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Meridiani Planum sediments on Mars formed through weathering in massive ice deposits

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The sulphate-rich deposits at Meridiani Planum, Mars, discovered by the rover Opportunity, were proposed to be playa evaporites that had been reworked by eolian processes. Alternative hypotheses include volcanic or impact-driven formation of the sediments. Here we argue that the cation chemistry, scale, mineralogy and structure of the Meridiani sedimentary deposits are best explained by eolian or impact-driven reworking of the sublimation residue from a large-scale deposit consisting of dust and ice. We suggest that silicate material underwent significant acid weathering inside the ice deposit when thin films of water, formed through radiant heating, enabled the reaction between silicate material and sulphate-rich aerosols deposited from the atmosphere. The massive ice deposit could have formed during a period of high obliquity or polar wander, and subsequently sublimed away when obliquity changed or the pole moved to a new location. We propose acid weathering inside massive ice deposits as an explanation for the formation of many of the sulphate-rich layered deposits on Mars, which share many characteristics, including mineralogy, structure, erosional characteristics and size, with the sediments found at Meridiani Planum.

The playa hypothesis[1,2] was strongly influenced by Burns[3], who had described a scenario where H_2SO_4 aerosols in the atmosphere rain out to weather igneous rocks and create acidic groundwater that is stabilized at low temperature and pH by permafrost. Under these conditions, Burns[3] argued that ferric sulphates such as jarosite could be formed and may be contributing to the global dust as exposed permafrost is removed through sublimation. The playa hypothesis[1,2] did not feature the low temperatures discussed by Burns[3], favouring instead massive groundwater upwelling[2,4] to help explain the enormous volume of the deposit at Meridiani Planum. However, this idea is not without its problems, which include: indications of cation-conservative weathering, the lack of a topographic basin, the intimate commingling of the most-soluble and least-soluble salts and the overall scale of the deposit[5–7]. These observations are important challenges to the playa scenario, and suggest that the sediment was derived from a different source.

A number of studies are now suggesting that ice may have had an important role in the weathering of martian materials and the formation of martian sediments[8–10]. Zolotov and Mironenko[8] suggest that ice sheets helped collect and concentrate acid rained out from the atmosphere causing sub-glacial weathering in the northern lowlands and some parts of the southern hemisphere. Catling *et al.*[9] have proposed that sulphate-rich layered deposits in Juventae Chasma may have formed through atmospheric co-precipitation of ice and sulphate minerals through photochemical conversion rather than aqueous processes within the ice deposits themselves.

Ice-weathering model

We propose a new model for the provenance of the sediments at Meridiani Planum, which is based in principal on geochemical ideas pioneered by Burns[3], and sedimentological ideas proposed by Tanaka[11]. In our model, the sediments now located at Meridiani Planum were sourced from a nearby, massive dust–ice deposit that was located adjacent to Meridiani Planum. This massive dust–ice deposit formed through precipitation of ice around dust grains and aerosols, and it resembled the polar layer deposits that exist today in the martian north and south polar regions (Fig. 1a). Early volcanism on Mars is likely to have included large emissions of sulphur gases, and this volcanism paired with an increased impact flux suggests that the early atmosphere of Mars would have been appreciably enriched in dust and sulphur-rich volcanic aerosols compared with the present day[12]. Suspended particulates provide nucleation points for ice crystals to form, which is an important driver for the precipitation of water ice in the present-day polar caps[13] and would have been more prevalent on ancient Mars.

Exposure of the ice deposits to sunlight during the summer seasons enabled radiant heating of dark grains within the water ice matrix. A similar effect has been observed where radiant heating of soil grains, trapped in ice deposits in Antarctica, causes melting and migration resulting in the formation of aggregates[14] (Fig. 1b). The radiant heating led to the formation of thin water films sufficient to enable reaction with the volcanic aerosols to create acidic solutions[10]. The ice matrix provided a physical barrier enclosing each grain or aggregate of grains within a closed-system environment at low temperatures with low water/rock ratios. The acidic solutions weathered silicate grains to form poorly crystalline aluminosilicates and sulphates[3,15]. The cold temperatures of the polar environment provided a mechanism for limiting water/rock ratios while simultaneously forming more concentrated solutions through freezing of excess solution.

