

Origin of the Martian Crustal Dichotomy: Evaluating Hypotheses

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Any hypothesis for the origin of the Martian global dichotomy should survive three elementary tests: (1) it must account for the observed plan shape and apparent depth of the Martian northern lowland, (2) it must be physically consistent, and (3) it must be compatible with available geological and geophysical data. At present, there are three contending types of hypotheses for the origin of the dichotomy: creation by some endogenic process or processes, creation by a single mega-impact, or creation by several overlapping large impacts. None of these hypotheses can survive all three tests without the incorporation of additional processes. The endogenic and mega-impact hypotheses require the presence of additional impact basins to explain many of the topographic details of the Martian northern lowland and of the dichotomy boundary, and the mega-impact hypothesis probably also requires extensive primordial erosion. The multiple-impact hypothesis requires an additional process or processes to account for the large portion of the northern lowland that is external to the rims of the basins inferred to be the cause of the lowland. While we believe that aspects of the multiple-impact hypothesis are required to account for some topographic details of the boundary and of the lowland, other processes appear better able to account for the dichotomy as a whole. These could include an early mega-impact, endogenic processes, or some combination of these. © 1991 Academic Press, Inc.

INTRODUCTION

The dramatic topographic and geologic contrast between the northern lowland third and the southern upland two-thirds of Mars implies a related contrast in thickness of the crust. This crustal dichotomy has been explained by three general types of hypotheses: endogenic, single impact, and multiple impact. Wise *et al.* (1979a,b) proposed that the contrast in crustal thickness was caused by local subcrustal erosion over a large, first-order mantle convection cell that existed prior to core formation; this

model therefore implies an early origin for the dichotomy. McGill and Dimitriou (1990) argued that the geological evidence points instead to an endogenic origin after the end of primordial bombardment. Thinning of the crust above a mantle convection cell or large plume was suggested. Wilhelms and Squyres (1984) proposed that the crust was locally thinned and the lowland created by a single gigantic impact event, forming what they called the Borealis basin. Finally, Frey and Schultz (1988, 1990) argued that the crustal dichotomy and its associated lowland can be explained as due to a modest number of large (but not gigantic) overlapping basin impacts. Both impact hypotheses involve processes that must have occurred before the end of primordial bombardment, and therefore they also imply an early origin for the dichotomy.

The intent of this paper is to apply some simple consistency tests to these hypotheses, and to discuss briefly what we believe is required to unequivocally support or refute each of them. Any hypothesis for the origin of the Martian crustal dichotomy may be evaluated in three broad areas:

1. Explanation of the observed plan shape and apparent depth of the Martian lowland.
2. Consistency with reasonable physical processes.
3. Compatibility with geological and geophysical observations.

In considering arguments in these three areas, it is important to consider carefully which are relevant to an explanation of the Martian crustal dichotomy as a whole, and which are more relevant to second-order topographic details. The global-scale topographic contrast between the northern lowland and the southern upland of Mars, and the inferred associated crustal dichotomy, may well have a different cause than the topography within the

lowland and the local shape characteristics of the dichotomy boundary.

THE BOREALIS BASIN HYPOTHESIS

1. Explanation of the Lowland

A single, gigantic impact will produce a very large, deep, roughly circular depression. However, any attempt to circumscribe the northern lowland with a single circle demonstrates that the lowland departs rather dramatically from a circular shape in places (e.g., Fig. 1 of Parker *et al.* 1989). Consequently, a single mega-impact cannot explain the shape of the northern lowland without appealing to additional processes.

Many of the deviations of the lowland shape can be accounted for as due to the effects of later, but still primordial, basin impacts cutting the perimeter of the circle. Examples of peripheral impacts include the Utopia and Isidis basins, both of which clearly must be superposed on the Borealis basin if that basin exists (McGill 1989). Therefore the basins invoked in the multiple-impact hypothesis clearly are necessary to explain some topographic details if the Borealis basin exists.

