MARTIAN GROUNDWATERS THOUGH TIME AND THEIR IMPACT ON THE MARS SYSTEM: AN APPRAISAL.
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Introduction: The 8th Mars conference debated the climate implications of the extent and environmental diversity of settings with liquid water on Mars [1-4]. One aspect of this discovery and discussion was the prevalence of ancient terrains with minerals hypothesized to form via subsurface water-rock reaction, which did not require a warm, wet Mars for extended periods. From orbit, the unambiguous indicator minerals of subsurface waters are hydrothermal/low-grade metamorphic minerals like prehnite and aqueous mineral assemblages with compositions isochemical to basalt [5]. Since 8th Mars, our understanding of Martian groundwaters, their chemistry, and their importance in the search for life as well as the climate system has deepened via continued analyses of orbital datasets, in situ exploration by Curiosity and Opportunity, novel modeling, and a growing understanding of the geobiology and preservation of subterranean ecosystems on Earth. Here, I review findings of the last 5 years, priority outstanding questions, and exploration approaches.

A Range of Groundwater Environments/Habitats: Orbital data continue to show that ancient Martian environments were widespread spatially but diverse chemically. Mg carbonate indicating alkaline waters is found in deep basin mineral deposits at McLaughlin crater [6]. Indicating acidic waters, alunite is found in basins and local features in Terra Sirenum [7,8] and jarosite has mineralized 500-m tall fractures at NE Syrtis [9]. Clay and/or quartz fractures form in clay bearing units at Nili Fossae [10]. In contrast, chloride deposits appear entirely divorced from deep groundwaters [8]. A small percentage of impact craters may have hosted impact-generated groundwaters [e.g., 11].

While preserved ancient groundwater environments like those above remain to be explored in situ, a deep sedimentary basin has been explored in situ by MSL and a shallow sedimentary basin has been explored in situ by Opportunity. Results show that overprinting of groundwater-formed minerals even at a single place may be common. Early quasi-isochemical formation of nodules and syneresis cracks filled by clay minerals was followed by sulfate mineralization at Yellowknife Bay [12-15]. At Garden City, at least 3 generations of veins are observed, including dark Zn-rich materials and veins inferred to form via hydrofracture [16].

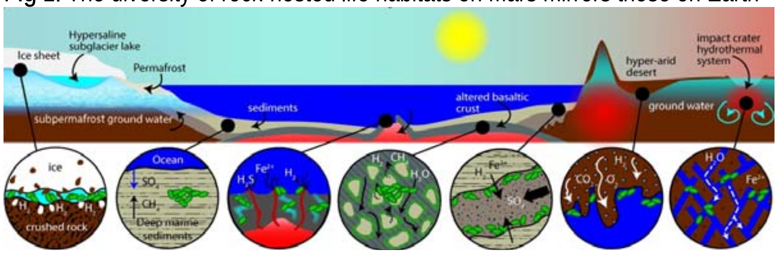
In situ exploration by Opportunity shows the role of multiple generations of fluids in mineral precipitation and dissolution, shaping the sulfate/hematite/chloride mineralogy of the Burns formation sedimentary rocks [17]. At the end of the mission, exploration of Noachian materials exposed by impact showed Fe/Mg clay-bearing breccias contain cm-thick leached zones of Al clays from post impact hydrothermal fluids [18, 19].

Groundwater Plumbing and Communication with Magmatic Systems: Clearly, Mars hosted multiple types of groundwater systems varying in space and time. The drivers of the chemical diversity are understood in only a few cases. In many cases, sulfur supplied by upwelling groundwaters leaching basaltic rocks may be sufficient to form sedimentary sulfate deposits without invoking atmosphere or magmatic sources [20]. A growing number of alunite deposits associated with discrete <1km zones within sedimentary deposits in deep basins may instead point to localized magmatic sources in some locales [8]. The relvative influences of weathering, magmatic volcanic volatiles, and subsurface magmatic sources in contributing to groundwater chemistry is a key open issue, even at the landing sites.

