

Impact origin of sediments at the Opportunity landing site on Mars

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Mars Exploration Rover Opportunity discovered sediments with layered structures thought to be unique to aqueous deposition and with minerals attributed to evaporation of an acidic salty sea. Remarkable iron-rich spherules were ascribed to later groundwater alteration, and the inferred abundance of water reinforced optimism that Mars was once habitable. The layered structures, however, are not unique to water deposition, and the scenario encounters difficulties in accounting for highly soluble salts admixed with less soluble salts, the lack of clay minerals from acid-rock reactions, high sphericity and near-uniform sizes of the spherules and the absence of a basin boundary. Here we present a simple alternative explanation involving deposition from a ground-hugging turbulent flow of rock fragments, salts, sulphides, brines and ice produced by meteorite impact. Subsequent weathering by intergranular water films can account for all of the features observed without invoking shallow seas, lakes or near-surface aquifers. Layered sequences observed elsewhere on heavily cratered Mars and attributed to wind, water or volcanism may well have formed similarly. If so, the search for past life on Mars should be reassessed accordingly.

Sediment layers discovered by Mars Exploration Rover (MER) Opportunity have been interpreted as siliclastic material deposited by highly acidic waters, which then evaporated to produce Ca/Mg sulphates, chlorides, bromides and jarosite¹. Haematite-rich spherules are then thought to have subsequently formed in the subsurface as concretions, and large crystals were dissolved to produce voids². The strata are considered to represent a once habitable environment by analogy with terrestrial extremophiles inhabiting the acid waters of the Rio Tinto River, Spain². Evidence for deposition in an aqueous system was declared “conclusive”³ and the result has been widely hailed as a milestone in humankind’s search for life elsewhere in the Universe⁴. However, deposition from the surge ejecta of a large meteorite impact is a simple alternative interpretation that accounts for all the observed features and avoids previously unrecognized problems with the aqueous deposition scenario.

Impact surge

Surges are density currents composed of crater ejecta and gases that sweep radially over the substrate away from an explosive crater during its formation (Fig. 1). They are well-known for near-surface tests of chemical and nuclear explosives^{5,6}, described in detail for volcanic explosions⁷, predicted for large planetary impact structures⁸, and found in ejecta from the Chicxulub impact structure⁹. They form layered and cross-bedded deposits that extend radially up to several crater radii away from a crater rim. Emplaced by multiphase, granular flow and influenced by shock wave propagation, the surge and its mechanism vary depending upon the type of cratering event. For impact craters, surges hypothetically originate by winnowing of fine ejecta from the ballistic curtain¹⁰, secondary debris mobilized by ballistic ejecta¹¹, by secondary vapour explosions caused by interaction of residual impact melt and saturated target rocks¹², and by density currents formed from impact breccia and late-stage or distal ejecta¹³. Surge deposition should be an important feature of impact craters on Mars because of atmospheric influence on ejecta

dispersion and the abundant water, ice and/or brine in the regolith^{12,14,15}. Supporting this are the distinctive, ‘fluidized’ ejecta deposits surrounding many martian impact craters (‘rampart’ craters) that display textural features indicative of surge-like flow⁷. Important aspects of surge transport include its ability to deposit ejecta over a larger area than that typical of continuous ballistic ejecta^{16,17}, its deposition of multiple ejecta layers that resemble aeolian or water-laid strata⁷, the wide range of dune-like structures deposited⁷, the extensive production of spherules by accretion of dust-sized particles¹⁸, and the effects of condensation of components of the gas phase^{7,19}.

The high-albedo, cross-laminated stratum at the Opportunity landing site is visible in orbital photographs, and apparently extends over tens of thousands of square kilometres (ref. 2). A key issue is the size of an impact crater that could produce such a large surge deposit. Garvin *et al.*¹⁷ used MOLA (Mars Orbiter Laser Altimeter) data to



Figure 1 | Nevada Test Site nuclear test explosion that produced crater Sedan. The cloud of suspended particles expanding outward along the ground surface is the surge. This surge left a cross-bedded sand deposit up to 1 m thick⁵.

