IMPACT ORIGIN OF SEDIMENTS AT THE OPPORTUNITY LANDING SITE ON MARS

L. Paul Knauth[1], Donald M. Burt[1], & Kenneth H. Wohletz[2]

[1]*Department of Geological Sciences, Arizona State University, Box 871404, Tempe, Arizona 85287-1404, USA.* [2]*Earth and Environmental Sciences, Los Alamos National Laboratory, Los Alamos, New Mexico, 87545, USA.*

Mars Exploration Rover Opportunity discovered sediments with layered structures thought 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. However, the layered structures are not unique to water deposition and the scenario encounters difficulties accounting for highly soluble salts admixed with less soluble salts, lack of clay minerals from acid-rock reactions, high sphericity and near-uniform sizes of the spherules, absence of a basin boundary and many other features. A simple alternative explanation involves deposition from a ground-hugging turbulent flow of rock fragments, salts, sulfides, brines and ice produced by meteorite impact. Subsequent weathering by intergranular water films can account for all 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 sulfates, chlorides, bromides, and jarosite[1]. Hematite-rich spherules subsequently formed in the subsurface as concretions, and large crystals were dissolved to produce voids[2]. The strata are considered to represent a once habitable environment by analogy with terrestrial extremophiles inhabiting the acid waters of the Rio Tinto River, Spain[2]. 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 universe[4]. 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 heretofore 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 explosions[7], predicted for large planetary impact structures[8], and found in ejecta from the Chicxulub impact structure[9]. 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 curtain[10], secondary debris mobilized by ballistic ejecta[11], by secondary vapor explosions caused by interaction of residual impact melt and saturated target rocks[12], and by density currents formed from impact breccia and late-stage or distal ejecta[13]. 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 flow[7]. 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 strata[7], the wide range of dune-like structures deposited[7], the extensive production of spherules by accretion of dust-sized particles[18], 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 photos and apparently extends over tens of thousands of square kilometers[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 investigate ejecta thicknesses around Martian impact craters with respect to the ejecta thickness function (ETF), $t_e = a(r/R_a)^b$, for which 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 craters[16], 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 $b = -3\pm0.5$ commonly cited for impact craters[8]. 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 EFT value of b = -1 in support of the Garvin et al. interpretation (Fig. 2a). Extrapolating this volcanic surge EFT 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 ejecta[11]. Surge transport is governed by transformation of gravitational potential energy to translational kinetic energy[6] and by creation and dissipation of turbulence[7]. 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 km^2 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 behavior 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 colored layer identified from orbit is not a single chronostratigraphic unit but rather owes its light color to sulfate 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 eolian 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 channeling and delta-like fore-set bedding results. Multiphase sound speed can be as low as several tens of meters 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 which clump together in the atmosphere and flow to the ground as density currents [22].

Festoon cross-bedding observed in Eagle Crater was interpreted as uniquely subaqueous in origin[2]. 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 on the order of several meters, perhaps consistent with multiple surge events. A single surge event can emplace a deposit of multiple layers[23] and a single impact event might produce multiple surges if vapor explosions continue after formation of the transient crater[12].

Origin of salts

A serious flaw in the evaporating lake scenario is that the most soluble salts (halides, Mg-sulfate) occur together with the least soluble salts (Ca-sulfate, 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 toward the center of the basin[25]. Bromide, in particular, is so soluble that bromide-rich evaporites should never precipitate together with sulfates.

Squyres et al.[1] suggest that basaltic material was weathered in surrounding areas, transported to the site by water, and deposited together with sulfates 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 fragmental debris in the martian regolith. Clay minerals are produced and the solution is neutralized[26]. The apparent presence of only trace amounts of clay minerals on Mars[3] 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 3000 years of human mining activity on the

Earth's largest-known volcanogenic sulfide deposit. No such clay deposits, upland massive sulfide 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[27] is an additional problem.

An alternative explanation for the widespread presence of sulfates 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[28]. Up to 90% of this water was lost from the planet based on the current D/H ratio of the atmosphere[29]. Loss of this water from the atmosphere would *necessarily* have caused the remaining hydrosphere to become evapoconcentrated into a brine[15]. 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, Cl, Br, and sulfate salts, and highly concentrated, eutectic brine with freezing points below current martian equatorial temperatures[30]. 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 sulfates, 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, 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 vapor 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 ripening[33] where smaller crystals scattered through the mechanical mixture yield to larger ones. Such mineralogic stabilization after deposition is inevitable, especially considering that >3 billion years were available.