Other deviations from circularity cannot be explained by subsequent basins; for example, in the general region of Chryse and Acidalia planitiae even the proposed Chryse basin (Schultz *et al.* 1982) does not fully account for the shape of the lowland. If the dichotomy was created by the Borealis impact, then deviations from a circular shape that cannot be attributed to younger basin impacts must be due to other causes. Erosional modification of the dichotomy boundary has been suggested (e.g., Hiller 1979) and will be discussed further in Section 3 below.

2. Reasonableness of Physical Processes

Recent models for the accretion of terrestrial planets (e.g., Wetherill 1985) support the high probability of one or more truly giant impacts occurring late in the accretion process. Indeed, the currently favored explanation for the origin of the Earth's Moon involves an impact event substantially larger than the Borealis impact. The issue was addressed by Wilhelms and Squyres (1984), who showed that the size of the body required to form Borealis is comparable to sizes predicted by accretion models or observed for large asteroids. There is thus significant theoretical support for the physical reasonableness of a Borealis basin despite its unusually large size.

On the other hand, Frey and Schultz (1988) argue that Borealis is statistically improbable because it is so much larger than other observed basins on Mars. We believe that this argument is invalid because it involves defining a hypothetical basin population using a diameter/frequency

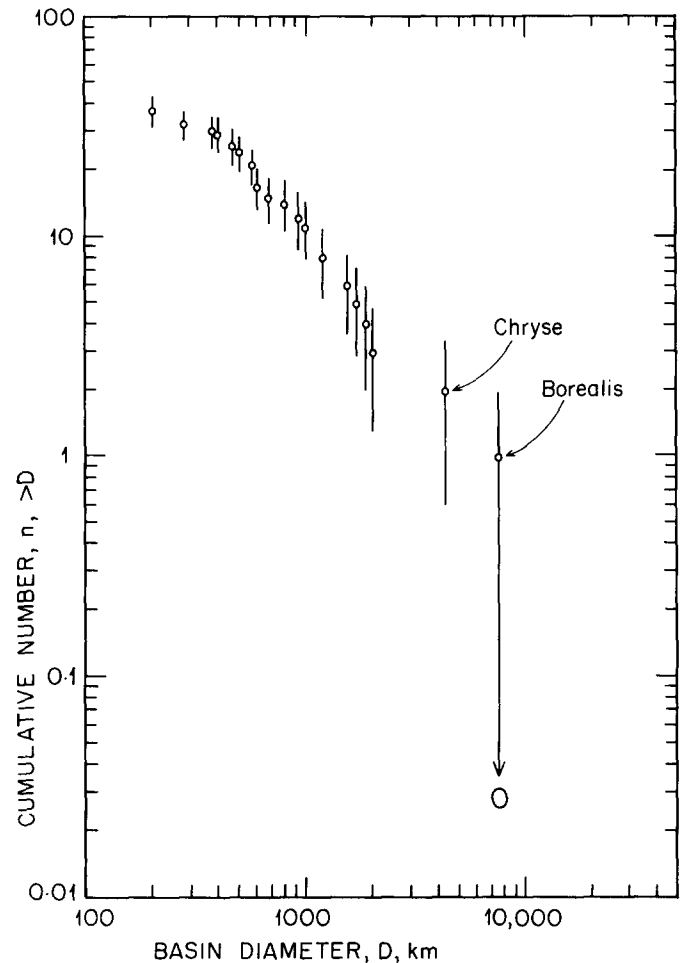


FIG. 1. Log/log plot of cumulative number vs diameter of Martian basins similar to Fig. 2b of Frey and Schultz (1988) except that 1σ error bars have been added. Any reasonable production curve fit to these points will intersect the Borealis basin error bar.

plot based on only one basin. Figure 1 plots the same data as in Fig. 2b of Frey and Schultz (1988), except that standard 1σ error bars (Crater Analysis Techniques Working Group 1978) have been added. For the single largest basin, $n = 1$, and the 1σ limits on the error bar are 0 and 2. Clearly, any curve that fits the rest of the basins on the plot will intersect the Borealis error bar. The proper interpretation of this fact is that the single largest basin (Borealis) can belong to the same population as the others; it certainly is much more likely that Borealis does belong to this population than to a hypothetical unique population defined by Borealis alone, as is the case for the "straw man" hypothesis of Frey and Schultz (1988, Fig. 2b). In fact, relationships such as those shown in Fig. 1 demonstrate that the maximum size of the largest individual in a crater or basin population cannot be constrained statistically as long as the production population has a negative slope on a log diameter/log frequency plot.

