

EVOLUTION OF LIFE IN THE SOLAR SYSTEM

WESTALL, FRANCES SN2-Johnson Space Center, Houston TX 77058, USA.

Introduction

It is in the nature of man to be curious about his environment in the widest sense. Recently, curiosity about life beyond the Earth was further stimulated by reports of evidence for life in a Martian meteorite (McKay *et al.*, 1996). Although there has been enormous debate about the validity of the evidence, there is no denying the significant boost given to all aspects of the search for extraterrestrial life, including a new look at life on Earth. Investigation into the evolution of life, its distribution and limits, and its remains in the rock record (biomarkers *s.l.*) is concomitant with the search for environments on other solar system planets which might have harboured life, and the search for Earth-like planets in our galaxy as well as any signs of intelligent life elsewhere (the SETI project).

This paper will review on the early evolution of terrestrial life and the fossil evidence for early life, and then consider the possibility of similar scenarios on Mars and, briefly, Venus, Europa and Titan.

The early evolution of life on Earth

The essential ingredients for life are three: liquid water, certain biogenically important elements (C, O, H, P, S, N), and an energy source (Jakosky and Shock, 1998). On Earth liquid water would have condensed on the surface as soon as the planet had cooled down sufficiently (about 4.4 b.y.). The biogenically important elements would have been readily available at the surface and within the crust. Carbon, the all important element for life, was a component of the dust/gas nebula which condensed to form the planets and was incorporated within the material forming within the Earth. It was also brought in by cometary impact, an important phenomenon during the early history of the Earth (Chyba and Sagan, 1988). Sources of energy were provided by chemical reactions producing energetic disequilibria, sunlight, geochemical energy from hydrothermal systems, and mineral weathering (Jakosky and Shock, 1998). With these basic requirements met, life could have appeared on Earth at any time after about 4.4 b.y. The processes by which life emerged, however, are still not well understood.

Conditions on Earth at this critical period were extreme and inhospitable by modern standards but "normal" for early life (and, indeed, they are still normal for the Prokaryote Kingdom). The

length of day was shorter and the tides higher because the moon was closer to the Earth. The sun had less luminosity which would have resulted in low ambient temperatures, but this was counteracted by the greenhouse gas, CO₂ (Kasting, 1993). The atmosphere had little or no O₂ (<1%, Kasting, 1993) and, therefore, no ozone layer to protect against harmful UV rays. Study of the impact history of the moon shows that the inner planets, including the Earth, underwent severe bombardment until about 3.8 b.y. ago. It is estimated that some of the impacts could have been of planet-sterilising magnitude, with fatal consequences for early life (Maher and Stevenson, 1988). Life either had multiple starts as a result of these impacts, or it could have taken refuge in, or even have been restricted to, hydrothermal vents, as suggested by the 16sRNA studies. Despite these difficulties, life emerged and took firm hold on Earth, apparently as a natural consequence of the prevailing geochemical environment (Jakosky and Shock, 1998), and probably rapidly (in about 10 million years, Lazcano and Miller, 1994).

What were the first organisms like? The oldest indication of life is carbon fractionation dated at 3.8 b.y. (Schidlowski, 1988; Mojzsis *et al.*, 1996). The first body fossils occur in cherts 3.5-3.3 b.y.-old (Walsh, 1992; Schopf, 1993; Westall *et al.*, 1999). Both the isotopic fractionation and the body fossils are derived from bacteria (the term bacteria here refers to the Prokaryote Kingdom, *i.e.* both the Bacteria and the Archaea). Bacteria are considered to be already well-developed organisms since they are incredibly complex in terms of evolution (Nealson, 1997), despite their apparent simplicity. 16sRNA analyses suggest that the last common ancestor was hyperthermophilic (*i.e.* heat-loving bacteria, Woese, 1987) and one theory has life originating in hydrothermal vents (Baross and Hoffman, 1985; Russell and Hall, 1997), although another argues for a "cold" origin (Galtier *et al.*, 1999). It is believed that the earliest cells had a heterotrophic metabolism (*i.e.* they used carbon as a source of energy). There are also indications that the earliest organisms, and maybe even the protocells, used phototrophy (energy from the sun). Furthermore, some studies link phototrophy (Nisbet and Fowler, 1996) with a possible hydrothermal

origin. However, there is no consensus as to the exact nature of the last common ancestor.

