CONSTRAINTS ON THE MARTIAN CRATERING RATE BASED ON THE SNC METEORITES AND IMPLICATIONS FOR MARS CLIMATIC HISTORY

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Abstract

Two constraints placed upon the cratering flux at Mars by the SNC meteorites are examined: crystallization ages as a constraint on surface ages and cosmic ray exposure ages and number of impacts as a constraint on absolute rates. The crystallization ages of the SNC meteorites appear to constrain the Martian cratering rate to be 4xLunar or more if the parent lavas are in the north of Mars and the number of SNC ejecting impacts are small. If the SNCs result from a single impact that formed the Lyot basin then the cratering rate must be at least 7xLunar or higher to produce a basin age less than the SNC crystallization age because the basin ages are themselves determined by crater counting. Assuming multiple uncorrelated impacts for SNC ejection from Mars over 10 million years a cratering rate of approximately 4xLunar is also found for ejecting impacts that form craters over 12km in diameter. Therefore, both crystallization ages and ejection ages and number of impacts appear consistent with a 4xLunar cratering rate at Mars. The effect on Martian chronologies of such a high cratering rate is to place the SNC crystallization ages partly within the epoch of channel formation on Mars and to extend this liquid water epoch over much of Mars history.

1. Introduction: The SNCs and Martian Chronologies

The SNC (Shergotty-Nakhala-Chassigny) meteorites are believed to be samples of Mars surface lavas that are secondary fragments from a small number of impacts on the Martian surface. The number of impacts ranges from three impacts (Bannin *et al.*, 1992) based on an apparent clustering of SNC compositions and cosmic ray exposure ages into three groups, to one large impact (Vickery and Melosh, 1987), believed to be the impact that formed the basin Lyot, near Deuteronilus Mensa. However, the measured crystallization ages of the SNCs range from .2-1.3 Gyr (Billion years) which creates a discrepancy with conventional cratering chronologies (Neukum and Hiller, 1981, Neukum and Wise, 1976, Hartmann *et al.*, 1981) used to date the surface lava units and large impact basins on Mars.

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The discrepancy occurs because the range of SNC crystallization ages falls far below the estimated range of lava ages, estimated by crater densities, that cover any significant fraction of the Martian surface and far below the estimated age of the Lyot basin, which is the youngest large impact basin on Mars. This conflict has led some to propose that the presence of thin-widespread-young (TWY) lavas on Mars (Bannin *et al.*, 1992) forms a veneer on the surface and does not disturb cratering statistics, meaning that the true surface age is decoupled from the large crater statistics and that crater statistics on Mars are thus of limited usefulness. While some evidence of type of lava flow on Mars has been reported (Plescia, 1990) the TWY lava hypothesis presents its own set of problems and these will be discussed in the context of SNC multiple impact origin models. Therefore, it is the primary assumption of this paper that true surface ages on Mars can be correlated with crater statistics on Martian surfaces, as they have been correlated on the Moon, and that the young age of the SNCs argues for the adjustment of Mars chronologies derived from cratering statistics, rather than their rejection.

If we assume that crater densities can give us a true estimate of surface age and that the SNCs did originate as surface rocks, then even given the poor sampling associated with a small number of impacts, the SNC crystallization ages argue strongly that major portions of the Martian surface or the major impact basins that they contain, must lie within the SNC age band. The conflict between the crater dating models and the SNC crystallization ages can be resolved however, because the dating models depend crucially on one unknown parameter, the CCF(Cumulative Cratering Flux) at Mars.

In both cases, the ages of lava units and the ages of impact basins, the ages are determined by counting cumulative crater densities (the number of craters above a certain diameter per unit area) and converting this density to an age by dividing it by a cratering flux. The CCF at Mars is presently unknown. However, it is assumed in most models to lie close to that seen on the Moon, being 1 or 2xLunar(Hartmann *et al.* 1981, Neukum and Hiller, 1981) . Therefore, it is the assumed value of the CCF that determines the range of ages of surface units on Mars and thus determines the disparity between the SNC crystallization ages and the model determined surface ages. Accordingly, the crystallization ages of the SNCs can be used to constrain the unknown value of the CCF at Mars.

