THE FILLING OF THE LUNAR MARE BASINS*

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Abstract. The surface of each mare is not a homogeneous geomorphological unit, but displays a variety of geomorphologies. The interpretation of this phenomenon depends on the assumptions one is willing to accept. If the filling of the mare basins occurred relatively slowly, then the geomorphologies are a time function and indicate a time span of not less than three quarters of a billion years between the beginning and the end of the mare filling activity. If, on the other hand, the maria were filled by lava immediately after the basin formation and remained liquid for a relatively long time during which the extensive bombardment stopped, then the different morphologies indicate vagaries in the final stages of the bombardment and of the cooling history.

1. Preamble

It may be said that, after the discovery of the lunar craters, the discovery of the lunar mascons marks the most important landmark in our progress of increasing knowledge of the Earth's Moon. The mascons are basic features of our Moon and should present definitive boundary conditions in any theory of lunar origin and evolution.

At the risk of being presumptious, I feel that Professor Urey would subscribe to the above statements. At the several meetings and lunch-table discussions in which I had the pleasure of seeing and hearing Professor Urey, I never saw him fail to stress the importance of the mascons.

The mascons are, indeed, a lunar characteristic difficult to explain. The paradox of a Moon, sufficiently hot to produce lava flows but sufficiently cold to have the rigidity of holding the mascons, is a stumbling block for many theories. Like all paradoxes, undoubtedly it will be shown that it is based on incorrect premises. For a complete discussion of this subject, the reader is referred to Urey and MacDonald (1971).

The purpose of this paper is to present a small piece of information that is likely to be related with the problem of the mascons. It will be shown that the present surfaces of the lunar maria have not the same morphology everywhere. Also, within each mare, we find surfaces of different morphologies. A possible explanation of this phenomenon is that morphology is a function of the age of the surface. If this is the case, it means that a mare surface is not isochronous, but composed of units of different ages. If we accept the Apollo radiometric ages as being the ages of the

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landing sites' surfaces and we extrapolate, then the time difference between the youngest and oldest surface is not less than three quarters of a billion (10^9) years and probably more. On the other hand, Professor Urey favors the theory that the mare basins were filled immediately after the collision (Urey and MacDonald, 1971, p. 222) and the filling material stayed fluid for as long as 100000 yr, during which time the intense bombardment stopped (op. cit., p. 225). If this is the case, then the different morphologies represent different stages of solidification of the surface. The age relationship still exists, but becomes squeezed into the 100000 yr in question.

2. Statistical Geomorphology of a Cratered Surface

A remotely performed description of the geomorphology of the lunar surface is based almost exclusively on two parameters: crater number density (number of craters per unit area) and degree of erosion displayed by the craters. A function has been previously developed which relates the number density of craters to the number of these craters which show essentially no erosion. The value of this function at different locations was defined as the geomorphic index of that location. It is believed that the geomorphic index is a better representative of an area than crater number density or erosional stage taken separately, because the index is the result of two independently measured parameters.

A complete description of the method was given in Ronca (1972) and only a brief summary will be given here. The University of Arizona catalog (Arthur *et al.*, 1963, 1964, 1965, 1966) classifies lunar craters on a scale of 1 to 5 on the basis of their conditions. Very sharp and fresh looking craters are classified as 1, craters with blurred rims as 2, craters with extensively broken rims as 3. Craters usually described as ruins are classified as 4, and ghost craters as 5. This classification was maintained in the description of new craters shown by the Orbiter photographs and not included in the telescope-based Arizona catalog. As will be shown later, the calculation of the geomorphic index necessitates the determination of craters of class 1, the fresh looking craters, and of craters of class 4 and 5, the ghost craters, and not of intermediate classes, thus facilitating the task.

No age relationship is intended in the definition of these classes. Intuitively, however, it appears possible that the classes may represent an age sequence. It is possible to perform a test to check the hypothesis that the classes do indeed represent an age sequence. If only those craters larger than a few kilometers are considered (for this size crater saturation is not reached), then, the older a lunar surface is, the more highly cratered it will be. If the classes are a time sequence, then class-5 craters should be common in highly cratered areas, while class-1 craters should be common in areas of low crater densities. This is not actually the case. If we plot the percentage of class-5 craters versus the number of craters per unit area for the craters of the lunar near-side (excluding the limbs) larger than 3.5 km in diameter, we can see that the percentage of craters which are of class-5 increases to a maximum very quickly for areas of low-intermediate crater densities and finally decreases for areas of high crater densities. Contrary to the hypothesis, areas of high crater density are relatively low in craters of class 5.

