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57-91 ABS. ONLY N94-33197

CONSTRAINTS ON THE MARTIAN CRATERING RATE IMPOSED BY THE SNC METEORITES AND VALLIS MARINERIS LAYERED DEPOSITS.

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Introduction: Martian Cratering Rate and Mars Past: The rate at which craters form on the martian surface is a crucial parameter for understanding the geologic history of that planet. However, until samples can be returned from known locations on Mars, the rate of cratering cannot be correlated accurately with geologic ages but must be estimated. In this paper an attempt is made to use two separate bodies of data that seem incongruous with currently accepted models for correlating cumulative crater densities with geologic ages: the measured depths of the interior layered deposits in the Candor Chasma region [1] and nearby areas of the Vallis Marineris system and the measured cosmic ray exposure times and crystallization ages of the SNC meteorites [2], to constrain estimates of the martian cratering rates. That is, rather than considering these two bodies of data to represent special or peculiar circumstances in conventional cratering age schemes, we instead assume they represent conventional circumstances and attempt to find what adjustments to present cratering-age correlation models are required for the models to be reconciled. The preliminary results of this study indicate that the interior layered deposits, which may be lake sediments dating from the "liquid water era" on Mars (the period when large amounts of liquid water apparently helped shape the planets surface), and the SNC meteorites, which are believed to represent samples of the martian surface carried to Earth by one or several impacts on the martian surface, independently constrain the past martian cratering rate to be many times the past lunar cratering rate.

Several models for correlating geologic ages with cumulative crater densities have been proposed [3,4]. These models assume that the rate of crater formation has varied in time beginning with an intense period of bombardment shortly after the formation of the planet followed by a period of lower cratering rate in the later periods of planetary history. The models differ principally in their assumed rate of cratering in this later period. These rates are usually represented as being a multiple of the lunar rate of cratering, the Moon being the one planetary surface where cratering history has been preserved and from which samples have been returned. The models of Neukum and Hiller [5] are most illustrative of this type of model and demonstrate that if the rates of martian cratering are assumed to be 1, 2, and 3× the lunar rate (Neukum and Hiller models I, II, and III respectively, hereafter referred to as NHI, NHII, and NHIII) then the picture of Mars varies dramatically. The difference between the history of Mars under NHI and NHIII is the difference between a planet whose climate was Moon-like and one that was Earth-like for much of its history (see Fig. 1).

Under NHI the cratering rate is assumed to be lunar, and the erosive rate must be low to give the observed cumulative crater densities. What results is a very lunar set of ages for many martian surface formations, and an age for most water channels that is very old, indicating that Mars must have had a dense Earth-like atmosphere and temperatures for only a geologically brief period of 1 b.y. This means that most liquid-water-produced features must have ages of 3.5 b.y. and mean surface ages of approximately 3.0 b.y. However, under NHII Mars was a dynamic changing planet for most of its history, with the liquid water era and vigorous channel formation lasting until late in the planet's history. The effect of the 2× lunar cratering rate assumed under NHII is not only to make the mean age of large areas of the martian surface younger but also to increase the variation of ages. This occurs because (1) the ages of many surface formations that were formerly confined to a narrow range of ages between 3 b.y. and 4.5 b.y. are now expanded across the span of martian history, and (2) the model is consistent with an Earth-like climate for Mars for much of its history, allowing free movement of liquid water across its surface. The model NHII is thus consistent with water-formed features late in the planet's history and a mean surface age of approximately 2 b.y. The consistency of NHII and the even more extended model NHIII with late water-formed features allows features such as the Candor Chasma layered sediments to be accommodated easily without recourse to special models.