The CCF at Mars is of central importance in determining the character of Mars geo-climatic history and is estimated to lie within the range of 1xLunar to 4xLunar (Hartmann *et al.* 1981) with the value of 2xLunar considered most likely. In this paper we will assume 4xLunar to be an upper bound on the CCF. If the value of the CCF of 1xLunar is used then a very Lunar picture of Mars emerges (Figure 1) (Neukum and Hiller, 1981) with Mars as a geologically active and surface water bearing planet for only a brief initial period of .5 Gyr, followed by 3Gyr of little activity. If a higher value of CCF, 2xLunar, is assumed then the geo-climatic history becomes less Lunar and more Terrestrial, with channel formation and volcanic activity lasting for a large fraction of Mars history, 2.5 Gyr, (Figure 2) (Neukum and Hiller, 1981). However, even at a CCF of 2xLunar the range of ages of the northern plains lavas, the largest region of young lava on Mars, and thus most likely source of the SNCs, falls outside the range of SNC ages. This is especially important if the SNCs come from multiple impacts and thus sample a large area of Mars.

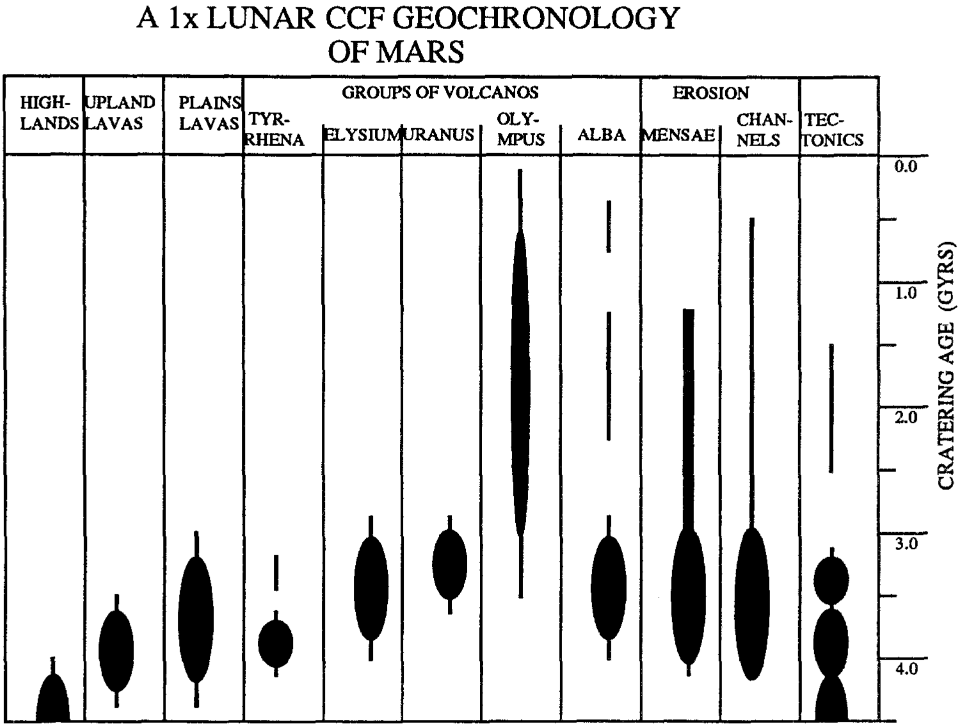

Fig. 1:
A 1xLunar CCF chronology, adapted from Neukum and Hiller Model -I , Neukum and Hiller 1981.
Note that this Lunar CCF creates a very "Lunar" geochronology for Mars , with widespread geologic activity ending early in Mars history.

2. Multiple Impact Scenario Constraints on the CCF at Mars

In the case of multiple impacts as the source for the SNCs, a scenario which now appears most likely due to the diversity of lithologies and cosmic ray exposure ages seen in the SNCs, the crystallization ages of the SNCs define a range of ages for some large portion of the Martian surface and also define a rate of large impacts. If we assume that the impacts took place in the northern portion of Mars they would occur on some of the youngest lavas on Mars, in the Tharsis Region and also on the northern Plains. William Hartmann and his colleagues dated these units under the assumptions of CCF being 4xLunar as an upper limit and found a range of ages of .3-1.5Gyr for large areas (Hartmann *et al.*, 1981)(see table 1). Thus, the young crystallization ages of SNC can be readily accommodated in a 4xLunar CCF based chronology, if the low number of impacts, 3, occurred preferentially in the north of Mars on younger lavas or that similar impacts in the southern highlands are less efficient in ejecting SNCs to Earth.

