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The Primeval Axis of Rotation of the Moon

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The primeval axis of rotation of the Moon

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[Plates 1–3]

The palaeopoles of the Moon have been calculated from the palaeomagnetic directions of lunar crustal strata, determined by Coleman, Russell and Hood from Apollo 15 and 16 sub-satellite data. Because of the dominant role of the Coriolis force in the core dynamo hydromagnetics, the lunar dipole magnetic field would have been aligned along the axis of rotation. As the palaeopoles lie in bipolar groupings along 3 different axes, far from the present axis (the magnetizations are dated at 4.2 Ga, 4.0 Ga and 3.85 Ga ago), it is concluded that the Moon was reoriented at least three times. These polar displacements are attributed to the creation of multi-ring basins at these times by the collision of fragments of at least three lunar satellites, the orbits of which decayed by tidal friction. The actual paths of the pole are explained by Euler's theorem applied to a moon in which the interior can flow by solid state creep.

Introduction

The positions of the pole of rotation on the surface of a solid planet or satellite in past epochs can be determined by palaeomagnetism. The necessary assumption is that the mean direction of an internally generated planetary magnetic field is aligned along the axis of rotation. That this assumption is securely based is attested both by its success in the terrestrial applications of palaeomagnetism and by the alignments of the present dipole directions of Mercury, Jupiter and strikingly of Saturn (clearly controlled by their axes of rotation). The explanation lies in the dominance of the Coriolis force in the magnetohydrodynamic equation of fluid electrically conducting cores – iron in the terrestrial planets, metallic hydrogen in the major planets – in which the fields are generated by the dynamo process.

So far, the necessary palaeomagnetic directions are available only for the Moon and have revealed successive reorientations of the Moon relative to its axis of rotation. Such data will, however, become available for other bodies, especially Mars. Thus palaeomagnetism is of importance in understanding the dynamical phenomena in the early Solar System.

Lunar magnetic observations

Evidence for widespread remanent magnetization of the lunar crustal strata was obtained from:

(1) the returned Apollo and Luna samples, especially lavas;

(2) the interaction of the solar wind with magnetic anomalies near the surface of the Moon (arising from the magnetized crust) studied from orbiting satellites;

(3) surveys of magnetic anomalies by three component magnetometers placed on the surface

in the Apollo 12, 14, 15 and 16 landings and by Lunakhod and, most importantly, carried in the sub-satellites launched in the Apollo 15 and 16 missions.

Although the hypothesis that the Moon had an early magnetic field generated by dynamo action in an iron core was put forward to explain the remanent magnetization of the lunar rocks returned by the Apollo 11 mission, and its absence today explained either by the freezing of this core or by the diminished vigour of the convection in it, alternative processes were proposed. It was suggested, for example, that the remanent magnetizations were caused by meteorite impacts and the attendant electromagnetic phenomena (Hide 1972). The attraction of such local magnetization processes was that, although the existence of an iron core in the Moon was earlier suggested (Runcorn 1967), evidence was only slowly obtained. Further, at the time of the Apollo 11 landing, the Moon was thought to have remained cold since its accretional origin, and even now the nature of the heat sources, which melted the Moon (the petrological evidence that at least the outer part was differentiated was one of the first discoveries of the Apollo landings) and which ran the dynamo, remains a considerable mystery.

The arguments that the remanent magnetization of the crust was acquired from a primeval dipole field generated by the core dynamo process have gradually strengthened especially because of

(1) the widespread nature of the remanent magnetization,

(2) the absence of a dipole moment arising from the crust (Russell *et al.* 1974) is paradoxically consistent with the crust having been magnetized by an internally generated field (Runcorn 1975),

(3) Stephenson *et al.* (1975) concluded that the palaeointensity (TRM and ARM) measurements showed that the returned samples were magnetized by a field that only depended on the age of the rocks and had decayed from about 1 gauss at 3.9 Ga ago to a small fraction of this 3.2 Ga ago†. This result was much more easily explained by a core dynamo, which ran down through the gradual diminution of the energy sources driving convection, than by local processes. The evidence that the palaeointensity is a function of age has since been strengthened notably by the development of the IRM method by Cisowski *et al.* (1975, 1983).

The assumption will be made in the rest of this paper that the palaeomagnetic directions are the directions of the primeval lunar dipole field at the time the crustal strata were magnetized, and it will be argued that the conclusions reached about the rotation of the Moon between 4.2 Ga and 3.8 Ga are in accord with dynamical principles.

Palaeomagnetic directions

The directions of the ancient lunar field were not determined from the returned samples (their original orientations were unknown) but were inferred from the magnetic surveys of the Apollo 15 and 16 sub-satellites (Coleman & Russell 1977). The observed magnetic anomalies were first fitted by dipole sources and it was found that the dipoles had to be placed for best fit about 50 km below the lunar surface. As the Curie point for iron – the carrier of magnetization in the Apollo samples – is exceeded at such depths, it was shown by Runcorn (1978) that this empirical result implied that the actual sources were strata uniformly magnetized over 100 km or so. This was further evidence that a global field was the likely cause of the magnetization.

† 1 gauss = 10^{-4} T.

