THE PROCESSING OF ORGANIC MATTER IN IMPACT CRATERS: IMPLICATIONS FOR THE EXPLORATION FOR LIFE

John Parnell, Paula Lindgren

Department of Geology and Petroleum Geology, University of Aberdeen, Aberdeen AB24 3UE, U.K.
Email: J.Parnell@abdn.ac.uk

ABSTRACT

The study of organic matter in impact craters is important to understanding the relationships between impact events and the origin and preservation of biologically relevant materials on Earth and other planets. Case studies show the effects of moderate heating (maturation), strong heating (melting), and interaction with irradiation on organic matter.

Moderate heating in craters can be assessed using biomarker distribution. Measurements in the 24km diameter Haughton Crater, Canada, show that most organic matter at these moderate-sized impact sites may survive, including biomolecules, fossilized remains, and even extant microbial life. Stronger heating in crater centres should cause melting of carbon. Melt fragments in the Gardnos Crater, Norway, preserve abundant carbon, showing that despite high-temperature processing it may be available for reworking into biologically relevant organic molecules. Irradiation can cause the polymerization of simple organic molecules, causing an increase in complexity and the concentration of carbon, exemplified in the Lockne Crater, Sweden.

1. INTRODUCTION

Numerous impact craters contain organic matter, sometimes abundantly, suggesting that impact events can have a significant role in hydrocarbon generation and concentration [1,2]. The survival of organic matter following hypervelocity impacts is also of high interest because impact craters are viewed as possible sites for the establishment and evolution of primitive life on Earth and other planets such as Mars [3,4,5]. Impact craters have a further role in planetary exploration in providing a potential window through the surface zone of irradiation and oxidation in which most organic molecules may be destroyed [3].

2. ORGANIC MATTER IN IMPACT CRATERS

Carbonaceous matter in impact craters has been identified as particularly deserving of study [6]. A wide range of carbon forms is created at impact sites, including graphite, diamonds, silicon carbide, and fullerenes [7]. However, this documentation of mineralogical phases places an emphasis on high-temperature/high-pressure refractory forms, which are limited to the very centre of a crater. Over almost all of the crater volume, the response of organic matter is likely to be less extreme. Issues that deserve research include:

(i) Whether organic matter is entirely carbonized (i.e. all hydrogen lost), or if identifiable organic molecules survive.
(ii) Whether gradients in thermal alteration can be determined across a crater, and can be interpreted in a quantitative way.
(iii) Whether other processes pertinent to the impact environment affect the organic matter.

Addressing these issues will help us to predict the degree to which we might seek biosignatures within impact crater systems on Mars.

3. MODERATE HEATING

Moderate heating in craters can be assessed using biomolecules whose distribution is dependent upon thermal maturity. The 24km diameter Haughton Impact Structure, Canada, formed in rocks which contained pre-existing liquid hydrocarbons. Biomarker ratios in the hydrocarbons show a consistent pattern of variation in degree of heating across the structure (Fig. 1). The heating reached a maximum at the crater centre, and is attributed to hydrothermal activity following impact. Kinetic modelling, using absolute temperatures from fluid inclusion data, suggests a time scale of about 5000 years for the heating, at a maximum temperature of 210 ºC [8]. The short time scale suggests that in moderate-sized craters, which are abundant on Mars, heating may have been short-lived in terms of organic evolution, but concomitantly did not present such an extensive source of heat that existing organic matter was obliterated. Most organic matter at these moderate-sized impact sites may have survived, including biomolecules, fossilized remains, and even extant microbial life.

Studies of impact melt breccias within the Haughton crater have shown that biomarkers are even preserved within clasts of bedrock suspended within the melt matrix [9]. This is despite a probable original superheated melt temperature of 2000+ ºC and a melt crystallization temperature of 600+ ºC [10]. Clasts falling into the melt would have experienced a minimum contact temperature of the crystallization temperature, but although the organic matter within them has been thermally altered from brown to black colour (Fig. 2) because of carbonization, organic molecules can still be extracted. Lower ratios of melt volume to transient crater volume on Mars, consequent of lower gravity, mean that the clast content of Martian impact melts should be greater than on Earth [11], so clasts may be an important target for biosignatures on Mars.

