VOLCANICALLY MODIFIED IMPACT CRATERS (Part 1): WHAT SHOULD WE EXPECT ON EARTH?

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Overview: Although no volcanically-modified impact structures are presently recognized on Earth, the number and broad distribution of active terrestrial volcanoes strongly suggests that, over time, volcanism should have affected some number of terrestrial impact sites. One simple estimate places this number at ~2 craters (D>5 km) every 10 million years.[1] Several factors could modify the likelihood and nature of crater-magma interactions on Earth, however. First, regional variations in magma and crustal properties can significantly affect the nature of crater modification. Second, terrestrial sedimentation can probably ward a crater from volcanic modification in less than 10-20 m.y. Third, regional variations in erosion can also affect the likelihood of preserving a modified crater. Thus, the likelihood and nature of volcanic crater modification on Earth is likely to be strongly dependent on the regional setting and local rates of erosion/deposition.

Introduction: The lack of terrestrial examples complicates our efforts to understand how impact craters interact with later magmas. Some models have been developed for crater-magma interactions,[2,3,4] but the critical factors and interactions in these models mostly lie below the surface, and thus are only loosely constrained by the available image data. To complicate matters, there are also indications that the nature of magma-crater interaction may vary with planetary setting.[3] Still, the existing models for magmatic crater modification provide the best basis with which to assess the apparent lack of volcanically modified craters on Earth; and the goals of this paper are (1) to explore the factors which might influence the development and preservation of such craters on Earth, and (2) to discuss how these factors might vary with location and setting.

Modes of Crater Modification: The planetary record exhibits three basic styles of volcanic crater modification: passive embayment, structurally controlled interior flooding, and structurally controlled, crater-hosted intrusions. The first of these styles, embayment, is the simplest, requiring only that an eruption of lavas somewhere outside a crater flow onto or into the impact structure. This style is probably the most commonly recognized, but it also requires the least degree of interaction between an impact feature and later magmatism. The second style, interior flooding, reflects the eruption of lavas directly into a crater's interior, and it requires a diversion at depth of crustal magmas into the network of faults and fractures resulting from crater formation. Such flooding is clearly visible in several mare-floored craters on the Moon (e.g. Plato, Tsiolkovsky, and the mare basins), and it also appears to be a major mode of crater modification on Venus.[5] Finally, crater-hosted intrusions require the greatest degree of magma-crater interactions. Here, magmas seem to be diverted into a crater's structure and then trapped in a breccia-defined zone of neutral buoyancy beneath the crater floor.[2,4] With continued magma injections, this intrusion then inflates into a large, laccolith-like body, fracturing the crater floor and in some cases uplifting it by hundreds to thousands of meters.[2] Such floor-fractured craters are best preserved on the Moon [e.g., Haldane, Posidonius, Gassendi], but similar structures have also been identified on Mars and Venus.[3,6]

Controlling Factors: The two biggest factors affecting the likelihood of magma-crater interactions are, of course, the size of an impact crater and the frequency of regional volcanism around it. Bigger craters make bigger targets, and greater fluxes provide more opportunities for an interaction. Consequently, any estimation of the potential importance of volcanic crater modification on Earth needs to account for both regional variations in volcanism and the inverse relation between crater size and crater frequency.[1]

The detailed nature of magma-crater interactions, however, is likely to depend on such factors as the regional magmastatic head, the nature of regional magma plumbing, the level(s) at which magmas can enter the crater structure, and the relative buoyancy of magmas inside and outside of the crater structure. As a result, many variables should affect how a crater will interact with nearby magmas. Some very likely candidates include:

- the relative densities of the magma, the bulk crust, and the breccia lens;
- the depth and extent of fracturing around the crater; the size and depth of the crater cavity;
- the depth of any local or regional magma reservoirs and neutral buoyancy zones,
- and of course such magma properties as viscosity, explosivity, and supply.

In the planetary record, such variations in magmatic and crustal variables are probably responsible for most of the observed changes in the style of crater modification with planetary setting[3] (e.g., lunar mare vs highlands, Moon vs Mars, Moon vs Venus). On the Earth, similar variations may also occur on a regional scale, especially between oceanic crust and magmatic arc settings. Nevertheless, we must also recognize that, over time, weathering, erosion, and sedimentation can affect several of the major variables as well. Consequently, in addition to considering simple spatial variations in the probability and nature of volcanic crater modification on Earth, we also need to consider the possibility of temporal variations in the vulnerability and response of craters to magmatic activity.

Of the various possible temporal processes, sedimentation probably has the greatest effect. As sediments fill a crater cavity, they reduce the topographic head values favoring magma migration into that crater. They also act to compress and consolidate fractures and open pore space in the impact breccias, thereby reducing their susceptibility to magmatic intrusion and the stability of any magmatic intrusions that do occur. Eventually, when a crater has been totally infilled, its susceptibility to volcanic modification should be essentially eliminated. Any subsequent surface eruptions would only bury the structure further, without significantly encountering the crater at all. Further, while the sediments and consolidated breccias might still comprise a localized low density zone, the effect of sediment loading should have minimized the size and stability of any magmatic neutral buoyancy regimes remaining in the structure.

Erosion can also affect terrestrial impact sites to a greater degree than most planetary craters, but it probably has a much smaller effect on their susceptibility to volcanic modification. First, while erosion can eventually remove an impact structure from the geologic record, it does so very slowly in comparison to crater infilling. Based on the values in [7], it takes some 30 to 270 m.y. to remove the topographic signature of a 20 km crater, and much greater lengths of time to remove the remaining impact structures that lie below the crater floor. In contrast, the rates of crater filling observed at Meteor Crater[8] and Kärdla[9] indicate that a comparably sized crater can be infilled in approximately 1 to 16 m.y. Note that erosion is not completely insignificant, however. First, even after a crater is infilled, erosion will still act to permanently remove it from the geologic record. Second, even during infilling, erosion can act to reduce or locally eliminate the crater rim, thereby increasing the vulnerability of a crater to embayment or infilling by a nearby volcanic vent.

Implications for Earth: Terrestrial geologic settings thus exert two nearly independent sets of controls on volcanic crater modification. First, the likelihood of crater-modifying volcanism should be directly affected by regional variations in the properties, nature and frequency of magmatic activity. Continental cratons should have nearly negligible rates of magmatic crater modification, oceanic spreading zones or hotspots could have very high likelihoods for crater modification, and magmatic arcs and continental rifts probably have more intermediate rates of crater-associated volcanism.[1] Second, unlike craters in other planetary environments, terrestrial craters seem to have a limited window of vulnerability to volcanic modification. The exact length of this window will vary with local erosion and sedimentation rates, but it is unlikely to exceed a few tens of million years. In many cases, it may only last for a few hundred thousand or million years. Indeed, in cases like the Chesapeake Bay crater, impact-induced tsunamis or other factors may even fill the crater immediately,[10] and essentially preclude later volcanic modification.

On Earth, therefore, it seems that the development of crater-modifying volcanism is likely to require a relatively fresh crater, and thus crater formation in the immediate vicinity of an active volcano. A companion abstract[11] presents a preliminary assessment of the likelihood for volcanic crater modification in different terrestrial settings given this precondition. It should be noted, however, that this condition is itself significantly different from the examples observed elsewhere in the planetary record. There, volcanic crater modification nearly always has resulted from a distinctly later episode of volcanism. On Earth, the arguments above suggest that such episodes of delayed, crater-centered volcanism may be extremely rare, and that the more common case on the Earth may involve some form of impact-triggered magmatism.

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