SECONDARY CRATERS AND THE LIBERATION OF ICE ON MARS. K. J. Zahnle[1] and A. Colaprete[2], [1]NASA Ames Research Center (Mail Stop 245-3, Moffett Field CA 94035, kzahnle@mail.arc.nasa.gov), [2] NASA Ames Research Center (tonyc@freeze.arc.nasa.gov).

Introduction: In 1983, Carr pointed out that the historic activity of water on Mars appears to have declined more-or-less synchronously with the decline of impact cratering. This gave rise to the suspicion that the two might have been linked – that somehow it was through impact craters that water was mobilized and the martian climate made, however briefly, clement.

Carr (1989) asked whether impacts could have recycled carbonate rock quickly enough to maintain a substantial CO_2 greenhouse. He concluded that they could not: the high temperature footprint of the primary impact is not big enough. Sleep and Zahnle (1998) revisited the question and drew the same conclusion: primary impacts do not deliver enough energy, do not mobilize enough CO_2, and do not directly mobilize enough water. They specifically concluded that the water directly mobilized by the impacts falls at least two orders of magnitude short of the rainwaters required to account for the observed amount of erosion. To make the hypothesis work, the typical raindrop would need to cycle 1000 times between gully and cloud.

Segura et al. (2002) improved significantly on the earlier work. They studied the fate of impact-liberated water vapor using a radiative-convective atmosphere, and they included an explicity accounting of the slow dissipation of residual heat left over from the impact. However, Segura et al did not include a hydrologic cycle, and so the warm wet epochs following large impacts lasted just tens of years, which is similar to what Sleep and Zahnle had asserted. Moreover, major effects required big impacts that make craters hundreds of kilometers diameter. There are too few young craters bigger than 200 km to account for the volume of water-caused erosion of similar age.

Recently, McEwen et al (2005) reported the discovery of a 10.1 km diameter rayed crater on Mars. The crater, named Zunil, is a very young impact crater set in martian lavas that are themselves young. Its secondary craters are obvious, distinctive, and very numerous, in country where other craters are rare. From crater counts McEwen et al. estimate that Zunil produced at least 10^7 secondary craters wider than 10 m diameter within 1200 km of the primary. They infer, through use of a sophisticated 3D hydrodynamical numerical model, that at least another 10^8 secondary craters of similar size are distributed globally.

These are staggering numbers. The surface area disturbed by these secondaries is enormous, much greater than the surface area directly impact by the primary. Moreover, Zunil's 10 m diameter secondaries are big enough to begin to exhume shallowly buried water ice of the kind inferred to be present now over a significant fraction of Mars's surface (Feldman et al 200x). Previous models of impact effects neglected secondary craters. If typical martian craters are like Zunil, the cumulative effects of $>10^8$ secondary craters might exceed any effects directly attributed to the primary.

McEwen et al. (2005) stress that the true size-number distribution of the larger Zunil secondaries is very steep. When the cumulative distribution of crater diameters is put in the form of a power law, $N(>D) \propto D^{-b}$, they find b=5 for secondaries with diameters D>10 m. This distribution is much too steep to extend to indefinitely small craters. At what size the distribution turns over is unknown. McEwen et al. suggest that b=3 for D<10 m, but both b=3 and D=10 m are best regarded as upper limits. The cumulative surface area of the secondary craters diverges if b>2. We will use b=5 for secondary craters bigger than a fiducial diameter D_{gk} and b=2 for secondary craters that are smaller than D_{gk}. We will associate the fiducial diameter D_{gk} with secondaries made by Grady-Kipp fragments (below).

A model of secondary cratering: To describe impact ejecta and the resultant secondary craters in more detail we develop a simple general description of secondary cratering based on theoretical ideas proposed by Melosh (1984, 1985, 1987, 1989) and first implemented by Vickery (1986). Melosh divided impact ejecta into two basic cartegories: "Grady-Kipp fragments" that describe shocked rock from below the surface that are associated with the main excavation flow, and "spalls" that originate from a competent surface where the excavation flow breaches the surface. Our model predicts the number and sizes of ejecta in each category. At this level of description the model has no free parameters. However, there is an ambiguity in the size of spalls that relates to their originating as thin plates of rock. The spall plates are expected to break up into fragments of a scale comparable to the thickness of the plates. We found it necessary to introduce a free parameter to describe the partitioning of the spalls between the "tabular" plates and the "equant" fragments. With this limitation understood, our model successfully reproduces the observed size-number distributions of small craters on both Mars and Europa (Zahnle et al 2007).

