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IMPACT CRATERS ON VENUS: AN OVERVIEW FROM MAGELLAN OBSERVATIONS.

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Magellan has revealed an ensemble of impact craters on Venus that is unique in many important ways. We have compiled a database describing 842 craters on 89% of the planet's surface mapped through orbit 2578 (Fig. 1) (the craters range in diameter from 1.5 to 280 km). We have studied the distribution, size-frequency, morphology, and geology of these craters both in aggregate and, for some craters, in more detail [1,2]. We find that (1) the spatial distribution of craters is highly uniform; (2) the size-density distribution of craters with diameters ≥35 km is consistent with a "production" population having a surprisingly young age of about 0.5 Ga (based on the estimated population of Venus-crossing asteroids); (3) the spectrum of crater modification differs greatly from that on other planets: 62% of all craters are pristine, only 4% volcanically embayed, and the remainder affected by tectonism, but none are severely and progressively depleted based on size-density distribution extrapolated from larger craters; (4) large craters have a progression of morphologies generally similar to those on other planets, but small craters are typically irregular or multiple rather than bowl shaped; (5) diffuse radar-bright or -dark features surround some craters, and about 370 similar diffuse "splotches" with no central crater are observed whose size-density distribution is similar to that of small craters; (6) other features unique to Venus include radar-bright or -dark parabolic arcs opening westward [3] and extensive outflows originating in crater ejecta.

The first three observations are entirely unexpected. We interpret them as indicating that the planet's cratering record was erased by a global volcanic resurfacing event or events, the latest about 0.5 Ga, after which volcanic activity declined (but did not cease entirely) and a new crater population began accumulating. Several members of the Magellan team have proposed variations of an equilibrium resurfacing model, which requires equilibrium between the rates of volcanism and impact cratering to account for the uniform and spatially random global crater distribution [4–7]. However, the geologic evidence and new Monte Carlo computer simulations of resurfacing using the observed crater distribution totally rule out equilibrium with less-than-global volcanic resurfacing events. Convective thermal-evolution models support our interpretation of a global volcanic resurfacing of the planet about 0.5 Ga [8–11].

Fig. 1. Map in sinusoidal equal-area projection showing 840 impact craters on 89% of Venus. Basemap is continuous-tone Magellan altimetry (white-highest, black-lowest). Areas of planet not covered through orbit 2578 shown inside white lines.

The dense atmosphere of Venus has strongly affected the production of craters. Large impactors have been relatively unaffected, intermediate-sized ones have been fragmented and have produced overlapping or multiple craters, a narrow size range (few hundreds of meters in diameter) has produced shock-induced "splotches" but no craters, and the smallest bodies have had no observable effect on the surface. The number of craters eliminated by the "atmospheric filter" is enormous—about 98% of the craters between 2 and 35 km in diameter that Magellan could have observed on a hypothetical airless Venus. Unique crater-related surface features such as parabolas and outflow deposits demonstrate the roles of Venus' high atmospheric density and temperature in modifying the crater-formation process, through interactions as yet poorly understood.

Impact craters have been tentatively classified as six morphologic types largely related to size: those having multiple rings, double rings, central peaks, structureless floors, and those that are irregular or multiple. In part, the sequence of morphologies of venusian craters with increasing diameters is similar to that of craters on other planetary bodies.

Six multiring craters and 41 double-ring craters have been observed on Venus. The onset diameter to ring craters from central-peak craters is about 40 km, compared with 140, 85, 45, and <25 km on the Moon, Mercury, Mars, and Earth [12], respectively. For most of the terrestrial planets—now including Venus—the onset diameter from central-peak craters to double-ring craters shows a general inverse relationship with gravity [13–15], although effective viscosity and other target properties may also be important [15]. For Mars, the onset diameter is about half as large as would be expected on the basis of gravity considerations alone, indicating the importance of possible target characteristics unique to Mars [16].

Adjacent ring-interval ratios on Venus generally fall in the same three groupings as those reported for double- and multiring basins (1.4–1.5 and 2.0) and protobasins (3.3) on the Moon, Mercury, and Mars [17–20]. Mean ring ratios for double- and multiring craters on Venus were found to change as a function of rim diameter (Fig. 2). Similar but respectively less well defined, inverse relationships between ring ratio and basin diameter have also been observed on Mercury, Mars, and the Moon [20]. For venusian double-ring craters ≤60 km in diameter, the ring-spacing mean ratio is 2.8 ± 1.0, a value approaching that of protobasins on the other terrestrial planets. On Venus, however, no well-defined protobasins with both central peaks and incipient inner rings have been observed. For double-ring craters ≥60 km in diameter, the mean ring ratio is 2.05 ± 0.33, the most typical spacing for double- and multiringed basins on the other terrestrial planets. The six multiring craters observed on Venus have a mean ring-spacing ratio for adjacent rings of 1.52 ± 0.2. The transition diameters from simple to complex craters, central-peak to double-ring craters, and double- to multiring craters on Venus are better defined than on any of the other terrestrial planets. Thus they should be extremely useful in further understanding the processes of formation of these structures on all solid bodies in the solar system.

