Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

Mon. Not. R. Astron. Soc. **404,** 1457–1463 (2010) doi:10.1111/j.1365-2966.2010.16350.x

The making of Martian meteorite Block Island

Martin Beech[1]★ and Ian M. Coulson[2]

[1]*Campion College, The University of Regina, Regina, SK S4S 0A2, Canada*
[2]*Department of Geology, The University of Regina, Regina, SK S4S 0A2, Canada*

Accepted 2010 January 14. Received 2009 December 27; in original form 2009 November 16

ABSTRACT

An analysis of the circumstances leading to the placement of the large iron meteorite, unofficially named Block Island, on Mars is presented. We investigate the possibility that Block Island fell during the late Noachian period on Mars when its atmosphere was much denser (and hence much more massive) than at the present time. Indeed, we find that in order to produce a non-crater-forming, non-fragmenting meteorite with the characteristics of Block Island, the surface pressure of the Martian atmosphere must have been at least one to two orders of magnitude larger than it is at the present epoch.

Key words: meteors, meteoroids.

1 INTRODUCTION

The Solar system is awash with meteoroids and all exposed surfaces and atmospheres are liable to interact, on occasion, with meteoroids derived from the main-belt asteroid region (Horner et al. 2009). The recent discovery of numerous meteorites upon the surface of Mars highlights this fact and also provides us with a second arena, after that of the Earth, in which to study the conditions under which meteorites can be implanted on planetary landscapes (Davis 1993; Schröder et al. 2009).

Any planet supporting a substantive atmosphere possesses an active filter against low-mass meteoroids surviving to impact the ground, and this establishes a lower limit M_L to the expected meteorite mass range. The first Martian meteor/fireball was detected by the *Spirit* Mars Exploration Rover on 2004 March 7 and identified by Selsis et al. (2005) as being derived from comet 114P/Wiseman-Skiff. The atmospheric filtering of meteoroids, however, only works up to a point with respect to their ablation destruction and/or their potential ground impact speed. Once above a critical mass, M_U, meteoroids will strike a planet's surface with speeds close to those of their cosmic velocity and produce, thereby, an impact crater (Melosh 1989). For meteoroids with masses M in the range $M_L < M < M_U$, non-crater-forming meteorite impacts are possible. While it is the mass of the atmosphere through its direct influence on the surface pressure and density that determines M_U, one can in principle turn the situation on its head and use the annotated values of meteorite masses to estimate the essential characteristics of the atmosphere. This latter possibility has recently been made possible through the discovery of a particularly large iron meteorite on Mars, a meteorite, in fact, that appears to be much more massive than the M_U value set by the present Martian atmosphere (as described below).

★E-mail: beechm@uregina.ca

2 METEORITES ON MARS

While many tens of thousands of meteorites have been found on Earth, the first discovery of a meteorite on another planetary body was that made by the *Opportunity* Mars Exploration Rover in 2005 January (Schröder et al. 2009). The so-called Meridiani Planum meteorite was found serendipitously when the rover was commanded to investigate and photograph the remains of its earlier discarded heat shield. Analysis of the meteorite's exposed surface revealed that it was of a nickel–iron composition and consistent with being an IAB (complex) iron. Two additional meteorite candidates, unofficially named Barberton (a 3 cm-sized mesosiderite) and Santa Catarina (a 14 cm-sized mesosiderite), have also been discovered by *Opportunity* in the Meridiani Planum region (Schröder et al. 2008). The *Spirit* Mars Exploration Rover has further discovered two suspected iron meteorites (unofficially named Allan Hills and Zhong Shan) in the Columbia Hills region of the Gusev Crater.

The most recent *Opportunity* iron meteorite finds were made in 2009 August, September and October. The August find (Fig. 1), unofficially named Block Island, shows small regmaglypt-like features and numerous deep pits upon its surface. Close-up photographs of its surface further reveal the presence of distinctive triangular (Widmanstaten pattern-like) features that are a diagnostic of its nickel–iron alloy composition. Upon completing its study of Block Island, on 2009 September 11, the *Opportunity* Rover had travelled just 700 m before it came upon another iron meteorite. This find was unofficially named Shelter Island. The *Opportunity* Rover found yet another meteorite on 2009 October 17 just days after moving on from Shelter Island. The latest find, unofficially called Mackinac Island, is again an iron meteorite.

Given the relatively small surface area of Mars that has been surveyed by the *Spirit* and *Opportunity* Rovers, it is becoming clear that the surface conditions on Mars must be excellent for iron meteorite preservation. Indeed, weathering is expected to be very slow on Mars given its frigid, oxygen and water-free atmosphere (Bland &

Figure 1. Proximity image of the Block Island meteorite. Note that the meteorite is resting on apparently undisturbed bedrock. The longest dimension of the meteorite is of the order of 0.6 m. Image number: 1N302095661EFFA5ARP0713R0M1 courtesy of NASA.

