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Age relations of Martian highland drainage basins

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Abstract. Dendritic valley patterns in the equatorial highlands of Mars show evidence of internal drainage into restricted basins, which are interpreted to be floored with sedimentary fill. Based on crater frequency characteristics of six areas of enclosed basins, the origin of these intercrater plains fill units ranges from middle to late Noachian. In contrast, the age of modification of the same plains units derived from the frequency of fresh craters occupies a relatively narrow range centered on the Noachian/Hesperian boundary. In half the areas studied the timing of highlands and plains crater modification is consistent with a sedimentary origin for basin fill materials. The other plains units most likely consist of interlayered sedimentary and volcanic materials. Relations between the age of stability of these internally drained highland units and their elevation are not as distinct as prior studies suggested; a trend of decreasing age with decreasing elevation for the plains materials is not matched by similarly derived ages of the dissected highlands. Remapping and age dating of the dissected highlands and associated basins suggest that volcanic plains may be more extensive than those used in past models for magma and volatile evolution, and support local volcanism rather than a global-scale magmatic head model for highlands plains formation.

Introduction

In addition to the well-known runoff and outflow channels, layered polar deposits, and other surface features, the record of climate change on Mars is recorded by the state of preservation of highland surfaces and, in particular, the highland crater population [*Arvidson*, 1974]. Prior investigations of the Martian highlands have emphasized the role of fluvial [*Craddock and Maxwell*, 1993], aeolian [*Grant and Schultz* 1990; 1993], and a combination of processes [*Chapman and Jones*, 1977] in modifying the highlands. Investigations of Martian channels have delineated a variety of ages for their origin based largely on stratigraphic arguments: large outflow channels appear to have formed in the relatively recent (Amazonian) past [*Baker and Kochel*, 1979; *Tanaka*, 1986], whereas investigators agree that the dendritic valleys of the highlands are much older [*Malin*, 1976; *Masursky et al.*, 1977; *Pieri*, 1980; *Carr and Clow*, 1981; *Carr*, 1986]. While the timing of Mars channel formation is thus somewhat constrained, the mechanism of their formation is not, and unambiguous evidence for either runoff or sapping has not yet been identified.

In studies based on available topography and published geologic maps at the 1:15M scale, we used the frequency of fresh craters to determine the time at which highland modification ceased in the plateau and dissected materials of the highlands [*Craddock and Maxwell*, 1993]. Earlier work in the eastern hemisphere had suggested that fluvial erosion of highland terrain was the primary agent responsible for modification of the older crater population [*Craddock and Maxwell*, 1990]. Although both aeolian and volcanic modification no doubt aided highland modification in certain regions, highland valley networks occur on the oldest Martian terrain characterized by a degraded crater population, and are located throughout the equatorial region. The widespread distribution of these networks suggests the necessity of a planetwide mechanism(s) for terrain modification. We found that the age of stability represented by the fresh crater population varied with elevation such that the most elevated parts of the cratered terrain became stable first, followed by successively lower elevations, suggesting a causal relationship with a decreasing Mars atmosphere required by the need for recharge of the fluvial channels [*Craddock and Maxwell*, 1993]. *Dohm and Scott* [1993] found similar relations between the elevations and ages of Martian channels. In our prior studies, crater populations were binned by geology, latitude, and elevation, and the number of fresh impact craters per unit area was taken to represent the time at which degradation ceased and the surface became stable. Only the Noachian dissected plateau and highland plateau units (Npld and Npl_1 units of *Scott and Tanaka* [1986] and *Greeley and Guest* [1987]) were used because of their erosional characteristics and widespread occurrence.

Among and within the exposures of ancient (Noachian) materials are relatively smooth deposits of intercrater plains; their extent is not great enough in most instances to require separation on small-scale mapping, but they can be delineated on the 1:2M mosaics and the 1/256 degree/pixel Mars Digital Image Mosaic (MDIM). Because of the smooth, subdued nature of these units, they may consist of sedimentary materials shed from the surrounding highlands. In fact, *Scott et al.* [1992] and *Goldspiel and Squyres* [1991] have argued that basins containing such materials may once have held standing water. Such deposits may be of varied origin; where wrinkle ridges are prominent, plains units have been interpreted as volcanic flows [*Greeley and Spudis*, 1981]. But even within such units, an admixture of sediments may be present as an underlying unit or a thin surface veneer, and ridges are not a unique indicator of volcanic plains [*Plescia and Golombek*, 1986; *Watters*, 1992].

In order to test whether local erosion was a major contributor of material to the intercrater plains, and whether the timing of erosion of the dissected highlands is coincident with deposition of a sedimentary cover, we have remapped and determined fresh

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crater and total crater size-frequency statistics for six discrete areas in the Martian highlands characterized by internal drainage and intercrater plains. Four of these areas were interpreted to represent depositional basins by *Goldspiel and Squyres* [1991], and we have studied two additional areas where dendritic drainage and intervening plains also suggest internally drained systems. The use of fresh craters to determine the time at which the surface became "stable" is predicated on the hypothesis that the process(es) that modified the degraded crater population were not related to substrate characteristics (strength, degree of hydration), and were those responsible for the formation of highland valleys. The evidence that substrate is not involved, at least for the plateau and dissected plateau units, lies in the observation that the fresh and degraded crater frequency within those two units does not vary as a function of geologic unit [*Craddock and Maxwell*, 1993]. Whether the fresh crater statistics of the dissected highlands and associated plains are similar thus provides an additional test of a causal relation.

The results reported here address four questions. (1) What are the time relations between dissected terrain and neighboring smooth intercrater materials, presumably the sinks of the eroded highland material? If the fresh, unmodified crater population on the dissected highlands represents the age at which significant modification ceased, then the neighboring intercrater plains should have formed contemporaneously or earlier than that time, assuming a sedimentary origin. (2) Do the age/elevation relations determined previously [*Craddock and Maxwell*, 1993] hold up on a local level by looking at different internally drained basins? The basins studied here occur over a 5-km elevation range, allowing us to test at a different scale the variation of surface stability age with elevation (albeit with a much smaller sample size). (3) What is the temporal variation of different intercrater plains "deposits" in the Martian highlands? Prior work based on geologic relations among highland units suggested to *Wilhelms and Baldwin* [1989] that extensive sills in the highlands were responsible for the lack of sharpness of unit contacts, and the varied morphology of channels. If such sills and modification of overburden resulted from a contemporaneous magmastatic head, then we would expect the ages of different intercrater plains deposits to be similar within the highlands. (4) Can crater-age relations be used to help distinguish among sedimentary versus other modes of origin of the intercrater plains? In addition to formation by softening of overburden via intrusions, the relative contribution of volcanism versus sedimentation remains poorly understood.

Methods

Geologic Mapping

In each of the six areas studied (Figure 1), the geologic boundary between dissected and smooth highland materials was remapped on the 1:2M Viking Orbiter controlled mosaic using images derived from the MDIM and individual Viking Orbiter frames as a guide to unit classification. Nearly all of the terrain in these areas was originally mapped at the 1:15M scale as Noachian dissected plateau or Noachian highland plateau materials [*Scott and Tanaka*, 1986; *Greeley and Guest*, 1987], but we further subdivided those materials into dissected (d) and intercrater plains (Ip) components. In all of the six areas studied, an additional guide to classification was the presence of discrete fretted mounds, previously identified as sedimentary remnants in the drainage basins studied by *Goldspiel and Squyres* [1991]. As also noted by *Wilhelms and Baldwin* [1989], we found that the boundaries between intercrater plains materials and dissected highland terrain are sometimes diffuse (especially where resolution does not permit delineation of a distinct boundary), and in some cases the use of channels alone is of no help in distinguishing the different terrain types. While dendritic channels occur primarily on the highland terrain, other, "throughgoing" channels occur in the intercrater plains, suggesting that the uppermost surface of some intercrater plains units was present prior to the end of fluvial dissection.

Crater Statistics

As noted in studies since Mariner 9, the Martian highland crater population displays a wide variety of morphologies resulting from erosion [*Chapman and Jones* 1977; *Craddock and Maxwell*, 1990, 1993], aeolian infilling [*Moore*, 1990; *Grant and Schultz*, 1990], and volcanic modification [*Arvidson et al.*, 1980]. For this study, a binary classification of modified and fresh craters was applied to each area, and crater counting was used to determine the total age of the unit as well as the age of stability represented by fresh craters with complete rims and undisturbed ejecta (as resolution would permit detection). In doing this work on restricted areas of internally drained highlands, our sample size ranged from 56,168 to 568,181 km^2 (Table 1), much smaller than previous work, but large enough to compare among the different units.

All craters greater than 1 km were measured and classified using the 1:2M Viking Orbiter controlled mosaics as a base, and images from the MDIM as a supplement to identify whether a rim and ejecta blanket were present. Although the plots shown here indicate crater frequencies down to 1 km diameter, craters in that size range are most subject to counting and classification error because of resolution. The best size class for distinguishing ages in the surface extents used in this study are in the 2- to 10-km diameter range; below this size, resolution problems and slope effects enhancing small crater degradation dominate, and above this, the poor statistics of relatively small counting areas become important. For ease of comparison among the different units and with Martian time stratigraphic boundaries [*Tanaka*, 1986], we report ages at the N(5) range, the cumulative number of craters greater than 5 km diameter per million km^2.