We can make a similar test excluding craters of class 4 and 5. If only craters of class 1, 2, and 3 are considered, then the results fit the hypothesis. The percentage of craters which are of class 3 is low in areas of low crater density and increases monotonically with the crater density. These relationships can be interpreted to indicate that classes 1, 2, and 3 are a time sequence, while classes 4 and 5 are not.

The next step is to check this interpretation by observing a large number of individual craters. For brevity's sake, only the conclusions will be presented here. They are as follows: All the erosional processes operating on lunar craters can be grouped in two categories. The first category produces a degradation by erosion through time from class 1 to class 3, and in some cases, class 4. This can be called the *continuous degradation sequence*. The second category of erosional agents is responsible for the conditions of craters of class 5 and of some of class 4. This is not a continuous process, as it can happen to craters belonging to any class. This category will be called the *discontinuous degradation*. It can also cause rejuvenation, that is, the complete disappearance of craters. A detailed presentation of the above was published in Ronca and Green (1970).

The erosional agents which cause the continuous degradation sequence operate more or less continuously through time (not necessarily at the same rate). Micrometeoritic impact, possible electrostatic erosion, and space weathering are likely to be the dominant agents, accompanied by other processes, such as terrace collapse, isostatic recovery and perhaps large-scale tectonics. Specific details of the continuous modification of a crater after its formation have been described by Pike (1967), Ross (1968), Neukum and Dietzel (1971).

The erosional agents which cause the discontinuous process are primarily two. Filling by mare material leaving only a rim or part of a rim above the surface is one. The other is ballistic sedimentation and destruction by seismic waves created by large impacts.

It is evident that if we are interested in a time-related parameter, we must concentrate on the continuous degradation sequence. Craters of class 4 and 5 are, in the great majority, relics of a previous chapter of the geomorphic history of that particular area.

We are now ready to define the geomorphic index. It can be shown (Ronca and Green, 1970) that if we plot the logarithm of the percentage of craters of class 1 versus the logarithm of the number of craters per unit area for the craters of the near side larger than 3.5 km in diameter, the data distribute themselves along a line of slope -1. The following model fits this observation. Let us start with a newly formed surface. For a very short time, it will be without any large crater. Soon impacts will begin to create more and more craters. At first, all craters will be of class 1, but soon the earliest craters will become class 2. If no large crater and no mare flooding of significance occur to produce any discontinuous degradation, each crater will proceed from class 1 to class 2 and finally to class 3 (a few craters will reach class 4). A newly formed crater will remain in class 1 during the length of time, t, necessary for the crater density of the area to increase by a number, K, of craters per unit area [note that if the impact flux varies through the lunar geological time, (Hartmann 1965, 1966) this length of time, t, will not be the same through geologic time]. It can be easily proven that if this model is correct, then the data must distribute themselves on a logarithmic plot on a line of slope -1, for any value of K. This is actually the case, as discussed above. The geomorphic index is defined as the position, in arbitrary unit, on the line of slope -1.

The geomorphic index of a lunar area is more reliable than the crater density or the average crater class because it combines two independently measured parameters – crater density and crater class. Although the combination of these two parameters could be obtained more simply by calculating their ratios, this procedure would not take into account the scattering of data. The calculation of the geomorphic index is able to eliminate the scattering not in an arbitrary statistical fashion, but as a direct result of a proposed geological model.

An independent test of the significance of the geomorphic index was made by measuring the index of the upper surface of defined rock-stratigraphic units and compare their index with the stratigraphic position. Copernican and Eratosthenian terrains show mainly the efforts of the discontinuous degradation, being mainly composed of ballistic sediments produced by recent or almost recent impacts. For the other terrains it was shown that the linear correlation coefficient between the stratigraphic level and the geomorphic index is 0.86. If the studied areas are assumed to represent a sample of all the areas, then the null hypothesis that there is no correlation between stratigraphic position and geomorphic index must be rejected at better than the 0.1% probability level (or, in other words, the chances that we make the wrong decision in rejecting the no-correlation hypothesis are less than 0.1%).