3. Consistency with Geological and Geophysical Evidence

The geological evidence for Borealis consists primarily of five massifs that lie on a small circle which encloses much of the northern lowland (Wilhelms and Squyres 1984). It has also been argued, however, that these massifs lie on the rims of other smaller basins (McGill and Dimitriou 1990). There seems to be no geological or geophysical evidence for an ejecta blanket associated with Borealis. The volume of crust that must be displaced to produce the northern lowland is on the order of 10^9 km^3 (McGill and Dimitriou 1990), and a direct analogy with ordinary large lunar basins would suggest that most of this ejected crust should be found in an annulus around the lowland.

The absence of geological evidence for an ejecta blanket is not surprising because the Borealis impact, if it occurred, must have taken place very shortly after the $\sim 4.55 \text{ Ga}$ origin of Mars, and hence the textural indicators of an ejecta blanket would be destroyed by younger intense bombardment or by other processes of erosion and deposition. In fact, surface textures that are characteristic of basin ejecta deposits on the Moon are exceedingly rare on Mars even around well-preserved basins, implying that processes active during or following the primordial bombardment have been quite efficient in modifying the surface. There is no reason to believe, however, that ejecta deposits around most Martian basins are actually missing simply because the diagnostic surface textures common on airless bodies are no longer evident.

The absence of geophysical (as opposed to geomorphic) evidence for greatly thickened crust peripheral to the lowland (Sjogren 1979) is the greatest potential difficulty facing the Borealis hypothesis. However, Borealis is so much larger than lunar basins that they may not be valid analogues. Because the size of the basin would be comparable to the size of the planet itself, effects deriving from planetary curvature and radial gravity could work to distribute Borealis' ejecta more uniformly around the globe, effectively resurfacing the planet with a layer of average thickness about 7 km. For example, the significantly larger impact inferred to have formed the Earth's Moon launched large quantities of ejecta into Earth orbit (Benz *et al.* 1986, 1987, 1989), suggesting that a fairly uniform global distribution of ejecta for the Borealis impact is plausible. Calculations of the expected ejecta distribution for an impact of Borealis' size have not been carried out; quantitative verification of this idea is needed if near-global distribution is to be accepted as a valid way to account for the large volume of ejected material. Geological evidence from widely separated localities for a single ancient ejecta blanket covering much of the southern hemisphere also would be very convincing evidence for a Borealis basin.

Degraded rims of craters dating from the primordial bombardment are present as inliers showing through younger plains materials in many places within the northern lowland (Mutch *et al.* 1976, Scott 1978, McGill 1989, McGill and Dimitriou 1990). It is easy to show (McGill and Dimitriou 1990) that no extensive erosion postdating formation of these craters can have occurred where they are present; hence these areas either (1) have been exposed at their present low elevations since before the end of primordial bombardment or (2) were warped or faulted downward to their present low elevations since the end of primordial bombardment. Where these crater-rim inliers occur inside the proposed rim of the Borealis basin, either explanation clearly could be valid; where these crater-rim inliers occur outside of the proposed rim of the Borealis basin (e.g., Isidis planitia to Protonilus Mensae) the situation is more complex. Alternative (1) requires a major episode of erosion after the Borealis impact but before the accumulation of the remainder of the early Noachian crater population. No geological evidence for such an early erosional episode is preserved, but the required erosion rate ($\sim 10^{-3} \text{ cm year}^{-1}$) is modest by terrestrial standards and may be plausible for conditions on early Mars. Alternative (2) would explain low elevations that are external to the rim of the putative Borealis basin as due to post-early bombardment faulting or warping, for which there is some geological evidence (McGill and Dimitriou 1990, Dimitriou, submitted for publication). This evidence has been cited to support an endogenic origin of the dichotomy.