Smith 2000) – indeed, similar conditions have favoured the preservation of Antarctic meteorites on Earth. To date the largest meteorite find on Mars is that of Block Island, and it is the fall circumstances of this meteorite that we investigate below.

Using terrestrial samples as our guide, the density of an iron meteorite can be taken as $7800\,\mathrm{kg\,m^{-3}}$, and if this value is combined with the estimated volume of Block Island (taken to be a square slab having dimensions $0.6 \times 0.6 \times 0.3\,\mathrm{m^3}$) a mass of the order of 850 kg is indicated. The immediate question that this mass estimate raises is as follows: can such a meteorite be reasonably produced on Mars given the planet's present atmospheric characteristics? At issue specifically is the atmosphere's ability to decelerate the progenitor body's cosmic velocity to a level below which crater formation is suppressed. This latter condition is established according to the discovery images of Block Island which show it to be resting on apparently undisturbed bedrock (Fig. 1).

Some idea of the characteristic minimum size for a meteoroid to penetrate an atmosphere and still retain its cosmic, i.e. hypersonic, velocity can be gauged according to the rule-of-thumb that the meteoroid mass must be greater than 10 times the atmospheric column mass that it intercepts (Melosh 1989). For a sphere of diameter D, the atmospheric column mass encountered will be of the order of $\{P_0/g \sin(90 - Z)\}\,\pi(D/2)^2$, where P_0 is the atmospheric surface pressure, g is the surface gravity and Z is the zenith angle of entry. If the meteoroid has a density ρ_m, then the condition for hypersonic impact is $D > 15\ \{P_0/\rho_\mathrm{m}\, g \sin(90 - Z)\}$. The present Martian atmosphere exerts a surface pressure of 600 Pa, and accordingly, for entry angles varying between vertical and 45°, it is expected that iron meteoroids with characteristic dimensions $D > 0.35$ m will encounter the Martian surface at hypersonic speed and thereby produce impact craters. Since Block Island and Shelter Island both exceed this hypersonic-impact limiting size, it is surprising, given the present atmospheric conditions on Mars, that they did not produce impact-related structures or that they were not destroyed or severely fractured upon impact. In order for the characteristic length D to appreciably exceed the 0.5–0.6 m characteristic dimensions of Block Island and Shelter Island the atmospheric pressure at the Martian surface must, apparently, have been at least three to four times greater than it is at the present epoch. The mesosiderites that have been discovered with characteristic dimensions of 3 cm (Barberton) and 14 cm (Santa Catarina) are consistent with having fallen under conditions similar to, or indeed pertaining to, the present-day Martian atmosphere. The size of Meridiani Planum, being some 0.3 m wide along its greatest dimension, is about the maximum size for an iron meteorite that might be expected to fall on Mars, under its present atmospheric conditions, without producing a substantive impact structure. In the sections that follow, we investigate the conditions under which ablation might be expected to take place within the current Martian atmosphere. To make progress with this question, we utilize the engineering model for the Martian atmosphere as described by Padevet (1991). This model conveniently expresses the atmospheric density in terms of a series of height-dependent exponential equations (see Appendix A).

3 NUMERICAL PROCEDURE

In the following analysis it will be assumed that Block Island was derived without fragmentation, and accordingly a single-body ablation model has been employed to investigate the atmospheric interaction – our ablation model is described in Appendix A. This being said, the numerical code does follow the time variation of the on-coming ram pressure $P_\mathrm{ram} = \rho_\mathrm{atm} V^2$, where ρ_atm is the atmospheric pressure and V is the velocity, and tests to see if this exceeds the parent bodies' tensile strength S. We allow for a mass variation in the fragmentation condition by a Weibel approximation and the test condition is $P_\mathrm{ram} > S = S_0(m_0/m)^\alpha$, where according to Svetsov, Nemtchinov & Teterev (1995) the constants S_0, m_0 and a are 4.1×10^6 Pa, 1.0 kg and 0.1, respectively. These values are derived from experiments carried out on a fragment of the Sikhote-Alin (IIAB, coarsest octahedrite) iron meteorite. The mass reduction and deceleration equations are solved for numerically with fourth-order Runge–Kutta integration routines, and the motion of the meteoroid is followed until it either fragments, all of its mass is lost through ablation, or the object strikes the ground.

The standard equations of meteoroid ablation describe the mass and velocity reduction as a function of atmospheric flight and require the input of five parameters for their solution. In this analysis we assume that we know the meteoroid density, it being that of iron meteorites with $\rho_\mathrm{met} = 7800\,\mathrm{kg\,m^{-3}}$. After this, the only other constraints that we impose are that an 850 kg object reaches the surface of Mars with an impact velocity smaller than $1.0\,\mathrm{km\,s^{-1}}$. The exact impact limit for non-cratering and small impactor deformation is not well defined, but we note that experiments conducted with small fragments of the Gibeon (IVA, fine octahedrite) iron meteorite, fired into quartz sand and JSC Mars-1 soil simulant, by Bland et al. (2001) indicate that deformation of the impactor begins once the impact speed exceeds $1\,\mathrm{km\,s^{-1}}$. The lower the value of the impact velocity, V_imp, the smaller is the kinetic energy of impact $K_\mathrm{imp} = \frac{1}{2} m V_\mathrm{imp}^2$, and this favours meteorite survival and reduces the likelihood of a crater being formed. Crater formation is further dependent, in a non-trivial manner, upon the density, porosity and yield strength of the target material, and these components will change according to whether the impact occurred in dry sand, wet sand and/or against bedrock. Below, we shall argue that Block Island most probably fell in the ancient past when the surface conditions in the Meridiani Planum region likely resembled those of wet sand. The recent 2007

