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Carbon sequestration on Mars

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Martian atmospheric pressure has important implications for the past and present habitability of the planet, including the timing and causes of environmental change. The ancient Martian surface is strewn with evidence for early water bound in minerals (e.g., Ehlmann and Edwards, 2014) and recorded in surface features such as large catastrophically created outflow channels (e.g., Carr, 1979), valley networks (Hynek et al., 2010; Irwin et al., 2005), and crater lakes (e.g., Fassett and Head, 2008). Using orbital spectral data sets coupled with geologic maps and a set of numerical spectral analysis models, Edwards and Ehlmann (2015) constrained the amount of atmospheric sequestration in early Martian rocks and found that the majority of this sequestration occurred prior to the formation of the early Hesperian/late Noachian valley networks (Fassett and Head, 2011; Hynek et al., 2010), thus implying the atmosphere was already thin by the time these surface-water-related features were formed.

As Lee et al. (2016) rightly highlight in their Comment, the meteorite record provides important constraints on Martian carbon sequestration processes. The example used in the discussion by Edwards and Ehlmann of the possibility of deep diffuse carbonate alteration—rather than precipitation of carbonate in discrete rock deposits like those analyzed—was selected based on measurements of carbonate in dust, *in-situ* mission data, and meteorites. That is, a 1 km global crustal layer of 1 vol.% carbonate-bearing materials, similar to the abundances in the Nakhalite-class Lafayette meteorite (Changela and Bridges, 2010; Nyquist et al., 2001; Tomkinson et al., 2013; Wright et al., 1992), if formed from waters in contact with the atmosphere, would lead to sequestration of ~500 mbar CO_2.

To sequester significantly more carbon than this from the Martian atmosphere requires an assumption that typical Martian rocks and soils have vol% carbonate several factors greater than that observed in Martian meteorites. Abundances as high as this would be more readily detectable to remote sensing and landed missions, but are so far observed only rarely or at abundances of a few percent or less (e.g., Leshin et al., 2013; Niles et al., 2013) except in an isolated olivine-rich region of the Columbia Hills, Gusev crater (Morris, 2010). Thus, a 1–5 vol% carbonate range over a large volume of crust is a reasonable estimate, which leads to a maximum of ~1–2 bars sequestered since valley network formation, under most environmental scenarios, a value consistent with isotopic evidence and known geologic processes (e.g., Hu et al., 2015), including newly measured escape processes (Jakosky, 2015). Interestingly, the period prior to valley network formation likely had additional carbon sequestration by different processes to remove early or pre-Noachian atmosphere (Wray et al., 2016). Future landed missions are considering visiting a site with in-place carbonate-bearing materials (http://marsnext.jpl.nasa.gov; Hand, 2015), possibly returning samples from them, a prospect which would provide a key suite of petrologic and isotopic data to address this most important question about Mars atmospheric and climate evolution: the fate of the atmosphere.

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