Crystal molds visible in the upper light-colored layer have been interpreted as monoclinic crystals, possibly gypsum, that formed diagenetically and were subsequently dissolved[2]. The rock matrix is inferred to presently have up to 30-40% finer-grained sulfate[2]. 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 likely 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 sulfates left behind. Deliquescent phases would be removed by ice melt during warm periods and/or would absorb water vapor, become fluid, and drain out. This simpler scenario for the molds does not require larger crystals to dissolve preferentially to smaller ones and does not require introduction of late, fresh groundwaters. In the exceedingly dry atmosphere of Mars, further near-surface concentration of sulfates could occur by “wicking up” processes similar to those that produce sulfate efflorescences on desert mine dumps on Earth.

Differential solubility thus explains the observed cavities and the relatively abundant sulfate 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, hematite-rich grains about 5 mm in diameter occur as several % of the bedrock and accumulated as a lag on the surface[2]. Occasional banding and grooves parallel to bedding, termination of crystal molds 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 system[2].

Concretions in the Navajo Sandstone have been invoked as a possible terrestrial analogue[34].

While 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, non-linear clumps of multiple concretions of random size and orientation[34]. They represent almost pure quartz sand cemented locally by small amounts of goethite, hematite 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 and being spheroidal. The martian spherules carry the orbital TES hematite signature and are thus inferred to cover an area of 150,000 km[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 due 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 hail stones . 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 oxidized[38]. 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 interaction[39].

Large impacts are known to produce condensation spherules (including doublets) of similar size to the lapilli[40]. Regional sheets of accretionary lapilli and impact condensation spherules occur in terrestrial Archean 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 hematite signature. Well-sorted spheroids may thus have been produced from impact events and then deposited by a surge or more distal density currents[22]; 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 hematite 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 hematite during volatilization/condensation is most likely but later weathering could also account for the enhanced hematite signal visible from orbit. Chemical analyses indicate a good correlation between Ni and Fe when comparing spherule-rich vs. non spherule-rich areas[42]. 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 abrades 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 RAT 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, 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 *truncation*[2] 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. 5 D,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 jarosite[43]. This mineral develops in arid regions on Earth when rocks bearing iron sulfide minerals are mined, crushed, and exposed to weathering[44]. The fresh sulfides react rapidly with oxygen and small amounts of water to produce films and rivulets of acid sulfate which immediately react with the silicate host rocks to produce clays and coatings of jarosite. Following rains, jarosite is eventually converted into goethite or hematite via incongruent dissolution. Mixtures of jarosite, goethite, and hematite thus occur together in mine dumps and tailings that contain sulfide. An impact surge deposit on Mars might have 3 sources of S sufficient to account for jarosite alteration: (1) Fe-reduction of evaporitic sulfate to sulfide during impact devolatilization, (2) primary sulfide concentrations near the bottoms of impact excavated mafic magma chambers and flows[45], (3) sulfide (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 sulfuric acid which are then partly neutralized by reaction with the pulverized rocks to produce localized coatings of jarosite. The co-existing hematite 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 surfaces[46]. 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 inferred[1]. 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 common[47]. 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 (sulfates) remained or even wicked toward the surface. Acid sulfates formed by oxidation of sulfides 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 the Spirit Landing site data[48].

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, eolian, 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 orbit[49]. 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 biosignatures[50]. 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.

1. Squyres, S.W. *et al.* The Opportunity Rover's Athena science investigation at Meridiani Planum, Mars. *Science* **306**, 1698-1703 (2004).
2. Squyres, S.W. *et al.* In situ evidence for an ancient aqueous environment at Meridiani Planum, Mars. *Science* **306**, 1709-1714 (2004).
3. Christensen, P.R. *et al.* Mineralogy at Meridiani Planum from the Mini-TES experiment on the Opportunity rover. *Science* **306**, 1733-1739 (2004).

