Lunar mare volcanism

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Abstract

Here we report on new crater size-frequency distribution data for 139 spectrally and morphologically defined basalt units which are exposed in 6 nearside impact basins (Australe, Tranquillitatis, Humboldtianum, Humorum, Serenitatis, and Imbrium). We also present our results on the flux of lunar mare volcanism, the relationship between titanium concentration and age of a basalt unit, and the influence of crustal thickness on the eruption of a basalt onto the lunar surface.

Introduction

Lunar mare basalts cover about 17% of the lunar surface but represent only 1% of the volume of the lunar crust [1]. Despite the long tradition of lunar exploration numerous questions concerning the lunar mare basalt volcanism are still unanswered. Here we make contributions to answer some of these questions: When did basalt volcanism start and when did it end? Was lunar volcanism continously active or do we see periods with higher activity? What is the flux of lunar volcanism? Is there a trend in the spatial distribution of basalt ages? Is there a relation between the formation of an impact basin and the occurrence of basalt eruptions? What influence has crustal thickness on these eruptions? And finally, is the concentration of titanium related to the age of a basalt? Our approach and the data base for our investigation is described elsewhere [2,3].

Results and Conclusions

On the basis of analysis of eastern and central nearside mare basins we find:

1. <u>Range of Ages:</u>

Our data indicate that lunar volcanism was active for at least 2.0 b.y., starting at about 4.0 b.y. and ceasing at 2.0 b.y. Numerous dark halo craters in the Australe region suggest the presence of a cryptomare and therefore volcanism must have been already active, at least locally, before the majority of basins were formed in pre-Nectarian and Nectarian times. Since cryptomare cannot be dated with crater size-frequency distribution measurements directly, it is not possible to derive ages for the very first beginning of lunar volcanism. The basalts that could be dated were erupted primarily in the Imbrian Period from 3.4-3.8 b.y. Only a minor number of basalts erupted during the Eratosthenian period, and basalts of Copernican age were not found in any of the investigated basins. *Schulz & Spudis* [4] suggest that the basin filling volcanism started at about 4.0 b.y. ago and was terminated at about 1.0 b.y. ago. These youngest basalts which are exposed in the Oceanus Procellarum embay the Copernican crater Lichtenberg but were not investigated in this study. The increase of lunar volcanic activity was relatively fast, reaching the maximum number of eruptions only 300 m.y. after the onset of basin filling volcanism. We see a maximum at 3.6-3.7 b.y., and a smooth decline of eruptions from 3.6 to 3.2 b.y. A second maximum appears at 2.9-3.0 b.y. Therefore, volcanism was not continously active but clearly had periods of high activity, separated by periods of lesser activity. In the youngest basins, Serenitatis and Imbrium, we see a longer period of active basin filling volcanism (1.5-1.6 b.y.) which is 500 m.y. longer than in the Australe and Humorum and even ~1.0 b.y. longer than in Tranquillitatis and Humboldtianum. Regional dark mantle deposits exhibit ages in the range of 3.6-3.8 b.y. and are not products of a young volcanism.

2. <u>Spatial distribution of ages:</u>

We investigated basalts in six lunar impact basins which are distributed over the entire lunar nearside, therefore allowing us to study large-scale differences in age and geochemistry between eastern and western basalts. *Soderblom et al.* [5] reported such differences in age, chemistry, and magnetism between basalts of eastern and western basins. According to this work, eastern basalts are in general older, more magnetized and less radioactive than their western counterparts. Calculating the mean age of all basalts within a basin, we see that eastern basins in fact exhibit older basalts compared to the western basins. Therefore, volcanism was active longer in the western parts of the nearside than in the eastern regions. However, this trend is not very pronounced in our data. If we further look at the age/frequency distributions in the basins we see that basin formation and volcanism are overlapping geologic processes. That means that basin filling volcanism already has started in some basins before the end of the heavy lunar bombardment at 3.84 b.y. (Orientale event).

