Searching for Ancient Venus. Peter H. Schultz, Department of Geological Sciences, Brown University, Providence, RI 02912.

The cratering record on Venus provides one of the few available remote chronometers for establishing relative age. Because the dense atmosphere shields the surface from smaller impactors, the most statistically significant fraction of the cratering record is incomplete at best and indeterminate at worst. Larger craters represent survivors of entry but occur too infrequently for delineating statistically significant ages on a local scale (1). This contribution reconsiders processes affecting the statistical cratering record and argues that the globally averaged age approaches 2-3 by with isolated relict surfaces dating back to 3-4 by.

**Global Crater Production Curves:** The cumulative power-law function for the global cratering record on Venus exhibits a segment that resembles, at first glance, a crater production curve (1). Consequently, initial studies often assume that a direct comparison can be made, after adjustments for flux and scaling differences. The statistically significant portion of the global cratering curve, however, represents a very narrow window (factor of two in size from 50 km to 100 km) limited at small sizes by atmospheric shielding effects and loss processes. Uncertain regional geologic histories (2), visible effects of enhanced crater enlargement for craters larger than 100 km (3), and statistical uncertainty of small numbers lessen the confidence at large sizes. This narrow range of diameters may yield a production-like slope, but its slope may have little significance. The Apollo 17 site on the Moon also exhibited a production-like slope and indicated that this site would provide some of the youngest basalt samples (4), yet the returned sample ages were among the oldest (5). Enhanced degradation of small craters in a thick particulate surface layer and an insufficient counting area at large sizes accounted for this incorrect estimate (6,7). Yet, the correct relative age could have been easily predicted from simple embayment relations with adjacent maria, thereby underscoring the importance of understanding the local geologic context, stratigraphy, and operative processes - - as well as statistical significance.

Although the tangent of the Venus global curve with a lunar calibration curve can yield a minimum average age, such an approach implicitly assumes that the relative impactor flux and crater scaling relations are reasonably well understood. But the dense atmosphere of Venus introduces significant scaling effects by changing the shape (8) and effective density (9) of the impactor and by arresting lateral crater growth (3). Laboratory experiments clearly demonstrate that crater diameter is largely controlled by impactor size, while at a given velocity depth can be controlled somewhat independently by impactor density for a given target (9). If no other processes operate, an aerodynamically flattened impactor (8) will increase crater diameter for a given mass striking a gravity-controlled particulate target, whereas an aerodynamically streamlined impactor (3,10) will decrease crater diameter. In natural materials with strength, however, gravity-controlled growth requires shock-preconditioning the target into a near-strengthless medium. If impactor velocity has been reduced significantly (6 km/s), gravity scaling laws become inappropriate.

Laboratory experiments also reveal that a dense atmosphere introduces both static and dynamic pressure effects (3,11). Even though the total excavated crater mass greatly exceeds the displaced atmospheric mass, crater ejecta leave the cavity within a relatively thin wall (i.e., curtain), thereby substantially decreasing the mass per unit area at any given time (3). At laboratory scales, dynamic pressure effects can reduce cratering efficiency by an order of magnitude (3). Dynamic forces acting to retard outward advance of the base of the curtain are transmitted hydrostatically to the cratering flow field. This can be illustrated experimentally by using a plate positioned just above the surface with a hole to allow passage of the impactor. Ejecta striking the plate spray outwards without returning to the cavity, but interactions with the plate reduce cratering efficiency similar to observed atmospheric effects. Because craters grow non-proportionally (i.e., continuously changes shape by first growing downward, then outward), atmospheric dynamic pressure prematurely arrests lateral growth as shown in Figure 1. The process of arrested lateral growth can be modeled analytically as a cylinder expanding with a constant velocity and constant thickness (3) or numerically using variable thickness and decreasing velocity once subsonic (12), both approaches being consistent with experimental results. Scaling to Venus can be justified since outward crater growth is subsonic for most of the later stages of crater growth and since atmospheric blast effects appear to be offset from crater excavation (3). This approach reveals that excavation craters on Venus could be reduced by as much as a factor of two. This process is consistent with observations of more pronounced rim heights and greater depths than expected (1,13), particularly once empirically adjusted for gravity (14). If correct, the minimum average age from the global crater inventory approaches 2-3 by, in contrast with previous estimates of 0.5-1.5 by (1).

**Crater Preservation States:** Craters on Venus seem to be in remarkably similar states of preservation (1). This observation has been used to argue that catastrophic global resurfacing has reset the cratering chronometer (15) or that the surface preserves a record of catastrophic bombardment (16). But similar preservation states of radar-bright ejecta facies may not indicate a common maximum age but resistance to weathering and or very weak erosional processes in order to produce the obvious range of expected morphologies found on the other planets.
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The formation of an impact crater in an atmosphere must generate an intense atmospheric response due to the outward kinematic interactions with the ejecta curtain and containment of the vapor cloud (3,11). As a result, emplacement of the inner ejecta will be accompanied by intense winds and vortices with velocities (100m/s - 400m/s) sufficient to winnow and entrain smaller (<meter scale) ejecta, leaving behind a blocky lag surface for the inner facies and creating turbidite-like, run-out flow of smaller (radar-dark) materials. If winds are the primary erosional agent on Venus, then the inner facies will be archived unless winds of comparable magnitude occur again while the outer deposits provide Venus with a local reservoir of particulates.

Impact-generated wind storms may represent one of the principal erosional agents on Venus. Such storms can be inferred from laboratory experiments and from the geologic record (3,17). For example, radar-bright and -dark wind streaks associated with the crater Carson are interpreted as the consequence of upper level winds deflected by the expanding, impact-generated, vapor cloud (3). Equally important, however, is the radar-bright, linearized zone extending westward from Carson and eroding ejecta and run-out flow deposits of the crater Aglaonice (600km away from Carson). This scour zone is interpreted as the trail of the late-stage thermal disturbance initially created by Carson but subsequently dragged westward by the strong winds aloft. Other craters with a wide range of preserved facies exhibit evidence for similar impact-generated windstorms (3,17). The widespread occurrence of other wind streaks could represent more gentle, less intense circulation patterns (18,19) or the final stages of impact-generated disturbances far from the source. Conversely, the absence of similar effects around all craters underscores a true continuum of degradational states, in contrast with the perception of a catastrophic flux.

Identifying Ancient Terrains: Relict ancient terrains on Venus should be characterized by the following features: spatial clustering of relatively large craters with different impact trajectories in a common geologic/tectonic setting; evidence for a wide range of preservation states of the outer radar-dark facies; mantling of crater interiors by radar-dark materials; and occurrence in a radar-dark regional setting. The last characteristic should result from the disturbances far from the source. Conversely, the absence of similar effects around all craters underscores a true continuum of degradational states, in contrast with the perception of a catastrophic flux.

Fig. 1. Atmospheric effects on crater growth from quarter space laboratory impact experiments. Atmosphere retards outward growth of curtain because it behaves as an impermeable plate. Craters in non-cohesive sand form a deep bowl-shaped transient cavity resembling an early stage of growth in a vacuum (left). The transition profile collapses in sand (bottom right) but is preserved in compacted pumice (3,17).

Fig. 2. Effect of impact-generated windstorm created by formation of the crater Carson (middle right). Downrange fireball is carried westward by winds aloft creating a radar-brightened surface (upper) and scouring ejecta deposits of Aglaonice. Radar-bright wind streaks, scour zones, and radar-dark streaks represent superposition of gradually decreasing winds through time. Different impact directions (arrowed) and angles indicate separate impact events. This area is proposed to be an ancient relics of Venus.