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Volcaniclastic habitats for early life on Earth and Mars: A case study from ~3.5 Ga-old rocks from the Pilbara, Australia

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A B S T R A C T

Within the context of present and future *in situ* missions to Mars to investigate its habitability and to search for traces of life, we studied the habitability and traces of past life in ~3.5 Ga-old volcanic sands deposited in littoral environments an analogue to Noachian environments on Mars. The environmental conditions on Noachian Mars (4.1–3.7 Ga) and the Early Archaean (4.0–3.3 Ga) Earth were, in many respects, similar: presence of liquid water, dense CO_2 atmosphere, availability of carbon and bio-essential elements, and availability of energy. For this reason, information contained in Early Archaean terrestrial rocks concerning habitable conditions (on a microbial scale) and traces of past life are of relevance in defining strategies to be used to identify past habitats and past life on Mars.

One such example is the 3.446 Ga-old Kitty's Gap Chert in the Pilbara Craton, NW. Australia. This formation consists of volcanic sediments deposited in a coastal mudflat environment and is thus a relevant analogue for sediments deposited in shallow water environments on Noachian Mars. Two main types of habitat are represented, a volcanic (lithic) habitat and planar stabilized sediment surfaces in sunlit shallow waters. The sediments hosted small (<1 μm in size) microorganisms that formed colonies on volcanic particle surfaces and in pore waters within the volcanic sediments, as well as biofilms on stabilised sediment surfaces. The microorganisms included coccoids, filaments and rare rod-shaped organisms associated with microbial polymer (EPS). The preserved microbial community was apparently dominated by chemotrophic organisms but some locally transported filaments and filamentous mat fragments indicate that possibly photosynthetic mats formed nearby. Both microorganisms and sediments were silicified during very early diagenesis.

There are no macroscopic traces of fossilised life in these volcanic sediments and sophisticated instrumentation and specialized sample preparation techniques are required to establish the biogenicity and syngenicity of the traces of past life. The fact that the traces of life are cryptic, and the necessity of using sophisticated instrumentation, reinforces the challenges and difficulties of *in situ* robotic missions to identify past life on Mars. We therefore recommend the return of samples from Mars to Earth for a definitive search for traces of life.

1. Introduction

1.1. Early Earth and early Mars

Rocks recording habitable conditions on the early Earth, as well as traces of early life, are of particular relevance for investigations of habitability on early Mars and for the search for past traces of life because environmental parameters on the two planets during their early histories were, in many respects, similar (McKay and Stoker, 1989; Jakosky et al., 2007; Westall, 2005a, 2008). The basic criteria for habitable conditions (related to carbon-based life, as we know it) are the presence of liquid water, the availability of organic carbon and biologically essential elements (H, N, O, P, S, as well as trace amounts of transition metals), and the availability of energy (Nisbet et al., 2007; Southam et al., 2007a).

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Liquid water is essential for life—it provides a medium for chemical exchange without which life would not be able to appear (Brack, 2002). On Mars there is overwhelming geomorphological and geochemical evidence from the recent orbital and *in situ* missions for a significant amount of water during the Noachian period (4.1–3.7 Ga) (Bibring et al., 2006; Carr, 2006; Carr and Head, 2010) (after about 3.7 Ga climatic conditions on Mars deteriorated and the presence of water appears to have been more episodic (Bibring et al., 2006; Carr, 2006; Carr and Head, 2010). Although Mars did not have a global ocean as did the early Earth, there is evidence during the Noachian for a large ocean in the Northern hemisphere (e.g. Perron et al., 2007; Ruiz et al., 2004) and for large bodies of standing water in impact and volcanic craters (Cabrol and Grin, 1999; Carr, 2006; Heisinger and Head, 2002). The presence of a large amount of water on the planets' surface requires a relatively dense atmosphere, most likely consisting of primarily CO_2 (Jakosky and Phillips, 2001) with admixed greenhouse gases, such as methane, water vapour, sulphur gases, and other compounds, whereas oxygen contents were extremely low (Kasting and Ono, 2006).

Given the volcanic nature of the Martian crust, the sediments deposited in these bodies of water and around their edges would have been largely volcanic in origin. Owing to the high heat flow from the mantle during its early history (Spohn, 1991), hydrothermal environments (Bishop et al., 2008) associated with volcanics and impacts would also have been common, as on the early Earth (Hofmann and Bohlar, 2007).

As an ingredient of life, carbon probably originated from both extraterrestrial and *in situ* sources. Carbon molecules were formed in the solar nebula and delivered to Earth by meteorites, micrometeorites, and comets (Mullie and Reisse, 1987; Cronin and Chang, 1993; Duprat et al., 2010). Relatively large amounts of carbon are also produced in hydrothermal systems (Holm and Andersson, 1998; Martin and Russell, 2007). Thus, carbon molecules were abundantly available on the primitive planets. The biologically essential elements, H, N, O, P, S, and the transition metals would have been also abundantly available in the volcanic rocks, minerals and volatiles on both planets (Nisbet et al., 2007).