If the idea that the small number of impacts preferentially fell only on young lavas is to be tenable, then the young lava region would have to be as large as possible to give a non vanishing probability for this series of impacts. The fact that possible source regions for the

TABLE 1. The ages of various volcanic regions and features under various assumed values of the CCF.

Geologic Province	Crater Density Relative to Avg Lunar Maria	Estimated Crater Retention Age in billions of years (b.y.) 4xLunar	2xLunar	1xLunar
Central Tharsis volcanic plains	0.1	0.06	0.3	1.0
Olympus Mons	0.15	0.1	0.4	1.1
Extended Tharsis volcanic plains	0.49	0.5	1.6	3.3
Elysium volcanics	0.68	0.7	2.6	3.5
Isidis Planitia	0.76	0.8	2.8	3.6
Solis Planum volcanic	0.9	0.9	3.0	3.7
Chryse Planitia volcanic plain	1.1	1.2	3.2	3.8
Lunae Planum	1.2	1.3	3.2	3.8
Noachis ridged plains	1.3	1.7	3.3	3.8
Tyrrhenum Patera volcano	1.4	1.8	3.4	3.8
Tempe Fossae faulted plains	1.6	2.3	3.4	3.8
Volcanic plains on Hellas south rim	1.7	2.6	3.5	3.8
Alba shield volcano	1.8	2.6	3.5	3.8
Hellas floor	1.8	2.6	3.5	3.8
Syrtis Major volcanic plains	2.0	2.0	3.6	3.9
Heavily cratered plains				
- small *D* (<4 km)	1.4	1.8	3.4	3.8
- large *D* (>64 km)	13.0	3.8	4.0	4.2

Source: Hartmann et al. 1981.

SNCs are much larger under an assumed 4xLunar CCF at Mars than under 2xLunar is seen easily by comparing the areas of volcanic stratigraphies falling within the SNC crystallization ages. Volcanic terrains cover approximately 60% of Mars surface. Under the Hartmann-Tanaka chronology, which assumes a 2xLunar CCF, volcanic stratigraphies ranging approximately from the Upper Amazonian to the Early Amazonian 0-1.8 Gyr are available to serve as source regions for the .2-1.2 Gyr SNCs. These stratigraphical regions occupy 16% of Mars surface or 24% of the total volcanic terrain. If, however, the CCF is 4xLunar then the stratigraphies from the Upper Amazonian through the Upper Hesperian fall into the approximate age range of the SNCs and these stratigraphies occupy approximately 24% of Mars surface or 40% of the total lava terrain. The probability of three random impacts into such a larger area is 3 times greater under 4xLunar than into the smaller area under 2xLunar. Thus if the CCF is allowed to rise to 4xLunar, the upper limit of the range considered reasonable by Hartmann *et al.* (1981), then almost half of Mars lava surfaces can serve as the source region for the SNCs and the discrepancy between surface ages and the SNCs essentially vanishes. Therefore, the SNCs constrain the CCF within the limits of 1xLunar to 4xLunar to be most probably the upper limit of 4xLunar, since this gives the largest possible source area for the SNCs.

However, this explanation requires that a sample of other regions of Mars surface be found, particularly of the very old southern highland lavas, representing the impacts that occur in that region even at lower efficiency. A meteorite of Martian origin, ALH84001,apparently