The oldest body fossils, recognisable as being similar to simple, cellular life as we know it, *i.e.* bacteria, occur in cherts from the early Archaean (3.5-3.3 b.y.) greenstone provinces of Barberton in South Africa (Walsh, 1992; Westall *et al.*, in press) and Pilbara in Western Australia (Schopf, 1993). These fossils are mostly of the filamentous type (Walsh, 1992; Schopf, 1993), although rod-shaped and coccoid fossils also occur (Westall *et al.*, in press), and are associated with thick accumulations of silicified microbial mats representing stromatolites. The formation of repetitive layers of mats indicates upward growth of the organisms creating them (either along a chemical gradient or towards light, *i.e.* phototactic activity). Mats would also provide protection for organisms from harmful UV rays, with the upper layers of dead organisms protecting the underlying layers from the rays but still permitting them to utilise the sunlight (Pierson and Olson, 1989). Modern microbial mats are dominated by oxygenic, photosynthetic cyanobacteria (Gerdes and Krumbein, 1987) and Walsh (1992) and Schopf (1993) interpreted some of their filamentous fossils as being of possible cyanophyte origin. This would mean that oxygenic photosynthesis, a relatively evolved metabolic process, arose at a very early point in the history of the Earth. On the other hand, the fossil morphologies are also consistent with other, mat-forming, anoxygenic, photosynthetic filamentous bacteria (*e.g.* purple sulphur and non sulphur bacteria, green sulphur bacteria and possibly anoxygenic cyanobacteria) (Pierson and Olson, 1989). Indeed, the phylogenetic studies indicate that anoxygenic photosynthesis probably predated oxygenic photosynthesis (Pierson and Olson, 1989).

The appearance of oxygen-producing cyanobacteria is fundamental to the further evolution of life on Earth because it is through the action of these bacteria that oxygen gradually built up in the atmosphere (Knoll and Holland, 1995). The first biochemical evidence for cyanobacteria is at 2.7 b.y. (Summons *et al.*, 1999) and although there are indications of the contemporaneous appearance of organisms with some eukaryotic characteristics (Brocks *et al.*, 1999), the first body fossils occur at 2.1b.y. (Han and Runnegar, 1992). These fossils are concomitant with a significant rise in atmospheric O₂ (Knoll and Holland, 1995).

Scenario for evolution on Mars

Compared to Earth, Mars, being smaller, probably cooled down more rapidly after initial aggregation, consequently, there could have been liquid water on its surface earlier than on Earth (water has a number of physical characteristics which make it an ideal medium for the support of life (Chang 1994; Jakosky, 1998). Whereas on Earth liquid water has remained at the surface of the planet since about 4.4 b.y. (with some possible interregnums caused by planet-sterilising impacts before 3.8. b.y. (Maher and Stevenson, 1988) and perhaps a number of periods of a totally frozen Earth (Hoffman *et al.*, 1998), this was not the case with Mars. At a fairly early period (about 3.8 b.y., Carr, 1996), significant accumulation of liquid water disappeared from the surface of the planet, probably forming a subsurface cryosphere (Fanale *et al.*, 1986; Squyres and Carr, 1986), as the planet lost its atmosphere and cooled down. However, there is abundant evidence for the episodic appearance of liquid water at the surface of the planet throughout its history, possibly in response to impact-related heating of the frozen aquifer.

Conditions on early Mars are believed to have been similar to those on Earth, although there is discussion as to exactly how "warm" the planet was (Carr, 1996). With a similar exogenous and endogenous input of organics and life-sustaining nutrients as is proposed for the Earth (McKay *et al.*, 1992), life could have arisen on that planet, possibly slightly earlier than it did on Earth. Or it may have been "seeded" by terrestrial meteorites (and *vice versa*). There may even have been sufficient time for life to have developed into something similar to the terrestrial prokaryote stage before the surficial water disappeared. However, given the early environmental deterioration, it is unlikely that it evolved into the eukaryote stage or even to the stage of prokaryotic, oxygenic photosynthesis (Jakosky and Shock, 1998). Thus, the search for life on Mars is concentrated on single celled life similar to bacteria.

If life did evolve on the planet, it may be extinct now because of the limited availability of liquid water for sufficiently continuous periods of time (Friedmann and Koriem, 1989). We would, therefore, search for the fossilised remains of Martian life. Even if life had taken refuge in the deep frozen subsurface aquifers with intermittent reappearance during impact-related reheating events, its remains would still be preserved as fossils both on the surface and in the subsurface.

We do not know if there is extant life at the surface of Mars, but so far there are no signs of it.

