EARTH ROCKS ON MARS: MUST PLANETARY QUARANTINE BE RETHOUGHT?

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Recent geochemical, isotopic and rare gas studies (1) have convinced a majority of planetary scientists that the eight SNC meteorites originated on the planet Mars. In addition, three meteorites found in Antartica clearly originated on the moon (2). Detailed consideration of the mechanism by which these meteorites were lofted into space strongly suggest that the process of stress-wave spallation near a large impact (3) with, perhaps, an assist from vapor plume expansion (4), is the fundamental process by which lightly-shocked rock debris is ejected into interplanetary space. In the most plausible scenario, the SNC meteorites were ejected from Mars in the form of 10 m or greater diameter boulders 180 Myr ago by an impact that created a crater at least 100 km in diameter (5). These boulders were large enough to shield a substantial fraction of their interiors from cosmic rays until a breakup in space several million years ago exposed them to cosmic ray bombardment before they fell to the earth's surface.

The earth has also been struck by meteorites large enough to produce craters more than 100 km in diameter, such as Sudbury in Ontario, Canada (140 km diameter, 1850 Myr old), Veredefort in South Africa (140 km, 1970 Myr old), Poipgay in Siberia (100km, 39 Myr), Manicougan in Quebec, Canada (100 km, 210 Myr), and perhaps also the recently located Acraman structure in Australia (>90km, 600 Myr). In addition to the known large craters, the mounting evidence that the Cretaceous era was ended by the impact of a 10 km diameter asteroid or comet suggests that many other large impacts have occurred in Phanerozoic time whose craters either have not yet been found, or which have been modified beyond recognition. No craters have yet been located on the sea floor, which constitutes about 3/4 of the earth's present surface area.

These considerations lead naturally to the question, if Mars rocks are found on earth, why should not earth rocks be found on Mars? Furthermore, if earth rocks should find their way to Mars, might they contain spores or some sort of viable microorganisms that might then have the opportunity to colonize Mars?

To answer the first part of the question, I used the theory of spall ejection (6) to examine the mass and velocity of material ejected from the near vicinity of an impact. Since the spall mechanism only operates in the near vicinity of a free surface, the ejected rocks would all have originated from close to the surface, consistent with observations on both the Martian and lunar meteorites. The near surface is also the most biologically active region of the earth's crust, so the chance of ejecting spores and microorganisms with the spalled material is relatively high. The theory indicates that the volume of material ejected at a velocity greater or equal to greater than a predetermined velocity v_e is

$$\frac{V(\text{velocity} \geq v_e)}{V(\text{projectile})} = 4.8 \frac{P_M}{\rho \beta c_L U} \left[1 - \left(\frac{2v_e}{U}\right)^{1/3} \right]$$

where the volume is normalized by the projectile volume, ρ is the density of the target, $\beta = 4$ for most applications, U is the impact velocity, c_L is the speed of the shock wave in the target, and P_M is the maximum pressure achieved in the material ejected.

If the ejection velocity v_e is taken to be the earth's escape velocity, this equation will yield the volume of material ejected from the earth for a given velocity and size of the initial impactor. However, this equation neglects the effect of atmospheric interference, which could be of overriding importance on the earth. Numerical computations of the effect of a 10 km diameter asteroid on the earth's atmosphere (7) indicate that such a projectile clears the atmosphere away from its immediate vicinity, leaving behind a "hole" that takes minutes to close and through which early, fast spalled ejecta may escape. However, to be on the conservative side, I performed spall computations in which I assume that the atmosphere is present at its normal density. In a large impact the sheer mass of high velocity spalled material is so large that it exceeds the mass present in the atmospheric column, and so the spalled surface rocks may not be greatly hindered by the atmosphere. For the purposes of the computation I averaged the momentum of that spalled material which was ejected faster than the earth's escape velocity and the atmospheric gases along the escape trajectory. If the final velocity of both the spalled material and the atmosphere still exceeded escape velocity, then this material was counted as having escaped. If the average was less than escape velocity, then it was presumed that the material was stopped by the atmosphere and fell back to earth.

Much of the spalled material, while protected from the maximum pressure occurring in the shock wave by rarefactions from the free surface, nonetheless suffers significant shock damage. One of the SNC meteorites (EETA 79001) contains impact melt glass and may have experienced pressures as great as 50 GPa. Any organisms residing in the rock would certainly have been killed by the heat generated by the shock event. Only the rocks nearest the surface which receive the maximum protection from shock would escape heating to less than 100°C and thus retain viable microorganisms and spores. I take the corresponding shock pressure as equal to the stress necessary to crush the rock (when internal pores collapse the PdV work done during the collapse greatly enhances the energy deposition and at this point residual temperatures greatly exceed 100°C), or about 0.1 GPa (1 kilobar). The volume of ejected material escaping sterilization is thus considerably less than the total volume of spalled rock. However, this near-surface zone begins with a full complement of soil microorganisms, some of which appear likely to survive the ejection process. Behind the surface skin of spalled rock which has been raised to less than 100°C (which I will call the *fecund zone* in the following) is a larger mass of hot, sterilized rock that pushes the meter-plus-diameter boulders from the fecund zone through the atmosphere. Although some brief heating may occur at the surface of the fecund zone as the atmosphere is compressed in front of it, this heating is of short duration, since at 11 km/sec the ejecta clears the lower atmosphere in a matter of seconds. The thermal penetration depth of such a heat pulse is only a few millimeters, so that most of the ejected organisms will survive.

