THE RELATIONSHIP BETWEEN LUNAR HOT SPOTS AND THE GEOMORPHIC INDEX*

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Abstract. The previously developed geomorphic index of lunar surfaces is applied to the surface distribution of the lunar hot spots. It was found that the hot spot number density is the highest in areas of intermediate geomorphic index, corresponding to mature maria. Young and old maria and the terrae have fewer hot spots per unit area. An hypothesis is presented relating the probability of formation of a hot spot by impact with the evolutionary stage of the regolith of the target surface. The older is the surface, the deeper is the regolith and also the smaller is the average boulder size. For these reasons hot spots will be less probable. The paucity of hot spots in young maria could also be related with the evolution of the regolith, but fundamental changes in the petro-physics of the mare effusions cannot be ruled out.

1. Introduction

Previous work (Ronca and Green, 1970) has led to the development of a method to quantitatively describe the geomorphology of lunar surfaces. This was accomplished by determining a function which relates the number density of craters (excluding ghost craters) to the number of these craters which are essentially uneroded. The value of this function at different areas was defined as the *geomorphic index* of that area. This index describes a lunar area better than the crater number density because it combines two independent parameters – crater number density and erosional stage.

What is the geological meaning of the geomorphic index? It is a description of the geomorphic age of an area. Non-geologists may be unfamiliar with the concept of geomorphic age and a short explanation may be necessary. To use an example, a river system on the Earth is variously referred to as being in its youthful, mature, or old stage. This means that there is a sequence of characteristics which a river system displays consecutively from the time of its formation. The same concept can be applied to a lunar surface, from the time of its formation, when presumably no or only endogenous craters are present, to the time when the surface is completely covered with impact craters, many of which are highly eroded. The geomorphic index is the position of the lunar surface in this progression.

It is important to realize the basic difference between geomorphic age and geologic age. Just as on Earth a river may reach its old stage in a much shorter time than another river in a different area, so on the Moon one surface may reach a high geomorphic index sooner than another. Geologic age, on the other hand, is simply the age in years (or its position in the stratigraphic column) of a feature. Only under certain conditions of equal exposure to the modifying agents can the geomorphic age be assumed to be proportional to the geologic age.

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Implicit in the concept of geomorphic age is the concept of *rejuvenation*. On the Earth the extreme tectonic activity gives plenty of examples of 'pushing back the geomorphic clock'. On the Moon, if all the areas were formed at the same time and progressed through essentially the same history, they should all have the same geomorphic index. In reality the index ranges from approximately 5–13 for the mare surfaces and 13–20 for the terra surfaces. The simplest way to explain the range in indices is to call for rejuvenative processes, which occasionally wipe out most or all craters in an area.

The most evident process of rejuvenation on the Moon is *mare flooding*. This process actually creates a new surface, young both geologically and geomorphologically. Impact craters are soon formed and the geomorphic index begins to increase in value. In general, for mare surfaces, the geomorphic index is proportional to the geologic age. This was exploited in the referred paper (Ronca and Green, 1970) in which the relative ages of the mare surfaces were presented. Care must be taken in this assumption, however, as the impact of a large asteroid on or near a mare surface will 'geomorphically age' the mare surface prematurely. For example, the area surrounding Copernicus shows a higher geomorphic index than the mare proper, probably as a result of the Copernicus impact.

Mare flooding is not the only process of rejuvenation. It can be shown that the geomorphic index increases as the distance from a very large impact increases. A contour map of the geomorphic index of the southern terrae clearly show that as the distance from the mare shores increases, the index also increases in value. This was interpreted as follows. When a large impact occurs, the surrounding area is subjected to the highly erosive action of the ballistic ejecta and seismic activity. It was calculated that even if only 10^{-4} of the impact energy is converted into seismic energy, a mare-size impact would create moon-quakes of approximately magnitude 10 on the Gutenberg-Richter scale, which is considerably larger than any earth-quake recorded on Earth.

Under the dual attack of the seismic waves and ballistic sediments, crater rims will be completely or partially obliterated. From a geomorphological point of view, if no craters or only ghost craters are left, the area has been rejuvenated. The amount of rejuvenation should decrease progressively as the distance from the impact increases. A clear evidence of this type of rejuvenation is shown by the terrain around Mare Orientale and was discussed in a previous publication (Ronca and Green, 1969).