4. Kerr, R.A. On Mars, a second chance for life. *Science* **306**, 2010-2012 (2004).
5. R.H. Carlson, & Roberts, W.A. *Ejecta studies, Project Sedan* Univ. Calif. Lawrence Radiation Lab, PNE-217P (1962).
6. Glasstone, S. & Dolan, P. J. *The Effects of Nuclear Weapons*. U. S. Department of Defense and Energy Research and Development Administration, Washington, D. C., 3rd ed., 653 p. (1977).
7. Wohletz K.H. Pyroclastic surges and compressible two-phase flow. In: *Developments in Volcanology, From MAGMA to TEPHRA, Modelling Physical Processes of Explosive Volcanic Eruptions* (eds. Freundt A., Rosi, M.) 247-312 (Elsevier, Amsterdam, 1998).
8. Melosh, H.J. *Impact Cratering* 245 p. (Oxford, New York, 1989).
9. Dressler, B.O., Sharpton, V.L., Schwandt, C.S., &Ames, D. Impactites of the Yaxcopoil-1 drilling stie, Chicxulub impact structure: Petrography, geochemistry, and depositional environment. *Meteoritics and Planet. Sci*. **39**, 857-878 (2004).
10. Oberbeck, V.R. The role of ballistic erosion and sedimentation in lunar stratigraphy. *Rev. Geophys. Space Phys.* **13**, 337-362 (1975).
11. Schultz, P.H. & Gault, D.E. Atmospheric effects on Martian ejecta emplacements. *J. Geophys. Res.* **84**, 7669-7687 (1979).
12. Carr, M.H. *et al.* Martian impact craters and emplacement of ejecta by surface flow. *J. Geophys. Res.* **82**, 4055-4065 (1977).
13. Osinski, G.R., Grieve, R.A.F., & Spray, J.G. The nature of the groundmass of surficial suevite from the Ries impact structure, Germany, and constraints on its origin. *Meteoritics and Planet. Sci*. **39** 1655-1683.

14. Wohletz, K.H. & Sheridan, M.F. Martian rampart crater ejecta: Experiments and analysis of melt-water interaction. *Icarus* **56**, 15-37 (1983).

15. Knauth, L.P. & Burt, D.M. Eutectic brines on Mars: Origin and possible relation of young seepage features. *Icarus* **158**, 267-271 (2002).

17. Garvin, J.B., Sakimoto, S.E.H., Frawley, J.J. & Schnetzler, C. Global geometric properties of Martian impact craters. *Lunar and Planetary Science*, **33**, Abstract #1255, (2002).

18. Sheridan, M.F. & Wohletz, K.H. Origin of accretionary lapilli from the Pompeii and Avellino deposits of Vesuvius. In *Microbeam Analysis* (ed. R. Gooley), 35-38 (Univ. San Francisco Press, San Francisco, 1983).

19. Kieffer, S.W. & Simonds, C.H. The role of volatiles and lithology in the impact cratering process. *Rev. Geophys. Space Phys.* **18**, 143-181 (1980).

20. Valentine, G.A., Buesch, D. & Fisher, R.V. Basal layered deposits of the Peach Springs Tuff, northwestern Arizona, USA. *Bull. Volcanol.*, **51**, 395-414 (1983).

21. Mitchell, D.E., Sakimoto, S.E.H. & Garvin, J.B. MOLA topography and morphometry of rampart and pedestal craters, Mars. *Lunar and Planetary Science*, **33**, Abstract #1805 (2002).

22. Melosh, H.J. Impact ejecta sedimentation processes in the atmosphere and ocean, *Meteoritics & Planet. Sci.* **39**, Abstract #67 (2004).