ENDOGENIC HYPOTHESES

1. Explanation of the Lowland

Endogenic hypotheses imply no a priori tendency toward a roughly circular shape for the Martian northern lowland. On the contrary, the observed plan shape imposes a constraint on the geometry of the convection cell or plume that is invoked to cause the dichotomy. The local details of lowland shape are again easily ascribed to the few known large basins that lie partially or entirely within the lowland, or to local younger erosion.

2. Reasonableness of Physical Processes

Large-scale stretching and internal redistribution of lithospheric, including crustal, material is commonly invoked in tectonic models for the Earth. It is abundantly clear that we do not entirely understand what mantle processes are responsible for the Earth's tectonics, but there is general agreement that mantle convection, as cells or as plumes, is involved. Defining diagnostic tests for the endogenic process or processes responsible for specific crustal features is difficult on Earth where we have abundant data; on Mars, it simply is not possible to truly test

for any specific endogenic model with the geological and geophysical data now in hand. Such models are worth considering in part because of the overwhelming importance of endogenic processes in shaping Earth's surface features, and in part because at least some of the geological evidence suggests that the dichotomy was formed at a time that is not consistent with impact as the cause.

Because the creation of a core constitutes a singularity in Mars' history, it is tempting to explain the crustal dichotomy, a large structural singularity, as somehow related to core formation. It also is easier to understand the large size and roughly circular shape of the lowland if it was caused by a large, plume-like first-order overturn, as might be expected during rapid core formation (Wise *et al.* 1979a,b). However, recent thermal models of Mars based on geochemical and petrological evidence from SNC meteorites (McSween 1985) appear to exclude significantly delayed core formation (Schubert *et al.* 1989, 1990). If the thermal models are correct and if the SNC meteorites really are from Mars, then the apparent peak in tectonic and thermal activity in late Noachian and early Hesperian (McGill and Dimitriou 1990) cannot be related directly to core formation. At present, models defining the probable range of convective patterns in the mantle of Mars (Schubert *et al.* 1989, 1990) do not provide convincing explanations for any of the major crustal features of the planet, including not only the dichotomy, but also the Tharsis rise and the concentration of volcanism at Tharsis and Elysium. As was the case for continental drift on the Earth before the discovery of sea-floor spreading, this lack of a good geophysical model clearly is a weakness of endogenic hypotheses for the origin of the Martian crustal dichotomy. Whether this weakness is fatal or merely due to poor data will probably not be known until we have much more information concerning the interior of Mars.

3. Consistency with Geological and Geophysical Evidence

There is abundant geological evidence for internally driven tectonic events that are areally related to the northern lowland or its boundary, and that clearly occurred after the end of primordial bombardment. Of particular interest are extensive fracturing and related igneous activity of late Noachian to early Hesperian age (Greeley 1987, Tanaka *et al.* 1988, Wilhelms and Baldwin 1989, McGill and Dimitriou 1990, Dimitriou, submitted for publication). Critical to the interpretation of these observations is whether they actually require, rather than simply permit, origin of the crustal dichotomy after the end of primordial bombardment; if they require it, then both impact hypotheses are untenable. In some localities lying between the putative Borealis basin rim and the scarp defining the dichotomy boundary there