By looking at the age of intercrater plains as defined by the total crater population, we are determining an age that represents the time over which the plains units were emplaced, as opposed to only the end of the period of modification as represented by fresh craters in the highlands. Craters formed on older surfaces within or below the plains deposits may protrude through the youngest deposited materials, thus leading to an apparent older (total) age of the surficial material. This effect is a function of crater size, which is why craters in the 2- to 10-km size range are suitable for dating plains units of 40- to 300-m thickness (using nominal rim height relations as determined by *Pike and Davis* [1984]).

Figure 2 shows schematically our interpretation of crater-frequency ages for the dissected highlands and the intercrater plains. If the channel-forming processes that modified the dissected plateau material were those responsible for deposition of the intercrater plains units, then we would expect that the age of the uppermost materials of the intercrater fill would approximate the age of the end of dissection of the neighboring highlands (the time at which crater modification ceased), assuming no later contribution to the plains unit from other

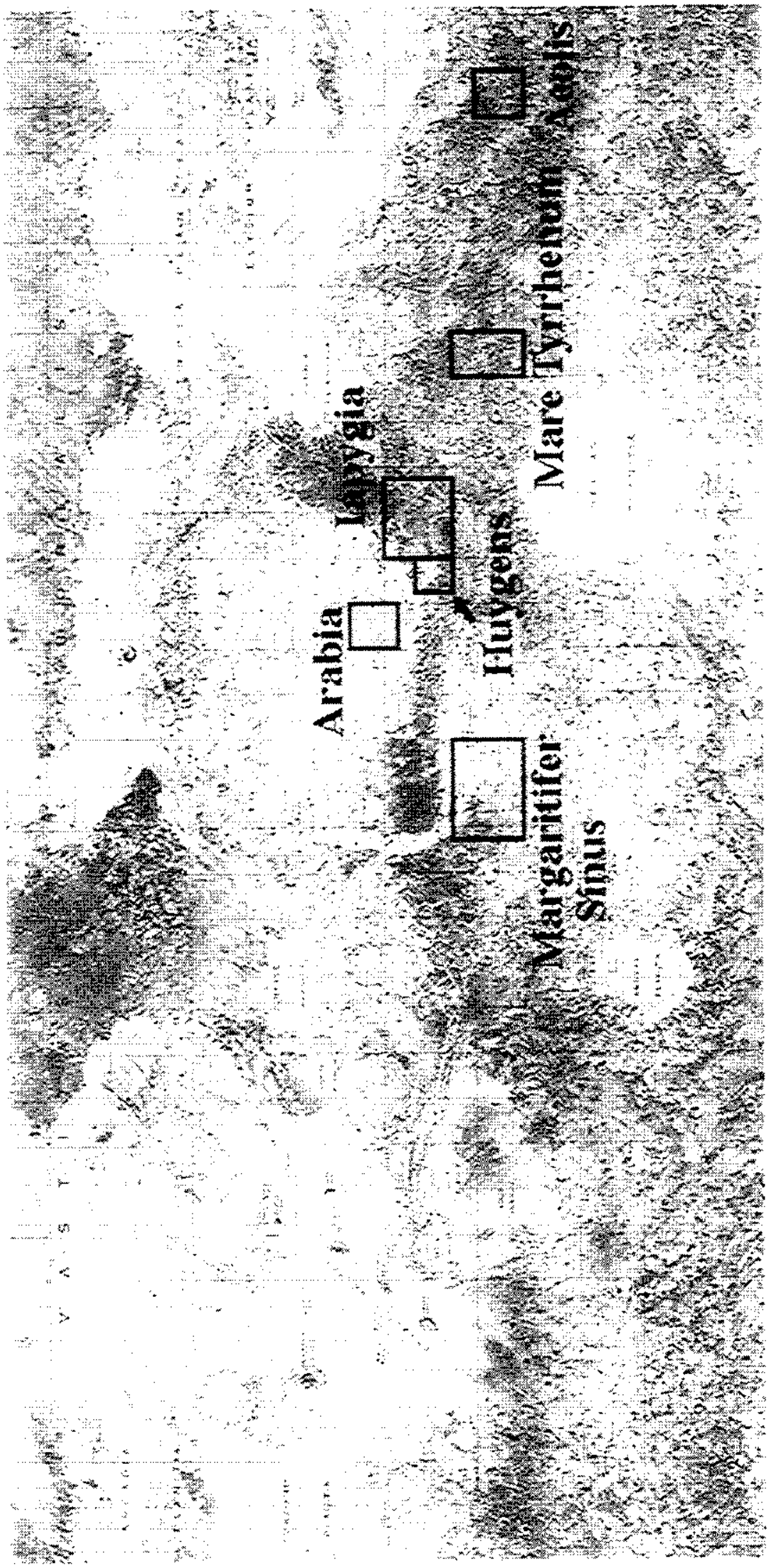


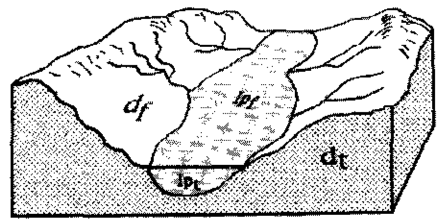
Figure 1. Mercator projection of the equatorial region of Mars showing areas of the highlands characterized by internal drainage networks on dissected terrain and smooth intercrater plains.

Table 1. Crater Counting Statistics for Highland Drainage Basins

	Location	Area, km^2		Total Craters		Age N(5)			
		A_d	A_{Ip}	d	Ip	d (Total)	d (Fresh)	Ip (Total)	Ip (Fresh)
Tyrrhenum	15° to 30°S 260° to 270°W	335,740	149,230	524	153	877	243	255	154
Iapygia	0° to 15°S 292.5° to 312.5°W[a]	437,374	400,566	466	334	490	251	315	167
Margaritifer Sinus	15° to 30°S 0° to 22.5°W	436,681	568,181	566	639	501	217	382	187
Huygens	7.5° to 15°S 307.5° to 317.5°W	202,128	56,168	160	58	480	188	534	303
Aeolis	20° to 30°S 202.5° to 212°W	204,844	97,627	264	112	659	205	430	256
Arabia	2.5°S to 7.5°N 320° to 330°W	197,987	152,474	188	184	490	217	413	151

Here, d, dissected highlands; Ip, intercrater plains; N(5), number of craters ≥5 km diameter/10^6 km^2

[a] Extends to 315°W north of 7.5°N.



$Ip_f = d_f$ Crater modification process stopped in both units at the same time.

$Ip_t = d_f$ Time at which intercrater plains was emplaced = time at which highlands became stable.

$Ip_t > d_f$ Emplacement of intercrater plains ended before the end of highland *degradation.*

$Ip_t < d_f$ Emplacement of fill younger than end of highland degradation suggests alternative emplacement mechanism for plains.

Figure 2. Schematic guide to interpretation of crater frequency ages for intercrater plains (Ip) and dissected highlands (d). Subscripts "t" and "f" refer to total and fresh crater populations.

processes. Later, or additional fill in the intercrater plains from sources other than highland erosion would result in ages for the total fill being significantly younger than the time of highland stability. Conversely, plains fill may appear older than its true age by craters on underlying materials protruding through a thin fill. Thus, morphologic studies of each area are a prerequisite to interpretation of crater-frequency relations.

Sources of Error

In order of increasing importance, the primary sources of error in deriving timing relations for the highlands are in the geologic assignment of units, the crater classification of fresh versus degraded craters, and the inherent low resolution of available topography. At the 1:2M scale, distinguishing expanses of highly dissected, rugged upland materials from smooth plains is not difficult, but the exact boundary is subject to error due to both image resolution and the gradational effects of subsequent geologic processes. A major problem in interpretation of the smooth intercrater plains is those units with throughgoing drainage channels. These channels are not dendritic, but go on for tens of kilometers with few or no tributaries, and we have assumed that the smooth, uncluttered surface indicates that those units are indeed plains fill of some type. Such materials with throughgoing channels were emplaced prior to the time at which highland fluvial activity ceased, in which case the age of the deposit should be greater than the age of highland stability as represented by the fresh crater population in the highlands. Even with the lack of such diagnostic features as wrinkle ridges or flow fronts, these materials may represent an older period of volcanic plains formation, capped by a *sedimentary mantle that formed throughout the period of* highland erosion and deposition.