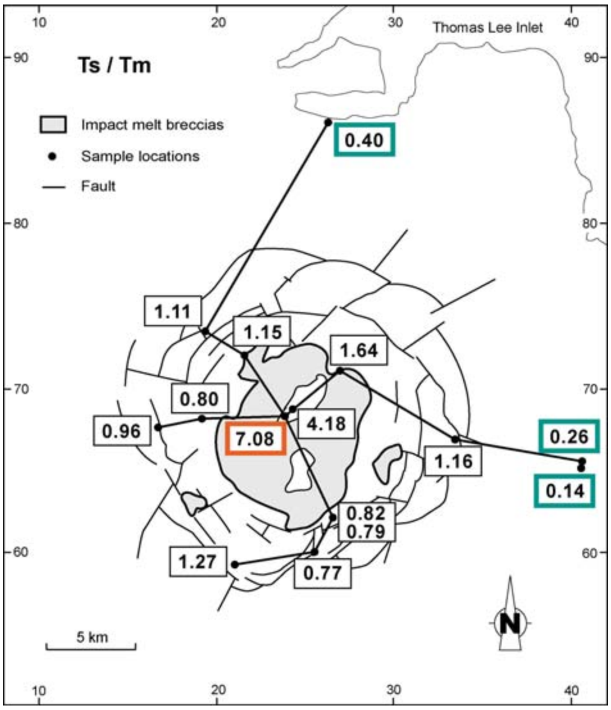

Fig. 1. Variations in biomarker ratio Ts/Tm, which increases with thermal maturity, across Haughton Crater, Canadian Arctic. Maximum maturity recorded at Crater centre, minimum maturity outside crater limits. From [8].

Fig. 2. Clasts of organic-rich target rock, Haughton Crater, Canadian Arctic. Upper row from bedrock coloured brown, reflecting moderate thermal maturity; Lower row from melt breccia coloured black, reflecting severe thermal alteration. Pen scale 15cm.

4. STRONG HEATING

Stronger heating in crater centres should cause melting of carbon. Melt fragments in melt breccias from the Gardnos Crater, Norway, contain abundant carbon. The carbon is ultimately derived from an organic-rich shale source, which is almost certainly the Cambrian Alum Shale as no other source has the requisite amount of carbon to explain the amount preserved in the melt fragments. A high proportion of the carbon present in the original melt was preserved, located at the boundary between two immiscible silicate phases in melt fragments (Fig. 3). The silicates represent alteration products from immiscible glasses in the original melt [12]. The stripping of hydrogen from carbon during melting prevents later hydrocarbon formation, hence the carbon is fixed in place rather than volatilized. Underlying lithic breccias that were not melted record hydrocarbon generation as a response to less extreme heating. Despite the high temperature history of the melt, the carbon is highly disordered as determined by Raman spectroscopy, rather than ordered crystalline graphite, and in this respect is comparable with carbon in chondrite chondrules. Hence carbon preserved through impact or other melting processes may be available for reworking into biologically relevant organic molecules.

