Timing and Distribution of Single-Layered Ejecta Craters Implies Sporadic Preservation of Mars' Tropical Subsurface Ice. 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 ~6-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. 54 craters from the Robbins and Hynek [6] database between ±30ºN and with diameters (D) ≥5 km have been analyzed. 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. [7] 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 [8].

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 bin derived from the martian epochs defined by Tanaka et al. [9] for the Neukum chronology: 0-0.3 Ga, 0.31-0.8 Ga, 0.81-1.2 Ga, 1.21-2.3 Ga, 2.31-3.4 Ga, and > 3.4 Ga. 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 depth to the subsurface ice in recent epochs.

Results and Discussion: Of the 54 equatorial SLE craters examined, we ascertain that 28 of them have high confidence model ages. Fig. 1 shows the normalized number of craters vs. age for the full dataset of ages and the subset of high confidence ages. Statistically both datasets in Fig. 1 are consistent with a flat, average trend, as represented by the solid black and red lines. A chi-squared test comparing the data to the average value indicates the probability (p-value) is < 0.01% that the data deviate from that average (note we do not include the ">3.4" bin in this calculation as it is likely biased due to the higher removal rate of craters during the Hesperian and Noachian). Therefore, we cannot reject the hypothesis that SLE crater formation rate has stayed the same as the formation rate for all low-latitude craters throughout the Amazonian.

Furthermore, the smallest SLE crater examined (of the high confidence set) appears to likely be around a billion years old (Table 1). Since excavation depth is related to crater diameter (through the transient diameter; [10]), this indicates recent tropical ice as shallow as 300-400m in this location (Noachis Terra).

Finally, we plot the occurrence of layered ejecta craters vs radial (lunar-like ballistic) ejecta craters in a representative area of Noachian highlands (Fig. 3). Craters with discernible ejecta comprise about half of all the craters, and of these craters, 41% have layered ejecta. The spatial mixing of layered and radial ejecta craters is striking: the median intercrater distance considering both classes is only 24 km and the correlation length (range of a spherical variogram fitted to binary class data; [11]) is just 7 km. In other words, finding

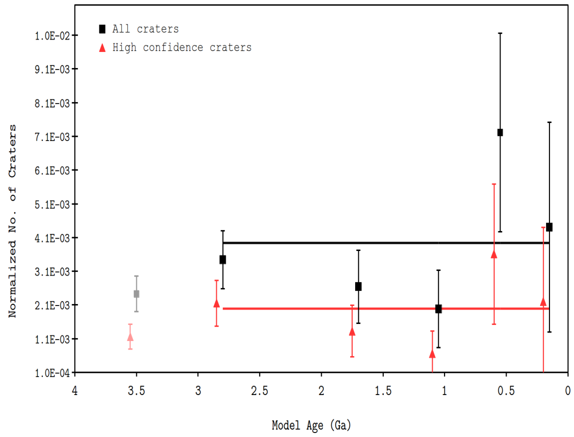

Figure 1. Normalized number of tropical SLE craters for defined age bins. Error bars are Poisson. Solid lines represents no change in formation rate of SLE craters with respect to all low-latitude craters.

another crater of the same class has a higher probability than randomly sampling the overall distribution only within 7-km distance.

Our result that SLE crater formation rates appear to track the overall cratering rate implies that the ground-ice configuration is largely static and that each new layered ejecta crater is simply a probe of that fixed arrangement (inferring that the formation of any layered ejecta crater requires subsurface ice to be present, without entering into the debate about the nature of the distribution of volatiles with depth that may control occurrence of single, double, and multiple layered craters). Meanwhile, the 7-km correlation length between craters of the same class (layered or radial ejecta) reflects the characteristic dimension for ground-ice heterogeneity in the tropical cryosphere. The overall areal fraction of ground ice is roughly the proportion of craters with ejecta that show a layered morphology, 42% in Fig. 3 and 43% globally over ±35° latitude. The upper crust of Mars must be highly laterally heterogeneous in this scenario, with large variations in pore size or tortuosity that sharply restricts sublimation to less than hundreds of meters within 10 km of sites where most or all of the ice in the cryosphere has been lost, perhaps to depths of several km.

Conclusion: Formation model ages have been computed for 54 equatorial SLE craters using the density of smaller craters superposed on their ejecta blankets. For 28 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 1 Gyr. These results imply tropical subsurface ice has not been substantially diffused away and is still present today, at least locally.

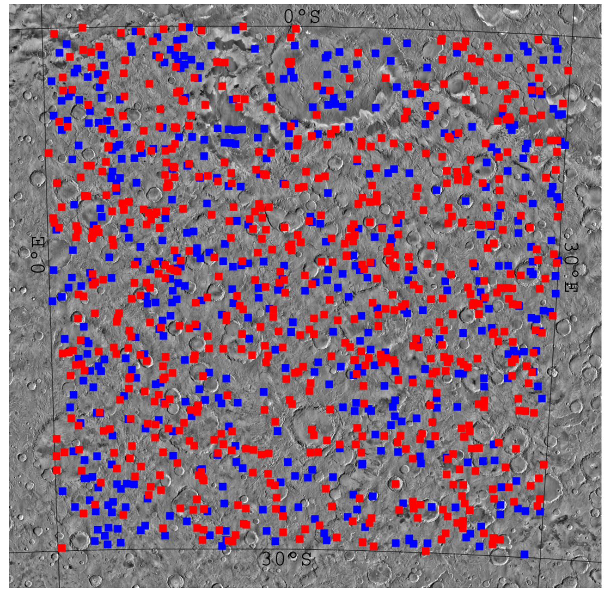

Figure 2. Locations of layered ejecta craters (blue; all subclasses) and radial (lunar-like ballistic) ejecta craters (red) with D = 3 to 52 km in a 30°x30° area centered at 15°S, 15°E.

Moreover, this ice could be locally quite shallow, at least within 300-400 m of the surface. However, the intimate mixing of layered and radial ejecta craters implies strong lateral heterogeneity of ground ice.

Table 1. High Confidence Model Ages for SLE Craters Likely Formed in the Late to Middle Amazonian

Latitude (°N)	Longitude (°E)	D (km)	Age (Ga)
-7.80	86.01	8.85	0.3 -0.3/+0.8
-28.35	271.95	8.94	0.6 -0.4/+1.0
-29.16	207.95	8.29	0.7 -0.6/+1.0
-1.60	350.10	10.01	0.8 -0.7/+1.5
-5.97	10.94	7.50	1.1 -0.6/+0.9
20.20	326.63	8.10	1.2 -0.7/+1.2

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