Preservation of Tropical Subsurface Ice into the Very Recent History of Mars. M. R. Kirchoff and R. E. Grimm. Southwest Research Institute, 1050 Walnut St., Suite 300, Boulder, CO 80302. Email: kirchoff@boulder.swri.edu.

Introduction: The history of volatiles on Mars and implications for climate and geology are intimately linked to the evolution of subsurface tropical ice. Ice is currently not stable below the mid-latitudes [e.g., 1], but the actual, time-integrated loss is uncertain [2, 3]. Layered-ejecta craters have long been thought to tap buried ice [e.g., 4]. They are present at all latitudes and sample to greater depths (kms) than possible with neutron spectroscopy or even surface-penetrating radar. With the advent of near-global 10-m/pixel imaging of Mars, formation model ages of individual layered ejecta craters can be estimated from smaller craters superposed on their ejecta blankets [e.g., 5]. We focus on single layered ejecta (SLE) craters because of their prevalence at tropical latitudes. 50 craters from the Robbins [6] database between ±30ºN and with diameters (D) ≥5 km have been analyzed so far. These craters are chosen mostly from low dust regions (as indicated by Thermal Emission Spectrometer [7]) to minimize effects due to dust deposition. Ages of these craters provide new constraints on when and where subsurface ice existed at tropical latitudes.

Methods: To estimate the formation model ages of SLE craters, we measure small, superposed craters (SSCs) on their ejecta blankets. The Neukum et al. [8] production function is fit to the resulting SSC size-frequency distributions (SFDs) and their chronology function is used to compute model ages. However, several issues introduce uncertainty in the age calculations: removal of SSCs by erosion and/or dust deposition, inclusion of craters only partially buried by the ejecta blanket, inclusion of secondaries, and errors in the chronology. While there is little we can do about the last issue, we have developed some strategies to mitigate the first three. Here we summarize these strategies, which are discussed in detail in [9].

The first strategy is measuring craters of similar sizes to the SSCs within a nearby reference area that is on the same geological unit. Comparison of crater SFDs for the two areas can indicate if any of these issues need to be considered. Our second strategy is to compare these two area's SFDs to a subset of the SSC SFDs only including degraded craters and obvious secondaries (those that form in chains and clusters). Similarities in these crater SFDs suggest that the SSC SFD has been likely modified. Finally, the third strategy is to evaluate production function fits to the SSC SFDs. Diameter ranges that do not match within error are not considered reliable for estimating model ages.

In the process of applying these strategies, we determine those model ages which appear to be the least affected by crater removal, partially buried craters, and secondaries. These are classified as “high confidence” model ages, and are also analyzed for verification of the full data set.

Once model ages are determined, we assess whether the formation rate of equatorial SLE craters has deviated from the formation rate of all low-latitude craters. Our approach is to first determine the number of SLE craters with model ages that fall into a given 0.5 Gyr bin (i.e., 0.25-0.75 Ga, 0.75-1.25 Ga, etc.). These values are then normalized to the number of all craters expected to form for the Neukum chronology in each bin. A resulting plot of normalized number of craters vs. age (e.g., Fig. 1) is used to assess if and how the tropical SLE formation rate has deviated from the background flux.

We also use the SLE crater model ages, along with the craters' diameters to determine if and how depth to the subsurface ice has varied with time.

Results and Discussion: Of the 50 equatorial SLE craters examined so far, we ascertain that 29 of them have high confidence model ages. Fig. 1 shows the normalized number of craters vs. age for the high confidence set (results are similar for the full data set). Data are currently insufficient to robustly conclude how the SLE crater formation rate is changing with respect to the formation rate of all low-latitude craters. The SLE cratering rate first appears to decrease from ~3 to 1 Ga and then increase again for the last billion years, but uncertainties are still large.