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investigate ejecta thicknesses around martian impact craters with respect to the ejecta thickness function (ETF), $t_e = a(r/R_a)^b$, where t_e is the ejecta blanket thickness, r is the radial distance, R_a is the apparent crater radius, and a and b are fit constants. The ETF is based on scaling studies of explosive and impact craters¹⁶, and thus includes a basic scaling of gravitational and atmospheric effects. Their results show a high variability of the exponent b , with $-24 < b < -0.3$ for craters bisected by MOLA data, which contrasts to the $b = -3 \pm 0.5$ commonly cited for impact craters⁸. For craters surrounded by lobate ejecta blankets of relatively flat profile, they found b to be less than -2 , with cited examples of $b = -1$ and $b = -0.7$. Accordingly, they interpret ejecta profile flatness as a measure of ejecta fluidization and target volatile content. Data for terrestrial volcanic surge deposits^{7,20} yield a best-fit ETF value of $b = -1$ in support of the Garvin *et al.* interpretation (Fig. 2a). Extrapolating this volcanic surge ETF to ejecta deposits for hypothetical 100- and 400-km-diameter impact craters on Mars (Fig. 2b) shows >1 m thicknesses extending up to 600 km from the crater rim.

Rigorous relationships developed specifically for surge deposits have not been published, although the effects of gravity and atmosphere have been applied to martian ballistic ejecta¹¹. Surge transport is governed by transformation of gravitational potential energy to translational kinetic energy⁶ and by creation and dissipation of turbulence⁷. Because gravitational acceleration drives surge run-out but also causes deceleration during frictional contact with the substrate, the scaling of gravity is not expected to be critical for considerations of surge dispersal. However, turbulence is created

from drag that is directly proportional to atmospheric density and has greatest influence at transonic speeds for ejecta moving through the atmosphere. The interplay of a lower rate of turbulence creation for subsonic speeds but higher Mach numbers for martian ejecta remains unexplored.

Mitchell *et al.*²¹ characterized 85 impact crater forms, and found that ejecta deposit diameter is larger than crater diameter by a factor of 2.7 to 4.5, representing a radial extent of about 1 to 2 crater diameters from the crater rim. Overall, these results suggest that for large impact craters (1) surge ejecta deposits show little change in thickness ($<10\%$) over distances of 100 km; (2) surge deposits greater than 2 m in thickness might extend over 500,000 km² from a single impact crater; and (3) observed impact surge deposit extents are likely to be less than their initial range because of erosion or late-stage non-newtonian flow behaviour displayed as pedestal or rampart formation.

It is thus possible that the layers traversed by the rover resulted from one impact event, possibly the 450-km-wide crater Schiaparelli lying about 2 crater diameters to the east. Alternatively, they could be made up of multiple, interlaced surge deposits from numerous smaller and closer craters. In this case, the light-coloured layer identified from orbit is not a single chronostratigraphic unit, but rather owes its light colour to sulphate wicking as described below. In any case, impact surge is a reasonable mechanism for thinly layered deposits on Mars, even at great distances from the source craters.

Bedding and cross-bedding

Bedding and sedimentary structures created by surge closely resemble those produced by aeolian and subaqueous deposition. Because of the complexity of multiphase granular flow, a remarkably wide range of depositional conditions develop that are dimensionally analogous to other sedimentary environments. For example, surges may be erosive or depositional, such that channelling and delta-like fore-set bedding results. Multiphase sound speed can be as low as several tens of metres per second, such that standing shock waves exist and create effects similar to those of the transition from supercritical to subcritical flow in aqueous conditions. Cross-bedding and other sedimentary structures can also be created from impact ejecta that clump together in the atmosphere and flow to the ground as density currents²².

Festoon cross-bedding observed in Eagle crater was interpreted as uniquely subaqueous in origin⁷. However, such cross-bedding occurs in terrestrial surge deposits^{23,24} (Fig. 3). The long, low-angle cross-beds in the darker layers underlying the high-albedo rim unit at Endurance crater (Fig. 4a) are common in surge deposits (Fig. 4b), as are the high-angle cross-beds that underlie these. The combined thickness of the observed stratified units is of the order of several metres, perhaps consistent with multiple surge events. A single surge event can emplace a deposit of multiple layers²³, and a single impact event might produce multiple surges if vapour explosions continue after formation of the transient crater¹².