are degraded remnants of rims from an early Noachian crater population. These degraded rims define craters of a wide range of sizes, including some as small as 10–20 km in diameter (McGill and Dimitriou 1990, Dimitriou, submitted for publication). Based on the diameter/rim height relationships of Pike and Davis (1984), these rim remnants cannot have survived more than a small fraction of the 2–3 km of erosion necessary to account for the low elevation of these localities if this erosion occurred after the remnant crater population was formed. Either one subscribes to the hypothesis that the needed erosion occurred during the early part of the primordial bombardment, or one must accept that the boundary in these localities is due to faulting or flexing that occurred after the end of primordial bombardment. There are localities where the dichotomy boundary does not coincide with any basin rim and also is an abrupt scarp cutting upland surfaces of late Noachian to early Hesperian age. In these locations the scarp must be younger than late Noachian/early Hesperian, and Dimitriou (submitted for publication) has used this observation to argue that the northern topographic depression itself is that young as well. Furthermore, the existence of boundary segments where there is simply a gradual transition from upland to lowland, such as east of Chryse planitia, is explained in a more straightforward manner by endogenic warping than it is by any impact mechanism.

As a counter to the endogenic arguments of McGill and Dimitriou (1990), D. Wilhelms (personal communication) has suggested that some tectonic and igneous events occurred where they did because of structural weaknesses in the crust inherited from the Borealis impact. The similarity of fractured ancient surfaces on the upland and lowland side of the boundary would thus be explained as due to continuous exposure and similar tectonic histories of both surfaces since the formation of the Borealis basin, and the presence of the abrupt scarps that locally define the dichotomy boundary would be explained as due to local younger modification by erosion. For parts of the dichotomy boundary a similar relationship with other basin structures could be postulated. This is a reasonable argument for those places where the dichotomy boundary coincides with the rim of Borealis or some other basin; it is more problematical for those places where the boundary seems not to be related to any basin structure, in part because of the time-of-erosion constraint discussed above.

Unequivocal evidence that large segments of the dichotomy boundary resulted from faulting or flexing that was clearly younger than the end of primordial bombardment would constitute very convincing support for an endogenic hypothesis. Even though determination of the structural cause and age of the dichotomy boundary is exceedingly difficult with existing data, there is a reasonable

probability that continued careful geological studies can improve substantially on our present understanding of this problem.

MULTIPLE-IMPACT HYPOTHESIS

1. Explanation of the Lowland

The evidence cited as favoring the origin of the lowland by multiple impact is the obvious correlation of segments of the dichotomy boundary with the inferred rims of several large impact basins (Frey and Schultz 1988). But there are large parts of the northern lowland exterior to the rims of these basins. If the Martian lowlands were formed by only these few large basins, then by direct analogy with basins on the Moon and elsewhere on Mars their rims and inner ejecta should stand at or above typical upland elevations. This is clearly not the case for the large basins that have been identified in the lowlands; for example, most of the rim and inner ejecta of the Utopia basin are much lower than the uplands (McGill 1989). Furthermore, there are areas well within the northern lowland that are external to all these basins; these areas must be underlain by multiple overlapping ejecta blankets and should therefore stand at a similar or higher elevation than the original planetary surface rather than lower. One such area is centered near 120° West, 60° North (Fig. 2). Except where much younger volcanics and polar deposits are present, this region of overlapping ejecta blankets is not as high as the probable elevation of the original Martian surface (i.e., the present mean elevation of the southern highlands), as expected. On the contrary, it averages at least 2 km lower than the original Martian surface. If erosion is inferred to be the cause of the low elevations, volume and space problems arise that may be insurmountable. The erosion must not only remove all of the missing ejecta but an additional 2 or more km of crust in order to produce the present topography. Where could all this material have gone? If the ejecta are redeposited in the cavities within the basin rims the region would be returned to approximately its original level. Hence lowering the entire area, both within and external to basin rims, by at least 2 km does not seem possible if the only processes available are the basin impacts and erosion.

