Changes in Mars's habitability could have been driven by carbonate formation and transient oases

Mars has had periods of potential habitability, seen in its geological record of surface water and shallow groundwater. Models that incorporate feedback between carbon sequestration, atmospheric pressure and temperature – backed by discoveries of carbonates by NASA's Curiosity rover – suggest that this intermittent habitability could have arisen through self-regulating feedback loops on the planet's surface.

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The problem

The surface of Mars has been modified by liquid surface water in the past, and there is abundant evidence that the planet's surface was intermittently habitable. What controlled this potential habitability, and why was it lost? The loss might be explained by the sequestration of carbon dioxide – Mars's main greenhouse gas – into sedimentary rocks as carbonate deposits, as occurs on Earth[1]; this process depends on the presence of liquid water. But this mechanism has often been dismissed because of the small volume of carbonate-rich rocks detectable from orbit[2].

However, the Mars Science Laboratory's Curiosity rover has recently found 'cryptic' carbonates (those not detected from orbit) in Mount Sharp at Gale Crater[3] – a site thought to be a reference section for Mars's global stratigraphy. With the newly found abundance of potentially widespread cryptic carbonates, the question re-emerges: did the formation of sedimentary rocks cause Mars's disappearing habitability?

The solution

Assuming that the discovered carbonate abundances from Gale Crater are globally representative, we modelled the time evolution of Mars's temperatures from 3.5 billion years ago (Ga) to the present day, while accounting for chaotic orbital forcing, geography, carbonate formation, the escape of the atmosphere to space, and seasonal and diurnal temperature variations. With snowmelt assumed as the water source, this model set-up results in warm episodes during periods of favourable orbital forcing, increasing the availability of liquid water in different oases on the surface. This liquid water jump-starts the formation of sedimentary rocks, which also involves the drawdown of CO_2 from the atmosphere, resulting in carbonate production. This, in turn, cools the planet, enabling the maintenance of a self-regulating, negative feedback loop (Fig. 1).

Our model's end result is global aridification. However, Mars's climate varied between warm, water-rich episodes and cold, dry periods from 3.5 Ga to the present day, regulated by the planet's chaotic obliquity – unpredictable, large variations in axial tilt over time – and by carbonate formation. The model predicts that Gale Crater is a global maximum for liquid water availability and, by extension, for sedimentary rock formation – consistent with observations. (Other maxima include regions that coincide with a substantial volume of sedimentary rocks on Mars's current surface.) The model also predicts that the warm and cold periods of Gale Crater are representative of global climate patterns.

The implications

Key influences on Mars's climate after 3.5 Ga include solar brightening, orbital forcing and atmospheric pressure. These factors are incorporated into our model, the results of which indicate that the formation of sedimentary rocks could be the cause of Mars's loss of habitability over time. This is supported by the discovery of cryptic carbonates. Our model describes Mars after 3.5 Ga as a self-regulating desert planet, with intermittent occurrences of oases.

Our approach assumes that the rocks at Gale Crater are globally representative[4]. However, we do not know for sure how pervasive cryptic carbonates are at Gale Crater or elsewhere on Mars. So far, they have been detected in some 200 metres of sedimentary thickness. In the future, the Curiosity rover will encounter hundreds of metres of sediment that can be tested for carbonates. Only further study by Curiosity can confirm or falsify our assumptions, given that this carbonate abundance is undetectable from orbit.

The obvious next step will be to continue ground-based observations of Mars's sedimentary rock record. As Curiosity continues to ascend Mount Sharp, the rover should be able to find out whether the cryptic carbonates encountered at the base of the mound continue uphill. However, to fully understand the applicability of our model, ground-based exploration of other global maxima and sedimentary deposits on Mars – at Valles Marineris, for instance[4] – will be needed.

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EXPERT OPINION

"This work provides a novel hypothesis supported by a robust model to explain the formation of young carbonates found at Gale Crater, Mars. It also provides an explanation for how sporadic water could manifest at the surface of Mars late in its history. The model is the first of its kind for Mars and provides a reason for the drawdown of Mars's atmospheric pressure to the present value, which precludes surface habitability today."