Origin of salts

A serious flaw in the evaporating lake scenario is that the most soluble salts (halides, Mg-sulphate) occur together with the least soluble salts (Ca-sulphate, jarosite). This does not happen in evaporating water masses where the least soluble salts precipitate first and line the coastal areas. The most soluble salts form in residual brine pools in the lowest areas, usually towards the centre of the basin²⁵. Bromide, in particular, is so soluble that bromide-rich evaporites should never precipitate together with sulphates.

Squyres *et al.*¹ suggest that basaltic material was weathered in surrounding areas, transported to the site by water, and deposited together with sulphates and jarosite during evaporation of the inflowing acid waters. However, acid rivers, lakes, and aquifers on and within a basaltic substrate cannot be sustained because basalt reacts rapidly with acid, particularly basalt in the form of glass and

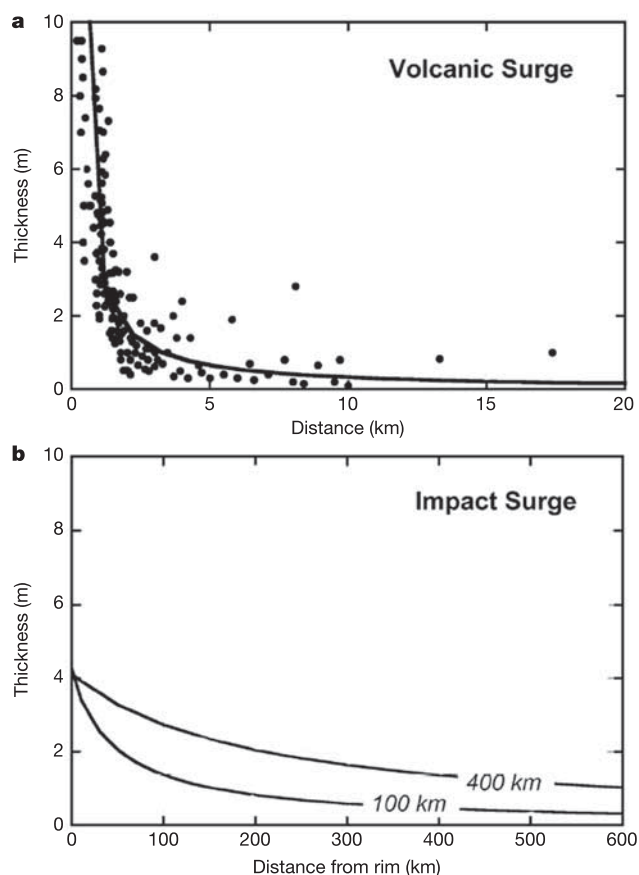


Figure 2 | Plots of surge deposit thickness versus radial distance. **a**, The variation in thickness for terrestrial volcanic surge deposits is plotted as a function of distance from crater centre (points beyond 20 km are not shown). **b**, The best-fit Ejecta Transfer Function from the volcanic data are used to estimate the thickness of impact surge deposits for 100- and 400-km-diameter craters on Mars.

fragmental debris in the martian regolith. Clay minerals are produced and the solution is neutralized²⁶. The apparent presence of only trace amounts of clay minerals on Mars³ thus contradicts scenarios involving large acid water masses and, particularly, acid ground waters. The terrestrial Rio Tinto River analogy is not ideal, because the sediment from this river has voluminous clay minerals and the acid level is enhanced by over 3,000 years of human mining activity on the Earth's largest-known volcanogenic sulphide deposit. No such clay deposits, upland massive sulphide source, upland drainage channels, or deltas extending into the putative lake have been observed near Meridiani Planum. The lack of any visible shorelines or other basin boundary (ref. 27, and references cited therein) is an additional problem.

An alternative explanation for the widespread presence of sulphates and chlorides mixed with basaltic fragments arises as a