The modelling of magnetic anomalies (though based on a restricted coverage of the Moon) has yielded (Coleman & Russell 1977; Hood *et al.* 1978, 1981 and Hood 1980, 1981) results of the highest significance. From the palaeomagnetic direction inferred for each source the position of the N magnetic pole can be calculated. Although it has been supposed that the pole positions are distributed randomly, Runcorn (1982) showed empirically that the N poles fall into six groupings, pairs of which give mean directions nearly 180° apart and thus three axes are defined, all different from the present axis of rotation of the Moon. These are shown in figures 1*a*, *b* and *c*. By applying the Fisher statistical method to each grouping, the means and

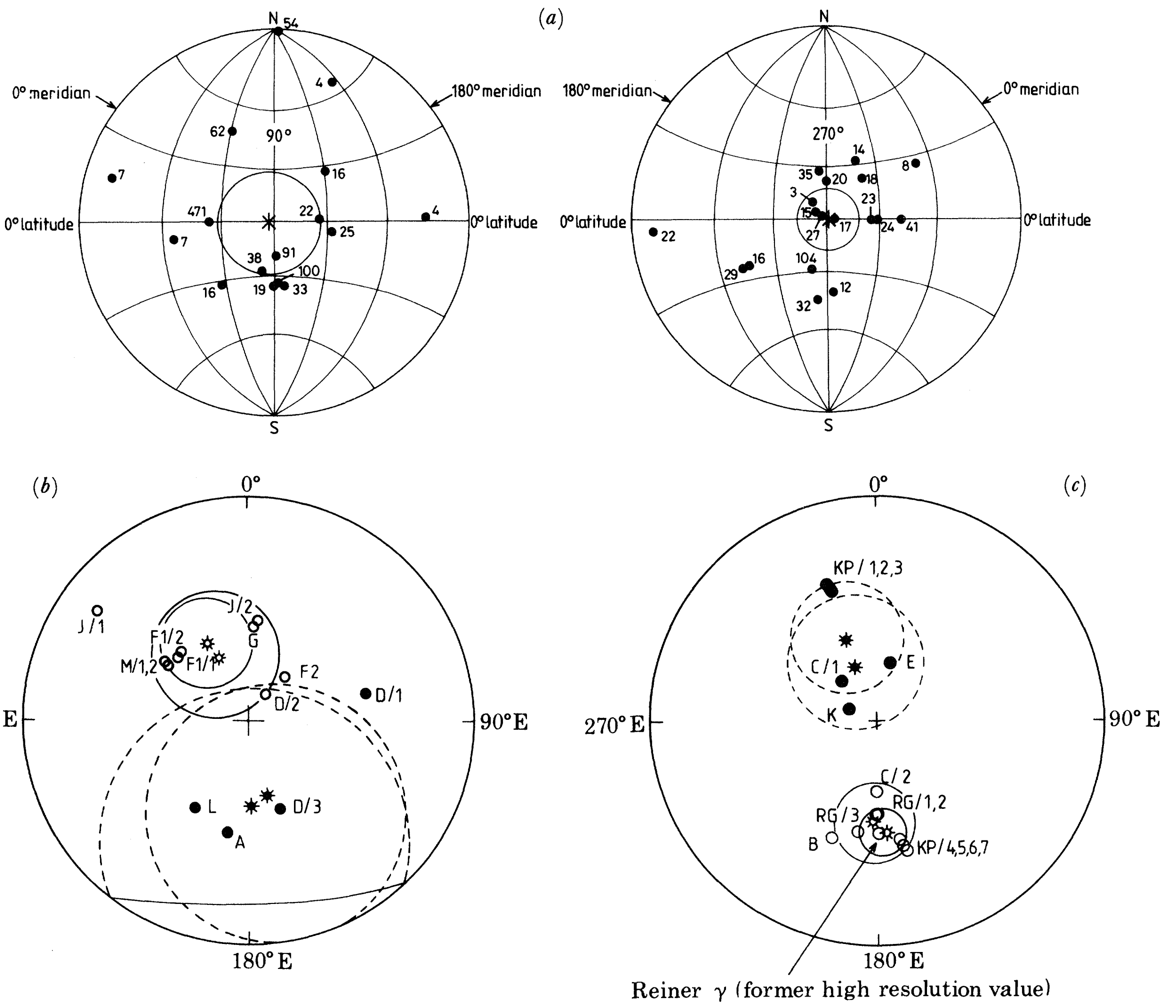

FIGURE 1. Palaeomagnetic poles (N magnetic). (*a*) Pre-Nectarian Equatorial stereographic projections for eastern (left) and western (right) hemispheres. (*b*) Lower Nectarian. (*c*) Upper Nectarian–Lower Imbrian. In (*b*) and (*c*) open circles represent northern hemisphere poles, closed circles southern hemisphere poles, stars represent mean poles; (*b*) and (*c*) are polar stereographic projections 95%. Circles of confidence are shown.

the associated 95% circles of confidence, calculated both for each disc given equal weight and for mean directions determined for the discs that model each magnetic anomaly, are seen to define these three axes. The opposite grouping of N magnetic poles, so reminiscent of terrestrial palaeomagnetic stereographic plots, may be interpreted similarly as reversals of the lunar core dynamo, but may also result because the magnetic anomalies arise from variation in the thickness of, or the intensity of magnetization of, the source strata (for a uniformly magnetized plate of infinite extent has no external magnetic field).

The grouping of the palaeomagnetic poles suggests that the corresponding source strata were magnetized in the same epoch of lunar history. I have argued that the three epochs represented by the groupings of poles are Pre-Nectarian (4.2 Ga), Lower Nectarian (4.0 Ga) and Upper Nectarian–Lower Imbrian (3.9 Ga) (Runcorn 1982). Sources are shown in figure 2.

Thus an additional inference is drawn from the observations: that the Moon has been reoriented at least three times since the earliest epoch. Thus lunar palaeomagnetism gives important information about the early rotation of the Moon.