The geomorphic index permits a quantitative description of the geomorphology of a lunar surface. As such, it can be used for correlations and other statistical treatments. Work is in progress to correlate the index with the lunar stratigraphic scale and with the absolute ages of the Apollo samples. The purpose of this paper is to show the relationship between the index and the hot spots, the punctiform areas which cool more slowly than the surroundings during eclipses.

2. Hot Spots and the Geomorphic Index

Lunar infra-red measurements (Saari and Shorthill, 1965; Shorthill and Saari, 1969;

Winter, 1967) have revealed that the lunar surface exhibits a considerable degree of thermal heterogeneity during eclipse and lunation cooling. The most striking features are the more than one thousand hot spots, punctiform areas which, during eclipses, cool more slowly than the surrounding.

It is not the purpose of this paper to go into the thermophysical nature of the hot spots. Winter (1969), Shorthill and Saari (1969) and others have discussed this problem. The following observations will suffice:

(1) Most of the hot spots are related with a fresh crater, but not all fresh craters are hot spots.

(2) The thermophysical *raison d'être* of the hot spot is not endogenous heat nor a peculiarity in the petrographical composition, but is a physical characteristic of the ballistic sediments, rim, and/or floor of the crater. An abundance of boulders, sharp and uneroded in outline, is the most probable cause.

(3) The erosive processes which degrade lunar craters also extinguish the hot spots. Green (1968), for reasons based on crater densities, has shown that hot spots become extinguished while the corresponding crater still maintains its fresh appearance. In other words, craters with hot spots are *very* fresh craters.

(4) The distribution of hot spots is strongly controlled by the lunar physiography. Green (1970) has applied a trend-surface analysis to the hot spot distribution and to the lunar physiography and has shown a strong correlation between the albedo and the hot spots number density. The hot spots occur more abundantly, but not exclusively, on the maria.

Very recent impact craters should be scattered on the lunar surface without preference of physiography. If the only requirement for a hot spot is a very recent impact crater, then all the hot spots should be distributed in equal abundance on maria and terrae. The fact that they are more common on the maria than on the terrae implies that, for some reason, mare surfaces are more likely to produce the necessary thermophysical properties. It is evident that testing the relationship between hot spots and the geomorphic index is an obvious step.

To avoid possible instrumental effects in the counting of hot spots (Saari, personal communication), only the area within 60° of the center of the lunar disk was taken in consideration. This area shows a range in geomorphic index from approximately 4–20.

The number of hot spots occurring on terrains with geomorphic index values between 4 and less than 5 was counted. Next the number of hot spots in terrains of geomorphic index between 5 and less than 6, and so on until terrains of geomorphic index between 19 and less than 20. The results are presented in Table I and displayed as the lower histogram of Figure 1. As the terrains in each index step have not the same area, the number of hot spots in each terrain step was normalized for a constant area of 15×10^5 km^2. The results are presented in Table I and in the upper histogram of Figure 1.

Figure 1 has some indications that the relationship between hot spots and geomorphic index is stronger than that dictated solely by the mare versus terra dichotomy. Rather than a single step function, i.e., high on the maria and low on the terrae, there

TABLE I

Number of hot spots in terrains of different geomorphic index

Geomorphic index span	Area in 10^3 km^2	No. of hot spots	Normalized No. of hot spots
1 to 2–	0	0	–
2 to 3–	0	0	–
3 to 4–	0	0	–
4 to 5–	174	15	129.3
5 to 6–	464	47	151.8
6 to 7–	1102	129	175.4
7 to 8–	638	75	176.3
8 to 9–	928	124	200.9
9 to 10–	986	130	197.6
10 to 11–	812	62	114.7
11 to 12–	522	45	129.2
12 to 13–	464	35	113.1
13 to 14–	580	48	124.3
14 to 15–	986	48	73.0
15 to 16–	638	35	82.3
16 to 17–	290	8	41.4
17 to 18–	232	12	77.6
18 to 19–	116	4	51.7
19 to 20–	58	5	129.3