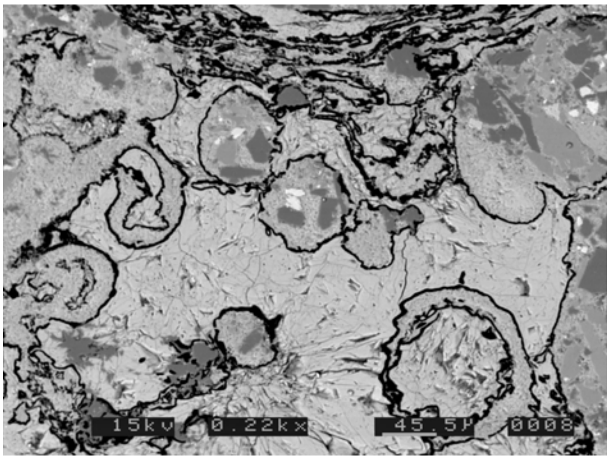

Fig. 3. Backscattered electron micrograph of melt fragment from Gardnos Crater suevite, showing immiscible fabric of two silicate phases separated by carbonaceous film (black). Scale bar 45.5 microns.

The response of hydrocarbon source rocks to flash heating will show a gradation with intensity of heating. With decreasing intensity the response will range through vaporization, melting, carbonization (graphitization), hydrocarbon generation, and lesser degrees of thermal maturation. These effects will be evident in different parts of a crater system. In the Gardnos crater, the products are carbon-rich melt and hydrocarbons. While the melt is generated almost instantaneously by the impact, the generation of hydrocarbons is kinetically-controlled and will occur during post-impact hydrothermal activity.

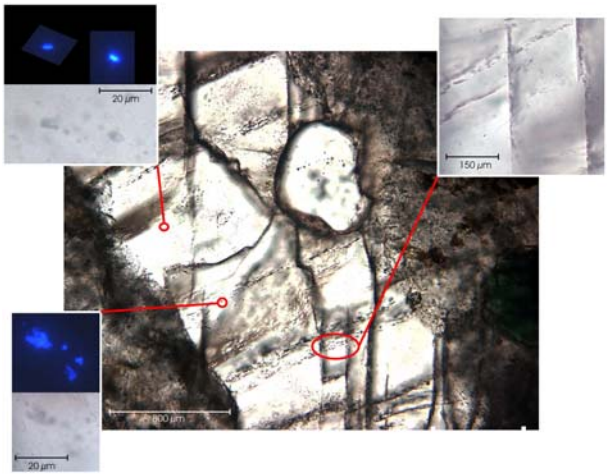

Fig. 4. Fluid inclusions in quartz vein in suevite, Gardnos crater. Fluorescing inclusions are liquid hydrocarbons; non-fluorescing inclusions contain aqueous fluid. (Photo courtesy D. Mark).

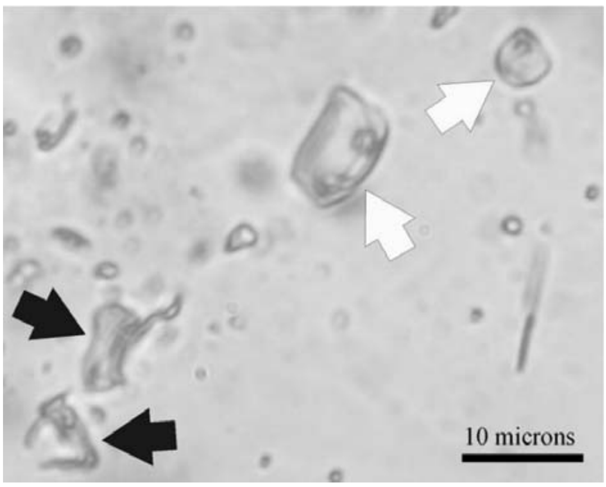

Fig. 5. Fluid inclusions in shocked quartzite, Gardnos Crater. Aqueous inclusions (white arrows) coexist with methane inclusions (black arrows).

In the suevite, cross-cutting quartz veinlets contain fluid inclusions with liquid hydrocarbons (Fig. 4). Beneath the melt-bearing rocks, shocked quartzite in lithic breccias contains traces of graphite, and methane sealed in fluid inclusions [13] (Fig. 5). They represent products of the hydrocarbon generation under less extreme heating.