If the trend were flat, as represented by the red line, then the SLE crater formation rate has stayed the same as the assumed rate for all low-latitude craters and the amount of tropical ice has not considerably changed. If the normalized number of craters decrease with decreasing age, then the SLE crater formation rate has declined implying reduced tropical subsurface ice. There is not, however, a straightforward explanation why the SLE crater formation rate would increase towards the present. We suggest four possible explanations: 1) some SLE crater model ages are not formation ages because of undetected removal of SSCs; 2) the impact rate is higher for the last billion years than currently estimated by the Neukum chronology (as suggested by lunar studies [e.g., 10–12]); 3) SLE crater ejecta is destroyed at a faster rate decreasing the number of older SLE craters that can be identified; 4) ice has been recently cold-trapped at shallower levels due to vapor diffusion resulting in the increased formation of young SLE craters. Explanations (1-3) would mean that the increase is not real, but a result of uncertainties in the analysis, and would change if the biases were quantitatively known and could be accounted for. Ex-

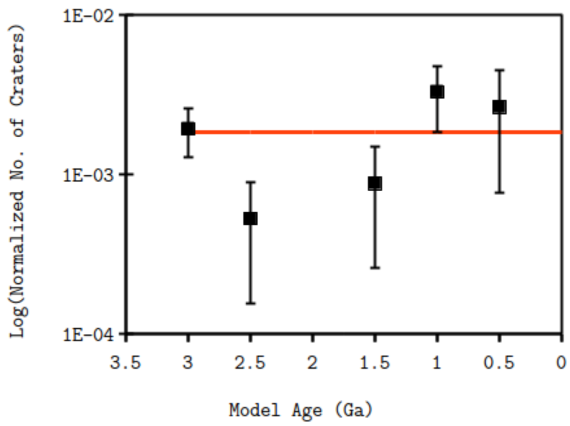

Figure 1. Number of tropical SLE craters with ages in the given 0.5 Gyr bins (data plotted at center of the bin) normalized to the total number craters expected to form between ±30ºN for the Neukum chronology [8]. Error bars are Poisson. Red line represents no change in formation rate of SLE craters with respect to all low-latitude craters.

planation (4) would mean the increase is real and some information is missing on the understanding of movement of subsurface volatiles. Overall, current limitations on the data and our understanding of crater erosion, movement of subsurface ice, and the chronology inhibit fully resolving this issue.

Nevertheless, a key result from our estimation of formation model ages is that SLE craters appear to have formed throughout the Amazonian (Table 1). Moreover, we have potentially found at least 2 SLE craters that have formed within the last 500 Myr (up to 5 if lower confidence model ages are included). This implies that tropical subsurface ice has been retained even into very recent times.

Furthermore, the smallest SLE crater examined (of the high confidence set) appears to likely be less than a billion years old (D=5.8 km, -24.3ºN, 95.8ºE, age=0.7 –0.5/+0.8 Ga). Since excavation depth is related to crater diameter (through the transient diameter; [13]), this indicates recent tropical ice as shallow as 300-400m in this location (Tyrrhena Terra). In addition, a much older age for the second smallest crater (D=6.2 km, -27.8ºN, 3.41ºE, age=3.5 -2.5/+0.3) indicates ice was this shallow even in the past, although it is in a different area (Noachis Terra). Therefore, we can broadly conclude that relatively shallow subsurface ice has been present throughout most of Mars history, but that the location may have varied through time.

Table 1. High confidence model ages for equatorial SLE craters likely formed in the Amazonian

Latitude (°N)	Longitude (°E)	D (km)	Age (Ga)
-7.803	86.01	8.85	0.3 -0.3/+0.8
-8.54	58.22	7.669	0.5 -0.5/+1.1
-28.35	271.95	8.943	0.6 -0.2/+1.0
-24.26	95.83	5.825	0.7 -0.5/+0.8
-1.6	350.1	10.011	0.8 -0.7/+1.4
-5.97	10.94	7.498	1.1 -0.6/+0.9
20.2	326.63	8.097	1.2 -0.8/+0.2
-27.39	148.51	7.863	1.5 -0.5/+0.6
-14.42	103.15	8.761	1.6 -1.0/+1.7
17.09	128.29	9.412	2.5 -1.4/+1.0
-25.9	152.41	8.958	2.5 -1.8/+1.1
-7.1	32.91	6.544	2.6 -2.6/+1.1
-18.13	2.22	10.182	2.9 -1.5/+0.7

Conclusion: Formation model ages have been computed for 50 equatorial SLE craters using the density of smaller craters superposed on their ejecta blankets. For 29 of the estimated model ages, we have a high confidence that the superposed crater SFDs are likely not considerably altered by crater removal, partially buried craters, and secondary craters. Analysis of these ages indicates SLE craters have formed at low latitudes throughout the Amazonian (0-3 Ga), with a few forming within the last 500 Myr. These results imply tropical subsurface ice has not been substantially diffused away and is still present today. Moreover, this ice has been regionally quite shallow, at least within 300-400 m of the surface, throughout Mars' history.

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