Three approaches to this problem are possible. Frey and Schultz (1989, 1990) represented basins as large holes that never had ejecta blankets (Frey and Schultz 1990, Fig. 1), apparently inferring that the present absence of textures diagnostic of basin ejecta means that no ejecta were ever present. An explanation of why the ejecta from Martian basins would be completely removed from the vicinity of the basin rims is clearly needed, because this runs counter to experience on the

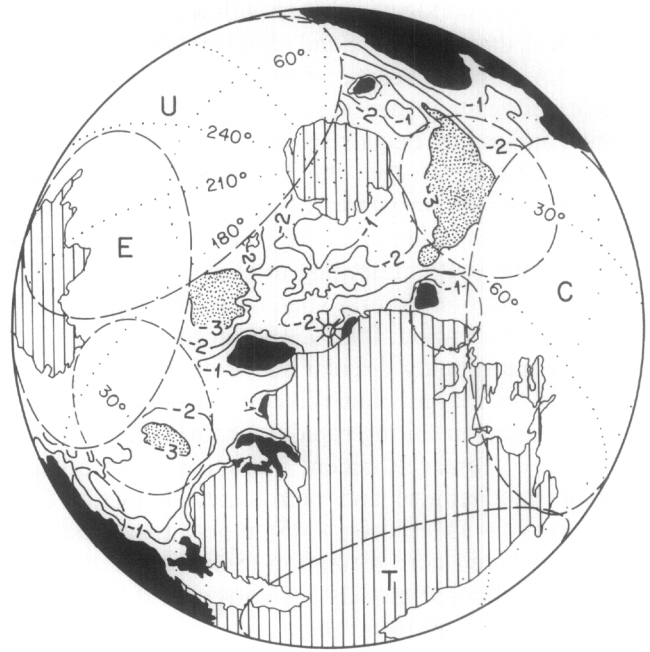


FIG. 2. Northern lowland topography (USGS 1989) centered at 120° West, 60° North. Contour interval = 1 km; areas lower than -3 km lightly stippled; areas higher than 0 km solid black. Contoured area is underlain by overlapping ejecta blankets of E = Elysium, U = Utopia, C = Chryse, and T = Tharsis basins, which are defined by the largest ring diameters inferred by the authors originally proposing these basins. Unlabeled rings are new basins proposed by Schultz and Frey (1990). Areas covered by volcanics or by young polar layered deposits are vertically striped.

Moon and to expectations for Mars (e.g., Wichman and Schultz 1989). A second approach, also proposed by Frey and Schultz (1989, 1990), is to postulate some combination of cooling at depth and crustal loading by later volcanism in order to lower areas of lowland outside of basin rims. A third possibility is to postulate the existence of additional, now cryptic basins within the lowland due to impact clustering. The second and third approaches are discussed in greater detail in the next section.

2. Reasonableness of Physical Processes

Overlap of large basins clearly does not violate any physical principles. However, attempts to explain how areas outside the rims of all these overlapping basins become lowered by several kilometers run into consistency problems. The recent model of Frey and Schultz (1989, 1990) suggesting that loss of impact-generated heat would cause overall subsidence sufficient to explain relationships such as seen in Fig. 2 contains two significant unresolved problems: (1) Geophysical models of basin subsidence (Bratt *et al.* 1985) indicate that essentially all post-impact-basin subsidence due to loss of

impact heat is confined to the area within the rims of basins, and therefore cannot account for the significant amount of required subsidence of terrain external to basin rims; and (2) the model depends in part on the original absence of ejecta adjacent to the basins, an assumption that is almost certainly invalid. Furthermore, most younger volcanics also will occur within the basin rims simply because these volcanics will tend to pond in places that already are low. This certainly is the dominant pattern on the Moon (e.g., Solomon and Head 1979, 1980). The loci of the Elysium and Tharsis volcanic provinces may be related to overlapping basin structures, as suggested by Frey and Schultz (1990), but these provinces are not properly located and are generally too young to have any relevance for the origin of the topographic dichotomy as a whole. Although more work on some of these ideas is warranted, the thermal/volcanic mechanisms proposed to date do not seem to be effective ways to produce the entire lowland from a small number of basins.

Another point concerning the multiple-impact hypothesis deals with the need for a statistical clustering of basins. Unless the planet possesses some inherent hemispheric inhomogeneity in the way the crust responds to impacts, *any* attempt to explain the dichotomy via impact depends on a statistical clustering of impacts in the northern lowland. This point is independent even of any assumptions about the behavior of ejecta. Unless impacts are significantly more numerous within the lowland than elsewhere, there simply is no reason to expect that the lowland will differ in any way from the rest of the planet.