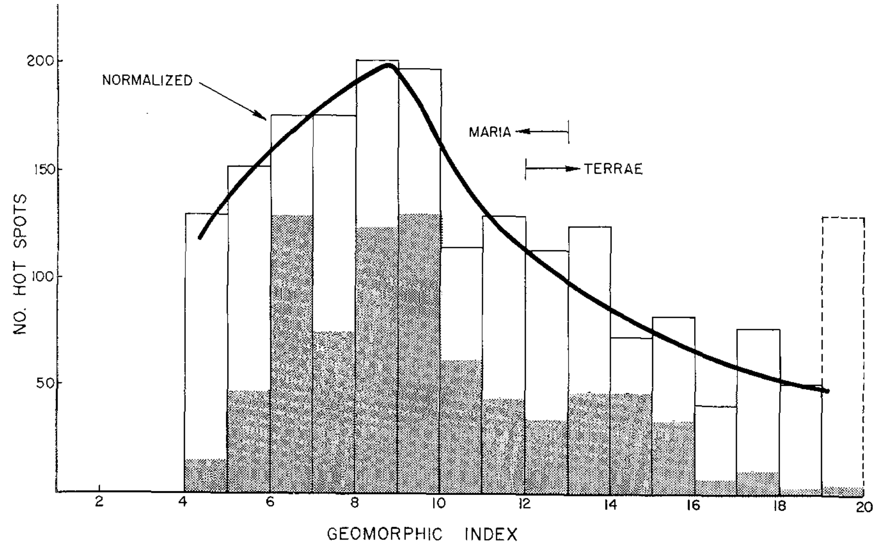

Fig. 1. The number of hot spots in terrains having the indicated geomorphic index. The lower histogram (dark columns) shows the actual number of hot spots; the upper histogram shows the normalized number of hot spots (number per 15×10^5 km^2).

appears to be a continuous relationship within the maria as well as between maria and terrae, as shown by the black curve of Figure 1. An interesting property of this curve is that the maximum does not occur at the border between maria and terrae, but within the maria. The maximum in hot spot number density appears to occur for geomorphic index values of 8–10, corresponding to mature maria.

If this interpretation is correct, it is important in the development of a theory for the origin of hot spots. It means that, although old maria are physiographically different from the terrae, they are equivalent as far as hot spots are concerned. This interpretation can be checked in another way.

In the previous paper (Ronca and Green, 1970), 22 mare and 18 terrae provinces were defined. The provinces were drawn in the attempt to define areas where the geomorphology is homogeneous, within the restriction of the computer program used. The mare provinces were relatively easy to define and are reasonably homogeneous, while the terrae provinces were only indicative. The geomorphic index, including the error bar, of each province was calculated.

It is evident that these provinces allow a good way of checking the postulated interpretation. The number of hot spots in each province was measured and the results are displayed in Table II and Figure 2 (the terrae provinces used here are slightly different

TABLE II

Number of hot spots in the geomorphic provinces

Province	Geomorphic Index		No. of hot spots		Area	No. hot spots per 10^5 km^2	
	Min	Max	Min	Max	in 10^3 km^2	Min	Max
Nectaris	9.4	11.0	1	3	77.28	1.29	3.88
Fecunditatis	9.9	10.8	18	20	225.40	7.99	8.87
Imbrium	6.8	7.4	77	90	631.12	12.20	14.26
Serenitatis	5.5	6.5	33	40	270.48	12.20	14.79
Humorum	6.9	8.2	11	15	70.84	15.52	21.17
Tranquillitatis	8.5	9.2	54	60	270.48	19.96	22.18
NC Procellarum	6.2	7.7	19	24	115.92	16.39	20.70
SC Procellarum	5.5	6.6	12	16	109.48	10.96	14.61
Nubium	8.4	9.2	24	30	154.56	15.53	19.41
Vaporum	6.8	8.5	9	14	77.28	11.65	18.12
Frigoris	9.3	10.1	18	27	206.08	8.73	13.10
Riphaeus-Fra Mauro	7.4	8.7	13	17	83.72	15.53	20.31
North of Mösting	10.1	11.2	8	12	96.60	8.28	12.42
Terra Province No. 1	12.9	13.7	9	11	231.84	3.88	4.74
Terra Province No. 2	12.6	13.3	15	17	231.84	6.47	7.33
Terra Province No. 3	13.5	14.6	10	12	231.84	4.31	5.18
Terra Province No. 4	14.5	15.6	2	3	231.84	0.86	1.29
Terra Province No. 5	13.0	13.6	5	6	231.84	2.16	2.59
Terra Province No. 6	14.8	15.7	13	15	231.84	5.61	6.47
Terra Province No. 7	16.1	17.9	7	9	231.84	3.02	3.88
Terra Province No. 8	15.9	16.8	7	9	231.84	3.02	3.88
Terra Province No. 9	14.9	15.9	6	7	231.84	2.59	3.02
Terra Province No. 10	14.9	16.8	8	10	231.84	3.45	4.31
Terra Province No. 11	14.2	15.3	6	8	231.84	2.59	3.45
Terra Province No. 12	16.0	17.1	7	9	231.84	3.02	3.88