3. The Geomorphology of Mare Surfaces

From the above discussion, it seems safe to conclude that the geomorphic index of mare surfaces uncovered by substantial amounts of ballistic sediments, is a monotonic function of time, i.e., the higher the index of a surface, the older the surface. Without other data and assumptions it is impossible to estimate the length of time involved. The relative order is, however, of interest.

Figure 1 shows the distribution of the geomorphic index on the surface of almost all of the maria. The following conclusions can be reached:

(1) The surfaces of the maria are formed by areas displaying a considerable range in geomorphology. In general, the surface of any mare is not a homogeneous geomorphological body.

(2) In almost all cases there is one geomorphology which is more abundant than any of the others. This is shown by the cross-striped column in each of the histograms of Figure 1. On the basis of the position of this maximum, we can see two families of maria. Serenitatis, Imbrium, Procellarum and Humorum have terrains of 'intermediate' geomorphology (geomorphic index between 5 and 8 units) as the most

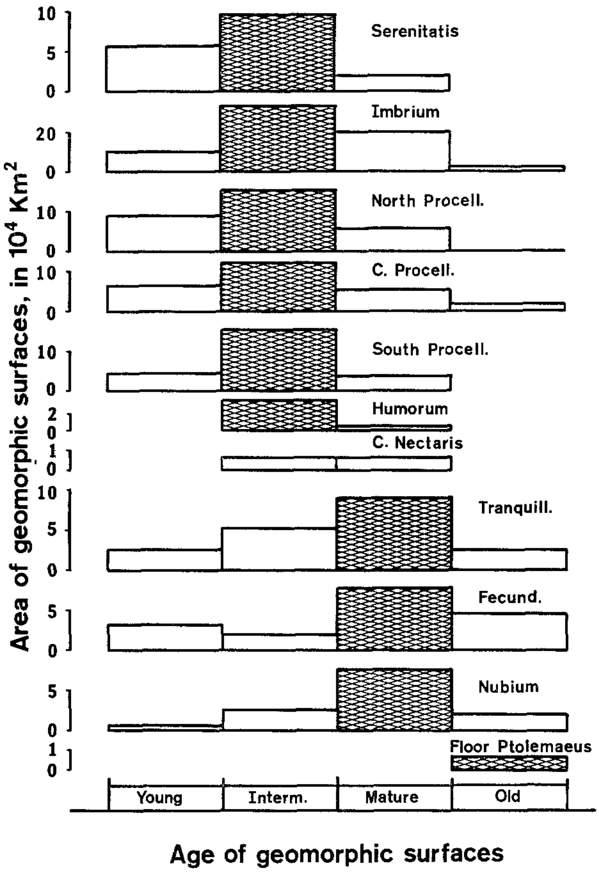

Fig. 1. Diagrammatic representation of geomorphologies displayed by each mare. The horizontal axis shows the geomorphologies, respectively young (geomorphic index less than 5 units), intermediate (index from 5 to 8), mature (index from 8 to 11) and old (index more than 11). The vertical axis shows the amount of area of the indicated mare having the corresponding geomorphology. For quick localization, the most common geomorphology in each mare is shown by cross-striping. As discussed in the text, two families of maria are recognizable, one with the most common geomorphology being intermediate, the other mature.

common surface. On the other hand, Tranquillitatis, Fecunditatis, and Nubium have 'mature' (geomorphic index between 8 and 11) as their most common geomorphology.

(3) If we accept the hypothesis that the geomorphology of mare surfaces is a monotonic function of time, we can propose the following sequence of mare filling:

Phase 1: Filling of the floor of Ptolemaeus, beginning of the filling in Nubium, Fecunditatis Tranquillitatis, Imbrium, Central Procellarum. (For other maria, this phase may be absent or buried).

Phase 2: Maximum filling in Nubium, Fecunditatis, Tranquillitatis, beginning of filling in Northern and Southern Procellarum, Humorem, Nectaris, Serenitatis.

Phase 3: Maximum filling of Serenitatis, Imbrium, Procellarum, Humorum.

Phase 4: Final filling in Serenitatis, Imbrium, Procellarum, Tranquillitatis, Fecunditatis, Nubium.