The effect of resolution manifests itself in two ways: it reduces our ability to recognize craters at the small end of the size spectrum (where other processes such as haze [*Kahn et al.*, 1986] and aeolian blanketing [*Soderblom et al.*, 1973] also influence counting statistics), and it makes it difficult to

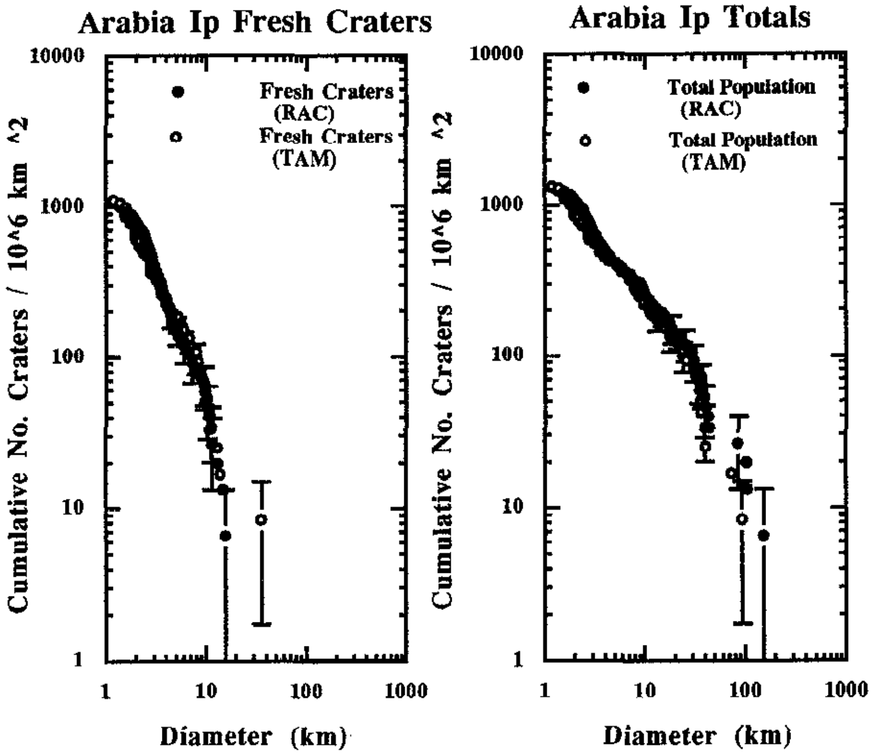


Figure 3. Crater frequency plots derived independently by the authors for the Arabia region. Operator error in classifying crater morphology was tested for three areas, and found to be within the $\sqrt{n}$ standard deviation.

determine whether the rim and ejecta are in relatively fresh or degraded condition. We have tested the effects of "operator error" by independently classifying and counting three of the areas studied here. As Figure 3 indicates, the similarity of the crater curves derived independently by the two authors suggests that operator error is at the same level as the $\sqrt{n}$ formal error shown on the graphs. For diameters less than 10 km, this error is about the size of the plot symbols. For each of the plots, we show curves as well as N(5) values that are derived from the tabular data. This approach avoids introducing bias from fitting the crater count data to a production curve [*Maxwell and McGill*, 1988]. As noted below, several of the curves have pronounced bends, consistent with the geologic observations of resurfacing in both the highlands and intercrater plains.

The comparison of the ages reported here with elevation is subject to the inherent low resolution of available Martian topography. The absolute accuracy in elevation for the areas studied is stated to be ±1 km [*U. S. Geological Survey* (USGS), 1991], so that correlation of small sampling areas with elevation should be considered tentative. In remapping the geology of the drainage basins, we noted that the generalized contours do not always follow what would intuitively be the normal to the apparent slope, and within each area studied, the topographic resolution does not permit separation of the dissected highlands from the intercrater plains.

Highland Drainage Basins

The age relations within each of the highland drainage basins are treated below in order of increasing complexity of timing. In the Tyrrhenum and Iapygia regions, ages of intercrater materials are equal to the age of highland stability, whereas in the Margaritifer Sinus, Huygens, Aeolis, and Arabia regions, age relations are more complex. Geologic relations within the plains units are also complex. Such units may consist of volcanic or sedimentary materials, which have not been distinguished on the basis of mapping alone. The areas, number of craters, and N(5) ages of the areas studied here are summarized in Table 1.

Tyrrhenum

A broad area of dissected terrain centered 500 km west of the Tyrrhena Patera volcanic complex consists of small highland patches of interior drainage that appear to debouch into smooth intercrater plains (Ip) deposits. Intercrater plains in this region are both featureless (Figure 4a), and where connected with obvious volcanic units of Tyrrhena Patera, they may display wrinkle ridges and a few possible flow fronts. *Greeley and Crown* [1990] interpreted the smooth plains materials at the eastern part of the study region as basal ash flow deposits of Tyrrhena Patera (unit Hsp). Smooth plains materials at the southernmost part of this region were designated highland plateau materials [*Crown et al.*, 1992], consistent with their depiction on the 1:15M geologic map series [*Greeley and Guest*, 1987]. Because of the absence of unique volcanic indicators, the demarcation between volcanic deposits and potential sedimentary fill is difficult here. We are confident that the basin located at 25°S, 264°W is floored with highland-derived materials, but since the surface grades into the Hsp and Tyrrhena units to the east, there may well be a mixture of volcanic and sedimentary fill. For consistency, and because of the great number of highland drainage channels, we used all smooth plains materials in this region to derive an age for the uppermost units of the plains.

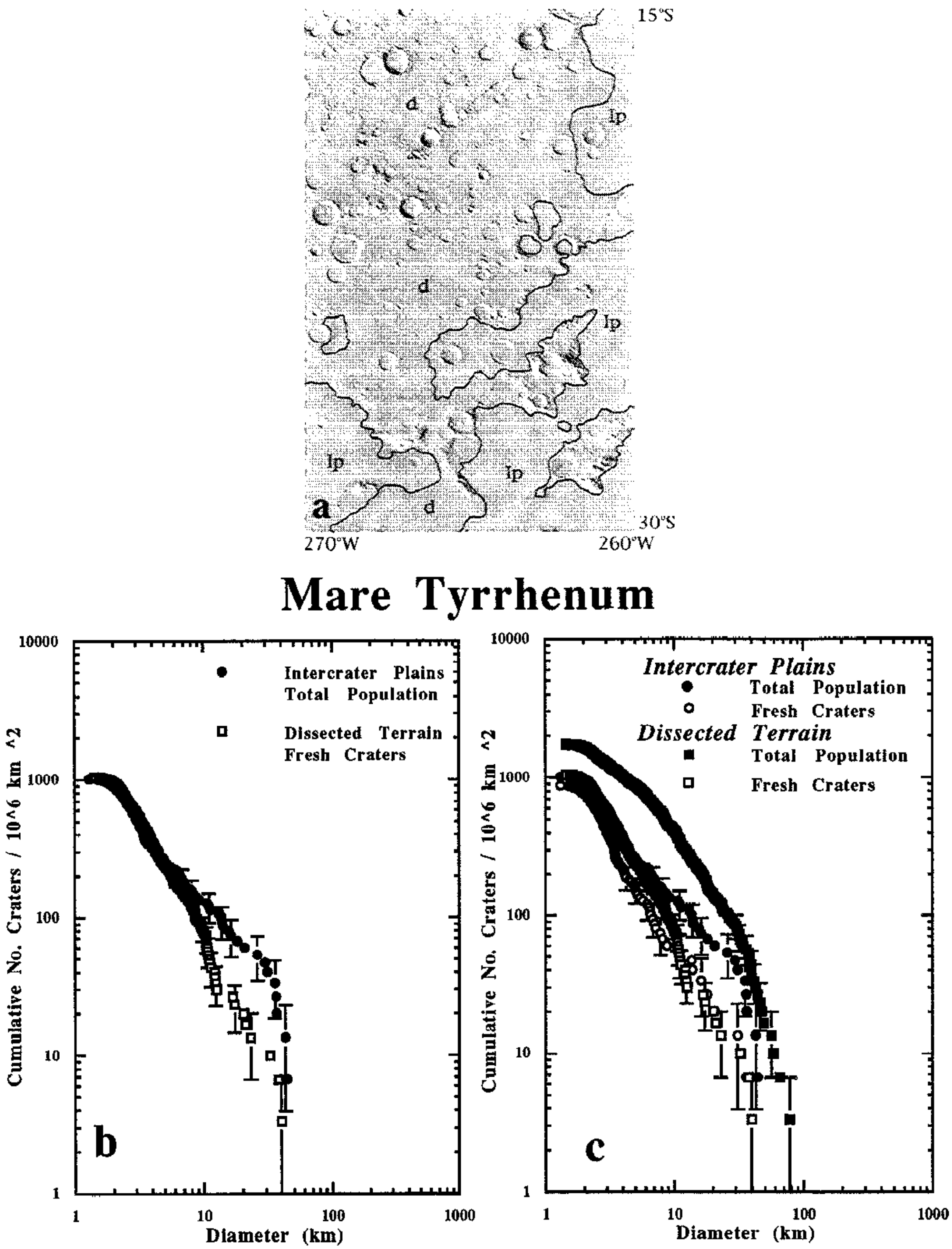


Figure 4. (a) Dissected (d) terrain and intercrater plains (Ip) of the Tyrrhenum region, west of Tyrrhena Patera. (b) Cumulative crater frequencies comparing the total population of craters on the intercrater plains with the fresh crater population on the dissected highlands, which indicates the coincidence of plains formation with the end of highland crater modification. (c) Summary diagram of crater frequency on each unit.

A comparison of the crater frequency curves of the intercrater plains with those derived from only the fresh craters of the dissected terrain indicates that the two frequencies are indistinguishable for crater diameters between 2 and 10 km (Figure 4b), suggesting that the age of the fill material is coeval with the onset of stability of the highland surface. Since the fresh crater population of both the dissected and plains materials is similar (Figure 4c), we believe that volcanic resurfacing within the two structural troughs was relatively minor, and that the primary source for the intercrater plains (basin fill) was material shed from the highlands. The crater age of the deposit (N(5)~250) indicates a late Noachian time of deposition, consistent with the stratigraphic age of intercrater fill defined on the 1:15M map series [*Greeley and Guest*, 1987], but slightly older than the Hesperian age of the smooth plains as defined by *Greeley and Crown* [1990].