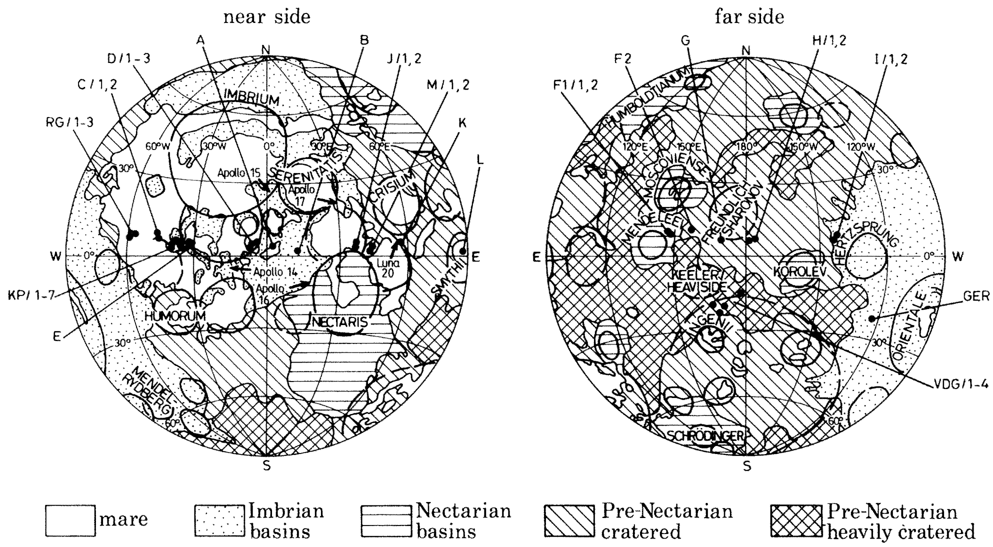

FIGURE 2. Geologic map of the Moon showing the sources from which palaeopole positions are calculated.

PALAEOPOLES AND PALAEOEQUATORS

It has been shown that the palaeoequators of Lower Nectarian and Upper Nectarian–Lower Imbrian epoch lie close to the multi-ring impact basins of corresponding age, as determined by Wilhelms (1984) by the principle of superposition and by crater counting. This fact is evident from figures 3 *b* and *c*, plates 2 and 3. Similarly it is seen in figure 3 *a*, plate 1, that the Pre-Nectarian basins are, with the notable exceptions of Lorentz, Grimaldi and Smythii, close to the palaeoequator of this age, determined from the mean palaeomagnetic poles for this age (Runcorn 1978).

Because this association of the palaeoequators with the impact basins of corresponding ages has led to the important conclusion that the Moon had a satellite system, the multi-ring impact basins being caused as the orbits of the satellites decayed by tidal friction, it is necessary to provide a statistical test for the significance of the association. The Bingham frequency distribution exp $(K \cos 2\Theta)$ is, in principle, more appropriate than the Fisher distribution exp $(K \cos \Theta)$ for discussing such bipolar groupings encountered in palaeomagnetic data, but is a refinement which has not been thought useful in terrestrial palaeomagnetic work. Here, however, it is of key importance, for if K is negative, the Bingham frequency function describes a girdle or a nearly equatorial distribution of points appropriate for discussing the distributions

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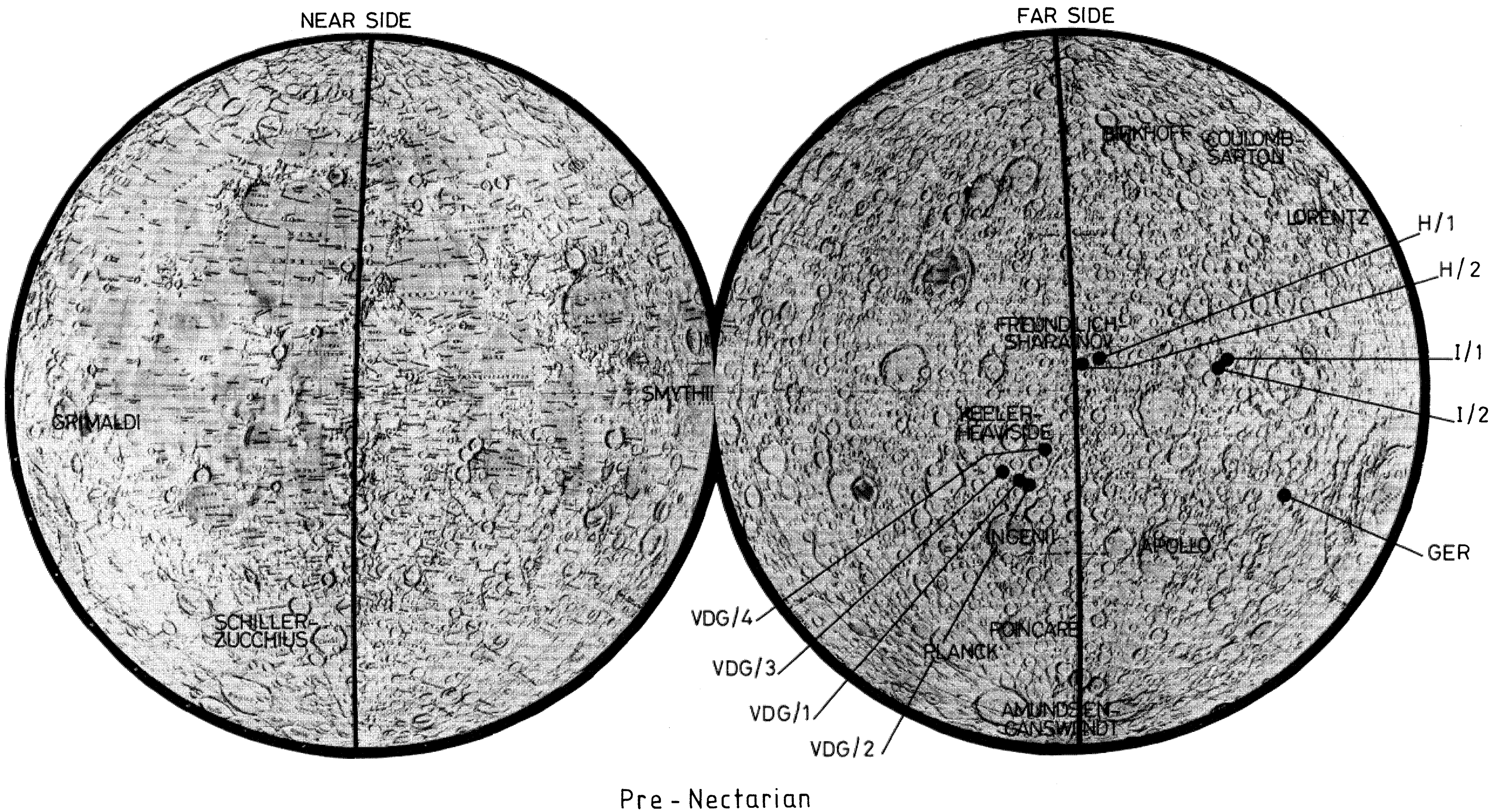

FIGURE 3. Palaeoequators determined from palaeomagnetic data: (*a*) Pre-Nectarian; (*b*) Lower Nectarian, plate 2; (*c*) Lower Imbrian and Upper Nectarian, plate 3.

