O_2 Solubility in Martian Surface Environments and Implications for Extant Aerobic Life on Mars

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Introduction: Due to the scarcity of O_2 in the modern Martian atmosphere, Mars has been assumed incapable of producing environments with sufficiently large concentrations of O_2 to support aerobic respiration. Here we present a thermodynamic framework for the solubility of O_2 in brines under Martian shallow subsurface conditions and discuss implications for deeper subsurface environments, where liquid water is much more likely to exist. We find that modern Mars can support shallow subsurface liquid environments with dissolved O_2 values ranging from $2.5 \cdot 10^{-6}$ mol m^{-3} to 2 mol m^{-3} across the planet, with particularly high concentrations in polar regions because of lower temperatures at higher latitudes promoting O_2 entry into brines. General circulation model simulations show that O_2 concentrations in shallow subsurface environments vary both spatially and with time — the latter associated with secular changes in obliquity. Even at the limits of the uncertainties, our findings suggest that there can be subsurface environments on Mars with sufficient O_2 available for extant aerobic microbes to breathe [1]. The availability of liquid water is ultimately the main modulating factor and will likely scale with subsurface depth and location.

Methods: We develop a new comprehensive thermodynamic framework applicable to Martian conditions that calculates the solubility of O_2 in liquid brines. We then couple this solubility framework to a Mars general circulation model (GCM) [2, 3] to compute the solubility of O_2 as a function of annually averaged values of pressure and temperature varying with location on Mars today in shallow subsurface environments (for an obliquity of ~25°). Following this, we examine how the distribution of shallow subsurface aerobic environments evolved over the past 20 Ma and how it may change in the next 10 Myr. To achieve this, we extend the modern-day Mars climate model [2, 3] using different values of obliquity to obtain annually averaged climate maps for each obliquity, and use calculations of Mars' obliquity changes over the past ~20 Ma and the next ~10 Myr [4] to identify those epochs in time with different axial tilts. Last, we discuss implications for deeper subsurface environments where oxygen may be sourced differently.

Results: We find that, on modern Mars—accounting for all uncertainties—the solubility of O_2 in various fluids can exceed the level required for aerobic respiration of ~10^{-6} mol m^{-3} for microbes [5, 6] by ~1-6 orders of magnitude. Thus, in principle, Mars could offer today a wide range of shallow subsurface environments with enough dissolved O_2 for aerobic respiration like that seen in diverse groups of terrestrial microorganisms. Moreover, for supercooled Ca- and Mg-perchlorate brines on Mars today, ~6.5% of the total Martian surface area could support far higher dissolved O_2 concentrations—enabling aerobic oases at levels of $[O_2]_{aq}$>$2 \cdot 10^{-3}$ mol m^{-3} sufficient to sustain respiration demands of more complex multicellular organisms like sponges [7]. Such shallow subsurface aerobic oases are common today at latitudes poleward of ~67.5°N and ~72.5°S. Other shallow subsurface aerobic environments with intermediate $[O_2]_{aq}$ values of ~ 10^{-4}-10^{-3} mol m^{-3} can occur today closer to the equator in areas of lower topography like Hellas, Arabia Terra, Amazonis Planitia, and Tempe Terra, with larger mean surface pressures. The trends for shallow subsurface environments we show here are robust, as they can be tracked back to model-independent findings: (1) higher solubility for lower temperature and higher pressure, (2) temperature as the main control factor for solubility, (3) the poles being colder than the equator for modern Mars, and (4) the poles warming at higher obliquities.

The first part of this study focused on shallow subsurface environments. However, liquid water is much more likely to exist in the deep subsurface [see [8] for potential evidence of some form of deep liquid water]. Our results also imply that the O_2 solubility in such deep reservoirs would be high, raising the possibility that they could be rich in O_2 if the supply either from intermittent communication with the atmosphere or from the radiolysis of water is sufficiently large. Last, we discuss pathways to explore modern-day subsurface habitability and extant subsurface life in the coming decade [9].

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