Brian Hynek is at the University of Colorado Boulder, Boulder, Colorado, USA.

FIGURE

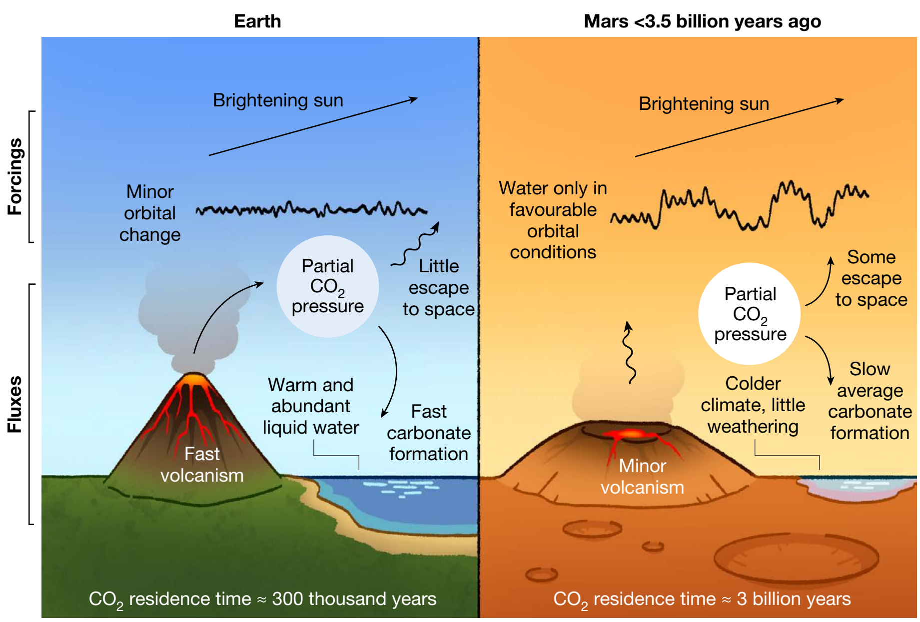

Figure 1 | Comparing carbonate cycles. Fluxes and forcings that influence carbonate formation on Earth and on Mars between 3.5 billion years ago and the present day. On Earth, fast volcanism (associated with volcanic eruptions) results in carbon dioxide outgassing, an increase in the partial CO_2 pressure and rising temperatures, which are balanced by fast carbonate formation in the presence of abundant liquid water. The context is a brightening Sun and minor orbital changes. On Mars, there is less volcanism and temperatures rise slowly and only as a result of solar brightening; this tendency towards rising temperatures is balanced by slow average carbonate formation. Higher rates of carbonate formation occur locally where there are oases of liquid water, which occur during orbital optima. The residence time of CO_2 is measured for the atmospheric and surface water reservoirs. Kite, E. S. *et al.*/*Nature* (CC BY 4.0).

BEHIND THE PAPER

The evolution of Mars's climate has been one of the biggest open questions in planetary science. Despite international exploration efforts, the loss of the planet's habitability and the notable absence of an implied near-surface carbonate sink remained unexplained.

This background contributed greatly to the excitement that met the initial discovery of abundant carbonates by the Curiosity rover at Gale Crater. After the initial sample-composition results came through from a drilling campaign, the next challenge for the science team at the Mars Science Laboratory was to work out whether the carbonates were persistent, or whether abundances would drop with another drill sample. Curiosity has now found carbonate abundances of between 5% and 11% by weight in another four samples.

The discovery opens up possibilities for understanding the climate and habitability of Mars — and its long-sought carbonate sink.

M.L.T.

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FROM THE EDITOR

At some point in its distant past, Mars probably supported an intermittently warm and moist climate. The mechanisms supporting the intermittency are unclear. Ideas abound, with most arising from models without firm observational constraints. Edwin Kite and colleagues capitalize on the recent discovery of carbonates to provide a novel explanation linking chaotic orbital variations, liquid water and the carbon cycle. The data constraints are limited, but the new model is an elegant and testable hypothesis.

Michael White, Senior Editor, *Nature*