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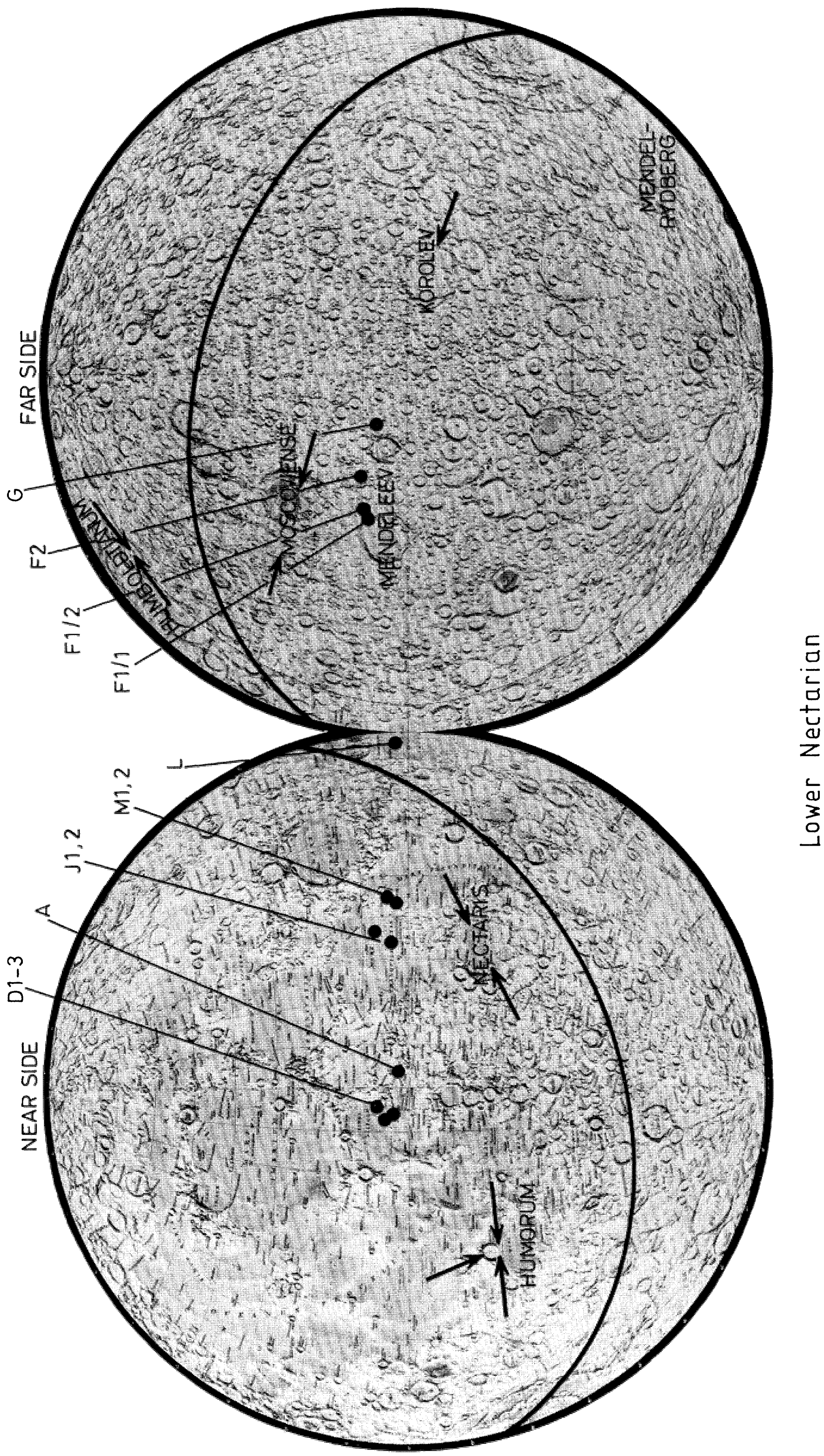

FIGURE 3 (*b*). Arrows indicate direction of the impacting bodies that produced the multi-ring basins.