The three largest impact structures on Venus (Mead, Meitner, and Isabella) have a ring outside what is inferred to have been the transient cavity. These rings are suspected to be fault scarps forming the outer boundary of downdropped and inward-rotated "megaterraces" created at some late stage, possibly after deposition of the ejecta.

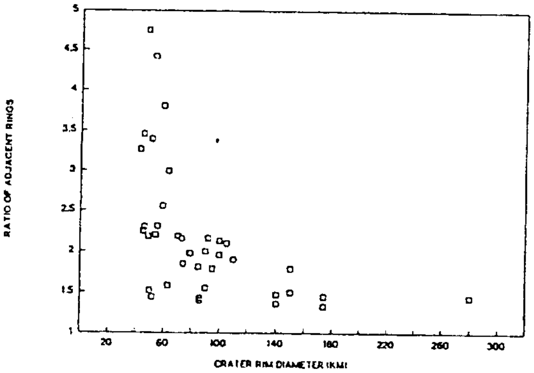

Fig. 2.

The depth/diameter ratios for fresh, large craters on Venus may be more akin to those on the Moon, Mercury, and Mars than to those on Earth. The reasons for this are presently unclear.

Lobate features partly surrounding a crater with a strong backscatter emanate from 43% of the impact sites on Venus. The flowlike features (outflows) extend tens or hundreds of kilometers from their crater rims and have a morphology consistent with a low-viscosity material. There is strong evidence that the outflows are composed primarily of impact melt, although the mechanism of their emplacement is not clearly understood. High temperatures and pressures of target rocks on Venus allow more melt to be produced than on the cooler terrestrial planets, because lower shock pressures are required for melting [21]. In addition, Venus' high atmospheric temperature may allow the melt to remain molten longer by about an order of magnitude than on the cooler planets [22]. The percentage of impact craters with outflows increases with increasing crater diameter. However, three of the largest craters, Mead, Kelenova, and Meitner, have no recognized outflows. Outflow occurrence is also correlative with impact incidence angle and the degree of asymmetry in the ejecta. Of craters with asymmetric ejecta, those with outflows are more numerous than those without above about 15 km in diameter. Forty-eight percent of asymmetric-ejecta craters have outflows, compared with only 34% of those with symmetric ejecta.

"Splotches" or "shadows" (features with low-backscatter centers surrounded by higher backscatter) are common on the surface of Venus. They range in diameter from 10 to 70 km with a mean of about 20 km. A variety of arguments suggest that if the splotches were produced by stony asteroidal objects traveling about 10 km/s, the bolides would have been several hundred meters in diameter with energies of order 10^{18-19}j (10^{25-26} ergs or roughly 100 megatons). A small fraction of the bolides that would have produced 2–10-km craters on an airless Venus (but were filtered in the atmosphere) are thought to have produced the observed splotches. Bolides <100 m in diameter are not thought to affect the surface.

Heavily fractured craters and lava-embayed craters are found to have higher than average densities along the major fracture belts and rifted uplands connecting Aphrodite Terra and Atla, Beta, Themis, and Phoebe Regiones [23], thus providing physical evidence for recent (or ongoing) low-level volcanic and tectonic activity in these regions.

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N93-14370 3

ATMOSPHERIC EFFECTS ON CRATER GROWTH ON VENUS.

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Laboratory experiments allow examining the consequences of complex processes operating over a wide range of scales (both temporal and spatial) and frequently reveal effects that are obvious only in hindsight. Even though all processes may not scale directly, isolation of the controlling variables allows assessing first-order effects through analytical approximations. This approach can be illustrated by the systematic sequence of ballistic ejection [1], the response of an atmosphere to a strong energy source [2], the scaling of ejecta thickness [3], and the role of secondary cratering [4]. Here it is proposed that the effects of atmospheric pressure and density on crater growth (hence, scaling) observed in laboratory experiments [5,6] has particular relevance for craters on Venus.

Crater Growth: Both static (ambient) and dynamic (viscous drag) pressure reduce cratering efficiency (displaced mass/impactor mass) for craters produced in particulate target [5]. Target strength (i.e., internal angle of friction, ϕ) is shown to have minimal effect; in fact, similar reduction in cratering efficiency occurs for craters formed in compacted pumice ($\phi \sim 85°$), loose sand ($\phi \sim 33°$), and low-density microspheres ($\phi < 20°$). Rather, it is found that particle size plays the most important role: The smaller the constituent particle sizes, the greater the reduction in cratering efficiency. This result can be interpreted as the effect of aerodynamic drag acting on both individual particles and the ensemble of these particles comprising the ejecta curtain. By using a helium atmosphere (hence low density at high pressure), the role of static pressure can be separated from the role of dynamic pressure as clearly illustrated by the contrasting evolution of the ejecta curtain [7].

The principal effect of internal angle of friction is in the preservation of the transient crater. Craters in fine sand and microspheres with low internal cohesion collapse, whereas craters in compacted pumice retain their shape. Nevertheless, crater growth and the evolution of the ejecta curtain during growth are essentially the same for the same value of the ratio of drag to gravitational forces. The role of the atmosphere is to choke off crater growth. Since craters first grow downward and then outward [8,9], arresting