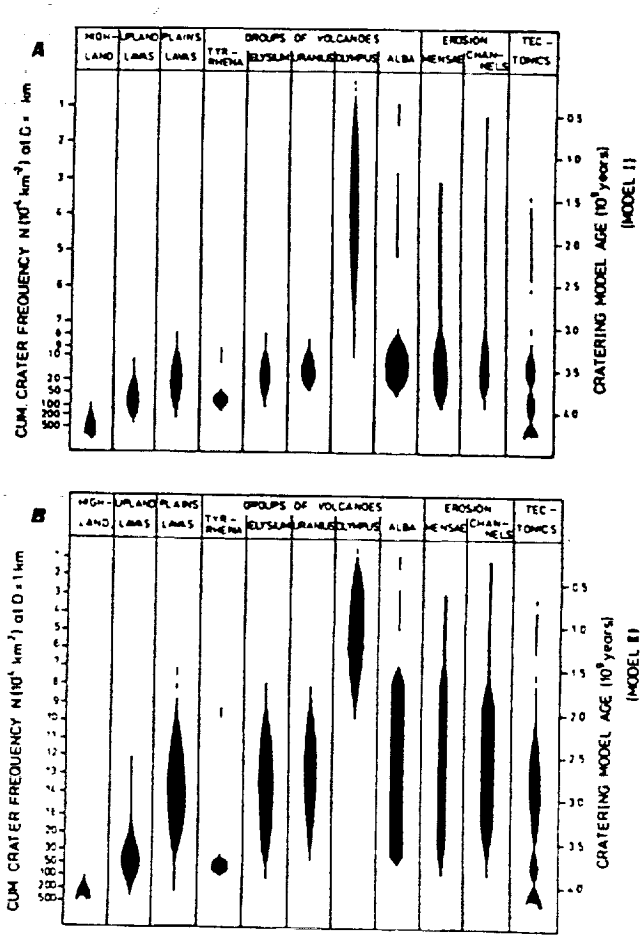

Fig. 1. (a) Neukum-Hiller model I: Mars cratering rate same as for the Moon. (b) Neukum-Hiller model II: Impact fluxes factor of 2 higher than on the Moon.

Layered Deposits of Candor and Associated Chasmas of Vallis Marineris: The interior layered deposits seen extensively in the Candor, Ophir, and Hebe Chasmas of the Vallis Marineris postdate the canyon system and appear roughly contemporary with the formation of the Tiu and Simud outflow channels [3], which are proposed to result from catastrophic floods. Thus the period of formation appears to coincide with a period where large quantities of water could move freely across the martian surface. The interior deposits themselves appear to be lacustrine, and because of their extensive lateral continuity, suggest deposition over a long period in a quiescent, low-energy aqueous environment, despite the fact that lava intrusions may have occurred periodically into the lake bottoms, since evidence of lava intrusion is seen in nearby Chasmas [5]. Because of these considerations it seems likely the interior layered deposits were formed during a time when liquid water was a thermodynamically stable state on the martian surface rather than being a peculiar circumstance of a nonequlibrium resection preserved under a thick ice sheet from an atmosphere in which it would boil away explosively once exposed. Thus the conditions of formation of the interior layered deposits seem most easily accommodated by conditions of atmospheric pressure approaching 1 bar.

The interior deposits are estimated to be approximately 5 km thick over large areas, implying they were emplaced over a long geologic period. These sedimentary depths are quite thick by terrestrial standards, where sedimentary depths average approximately 2 km and usually represent roughly 0.5 b.y. A terrestrial analog to the lacustrine origin for layered deposits is the Green River Formation [6] in the Wyoming-Utah area, where sediment depths reach 1 km and were believed to have formed over 4 m.y. for a deposition rate of 0.25 km/m.y. A Green River Formation analog gives an estimated deposition period of 20 m.y. for the layered deposits. This is a rapid buildup of sediments but is consistent with rates in terrestrial basins. An upper bound on this period of deposition, using an analog perhaps more in keeping with a low-energy environment, would be found in deep-ocean red clay sediment deposition [7]. The rate of this deep-ocean deposition is much slower, 3 km/b.y. The period of interior layered deposit deposition can thus be estimated between 20 m.y. to 1.5 b.y. based on Earth analogs. Accordingly, the interior layered deposits appear to suggest a geologically significant period of time when large bodies of liquid water could be stable on the martian surface. Since this coincides with the periods of catastrophic flooding into Chryse Planitia, this does not seem unreasonable; however, the floods were apparently geologically short-lived events, whereas the layered deposits were apparently formed over a long geologic period of apparently stable conditions.