September 15 Carancas cratering event near Lake Titicaca in Peru (Kenkmann et al. 2009) gives an example of a (H4-5 chondrite) meteorite impact on what was effectively wet sand, resulting in the formation of a shallow 2 m deep, 14 m diameter crater. Various estimates for the impact speed of the Carancas fall exist, but most cluster around the 1–3 $\mathrm{km\,s^{-1}}$ mark. As to the impact energy associated with the formation of the crater, the estimates vary from as low as 100 MJ to as high as 20 GJ, with most studies, however, favouring a value of the order of 10 GJ. With our estimate of 850 kg for the ground mass of Block Island and the assumption of a ground impact speed of 1 $\mathrm{km\,s^{-1}}$, a kinetic energy yield of 425 MJ would be realized (about 0.1 tonne TNT explosive energy equivalent), and this, we argue, might leave, at best, a shallow impact structure similar to, but probably smaller than, the Carancas crater. Since wet and/or dry sand has little structural cohesion, we would expect any small crater produced by the fall of the Block Island meteorite to be transitory and fairly rapidly eroded away.

For a given initial mass and velocity, the equations of ablation still require four additional parameters to be defined. Three of these are conveniently combined in the ablation coefficient $\sigma = \Lambda/2\Gamma\zeta$, where Λ is the heat transfer coefficient, Γ is the drag coefficient and ζ is the specific enthalpy of vaporization. For an iron meteoroid, the enthalpy of melting and vaporization will correspond to a value of $\zeta = 5 \times 10^6\ \mathrm{J\,kg^{-1}}$ (Passey & Melosh 1980). The drag coefficient will vary according to the shape of the meteoroid, but a characteristic value of $\Gamma = 0.5$ seems appropriate for an initial analysis. The heat transfer coefficient is one of the least well-understood parameters in all of ablation theory, but a value between $0.01 < \Lambda < 0.1$ is most likely appropriate for this study. With the above parameters, we have an ablation coefficient range varying from 0.2 to $2.0 \times 10^{-8}\ \mathrm{s^2\,m^{-2}}$. These values for the ablation coefficient fall in the vaporization-dominated mass-loss regime for iron meteoroids as described by ReVelle & Ceplecha (1994). The final parameter to be defined is that of the zenith angle Z, which indicates the entry angle of the progenitor body to the local vertical at the point of impact.

4 THE MOST LIKELY MARTIAN METEORITE MODEL

In a very general sense, the initial encounter velocity and zenith angle of meteoroid entry are determined according to the characteristics of Mars and its orbit about the Sun. The minimum velocity of encounter is that of the Martian escape speed, while the maximum encounter velocity is that set by the parabolic limit at the orbit of Mars. Accordingly, we have $5 < V_{\mathrm{inf}}(\mathrm{km\,s^{-1}}) < 58$. The zenith angle can in principle have any value between 90°, corresponding to an aerocapture condition, and zero, when the encounter is through the local zenith. Since our current model adopts a plane-parallel geometry we cannot follow aerocapture directly, so we assume a maximum zenith angle of 75°. While some meteors can be expected to encounter Mars with a velocity and zenith angle close to the extreme values just given, it is much more likely that the zenith angle will be close to 45° (Kopal 1971; Hughes 1993). Indeed, in a review article on oblique meteoroid impacts, Pierazzo & Melosh (2000) note that 77 per cent of expected meteoroid encounters will have zenith angles in the range $20 < Z(\mathrm{deg}) < 70$, and fewer than 1 per cent of encounters will have zenith angles greater than 85°, making aerocapture events, as one would expect, rare encounter outcomes. A detailed analysis of the conditions under which meteoroids might encounter Mars has been presented by Adolfsson et al. (1996), and they conclude that the most likely zenith angle of encounter is 48°.

Some confirmation of our approach is provided by the data related to recently recorded impact craters on Mars (Malin et al. 2006). Of the 20 new, 2–150 diameter, impact craters detected by the Mars Global Surveyor (MGS) Mars Orbiter Camera between 1999 May and 2006 March, none showed any evidence of being related to a strongly oblique impact. This being said, a recently formed crater chain (PSP_007009_1905) detected on an image collected by cameras aboard the MGS on 2008 January 24, in the extreme south-western region of Elysium Planitia, appears to show an extended 'strewn field' of craters. The estimated dimensions of the crater chain are ∼0.5 km wide by ∼5 km long (Ivanov, private communication), and this geometry is indicative of a step angle of entry for the initial meteoroid – this is a topic under further investigation.

