RECOGNITION OF DEGRADED IMPACT CRATERS ON EARTH, MOON AND TITAN.

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Introduction: Impact craters are nature's gift to planetary scientists. Impact craters have formed throughout the entire 4.5 billion years of solar system history, so simply counting their numbers provides information on the ages of planetary surfaces. The physics of crater formation is complex, but results in landforms with remarakbly consistent morphology, taking into account variations in projectile mass and velocity, and planetary gravity and crustal properties. Because impact craters have initially known morphologies, the appearance of a crater provides clues to the geological processes that have effected it since its formation. But the multitude of processes that modify impact craters over time also make their identification uncertain. In this paper I will review the initial morphologies of impact craters, and examine how those shapes are changed when acted on by different types of geologic processes.

Initial Morphologies of Impact Craters: Geologists have learned to understand impact craters by field work within terrestrial impact structures, mathematical modeling of the impact process, and especially by remote sensing study of craters on Earth's Moon. The Moon is an ideal laboratory to investigate craters because very low rates of erosion preserve craters of all sizes in nearly pristine conditons for up to a billion years. All impact craters result from hyper-velocity collisions, with the resulting crater size and morphology depending on the total impact energy. The following examples are for the Moon.

Simple craters. Lunar craters with diameters less than about 15 km have simple conical shapes, looking like they were turned out on a lathe. From an elevated rim a 20-30° scree slope leads to a small flat floor veneered with impact melt and boulders that tumbled down the walls. A bright nimbus of pulverized material surrounds the crater, and thin ribbons of ejecta and secondary craters (bright rays) churned up by the impact radiate away a distance of about 10 times the crater diameter.

Complex craters. On the Moon craters larger than about 15 km have more complex interiors. Central peaks appear on the crater floor, with peak size and complexity increasing with crater diameter. The walls of complex craters have collapsed, creating both mounds of debris along the edges of crater floors, and broad downdropped terraces that circle the floor. Ray systems and secondary craters are much more extensive, some extending nearly a 1000 km. Impact melt is often splashed outside the crater rim.

Multi-ring basins. At diameters of 300-400 km central peaks expand into an inner ring, about 50% of the diameter of the main rim. These are two ring basins. At larger diameters three or more rings occur, forming a multi-ring basin. Mare lavas typically flood the interiors of basins on the lunar nearside. On the farside where the crust is thicker, mare lavas are rare. A major difference between complex craters and basins is the colossal increase in the amount of ejecta that is thrown across the lunar surface. Ejecta thickness thins from a few kilometer near the basin rim to discontinuous patches hundres of kilometers away. Basin secondary craters may be up to 20-30 km in diameter.

Factors modifying crater formational morphologies. The simple, complex and basin morphologies that are well documented on the Moon are also seen on other planets and moons, but differences occur due most importantly to the gravity of the target world. The simple to complex transition that occurs at crater diameters of about 15 km on the Moon happens at about 3 km on Earth. On small moons and asteroids there are often no complex craters because the transition occurs at diameters larger than the objects size.

Modifications of Initial Morphologies:

Impact modifications. As soon as craters form they start to be modified. Seismic shaking from subsequent nearby impacts cause more down slope mass movement, ultimately smoothing out rim terraces and slump mounds. Impacts at various distances deposit debris on craters, shallowing their depths, burying central peaks, and covering rays and secondary craters. Craters that impact on top of others either totally destroy preexisting ones or take bites out of their rims and sometimes push crumpled piles of displaced material on to their floors.

Volcanic modifications. On the Moon, the only other important process for modifying impact craters is volcanism. Craters formed before the end of the mare epoch may be surrounded by later lavas, burying the rays and other exterior crater dposits. If the lava thickness is great enough, lavas may have cascaded over the crater rim, filling the crater floor (and covering the terraces and peaks), and perhaps completely inundating the crater, leaving little evidence for it existence.

Sedimentary infilling. On Earth, Mars and probably Titan, atmospheres transport sediments that may become trapped in craters, filling them in. On Mars, some ancient deposits are being eroded away, revealing old, buried craters.

Sand movement modifications. Active sand dunes are transitory landforms so that small craters formed on them may be rapidly distorted, filled in or covered over. A number of large craters on Titan are traversed by fields of longitudinal dunes. In some cases the dunes deviate around low rims, but for other craters the rims must be very low for the dunes don't deviate as they cross putative craters that can only be suggestively indicated by circular bright patches seen between the dunes.

Ocean modifications. The Earth and Titan are unique in the solar system for being the only places where liquids pond on surfaces, making oceans and lakes. Impacts into such liquids would not create a crater unless the liquid was relatively shallow. Widespread ocean waves would devastate nearby terrains. On Titan at least one impact crater has been flooded by liquids with only its circular rim remaining; presumably the same happened on Earth.

Fluvial erosion. Flowing liquids can be remarkably abrasive, cutting channels through even hard rocks. On Earth, Mars and Titan numerous impact craters have rims that have been cut through by rivers, with deposition of riverine sediments.

Ice modifications. The greatest modification that ice can do is to shear off topography and fill depressions as ice sheets flow across terrains. Non-flowing ice can bury earlier impacts, removing them from view unless climate warming occurs to melt the ice.

Tectonic modifications. The Sudbury impact basin on Earth is 62 km long but only 30 km wide. It was formed as a circular structure, but during its 1.8 billion year lifetime multiple crustal movements squeezed it into an ellipse. Other terrestrial craters were probably completely removed by plate tectonics subduction. On Mercury a global reduction in planetary radius created large folds that have squeezed some craters, but not as extensively as at Sudbury.

Sequence of Degradation: No matter what the process of degradation the thinnest and shallowest impact features disappear first. Impact melt sheets, crater rays and secondary craters are the first evidences of impact to be removed. Then infilling of the crater by ejecta, volcanism or windblow materials gradually removes the crater cavity, as the rim is also worn down. Often the only evidence of even a large earlier crater is short rim ridges that define a circle. On the Moon, some ancient basins that have been completely covered by mare lavas can be detected as shallow depressions due to compaction of their thick lava fill.

In general, we model degradation as a slow, long continuing process. But perhaps the most important modification events are very rapid, even for large areas. Two major examples are large volcanic inundations such as fill lunar basins, and especially the formation of large basins themselves, whose massive blankets of ejecta instantly destroy, cover and gouge hundreds of pre-existing craters over a wide area.

Identifying Heavily Modified Impact Craters:

Current investigation of Saturn's moon Titan has revealed only a handful of confirmed impact craters and a few dozen possible ones. Since there is no possibility of conducting field work, the correct identification of impact craters must rest on their morphology. That is, in fact, the same situation for suspect structures detected on satellite imagery of inaccessible parts of Earth. The most important characteristic of an impact crater is a circular outline. On the Moon there are no significant processes other than impact that make multi-kilometer scale circular structures so an impact origin can be confidently ascribed to almost any relict circular landform there. But on Earth, many other processes can create circular landforms, including volanism, erosion of batholiths, subsidence of large sedimentary basins, etc. Titan has such a complex and poorly understood geology that it may have additional unappreciated processes that make circular features, so to confidently interpret an eroded feature as impact requires more evidence than just shape. The best additional morphological element indicative of impact is a relict central peak. And the occurance of some characteristics can argue against impact. For example, if flow-like materials are near a suspect crater, or if there is a cluster of craters, a volcanic origin must also be considered. Without higher resolution we may never be able to identify crater origins with certainty.