A climatic shift (due to polar wander or obliquity changes) then led to conditions that favoured net sublimation of the massive ice deposit rather than deposition. The sublimation residue was made up of sand-sized agglomerates of fine-grained, chemically weathered and highly hydrated siliciclastic material mixed with sulphate salts. This material was reworked by eolian activity, transported and re-deposited in nearby large, hydrated, dune

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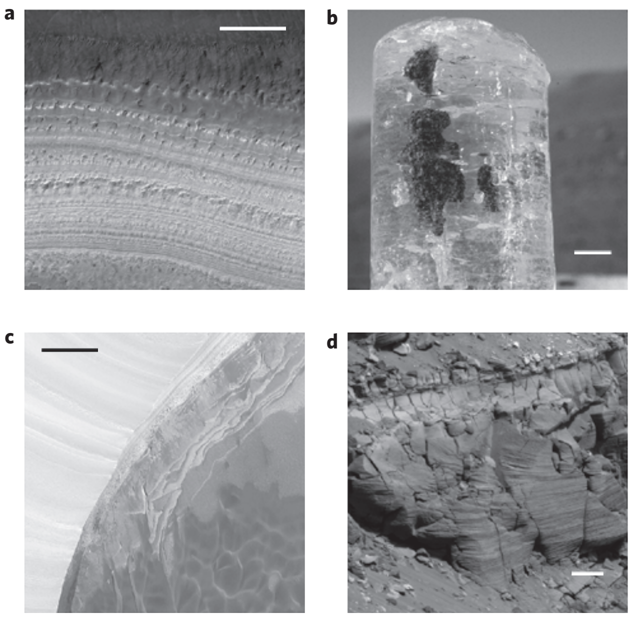

Figure 1 | Sequence of events in the ice-weathering model. a, HiRise image no. PSP_006286_1015 showing polar layered deposits. These deposits show the typical features of regularly spaced layering with varying albedos (Credit: NASA/JPL/University of Arizona). The scale bar is 1 km. **b**, Ice core from Antarctica with an aggregation of soil grains (Credit: Hans Paerl, University of North Carolina at Chapel Hill). The scale bar is 2 cm. These grains have migrated through the ice to form this aggregate by means of radiant heating[14]. **c**, Mars Orbiter Camera image no. E01-01773 showing dark-dune-forming material that appears to be weathering out of a polar layered deposit (Credit: NASA/JPL/Malin Space Science Systems). The scale bar is 600 m. **d**, Outcrop of the Meridiani sediments informally named Cape St. Vincent at Victoria crater. Large cross-bedding features consistent with eolian or impact base surge processes are clearly visible in the outcrop (Credit: NASA/JPL-Caltech/Cornell University). The scale bar is 1 m.

deposits[16] (Fig. 1c,d). Burial of these highly hydrated phases caused the release of structural water perhaps supplying sufficient water to facilitate the forced hydrolysis of jarosite to haematite[17]. Small amounts of extra water may also have been supplied by brief ice melting events enabling the possibility for surface runoff[1,16]. The low water/rock ratio and low temperatures created conditions where these fluids became supersaturated Fe-rich brines enabling the kinetic growth of the haematite spherules, but also preventing wholesale re-equilibration of the deposit and complete conversion of jarosite to haematite[17].

Alternatively, the sublimation residue may have been reworked primarily through impact events. Base surge deposits from these events would have similar cross-bedded sedimentary features and could extend for hundreds of kilometres beyond the impact crater[5]. Another advantage of this reworking process is that it also provides a means for precipitating the haematite spherules without invoking extensive diagenesis[5].

