instruments that operate from a distance. The rover then should proceed to study the ejecta blanket with the same techniques. The rocks from the deepest strata thereby are expected closest to the crater rim. After linking ejecta material to the wall rock stratigraphy, methods that need direct rock contact can be applied. The rocks on the ejecta blanket can be sampled, encountering significantly less hazards than in crater walls. Also, the structure of a large crater's ejecta blanket may be revealed by the small craters, as well as potential hot hydrous alteration that may have occurred there.

While much can be accomplished with the data acquired by orbiting and landed spacecraft, some investigations require the acquisition, return and analysis of Martian samples in Earth-based laboratories. In this way, the robotic precursor missions necessary to conduct the initial reconnaissance of candidate landing sites for subsequent sample return missions will significantly increase our understanding of the scientific and planetary context of those missions. The same logic holds true in planning for future human exploration: where many of the initial exploration tasks can be successfully carried out by robotic spacecraft. These missions will pave the way for more in-depth exploration by human and robotic teams that will have the necessary capabilities and analytical resources to investigate the highly varied Martian geologic environment.

In conclusion, craters provide ready access to outcrops of ancient strata for all science targets and exploration strategies. Their scientific importance and value to exploration are further increased if the crater once supported active hydrothermal systems that may have provided habitats for ancient life and led to the formation of the minerals and ores necessary to sustain future human exploration.

References:

ABRAMOV, O. & KRING, D. A. (2004): Numerical modeling of an impact induced hydrothermal system at the Sudbury crater.– J. Geophys. Res., 109 (E10007): doi: 10.1029/2003JE002213.

ABRAMOV, O. & KRING, D. A. (2005): Impact-induced hydrothermal activity on Early Mars.– J. Geophys. Res., 110 (E12S09): doi: 10.1029/2005JE002453.

ABRAMOV, O. & KRING, D. A. (2007): Numerical modeling of impact-induced hydrothemal activity at the Chicxulub crater.– Meteoritics Planet. Sci., 42: 93–112.

ARVIDSON, R. E., SQUYRES, S. W., ANDERSON, R. C., BELL III, J. F., BLANEY, D. et al. (2007): Overview of the Spirit Mars Exploration Rover mission to Gusev Crater: Landing site to Backstay Rock in the Columbia Hills.– Journal of Geophysical Research, 111: E02S01, doi: 1029/2005JE02499, 22 p.

BELL, J. (2008): *The Martian Surface. Composition, Mineralogy, and Physical Properties*.– 636 S.,; Cambridge (Cambridge University Press).

BIBRING, J.-P., LANGEVIN, Y., GENDRIN, A., GONDET, B., POULET, F. et al. (2005): Mars surface diversity as revealed by the OMEGA/Mars Express Observations.– Science, **307**: 1576–1581.

BIBRING, J.-P., LANGEVIN, Y., MUSTARD, J. F., POULET, F., ARVIDSON, R. et al. (2006): Global mineralogical and aqueous Mars history derived from OMEGA/Mars Express data.– Science, **312**: 400–404.

BRACK, A. (2006): Clay Minerals and the Origin of Life.– In: BERGAYA, F., THENG, B. K. G. & LAGALY, G. (2006): Handbook of Clay Science.– Developments in Clay Science, 1: 379–391.

BRAKENRIDGE G. R., NEWSOM, H. E. & BAKER, V. R. (1985): Ancient hot springs on Mars: Origins and paleoenvironmental significance of small Martian valleys.– Geology, **13**: 859–862.

CARR, M. H. (2006): The Surface of Mars.– 307 p.; Cambridge.

COCKELL, C. S. (2006): The origin and emergence of life under impact bombardment.– Phil. Trans. R. Soc. B, **361**: 1845–1856.

COCKELL, C. S., & BARLOW, N. G. (2002): Impact excavation and the search for subsurface life on Mars.– Icarus, **155**: 340–349.

COCKELL, C., S., LEE, P., BROADY, P., LIM, D. S. S., OSINSKI, G. R., PARNELL, J., KOEBERL, C., PESONEN, L., & SALMINEN, J. (2005): Effects of asteroid and comet impacts on habitats for lithophytic organisms – A sythesis.– Meteoritics Planet. Sci., **40**: 1901–1914.

COHEN, B. A., SWINDLE, T. D. & KRING, D. A. (2000): Support for the lunar cataclysm hypothesis from lunar meteorite impact melt ages.– Science, **290**: 1754–1756.

EHLMANN, B. L., MUSTARD, J. F., BISHOP, J. L., SWAYZE, G. A., ROACH, L. H. et al. (2008): Distinct provinces of aqueaous alteration in the Western Isidis region identified with MRO-CRISM.– Lunar and Planetary Science, **XXXIX**: #2326; Houston.

HARTMANN, W. K. & NEUKUM, G. (2001): Cratering chronology and the evolution of Mars.– Space Sci. Rev., **96**: 165–194.

JPL (2009): http://msl-scicorner.jpl.nasa.gov/scienceplanning/

KRING, D. A. (2000a): Impact events and their effect on the origin, evolution, and distribution of life.– GSA today, 10(8): 1–7.