What about life on the other planets in our solar system and their satellites? The early history of Venus is probably similar to that of the Earth and it is, therefore, possible that life arose there (Jakosky, 1998). However, a runaway greenhouse effect has created temperatures too high for life, and also too high for fossils to have been preserved (Ingersoll, 1969). Of the satellites, Europa, circling Jupiter, has possibly liquid water underneath an icy crust, but calculations suggest that it does not generate enough heat to provide sufficient energy for the geochemical reactions giving rise to life (Jakosky and Shock, 1998). Saturn's satellite, Titan, is considered to be an interesting laboratory for prebiotic reactions (Lunine and McKay, 1995).

Fossil bacteria

In order to be able to identify possible fossil bacteria or bacteria-like structures in Martian materials with any degree of confidence, it is necessary, in the first place, to be able to do the same with terrestrial materials. Fossil prokaryotes of a certain complexity, such as cyanophytes, are readily recognisable so long as they are relatively well preserved. However, in terrestrial rocks of comparable age to the ancient, water influenced Martian terrain, the microbial fossils are relatively simple (Walsh, 1992; Schopf, 1993; Westall, 1999; Westall et al., 1999) and additional information apart from morphology is valuable in order to correctly identify them. Such additional information includes macroscopic sedimentological and environmental studies (e.g. biolamination, evaporite deposits, hot spring deposits etc.), microscopic studies showing a relationship between the purported fossils and biofilm laminae, and biogeochemical studies, such as in situ carbon isotope measurements, concentrations of heavy minerals associated with the possible microbial structures (e.g. U, Cr, Ti), and in situ analysis of specific molecular biomarkers derived from microbes (e.g. hopanes, steranes, etc.).

There are few well-preserved, terrestrial sedimentary successions which overlap in age the period in which there may potentially have been life at the surface of Mars. Although the 3.8 b.y.-year old Isua and Akilia supracrustals on Greenland fall well within this period, these rocks have been severely metamorphosed. Despite the isotopic evidence for the existence of

microorganisms at the time of deposition of these sediments (Schidlowski, 1988; Mojzsis et al., 1996), there are no remains of recognisable microbial morphology. However, SEM imaging of kerogen/graphite trapped within metaquartzites, combined with preliminary TOF-SIMS indications of a biomarker trace for bacterial polymer support interpretations of a microbial presence (Westall, Steele, unpub. data). On the other hand, slightly younger sedimentary and early diagenetic cherts from the Early Archaean sediments (3.3-3.5 b.y.) from the Barberton greenstone belt and the North Pole area in Australia are exceptionally well-preserved and the fossils contained in them represent excellent analogues for potential Martian fossils. Combined petrological and high resolution scanning electron microscope (field emission gun, FEG-SEM) observations of these rocks have documented well-preserved simple bacterial structures (Walsh, 1992; Westall, 1999; Westall et al., 1999; Westall, unpub. data). An electron dispersive system attached to the FEG-SEM can map remnant carbon associated with the fossil structures.

Conclusions

Given the length of time (> 1 billion years) necessary for the evolution of relatively complex prokaryotes and the first organisms with some eukaryotic characteristics under "optimal" conditions, it is unlikely that potential life on another planet could have evolved past the simple, non-oxygenic, prokaryote stage. However, in our search for life or protolife elsewhere in our solar system, a better understanding of the evolution of life on Earth, its characteristics and distribution, and the imprint of life in the rock record is essential.

Acknowledgement

I would like to thank the NRC for support at the JSC, and my colleagues E. Gibson, A. Steele and D. McKay for their encouragement and collaboration.

References

- Baross, J.A. and Hoffman, S.E., 1985. Submarine hydrothermal vents and associated gradient environments as sites for the origin and evolution of life. *Origins of Life*, 15: 327-345.
- Carr, M.H. 1996 *Water on Mars*. Oxford Univ. Press, 229p., New York.
- Brocks, J., Logan, G.A., Buick, R., and Summons, R.E., 1999. Archaean molecular fossils and the early rise of eukaryotes. *Science*, 285: 1033-1036.