23. Fisher, R. V. & Walters, A.C. Base-surge bed forms in maar volcanoes, *Amer. J. Sci.* **268**, 157-180 (1970).

24. Fisher, R.V. & Schmincke, H.-U., *Pyroclastic Rocks*, 249-256 (Springer-Verlag, New York, 1984).

25. Hunt, C.B., Robinson, T.W., Bowles, W.A., Washburn, A.L. & Hunt, C. Hydrologic Basin, Death Valley, California, 138 p. (Professional Paper 494-B, U.S. Geological Survey, Washington, DC, 1966).
26. Bullock, M.A. & Moore, J.M. Aqueous alteration of Mars-analog rocks under an acidic atmosphere. *Geophys. Res. Lett.* **31**, L14701, 10.1029/2004GL019980 (2004).
27. Golombek, M.P. *et al.* Selection of the Mars Exploration Rover landing sites. *J. Geophys. Res.* **108**, 8072, 10.1029/2003JE002074 (2003) and references cited therein.
28. Baker, V.R. Water and the Martian landscape. *Nature* **412**, 228-236 (2001) and references cited therein.
29. Jakosky, B.M. & Phillips, R.J. Mars' volatile and climate history. *Nature* **412,** 237-244 (2001) and references cited therein
30. Burt, D.M. & Knauth, L.P. Electrically conducting, Ca-rich brines, rather than water, expected in the Martian subsurface. *J. Geophys. Res.* **108**, 8026, 10.1029/2002JE001862 (2003).
31. Christensen, P.R. & Ruff, S.W. Formation of the hematite-bearing unit in Meridiani Planum: Evidence for deposition in standing water. *J. Geophys. Res.* **109,** EO8003, 10.1029/2003JE002233 (2004).
32. Hynek, B.M., Arvidson, R.E., & Phillips, R.J., Geologic setting and origin of Terra Meridiani hematite deposit on Mars. J. *Geophys. Res*. **107**, 5088, doi:10.1029/2002JE001891 (2002).
33. Boistelle R. & Astier J.P. Crystalization mechanisms in solution. *J. Crystal Growth* **90**, 14-30 (1988).

34. Chan, M. A., Breitler, B., Parry, W.T., Ormo, J. & Komatsu, G. A possible terrestrial analogue for haematite concretions on Mars. *Nature* **429**, 731-734 (2004).

35. Graup, G. Terrestrial chondrules, glass spherules and accretionary lapilli from the suevite, Ries Crater, Germany. *Earth Planet. Sci. Lett.*, **55**, 407-418 (1981).

36. Bohor, B.F. & Glass, B.P. Origin and dagenesis of K/T impact spherules – From Haiti to Wyoming and beyond. *Meteoritics,* **30**, 182-198 (1995).

37. Schumacher, R., Schmincke, H.-U. Models for the origin of accretionary lapilli. *Bull. Volcanol.* **56**, 626-639 (1995).

38. Catling, D.C. & Moore, J.M. The nature of coarse-grained crystalline hematite and its implications for the early environment of Mars. *Icarus* **165**, 277-300 (2003).

39. Wohletz K.H. & McQueen R.G. Volcanic and stratospheric dust-like particles produced by experimental water-melt interactions. *Geology* **12**, 591-594 (1984).

40. Lowe, D.R. et al. Characteristics, origin, and interpretation of Archean impact-produced spherule beds, 3.47-3.22 Ga, in the Barberton Greenstone Belt, South Africa: Keys to the role of large impacts on the evolution of the early Earth. *Astrobiology* **3**, 7-48 (2003).

41. Lowe D.R. & Knauth L.P. The oldest marine carbonate ooids reinterpreted as volcanic accretionary lapilli, Onverwacht Group, South Africa. *J. Sed. Pet.* **48**, 709-722 (1978).

42. Brueckner, J. *et al.* Hematite on the surface of Meridiani Planum and Gusev Crater. *Lunar and Planetary Science* **36**, #1767 (2005).

43. Klingelhofer, G. *et al.* Jarosite and hematite at Meridiani Planum from Opportunity's Moessbauer spectrometer. *Science* **306**, 1740-1745 (2004).

44. Ditrizac, J.E. & Jambor, J.L., Jarosites and their application in hydrometallurgy, *Reviews in Mineralogy and Geochemistry*, **40**, 405-452 (2000).
45. Burns, R.G. & Fisher, D.S. Evolution of sulfide mineralization on Mars. *J. Geophys. Res.*, **95**, 14169-14173 (1990).
46. Cas, R.A.F. and Wright, J.V., 1987, *Volcanic successions modern and ancient*, Chapman & Hall, London)
47. McPhie, J., Walker, G.P.L., and Christiansen, R.L. Phreatomagmatic and phreatic fall and surge deposits from explosions at Kilauea volcano, Hawaii, 1790 A.D, *Bull. Volcanol.*, **52**, 334-354 (1990).
48. Golombek, M.P. *et al.* Climate change from the Mars Exploration Rover landing sites: From wet in the Noachian to dry and dessicating since the Hesperian. *Lunar and Planetary Science* **36**, #1539 (2005)
49. Gendrin, A. *et al.* Sulfates in Martian layered terrains: The OMEGA/Mars Express view. *Science* **307**, 1587-1591 (2005).
50. Knauth, L.P., Brilli, M., & Klonowski, S. Isotope geochemistry of caliche on basalt. *Geochim et Cosmochim Acta* **67**, 185-195 (2003).