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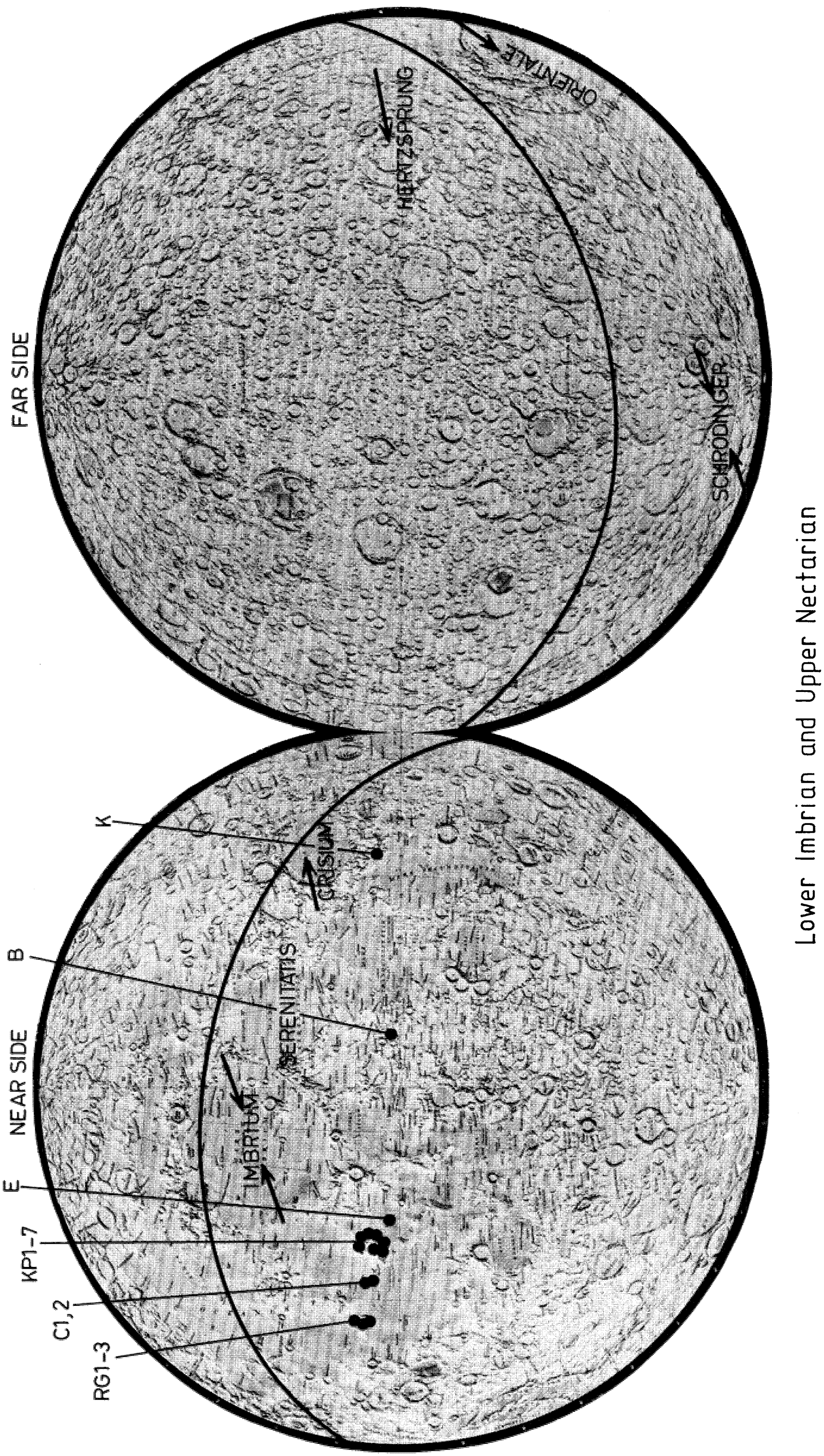

FIGURE 3 (*c*). Arrows indicate direction of the impacting bodies that produced the multi-ring basins.

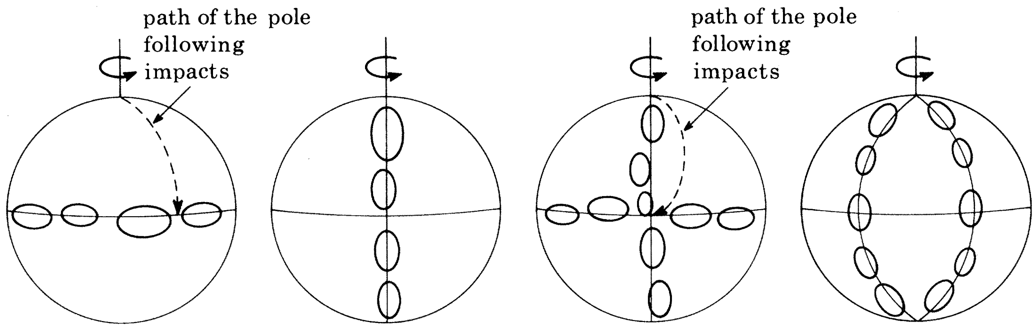

FIGURE 4. Reorientation of the Moon by basin formation from Pre-Nectarian to Imbrian times.

TABLE 1. DETERMINATIONS OF AXES OF ROTATION FOR THE THREE EPOCHS OF PALAEOMAGNETISM AND FROM BASIN DISTRIBUTION

age	rotation pole based on palaeomagnetic directions		rotation pole based on multi-ring impact basins	
Lower Imbrian and Upper Nectarian	352.1° E (6.5°)	41.2° S (10.3°)	339.0° E (22.6°)	39.2° S (42.2°)
Lower Nectarian	339.2° E (10.9°)	49.9° N (21.1°)	280.5° E (21.0°)	49.4° N (31.5°)
Pre-Nectarian	95.3° E (19.2°)	10.4° N (35.9°)	70.2° E (37.1°)	20.2° N (102.5°)

of multi-ring basins around the palaeoequators. So for each of the epochs, the axis of rotation can be determined, with its 95% circle of confidence, both from the N palaeomagnetic poles and from the centres of the multi-ring basins of corresponding age. These results are shown in table 1, the axes of circles of confidence being given in brackets.

POLAR DISPLACEMENTS

The explanation of the reorientations of the Moon with respect to the axis of rotation in space is based on the fundamental principles of the mechanics of the rotation of solid bodies, found by Euler. This is that a body will rotate with stability about its axis of maximum moment of inertia: in the case of a planet this is defined mainly by the hydrostatic equatorial bulge. Runcorn (1983) considered a planetismal impacting near the equator which penetrates into the less dense anorthositic highlands, the resulting explosion removing a considerable volume of the anorthosite. Even if isostatic equilibrium were restored instantly by the upwarp of the underlying more dense mantle, the resulting basin contributes negatively to the moment of inertia tensor. Hence the axis of maximum moment of inertia moves slightly: the pole nearer to the basin moving slightly towards it. After the resulting Eulerian nutation is damped out, the Moon would be rotating about its new axis of maximum moment of inertia but this would be no longer perpendicular to the plane of the equatorial bulge. Were the Moon rigid, no further reorientation would occur. But if the stresses set up by rotation cause the lithosphere to acquire a new ellipticity (which might involve fracturing in its outer and therefore more rigid par and the mantle below adjusts to its shape through solid state creep, the hydrostatic bulge woul again be perpendicular to the axis of rotation. As the basin would continue to cause the ax of maximum moment of inertia to move, the reorientation would proceed until the basin wa at the pole. Calculation of the speed of this process depends on the viscosity of the lunar interi at that time, and modelling seems pointless until more evidence of the timescale is obtaine from lunar geology. Melosh (1975*a*, *b*) has shown that plausible parameters yield quite sho timescales.