A 2x LUNAR CCF GEOCHRONOLOGY OF MARS

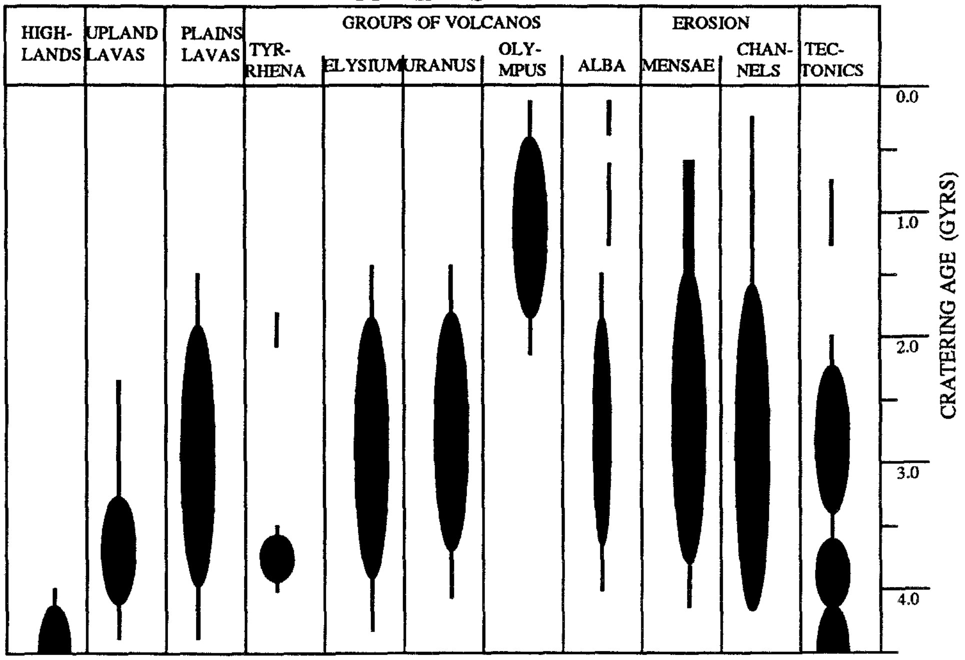

Fig. 2:
A 2xLunar CCF chronology, adapted from Neukum and Hiller Model -II, (Neukum and Hiller 1981). Note that this Lunar CCF creates a less "Lunar" geochronology for Mars , with widespread geologic activity occurring until the middle of Mars geologic history.

from the Southern Highlands, and being quite distinct mineralogically from the SNCs, has recently been identified (Middlefehlt,1994). It is apparently quite ancient, ~ 4.5Gyr crystallization age (Jagoutz E.,1994), and has an older ejection age of 15 Myr (Eugster, 1994). With the discovery of this new Martian meteorite the dichotomy of surface ages on Mars, long noted from crater statistics, is now being reproduced as a dichotomy of crystallization ages in the Martian meteorites.

It should be noted that an alternative explanation for the surface age-SNC age discrepancy, under the assumption of multiple SNC source impacts, is that surface ages are somewhat decoupled from ages of actual rocks at the surface. This is the TWY lava hypothesis, which proposes that widespread thin young lavas form the actual surface layer on Mars and do so in a manner that does not disturb crater statistics. While it has always been reasonable to consider that crater statistics can only give a gross structural age of a terrain on a planetary surface, and that small overlying deposits may occur that are much younger, the TWY lava hypothesis proposes that this phenomenon is both global and subtle on Mars. The problem with this hypothesis is that it requires widespread volcanic activity which is both recent and finely tuned. Lava flows must be numerous but small and not flood any large area to any depth. These would appear to be contradictory requirements and propose phenomenon that have not been seen either on the Moon or Earth, two bodies where considerable "ground truth" has been obtained. On both these bodies, depending on the epoch, lava flows are observed to be either sparse and localized, or widespread and voluminous, but never both widespread and localized. This stems from the fact that magma chambers that fuel widespread activity tend to be deep and large.

The main virtue of the TWY lavas is to reconcile the young SNCs as evidence of recent widespread volcanic activity on Mars while at the same time preserving the " Lunar " Mars chronologies, where Mars has widespread geological activity only in its distant past. However, if under the TWY lava hypothesis, the young SNCs are acknowledged to be evidence of recent widespread volcanic activity on Mars, then, to preserve the "Lunar" Mars model, the TWY lavas must represent some spurt of recent widespread activity after eons of inactivity. This does not seem probable. What appears required then for the TWY lava hypothesis to be tenable is that Mars be a geologically active planet over large areas for its entire history. Since this is also the picture of Mars that emerges under a 4xLunar chronology, the TWY hypothesis can be considered to be a different path to the same final result.