5. IRRADIATION

Irradiation can cause the polymerization of simple organic molecules, causing an increase in complexity and the concentration of carbon. This has been suggested as a mechanism that could have occurred on the early Earth, involving irradiation from radioactive minerals [14]. Could this process occur in hydrothermal systems in impact craters, which have been suggested as sites for prebiotic chemistry and primitive evolution? In terrestrial craters, it is difficult to assess if complex organic molecules can be created from abiogenic compounds because abundant biogenic materials are already present, but we can assess if (i) crater environments can support concentration of carbon by radioactive minerals, albeit from biogenic sources, (ii) carbon concentration can occur in both target rock and crater-fill sediments, and (iii) carbon is concentrated where it would otherwise be undetectable.

These ideas were tested in the Lockne Crater, Sweden [15], where organic matter occurs in both impact brecciated granite and in resurge deposits, but is most common in the impact brecciated granite. The organic matter is present as migrated hydrocarbons and carbon-rich shale fragments. Samples were taken at several localities across the crater, including impact-brecciated granite from a drill core, then prepared as polished blocks of ca 1 x 2 cm for investigation by electron microscopy. Petrographic studies show that carbonaceous polymers have precipitated around radioactive minerals in both granitic and impact breccia matrix (Fig. 6). Uranium/thorium-rich carbonaceous nodules were detected in 17 of 20 crater samples investigated (Fig. 7). No nodules were detected outside the crater, where 5 samples of granitic basement and 5 samples of Caledonian fault brecciated granite were examined. The size of the nodules varies between ca 50 to 200 µm. They are usually rounded, lobate and sometimes exhibit crenulated margins, indicative of replacement (Fig.6). The U/Th phase often occurs as small inclusions in the bitumen, which implies digestion of a pre-existing mineral (Fig.6). Sometimes a rim of carbonaceous matter is observed around a U/Th silicate crystal, suggesting that the mineral is indigenous to the granite and was later coated by the carbon. The distribution data suggests that the carbonaceous nodules are associated with an impact-related process. The deposition of the hydrocarbon could be a result of fracture-controlled fluid flow at any time after impact, including hydrothermal fluid circulating in the crater after impact. The impact event would have increased the fracture permeability in the target rocks. These results show that where radioactive minerals are present in the target rocks for craters, they are a preferred site both for carbon concentration, and for our detection of organic molecules.

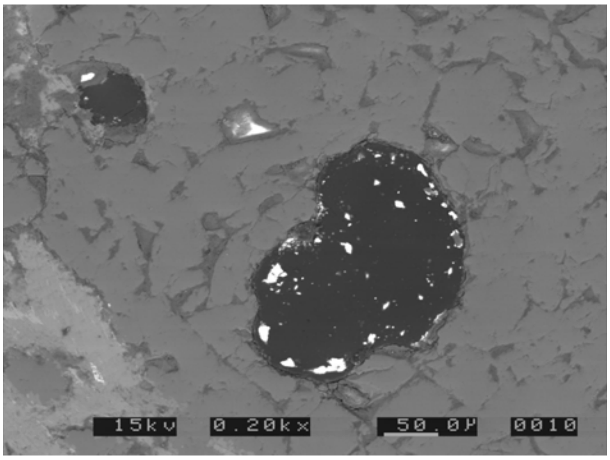

Fig. 6. Carbonaceous nodule (dark) containing uranium mineral inclusions (bright) in granitic quartzose clast, Lockne Crater. Scale bar 50 microns.