A key fact to keep in mind when this clustering issue is considered is the obvious point that all basins are not the same size. Instead, they possess a size-frequency distribution with many small basins and few very large ones. This fact means that the required clustering can occur in a variety of ways. At one extreme, many impacts of small to moderate size can be clustered for some reason within the lowland, with a significantly smaller basin concentration outside it. At the other extreme, the impactor population can possess, at the largest size, a single body that creates a single basin with a size comparable to that of the lowland. This is clustering, too, with a cluster size of one; the effectiveness of the clustering comes from the large size of the basin involved. Consideration of the need for clustering thus raises an important point: There is in some sense a continuum of impact hypotheses, ranging from domination by a single large basin to clustering of a number of smaller ones. Even if a single impact dominates, there will always be superposition of smaller basins. If instead multiple impacts were responsible, there always will be one impact that was the largest and most important. The key point that differentiates the "single-

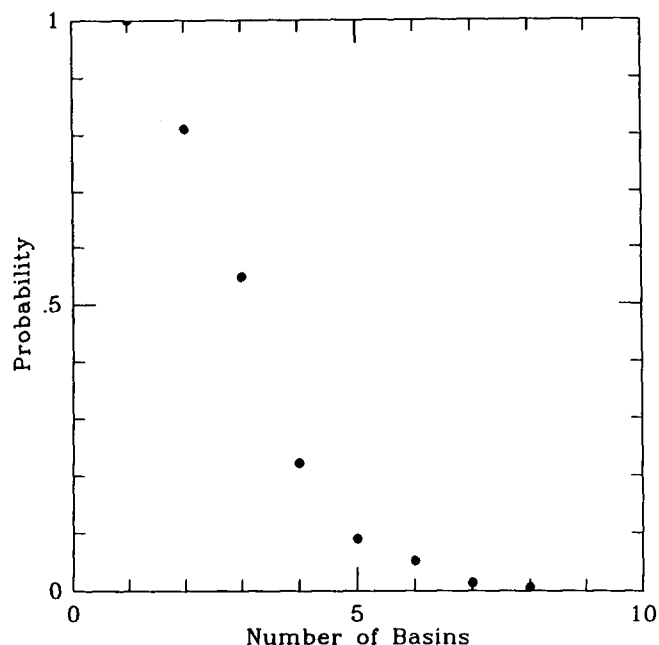


FIG. 3. Probability of chance clustering of basins within any area on Mars defined by a small circle with a radius of 65° .

impact" hypothesis from the "multiple-impact" hypothesis, however, is whether or not the largest basin in the distribution has a size comparable to that of the lowland itself.

None of the presently identified basins in the northern lowland, with the exception of Borealis, approach the size of the lowland. We have already explained why we believe that these identified basins cannot by themselves account for the lowland. So, simple geologic considerations suggest that the observed degree of clustering, such as it is and excluding Borealis, is inadequate. The only alternative requires the existence of still more, now completely masked basins located in places that should be high but are not (cf. Fig. 2). These cryptic basins *cannot* be balanced by equivalent impact densities outside the lowland; they must be concentrated preferentially within the lowland.

It is straightforward to show that chance concentration of even a modest number of additional basins in Mars' northern lowlands without equivalent basin formation outside of the lowlands is statistically implausible. We have performed a simple calculation of the probability of impact clustering on Mars using a Monte Carlo approach and assuming a spatially random distribution of impactors (Fig. 3). We give, as a function of the number of impacts, the probability that all of those impacts will be clustered within an arbitrary small circle with a radius of 65° , the approximate size of the Martian northern lowlands (for the calculation, an extra 500 km was added to this radius

to include any 1000-km basins at least 50% within the 65° circle). For one basin, of course, the probability is unity; for eight basins, it is substantially less than 1%. This simple exercise suggests that there are severe limits on how many hidden basins can be concentrated in the northern lowlands.