The three lunar satellites

The fact that between 6 and 12 multi-ring basins lie along each of the three palaeoequato shows that the above scenario is too simple. If, after one basin had formed but befo reorientation proceeded far, other impacts occurred near the equator, the pole would hav moved to a point on the great circle joining them, its position dependent on the relative si and position of the basins. After reorientation this great circle became a meridian. That suc a series of impacts spanned a relatively short time would have been the natural consequen of a large satellite breaking up at or just within the Roche limit, which is 2.5 times the lun radius from its centre. Although the speeds of the resultant satellites' journey to the Moon woul have been proportional to their masses, they were formed close to the Moon. It is reasonabl therefore, that they impacted within a time shorter than the time that elapsed before the ne series of impacts resulting from the breakup of the next satellite as it went through the Roc limit. Consequently, the next series of impacts in Lower Nectarian times produced basins alon the new palaeoequator as shown in figure 4. The position of the new axis of maximum mome of inertia can be determined on the basis of a simple model of a uniform sphere with two groov (each representing the lines of basins). As the moments of inertia of a hoop of mass m and radi a, about axes perpendicular to and in its plane are ma^2 and $\frac{1}{2}ma^2$ respectively, it is clear th

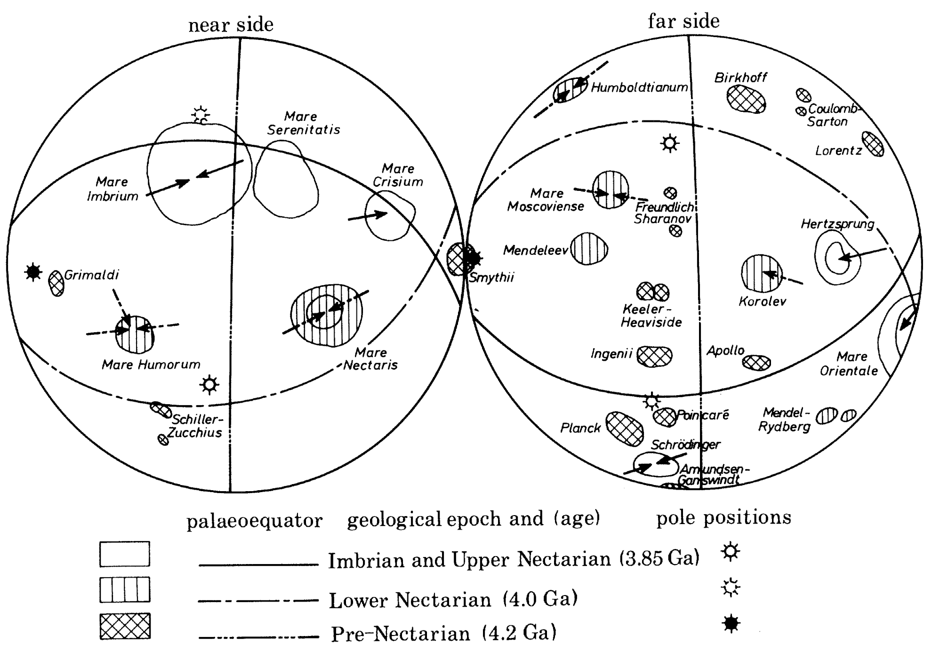

Figure 5. Pole positions and palaeoequators for the three epochs plotted on a lunar map to show their relationships. Arrows show directions of approach of bodies causing multi-ring basins (Wilhelms 1984).

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the new pole of rotation will lie at the intersection of the two great circles. It follows from these simple models that the pole moves through 90° from its Pre-Nectarian to its Lower Nectarian position and then again through 90°, but along a great circle at right angles to the former path, to its Upper Nectarian–Lower Imbrian position. These simple principles of mechanics explain a most puzzling feature of the palaeomagnetic observations: that the two younger palaeomagnetic sets of observations give palaeoequators that intersect near the present equator and limb of the Moon, close to the Pre-Nectarian pole (figure 5). To put it another way, the Pre-Nectarian at about 0° N 90° E after reorientation moves near to the present prime meridian of the Moon in the northern hemisphere. The next reorientation takes it to a position approximately 90° away but still in the prime meridian of the Moon. As these relationships are fitted by the palaeomagnetic pole positions (figure 5), very strong evidence for the correctness of the whole scenario exists. Reid (1973) suggested the idea of lunar satellites on wholly other grounds.

The question now arises as to when the present orientation of the Moon took place. The clue here is a paper of Melosh (1975*a*, *b*) in which he too considers a simple model of the Moon as a uniform sphere but with the addition of masses to simulate the gravitational anomalies over the circular maria, discovered by Muller & Sjogren (1968), and which are now attributed to the addition of plates of lava that result from the flooding of the latest of the great circular basins on the near side of the Moon between 3.6 and 3.2 Ga ago. Melosh found from his simple model that the axes of maximum and minimum moments of inertia of this model are within 5°–10° of the present axis of rotation and the direction to the Earth respectively. We may conclude that the Moon became stabilized about its present axis sometime about 3.2 Ga ago.

Conclusions

Knowledge of reorientations of the Moon with respect to its axis of rotation in its early history is important for discussions of the possibility of trapping of water in craters near the poles; and the changes in the lithosphere shape may be relevant in the explanation of the 'grid system' and other tectonic features.