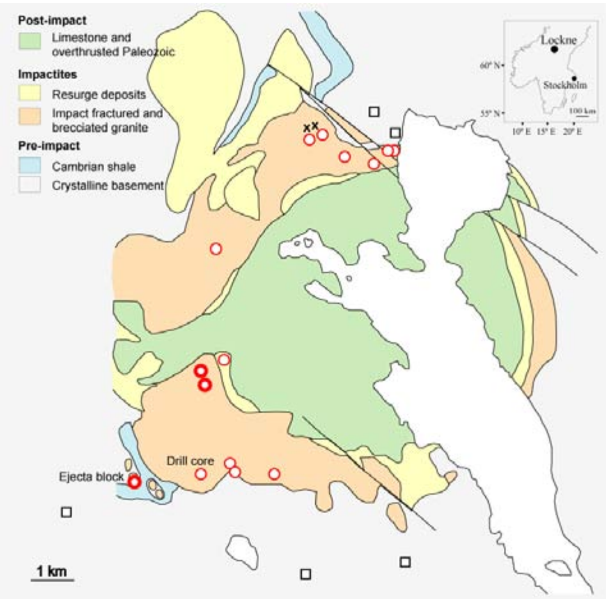

Fig. 7 Map of Lockne impact crater, Sweden, (simplified after [15]) showing the distribution of carbonaceous nodules.

White circles with red rims represent samples from impactites where U/Th- rich carbonaceous nodules have been detected. Nodules were detected in 17 of 20 crater rocks. The circles with a thinner red rim represent samples where 1-4 nodules in each thin section of ca 1x2 cm have been detected. The circles with a thicker red rim represent samples where 8-12 nodules have been found in a single thin section. From the drill core (see map), 3 of 4 samples investigated contained nodules. Crosses represent the other two samples investigated where nodules were not detected in the crater rocks, and occur in an unusual overturned granite flap. White squares represent samples of granite from outside the crater where no nodules have been detected.

6. PLANETARY EXPLORATION FOR BIOMARKERS

The relationships discussed above have implications for the search for organic molecules during planetary exploration. The survival of biomarkers despite impact heating means that sampling from a crater central uplift, impact ejecta blanket or melt breccia on Mars could allow detection of any fossil biomarkers present in the impact target rocks. In addition, impact-generated hydrothermal systems might well be a focus for any extant life (Fig. 8). An overwhelming advantage of sampling such materials in a relatively young crater is that the impact will have excavated them from beneath the depth at which irradiation/oxidation would have destroyed the majority of organic molecules [3]. Estimates using amino acid stabilities suggest that for surface samples older than 100-500 Ma, this depth of destruction reaches about 2-3m [16]. For younger samples, the accumulated irradiation dose is less and there is a better chance of organic molecules being preserved. Thus in a younger crater, ejecta and other breccias, and the newly exposed central uplift, offer this chance of preservation of fossil biomarkers. Any subsurface life in the same bedrocks, extant at the time of impact, could also leave a biomarker record. As the samples may be excavated from a depth below the liquid water isotherm, this need not be psychrophilic life. Contemporary life could become focussed in hydrothermal systems induced by impact activity. If there is any subsequent extant life, the fractured nature of the bedrock and ejecta, and shocked clasts in melt breccias, provide it with a habitat for colonization (Fig. 8), which has been demonstrated in the Haughton crater [17, 18, 19].

We can estimate an approximate minimum crater size required to sample ejecta from below the alteration depth. For relatively small craters, with a diameter/depth ratio of about 5:1 and ejecta derived mostly from the top third of the crater [20, 21], a crater of 300+m diameter gives a high level of confidence that a single ejecta block derives from below a 2m alteration depth (Fig. 9). In a young crater, this strategy would allow sampling of material that has been protected during burial from surficial alteration, but will not be exposed for long enough after ejection from the crater to be strongly affected. Evidence through thermal inertia data of hydrated minerals in impact ejecta within Noachian terrain on Mars [22] suggests that this could be a promising strategy in future exploration for organic remains from early in Mars' history.