Iapygia

Surrounding the north and east edges of the crater Huygens (15°S, 305°W) are numerous patches of intercrater plains bounded by dissected highlands (Figure 5a). Within several of these plains units are 20- to 30-km diameter, dissected mounds of material, similar to the fretted material interpreted previously as "aqueous basin fill" [*Goldspiel and Squyres*, 1991] or "fretted terrain" of *Baker* [1982, p. 63]. Although such deposits may have also formed as part of an aeolian mantle, their occurrence in the central portions of the smooth plains suggests that they are the remnants of fluvial or lacustrine deposits; no such fretted mounds were noted on the dissected terrain, as would be expected from an airfall deposit. As is the case with the Tyrrhena region, the intercrater plains east of Huygens may have some component of volcanic fill, suggested by the dark patchy nature and subtle lobate boundaries within the plains. Elsewhere in this quadrangle, the boundary between plains and dissected highlands is more diffuse, consisting of a gradation from gullied highlands into neighboring "sinks." Continued fluvial modification beyond the time of intercrater plains formation is indicated by a valley (Naro Vallis) incised in the smooth plains surface north of Huygens.

The total crater population of the intercrater plains in the 2- to 8-km size range is nearly identical to that of the fresh craters on the neighboring dissected highlands (Figure 5b), although the plains population is slightly older (Table 1). For crater diameters greater than 8-20 km, the population curve of the intercrater plains approaches that of the highlands, suggesting that the plains fill is relatively thin since larger diameter craters tend to protrude through the fill. Such a correspondence in the crater curves is consistent with the observations of "ghost" craters within the plains. In addition, the fresh plains crater population (N(5)~170, early Hesperian) is slightly younger than the fresh crater population of the highlands (N(5)~250, late Noachian), suggesting later resurfacing of the plains, perhaps by the continued fluvial processes as indicated by the presence of Naro Vallis incised into the plains surface.

Margaritifer Sinus

The highly dissected terrain in the Margaritifer Sinus region (MC-19SE) contains both more extensive plains units than the Tyrrhena or Iapygia regions, and more numerous exposures of fretted (sedimentary?) mounds. Only the central part of this region was originally mapped as dissected highlands (Figure 6a), but remapping of this region at a larger scale indicates that even the Noachian plateau materials (Npl_1) of *Scott and Tanaka* [1986] contain dendritic channels. The intercrater plains here have a varied morphology, ranging from a smooth surface with aeolian splotches in the east (23°S, 4°W) to an irregular surface with wrinkle ridges and possible flow fronts. In places, irregular scarps and throughgoing channels suggest post deposition, erosional modification of the plains.

Age relations among the dissected highlands and intercrater plains are not as clear as those in Tyrrhena or Iapygia, but still suggest that the deposition of the majority of the fill ceased at the time of highland stability (Figure 6b). This interpretation is based on craters in the 2- to 4-km diameter range, but at diameters of 5 km, the age of the plains (N(5)=382) is greater than that represented by fresh craters in the highlands (N(5)=217). At diameters greater than 4-5 km, total counts for the highlands and plains units approach each other (Figure 6c). Consequently, we interpret the age difference between the fresh highland crater population and the total plains population to indicate the relatively thin fill of the plains, which causes older craters of the highland surface to show through. The throughgoing channels indicate that the uppermost strata of the intercrater plains were present prior to the end of fluvial erosion or any subsequent deposition was insufficient to mask the valley. It is apparent from the fresh crater populations in both geologic units that the period(s) of crater degradation ended at about the same time in both units (N(5)~220), or late Noachian.

Huygens

The area of dissected terrain west of the crater Huygens (Figure 7a) represents the most elevated region studied (elevations >5000 m), where radial drainage off the west flank of Huygens disappears into local smooth terrain, and a broad zone of northward trending dendritic drainage (Tisia Valles) also debouches to the north into smooth material. This region was mapped completely as dissected plateau material in prior work, but several expanses of smooth plains interrupt the cratered highlands in the northern part of the region, and a few scattered mounds of fretted material are present in the plains.

Unlike the three areas discussed above, the age of the intercrater plains (N(5)=534) is much older than the fresh crater age of the highlands (N(5)=188; Figure 7b). In the <10 km diameter range, the age of the plains approximates that of the highlands, and in fact, the frequency of plains craters is even greater than that of the (stratigraphically) older highlands. We attribute this apparent inconsistency in total crater frequencies to the preferential recognition of small craters in the smooth plains as opposed to the more rugged highlands, and note also that this is the smallest of the areas counted, with only 58 craters in the plains material. In addition to the possibility of observational bias, the total population of plains craters suggests thin deposits that do not completely mask the crater frequency of the underlying highlands.

The fresh crater populations differ on these two units, with the intercrater plains retaining a greater population of fresh craters than the highlands. Such a relationship could result from continued erosion of the highlands with little material being transported to the basins, or from differential erosion, the craters in the volcanic (?) plains being more resistant to erosion than their highland counterparts. Because of the small counting area, observational bias may be responsible for these results.

Aeolis

In the Aeolis quadrangle (MC-23 SW), one of the best examples noted previously as an interior drainage basin [*Goldspiel and Squyres*, 1991], a trough-like exposure of smooth material with wrinkle ridges is flanked by dendritic drainage flowing into it from both the west and east (Figure 8a). In addition to this north-south oriented trough, identical plains materials occur both within large craters (whose rims display both interior and exterior drainage), and in irregularly bounded areas delineated by the abrupt termination of drainage channels. Ridges and possible flow fronts are more numerous on these plains units than in regions discussed above, suggesting that volcanic cover may overlie any sedimentary fill, if present.

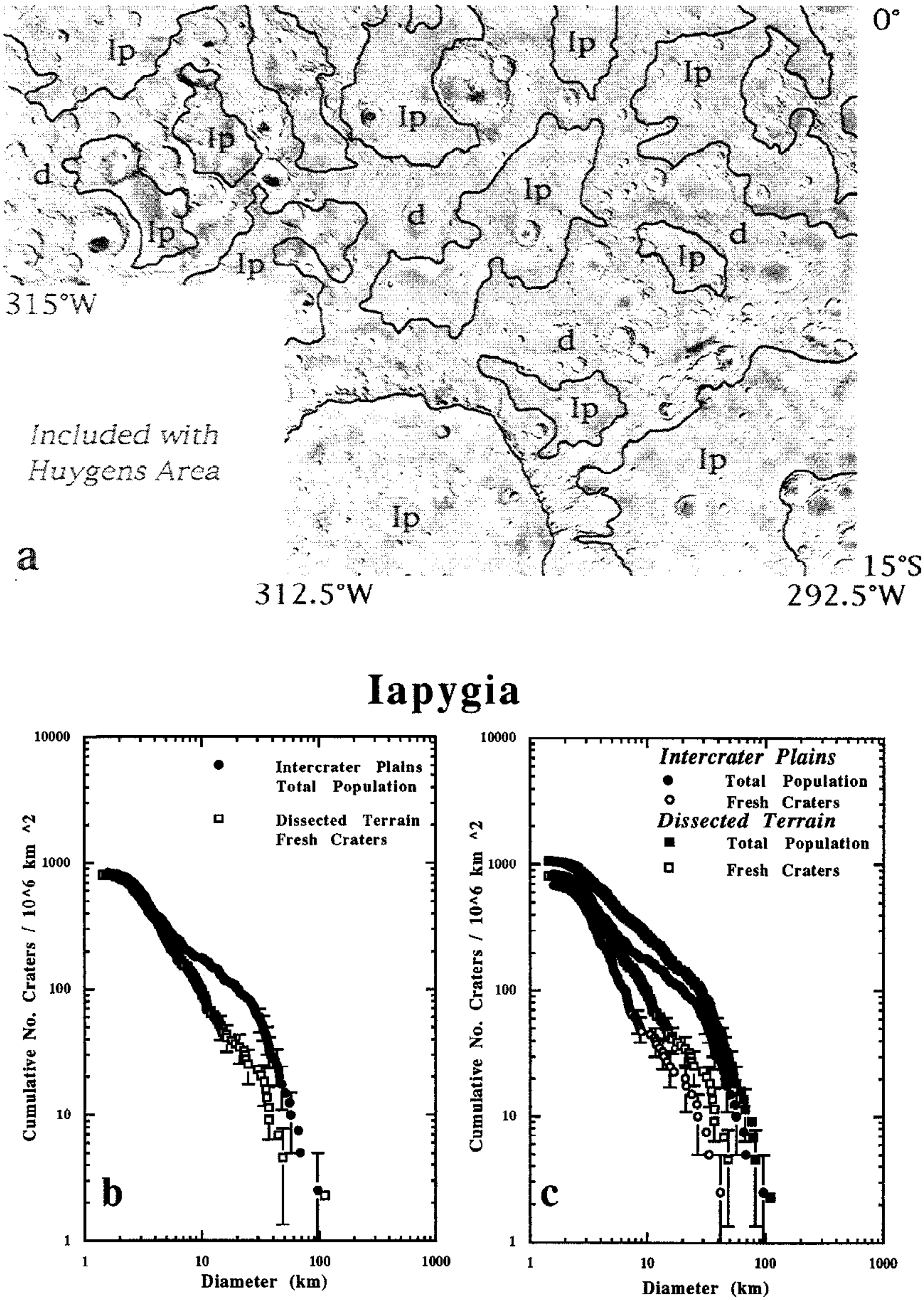


Figure 5. (a) Dissected (d) terrain and intercrater plains (Ip) of the Iapygia region. (b) Cumulative crater frequencies comparing the total population of craters on the intercrater plains with the fresh crater population on the dissected highlands. Crater frequencies in the 1- to 8-km-diameter range suggest deposition of plains via highland erosion. (c) Summary diagram of crater frequency on each unit.