3. Single Impact Scenario Constraint

Alternatively, the SNCs can be considered to come from one large impact rather than several small impacts, although this scenario now seems less likely than one involving multiple impacts. The crater Lyot is believed to be the youngest large impact crater in theNorth of Mars and has been proposed as the source impact of the SNCs (Vickery and Melosh, 1987). If the impact had occurred in the Southern highlands lavas of 3Gyr old age would likely have been found in the SNCs. The variation of SNC compositions and cosmic ray exposure ages can only be explained in a single impact scenario if the impact is very large and can expel boulders tens of meters in diameter to provide shielding of a large interior region from cosmic rays, with the boulders themselves undergoing collisional breakup in space. Because of this requirement of a very large impact in the north, the crater Lyot, at 227km diameter, was assumed to be a leading candidate. However, to be the source of the SNCs the Lyot impact basin must be younger than the youngest SNC rock and since the impact basin is dated by means of crater dating itself, even a single large impact assumption constrains the CCF at Mars.

The Lyot impact basin has been dated by its stratographical context to be in the earlyAmazonian era (Tanaka, 1986). Interestingly, this period appears to mark a transition between epochs of vigorous channel formation in the Noachian and Hesperian eras and the relatively sparse channel formation in the early and middle Amazonian. This transition occurs in the Neukum and Wise (1976) 1xLunar chronology at between 3.55 - 2.5Gyr ago and in the Hartmann and Tanaka 2xLunar chronology (Hartmann et. al. 1981) at 1.8 - .7Gyr ago. In order for the Lyot basin age to drop to below .2Gyr the CCF would have to rise by at least a factor of 3.5 to be 7xLunar. Therefore the assumption of a single impact creating Lyot as the source of all SNCs applies an even more stringent constraint to the CCF on Mars than the assumption of multiple impacts.

The examination of numerous craters in the Tharsis region as a source for all the SNCs (Mouginis-Mark et al.1992) found that if the size constraint for a large single ejecting crater was relaxed considerably, to 30km diameter from 100km, (seemingly at odds with the requirement that the broad range in cosmic ray exposure ages that requires a large body to be ejected under single impact) then many more candidate craters appeared. However, no one crater appeared to access lavas of the right age range. In general, once the few very large impact basins are eliminated from consideration because they are too old, the search for a single source crater for the SNCs becomes the search for a large region of young lava, as in the case of multiple impacts, but with the added constraint that this region allow contact of lavas of various ages, so that one crater could eject lavas of several ages. Tharis is the one large region on Mars where young lavas are found, however, to produce the range of SNC crystallization ages of .2-1.2 Gyr from one impact was very difficult. This problem occurred because the lava units in Tharsis are large and crater dating chronologies assuming 2xLunar or lower give either very young ages or very old ages. Allowing all the lava ages to become younger and thus more closely grouped in age can be accomplished by allowing the CCF to rise to 4xLunar however, so that mixtures of lavas in the SNC age range that might be sampled by a 30km diameter crater seems less unlikely (Hartmann *et al.*, 1981)(see table 1).. Therefore, even the single crater ejection model for the SNCs seems to require a higher CCF because the terrains on which candidate craters are located appear to have ages that are too old.

Therefore it can be said that the SNC crystallization age constraint on the CCF at Mars is robust to the assumed number of impacts causing SNC ejection. If the impacts are multiple then large areas of Mars must be young and this can only be explained by a higher CCF to give proper crater counts on these areas, if the impact was single then the impact must be large enough to have significant crater counts and also be young, also requiring a higher CCF to give the proper age to crater count. If the impact for single ejection is allowed to be small, to allow more candidate craters, then the problem become essentially the same for multiple impacts, that of finding a large lava region with the proper mixture of ages, which requires, in turn, a higher CCF chronology. In general, the estimates for surface ages of the northern plains lavas of Mars can be brought into agreement with the SNC crystallization ages, allowing them to be the source regions of the SNCs, only if the CCF is allowed to rise to 4xLunar or higher.

4. A Direct Estimate of CCF from SNC Cosmic Ray Exposure Data

The clustering of cosmic ray exposure ages of the SNCs and their values allows an independent method for estimating the CCF besides crystallization ages. This method of constraining the CCF considers that the impacts into the young lavas were not preferential but instead were just three of many impacts on Mars during some interval of time, but with impacts on young lavas being much more efficient in ejecting lava samples from Mars. It appears likely that the SNCs were ejected in three groups: a 0.5 Myr ago ejection of EETA 79001, 2.6Myr ejection of Shergotty, Zagami and ALHA 77005, and 11 Myr ago ejection of the Nakhlites and Chassigny (Bogard *et al.*, 1984) The multiple impact origin model for the SNCs thus gives approximately 3 impacts within approximately 10 Myr on the younger volcanic regions of Mars. Such regions, encompassing the stratigraphy of the Upper Hesperian and Amazonian epochs on Mars, comprise approximately 24% of Mars surface under 4xLunar. SNCs can thus be used to estimate a CCF directly with the assumptions that