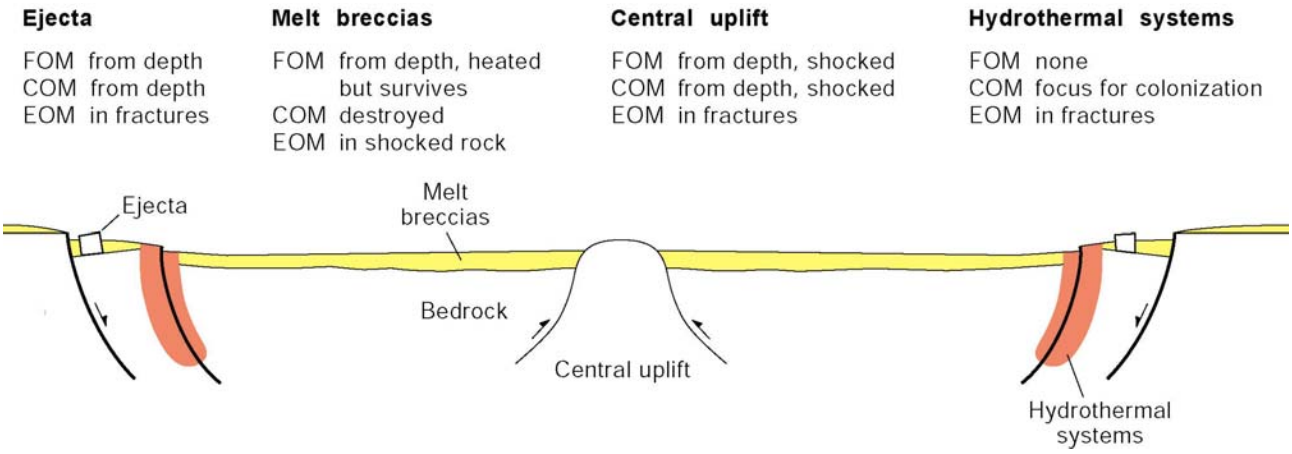

Fig. 8. Schematic cross-section of impact crater, showing four settings for sampling of organic matter (pre-existing fossil organic matter FOM, contemporaneous organic matter COM alive at time of impact, subsequent extant organic matter EOM).

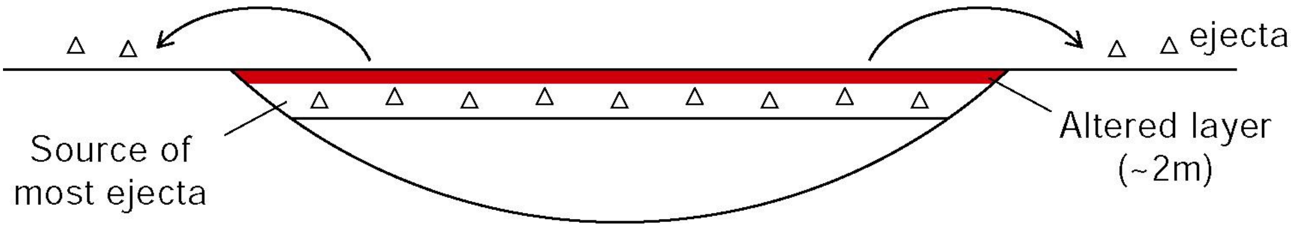

Fig. 9. Schematic cross-section of typical small crater with diameter-depth ratio of 5:1, and excavation of top third to form ejecta [20, 21]. Given a depth of alteration (irradiation, oxidation) of about 2m, the probability of an ejecta sample originating from below the altered layer is high for craters of >300+m diameter.

7. REFERENCES

1. Grieve R.A.F. and Masaitis V.L., The economic potential of terrestrial impact craters, *INTERNATIONAL GEOLOGY REVIEW*, Vol. 36, 105-151, 1994.

2. Grieve R.A.F., Terrestrial impact structures: Basic characteristics and economic significance, with emphasis on hydrocarbon production, *OKLAHOMA GEOLOGICAL SURVEY CIRCULAR*, Vol. 100, 3-16, 1997.

3. Newsom H.E., et al. Location and sampling of aqueous and hydrothermal deposits in Martian impact craters, *ASTROBIOLOGY*, Vol. 1, 71-88, 2001.

