Mem. S.A.It. Suppl. Vol. 16, 106

Memorie della
Supplementi

Life in extreme arid environments and implications for astrobiology

N. Stivaletta

Dipartimento di Scienze della Terra e Geologico-Ambientali Università di Bologna, Via Zamboni 67, 40126 Bologna, Italy, e-mail: nunzia.stivaletta@unibo.it

Abstract. Microorganisms have been studied in numerous extreme environments and it has been demonstrated that they can develop specific survival strategies in environments with temperature, radiation, salinity, pH, desiccation, pressure, oxygen availability at the edge of life. In this paper the microbial communities in arid and hyperarid (Atacama region (Chile) and Tunisian Sahara) are discussed. The evaporite (sulfates and chlorides) precipitation and arid conditions have supported the preservation of the microbial communities and their possible identification. The recent discoveries of hydrated sulfates on the Martian surface make useful the study of microbial life signatures in terrestrial arid and salty areas.

Key words. Evaporite, desert, Mars, astrobiology

1. Introduction

In the last decade the study of interactions between mineral/rocks and microbes has established the presence of microorganisms in wide range of environments, such as the ones alternatively characterized as high alkaline, acidic and hypersaline, with extreme dryness, high temperature range, high UV radiation, etc. The microorganisms able to adapt to these physical parameters are called extremophiles, and they are able to develop physiological, ecological, molecular adaptations in order to live in harsh conditions. Some of these environments and organisms are likely candidates for having given rise to life on Earth (Kasting & Ackerman 1986; Nisbet & Sleep 2001). The microbial life has flourished on Earth for more 3.5 Ga and dominated the Earth's biosphere for the first 2 Ga of its history. The studies of extreme ecosystems may, therefore, help to support hypothesis on the early life on Earth. Moreover, since a number of landforms, mineral compositions and interpretation of processes on Mars have terrestrial analogues, the study of signatures left by microorganisms in Earth analogues of Martian environments might be useful for the recognition of life during the forthcoming astrobiological missions planned by NASA and ESA. The Atacama Desert (Chile), for example, is considered analogous to certain Mars area because of its hyperarid conditions, it represents a paradigmatic example that offers the possibility of testing the ability of microorganisms to survive in extremely dry conditions (Dose et al. 2001; McKay et al. 2003; Navarro-Gonzales 2003; Warren-Rhodes et al. 2006; Wierzchos et al. 2006).

Extensive evaporite deposits (sulfates and chlorides) precipitate in arid environments

Send offprint requests to: N. Stivaletta

Fig. 1. Hyperarid region of the Atacama Desert (northern Chile, Salar Grande). The white spots indicate the fossil salts deposits.

within the ephemeral salt lakes and several microorganisms are associated with these deposits. The microbes that thrive in saline conditions are called halophiles and include taxa representing all three domains of life, Archaea, Bacteria and Eukarya. Depending on the salt (NaCl) concentration of the optimum growth rate of halophiles, they can be classified as slight (2-5% NaCl), moderate (5-20% NaCl) and extreme halophiles (20-30% NaCl). The halophiles are subject to high salt concentration and accumulate KCl or compatible solute in their cells to maintain high intracellular salt osmotically at least equivalent to the external concentrations (Oren 1999). Besides tolerating high salinity, microorganisms inhabitating desert areas are subject to the intense sunlight, the ultraviolet (UV) radiation and desiccation conditions. Under such conditions, the growth of microorganisms on surface areas directly exposed is largely prevented, whereas subsurficial locations become refuge for microbial communities. Certain microorganisms living in extreme arid environments can be considered to approach some of the physical limits for life. In their survival strategies, the extremophiles have to face hostile factors that are analogous, in some respect, to the present-day surface of Mars. In addition, the discovery of sulfates in area of the Martian surface (Squyres et al. 2004; Vaniman et al. 2004; Langevin et al. 2005; Bibring et al. 2007; Poulet et al. 2008) raises the possibility that traces of microorganisms might be found associated with these deposits.

This paper analyzes the microbial communities in extreme arid and salty environments, such as the Atacama (northern Chile) and Sahara Deserts (southern Tunisia). These areas are characterized by high precipitation of sulfates and chlorides in salt flats and ephimeral lakes that are thought to be the environments in which the evaporite minerals of the Martian surface may have precipitated.