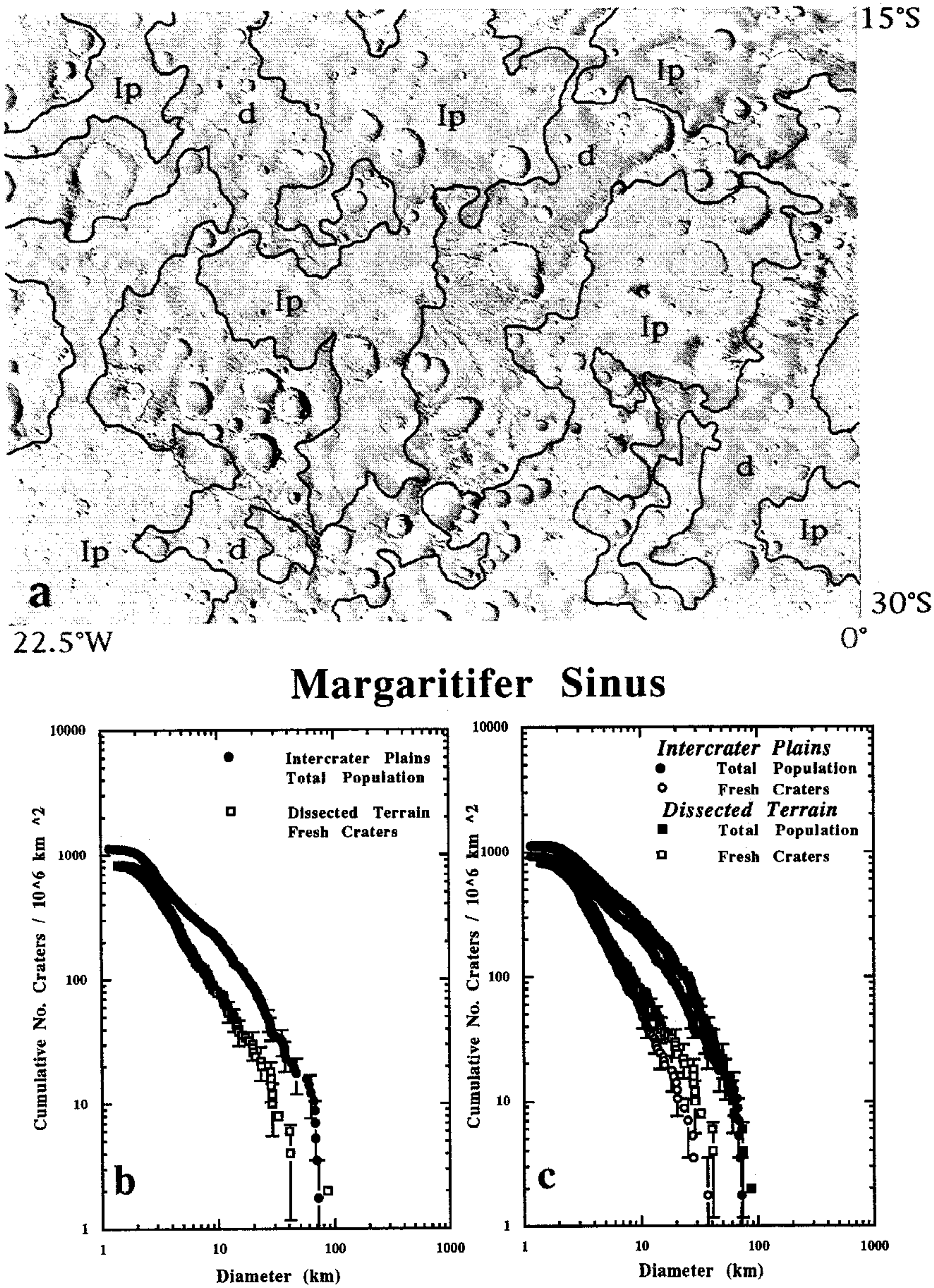


Figure 6. (a) Dissected (d) terrain and intercrater plains (Ip) of the Margaritifer Sinus region. (b) Cumulative crater frequencies comparing the total population of craters on the intercrater plains with the fresh crater population on the dissected highlands. A thin plains veneer of sediments is suggested by the match of the curves in the 1- to 5-km-diameter range. (c) Summary diagram of crater frequency on each unit.

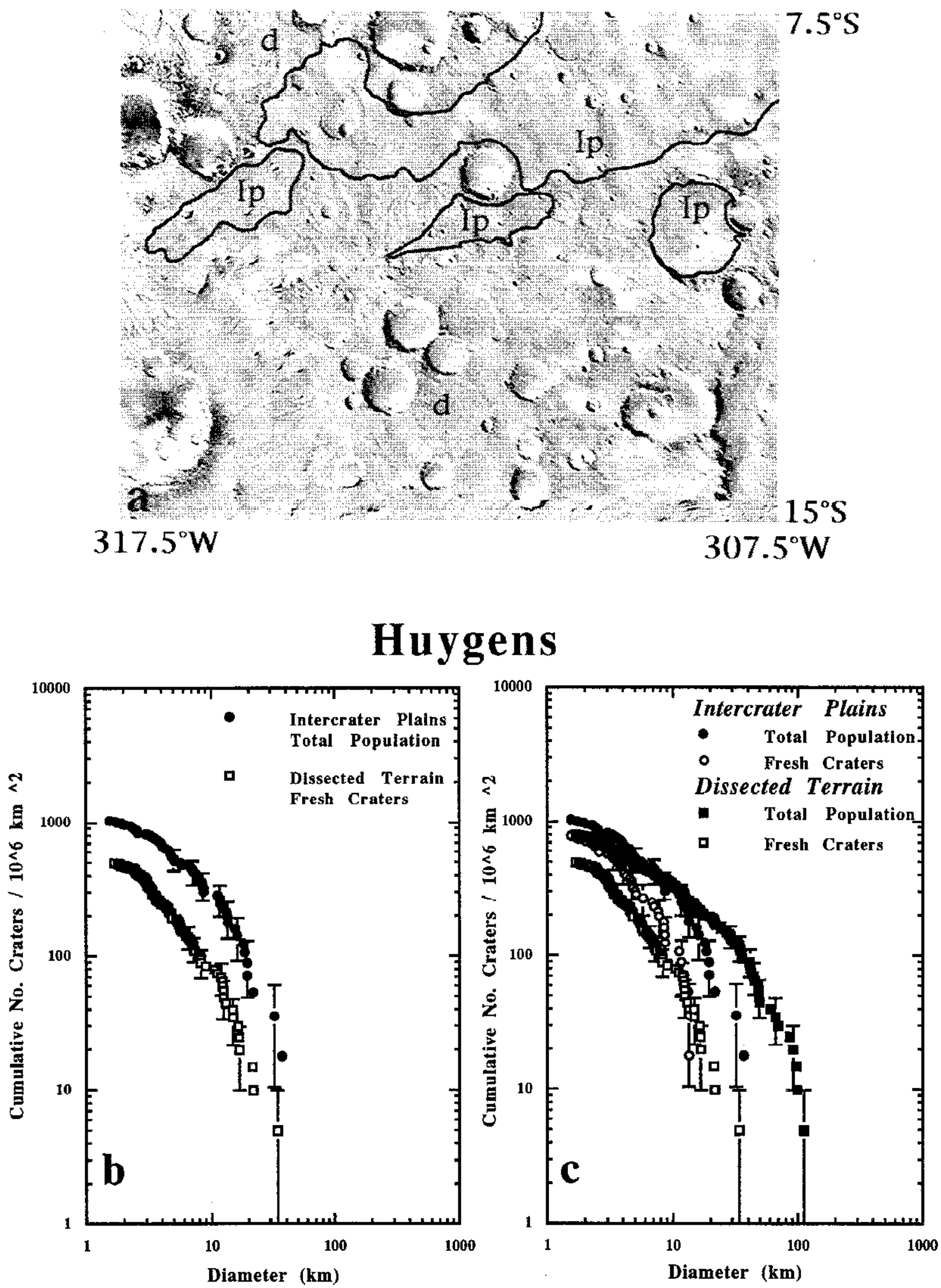


Figure 7. (a) Dissected (d) terrain and intercrater plains (Ip) of the area on the west flank of the crater Huygens. (b) Cumulative crater frequencies comparing the total population of craters on the intercrater plains with the fresh crater population on the dissected highlands. (c) Summary diagram of crater frequency on each unit. The correspondence of plains and highlands frequencies suggests a very thin plains unit.