consequence of the previously known evidence for a relatively brief period early in martian history when large amounts of water flowed over the surface (ref. 28, and references cited therein). Up to 90% of this water was lost from the planet, based on the current D/H ratio of the atmosphere (ref. 29, and references cited therein). Loss of this water from the atmosphere would necessarily have caused the remaining hydrosphere to become evapoconcentrated into a brine¹⁵. This brine, lodged in the megaregolith, would necessarily have reacted with the basaltic materials and evolved into Ca-Mg-Na-Cl⁻-rich brine. With the onset of global freezing, the brine in the megaregolith would have necessarily undergone fractional freezing to produce water ice, chloride, bromide and sulphate salts, and highly concentrated, eutectic brine with freezing points below current martian equatorial temperatures³⁰. Subsequent large impacts into the megaregolith would scatter not only basaltic materials over large distances, but also the included salts, ice and brine. In the surge scenario, a large impact might excavate through the entire megaregolith and thus eject the full complement of phases originally separated via evapoconcentration and fractional crystallization. Phases expected in a martian impact surge would therefore be sand-sized and finer basalt fragments and glasses together with a disequilibrium mechanical mixture of hydrohalite, antarcticite, Mg-Ca sulphates, minor clays, chlorides, bromides, ice, brine, and minor exotic salts formed during fractional crystallization.

The total thickness of deposits at Meridiani Planum could be 1 km,

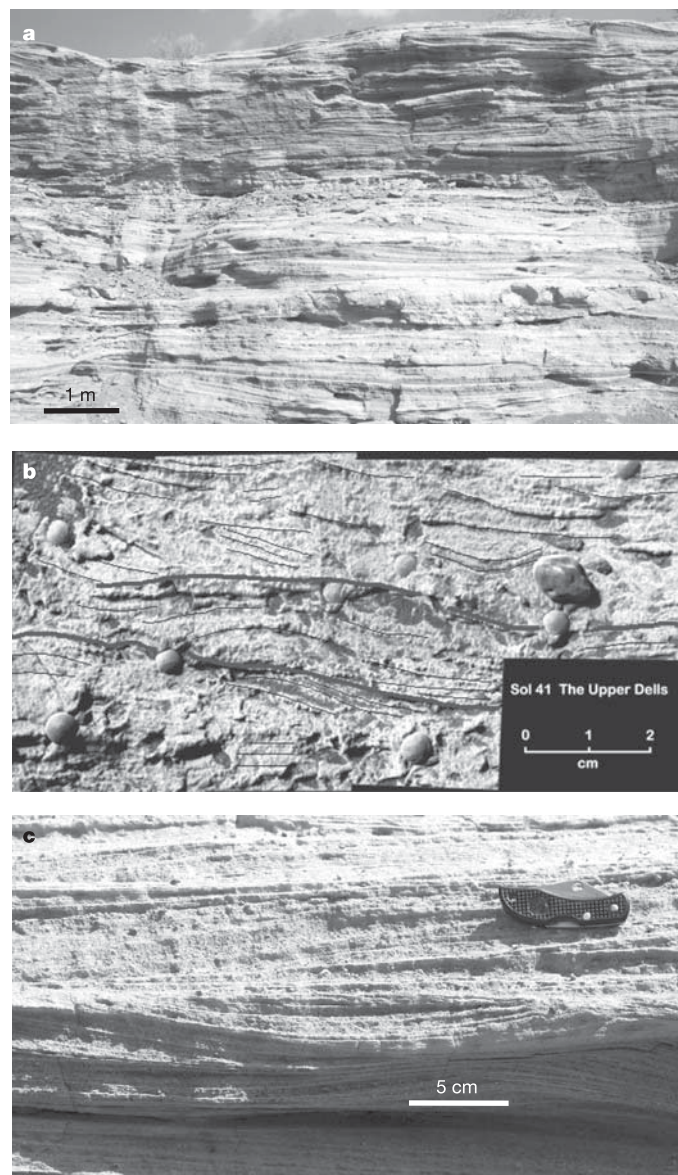


Figure 3 | Terrestrial surge deposits compared with cross-stratified martian deposits. **a**, Typical layered and cross-bedded aspect of a terrestrial deposit, Kilbourne Hole, New Mexico. **b**, Upper Dells mosaic taken on sol (martian day) 41. Lines added by the MER team to highlight cross-sets. **c**, Festoon cross-beds from Kilbourne Hole, New Mexico. Festoon cross-sets in terrestrial surges occur at the same scale as those observed on Mars and need not imply an aqueous origin.