Melosh (1985, 1989) approximates the thickness of the spall plate by

$$Z_{sp} = \frac{Yd}{\rho C_L v_e} \quad (1)$$

where the velocity C_L corresponds to the longitudinal sound speed in the target, Y corresponds to the strength of the material, d to the diameter of the asteroid or comet that strikes Mars, and v_e to the ejection velocity. The length and breadth of the spall plates are at genesis typically an order of magnitude larger than their thickness, although it is expected that the plates break up into more equant bodies with all three dimensions of order Z_{sp}.

The biggest Zunil secondary is 230 m diameter and 105 km from the primary (McEwen et al. 2005). This corresponds to a velocity of 0.63 km/s and a mass of 1.1×10^{12} g. If, in Eq (1), we take $Y = 2 \times 10^9$ dynes/cm^2, C_L=5 km/s, and d=1.0 km, we obtain Z_{sp} = 21 m. If width and length are each $8Z_{sp}$, a rectangular parallelepiped (tabular spall) would have mass 1×10^{12} g. Although we have tuned the parameters, this is in fact as good a match as one could hope for.

If we further demand that the more far flung spalls break up into bodies of dimension Z_{sp}, we find that the corresponding secondary craters on Mars should be 30-50 m diameter. Again, this is as good a match as we could hope for.

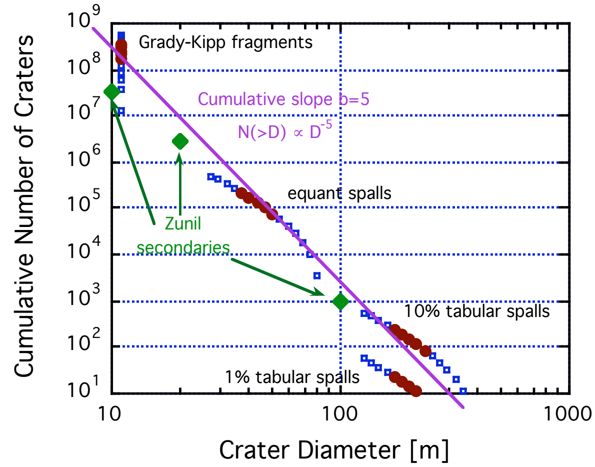
When comparing our predictions to the observed secondaries of Zunil (Figure 1), we find that tabular spalls represent less than 10% of the total mass in spalls.

Secondary craters made by spalls of size Z_{sp}^3 are roughly the same size anywhere on the planet, because $D \propto Z_{sp} v_e^{2/3} \propto v_e^{-1/3}$. If we write the throw distance $r \propto v_e^2/g$, we find that $D \propto r^{-1/6}$. For Zunil, these spall-made craters range from ~50 m diameter when 200 km from the primary to ~30 m diameter when on the other side of the planet.

The total mass of spalls as a function of ejection velocity v_e is obtained by integrating $Z_{sp}(r)$ over the surface area spalled. The number of spalls as a function of ejection velocity is obtained by integrated dN_{sp} as defined by $m_{sp} = dM_{sp}(>v_e)/dN_{sp}$.

High velocity crater ejecta in general are more highly shocked and more highly stressed than in the spall zone. These ejecta are more thoroughly broken up into what are called Grady-Kipp fragments.

Grady-Kipp theory estimates the size of fragments by comparing strength to the rate of change of the stress, while taking both the pre-existing size-number distribution of cracks and the crack propagation velocity explicitly into account.