One important issue to address with this model is the origin of the massive ice deposit. One possibility is that massive dust–ice deposits formed in the equatorial regions during long periods of ancient high obliquity[18]. The extent and timing of obliquity variations during early Mars history is not known; however, to accumulate the necessary ice deposits, a prolonged period ($>10^5$ years) of extreme obliquity ($>40°$) would be necessary[18]. In one simulation of the climate during high obliquity, a region of ice accumulation was located near Schiaparelli crater adjacent to Meridiani Planum[19]. Another possibility is that the spin axis of the planet was originally located near Meridiani Planum and has since moved away through true polar wander. Schultz and Lutz[20] originally proposed that the deposits in Meridiani and Arabia Terra were the result of palaeo-polar processes. This proposition has gained support from gamma ray and neutron data that have shown large hydrogen enrichments antipodally located in Arabia Terra and Amazonis Planitia[21,22] (Fig. 2), and by measurements of remnant crustal magnetism that require a low-latitude palaeo-magnetic pole[23]. Radar data from layered deposits of the Medusa Fossae Formation in Amazonis Planitia are also consistent with an ice-rich material[24]. More recently, Tanaka[11] has proposed that many deposits on Mars may be the result of massive dust–ice deposits in the Noachian. Although there are significant uncertainties associated with both of these possibilities and we cannot point to a specific location of a palaeo ice cap or delineate the location of past ice deposits, it is likely that obliquity shifts and/or polar wander could have resulted in massive ice deposits at low latitudes, in the vicinity of Meridiani.

Strengths of the ice-weathering model

The ice-weathering model resolves many problems of previous hypotheses including the large scale of the deposit; the source of the sediment; its compositional similarity across large lateral distances; the cation-conservative nature of the weathering processes; the presence of acidic groundwaters on a basaltic planet; the accumulation of a thick sedimentary sequence outside of a topographic basin; and the intimate mixture of silicates, sulphates and minerals with very different solubilities.

The enormous scale of the Meridiani Planum deposits presents a problem for every hypothesis that has been put forward to explain their origin. Data from orbital remote-sensing studies indicate that the chemical and mineralogical composition of the Meridiani sediments is similar over a large area[2,25], including the presence of haematite of identical spectral character across much of the deposit[26]. Thermophysical observations of the Meridiani Planum units and surroundings suggest that the deposit extends beyond the haematite-bearing plains to the north and east, effectively tripling its size[25,27]. The total volume of material has been estimated to be greater than 1×10^5 km^3 (ref. 27), and extraordinarily few geological processes could possibly create a deposit of this magnitude[7]. The current south polar deposits on Mars have been measured to contain 1.6×10^6 km^3 of material[28], which contains approximately 10–15% dust[29], yielding of the order of 2×10^5 km^3 of non-ice material. Thus, a polar source can account for the enormous scale of the deposits at Meridiani Planum, while providing a consistent explanation for the mineralogical similarity of the deposit over a large area. In addition, this massive source area could explain coherent deposition over hundreds of kilometres and the creation of relatively planar strata that conform to the regional slope[7].

The source of the sediment that forms the deposits at Meridiani Planum has been unclear because there is not an obvious nearby volcanic source, impact crater or large playa. In addition, the formation of the deposit occurred over a long period of time and was associated with both older and younger valley networks[7]. It is possible that these potential sediment sources have since been buried or removed, but we find a massive dust–ice deposit as the best explanation of this discrepancy. The massive ice deposit may have persisted for long periods of time[30] and when the ice had completely sublimed away, it left behind a massive sedimentary deposit with no obvious sediment source.

The cation-conservative nature of the weathering that modified the silicate materials has been noted by other authors[6,31] and places a strong constraint on the provenance and weathering of the sedimentary material. The variations in the chemical composition of the deposit have been modelled as either (1) a mixture between a weathered basaltic component and a sulphate-rich