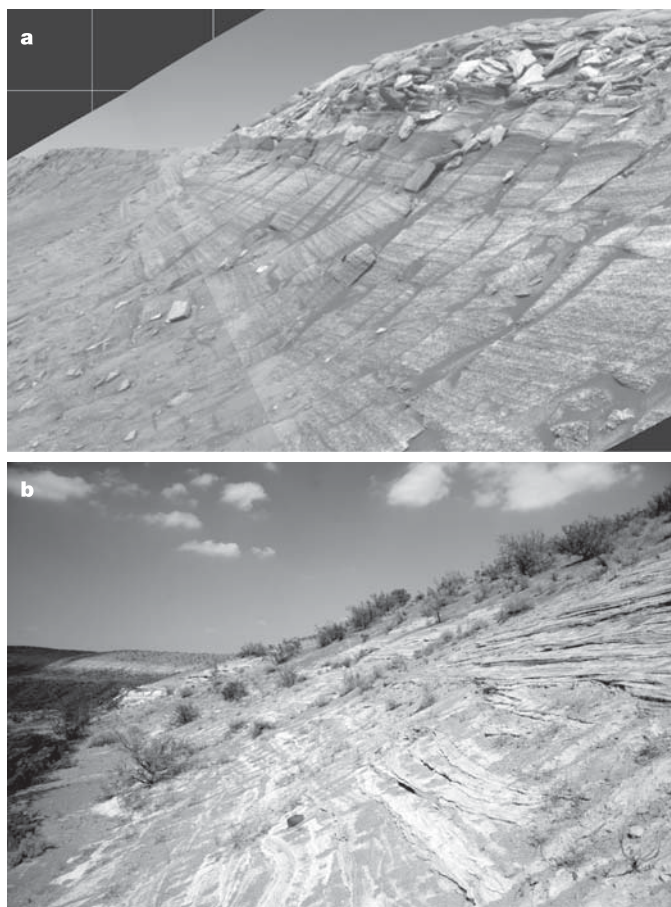


Figure 4 | Martian strata compared with terrestrial surge strata. **a**, Wall of Endurance crater on Mars, showing long, low-angle cross-sets overlying high-angle cross-sets (upper left part of photograph). The sloping straight line is an artefact of image stitching. The bedding displayed here is common in surge deposits. Impact surge explains all stratification in terms of only one process. **b**, Outcrop appearance of typical, layered surge deposits, Kilbourne Hole, New Mexico.

or more^{31,32}. An evaporite origin is unlikely if all are rich in sulphate because the amount of water implied is untenable. For example, evaporation of a 1 km column of terrestrial sea water yields less than 2 m of sulphate. Stacked surge deposits from numerous distant craters could be sulphate-rich, and might occur interbedded with volcanic ash and wind-blown deposits. In any case, only the topmost layers are visible to MER and these strongly resemble surge deposits.

Following emplacement, the heterogeneous jumble of mechanically emplaced phases would necessarily undergo diagenetic reorganization following mobilization of small amounts of interstitial waters and water films. Most of the salts are hygroscopic and/or deliquescent, and would absorb water vapour from interstitial cavities, ice and the overlying atmosphere. Mixed with melted ice from warm periods, local brine pockets would yield early diagenetic crystal growth, including that resulting from Ostwald ripening³³, where smaller crystals scattered through the mechanical mixture yield to larger ones. Such mineralogical stabilization after deposition is inevitable, especially considering that >3 billion years were available.

Crystal moulds visible in the upper light-coloured layer have been interpreted as monoclinic crystals, possibly gypsum, that formed diagenetically and were subsequently dissolved². The rock matrix is inferred to have at present up to 30–40% finer-grained sulphate². It is highly unlikely that the largest crystals would dissolve before smaller crystals of the same mineral. It is more likely that these larger crystals were a soluble halide such as hydrohalite, a monoclinic mineral that would probably have grown in briny pore fluids from the mechanically emplaced salt fragments via Ostwald ripening. With time and addition of minor water, brines would migrate downward and carry the most soluble components deeper into the sedimentary pile. Chloride and bromide salts would be preferentially removed and the less soluble sulphates left behind. Deliquescent phases would be removed by ice melt during warm periods and/or would absorb water vapour, become fluid, and drain out. This simpler scenario for the moulds does not require larger crystals to dissolve preferentially to smaller ones, and does not require introduction of late, fresh ground

waters. In the exceedingly dry atmosphere of Mars, further near-surface concentration of sulphates could occur by 'wicking up' processes similar to those that produce sulphate efflorescences on desert mine dumps on Earth.

