Reprinted from
Proceedings of the Eighteenth Lunar and Planetary Science Conference
Published by Cambridge University Press

Ages of Fracturing and Resurfacing in the Amenthes Region, Mars

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The timing of resurfacing events and structural modification of outlier plateaus and mesas in Mars' eastern hemisphere provides a constraint on the history of tectonic events along the cratered terrain—northern plains boundary. Based on a combination of superposition, crosscutting relations, and stratigraphy, the crater ages of discrete geologic units that can be used to bracket structural events have been determined for the Isidis basin rim, on which circumferential faulting ceased by N(5) = 235; cratered plateau material, which experienced a resurfacing event at N(5) = 230; and Syrtis Major Planum, emplaced at N(5) = 150. North of the boundary ages were determined for knobby terrain [resurfaced at N(5) = 190] that marks the transition between the cratered plateau and the smooth plains and various types of plains units [N(5) = 60-190]. Age determinations using production curves fit to crater density distributions are highly dependent on the choice of production curve, as are ages derived by subtracting and replotting populations that deviate from such curves. In order to determine crater ages of structural events in the Amenthes region, separate counts were made for geologic units that exhibit independent evidence for resurfacing or crosscutting by fractures. The oldest event dated by such techniques is the formation of the circumferential grabens surrounding the Isidis basin; they ceased forming before the final emplacement of ridged plains on the adjacent northern lowlands [N(5) = 190]. The cratered plateau east of the Isidis basin retains two crater populations; stripping of the rims of craters (an old population) was complete before downfaulting of the transition zone between the cratered terrain and the northern plains, and a young population of craters on the plateau records the same age as the ridged plains units north of the boundary. Faulting in this region is thus constrained to a narrow time period at about N(5) = 190. Similar sequences of faulting, erosion, and infilling by younger plains are observed at the northern edge of Elysium Mons [faulting between N(5) = 170 and 105], and at the western edge of Isidis Planitia [faulting between N(5) = 180 and 68]. Although the sequence of events was the same, the timing of this activity was unique to each geographic region. All these events postdate the presumed formation of the Martian dichotomy, and suggest that the formation of presently observed structures are the result of a long and complex geologic history.

INTRODUCTION

The Martian crustal dichotomy is generally believed to be a very old feature, due to mantle convection (*Wise et al.,* 1979) or a giant single impact (*Wilhelms and Squyres,* 1984). Later erosion has been proposed to explain the present location of the boundary between the northern lowlands and southern highlands in some localities, and to account for the numerous erosional remnants north of the present boundary (*Scott,* 1978; *Hiller,* 1979; *Maxwell et al.,* 1985; *Frey et al.,* 1986). The overall model of crustal history implied by the "mantle overturn" and "megaimpact" hypotheses involves a single, probably catastrophic, early structural event that created the crustal dichotomy, followed by episodic or continuous erosion and deposition that have modified the position and appearance of the boundary, and partially filled the northern lowlands with volcanic rocks and/or sediments (*McGill,* 1986; *Lucchitta et al.,* 1986). Mapping and crater dating of surfaces and materials on both sides of the present dichotomy boundary allow us to place limits on the later history of erosion and deposition, and suggest that the structural history of the northern plains is complex; explaining the dichotomy by a unique early structural "megaevent" may be a significant oversimplification.

In order to look at the detailed timing of structural events at the transition zone between the ancient cratered terrain and the northern smooth plains, we are concentrating our studies of crater dating in the Amenthes region, where relatively old surfaces are not obscured by the younger volcanic plains related to Tharsis volcanism. In this region the old upland

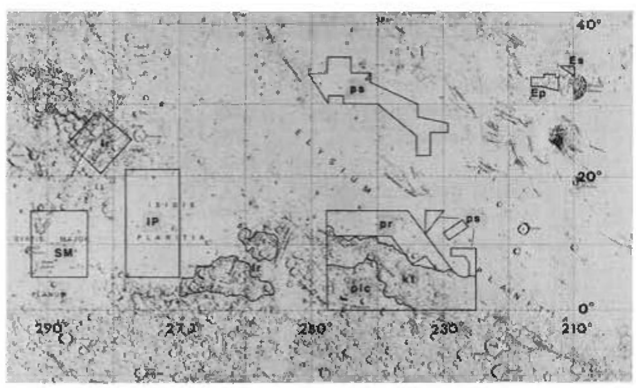


Fig. 1. Shaded relief map of the equatorial region of Mars' eastern hemisphere. Areas outlined were used for crater counts to determine age relations along the dichotomy. Ir = Isidis rim; plc = cratered plateau; SM = Syrtis Major plateau; kt = knobby terrain; pr = ridged plains; IP = Isidis Planitia; ps = smooth plains; Es = Elysium shield; Ep = Elysium plains. Base map is 1:15,000,000 Shaded Relief Map of the Eastern Region of Mars (*U.S. Geological Survey,* 1985).