The predicted and observed size-number distributions of Zunil secondary craters. The inferred actual number of secondaries are from McEwen et al (2005). Model results are shown for all of Mars (open symbols) and for the annulus between 200 km and 1200 km from Zunil (filled symbols). The model considers three classes of ejecta: tabular spalls (the form of the spall as launched), equant spalls (all dimensions equal to the thickness of the spall plate), and Grady-Kipp fragments. Aerodynamic effects have been neglected. The biggest secondaries are attributed to tabular spalls that strike the ground as coherent units. A relative dearth of large Zunil secondaries implies that at least 90\% of the tabular spalls break up and disperse before they hit the ground. The cumulative slope b=5 is shown for comparison.

The theory is sufficiently complicated that simple approximations are suspect; nevertheless Melosh (1989) has suggested that

$$L_{gk} = \frac{Yd}{\rho v_e^{2/3} v_i^{4/3}} \quad (2)$$

provides a useful approximation to the preferred size. In (2) the velocity v_i refers to the impact velocity of the primary.

For Zunil (v_i=10 km/s), (2) predicts 1.7 m fragments with v_e=2.5 km/s. This is within the envelope predicted by the detailed fragmentation models (two of which are variants on Grady-Kipp) that McEwen et al. explicitly consider (their Figure 11). An interesting property of (2) is that it predicts that the mass of Grady-Kipp fragments scales as v_e^{-2}, and hence that all the secondary craters produced by a single primary impact are the same size, regardless of where they are on Mars. Thus, for secondary craters, the preferred crater size D_{gk} that corresponds to the Grady-Kipp fragments of any given primary impact should be well-defined. For Zunil, D_{gk} = 11 m.

The total mass of ejecta is obtained using conventional excavation flow scalings $M_{ej}(>v_e) \propto v_e^{-1.66}$ and integrating dN_{gk} as defined by $m_{gk} = dM_{ej}(>v_e)/dN_{gk}$.

To compare our predictions to those made by McEwen et al., we use 1<v_e<5 km/s, the same limits that McEwen et al. use. We then obtain $N_{gk} = 6\text{x}10^8$. This is an enormous number. It implies that Zunil alone generated 6x10^8 secondary craters 10 m wide. This number is four times bigger than what McEwen et al. report. But if the true number of 10 m secondaries is smaller, the missing mass must be made up of an even larger number of smaller fragments making an even larger number of smaller secondary craters, given that the mass of ejecta at a given velocity is the more robustly determined quantity. On Mars the atmosphere doubtless affects the flight of the smaller faster fragments and so culls the number of the more distant secondaries; this matter is beyond the scope of the present study.

In the theory N_{gk} is the same for every primary crater. What changes as the size of the primary changes are D_{gk} and D_{sp}. Head et al (2002) point out that the presence of a regolith suppresses the launch of high speed spalls and thus is likely to suppress the numbers of the bigger secondaries of craters that don't form in young volcanic terrain. However, it is not clear that the size, number, or launch velocity of the Grady-Kipp fragments should be greatly affected by the presence of a regolith, and hence there we see no particular reason to discount either D_{gk} or N_{gk}.

To first approximation the model does a good job of matching Zunil (Figure 1). The model gets three things more or less right. First, it correctly predicts the size of the biggest secondaries. Second, it predicts the right order of magnitude for the number of craters. Third, it gets the steep cumulative slope of the size-number distribution right.

The model does not predict the partitioning of spalls between the tabular and the equant forms (nor does it predict the breakup of the equant spalls into Grady-Kipp fragments). To fit Zunil, most of the tabular spalls must break up and disperse before they hit the ground.

The good approximation to the b=5 power law stems from the relative numbers and sizes of the Grady-Kipp fragments and the spalls. Connecting these two peaks with a line is natural, but the model does not predict the corresponding number of craters of intermediate sizes. In fact the model predicts no craters of intermediate size. Of course reality generates a wide range of fragments bigger and smaller than the two preferred sizes we have defined, and there will be intermediate-sized craters. Filling in the holes requires taking mass out of the two peaks. This explains why the model seems to predict more secondaries than there actually are.