Acknowledgements LPK is supported by the NASA Exobiology Program. We thank Carleton Moore for supplying the iron condensation spherules from Meteor Crater and G.R. Osinski for comments on an early version of the manuscript.

Correspondence and requests for materials should be addressed to LPK (Knauth@asu.edu).

Figure Legends

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 meter thick[5].

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 center (points beyond 20 km are not shown). B. The best-fit EFT function from the volcanic data is used to estimate the thickness of impact surge deposits for 100- and 400-km-diameter craters on Mars.

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 41. Lines added by the MER team to highlight cross sets. C. Festooon cross-beds from Kilbourne Hole, NM. Festoon cross-sets in terrestrial surges occur at the same scale as those observed on Mars and need not imply an aqueous origin.

4. Mars strata compared with terrestrial surge strata. A. Wall of Endurance crater showing long, low-angle cross sets overlying high angle cross sets (upper left part of photo). The sloping straight line is an artifact 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, NM.

5. A. Terrestrial accretionary lapilli in surge deposit, Kilbourne Hole, NM. These are similar in size, shape, and sphericity to martian spherules B. Compacted, terrestrial

accretionary lapilli from the 3.5 Ga Onverwacht Formation, South Africa. Initially interpreted as volcanic accretionary lapilli[41], these may be impact surge accretionary lapilli because impact spherule beds occur in the same formation[40] and the two spherule types are locally intermixed. C. Iron condensation spherules, Meteor Crater, Arizona. D. Broken, cored 4 mm spherule, Sol 28. E. Broken spherule, Sol 142. Spherule is 4 mm and appears to have layered concentric structure similar to terrestrial accretionary lapilli.