(4) If we accept the hypothesis that the mare material filled the mare basin immediately after the mare basin formation and remained liquid for a relatively long time (Urey and MacDonald, 1971), then we can visualize a process as follows. The liquid body begins to form a crust. When the crust is sufficiently thick, craters are maintained on its surface. Due to either large impacts or natural turbulencies, segments of

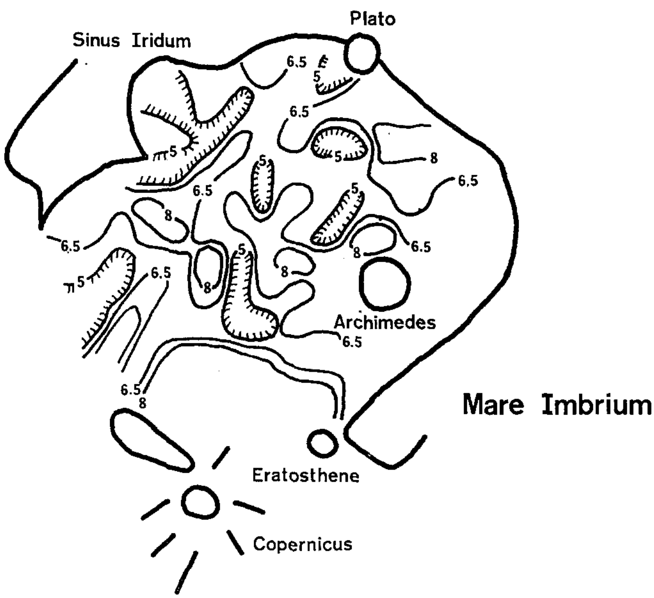

Fig. 2. Sketch contour map of the geomorphic index on Mare Imbrium.

the crust are made to sink in the still liquid substratum. A new crust begins immediatey to form in that location, but naturally the final geomorphology will be 'younger' than elsewhere. This process may have occurred more than once. Within this picture, the different positions of the cross-striped columns in Figure 1 can be explained as being due to varying amounts of crustal sinking on the different maria. Serenitatis, Imbrium, Procellarum and Humorum had the most active surface.

Figures 2, 3, 4, 5, 6, and 7 show respectively a sketch contour map of the geomorphic index of Imbrium, Procellarum, Nubium and Humorum, Serenitatis, Tranquillitatis, and Fecunditatis. Preliminary work indicates that, in places, relationships occur between the geomorphic index contours and eclipse infra-red maps.

If we accept the Apollo radiometric ages as being the ages of the landing sites' surfaces and compare them with the geomorphic index of the landing sites, we find:

(1) Apollo 11 ages group at approximately 3.65×10^9 yr (Albee *et al.*, 1970). The geomorphic index of the landing site is 10.3 units.

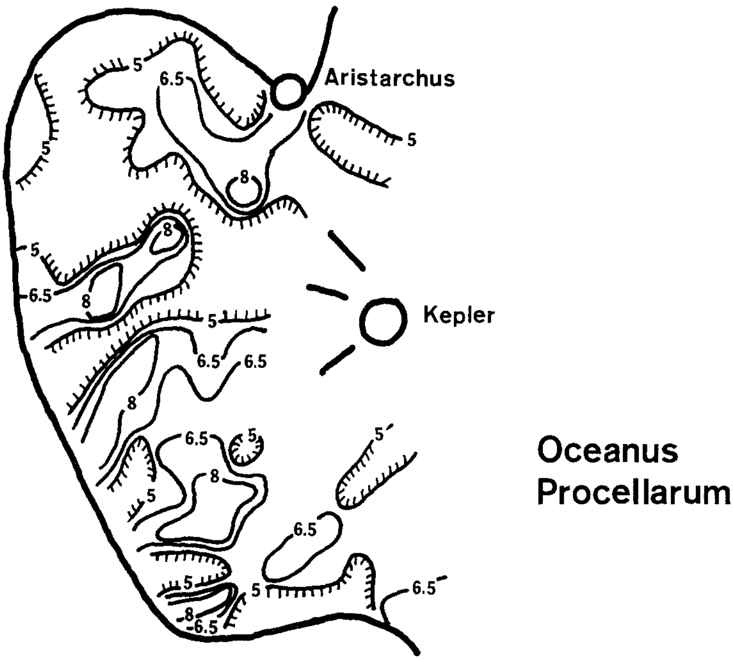

Fig. 3. Sketch contour map of the geomorphic index on Oceanus Procellarum.