Differential solubility thus explains the observed cavities and the relatively abundant sulphate as a lag and/or efflorescence following downward movement of the more soluble Cl. The entire mass need not have been bathed in water. Instead, there were films, pockets and preferred flow paths. Small areas that stayed relatively dry retained more of the initial composition that was rich in Cl and Br. This scenario also explains the paucity of observed clay minerals because only small amounts of neutral water were involved. The absence of clay minerals and playa mud layers is a serious problem for the evaporating acid lake hypothesis but not for the impact surge hypothesis.

Spheroids. Abundant well-sorted, largely spherical, haematite-rich grains about 5 mm in diameter occur as several per cent of the bedrock and accumulated as a lag on the surface². Occasional banding and grooves parallel to bedding, termination of crystal moulds against the spherules, their uniform distribution, the general lack of bedding disturbance, and the presence of rare, apparent doublets have been advanced as evidence that the spherules are concretions that formed diagenetically in the phreatic zone of a groundwater system². Concretions in the Navajo Sandstone have been invoked as a possible terrestrial analogue³⁴.

Although terrestrial concretions with almost perfect sphericity can occur, the size uniformity and high sphericity of the martian spherules are rare or even unknown over outcrop scales on Earth. The Navajo Sandstone concretions come in a wide variety of sizes and shapes, are not distributed uniformly in outcrop, and occur in clusters, zones and irregular, nonlinear clumps of multiple concretions of random size and orientation³⁴. They represent almost pure quartz sand cemented locally by small amounts of goethite, haematite and carbonate. The composition and internal nature of the martian examples are not yet fully known, but they do not resemble terrestrial concretions other than having an iron oxide component

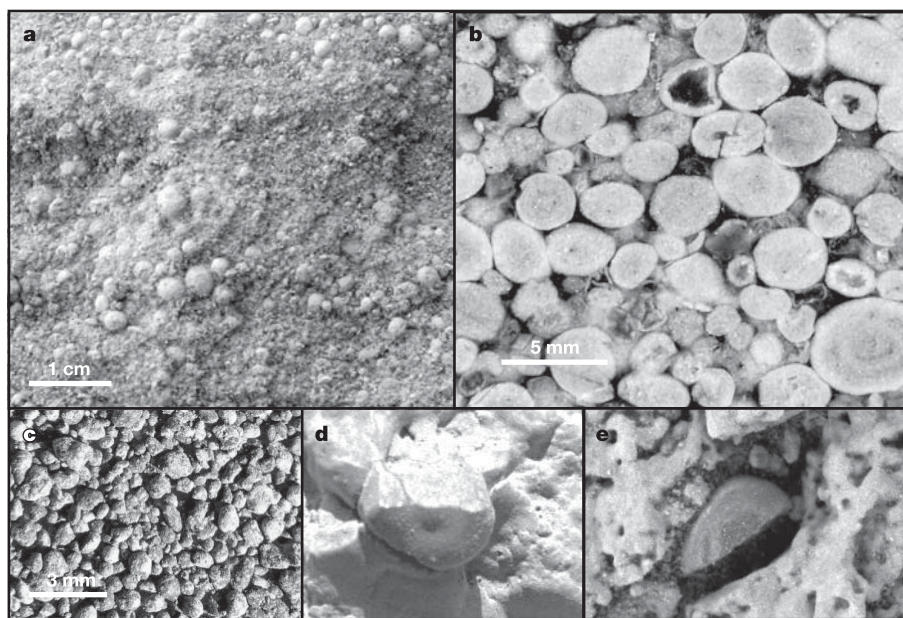


Figure 5 | Martian spherules compared with terrestrial accretionary lapilli and impact spherules. **a**, Terrestrial accretionary lapilli in surge deposit, Kilbourne Hole, New Mexico. These are similar in size, shape and sphericity to martian spherules. **b**, Compacted, terrestrial accretionary lapilli from the 3.5-Gyr-old Onverwacht Formation, South Africa. Initially interpreted as volcanic accretionary lapilli⁵⁰, these may be impact surge accretionary lapilli

because impact spherule beds occur in the same formation⁴⁰ and the two spherule types are locally intermixed. **c**, Iron condensation spherules, Meteor crater, Arizona. **d**, Broken, cored 4-mm spherule on Mars, sol 28. **e**, Broken spherule on Mars, sol 142. Spherule diameter is approximately 4 mm and appears to have layered concentric structure similar to terrestrial accretionary lapilli.

and being spheroidal. The martian spherules carry the orbital Thermal Emission Spectrometer (TES) haematite signature and are thus inferred to cover an area of 150,000 km (refs 2, 31). If concretions, they grew uniformly in a vast shallow unfrozen aquifer on a scale probably unknown in the rock record on Earth, which has always had widespread aquifers and abundant concretions of diverse mineralogies and forms.