The most likely meteoroid encounter speed with Mars can be constrained according to detailed modelling of impact probabilities with known Mars-orbit crossing asteroids. Wetherill (1989), for example, performed a series of detailed Monte Carlo calculations on the encounter conditions between asteroids and planets within the inner Solar system and found for Mars a mean encounter speed of 11.7 $\mathrm{km\,s^{-1}}$. In contrast, Flynn & McKay (1990) transformed the measured meteoroid encounter velocities at Earth's orbit to those appropriate to the heliocentric distance of Mars and deduced a mean encounter velocity of 10.2 $\mathrm{km\,s^{-1}}$. Steel (1998) has further analysed the expected distribution of impact speeds from known Mars-orbit crossing asteroids, weighted according to impact probability, and finds that the mean speed is 9.3 $\mathrm{km\,s^{-1}}$, but notes that 75 per cent of encounters are expected to occur with speeds of the order of 10.8 $\mathrm{km\,s^{-1}}$. Using these analyses as our guide, we take the typical meteoroid encounter speed to be 11 $\mathrm{km\,s^{-1}}$ at the orbit of Mars.

Fixing the encounter speed to 11 $\mathrm{km\,s^{-1}}$ and the zenith angle of entry to 48°, and adopting standard values for the ablation coefficients, Table 1 reveals the constraints imposed upon the progenitor masses required to produce an impacting meteoroid with a mass of 850 kg, or an impact velocity less than 1 $\mathrm{km\,s^{-1}}$. We find that for our adopted range of Λ values, no arrangement of parameters allows for the delivery of an 850 kg meteorite to the surface of Mars with an impact velocity less than 1 $\mathrm{km\,s^{-1}}$. In short, it does not appear possible to produce a meteorite with the characteristics of Block Island on Mars under the constraint of most likely encounter parameters.

If the entry velocity and the zenith angle of entry conditions are relaxed from being their most likely values, then the conditions for producing a Block Island meteorite are improved by reducing the entry velocity to its minimum possible value and by increasing the zenith angle to its allowed maximum. These changes, however, do not appear to greatly improve upon the situation, as illustrated in Table 2. By increasing the zenith angle and reducing the encounter

Table 1. Initial and final masses for meteoroids that satisfy either the 850 kg ground mass condition or the impact velocity less than the 1 $\mathrm{km\,s^{-1}}$ constraint. In each case, the encounter velocity is taken to be 11 $\mathrm{km\,s^{-1}}$ and the zenith angle is 48°.

$\sigma \times 10^{-8}$	Initial mass (kg)	Final mass (kg)	Impact velocity ($\mathrm{km\,s^{-1}}$)
2.0	930.5	850.0	10.58
2.0	0.01	0.003	1.0
0.2	857.9	850.0	10.58
0.2	0.0045	0.004	1.0

Table 2. Initial meteoroid mass and entry velocity that satisfy the 850 kg ground mass condition or the impact velocity being less than the 1 km s^{-1} constraint. In each calculation, the zenith angle is taken to be 75°.

$\sigma \times 10^{-8}$	Initial velocity (km s^{-1})	Initial mass (kg)	Final mass (kg)	Impact velocity (km s^{-1})
2.0	11	0.17	0.05	1.0
2.0	5	889.9	850.0	4.5
0.2	11	0.074	0.066	1.0
0.2	5	854	850.0	4.5

speed the final impact speed is lowered and so too is the mass of the parent body required to produce a meteorite with the characteristics of Block Island, but, once again, there appears to be no combination of parameters that will satisfy simultaneously the required mass and impact velocity constraints.

Given the results presented in Tables 1 and 2, it appears that there is no reasonable combination of ablation input parameters and encounter conditions that will allow for the production of a Martian meteorite with the characteristics of Block Island at the present time. One possible way to circumvent this apparent contradiction, as discussed below, is to posit that Block Island fell at a time when Mars had a significantly denser and hence much more massive atmosphere.

5 A DENSER MARTIAN ATMOSPHERE MODEL

To explore the effects of an enhanced Martian atmosphere, we adopt a first-order approximation model in which the engineering density model is enhanced according to a parametrized surface pressure P_0 (see e.g. Chappelow & Sharpton 2005). Indeed, for an atmosphere of mass $M_{\rm atm}$, the surface pressure P_0 will be of the order of $P_0 = M_{\rm atm}/(4\pi R^2/g)$, where g is the surface gravitational acceleration and R is the planetary radius. With an isothermal, exponential dependency law for the pressure, the ideal gas law dictates that a density variation with height h of the form $\rho = HP_0 \exp(-h/H)$ will develop, where H is the atmospheric pressure scaleheight (μ/RT) where R is the gas constant, T is the temperature and μ is the mean molecular weight. In effect, therefore, the parameter P_0 is linearly related to the mass of the atmosphere and constants related to the composition characteristics of the atmosphere and the physical make-up of the planetary body.