4. Farmer J.D., Hydrothermal systems: Doorways to early biosphere evolution, *GSA TODAY*, Vol. 10, No. 7, 1-9, 2000

5. Kring D.A., et al. Impact events and their effect on the origin, evolution and distribution of life, *GSA TODAY*, Vol. 10, No. 8, 1-7, 2000.

6. French B.M., The importance of being cratered: The new role of meteorite impact as a normal geological process, *METEORITICS & PLANETARY SCIENCE*, Vol. 39, 169-197, 2004.

7. Hough R.M., et al. Diamond and silicon-carbide in impact melt rock from the Ries impact crater, *NATURE*, Vol. 378, 41-44, 1995.

8. Parnell J., et al. Thermal alteration of organic matter in an impact crater and the duration of postimpact heating, *GEOLOGY*, Vol. 33, 373-376, 2005.

9. Lindgren P., et al. Preservation of biological signature within impact melt breccias, Haughton Impact Structure, *LUNAR AND PLANETARY SCIENCE*, Vol. XXXVII, abstract 1028, 2006.

10. Osinski, G.R. and Spray, J.G., Impact-generated carbonate melts: evidence from the Haughton structure, Canada, *EARTH AND PLANETARY SCIENCE LETTERS*, Vol. 194, 17-29, 2001.

11. Pope K.O., et al. Impact melt sheet formation on Mars and its implication for hydrothermal systems and exobiology, *ICARUS*, in press, 2006.

12. Lindgren P., et al. Liquid immiscibility in suevite melt, Gardnos impact crater, *LUNAR AND PLANETARY SCIENCE*, Vol. XXXVI, abstract 1629, 2005.

13. Andersen T. and Burke E.A.J., Methane inclusions in shocked quartz from the Gardnos impact breccia, South Norway, *EUROPEAN JOURNAL OF MINERALOGY*, Vol. 8, 927-936, 1996.

14. Parnell J., Mineral radioactivity in sands as a mechanism for fixation of organic carbon on the early Earth, *ORIGINS OF LIFE AND EVOLUTION OF THE BIOSPHERE*, Vol. 34, 533-547, 2004.

15. Lindstrom M., et al. The Lockne Crater: Revision and Reassessment of Structure and Impact Stratigraphy, In Koeberl C. and Henkel H. (eds) *Impact Tectonics*, Springer, Berlin, 357-388, 2005.

16. Kminek G. and Bada J.L., The effect of ionizing radiation on the preservation of amino acids on Mars, *EARTH AND PLANETARY LETTERS*, Vol. XX, in press, 2006.

17. Cockell C.S., et al. Impact-induced microbial endolithic habitats, *METEORITICS & PLANETARY SCIENCE*, Vol. 37, 1287-1298, 2002.

18. Cockell C.S., et al. Effect of asteroid and comet impacts on habitats for lithophytic organisms – A synthesis, *METEORITICS & PLANETARY SCIENCE*, Vol. 40, 1901-1914, 2005.

19. Parnell J., et al. Microbial colonization in impact-generated hydrothermal sulphate deposits, Haughton impact structure, and implications for sulphates on Mars, *INTERNATIONAL JOURNAL OF ASTROBIOLOGY*, Vol. 3, 247-256, 2004.

20. Melosh H.J., *Impact Cratering*, Oxford University Press, New York, 1989.

21. Grier J.A. and Hartmann W.K. Rayed craters as probes of the upper surface of Ma’adim Vallis and Elysium Planitia: Images from Mars Global Surveyor, *LUNAR AND PLANETARY SCIENCE*, Vol. XXXI, abstract 1478, 2000.

22. Costard F., et al. Detection of hydrated minerals on fluidized ejecta lobes from Omega observations; Implications in the history of Mars, *LUNAR AND PLANETARY SCIENCE*, Vol. XXXVII, abstract 1288, 2006.