Finally, life needs a source of energy. Chemical energy is provided in the form of thermodynamic disequilibria between chemical species in close proximity, such as reduction–oxidation (redox) contrasts. For example, reduction of ferric oxides in hot lava in contact with seawater produces hydrogen, a common electron donor for primitive microbial life (Nisbet et al., 2007; Southam et al., 2007b). Solar photons are a more effective source of energy but the biological mechanisms needed to capture this energy (photosynthesis) are relatively sophisticated and most likely developed at a later stage (at least on Earth) after the initial appearance of cellular life.

Both planets in their early histories thus satisfied the criteria for habitability. Their environmental conditions were also largely similar from a microbiological perspective, i.e. on small spatial and temporal scales. Thus, after life appeared on the planet, an environment that is only ephemerally habitable has the potential of being colonised and inhabited.

Therefore, as a result of the similarities between the habitable environments on early Earth and early Mars, the Early Archaean sediments and the fossil biota they contain can be considered as relevant analogues for the study of potential Noachian habitats and life. In this contribution, we therefore present a comprehensive study of a shallow water volcano-sedimentary habitat and the traces of life that the sediments contained. The example we use is the 3.446 Ga-old "Kitty's Gap Chert" formation in the Coppin Gap greenstone belt of the Pilbara. It consists of silicified volcanic sediments deposited in a tidal/mudflat environment (de Vries, 2004; de Vries et al., 2006; Westall et al., 2006a) (Fig. 1). The sediments contain cryptic (microscopic and optically invisible) traces of life directly related to specific volcanic habitats: volcanic particle surfaces, pore spaces in volcanic sediments, and sediment surfaces. A preliminary description of the biosignatures was made by Westall et al. (2006a). The cryptic nature of the biosignatures necessitated the use of multidisciplinary techniques to be identified and interpreted. The investigative techniques used are highly relevant for establishing the biogenicity of potential biological remains in ancient rocks on Mars.

Subaqueous volcaniclastic sediments on the early Earth were suitable habitats for microbial organisms, such as chemotrophs, because they are a source of bio-essential elements and because the redox reactions at their surfaces were a source of energy (Furnes et al., 2004; Nisbet et al., 2007; Southam et al., 2007a; Westall, 2005a, b, 2009). Other habitats on the early Earth included shallow water and littoral environments within the

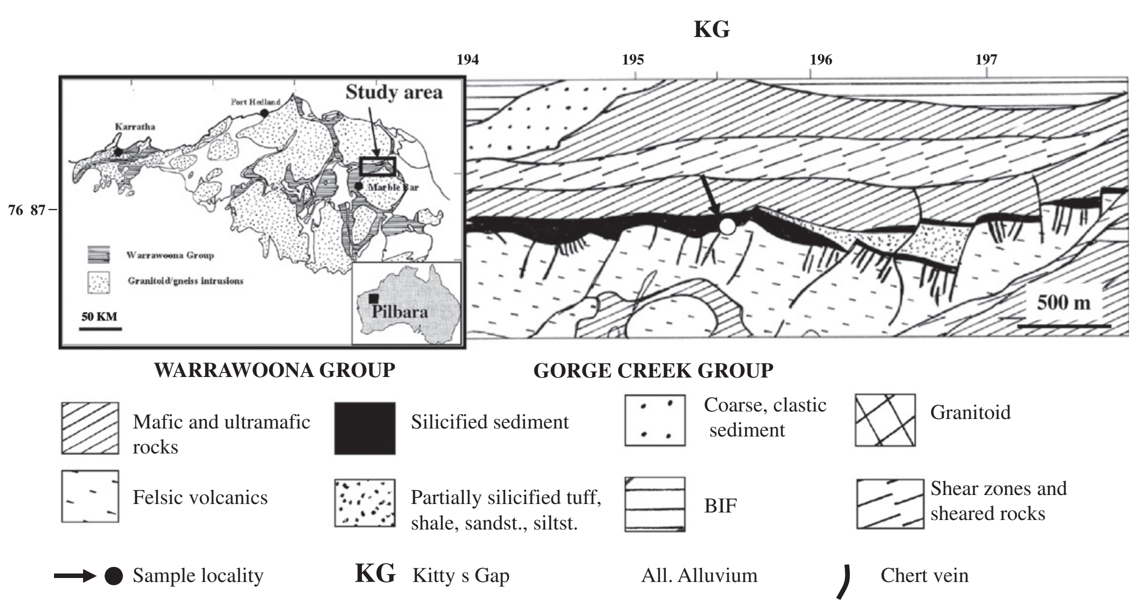

Fig. 1. Location and geological map of the "Kitty's Gap Chert" within the Coppin Gap Greenstone Belt (after de Vries, 2004; de Vries et al., 2006; Westall et al., 2006a).