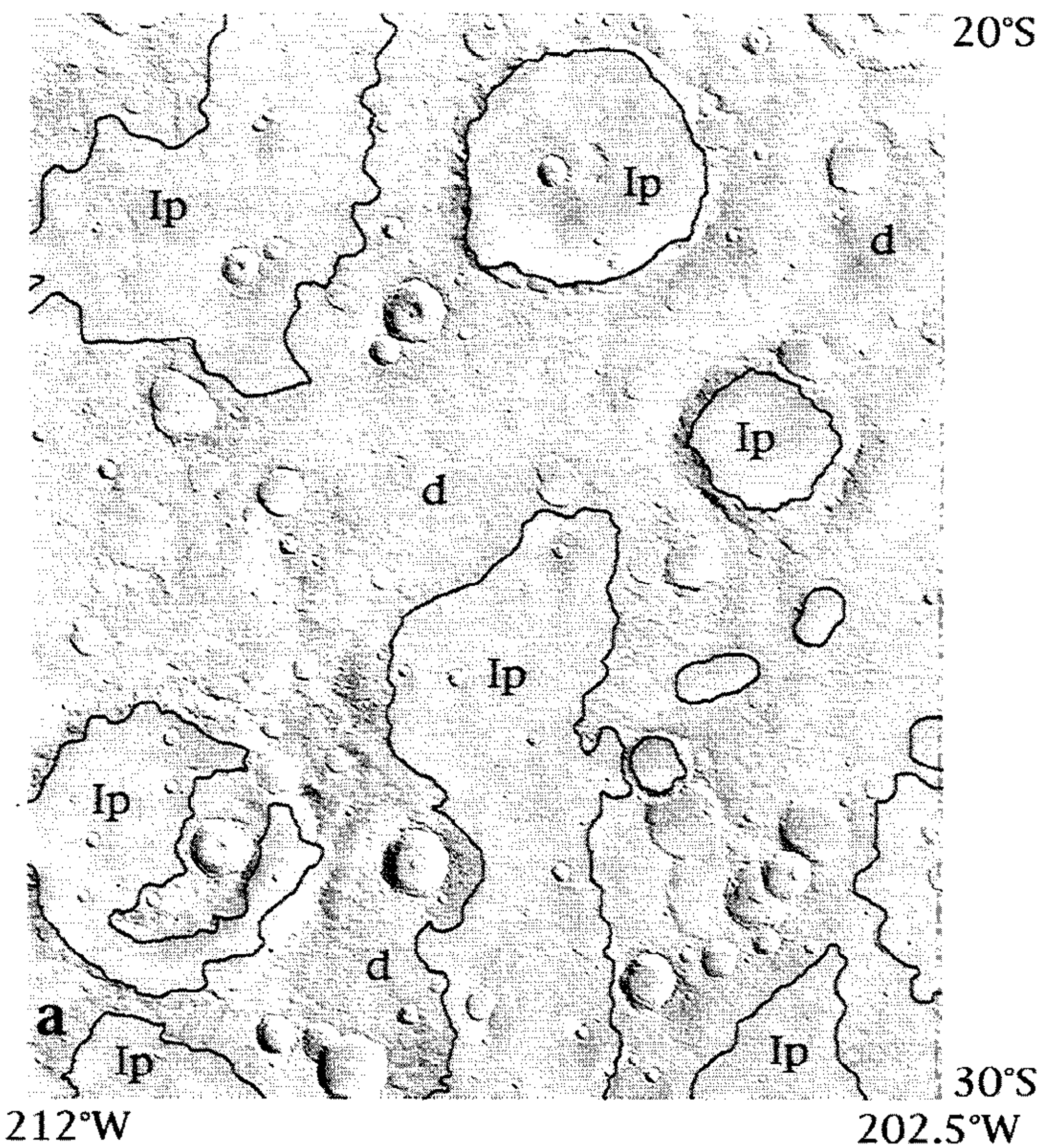


Figure 8. (a) Dissected (d) terrain and intercrater plains (Ip) of the Aeolis region. (b) Cumulative crater frequencies comparing the total population of craters on the intercrater plains with the fresh crater population on the dissected highlands. Stepped shape of the plains crater curve is consistent with a thin deposit and multiple resurfacing episodes. (c) Summary diagram of crater frequency on each unit.

Like the age relations in the Huygens region, the age of the fill material in the Aeolis region (N(5)=430) turns out to be older than the age of highland stability (N(5)=205; Figure 8b), and the older age of the plains materials suggests a plains origin unrelated to the timing of highland crater modification. Unlike the Huygens region, however, the fresh crater frequency on both units is similar (Figure 8c), suggesting that both units were emplaced prior to the cessation of crater modification. Because of the old total age of the intercrater plains, any late stage erosional contribution to the plains surface was likely minor. As shown in Figure 8c, the sequence of material emplacement and modification here is relatively simple; highland materials were emplaced during the middle Noachian (N(5)=659); the majority of plains materials in the later Noachian (N(5)=430), and crater modification via highland erosion and plains filling (but not enough to mask the true age of the deposit) continued into earliest Hesperian time (N(5)=205) on both units.

Arabia

Drainage patterns within the Arabia quadrangle are complex. In addition to the dissected highland material (in which the drainage appears to be truncated rather than forming true networks), Naktong Vallis heads in plains at the south edge of the region (2°S, 325°W), winds northward through dissected highland materials crossing a patch of smooth plains and a fretted mound, continues again through dissected terrain, forming the margin between highlands and intercrater plains before it passes northward out of the mapped area (Figure 9a). Both ridges and low scarps are present in the plains materials, although not as prevalent as in the Huygens and Aeolis regions. The area studied here is south of parts of Arabia where aeolian mantling is prominent [*Moore*, 1990; *Grant and Schultz*, 1990].

The age of the intercrater plains (N(5)=413) is greater than that of highland stability (N(5)=217), similar to relations found

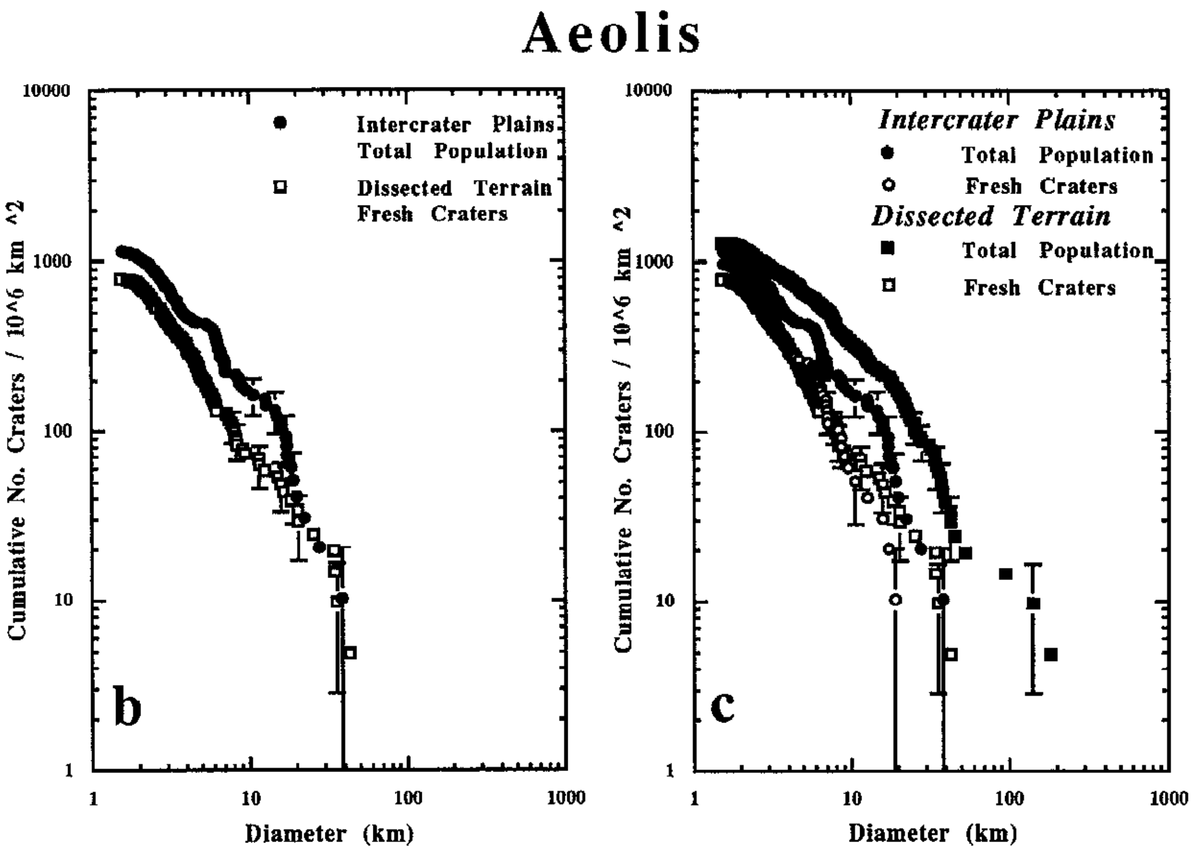


Figure 8. (continued)

in Huygens and Aeolis, but unlike those areas, there is little difference between the actual time of emplacement of both units as recorded in the total crater frequency record (Figure 9). Apparently, both the intercrater plains and adjacent highlands were emplaced during the middle Noachian, and both were subject to the late Noachian/early Hesperian surface degradation. Such age relations are consistent with the presence of Naktong Vallis, which crosscuts both geologic units, and we attribute the lack of integrated drainage in the plains units to a simple lack of suitable topographic slope on the previously emplaced plains, although gullies are present on the interior of old craters in the northern part of the area studied.

Summary

In all of the areas studied, the ages represented by the fresh crater population in the dissected terrain occupy a relatively narrow age range from N(5)=251 through N(5)=188, straddling the Martian time-stratigraphic late Noachian/early Hesperian boundary. The counts of total crater frequency in the dissected terrain are consistent with a middle Noachian time for formation of those materials, but it is apparent from the degraded nature of the terrain that erosion of those surfaces continued to modify the highlands until the early Hesperian, a time of major volcanism throughout the planet [*Frey et al.*, 1991].