TABLE 2. Impacts on SNC-Age Lavas for CCFs Derived from Hartmann-Tanaka in 10Myr

Crater Dia.	1xLunar	2xLunar	4xLunar
8km	.67	3.4	8
12km	.3	1.4	4
16km	.2	.8	2

TABLE 3. Impacts on Older Lavas for CCFs Derived from Hartmann-Tanaka in 10Myr

Crater Dia.	1xLunar	2xLunar	4xLunar
8km	5	8	13
12km	2	4	6
16km	1	2	3

three impacts occurred within 10Myr on these younger lava units of Mars and that the ejecting impacts produced craters of 12km diameter or greater, as was estimated to be capable of ejecting .5 meter rocks into space by Vickery and Melosh (1987).

As can be seen in Tables 2 and 3, the rate of 4xLunar gives reasonable agreement for a 12 km diameter minimum size ejection craters, since, under this CCF , approximately 18 impacts could be expected on the whole of surface of Mars in 10Myr with 4 of those impacts on young Martian lava terrains of the right age range. Estimated rates are also shown for craters of 8 km and 16 km to show the sensitivity to assumed ejection crater size. The 4 impacts into young lavas at 12km or greater diameter also requires approximately 14 impacts on other terrains for the same period, so that a lower efficiency of ejection must be assumed for impacts in such terrains. Since many of these terrains are fluvial and eolian deposits or even ices, low efficiency of ejection of these eroded materials from Mars is not surprising. The older highland lavas probably resemble highland breccias from the Moon and as does the newly discovered ALH84001 and likewise may not be ejected as efficiently as fresh lavas. The lavas older than the SNCs cover 34% of Mars and they would absorb 6 impacts within the same 10Myr under 4xLunar and would be expected to contribute some ejections even at lower efficiency. So these missing Martian meteorites create a problem for the 4xLunar model. The recently discovered Martian origin of ALH84001 (Middlefehlt, 1994) may provide us with an example of such an impact, though its ejection age is slightly outside the 10Myr interval of interest.