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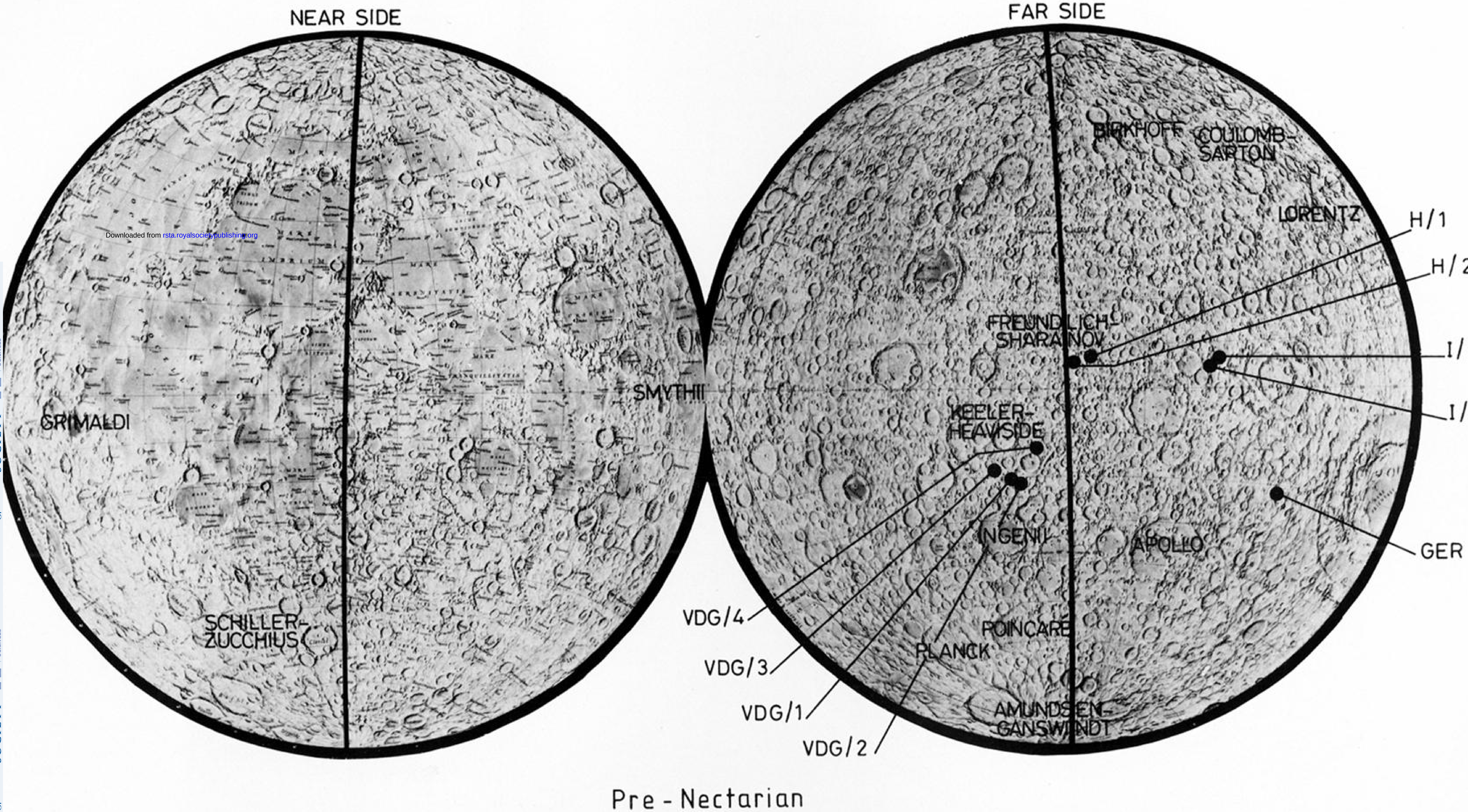

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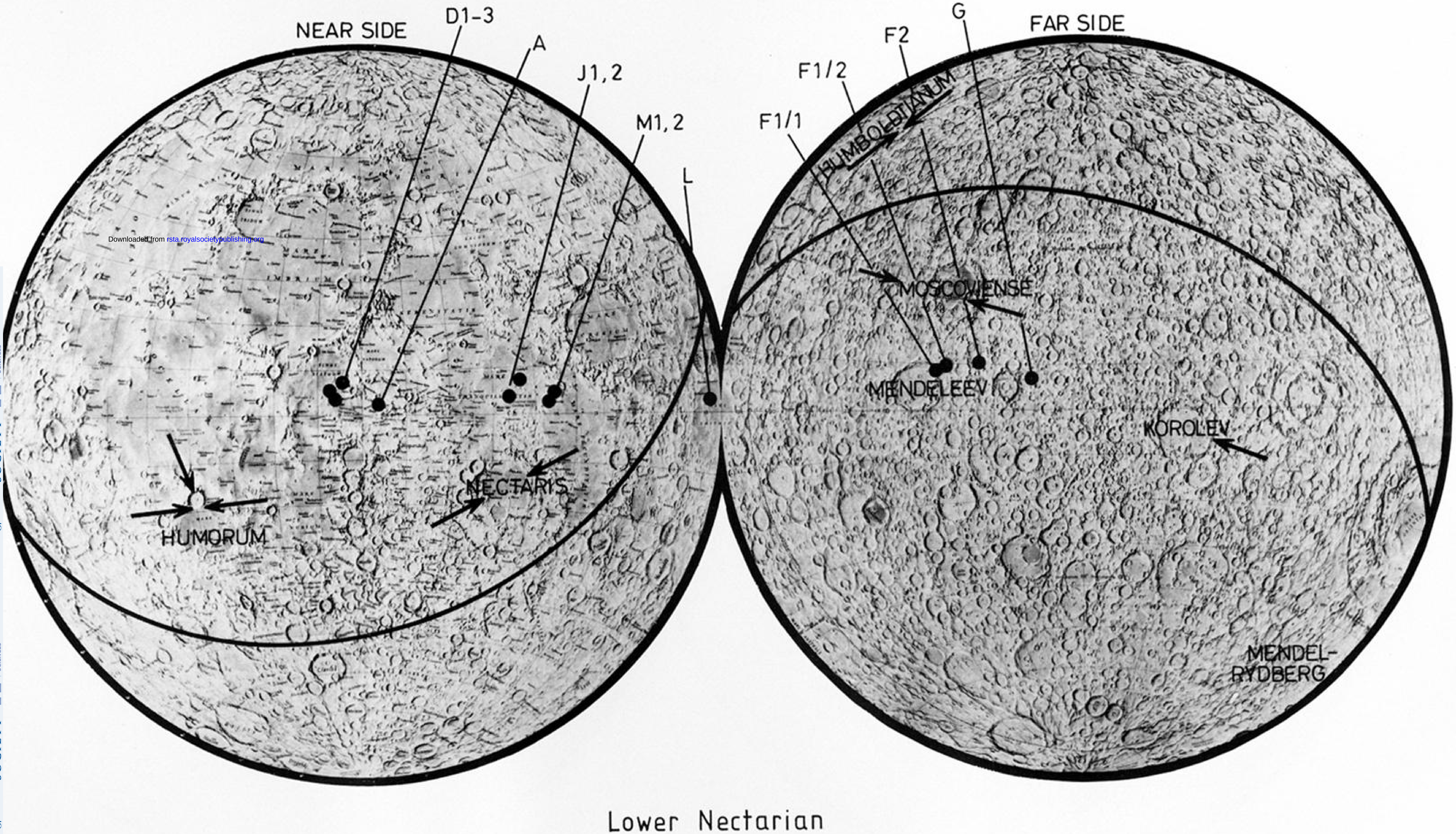