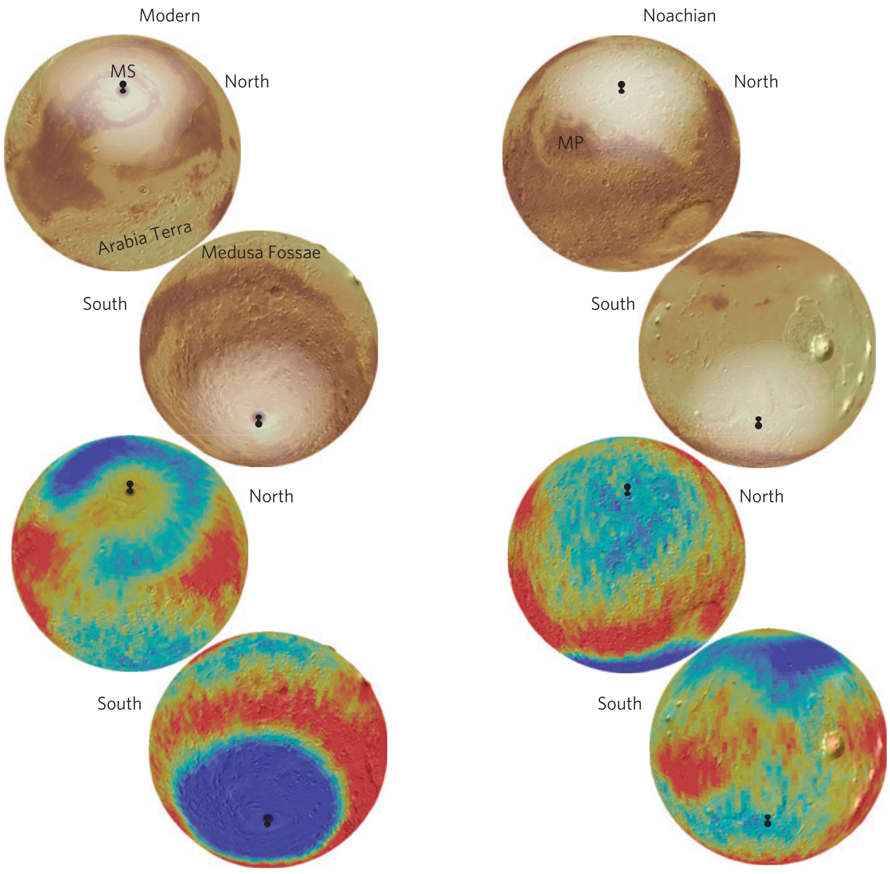

Figure 2 | Antipodal hydrogen enrichments on Mars. Global projection of Thermal Emission Spectrometer albedo (top spheres) and High Energy Neutron Detector epithermal neutron data (bottom coloured spheres), featuring the polar regions of Mars[22,40]. The four globes on the left feature the modern orientation of the spin axis, whereas the globes on the right feature a spin axis centred on Arabia Terra. This proposed palaeo-spin axis lines up with signatures of hydrogen enrichment at Arabia Terra and antipodally at Amazonis Planitia. Meridiani Planum is labelled 'MP'. Modern sulphate deposits located near the north polar layered deposits are labelled 'MS'.

evaporite component[1], or (2) an addition of SO_2 to a pristine basaltic composition[6]. Both models presume a basaltic starting composition that is reflected in the chemical composition of the outcrop. It does not seem that any cations have been appreciably enriched or leached from this composition (Fig. 3). In addition, textural relationships and centimetre-scale alpha-particle X-ray spectrometer analyses suggest that the Meridiani sediments preserve their original proportion of major elements through an intimate mixture of weathered silicates and sulphate-rich salts of varying solubilities (Fig. 4). Figure 3 shows that the chemical variations observed by the Opportunity rover can best be explained by diagenetic leaching of $MgSO_4$ (refs 31,32) and are not an indication of a mixing process (see Supplementary Information).

The fact that this assemblage has retained its basaltic cation abundances (Fig. 3) despite extensive modification to the original basaltic mineralogy suggests that the weathering took place under extremely low water/rock ratios[5,6,31]. A unique feature of weathering dusty material within a polar ice cap should be cation-conservative weathering on a centimetre scale due to the closed-system environment provided by the icy matrix. The cold temperatures should act to limit water/rock ratios, resulting in an intimate mixture of silicate and sulphate minerals[3]. This also provides an explanation for the close association of minerals with different solubilities because each grain or small agglomerate of grains is weathered in its own encapsulated environment. This provenance scenario does not require a mixing process that serendipitously recreates a basaltic cation composition[32] (see Supplementary Information), nor does it require that the sediments be weathered in place by a process that somehow acts equally on a centimetre scale across hundreds of kilometres[6].