A 4x LUNAR CCF GEOCHRONOLOGY
OF MARS

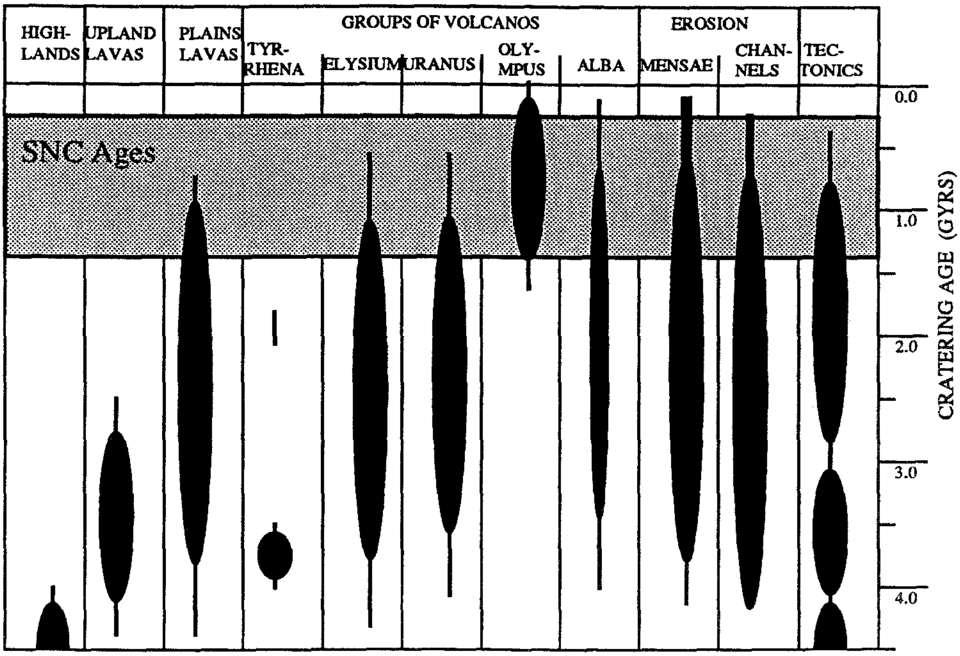

Fig. 3:
A 4xLunar CCF chronology, after Neukum and Hiller Model -II, (Neukum and Hiller 1981). Note that this 4xLunar CCF creates a Terrestrial" geochronology for Mars, with widespread geologic activity occurring throughout Mars geologic history. In particular the histograms showing erosion, indicative of the presence of liquid water on Mars surface, last until late in Mars history and intrude on the epoch of the SNC ages.

It should be noted that 2xLunar Hartmann and Tanaka chronology gives 9 impacts into the surface of Mars at 12km or greater diameter with only 1.5 impacts into lavas in the SNC age range. The 2xLunar also predicts 7.5 impacts into other terrains of which 4 are impacts into ancient lavas. Given the low numbers of impacts and thus poor statistics the probability favors the 4xLunar model, but only marginally, over the 2xLunar model.

Thus the estimated CCF from this method would be approximately 4xLunar subject to the conditions discussed, with the fact that statistics are poor being kept very much in mind. It must be emphasized that this calculation has several other sources of uncertainty: the rate estimate is sensitive to the estimated minimum diameter of the crater left by the ejecting impact and this minimum diameter is poorly constrained, the estimated number of ejecting impacts is not well known, and the estimate of surface extent of candidate SNC source terrains in the proper age range is subject to error, given that the age of the terrains must vary with the assumed CCF. Despite these problems however, the CCF estimated by this method is consistent with the CCF found from considering only crystallization ages.

5. Implications for Mars Climatic History

If the CCF at Mars is 4xLunar or higher, and this will dramatically affect geochronologies and models based on them. An immediate scientific result of a CCF at Mars that is 4xLunar or greater, is that Mars becomes a much more geologically active and dynamic planet throughout most of its history. In addition to vigorous volcanic activity, liquid water may have existed and moved in large quantities on Mars surface until late in its history (see Figure 3). The period of vigorous channel formation on Mars , the LWE or liquid water era, appears to run stratographically from the origin of the planet to the Hesperian-Amazonian transition. It is at the end of the Hesperian age that the massive floods near the terminus of the Vallis Marineris occurred, which dwarf similar floods known to have occurred on Earth. With a CCF of 4xLunar the Hesperian era and the LWE end at approximately .9 Gyr ago. This means that the LWE on Mars may have lasted 3.5Gyr or most of Mars history. Importantly, in a 4xLunar geochronology the LWE now overlaps the SNC ages, suggesting that the SNC parent lavas, assumed to be surface rocks, could have come into contact with liquid water at some point in their histories before the ejecting impact occurred. This result is consistent with the fact that most SNCs show signs of preterrestrial liquid water alternation (Gooding *et al.*, 1991,Treiman *et al.*, 1993).

6. Summary and Conclusions

It can be seen that the SNC crystallization ages apply constraints to the assumed CCF at Mars that are insensitive to assumptions about the number of impacts. In the case of the minimum of one impact the CCF appears constrained to be above 7xLunar and in the case of the maximum of 3 impacts the CCF appears constrained to 4xLunar by surface ages. One also arrives at approximately 4xLunar by direct measurement of CCF for ejection produced craters of 12km diameter or greater, although this latter calculation has many sources of possible error. This result for the CCF pushes the epoch of abundant liquid water on Mars surface into the band of SNC ages and is consistent with signs of preterrestrial water alteration found on many SNCs. The source of the greater than Lunar CCF at Mars is readily explainable because of the proximity of Mars to the asteroid belt, now believed to be the source of most Mars impactors. Recent assays of Mars crossing asteroids performed by Gene Shoemaker and colleagues are consistent with the 4xLunar CCF at Mars (Shoemaker,1994). Mars geochronologies, all of which are dependent on the CCF value at Mars, would be profoundly altered if the 4xLunar result is confirmed and with it our concept of Mars. In particular the Lunar Mars concept, dating from the early Mariner probes, may pass away, to be replaced by a New Mars, a dynamic active planet with liquid water erosion and widespread volcanism for most of its history.

7. Acknowledgment

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