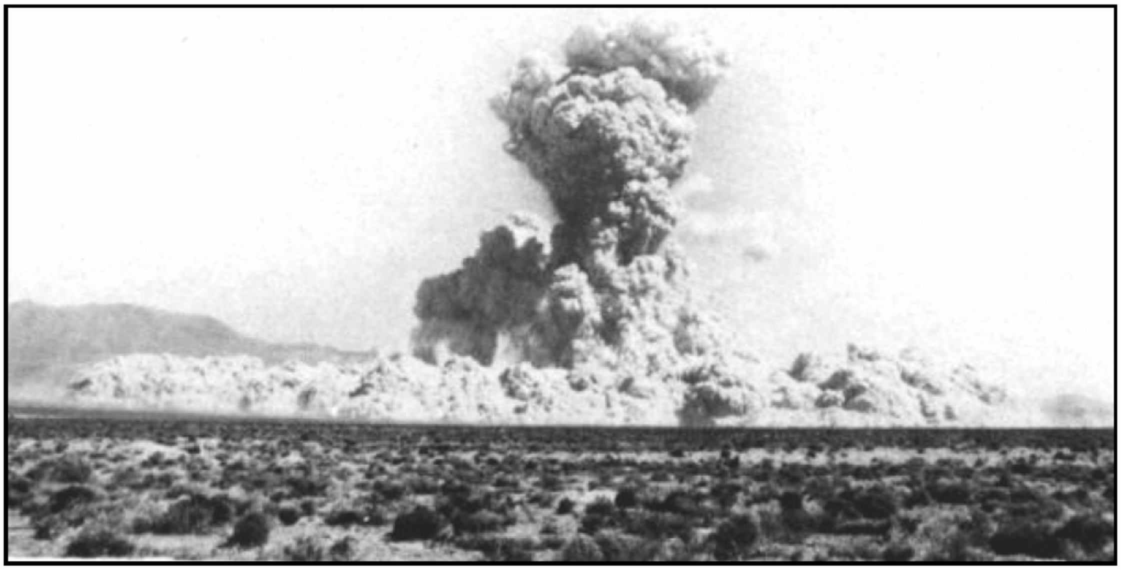

Fig. 1

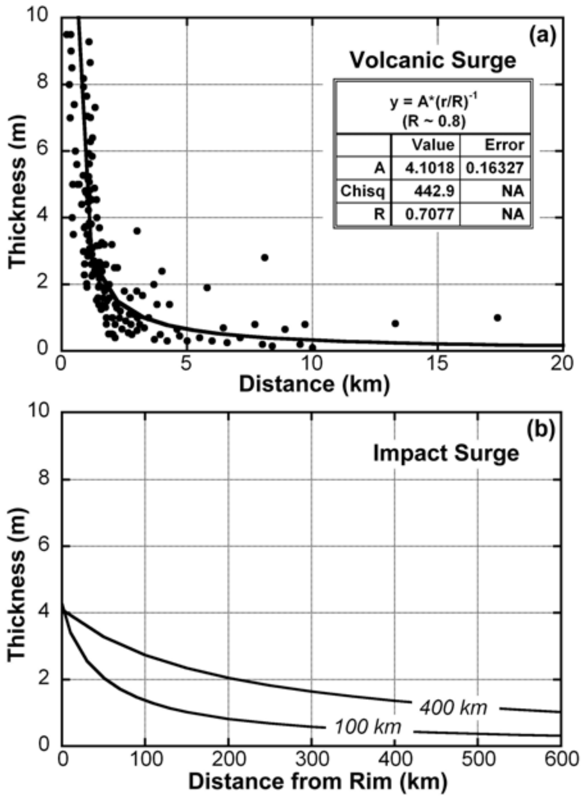
(a)
Volcanic Surge
y = A*(r/R)^-1
(R ~ 0.8)
Value
Error
A
4.1018
0.16327
Chisq
442.9
NA
R
0.7077
NA
Thickness (m)
Distance (km)
0
2
4
6
8
10
0
5
10
15
20
(b)
Impact Surge
400 km
100 km
Thickness (m)
Distance from Rim (km)
0
2
4
6
8
10
0
100
200
300
400
500
600