The problem the interior layered deposits create in cratering chronologies based on 1× lunar cratering rates is that the layered deposits postdate the formation of the Vallis Marineris canyon system or at least major portions of it, and the Marineris system apparently dates from the middle to late period of martian history. This means that for a period of the order of 0.02–1.5 b.y. during the middle to late period of martian history, ages 2.5–1.0 b.y., large lakes could apparently exist and quiescently collect sediment. Unless recourse is made to special geologic and thermodynamic circumstances, interior layered deposits thus indicate that the period of dense warm atmosphere favorable to liquid water, believed to have existed in the Noachian Era, persisted until at least the early Amazonian and possibly the middle Amazonian. Such conditions are only consistent with cratering chronologies assuming $\leq 2\times$ lunar crater rates on Mars. Thus the existence and properties of the interior layered deposits in the Candor and nearby Chasmas appear to constrain the assumed cratering rates to be much higher than lunar and thus much more consistent with NHII or perhaps even NHIII. Other independent constraints exist that suggest a similar requirement.

SNC Meteorites and Martian Cratering Flux: The discovery of the martian origin for the SNC meteorites at this point in our exploration of Mars has been extremely fortunate and may strongly effect the course of future Mars studies. Enough is known about Mars at this time from remote sensing to define major questions (for example, what was the volatile inventory, what is the average age of the martian surface, and how widespread was martian volcanism) so that the sudden availability of probable samples of the martian surface can make a major contribution to our understanding. Most major contributions to knowledge in a particular subject come as a surprise, and the data from the SNC meteorites are certainly surprising; the SNC data seem to indicate that the mean surface age of Mars appears to be much younger than previously supposed.

It is now believed that the SNC meteorites represent the result of at least three separate events on Mars [8], and may thus be a representative sampling of the martian surface. They differ in composition but are essentially basaltic and most show little shock damage. They were all ejected recently in geologic time, having cosmic ray exposure times from 0.5 m.y. to 11 m.y. Thus, they were apparently ejected from Mars by meteor impacts of large energy on that planet and became part of a general population of small bodies on chaotic orbits in Mars-Earth space before finally being swept up by the Earth. The brevity and variety of the cosmic ray exposure ages tells us that energetic impacts are probably much more frequent on Mars than previously supposed. However, a more direct method by which the SNCs argue for a higher cratering rate on Mars is that the crystallization ages are so much lower than expected.

If the SNC meteorites are truly martian and represent multiple events, as seems most likely, then their crystallization ages, which vary from 1.3 b.y. to 160 m.y., suggest that the mean surface age for Mars is on the order of 1 b.y. This is an enormous difference from the ~3.0 b.y. that is presently estimated using 1× lunar cratering flux, and suggests that the Mars cratering rate is several times this number, possibly 2 or even higher. Thus, NHII and NHIII are the only recent models that come close to providing the mean surface age required by the SNCs.

The fact that the SNC data forces an upward revision of the martian cratering flux is a robust result that is fairly insensitive to assumptions about the number of impacts ejecting SNC material. The model of ejection of the SNC material by one large impact [9] on a region of young lava suffers from the lack of a large recent crater on the Tharsis formations [10], thought to be the youngest lavas on Mars. Large craters have been found, and a large one is required to account for such a considerable amount of varied samples and breadth of exposure ages; however, the crater must itself be crater dated using an assumed rate of cratering. This means the only way to reconcile the recent ejection of the SNC material, in single event, with the large number of craters found in the ejection candidate impact basins is to dramatically revise the cratering rate upward. If one instead assumes that one of the smaller impact basins may have been the point of origin for the SNCs, then the number of candidate impact basins multiplies, the variation in SNC compositions becomes troublesome, and the single-impact theory becomes hard to justify.

Therefore, if the SNCs come from multiple impacts, they force the mean surface age downward, because if they are multiple they form representative samples of the crust and crystallized recently; if they are from a single impact in young lavas, they force the large crater ages downward, because they were ejected recently. In either case the cratering rate must move upward to produce the required downward shift in ages of the surface areas of interest. Finally, the very fact that recent impacts on Mars have transported comparable or even larger masses of martian material to Earth than has been transported from the Moon (the ratio of SNC to lunar meteorite recovered masses is quite large) reinforces the suggestion that the martian cratering rate must be many times lunar, though it is difficult to quantify this latter argument at this time. In any case, the simplest SNC scenario, that the SNCs were ejected by multiple events, appears only reconcilable with the NHII model or even higher cratering rate models.

Summary: Therefore, following two independent lines of evidence—estimates of the age and formation time of a portion of the martian geologic colunn exposed in the layered deposits and the crystallization and ejection ages of the of the SNC meteorites—it appears that the martian cratering rate must be double the lunar rate or even higher. This means models such as NHII or NHIII, which estimate the martian cratering rate as being several times lunar, are probably far closer to reality on Mars than lunar rates. The effect of such a shift is profound: Mars is transformed from a rather Moon-like place into a planet with vigorous dynamics, multiple large impacts, erosion, floods, and volcanism throughout its history.