In the following set of simulations, we continue to use the mean encounter speed of 11 km s^{-1} and the most likely zenith angle of 48° as employed in our earlier calculations since these are independent of the characteristics of the Martian atmosphere. A series of ablation models have been evaluated with the atmospheric mass $M_{\rm atm}$ being progressively increased with the surface pressure P_0 varying from two to 75 times the present-day surface pressure of 600 Pa. The results of these calculations are shown in Figs 2 and 3. While the final mass is the same in each case, and equal to 850 kg, the initial mass and impact velocity vary according to the atmospheric mass (through P_0) and the adopted ablation coefficient. With respect to the impact velocity (Fig. 2), the effects of changing the ablation coefficient from 0.02 to 0.2 are found to be small and in order to produce an impact velocity of 1 km s^{-1} or less the surface pressure must be at least 65 times larger than the present-day value. The parent body initial mass is much more sensitive (Fig. 3), as one would expect, to the specific value of the ablation coefficient, which in our simulation is essentially governed by the adopted value for the heat transfer coefficient. Our calculations reveal that under the

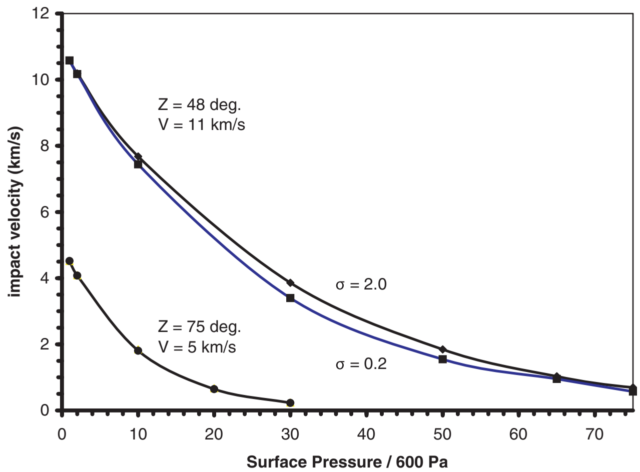

Figure 2. Impact velocity versus parametrized surface pressure in units of 600 Pa. Each curve is labelled according to the initial velocity, the zenith angle of entry and the ablation coefficient σ (in units of 10^{-8} s^2 m^{-2}) used in the numerical integrations. As the atmospheric surface pressure increases, according to the ablation coefficient adopted the impact velocity decreases.

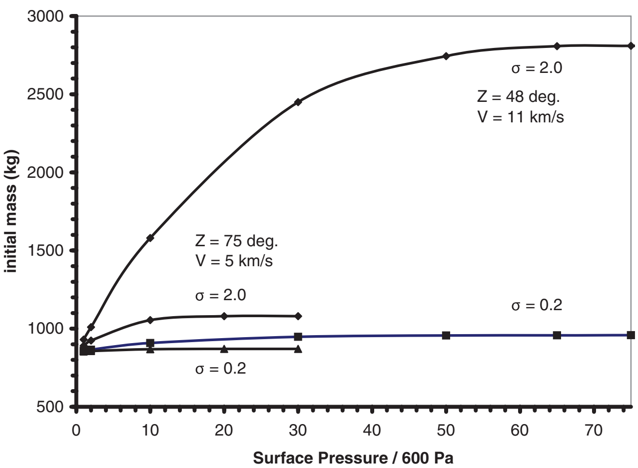

Figure 3. Initial mass versus parametrized surface pressure in units of 600 Pa. Each curve is labelled according to the initial velocity, zenith angle of entry and the ablation coefficient σ (in units of 10^{-8} s^2 m^{-2}) used in the numerical integrations. As the atmospheric mass increases, according to the ablation coefficient adopted the progenitor mass increases.

most likely encounter velocity and zenith angle of entry conditions the initial mass of the Block Island meteorite, when the atmospheric mass is enhanced by a factor of 65 times the present-day value, is of the order of 958 kg if $\sigma = 0.2 \times 10^{-8}$ s^2 m^{-2} or of the order of 2800 kg if $\sigma = 2 \times 10^{-8}$ s^2 m^{-2}. In addition, our simulations reveal that the putative parent body to the Block Island meteorite would probably not fragment during atmospheric flight, the atmospheric ram pressure never exceeding the tensile strength limit set by the Weibel equation.

Also shown in Figs 2 and 3 are the initial masses and ground impact velocities determined under the conditions that a meteoroid enters the Martian atmosphere with a zenith angle of 75° and a minimum initial velocity of 5 km s^{-1}. While these extreme conditions certainly favour the likelihood of a meteorite with the characteristics of Block Island being produced, we still find that the surface pressure parameter P_0 must be at least 15 times larger than the present-day value before both the 850 kg ground mass and impact velocity less than $1 \, km \, s^{-1}$ conditions are simultaneously satisfied. The variation in the range of possible initial masses is smaller in the low velocity, high zenith angle calculations, yielding almost independently of the ablation coefficient adopted (i.e. in our adopted range) a progenitor mass of the order of 1000 kg.