FIGURE 3 (*b*). Arrows indicate direction of the impacting bodies that produced the multi-ring basins.

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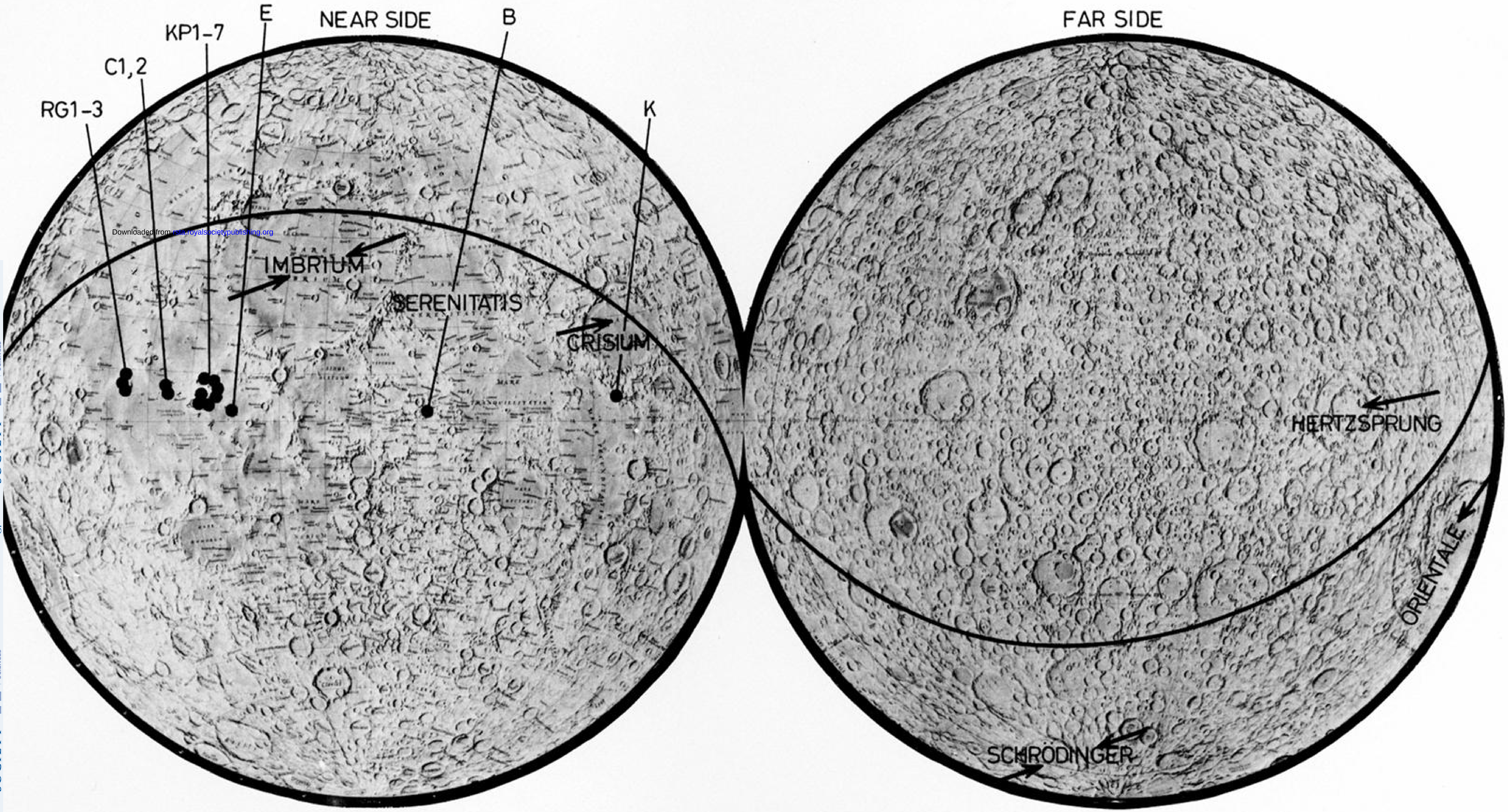

Lower Imbrian and Upper Nectarian

FIGURE 3 (*c*). Arrows indicate direction of the impacting bodies that produced the multi-ring basins.