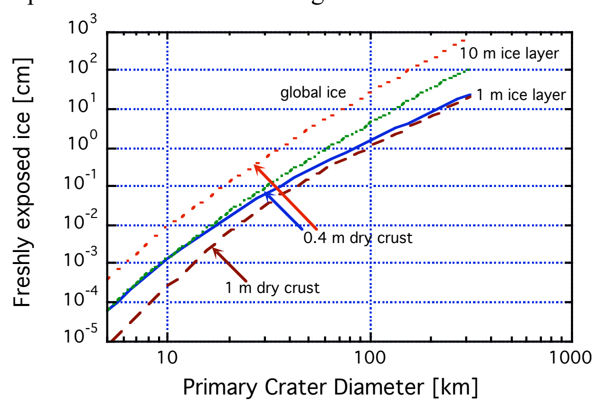
Secondaries as a means of excavating and liberating subsurface ice: Spacecraft observations using a gamma ray spectrometer indicate that subsurface water ice is ubiquitous within 30° of both martian poles (Feldman et al 2002). The ice is protected by an insulating cover that is ~40 cm thick. The ice itself is probably at least a meter thick and it may be thicker.

For simplicity we model the size-number distribution of secondary craters with a two slope power law. We identify the change in slope with the preferred D_{gk} crater size. For $D>D_{gk}$, we use b=5, and for $D<D_{gk}$, we use $b=2$. For the model we use $N_{gk}=3\text{x}10^8$.

The model suggests that, to first approximation, D_{gk} scales directly with the size of the primary crater.

We model the shape of secondary craters by paraboloids with depth/diameter ratio of 0.1. We assume that any ice inside the paraboloid is excavated and strewn across the surface, to freely evaporate if it should so choose. As a standard model we presume that the ice is protected by a 0.4 m thick insulating cap. We presume that the ice is 1 m thick. We presume that ice layer is 60% ice by volume, and that the ice is present over 1/6th of the martian surface.

We also consider three alternative models, one with the ice layer 10 m, one with 10 m of ice globally distributed rather than restricted to be near the poles (perhaps mimicking a younger Mars under a fainter Sun), and one with 1 m of ice under a 1 m thick insulating cap. Results are shown in Figure 2.



The total amount of water ice excavated by secondary craters, as a functiuon of the size of the primary crater. The amount of water is given as the depth of an equivalent global layer of liquid water. The four cases shown are discussed in the text. For comparison, the current martian atmosphere contains 0.001 cm of water vapor, while Earth's atmosphere contains a few centimeters. Thus 50-100 km diameter primary craters could create Earth-like conditions if other factors were favorable.

In most cases the amount of water ice liberated is greater than the amount of water liberated by the primary alone. The exception would be a direct hit on a thick water ice cap, such as the two small polar ice caps on Mars today. E.g., a typical 100 km impact crater on Mars today would excavate at least 2000 km^3 of ice and plausibly more than 20,000 km^3 (Figure 2). For comparison, a 100 km diameter crater striking an aquifer 100 m deep would release 800 km^3, a substantial amount, and much of it vapor, but a 100 m thick aquifer is itself substantial.

If this 100 km crater happened today, the liberated ice would evaporate and the water vapor would be transported to the north polar cap, where it would freeze out. The climate of Mars would not change drastically.

If this happened on a Mars at a different obliquity, or to a Mars with a thicker CO_2 atmosphere, things might turn out differently. The exposure of water ice via the process described above is modeled using the NASA Ames General Circulation Model. A hydrological cycle has been incorporated into the Ames MGCM that includes the formation of clouds, precipitation, and surface and regolith reservoirs. Previous simulations using this model have indicated a transition may occur from a cold, dry climate to a warm, wet climate following an impact of sufficient size (Colaprete et al., 2004). The magnitude and duration of an impact induced warming event depends on the availability of near surface water reservoirs; for the hydrologic cycle to remain active sufficient "usable" water was required. These simulations did not consider the liberation of water by secondary impacts. New simulations will be performed which include this additional source of "usable" water.

We will present some examples of how differently things can turn out when a hydrological cycle is considered. But the key point regarding excavation of near surface ice by secondary cratering is that we are discussing a known reservoir of water, and accessing it using an observed population of secondary craters of relatively frequent, relatively small primary impacts. Recycling of water ice by secondary cratering may provide a missing link between the disappearance of warm wet climates and the end of the late bombardment.

References:

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