Fig. 2

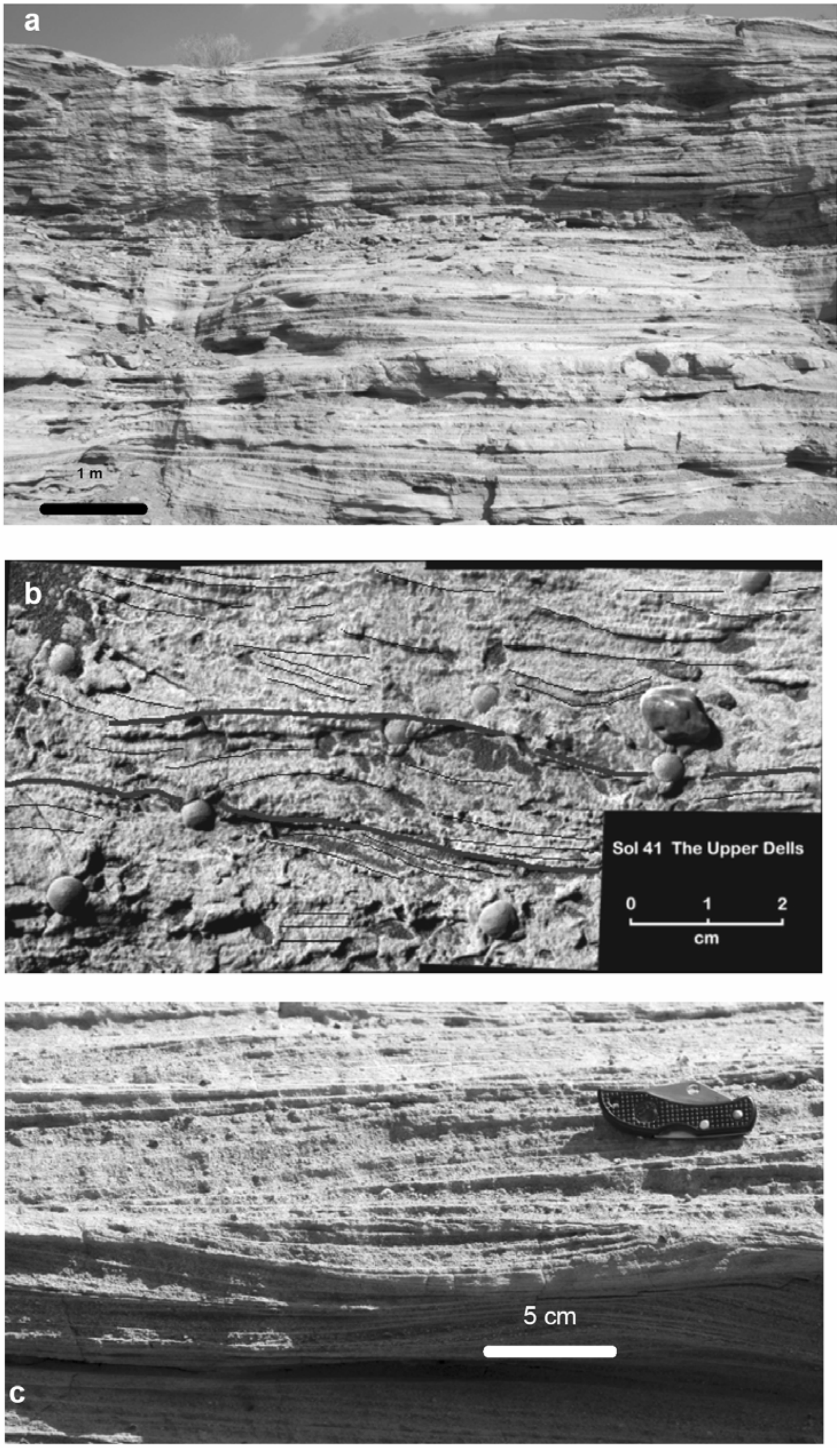

Fig. 3