surface immediately south of the northern plains boundary appears more modified than its pristine condition farther south. This modification is the result of one or more processes, including burial by lavas, planation, and pervasive fracturing followed by erosion and faulting. North of the dichotomy boundary, the modified upland is buried by younger materials, but remnants of older surfaces are present in many places in the form of knobs and mesas (*Scott,* 1978; *Semeniuk and Frey,* 1986; *McGill,* 1986). Geologic mapping based on Mariner 9 and early Viking Orbiter images allowed *Hiller* (1979) and *Scott et al.* (1978) to interpret the knobby terrain as remnants of the cratered plateau. *Tanaka* (1986) used crater densities read directly from cumulative distribution plots to infer that border faulting occurred between the Late Noachian and Early Hesperian Epochs. The exposure of faults and modified surface units provides the opportunity to place the various tectonic, depositional, and erosional events in chronological order, and to test crater counting methods for age determinations in an area where there is independent evidence for the timing of geologic events.

The rim material of the Isidis basin consists of faulted massifs marking a semicircular arc on the south side of the plains filled structure (Fig. 1). Additional ancient terrain deposits consist of the cratered plateau material (plc) south of the boundary, which also records resurfacing and reestablishment of a surface capable of retaining a crater population. Crater frequency counts were done on these units, as well as transitional units north of the boundary, and different plains units of the northern plains to bracket the timing of faulting and resurfacing. Counting results reported here also include areas of the shield and surrounding plains of Elysium, a large volcanic construct northeast of Amenthes.

The overall objective of this research is to determine whether there is any tectonic evidence in the relatively recent history of the boundary zone that will place constraints on the origin of the Martian dichotomy. Several individual questions are thus addressed: (1) Are the age relations determined by superposition, crosscutting faults, and visible resurfacing episodes consistent with those determined by crater counting methods that assume a specific Mars crater production curve (e.g., *Frey et al.,* 1987)? (2) What can the detailed age relations tell us about the evolutionary history in the Amenthes region itself? and (3) Is the sequence of "postdichotomy" events consistent with either the time of scarp modification or sequence of modification processes elsewhere in the eastern hemisphere, or are we looking at the results of an event (megaimpact or mantle overturn) unique to this particular region?

TABLE 1. Summary of surface ages in the Amenthes Region.

Region	n	Area (×1000 km^2)	N(1)*	N(1)†	N(5)‡	N(5)§	N(16)§
Elysium Region							
Surrounding Plains (Ep)	89	41	2000	3300	80	105	—¶
Northern Shield (Es)	84	23	4000	6800	140	170	—¶
Plains Units							
Isidis Planitia (Ip)	133	444	1600	3400	60	68	—¶
Smooth Plains (ps)	467	351	2100	4600	70	115	—¶
Syrtis Major (sm)	186	441	4100	8200	150	180	23
Ridged Plains (pr)	186	371	5100	12000	190	190	30
Transition Zone (kt)							
Postresurfacing	114	382	5000	13500	190	205	40
Old Surface	132	382	14000	62000	—¶	250	77
Upland Surfaces (plc)							
Postresurfacing	155	173	5800	11000	230	290	23
Cratered Plateau	272	173	19500	80000	790	790	175
Isidis Rim (Ir)							
Postfaulting (MC14-SW)	75	192	6000	27000	240	245	50
Postfaulting (MC13-NE)	54	117	3300	4900	120	120	—¶
Rim Material	102	192	19000	85000	—¶	390	135

All values given are number of craters greater than the given diameter/10^6km^2.
*Derived from *Neukum* (1983) crater production curve.
†Derived from *Neukum and Hiller* (1981) crater production curve.
‡Determined from 1983 production curve where it crosses 5 km diameter line.
§Determined directly from where crater distribution crosses the given diameter (*Tanaka,* 1986).
¶Ages are not given where craters were not counted in that diameter range, or for older units, where obvious effects of resurfacing have modified the crater distribution so that it is not fit by a production curve.

Methods

We have determined the ages of surface units and tectonic events in the Amenthes region (Fig. 1) by using traditional photogeologic mapping of material units, determining the ages of faults and fractures relative to erosional and depositional surfaces using superposition and cross-cutting relationships, measuring the crater size-frequency distributions of the surfaces, and determining the age of the surface with a variety of techniques (Table 1). In previous studies, *Wise et al.* (1979) used areas of "what appear to be homogeneous crater populations" to determine ages of surfaces, *Neukum and Hiller* (1981) used a Mars standard crater production curve fit to a variety of geologic units to determine relative and absolute ages, and *Tanaka* (1986) used a variety of crater sizes to determine relative and absolute ages for Mars time-stratigraphic system boundaries. Because we are investigating the relative timing of structural modification in a discrete area of Mars, we have not attempted to derive absolute ages. Instead, we are concentrating on the consistency of crater count methods for events in the boundary region and the implications for its structural evolution.

All resurfacing ages were determined by checking the superposition relationships for every crater used to derive an age. For upland surfaces in quadrangles MC-5 SW, MC-13 NE, and MC-14, we have determined a lower limit for the age of the old upland surface by counting all craters present, and the age of resurfacing by counting only those craters superposed on the eroded or partially buried upland surface.