2. Endolithic communities in arid environments

The occurrence of water is the basic requirement for life. Despite that, extremely arid environments (Fig. 1) harbour communities of microorganisms that find in the interior of the rocks sufficient water to live and reproduce. These communities are called endoliths and their mode of life includes several different ecological niches: chasmoendoliths live in cracks or fracture in rocks, euendoliths penetrate actively soluble carbonate and phosphate substrates and cryptoendoliths occupy pre-existing fissures and structural cavities in the rocks, such as the pore spaces between grain boundaries or spaces produced and vacated by euendoliths (Golubic et al. 1981). The endolithic environments keep greater amount of water than the surface: the pore water from soil, humidity, water vapour that condenses at night even in the hottest deserts, represent water reservoirs which are then absorbed by some specific rocks. Microbes are vulnerable to UV radiation, particularly at an early stage, when the screening pigments have not yet been developed. The millimetres thickness of rocks occupied by endoliths and the transparency of some minerals (that compose the rocks) provide protection from high UV radiation, but at the same time enable the processes of photosynthesis by microorganisms (Friedmann 1982). Cockell et al. (2002, 2008) have demonstrated that 5 min of exposure of *Chroococcidiopsis sp.*, a desiccation-tolerant cyanobacterium, to a UV irradiation similar to the one present in the Martian surface and visible light led to 99% loss of cells viability. However the same cyanobacterium could survive at 1mm below the surface of a rocks if the water and nutrient reqirements for growth were provided. In addition, the rock porosity provides interstitial spaces suitable for microbial colonization and the maintenance of certain amount of moisture. The colonization by microbes of rock surfaces and near surfaces is therefore selective and seems to be largely dependent on the mineral composition. The most common type of rocks that are suitable for colonization by endoliths as described in literature include sandstone, limestone halite and gypsum crusts.

3. Microbial communities of the Sahara salt lakes (southern Tunisia)

The southern Tunisia is characterized by several continental salt lakes (locally called chotts) in which periodic flooding (wet season) alternate with the dry season lead to dramatic changes of salt diluition that make unstable these environments. The salinity measured in these ephimeral lakes ranges between 29-37 % NaCl (Stivaletta & Barbieri 2009) and this allowed the precipitation of thick evaporite deposits. In spite of the high salinity and semiarid conditions of this area the microbiotic communities occur and are evidenced by intense coloration of the waters due to pigments produced by halophilic Archaea (Halobacteria) and eukaryotic algae (*Dunaliella salina*) (Fig 2). Depending on the species and environmental conditions, cells of microorganims can be green, when chlorophyll a and b are the main photosynthetic pigments, or red-orange color because of large amounts of carotenoids. In the Chott el Jerid, for example, the production of carotenoids is significant and during the salt precipitation cartenoid-rich microorganisms (e.g. the chloroficean alga *Dunaliella salina*) can be trapped making the crystals a deep red-orange color (Fig 3). On exposed surfaces in desert area microorganisms requires special protective mechanisms to avoid the photoinhibition of photosynthesis and the chemical damage of proteins, DNA and membranes (Cockell 2000). Therefore, over production of the carotenoids is an the indicator of light stress and the microorganims can evolve several mechanisms to reduce the negative of UV exposure, an example is the down-migration inside the rocks (endolithic mode life). Gypsum deposits occur extensively along

Fig. 2. Chott el Jerid (southern Tunisia) - The red-orange coloration of the water is due to the high concentration of carotenoids of halophilic Archaea and microscopic algae.

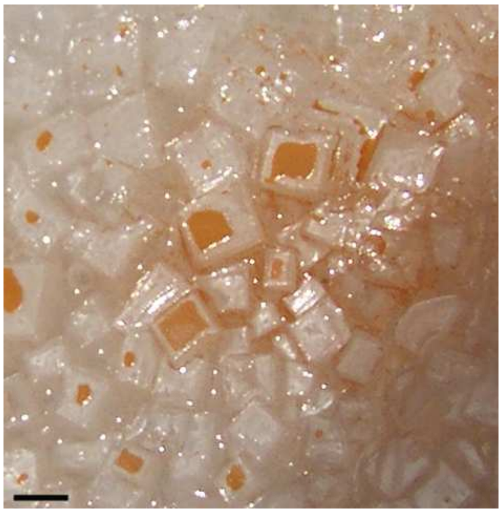

Fig. 3. Chott el Jerid - Microorganims trapped during the halite crystals growth. Scale bar: 0.5 cm.

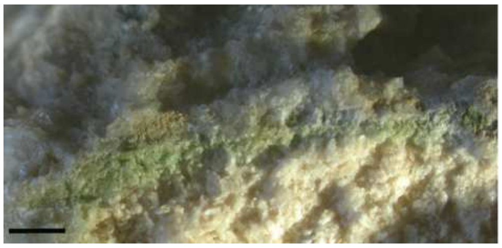

Fig. 4. Chott el Jerid - Cross fracture of a gypsum crust, note the green-brown colored layer just beneath the surface. Scale bar: 1cm.

the border of the Chott el Jerid and the rock surfaces appear lifeless.