3. <u>Relation of basalt ages to basin formation:</u>

Mare volcanism started within ~ 100 m.y. of basin formation. However, even if 100 m.y. are a comparably short period of time in lunar history, it is long in a terrestrial sense. From comparative planetology we induce that basin formation and basalt eruption are not directly linked as it is hard to imagine that the cause and effect could differ in age by 100 m.y. An independent argument against the idea that basin formation and volcanic activity are closely and causally related is that lunar volcanism was already active before the basin formation as numerous cryptomare indicate. Also, our data show that the basin filling volcanism lasted for 0.6-1.6 b.y., depending on the basin. If the assumption would be correct that magma only can reach the surface along impact-produced fractures, we consequently would have to assume that these fractures have to remain open for the period of active volcanism. As it seems highly unlikely that fractures can stay open for magma ascent for up to 1.6 b.y., we conclude that volcanism and basin formation and/or tectonics are not directly related.

4. Trends in titanium concentrations:

Our investigation shows that TiO_2-rich basalts tend to be older than TiO_2-poor basalts and are more often exposed in the eastern basins. Thus our results are consistent with the trend found in the returned samples with radiometric older basalts being generally richer in titanium than younger basalts. It is also obvious that with decreasing basin age the variety of ages and compositions increases. However, the most important result of our investigation is that the TiO_2-contents and ages of the basalts within each investigated basin are not correlated. We see that TiO_2-rich and TiO_2-poor basalts can erupt simultanously in different locations within the basin. In each single basin the TiO_2-concentrations seem to vary independently from the ages of the units. This probably suggests a highly heterogenious mantle or source region. We further conclude that petrogenetic models which are able to explain only one titanium-rich period at the beginning of the volcanism have to be revised.

5. Volume estimates and flux:

Our volume estimates are based on the assumption that a single basalt flow unit is ~10 m thick. Keeping this in mind we see that the main volcanic activity occured in the Imbrian Period and was at least larger by a factor of 3.5 between 3.4 and 3.7 b.y. compared to the period between 2.9 and 3.4 b.y. Therefore mare volcanism was not equaly active over long periods of time but peaked in the Imbrium Period. We calculated the mean volume for a single basalt flow to be less than 200 km^3. According to Blake [6] such a volume would correspond to a hypothetical spherical reservoir of about 50 km in diameter. The small diameters of the reservoirs in combination with heterogeneities in age and TiO_2 suggest that the basins were filled with a large number of moderate-scale eruptions rather than small number of very large-scale eruptions. From our volume estimates we conclude that large basins like the Imbrium basin, were filled by several thousands of eruptions. We also conclude that lunar mare volcanism is analogous to terrestrial flood basalts and is derived from deep seated reservoirs rather than being erupted from shallow reservoirs [8]. This concept is supported by the absence of large shield volcanoes and calderas which are usually located above such shallow reservoirs [9].

6. Crustal thickness:

Making use of the Clementine data for the crustal thickness [7] we found that the maximum thickness of the crust where basalts occur is 50-60 km, consistent with results from Yingst & Head [8]. This implies that crustal thickness may be a limiting factor for the eruption of lunar basalts onto the surface. Differences in crustal thickness can explain the sparsity of mare basalts on the lunar farside. Ascending magma preferentially extrudes to the surface where the crust is thin, i.e. the lunar nearside. On the farside the magma stalls and cools in dikes before reaching the surface. Also, thickening of the crust with a related compressional stress field within the crust or sinking of the buoyancy trap over time makes it more and more difficult for dikes to extrude to the surface. Consequently, we found that the youngest basalts are often exposed in or near areas with relatively thinnest crust. We conclude that in areas with a thinner crust dikes still could reach the surface even later in lunar history whereas in other regions the dikes stalled in the crust and couldn't propagate to the surface. This result is consistent with the predictions of the model by *Head & Wilson* [9].

7. Future work:

So far we investigated the central and eastern mare basalts and we plan to incorporate and study the western maria as the next step of our analysis. Especially the basalts near crater Lichtenberg which are supposed to be the very youngest basalts are of interest in order to define the end of lunar volcanism. We also plan to make use of high resolution Clementine color data in order to improve the definition of spectrally and morphologically uniform units and to test whether geochemical differentiation within long basalt flows is observable. Precise estimates of the flux, i.e. the volume of erupted basalts over time are a challenging problem. Combining the height of a flow front [10] with the areal extent of a basalt flow, which can be easily measured, will allow high precision calculations of single flow volumes.We seek to get such volume estimates from stereo processing of digitized high-resolution images of the Apollo metric camera.

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