On Earth, volcanic surge deposits commonly contain accretionary lapilli (Fig. 5a), as well as other small spherical particles, all of which have been found in terrestrial impact ejecta^{35,36}. Accretionary lapilli^{18,37} form largely owing to moisture within the moving surge cloud that causes grains to adhere one to another, building up concentric layers while in turbulent motion, much in the way of hailstones. The lapilli preferentially gather fine dust but do not begin formation until steam condensation has begun. Where iron-rich particles are accreted in these fumarole-like conditions, iron is rapidly oxidized³⁸. Once lapilli have grown large enough, they fall out of the surge cloud. At any one location within the surge deposit, their size is therefore fairly uniform. Spherical ejecta are also hydrodynamically formed in certain fragmentation modes of water/melt interaction³⁹.

Large impacts are known to produce condensation spherules (including doublets) of similar size to the lapilli⁴⁰. Regional sheets of accretionary lapilli and impact condensation spherules occur in terrestrial Archaean strata (Fig. 5b), often mixed in the same horizon and difficult to distinguish. The large geographic areas over which the terrestrial spheroids occur are comparable to the area yielding the orbital TES haematite signature. Well-sorted spheroids may thus have been produced from impact events and then deposited by a surge or more distal density currents²²; a regional aquifer is not necessary.

Meridiani Planum was selected as a landing site primarily because it is one of the few places displaying an extensive haematite infrared emission signature. In terms of our hypothesis, the TES signature itself may represent oxidized iron in accretionary lapilli made up largely of basaltic glass particles. However, the uniqueness of the deposit may indicate that the impactor was a large iron meteorite that yielded a large population of iron condensation spherules as well. Iron meteorites are rare and large iron meteorites that could produce a >100 km crater are rarer still. Iron condensation spherules are produced during iron meteorite impact events (Fig. 5c). Oxidation of the iron to haematite during volatilization/condensation is most likely, but later weathering could also account for the enhanced haematite signal visible from orbit. Chemical analyses indicate a good correlation between Ni and Fe when comparing spherule-rich and non-spherule-rich areas⁴¹. This is problematical for concretions, but is to be expected if there was a major nickel-iron meteorite component in the spherules. This site was specifically chosen because of its peculiar TES signature, so landing on a spot unusually rich in condensation spherules from an iron impactor would not be so fortuitous.

Spherules are typically girdled with rinds of matrix that eventually abrade away upon release from the rock. Remnant ridges and grooves are thus not compelling evidence for a replacement origin; cross-sections of the spherules made by the Rotary Abrasion Tool are typically circular. The large crystals that abut the spheroids are compatible with our scenario of impact surge deposition followed by diagenetic crystal growth. This scenario does not require removal of siliciclastic grains to make room for the spherules, which is something required in the concretion scenario. Accretionary lapilli and condensation spherules do not necessarily disrupt sedimentary lamination in known terrestrial examples, so the usual lack of such disruption on Mars need not argue for concretion growth. Some crystals terminate against spheroids, but this can happen during growth and does not imply truncation² indicative of later spheroid growth. At least two fractured and wind-polished concretions display possible concentric zonation similar to that in many terrestrial

accretionary lapilli (Fig. 5d, e). In any case, impact spherules and accretionary lapilli are commonly internally uniform and are compatible with all imagery returned so far.