When the gypsum deposit is mechanically broken, however, green-brown layers can be recognized (Fig 4) (Stivaletta & Barbieri 2009). Analyses of the pigment compositions were performed in selected portions (Stivaletta et al. 2010): from the surface layer (0-2 mm) and subsurface layer (2-4 mm). The surface layers are potentially exposed to higher ultraviolet radiation than the ones experienced by underlying subsurface layer. The results of chromatographic analyses have shown that the pigments diversity is higher within the surface layers. In particular the greater value of certain carotenoids, such as the canthaxanthin, compared to others, suggests a potential photoprotective role for this compound. This is the reason why the microorganisms grow near rock/mineral or sediment surfaces usually produce orange-brown color of the entire colonized layer (carotenoid pigments), whereas beneath the surface the sediment show a prevailing green coloration due to the abundance of chlorophylls. In order to resist the negative effect of UV radiation, microorganisms can also develop a strategy for repair the DNA, an example comes from the gypsum deposits of the Tunisia chotts where a member of the family Deinococcocales was detected by molecular techniques. This taxon is composed of microorganisms frequently isolated or detected in cold and hot desert (de la Torre et al. 2003; de Groot et al., 2005; Rainey et al. 2005) and are best know for their ability to withstand severe damages of their DNA having multiple copies of its genome and rapid DNA repair (Edwards & Battista 2003).

4. Microbial communities in Atacama Desert

The Atacama Desert (northern of Chile), covers more than 1000 Km and represents the driest and oldest desert on Earth surface (Clarke 2006). Such arid condition was established in the region several million of years ago (Dunai et al. 2005; Hartley et al. 2005) as result of the unique physiographic position that prevents eastern and western access of moisture. The extreme dryness with annual rainfalls of even less than 1mm, high altitude, daily thermic excursion, hypersaline conditions and hydrothermal phenomena make the region of Atacama Desert ideal for studies on the microrganisms in extreme environments. The driest (hyperarid) portion of the Atacama Desert is very close to Pacific and the only moisture comes from the early morning coastal fog. In this area a large fossil salt (NaCl) accumulation occur in the Salar Grande (salar= combination of evaporite crusts and saline lakes), which is considered hydrological inactive region (Chong 1988) (Fig 1). In these salt deposits of the hyperarid settings green-colored horizons have recently been detected just beneath the salt rock surface (Fig 5). The microorganisms identified belong to the *Chroococcidiopsis* morphospecies, a cyanobacterium genus able to remain for long period in the living state known as anhydrobiosis (Billi & Potts 2002).The hygroscopic nature of halite, which enables it to retain water when the relative humidity of air is greater than 70-75% (Davila et al. 2008) is an important factor to support microbial colonization. The condensed water vapour into aqueous solution on the crystal surface and/or between the crystals and the microcavities produced by dissolution create microniches that are favourable for the development of microbial life. Together with moisture retention, the light color and trasparency of evaporite minerals are a further useful factors to favour the colonization by photosynthetic microbes that find repair against high UV radiation.

In Atacama region, areas with more available water, such as Salar de Atacama, create shallow ponds characterized by high salt concentration between 160 and 180 g/l (Stivaletta et al. in press.). Similarly, in these ephimeral waters, the colonization of evaporite deposits occur few millimetes below the surface as a presumable photoprotection against the solar radiation (Fig 6). The microbial diversity evaluated by means of molecular tools (Stivaletta et al. in press.) shows that it strongly depends on the salt concentration and is composed by halophilic Archaea (genus *Haloadaptatus*), halophilic cyanobacteria (genus *Euhalothece*) and purple bacteria.

Fig. 5. Atacama Desert (Salar Grande, northern Chile) - High porosity of salt deposits of halite contains endolithic commmuties (green color)Scale bar: 1cm.

Fig. 6. Atacama Desert (Salar de Atacama, northern Chile) - Thick evaporite deposits precipitated in the ephimeral salt lakes showing just beneath the surface colored horizons due the presence of endolithic communities.