Figure 1 shows the volume of fecund material (which is only a few percent of the total spalled material) ejected from the earth as a function of impact velocity and transient crater diameter (the final crater will be about 65% larger than the transient crater size). Note that no ejecta escapes unless the impact velocity exceeds about 30 km/sec. This is a conservative limit: the spall model used to construct this plot assumes that no spall material is ejected faster than about 35% of the impact velocity. Direct observations on small scale impacts (8) indicate that some material may be spalled at speeds approaching 85% of the impact velocity. The contours in Figure 1 are labeled by the volume ejected in m^3. It is clear that a 50-75 km diameter transient crater (which would produce a final crater comparable in diameter to the *observed* large craters on earth) could eject roughly a million cubic meters of meter-plus-diameter boulders from the fecund zone.

It thus seems likely that the half-dozen largest impact events on earth would have each ejected considerable masses (millions of tons) of near surface rocks carrying viable microorganisms into interplanetary space. Much of the ejected debris would have been in the form of boulders large enough to shield those organisms even from galactic cosmic rays, not to mention ultraviolet radiation and low energy solar cosmic rays. Under such circumstances spores might remain viable for long periods of time. Even microorganisms active at the time of ejection might have been preserved for considerable periods by lopholization in hard vacuum. Viable organsims preserved by this process were recovered from the Surveyor 3 camera assembly after two and a half years on the lunar surface (9).

No computations have yet been performed to indicate how long earth ejecta would take to reach Mars. Similar computations on the migration of Mars ejecta to earth (10) indicate mean transit times of millions of years. However, since earth's greater mass may result in larger perturbations to the orbits of nearby debris, the transit time from earth to Mars may be considerably shorter. Some debris, of course, could make the trip much more quickly than the mean time.

Once at Mars, boulders falling to the surface would be slowed even by Mars' thin atmosphere and might even be fragmented and their interiors exposed by aerodynamic stresses at low altitudes. This process is especially important for small objects, meter size and below (11).

Terrestrial organisms in these rocks would thus have the *opportunity* to colonize the planet *if* they could find suitable conditions. I am not claiming that such conditions are present on Mars, only that it appears likely that viable terrestrial microorganisms have reached the surface of Mars by natural processes. It thus appears that the planets of the solar system are not completely isolated biologically: from time to time large impacts may inoculate planets the inner solar system with a sample of terrestrial life. The most recent such inoculation may have taken place 39 Myr ago with the event that created Popagi crater in Siberia.

In the light of these considerations the need for biological quarantine may not be as serious as was once supposed. Rocks from Mars have *already* fallen to earth without having undergone any sterilization other than that imposed by millions of years in space. Earth rocks may similarly have already reached Mars. In any event, the possibility that Mars has already been exposed to terrestrial microorganisms should be factored into any future discussions of planetary quarantine.

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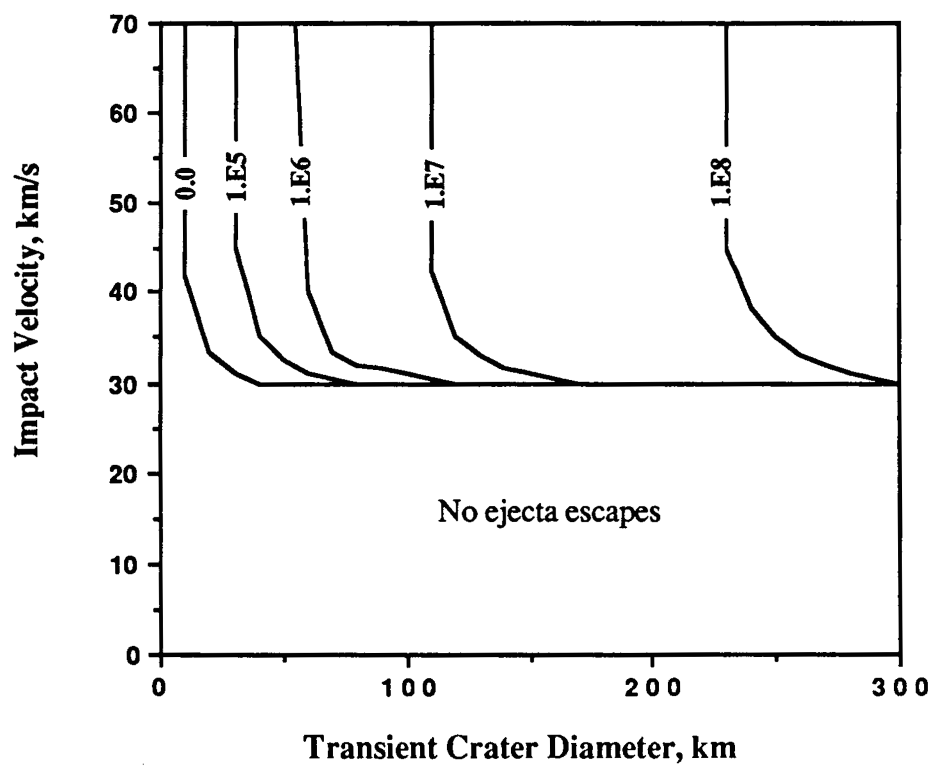

Figure 1.