than those of the referred paper). The number of hot spots is given as a range of values, as it has often been difficult to determine exactly the position of the hot spot with respect to the border of the province. Figure 2 shows the same relationship as Figure 1, i.e., the maximum is reached for geomorphic index values between 8 and 9, and the drop occurs within the values of maria. A curve can be drawn satisfactorily except for Nectaris, which seems to have an anomalous low number of hot spots.

Another way to check the interpretation is to use the cell grid, developed in the referred paper. The near side of the moon was divided into a grid of equiareal cells, of approximately 58 × 10^3 km^2. For each cell within 60° of the center of the disk the geomorphic index and the number of hot spots were calculated. The main objection to this procedure is that the cells are arbitrarily drawn and thus are likely to be geomorphologically non-homogeneous. For this reason the results will be highly scattered, as shown in Figure 3. The basic relationships, however, are still present. Cells with the maximum number of hot spots have a geomorphic index between 8 and 10. Two basic trends are apparent, shown with the two thick lines. One is the growth from 4–10, and the others is the decline from 8–16.

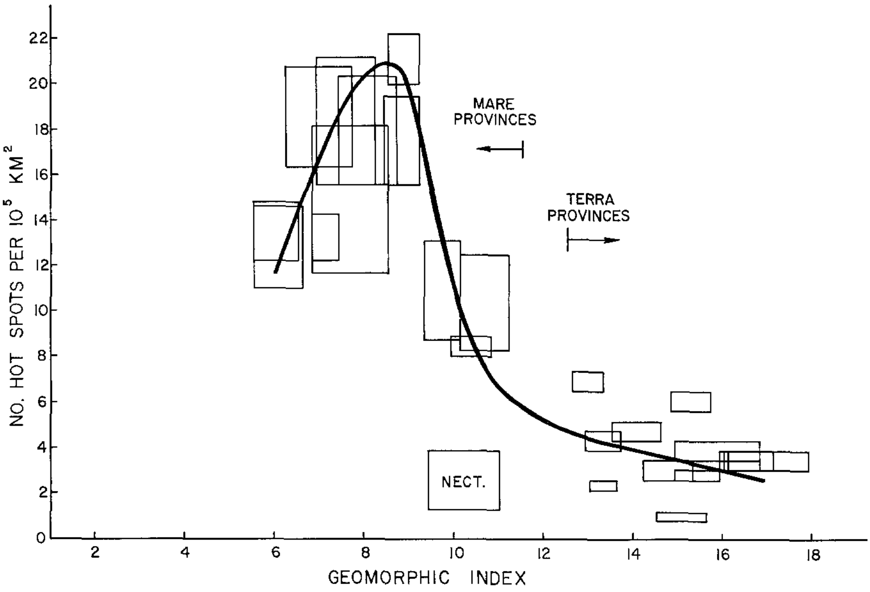

Fig. 2. Normalized number of hot spots in each geomorphic province versus the geomorphic index of the province.

3. Conclusions and Discussion

The following observations can be presented:

(1) As far as the hot spot number density is concerned, differences exist within the maria as well as between the maria and the terrae.

(2) The maximum in hot spot number density occurs in mature maria. Young and old maria have fewer hot spots per unit area.

(3) Old maria seem to behave, as far as the hot spots are concerned, like the terrae; i.e., they have few hot spots per unit area.

(4) If the smooth curves of Figures 1, 2 and 3 are true then a *continuous* relationship exists between hot spot density and the geomorphic index. As the geomorphic age of an area increases, the hot spot number density grows to a maximum and then decreases.

