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Exploring the astrobiological potential of rock varnish from a mars analogue field site of Ladakh, India

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A B S T R A C T

Rock varnish, a dark-coloured natural feature rich in manganese (Mn), iron (Fe), and clay minerals that forms on rock surfaces and subsurface rock fractures in extremely dry and cold environments, is believed to provide nutritional support to microbiota. Because varnish supports an extensive microbial community, this rock coating is considered a substrate for potential microbial life to thrive in extreme environments on Earth. Although research in the past decades have advanced understanding of the varnish microbiome, little is known about this microbial community in settings that are high altitude (lower oxygen), dry, and cold. We present here new morphological, chemical, and rock magnetic results of rock varnish from this environmental setting, the Ladakh, a potential analogue site for life in extreme environments. Our results include the presence of putative magnetofossils-in the form of nanochains present in the rock varnish layer. Further, the higher concentrations of oxidised Mn^{4+} and carboxylic acid functionality on the varnish surface revealed organic signatures. These collective results point towards the enriched concentration of magnetic minerals on the varnish layer that are possibly sourced through biotic forms. Consequently, the rock varnish can serve as an archive of ancient environmental records, as well as a potential geomaterial for astrobiological studies from the Martian analogue field location of Ladakh, which needs to be explored further for extensive biogeochemical studies.

1. Introduction

Rock varnishes are thin, dark-brown to black coatings of manganese and iron oxides on the surface of rocks held together by clay minerals and found in arid to semi-arid regions worldwide (Chaddha et al., 2021a, 2024; Dorn, 2024; Dorn and Oberlander, 1981; Potter and Rossman, 1977). Although abiotic and microbiological activities are thought to be important for its formation, the mechanism underlying the selective deposition of iron and manganese within the clay matrix remains uncertain (Krinsley et al., 2017; Kuhlman et al., 2006; Potter and Rossman, 1979).

To explain varnish formation, numerous conceptual models have been proposed. (i) Abiogenic precipitation due to mineral leaching by water under well-defined pH and Eh conditions to allow geochemical fractionation of Mn (Thiagarajan and Aeolus Lee, 2004).(ii) Biologically regulated mineralization as a function of cellular activities (Wang et al., 2011; Wang and Müller, 2009).(iii) Gram-negative bacteria, Gram-positive bacteria, and micro-colonial fungi thriving on rock surfaces collect and oxidise manganese particles from the air dust (Krumbein and Jens, 1981).(iv) A complex sequence of events supported by modest pH/Eh conditions that allow Mn to be released from airborne dust and concentrated in the varnish layer (Elvidge and Moore, 1980). (v) The activity of cyanobacteria, studied in hot desert settings (Lingappa et al., 2021). (vi) A photo-oxidative process that enhances the Mn in varnish, but a process that admittedly does not work in low-light settings (Xu et al., 2019). (vii) A silica binding model that depends on clay minerals not being a dominant component of varnish (Perry et al., 2006)- a view that rests in contradiction with almost all varnish scholarship (Chaddha et al., 2021, 2023; Dorn, 1998; Krinsley, 1998; Potter and Rossman, 1977, 1979).(viii) A polygenetic model that involves budding bacteria enhancing Mn and Fe, followed by abiotic nanoscale processes that insert Mn and Fe into clay minerals, cementing varnish to

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