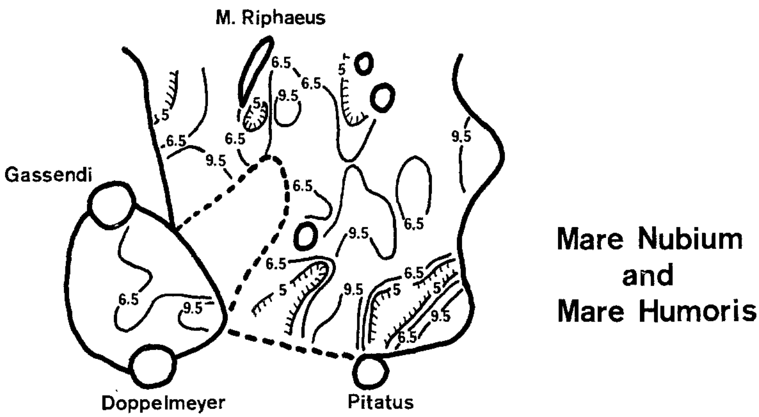

Fig. 4. Sketch contour map of the geomorphic index on Mare Nubium and Mare Humorum.

(2) Apollo 12 ages group at approximately 3.35×10^9 yr (Papanastassiou and Wasserburg, 1970). The geomorphic index of the landing site is 8.4.

(3) Apollo 14 landed in an area outside the continuous degradation sequence and, as such, the geomorphic index is not immediately applicable. However it may give us a maximum limit to the age of the Imbrium filling by providing the age of formation of the Imbrium basin. Husain *et al.* (1971) give an age of 3.75×10^9 yr for the formation of the basin. The highest geomorphic index on the surface of Imbrium is more

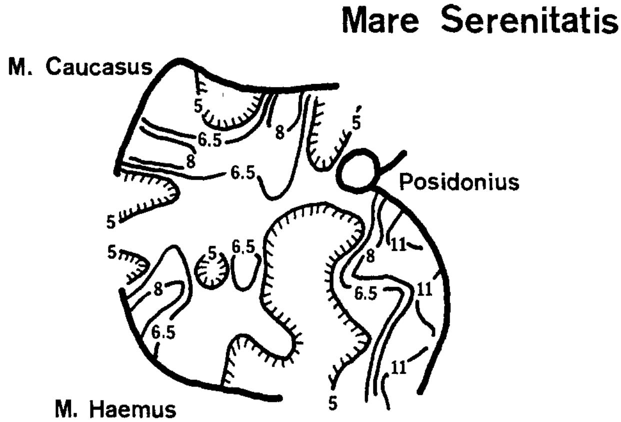

Fig. 5. Sketch contour map of the geomorphic index on Mare Serenitatis.

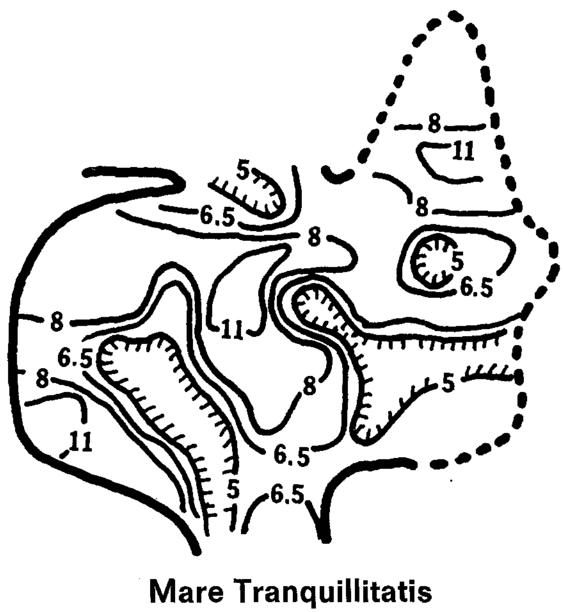

Fig. 6. Sketch contour map of the geomorphic index on Mare Tranquillitatis.

than 11 and less than 13.5. The oldest filling of Imbrium must necessarily be younger than the formation of the Imbrium basin.