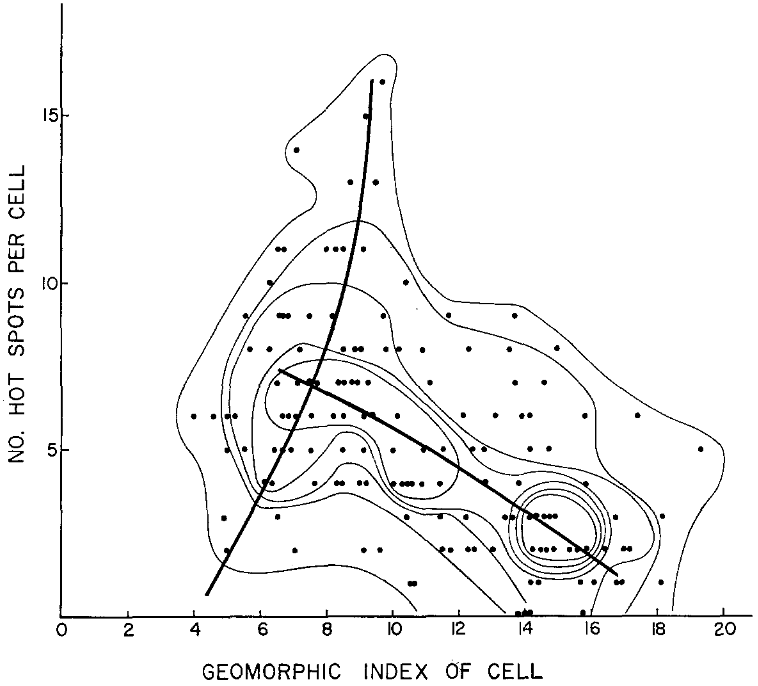

Fig. 3. Number of hot spots in each cell of the equiareal grid versus the geomorphic index of the cell. The contours indicate concentrations of datum points, as each point in the graph may correspond to more than one datum.

The first conclusion that can be reached from these observations is that the geomorphic age of an area is more important than the geological origin of the area. This is especially indicated by the third observation. We can also tentatively conclude that the *probability* of a crater being a hot spot is a function of the geomorphic index of the area of location of the crater. As it was mentioned before, a hot spot occurs when a crater is accompanied by a particular type of ballistic sediments. Is it any way to relate the type of ballistic sediments with the geomorphic index?

Considerable amount of work is presently being done in the study of hot spots, mainly by comparing them with radar anomalies (Shorthill, personal communication). It is hoped that this research will result in an understanding of the boulder size distribution of the hot spots. It is evident that we must wait for these results before a defined model can be presented. In the meanwhile the following generalization can be advanced.

The surface feature which is likely to be related with both the geomorphic index and the type of ballistic sediments is the regolith. Intuitively one would expect the ballistic sediments of a crater formed in an area of thin regolith to be different from the ballistic sediments of a crater of the same diameter formed in an area of thick regolith. The same consideration applies for the particle size distributions in the regolith.

As shown by Gault (1970), the regolith is the product of the comminution process of impact cratering. As such, it is likely to be a function of the geomorphic index. It is probably safe to assume that the thickness of the regolith increases with the geomorphic index. Green (1969) proposed the hypothesis in which a crater produces a hot spot only when the crater is large enough to penetrate through the regolith and eject some of the basement material, thus explaining how the probability of hot spot production is lower in areas of high geomorphic index. To this we must add that the average boulder size is probably smaller in areas of high index.

These considerations indicate that it is not difficult to explain the decrease in hot spots in old maria and in the terrae. The increase in hot spot number density from the young to the mature maria, on the other hand, is more puzzling. It is possible that an *optimum* in boulder size distribution is necessary, not too large and not too small. It is also possible that this increase is independent of the regolith and is caused by systematic differences in the evolution of the Moon. If a considerable amount of time elapsed between the formation of a young and a mature mare, the Moon may have evolved in that time so that the lava extrusion of the young mare is different from the lava extrusion of the old one. The porosity may have changed, for example. In this model, the intrinsic lava differences are the cause of the changing probability of hot spot production by impact craters.

Although no answer can be given at present, it is hoped that the relationship between hot spots and geomorphic index may be of help in the development of future models.

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