Any hypothesis that involves long-lived acidic groundwater to act on Mars must somehow explain the apparent paradox of an acidic aqueous system active on a basaltic planet[5,6]. The paradox exists because the amount of basalt available on or near the surface would act to neutralize any acidic solutions through water–rock interaction[8]. However, if the acidic solutions occurred as small pockets within a polar ice deposit, they would be effectively isolated from the basaltic crust of the planet. Under these conditions, it would have been feasible to create acidic solutions that maintained a low enough pH to form the jarosite observed in the Meridiani sediments. However, processes such as basal melting might create groundwater in the basaltic crust that might become alkaline in nature. Although it may not have happened in Meridiani, this model provides a means for both acidic weathering and alkaline, phyllosilicate-forming subsurface water–rock interactions to occur simultaneously in surficial ice deposits and in subsurface aquifers respectively, rather than in different geological epochs[33].

The Meridiani sediments are located in an area that does not form a natural basin[7,27], a problem for any hypothesis that includes an aqueous origin. A recent hydrologic study of Mars suggests that the Meridiani sediments are located in a region that would be an epicentre for extensive groundwater upwelling[4], and this has been cited as a possible mechanism for creating the sulphates in a traditional evaporite environment[2]. However, this hypothesis

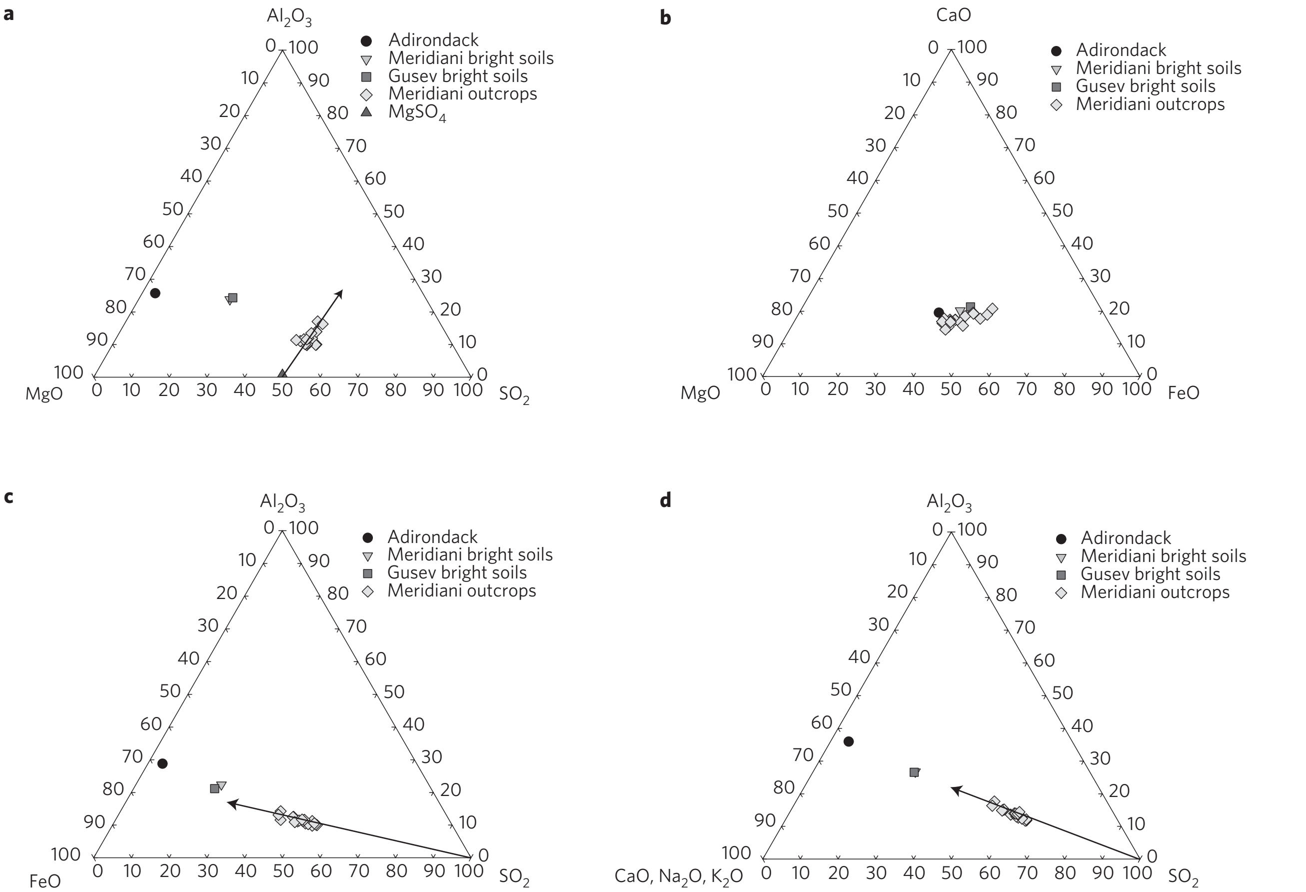

Figure 3 | Chemical compositions of Meridiani Planum sediments. a, The variation in the molar composition of the sediments at Meridiani Planum[31] can best be explained as addition/removal of $MgSO_4$ indicated by the arrow. **b**, The major cation composition of the Meridiani sediments strongly resembles a basaltic composition similar to an unaltered basalt (Adirondack). The Meridiani outcrops also show a close resemblance to bright soils observed at Meridiani Planum and Gusev Crater[41,42], which are similar to the global homogeneous dust[43]. **c**, **d**, The arrows trace constant Fe/Al and (Ca, Na, K)/Al ratios respectively. This indicates that Fe, Ca, Na and K have not been fractionated with respect to Al in the Meridiani sediments. Uncertainties on data points are smaller than the size of the points.