3. *Consistency with Geological and Geophysical Evidence*

Geological mapping and Viking LOS gravity clearly support the existence of several large basins within the northern lowland (Sjogren 1979, McGill 1989, Schultz and Frey 1990). There are no consistency problems for the multiple-impact hypothesis with respect to the second-order topographic details of the dichotomy; in fact, these basin structures clearly represent the best way to account for most of these details. The difficulty with this hypothesis lies not with the existence of these basins nor with their importance in defining topographic details, but with the issue of whether or not they can explain the dichotomy as a whole.

CONCLUSIONS

Three types of hypotheses for the origin of the Martian crustal dichotomy have been proposed: origin by endogenic processes, origin by a single mega-impact, and origin by multiple overlapping impacts. Each hypothesis is consistent with some of the geological and geophysical evidence now available, and each also experiences difficulty accounting for some of this evidence. All must encompass at least some erosional modification of the dichotomy boundary.

The large basins proposed as the cause of the dichotomy in the multiple-impact hypothesis almost certainly exist, and it is clear that they have had a profound effect on the topography within the lowland, and locally on the shape of the dichotomy boundary. However, we believe that reducing the large areas of northern lowland that lie outside of the rims of these basins to levels several kilometers below the upland requires an additional process or processes. The proponents of the Borealis basin would argue that these areas already were low before the younger basins formed; proponents of endogenic hypotheses would support a similar argument, except that endogenic lowering could occur either before or after the lowland basins were formed. Proponents of the multiple-impact hypothesis must argue for some combination of additional cryptic basins, no ejecta blankets close to basin rims, and thermal subsidence. In all cases, the real origin of the lowland is not the overlapping basins but the "additional" process or processes.

Although both the Borealis and endogenic hypotheses

can explain the dichotomy as a whole, both suffer from a lack of unequivocal geological and geophysical evidence in support of their reality. There is little concrete evidence for Borealis—its attractiveness derives from its simplicity and from the realization that such large events probably were not unusual early in Solar System history. Nevertheless, the continued search for geological and geophysical signatures of a possible Borealis impact is important. A post-early bombardment endogenic origin for the dichotomy is supported by a reasonable body of geological evidence. However, much of this evidence is circumstantial and therefore open to conflicting interpretations, particularly regarding whether endogenic activity caused the formation of the dichotomy or only its modification. Geological evidence is especially important for endogenic hypotheses because their validity (or lack of validity) rests almost entirely on interpretations of the geologic record.

The gathering of additional geological data is not likely to be as crucial for the multiple-impact hypothesis as it is for the other two because there is no need to prove the existence of the basins nor the reality of the impact process. The problems requiring attention relate instead to the extrapolation from a few basins to the entire lowland, both because much of the lowland is external to the rims of these basins and because even basins within the lowland will transport much of their ejecta to other points within the lowland. Models proposed in discussions or figures (Frey and Schultz 1988, 1990) to avoid these difficulties in our opinion involve controversial and unexpected mechanisms that need to be justified before the dichotomy as a whole could be explained as due to multiple impact.

Neither the Borealis mega-impact hypothesis nor any endogenic hypothesis can account for all the characteristics of the Martian dichotomy by itself. Both clearly require the presence of overlapping basins to explain many of the topographic characteristics of the dichotomy boundary and the lowland. Some erosional modification also is required. Nevertheless, these hypotheses seem better able to explain the dichotomy as a whole than is the multiple-impact hypothesis.

It may be possible to choose between the endogenic and single-impact hypotheses using data from future Mars missions. Such data might include an improved gravity model for the planet, accurate altimetry, higher-resolution images, and seismic investigation of the planet's crustal structure. Serious problems requiring attention include the reality and extent of erosion during the early stages of the primordial bombardment, the fate of the large volume of material removed to create the northern lowland, and the nature of a mantle process that could create such a singular feature as the Martian crustal dichotomy endogenetically.

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