5. Astrobiological implications

Several studies have demonstrated that sulfates and chlorides minerals appear to be an optimal refuge for microorganisms in terrestrial hostile environments (Wierzchos et al. 2006; Dong et al. 2007; Stivaletta & Barbieri 2009; Stivaletta et al. in press.). The discovery of hydrated sulfates on Mars surface has sparked off considerable interest in the astrobiological potential of the evaporite deposits and their associated microorganims (Barbieri 2006; Kumbrein et al. 2004; Stivaletta & Barbieri 2008). The evaporite deposits on Mars surface suggest a wet past and they can provide information on the history of water, which is a key aspect for defining the suitability of the planet to host life. Because every terrestrial environment that supports life has liquid-state water for a period of time, the strategies for the search of life outside of earth necessarily have to consider the environmental setting where the liquid water is (or has been) present for at least short time. Inhabitants of hypersaline and arid environments include stress resistant microorganims adapted to high salt concentration, desiccating conditions, rapid changes in salinity and water availability, highly intense sun light and UV radiation. Single cells, colonies, pigments can be trapped in the evaporite crystals and this rapid sealing could be suitable for testing the potential preservation of microbial signatures in the geological record (Barbieri 2006). A key factor in the adaptation to stressful parameters is the production of suites of protective mechanisms, such as the strategies of colonization of protected microhabitats that may provide more or less transient episodes of habitability. Microniches, such as the endolithic mode of life might occur in Martian environments when the Mars surface became progressively drier and colder (Friedmann & Koriem 1989). The endolithic microniches in evaporite environments, where the precipitating salts may have advantageous physical properties (e.g. light and hygroscopy), are considered to be a good terrestrial analogue for Mars (Wynn-Williams & Edwards 2000; Wierzchos & Ascaso 2002; Stivaletta & Barbieri 2008). The study of Earth's analogues of potential extraterrestrial environment is a prerequisite for astrobiology and planetary exploration. The astrobiologists have recognized the importance of investigating the survivability and adaptations of life to natural extreme environments that approach some of the martian environmental conditions.

References

Barbieri, R., et al., 2006, Planet Space Sci., 54, 726-736.

Bibring, J.P., et al., 2007, Science, 317, 1206-1210.

Billi, D., & Potts, M., 2002, Res. Microbiol., 153, 7-12.

Chong, G., 1988, Lecture Notes in Earth Sciences, 17, 137-151

Clarke, J.D.A., 2006, J. Geophys. Res., 112, G02030.

Cockell C.S., 2000, Planet Space Sci., 48, 203-214.

Cockell C.S. et al., 2002, Meteor. Planet. Sci., 37, 1287-1298.

Cockell C.S. et al., 2008, J. Photochem. Photobiol. B: Biol. 90, 79-87.

Davila, A., et al., 2008 J. Geophys. Res., 113, G01028.

de Groot, A., et al. 2005, Int. J. Syst. Evol. Microbiol., 55, 2441-2446.

de la Torre, J.R., et al., 2003, Appl. Env. Microbiol., 69, 3858-3867.

Dong, H., et al., 2007, J. Geophys. Res., 112, G02030.

Dose, K. et al. 2001, Origins of life and evolution of the biosphere, 31, 287-303.

Dunai, T.J., Lopez-Gonzales, G.A., Juez-Larre J., 2005, Geology, 33, 321-324.

Edwards, J.S., & Battista J. R., 2003, Trends Biotechnol., 21, 381-382.

Friedmann, E.I., 1982, Science, 215, 1045-1053.

Friedmann, E.I., & Koriem, A.M., 1989, Adv. Space Res., 9, 167-172.

Golubic, S., Friedmann, I., & Schneider, J., 1981, J. Sedim. Petrology, 51, 0475-0478.

Hartley, A.J., et al., 2005, J. Geol. Soc. London, 162, 421-424.

Kasting, F.J., & Ackerman T.P., 1986, Science, 234, 1383-1385.

Kumbrein, W.E., et al., 2004, Astrobiology, 4, 450-459.

Langevin, Y., et al., 2005, Science, 307, 1584-1586.

McKay, C.P., et al. 2003, Astrobiology, 3, 393-406.

Navarro-Gonzales, R., et al., 2003, Science, 302, 1018-1021.
Nisbet, E.G., & Sleep N.H., 2001, Nature, 409, 1083-1091.
Oren, A., 1999, Mol. Biol. Rev., 63, 334-348.
Poulet, F., et al., 2008, Icarus, 195, 106-130.
Rainey, F.A., et al., 2005, Appl. Env. Microbiol., 71, 5225-5235.
Squyres, S.W., et al. 2004, Science, 35, 794-799.
Stivaletta, N., & Barbieri, R., 2008, From Fossils to Astrobiology. Springer-Verlag, 319-333 pp.
Stivaletta, N., & Barbieri, R., 2009, J. Arid Env., 73, 33-39.
Stivaletta, N., et al., 2010, Geomicr. J., 27, 101-110.
Stivaletta, N., et al., in press, Geomicr. J.
Vaniman, D.T., et al. 2004, Nature, 431, 663-665.
Warren-Rhodes, K.A., et al. 2006, Microbial Ecology, 52, 389-398.
Wierzchos, J., Ascaso, C., & McKay, C.P., 2006, Astrobiology, 6, 415-422.
Wierzchos, J., & Ascaso, C., 2002, I. J. Astrobiol., 1, 51-59.
Wynn-Williams, D.D., & Edwards, H.G.M., 2000, Planet Space Sci., 48, 1065-1075.