KRING, D. A. (2007a): *Guidebook to the Geology of Barringer Meteorite Crater, Arizona (a k a Meteor Crater)*.– Field Guide for the 70th Annual Meeting of the Meteoritical Society, LPI Conribution Number 1355: 150 p.; Houston (Lunar and Planetary Institute).

KRING, D. A. (2007): The Chicxulub impact event and its environmental consequences at the Cretaceous–Tertiary boundary.– Paleogeogr., Paleoclimat., Paleoecol., **225**: 4–21.

LPI 2009: http://www.lpi.usra.edu/lunar/samples/

MEPAG (2008): *Mars Scientific Goals, Objectives, Investigations, and Priorities: 2008*.– J. R. Johnson (ed.): 37 p. white paper posted September, 2008 by the Mars Exploration Program Analysis Group (MEPAG) at http://mepag.jpl.nasa.gov/reports/index.html.

MEPAG ND-SAG (2008): *Science Priorities for Mars Sample Return*.– http://mepag.jpl.nasa.gov/reports/ndsag.html.

MOORE, H. J. (1976): *Missile Impact Craters (White Sands Missile Range, New Mexico) and Applications to Lunar Research*.– Contrib. Astrogeol., Geol. Survey Prof. Paper **812-B**: 47p.

MOORE, H. J. (1977): Nevada test site craters used for astronaut training.– Jour. Research U. S. Geol. Survey, **5** (6): 719–733.

MUSTARD, J. F. (2009): http://mepag.jpl.nasa.gov/meeting/jul-09/MEPAG_DSMustard_07-2009-v9.pdf.

MUSTARD, J. F., MURCHIE, S., PELKEY, S. M., EHLMANN, B. L., MILLIKEN, R. E. et al. (2008): Hydrated silicate minerals on Mars observed by the Mars Reconnaissance Orbiter CRISM instrument.– Nature, **454**: 305–309.

NEWSOM, H. E. (1980): Hydrothermal alteration on impact melt sheets with implications for Mars.– Icarus, **44**: 207–216.

NEWSOM, H. E., G. E. Brittelle, C. A. Hibbitts, L. J. Crossey, and A. M. Kudo (1996): Impact crater lakes on Mars, J. Geophys. Res, **101**(E6): 14,951–14,955.

NEWSOM, H. E., J. J. Hagerty, and I. E. Thorsos (2001), Location and sampling of aqueous and hydrothermal deposits in Martian impact craters, Astrobiology, **1**: 71–88.

NRC (2003): New Frontiers in the Solar System – Solar System Exploration Survey.– National Research Council, 232 p.; National Academy of Sciences.

PACE, N. R. (1997): A molecular view of microbial diversity and the biosphere.–Science **276**: 734-740.

POULET, F., ARVIDSON, R. E., GOMEZ, C., MORRIS, R. V., BIBRING, J.-P. et al. (2008): Mineralogy of Terra Meridiani and western Arabia Terra from OMEGA/MEx and implications for their formation.– Icarus, **195**: 106–130.

PRATT, L.M., AND THE MEPAG MRR-SAG TEAM (2009). Mars Astrobiology Explorer-Cacher (MAX-C): A Potential Rover Mission for 2018, 7 p. white paper posted September, 2009 by the Mars Exploration Program Analysis Group (MEPAG) at http://mepag.jpl.nasa.gov/decadal/index.html.

SCHWENZER, S. P. AND KRING. D. A. (in press): Impact-generated hydrothermal systems: capable of forming phyllosilicates on Noachian Mars.– Geology.

SEGURA, T. L., TOON, O. B., COLAPRETEA. & ZAHNLE, K. (2002): Environmental effects of large impacts on Mars.– Science, **298**: 1977–1980.

SHOEMAKER, E. (1960): Penetration mechanics of high velocity meteorites, illustrated by Meteor Crater, Arizona.– Intenational Geological Congress, Report of the Twenty-First Session, Norden 1960: 418–434; Copenhagen.

SQUYRES, S. W., ARVIDSON, R. E., BELL III, J. F., BRÜCKNER, J., CABROL, N. A. et al. (2004): The Spirit Rover's Athena science investigation at Gusev Crater, Mars.– Science, **305**: 749–799.

SQUYRES, S. W., ARVIDSON, R. E., ATHENA SCIENCE TEAM (2008): Overview of Recent Results from the Opportunity Rover at Victoria Crater.– 39th Lunar Planet. Sci. Conf., LPI Contribution No. 1391., p. 2192.

STÖFFLER, D., GAULT, D. E., WEDEKIND, J. & POLKOWSKI, G. (1975): Experimental hypervelocity impact into quartz sand: Distribution and shock metamorphism of ejecta.– J. Geophys. Res., **80** (29): 4062–4077.

VARNES, E. S., JAKORSKY, B. M. & MCCOLLOM, T. M. (2003): Biological potential of martian hydrothermal Systems.– Astrobiology, **3**: 407–414.