A strong shift upward in cratering rates on Mars apparently solves some glaring problems; however, it creates others. The period of time during which Earth-like atmospheric conditions existed, the liquid water era on Mars, persists in NHIII up to only 0.5 b.y. ago. Scenarios of extended Earth-like conditions on Mars have been discounted in the past because they would have removed many of the craters from the early bombardment era found in the south. It does appear that some process of crater removal was quite vigorous in the north during Mars' past. Evidence exists that the northern plains may have been the home of long-lived seas [11] or perhaps even a paleo-ocean [12], so models exist for highly localized destruction of craters in the north. However, the question of how the ancient crater population could be preserved in the south under a long liquid-water era found in any high-cratering-rate models is a serious question that must be addressed. It does appear to be a higher-order problem because it involves low-energy dynamics acting in localized areas, i.e., erosion of craters in the south of Mars, whereas the two problems with the low-cratering-rate models involve high-energy events acting over large areas: the formation of the Vallis Marineris, the SNC ejecting impacts, and the global atmospheric pressure and temperature conditions that allow liquid water to exist as a robust entity anywhere on the martian surface.

In any case, it appears Mars is a more complex and dynamic planet than previously supposed. It has canyons dating from the middle to late period of its history that contain apparent lake sediments bedded deeper than most sediments on Earth. Recent multiple, violent impacts on Mars have apparently provided us with multiple random samples of its surface that all crystallized less than 1.5 b.y. ago. These things cannot be accommodated in our present cratering chronologies of Mars, based on 1× lunar cratering rates, without great difficulties. These difficulties suggest that a new chronology, probably based on NHII or even NHIII, should be adopted; this new chronology will provide us with a new view of Mars as a dynamic planet of rich history.

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N94-33198

S8-91 ABS. ONLY

DEPOSITION RATES OF OXIDIZED IRON ON MARS.

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Introduction: The reddened oxidized surface of Mars is indicative of temporal interactions between the martian atmosphere and its surface. During the evolution of the martian regolith, primary ferromagnesian silicate and sulfide minerals in basaltic rocks apparently have been oxidized to secondary ferric-bearing assemblages. To evaluate how and when such oxidized deposits were formed on Mars, information about the mechanisms and rates of chemical weathering of Fe^{2+}-bearing minerals has been determined [1,2]. In this paper, mechanisms and rates of deposition of ferric oxide phases on the martian surface are discussed.

Mechanisms of Oxidation of Ferrous Iron: Oxidation of Fe^{2+} ions derived from basaltic olivine, pyroxene, and sulfide minerals may have proceeded via several mechanisms. They include:

1. *Solid-state processes involving atmosphere-surface interactions that occur without the intervention of water.* However, the kinetics of such processes involving dry mineral surfaces are extremely slow, as testified by the negligible oxidation products observable in the Magellan radar images of the surface of Venus. Nevertheless, photochemical processes may have produced coatings of oxidants on outermost arid surfaces of Mars [3], which subsequently could influence redox reactions of Fe.

2. *Reactions that occur in an aqueous medium.* Such processes involving dissolved Fe include (a) oxidation of aqueous Fe^{2+} in groundwater by dissolved atmospheric O

$$Fe^{2+}_{(aq)} + 1/4\ O_{2(aq)} + 3/2\ H_2O \rightarrow FeOOH_{(s)}\downarrow + 2H^+ \qquad (1)$$

the O being derived from photolysis of CO_2 or water vapor in the atmosphere [4]; and (b) photochemical oxidation in UV light of either Fe^{2+} ions in acidic solutions [5,6]

$$Fe^{2+}_{(aq)} + 2H_2O \xrightarrow{\text{UV } (\leq 287\text{ nm})} FeOOH_{(s)}\downarrow + 2\ H^+ + 1/2\ H_{2(g)}\uparrow \qquad (2)$$

or FeOH+ complex ions in near-neutral pH or slightly alkaline solutions [4–7]

$$FeOH^+_{(aq)} + H_2O \xrightarrow{\text{UV light} \leq 366\text{ nm}} FeOOH_{(s)}\downarrow + H^+ + 1/2\ H_{2(g)}\uparrow \qquad (3)$$