The ages of formation of the intercrater plains as recorded by the total population of craters show more variation than the ages represented by the fresh craters alone. The ages of intercrater plains units studied here range from N(5)=534 (middle Noachian) through N(5)=255 (late Noachian, Figure 10). Such timing relations are matched by the surface stratigraphy and morphology; where throughgoing channels are present, the total crater-age of the intercrater plains is older than that of the fresh crater population of the highlands, indicating that fluvial erosion affected the previously emplaced plains units as well as the dissected terrain. The wide range in plains formation ages relative to highland stability and the differences in sedimentary versus volcanic origins argue against an intrusive event during a discrete time period as a mode for widespread highland modification [*Wilhelms and Baldwin*, 1989].

There is no simple relationship among surface ages by comparing fresh crater populations on the intercrater plains with analogous populations on neighboring highlands. In most cases, the time at which fresh craters are retained is slightly younger on the plains than on the highlands, but in the Huygens region, the reverse is true. With the exception of Huygens (with $N(5)_{Fresh}$ ages of 188 and 303 for highlands and plains respectively), all fresh crater ages are within N(5) frequency values of 100, suggesting that the crater modification process shut off in both the highlands and plains at about the same time.

As a test of prior studies that suggested an age-elevation relation for the timing of highland crater modification [*Craddock and Maxwell*, 1993], we used the data obtained in this study to evaluate those results on a local level. Unfortunately, the available topography does not permit determination of elevations within the individual basins studied here. However, the basins and neighboring highlands span an elevation range of 3.5 km, allowing comparison among the areas studied. Figure 11 shows the ages of the highland fresh crater population, and both fresh and total population for the plains units as a function of elevation. Although the fresh crater ages of intercrater plains

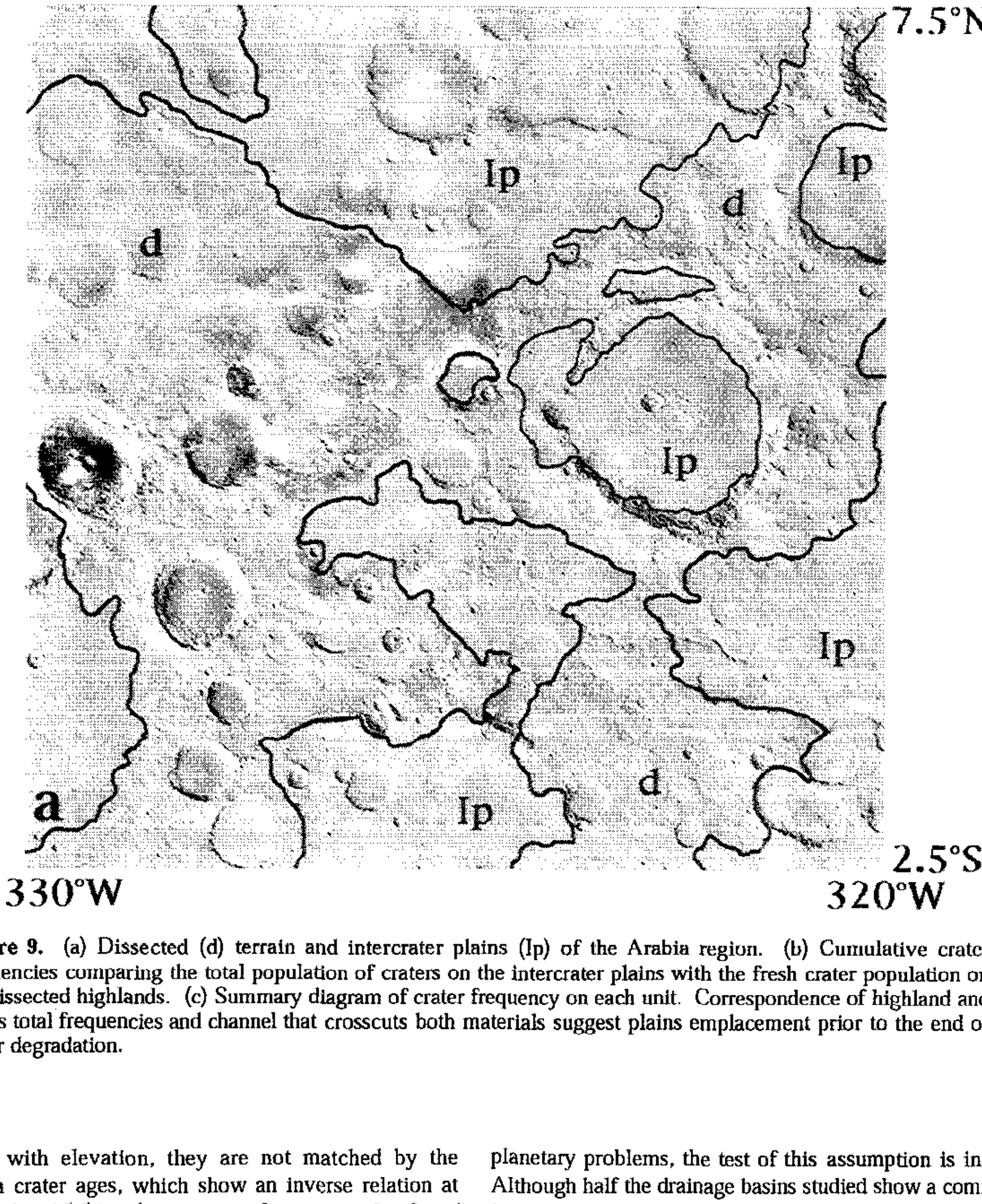


Figure 9. (a) Dissected (d) terrain and intercrater plains (Ip) of the Arabia region. (b) Cumulative crater frequencies comparing the total population of craters on the intercrater plains with the fresh crater population on the dissected highlands. (c) Summary diagram of crater frequency on each unit. Correspondence of highland and plains total frequencies and channel that crosscuts both materials suggest plains emplacement prior to the end of crater degradation.

units decline with elevation, they are not matched by the highland fresh crater ages, which show an inverse relation at elevations of 4.5 and 5.5 km (an inverse relation was also found at 5-6 km elevation in our prior work). The total ages of the plains units themselves also show no distinct relation with elevation. Given the relatively small size of the individual counting areas (~200,000 km^2 per area) and the coarse resolution of the topography, we are not surprised by this result, and attribute the variations to the small sample areas and topographic resolution rather than a conflict with our previous results. However, it does indicate that remapping of the highlands, separating units of intercrater plains from the true dissected materials at a larger scale than the 1:15M series might well be a test of atmospheric contributions to terrain modification, but only when suitable topography is available.

In testing whether the fill material of internally drained basins is related to the end of highland modification, we are making the tacit assumption that highland crater modification occurred over the same time period as the formation of highland valleys, and that both processes ceased at the time the surfaces were able to retain a fresh crater population. As is the case with many other planetary problems, the test of this assumption is inconclusive. Although half the drainage basins studied show a common age of highland stability and plains formation, half do not. In those drainage basins where the ages are not coeval, plains formation appears to be much older than the end of highland modification. However, even in those basins (Aeolis and Arabia), the internal drainage patterns of the surrounding highlands suggest that some sedimentary material should be present, either interfingered with the latest volcanic deposits that are too thin to be recognized by the crater frequency technique, or as a surface veneer.

While dealt with indirectly in this paper, the origin of highland drainage by rainfall versus sapping is not directly testable using crater frequency characteristics alone. Highland modification by fluvial erosion may have taken place by rainfall or by discharge from the subsurface, either of which could be responsible for crater degradation. If the drainage networks of the highlands formed by subsurface water release, then the widespread dendritic nature of the valleys requires a near-surface aquifer for their formation. However, the presence of drainage channels on small crater rims and other short topographic wavelength features down to the limit of Viking Orbiter