calls for large amounts of acidic groundwater transported through immense quantities of mafic crust to act as the mechanism for trapping the $>100{,}000\ km^3$ of material to form the mixture between sulphates and silicate material[2]. The large volume of water required by this hypothesis is in direct conflict with the observations of cation-conservative weathering and the intimate mixture of salts with different solubilities[5,6,31]. Acid-weathered silicate grains from a retreating massive ice deposit provide sufficient material to satisfy the scale arguments, and this mechanism is supported by the geological context and geochemical composition of the Meridiani sediments.

Application to the global geologic picture of Mars

The formation process of the sedimentary deposits in Terra Meridiani acted on such a large scale that it necessarily requires consideration of the broader regional and global geologic picture of Mars. Remote-sensing studies have linked the Meridiani deposits to a number of other martian surface features through mineralogic similarities, geomorphic similarities and regional associations. Many of these studies have noted that the Meridiani sediments are probably related to layered and mantling deposits in Arabia Terra[11,20,34]. If the Meridiani sediments are indeed reworked sublimation residue from massive ice deposits, then this process, which we would expect to act on a regional scale, was probably important in forming the layered deposits in Arabia Terra. Likewise, strong similarities have been noted between the deposits in Arabia and layered deposits located elsewhere on Mars including the interior layered deposits in the Valles Marineris system, southern Elysium/Aeolis, Amazonis Planitia and the Hellas basin[11,20,35,36]. Although they are separated by more than 1,000 km, Aram Chaos, Aureum Chaos, Ioni Chaos and Valles Marineris each contain sulphate paired with haematite that has spectral features identical to the haematite found in Terra Meridiani[26,37,38]. The thermal infrared spectrum of each of these areas shows an alignment of the haematite *c* axis, which is rare in terrestrial rocks and is probably caused by spherule growth[17]. The uniqueness of their thermal infrared signatures and the distance between these deposits suggest that all of these deposits share a common formation process that must have acted over a large area of Mars.