Recent Martian groundwaters?: Most gullies once thought to be signs of recent water [e.g. 21] now are in most cases (but perhaps not all) shown to be due to CO_2 ice sublimation [22-23]. After initial reports of perchlorate [24] in association with recurring slope lineae (RSL) [25] that seemed to imply geologically recent briny groundwaters seeping to Mars' surface, enthusiasm for RSL as sites of modern groundwater discharge has reduced. Thermal infrared measurements placed a very small upper bound on water content [26]; reanalysis of spectra showed perchlorate detections were suspect [27] and caused by an artifact of on-the-ground CRISM data processing [28]; and the timing and style of RSL emplacement is consistent with dust avalanching [27, 29]. While actual surface water seems unlikely at RSLs, this does not, however, preclude a role for near-surface ice, which may include a role for subsurface liquid.

More recently, a pond of subsurface liquid brine has been hypothesized based on a radar-bright material of high permittivity in a specific region of the south polar cap [30]. The results are intriguing albeit in some ways similar to the enigmatic radar bright layer that underlies other parts of the cap, which has not been attributed to liquid water [31]. It is challenging to produce subsurface water under most assumptions for the Martian geothermal gradient [32]. Thus, the modern

Fig 1. The diversity of rock-hosted life habitats on Mars mirrors those on Earth



Martian groundwater reservoir inferred to exist at depth [33] remains elusive to detect, confounded by the radar attenuaton properties of the deep subsurface. Heat flow from InSight is a key parameter for determining the depth of any waters.

The Search for Martian Life: Our understanding of habitability and biosignature preservation potential in the subsurface has tremendously expanded. Multiple chemolithoautrophic pathways provide energy for microbial life in the subsurface habitat. Latest calculations of H_2 gas production during radiolysis of igneous rocks show this pathway produces adequate flux rates to sustain biomatter [34]. The buried sediments of Gale crater contain abundant late diagenetic sulfate and organic matters, which could have sustained organisms via sulfate reduction [35] and diagenetic textures also suggest H_2 gas production during diagnenetic clay and magnetite formation [14-15].

A recent review [36] of terrestrial subsurface life and subsurface life's biosignature preservation showed 1) chemolithoautotrophic metabolic pathways had already evolved on Earth at the time Mars was habitable; 2) over large volumes of Earth's crust, subsurface life relies on chemical energy from abiotic processes like those on Mars (rather than detritus of Earth's photosynthetic life); 3) subsurface microbial cell concentrations are highest at interfaces with pronounced chemical redox gradients or permeability variations; 4) the footprint of subsurface life (minerals, chemical gradients, and their isotopic signatures) is often larger than the life itself (cells, organic products); and 5) the terrestrial rock record has biomarkers of subsurface life at least back hundreds of millions of years and likely to 3.45 Ga with several examples of excellent preservation. Collectively, subsurface Martian life is the most likely to exist and be preserved for discovery.

Gas Production and Impacts on Climate?: A new finding since the 8th Mars conference is the extent to which subsurface groundwaters may couple with The water-rock reactions in the subsurface to form serpentine and other clay minerals generate gases. Originally modeled for redox considerations [37], recent work has shown that the production of H_2 may have a significant greenhouse effect on ancient Mars if, rather than being released continuously, gas release is intermittent in response to obliquity driven ice sublimation [38-39].

Key Questions and Future Exploration Needs: The role of groundwater on Mars is far from settled. Key questions include:

- Much of mineral formation was ancient but how much was recent (Amazonian), driven by overprinting groundwaters? (as for recent jarosite [40])
- What are the sources of cations and anions in Martian groundwater and what controls geographic and temporal diversity?
- Are there new detection approaches for potential deep (<1km) modern groundwaters?
- How did communication between the surface and subsurface influence the Mars climate system?

Exploration demands in situ petrography for minerals, chemistry, isotopes, organics, and their textural relations [41]. For the paradigm-altering search for life on Mars, an exploration strategy that targets ancient subsurface life and scales spatially may stand the best chance for finding life on Mars. Efforts should focus initially on identifying rocks with evidence for groundwater flow and low-temperature mineralization, then identifying redox and permeability interfaces preserved within rock outcrops, and finally focusing on finding minerals associated with redox reactions and associated carbon and diagnostic chemical and isotopic biosignatures. This approach on Earth yields preserved life. Deep drilling is unnecessary as the outcrops preserving Mars' ancient subsurface habitable environments are exposed by tectonics and refreshed today by moden wind erosion. They are there for ready exploration by landed missions and human explorers.

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