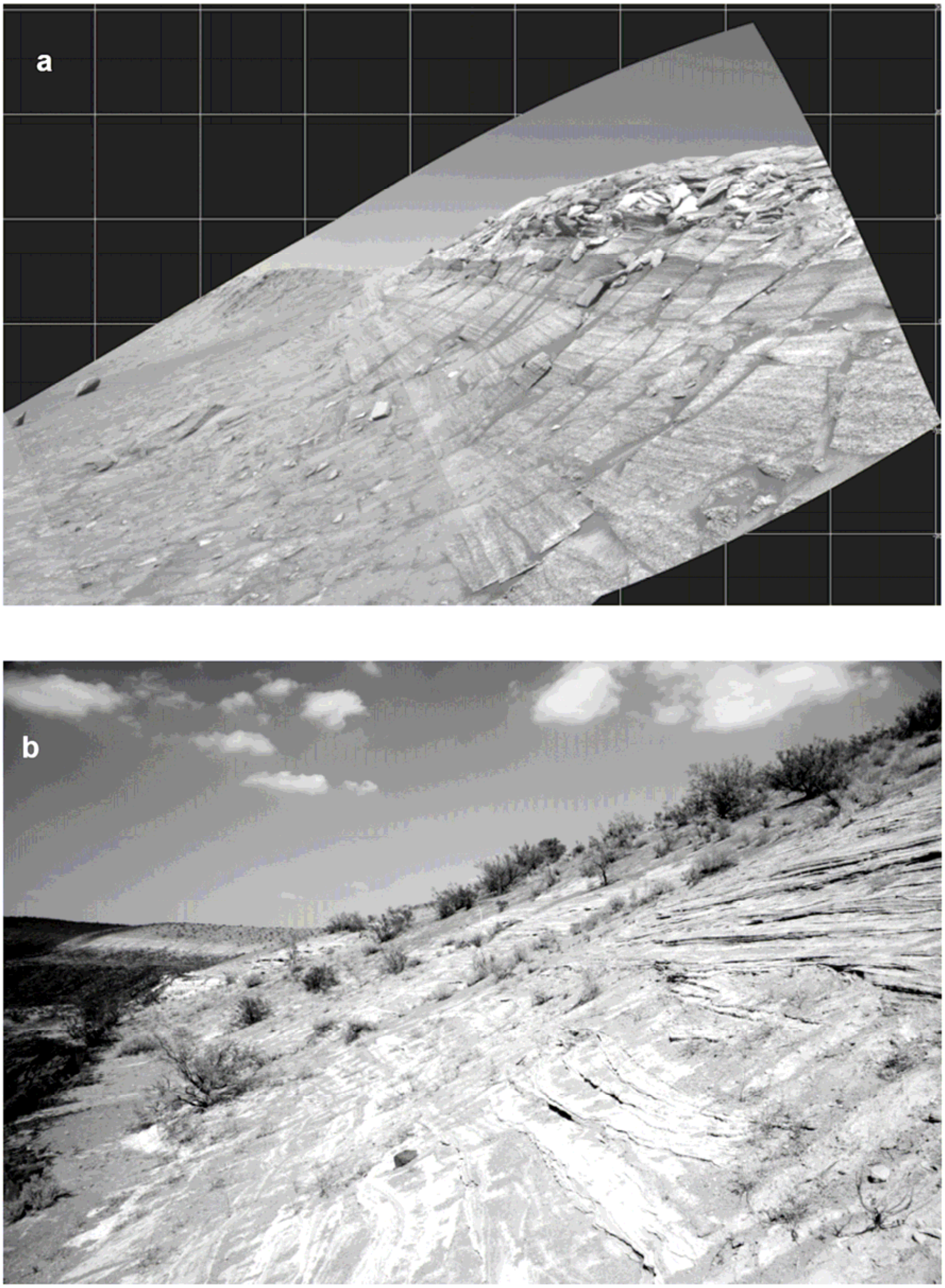

Fig. 4

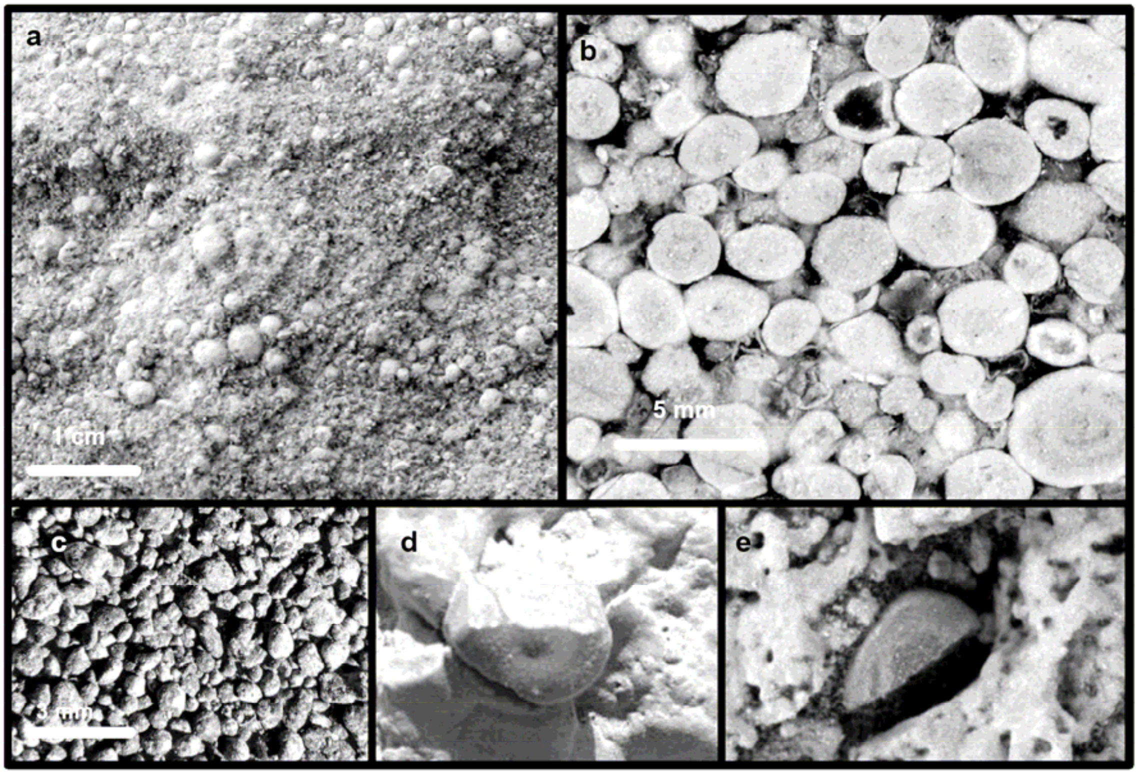

Fig. 5