The weathering model proposed here could potentially explain the origin of many layered sulphate deposits detected on Mars. Most of the sulphate deposits on Mars share common characteristics: they are layered, occur in mounds and ridges and lack an obvious provenance[33]. These deposits are located in three types of setting. The first is the circum-Meridiani region as subdued deposits exposed by erosion and tectonism. The second is within chasma or craters as mounds or deposits pasted against wall rock. The third is in dunes in the modern polar environment[39]. Weathering and sulphate formation in massive ancient ice deposits may provide a plausible geochemical and geomorphological origin for the first two types of these deposits. In these deposits, the sulphates are exposed in spectrally detectable layered deposits, some of which may reflect

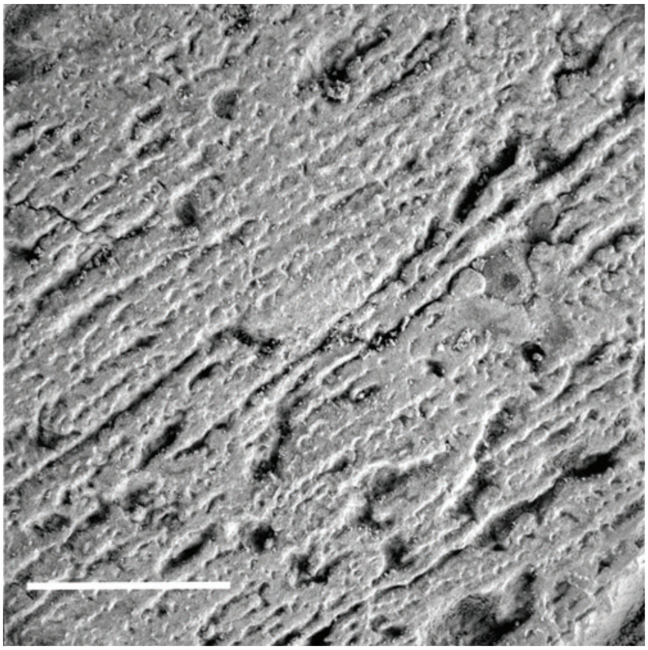

Figure 4 | Microscopic image of Meridiani Planum sediments. Image of outcrop of sediments at Meridiani Planum inside Endurance crater taken by the microscopic imager on sol 145 (Credit: NASA/JPL/Cornell/USGS). The image was taken after grinding with the Rock Abrasion Tool and reveals microscale textures within the rock. No obvious crystals or grains are visible, indicating that this outcrop is made up of aggregates of much smaller particles. Significant porosity is also revealed here, presumably from recrystallization and dissolution processes that occurred during diagenesis[44]. The scale bar is 10 mm.

the original morphology of layered ice deposits. Layered sulphate deposits may also have formed through eolian or impact reworking and transport of sublimation residue or through episodic fluvial processes driven by limited melting of ice. In chasmata, the sulphate mounds probably represent reworked sublimation residue from local ice deposits that was transported and pasted against canyon walls or against the edge of a retreating ice cap. Differences in hydration state within layered sulphates could represent different environmental conditions during the mobilization stage, or could represent diagenetic differences. The modern polar sulphate deposit is mineralogically and geomorphologically different from the first two deposit types, but its proximity to a massive ice deposit and its distribution in an erg deposit make it a potential modern analogue. This view of sulphate formation in Meridiani and elsewhere on Mars draws a direct comparison between ancient and modern geologic processes and suggests sulphate minerals could have formed on Mars during a past cold and desiccated climate.

The best explanation for the formation of the sediments in Terra Meridiani is that they were formed from dust and sand captured in a massive ice deposit along with large amounts of volcanic aerosols, weathered into highly hydrated mixtures of siliciclastic and sulphate minerals under acidic conditions within the ice, and then reworked by eolian or impact processes. Deposits of this material have subsequently gone through limited diagenesis due to dehydration and possible ice melting events. The results of this study suggest a mechanism for volatile transport and limited aqueous alteration on Mars without invoking an early greenhouse. They also imply a common formation mechanism for most of the sulphate minerals and layered deposits on Mars, which explains their common occurrence.

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Author contributions

P.B.N. wrote the majority of the manuscript. J.M. helped develop many of the ideas and figures, and wrote some sections of the paper.

Additional information

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