6 DISCUSSION

The fact that the Martian atmosphere must have been much more substantive in the past is evidenced by the planets' geomorphology (see e.g. Beech 2009 for a general discussion). Indeed, many Martian surface features clearly implicate running and/or long-lived standing bodies of water in their formation, and this would require a warmer, denser atmosphere than observed at the present time. The most likely mechanism for substantive atmosphere loss is impact erosion (Carr 1999; Newman et al. 1999; Horner et al. 2009; Shuvalov 2009), and although the calculation is uncertain due to the unknown flux and impactor size distribution, Melosh & Vickery (1989) estimate that during the late heavy bombardment the mass of the Martian atmosphere was probably reduced by a factor of the order of 100 to thereafter attain the mass that it has now. Independent calculations by Newman et al. (1999) suggest, however, that atmospheric impact erosion is much less efficient than the Melosh & Vickery (1989) calculation supposes. Given that this is the case, and that we must still have an atmospheric mass some 50–100 times more massive than at the present time to allow meteorites such as Block Island to fall on Mars, the implication is that the impactor flux at the orbit of Mars during the late heavy bombardment was significantly higher than Melosh & Vickery (1989) supposed, and/or that additional atmospheric erosion mechanisms must be considered.

To first-order approximation the surface pressure varies directly with the mass of the atmosphere, and our calculations indicate that to produce a meteorite such as Block Island the surface pressure (and in tandem the atmospheric mass) should be at least one to two orders of magnitude greater than at the present time. While variations in the Martian climate must have taken place since the late heavy bombardment, it is unlikely that conditions supporting a factor of 10- or 100-fold increase in the surface pressure have occurred (Catling 2009). On this basis, it is suggested that the Block Island meteorite may have fallen as far back in time as the late Noachian or early Hesperian epochs that existed on Mars from 3.5 to 4 billion years ago. This is clearly an extremely long time-scale for surface residency, and no such iron meteorite could survive on Earth for such an extended duration. At the present time, however, we do not know the exact weathering conditions for iron meteorites exposed on the surface of Mars. It is clear, however, that since the late Noachian no large bodies of freestanding water have existed on the Martian surface and therefore wind erosion is most likely the dominant weathering effect, and further that Aeolian processes have diminished in response to both a slowly weakening atmosphere and a lack of suitable abrading material (Bridges 1999; Thomson, Bridges & Greeley 2008). This being said, it is possible that Block Island has also undergone significant periods of shallow burial and exhumation by shifting surface sands. During such burial episodes it is possible that some aqueous alteration, due to interactions with sub-surface water, may have taken place. Indeed, if Block Island truly fell in the late Noachian then it has an age comparable to that of the carbonate and sulphate salts contained with the oldest known Martian meteorite ALH84001 (with a formation age of 4.5 Gyr) collected on Earth (see e.g. Gibson et al. 2005; Coulson, Beech & Nie 2007). The general appearance of Block Island (Figs 1 and 4), Shelter Island and Mackinac Island indicates that some considerable differential erosion and pitting of their exposed surfaces have taken place – indeed, their appearance is similar to those displayed by ventifacts formed in desert regions on the Earth (as well as Mars; Bridges 1999; Bridges et al. 1999). These surface cavities and pits would be highly interesting regions to study in detail since they could contain carbonate and/or sulphate mineral growths, and one may also speculate that they might have acted as protective havens within which early Martian microbial life might have thrived (Galletta et al. 2009).

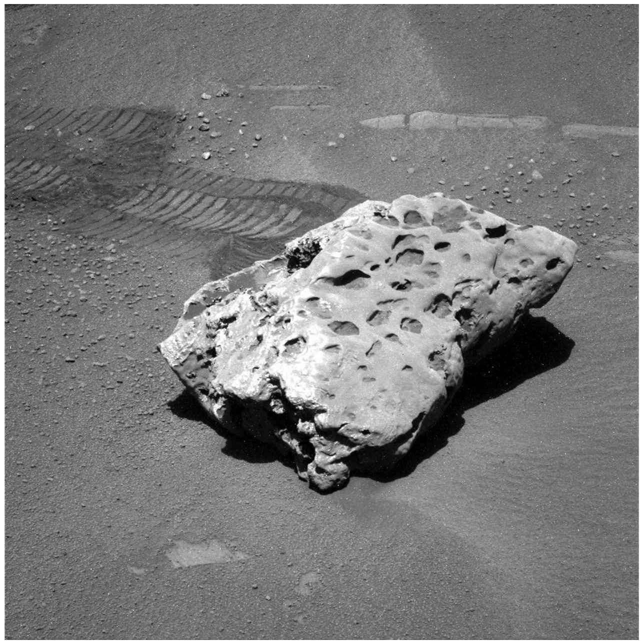

Figure 4. Close-up of surface features on Block Island interpreted as wind-abraded pits. Image number: 1P305830280EFFA5FWP2556R1M1 courtesy of NASA.