Jarosite and other features

About 28% of the Fe in the rock outcrops is inferred to be in jarosite⁴². This mineral develops in arid regions on Earth when rocks bearing iron sulphide minerals are mined, crushed and exposed to weathering⁴³. The fresh sulphides react rapidly with oxygen and small amounts of water to produce films and rivulets of acid sulphate, which immediately react with the silicate host rocks to produce clays and coatings of jarosite. Following rains, jarosite is eventually converted into goethite or haematite via incongruent dissolution. Mixtures of jarosite, goethite and haematite thus occur together in mine dumps and tailings that contain sulphide. An impact surge deposit on Mars might have three sources of sulphur sufficient to account for jarosite alteration: (1) Fe-reduction of evaporitic sulphate to sulphide during impact devolatilization, (2) primary sulphide concentrations near the bottoms of impact excavated mafic magma chambers and flows⁴⁴, and (3) sulphide (1–2 wt% S) contained in the iron bolide itself. Subsequent martian oxidative and frost weathering over billions of years could be comparable to terrestrial arid-region weathering. Minor water produces films of sulphuric acid, which are then partly neutralized by reaction with the pulverized rocks to produce localized coatings of jarosite. The co-existing haematite represents material that was not contacted by the acid films or where continued addition of small amounts of water leached the acid component of jarosite. Such surface and near-surface coatings of jarosite could cause this mineral to appear more plentiful than it actually is.

The Meridiani deposit is remarkable for its regional flatness and its paucity of ballistic ejecta blocks. The extreme flatness is characteristic of lake deposits, but it is also characteristic of the tops of terrestrial volcanic surge deposits. These flow with negligible yield strength and thicken over topographically low areas and pond within them, leading to a tendency to form flat surfaces⁴⁵. Topographic flatness is therefore compatible with either a lake deposit or an impact surge deposit. The lack of later ballistic ejecta blocks is problematic in all scenarios if the age of the deposit is several billion years as inferred¹. A younger age is no problem for the impact surge hypothesis but is difficult for the lake hypothesis because it would require standing bodies of water later than normally inferred. It is also possible that this area simply escaped heavy mantling by ballistic impact ejecta.

Possible desiccation cracks have been observed in Endurance crater and were attributed to wetting/drying episodes. Desiccation of inherently wet volcanic surge deposits on Earth is common⁴⁶. The martian examples could thus represent drying out of wet impact surge deposits.

Discussion

The impact surge hypothesis avoids the contradictions implied by aqueous deposition and accounts for all the features observed by the MER Opportunity with a minimum number of events and processes. The scenario calls for a large iron meteorite impact (crater probably >100 km) into a megaregolith containing salts, ice and brine. The enormous wet surge created by this impact, together with surges from secondary impacts, deposited an extremely flat, distal, cross-stratified and layered mechanical mixture of fine basaltic particles, salts, ice, brine, accretionary lapilli and condensation spherules. Over the next 3 billion years, diagenesis and downward flow of local, thin films and droplets of brine formed by salt deliquescence and dissolution of salts in ice-melt moved the more soluble phases (chlorides) downward while the least soluble salts (sulphates) remained or even wicked towards the surface. Acid sulphates formed by oxidation of sulphides in the excavated fragments could have produced jarosite coatings. In this scenario, the discoveries at Meridiani Planum do provide additional evidence of an early

evapoconcentrated hydrosphere on Mars, but this hydrosphere had already disappeared into the megaregolith when a large impact produced this surge deposit. This scenario is wholly compatible with the post-Noachian cold and dry environment currently advocated for Mars based on data from the landing site of Spirit, the other MER⁴⁷.

Although our discussion focuses on the Opportunity site, we note that meteorite impact provides a possible explanation for many finely layered deposits elsewhere on Mars that have previously been considered in terms only of aqueous, aeolian or volcanic origin. Many of the layered blocks observed at the Spirit site in Gusev crater are similar to what is observed at the Opportunity site with respect to fabrics, textures, mineralogy and chemistry, and may also be impact or volcanic surge deposits. Impacts into megaregolith rich in salts, ice and residual brine can readily account for the widespread distribution of salts in martian surface materials, as observed at previous landing sites and now from orbit⁴⁸. Impact surge deposition carries no particular advantage for microfossil preservation, so the search for past life on Mars should probably be re-directed. Better prospects lie, perhaps, in the tiny fractures in surface rocks everywhere. Small mineral deposits from aqueous films are likely there, some with potential isotopic biosignatures⁴⁹. In any case, impact surge should be seriously considered as an alternative, simple explanation for the origin of this and other layered deposits on Mars.

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