- Chang, S., 1988. Planetary environments and the conditions for life. *Philosophical Transactions of the Royal Society of London, A*, 325: 601-610.
- Chyba, C. and Sagan, C., 1992. Endogenous production, exogenous delivery, and impact-shock synthesis of organic molecules: an inventory for the origins of life. *Nature*, 355: 125-131.
- Fanale, F.P. Salvail, J.R., Zent, A.P., and Postawko, S.E., 1986. Global distribution and migration of sub-surface ice on Mars, *Icarus*, 67: 1-18.
- Friedmann, E.I. and Koriem, A.M., 1989. Life on Mars: How it disappeared (if it ever was there). *Adv. Space Res.*, 9(6): 167-172.
- Galtier, N., Tourasse, N., and Gouy, M., 1999. A nonhyperthermophilic common ancestor to extant life forms. *Science*, 283: 220-221.
- Han, T.-M. and Runnegar, B., 1992. Megascopic eukaryotic algae from the 2.1 billion-year-old Negaunee iron formation, Michigan. *Science*, 257: 232
- Hoffman, P.F., Kaufman, A.J., Halverson, G.P., and Schrag, D.P., 1998, A Neoproterozoic snowball Earth. *Science*, 281: 1342-1346
- Ingersoll, A.P., 1969. The runaway greenhouse: a history of water on Venus. *J. Atmospheric Science*, 26: 1191-1198.
- Jakosky, B., 1998. The search for life on other planets. Cambridge Univ. Press, 326p., Cambridge.
- Jakosky, B.M. and Shock, E.L., 1998. The biological potential of Mars, the early Earth, and Europa. *J. Geophysical research*, 103: 19,359-19,364.
- Kasting, J.F., 1993. Earth's early atmosphere. *Science*, 259: 920-926.
- Knoll, A.H. and Holland, H.D., 1995., in *Studies in geophysics: effects of past global change on life*, Natl. Acad. Press, pp. 21-32, Washington.
- Lazcano, A. and Miller, S.L., 1994. How long did it take for life to begin and evolve to cyanobacteria? *J. Molecular Evolution*, 39: 546-554.
- Lunine, J.I. and McKay, C.P., 1995. Surface-atmosphere interactions on Titan compared with those of the prebiotic Earth. *Advances in Space Research*, 15: 303-311.
- McKay, C.P., Mancinelli, R.L., Stoker, C.R., and Wharton, R.A., 1992. The possibility of life on Mars during a water-rich past. in H. Kieffer, B.M. Jakosky, C.W. Snyder, and M.S. Matthews (Eds.), *Mars*, Univ. Arizona Press, pp. 1234-1245, Tucson.
- McKay, C.P., Friedman, E.I., Wharton, R.A., and Davies, W.L., 1992. History of water on Mars: a biological perspective. *Advanced Space Res.*, 12: (4)231-(4)238.
- McKay, D.S., Gibson, E.K., Thomas-Keprta, K., Vali, H., Romanek, C.S., Clemett, C.J., Chiler, X.D.F., Maechling, C.R., and Zare, R.N., 1996. Search for past life on Mars: Possible relic biogenic activity in martian meteorite ALH84001. *Science*, 273: 924-930.
- Mojzsis, S.J., Arrhenius, G., McKeegan, K.D., Harrison, T.M., Nutman, A.P. and Friend, C.R.L., 1996. Evidence for life on Earth before 3,800 million years ago. *Nature*, 384: 55-59.
- Nealson, K.H., 1997. The limits of life on earth and searching for life on Mars. *J. Geophysical Research*, 102: 23,675-23,686.
- Nisbet, E.G. and Fowler, C.M.R., 1996. Some liked it hot. *Nature*, 382: 404-405.
- Pierson, B.K. and Olson, J.M., 1989. Evolution of anoxygenic photosynthetic procaryotes. In: Y. Cohen and E. Rosenberg (Eds.), *Microbial mats*, American Society for Microbiology, pp. 402-429, Washington, D.C.
- Russell, M.J. and Hall, A.J., 1997. The emergence of life from iron monosulphide bubbles at a submarine hydrothermal redox and pH front. *J. Geological Society, London*, 154: 377-402.
- Schidlowski, M., 1988. A 3,800-million-year isotopic record of life from carbon in sedimentary rocks. *Nature*, 333: 313-318.
- Schopf, J.W., 1993, Microfossils of the early Archaean Apex Chert: new evidence of the antiquity of life. *Science*, 260: 640-646
- Squyres, S.W. and Carr, M.H., 1986, Geomorphic evidence for the distribution of groundwater on Mars. *Science*, 231: 249-152.
- Summons, R.E. Jahnke, L.L., Hope, J.M. and Logan, G.A., 1999. 2-Methylhopanoids as biomarkers for cyanobacterial oxygenic photosynthesis. *Nature*, 400:554-557.
- Walsh, M.M., 1992. Microfossils and possible microfossils from the early Archaean Onverwacht Group, Barberton Mountain Land. *Precambrian Research*, 54: 271-292.
- Westall, F. , de Wit, M.J., Dann, J., van der Gaast, S., de Ronde, C.E.J., and Gerneke, D. in press. Early Archaean fossil bacteria and biofilms in hydrothermally-influenced, shallow water sediments, Barberton greenstone belt, South Africa. *Precambrian Research*.
- Woese, C.R., 1987. Bacterial evolution. *Microbiology Reviews*, 51: 221-271.