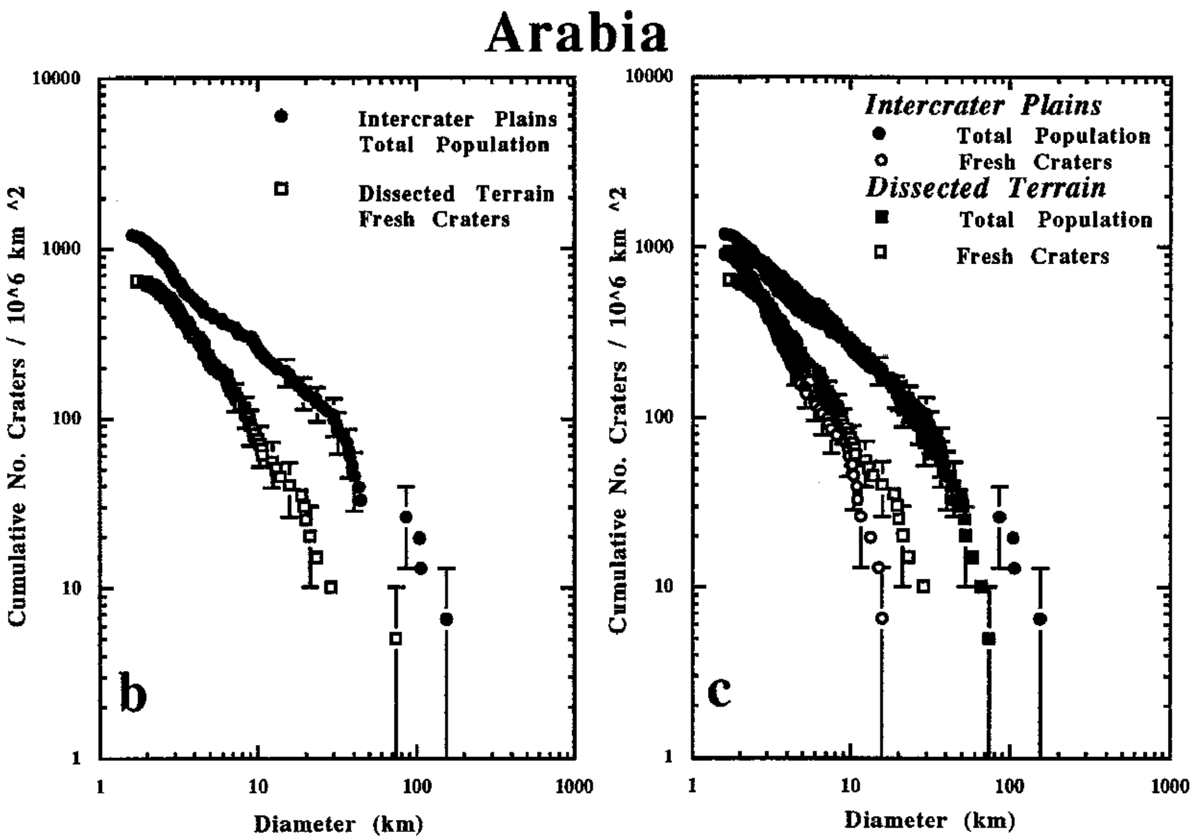


Figure 9. (continued)

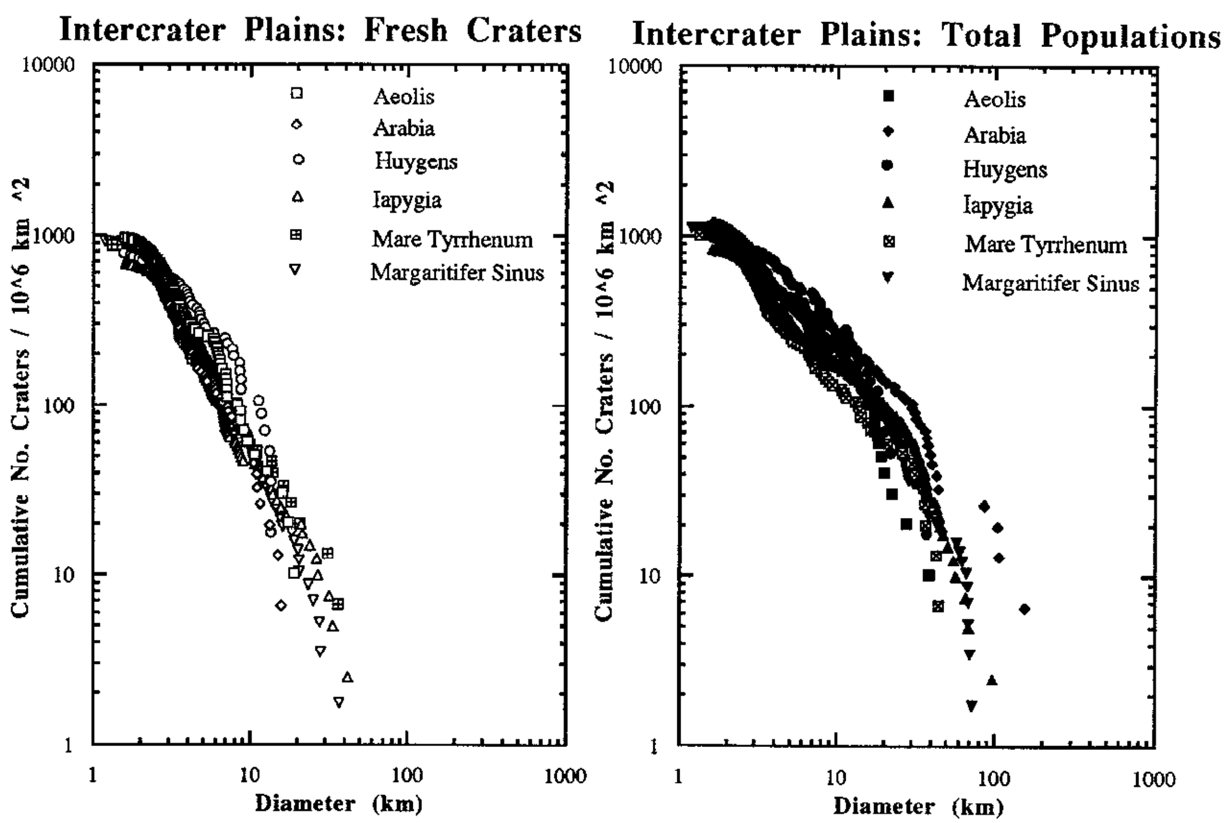


Figure 10. Comparison of fresh and total crater populations for intercrater plains units. The range in surface ages represented by the fresh crater population is narrower than that represented by the total population, suggesting a narrow range in time over which widely disparate plains units were able to retain a fresh crater population.

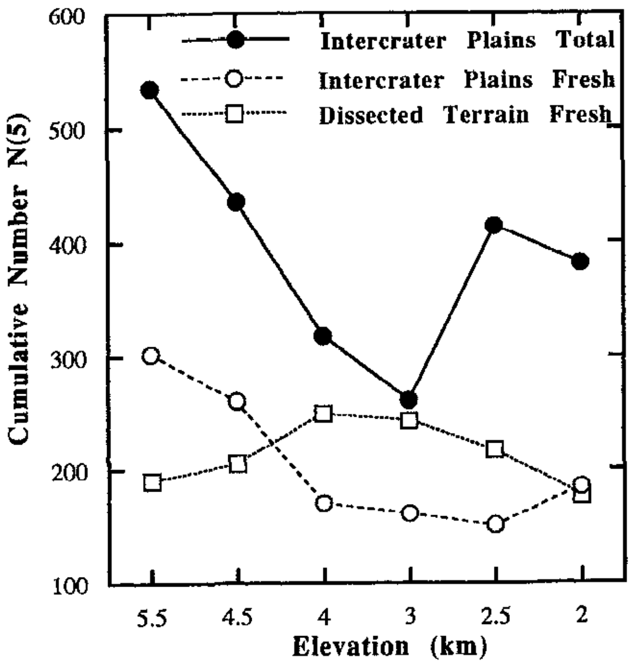


Figure 11. Ages of plains and dissected terrain shown as a function of elevation. The decline in fresh crater age with elevation of the intercrater plains is not matched by similarly derived ages for the dissected terrain. The ages of plains formation vary widely from middle (N(5)~550) to late (N(5)~250) Noachian, suggesting an extended time of formation, and no systematic relation with elevation. One standard deviation error of ages is the size of the plot symbol.

resolution argues for an atmospheric source rather than an interconnected aquifer that could provide a source for surface erosion on features at all scales.

In estimating the amount of juvenile water from volcanic sources, *Greeley* [1987] initially based volumes for plains volcanics on the "plateau plains" as mapped at the 1:15M scale [*Scott and Tanaka*, 1986; *Greeley and Guest*, 1987] using an average thickness of 1 km. *Greeley and Schneid* [1991] later reassessed the extent and inferred thickness of plains units, and estimated a thickness of 200 m averaged over the time of Martian volcanism. As shown here, much of the dissected highlands consists of true, rugged highlands materials with numerous interhighland plains. If some of these plains units are of volcanic origin (such as in the Aeolis region, where the plains age does not match that of the neighboring highlands), then estimates of middle to late Noachian volcanism, as well as derivative estimates of internal heating and volatiles may understate the role of volcanism in early Martian history.

Conclusions

1. The time at which both intercrater plains and neighboring highlands were able to retain a fresh crater population lies on the Martian time stratigraphic boundary between the late Noachian and early Hesperian periods. Significant modification of the terrain and associated craters ceased by that time, which has also been suggested as a time of peak volcanism in the history of the planet [*Greeley*, 1987].

2. The age of formation of the intercrater plains units studied here ranges from middle through late Noachian. In three of the areas studied, the age of the plains approximates the time of cessation of crater modification in the adjacent highlands, consistent with a sedimentary origin from material shed from the neighboring highlands. However, other basins have a wider range between the formation of the plains and the end of highland crater modification, suggesting thin fill (in Arabia and Aeolis), and in one case studied (Huygens), possible observational bias due to a small sample size.

3. A comparison of the terrain ages based on the fresh crater frequency shows that while there is some tendency for the age of plains surface stability ages to decrease with decreasing elevation, that trend is not as pronounced as in previous studies [*Craddock and Maxwell*, 1993]. Improved topography from a future Mars mission would help to resolve whether elevation played a role in the timing of crater degradation.

4. The wide range in plains formation ages suggests a varied origin for the intercrater plains. The formation of intercrater plains may be controlled by "local" factors such as sedimentation from erosion of neighboring highlands or volcanism, but modification of the plains (and neighboring highlands) was likely controlled by global factors (atmosphere, climate) based on the similarity of surface stability ages.

5. The varied ages of the plains units studied here do not support a global magmastatic head model for the origin of the plains. Interfingering volcanic and sedimentary materials, and in some instances, pure sedimentary deposits, are the most likely constituents of the highland plains.

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