The formation scenario for Block Island outlined above is but one of a number that can be envisaged. Given the very close proximity of Mackinac Island, Shelter Island and Block Island, it is possible that the *Opportunity* Rover has serendipitously moved into an extensive strewn field. Proximity alone, however, is not sufficient evidence to convince us of the strewn field scenario at this time. Data indicating a matched meteorite type, a common weathering history and the additional discovery of numerous smaller fragments seems to be the minimum requirement to establish that a strewn field has been found – these data, as of yet, are not available. In addition, even if the three meteorites so far discovered are paired, or are members of a more extensive strewn field, the lack of associated impact features and the lack of structural deformation of the meteorites themselves are still to be explained. It is certainly possible that over many eons wind erosion could have significantly altered the terrain in which the meteorites are now found, but again it seems surprising that there is absolutely no apparent evidence of associated cratering – all three meteorites, as their discovery images reveal, are sitting on undisturbed bedrock (Fig. 1). In addition, it is not inconceivable that the meteorites might be some form of ancient Martian glacial transports related to past climatic change brought about by variations in either/both Mars's orbit or/and its angle of obliquity. It is additionally possible that the meteorites are impact-produced fragments, derived from some nearby crater-forming event, and indeed, all three meteorites are situated close to the Victoria crater. There is no specific or compelling reason, however, to associate the meteorites with the formation of the Victoria crater or, for that matter, any other crater in the surrounding area. In addition to the above formation scenarios, it is also possible that Block Island (specifically) is the result of an aerocapture event that may have occurred in the relatively recent past. This being said, the highly restrictive conditions under which aerocapture can come about suggest that it is an unlikely scenario for the origin of Block Island (Pierazzo & Melosh 2000; Chappelow & Sharpton 2006).

At the present time, it is not clear that Block Island, Shelter Island and Mackinac Island are paired. While their close proximity is suggestive of a contemporaneous origin, it might equally be a result of the very slow weathering of iron meteorites on the Martian surface. Indeed, the Mars Exploration Rovers have found what amounts to a great abundance of meteorites considering the very small fraction of the Martian surface that has been surveyed. Given the atmospheric conditions that have persisted on Mars over the past three and half billion years, since the late heavy bombardment in fact, we would suggest that the abundance of finds is most probably a result of the long accumulation time and the incredibly slow weathering rate for iron meteorites upon the Martian surface. Indeed, Bland & Smith (2000) estimate that the chemical weathering rate of meteorites on Mars is possibly three orders of magnitude slower than that experienced by Antarctic meteorites found on Earth, which is consistent with a Martian meteorite weathering time-scale of the order of billions of years.

To order of magnitude the bulk density of chondritic (stony) meteorites is about half that of the iron meteorites, and accordingly the characteristic size limit beyond which hypersonic impacts are expected will be of the order of 0.7 m. On this basis, one would expect to find numerous chondritic meteorites on the surface of Mars (Chappelow & Sharpton 2006). Indeed, one can reasonably assume that the abundance of chondritic meteorites per unit area on Mars will, just as it does on Earth, greatly exceed that of the irons. The reason why the Mars Exploration Rovers have found only iron meteorites to date is no doubt due, just as it is on Earth, to the fact that iron meteorites are more distinctive and odd-looking than stone ones. The location-specific weathering rate of irons on Earth is known to be much slower than that of the chondrites, and given the lack of free atmospheric oxygen and the absence of surface water the weathering lifetimes of meteorites must be even longer on Mars. Indeed, the only weathering agents operating on the Martian surface at the present time are other impacts and the reduced action of dust-driven abrasion. With the above being said, it is presumably only a matter of time, however, before the first chondritic meteorites are likely to be identified on Mars.

ACKNOWLEDGMENT

We thank Dr Boris Ivanov for a very helpful review of this paper and for making several important suggestions for improvements.