(4) Apollo 15 samples give ages ranging approximately from 3.3 to 3.6×10^9 yr (Chappell *et al.*, 1972; Alexander *et al.*, 1972; Murthy *et al.*, 1972). The geomorphic age of the landing site is questionable because of the complicated geological relationship with the rille. It was calculated to be 9.2 units.

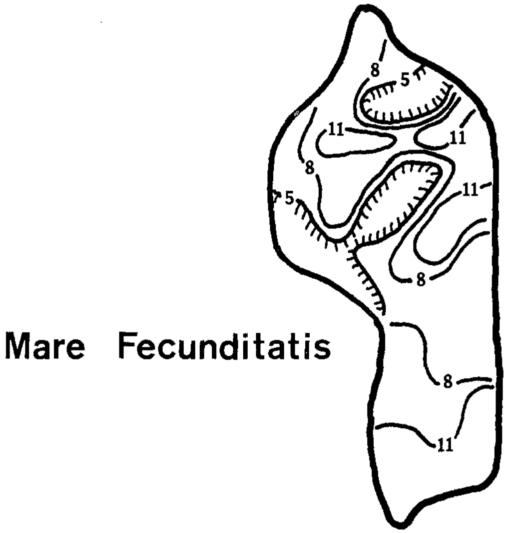

Fig. 7. Sketch contour map of the geomorphic index on Mare Fecunditatis.

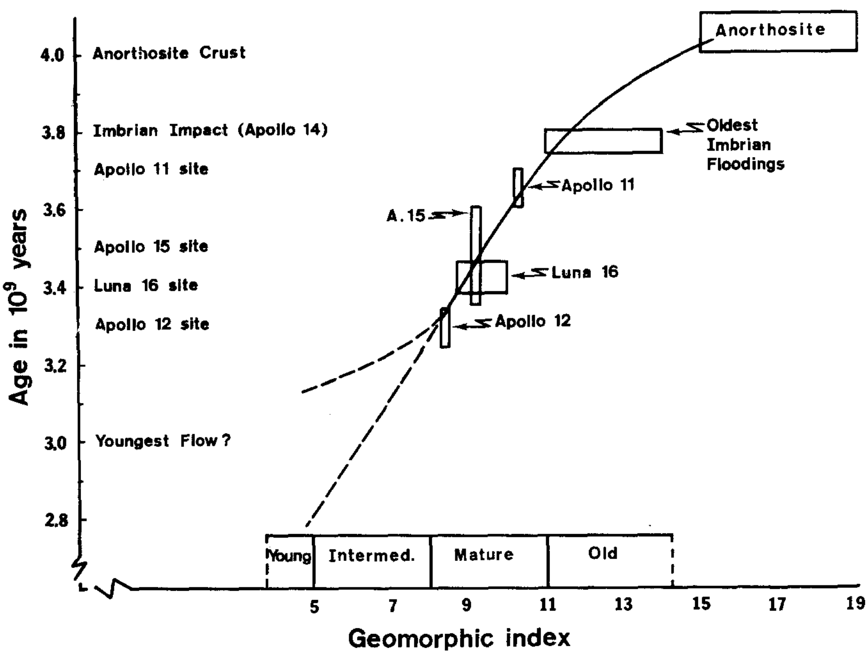

Fig. 8. A preliminary relationship between age and geomorphic index, with the assumptions explained in the text. The age of the youngest mare area appears to be of the order of 3×10^9 yr old.

(5) Luna 16 basalt gives a radiometric age of approximately 3.4×10^9 yr (Papanastassiou *et al.*, 1972; Huneke *et al.*, 1972). The geomorphic index of the landing site is questionable because of the extreme variability in the morphology of the area. It was calculated to be between 8.7 and 10 units.

(6) The range of the geomorphic indices of the highland terrains is 15 to 19.5 units. If we accept the age of the anorthosite fragments to be the age of the highlands, then we may attribute an age of more than 4×10^9 yr to these terrains (Husain *et al.*, 1972).

Figure 8 shows a plot of these six relationships. The youngest mare terrains have a geomorphic index of less than 5 units. It would be of interest to know the age of the most recent filling acrivity. Extrapolation is problematic, but it appears that the youngest mare surfaces have an age of about 3×10^9 yr, but could be as young as 2.8 or as old as 3.1.

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