REFERENCES

Adolfsson L. G., Gustafson Bo A. S., Murray C. D., 1996, Icarus, 119, 144
Beech M., 2009, Terraforming: The Creating of Habitable Worlds. Springer, New York, p. 125
Bland P. A., Smith T. B., 2000, Icarus, 144, 21
Bland P. A., Cintala M. J., Horz F., Cressey G., 2001, LPS Symp. 32, abstract 1764
Bridges N. T., 1999, The 5th Int. Conf. on Mars, LPI, abstract 6152
Bridges N. T., Greeley R., Haldemann A. F. C., Herkenhoff K. E., Kraft M., Parker T. J., Ward A. N., 1999. J. Geophys. Res., 104, 8595
Carr M. H., 1999, J. Geophys. Res., 104, 21897
Catling D., 2009, in Gornits V., ed., Encyclopedia of Paleoclimatology and Ancient Environments, Atmospheric Evolution of Mars. Springer, Dordrecht, p. 66
Chappelow J. E., Sharpton V. L., 2005, Icarus, 178, 40
Chappelow J. E., Sharpton V. L., 2006, Icarus, 184, 424
Coulson I. M., Beech M., Nie W., 2007, Meteoritics Planet. Sci., 42, 2043
Davis P. M., 1993, Icarus, 105, 469
Flynn G. L., McKay D. S., 1990, J. Geophys. Res., 95, 14497
Galletta G., D'Alessandro M., Bertoloni G., Castellani F., Visentin R., 2009, in Corbett F., ed., Highlights of Astronomy Vol. 15, XXVII IAU General Assembly (2009 August)
Gibson E. K., Socki R. A., Wentworth S. J., Romanek C. S., McKay D. S., 2005, Proc. 68th Annual Meeting of the Meteorological Society, Gatlinburg, Tennessee, Meteoritics Planetary Science Supplement. Abstract 5042
Horner J., Mousis O., Petit J., Jones B. W., 2009, Planet. Space Sci., 57, 1338
Hughes D. W., 1993, J. British Astron. Association, 103, 123
Kenkmann T., Artemieva N. A., Wunnemann K., Poelchau M. H., Elbeshausen D., Nunez Del Prado H., 2009, Meteoritics Planet. Sci., 44, 985
Kopal Z., 1971, Physics and Astronomy of the Moon, 2nd edn. Academic Press, New York, p. 241
Malin C. M., Edgett K. S., Posiolova L. V., McColley S. M., Noe Dobrea E. Z., 2006, Sci, 314, 1573
Melosh H. J., 1989, Impact Cratering: A Geological Process. Oxford Univ. Press, Oxford, p. 205
Melosh J., Vickery A. M., 1989, Nat, 338, 487
Newman W. I., Symbalistry E. M. D., Ahrens T. J., Jones E. M., 1999, Icarus, 138, 224
Padevet V., 1991, Bull. Astron. Inst. Czechoslovakia, 42, 206
Passey Q. A., Melosh H. J., 1980, Icarus, 42, 211
Pierazzo E., Melosh H. J., 2000, Annual Rev. Earth Planet. Sci., 28, 141
ReVelle D. O., Ceplecha Z., 1994, A&A, 292, 330
Schröder C. et al., 2008, J. Geophys. Res., 113, E06S22
Schröder E. K., Ashley J. W., Fleischer I., Gellert R., Klingelhöfer G., de Souza P. A., 2009, 72nd Annual Meeting of the Meteorological Society, Nancy, France. Abstract A188
Selsis F., Lemmon M., Vaubaillon J., Bell J., 2005, Nat, 435, 581
Shuvalov V., 2009, Meteoritics Planetary Sci., 44, 1095
Steel D., 1998, Planetary Space Sci., 46, 473
Svetsov V. V., Nemtchinov I. V., Teterev A. V., 1995, Icarus, 116, 131
Thomson B. J., Bridges N. T., Greeley R., 2008, J. Geophys. Res., 113, E08010
Wetherill G. W., 1989, Meteoritics, 24, 15

APPENDIX A

The calculations presented in this paper are based upon the numerical integration of the equations of single-body meteoroid ablation. These equations follow the variation of a meteoroid's mass m and velocity V during its atmospheric decent and are taken as

$$\frac{\mathrm{d}m}{\mathrm{d}h} = -C\sigma\rho_{\mathrm{atm}}V^2\, m^{2/3} \tag{A1}$$

$$\frac{\mathrm{d}V}{\mathrm{d}h} = -C\rho_{\mathrm{atm}}V\, m^{-1/3}, \tag{A2}$$

where h is the atmospheric height, σ is the ablation coefficient, ρ_{atm} is the atmospheric density and $C = \pi\Gamma[3/4\pi\rho_{\mathrm{met}}\,]^{2/3}/\cos Z$, where Γ is the drag coefficient, Z is the zenith angle of entry and ρ_{met} is the meteoroid density. The atmospheric density law is taken as

$$\rho_{\rm atm}(h) = A_0 + \sum_{i=1}^{6} A_i \exp[-h/(1.1 + i)], \qquad \text{(A3)}$$

where Padevet (1991) gives the A_i, $i = 0, 1, \ldots, 6$ terms as $9.315\,8555 \times 10^{-9}$, $-0.010\,789\,003$, $0.083\,087\,065$, $-0.292\,760\,01$, $0.592\,408\,17$, $-0.643\,526\,71$, $0.286\,203\,19$, respectively. In order to test for atmospheric fragmentation, the meteoroid ram pressure is compared against the tensile strength expressed via the Weibel approximation, with the fragmentation condition being given by the expression

$$P_{\rm ram} = \rho_{\rm atm} V^2 > S_0 \left(\frac{m_0}{m}\right)^{\alpha}, \qquad \text{(A4)}$$

where the constants S_0, m_0 and α are 4.1×10^6 Pa, 1.0 kg and 0.1, respectively.

This paper has been typeset from a Microsoft Word file prepared by the author.