Methods for reducing crater count data to standard frequencies of a given size crater per unit area have been reviewed extensively by *Neukum and Wise* (1976), *Neukum and Hiller* (1981), and *Tanaka* (1986). Briefly, the individual measurements for a given area are plotted as a cumulative distribution normalized to a unit area on logarithmic paper, and the number of craters greater than a given diameter [N(D)] is either read directly from the plot, or more commonly, determined from fitting a production curve to the data and reading values from the curve. *Neukum and Wise* (1976) and *Neukum and Hiller* (1981) used a unit area of 1 km^2 in calculation of their crater densities, but more recent work is based on number of craters per 10^6 km^2, and it is that value we adopt for this paper.

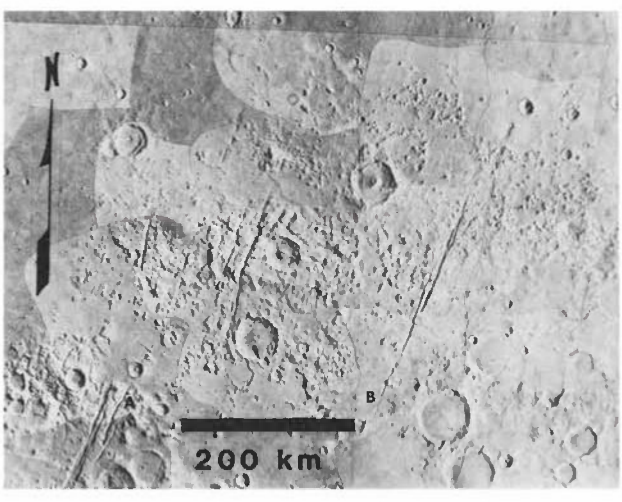


Fig. 2. Eastern rim of the Isidis basin. Two sets of northeast faults are evident; those flooded by plains (**a**) and those that cross cut plains units (**b**). Large discontinuous plains-flooded grabens are overlain by a younger population of craters that suggest stabilization of the surface by crater age N(5) = 240. (Viking Orbiter Photomosaic MC-14 SW).

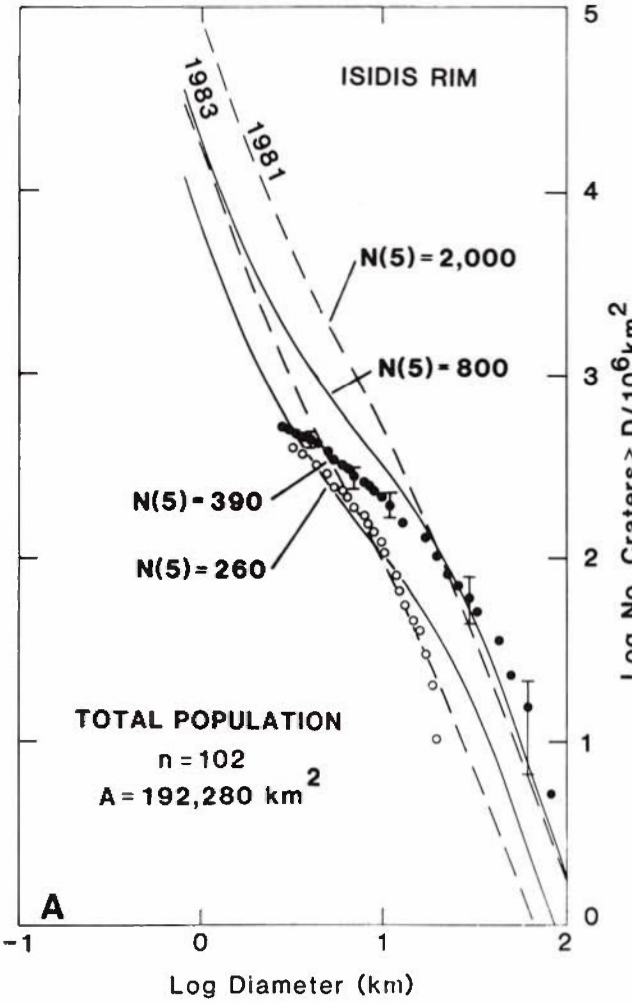
The key difference in absolute crater-density number (alias crater age or crater-retention age) determined by different workers is the choice of production curve used to fit the data. Although early work on Martian crater distributions suggested a D^{-2} power law distribution (*Hartmann,* 1973), more recent work by *Neukum and Wise* (1976) and *Neukum and Hiller* (1981) has suggested that a polynomial function best fits a variety of Martian terrains. These standard production curves were based on crater counts in the 0.1-20 km diameter range from Lunae Planum and other plains units. More recently, *Neukum* (1983) has added counts from additional areas on Mars and produced an even flatter standard production curve.

Additional complexities in surface-age determinations are due to resurfacing, the obliteration of craters smaller than a given diameter by erosion or deposition. Thus, *Neukum and Hiller* (1981) split their plots where they deviated from the production curve and replotted the smaller craters to obtain a resurfacing age. The results obtained with this method are acutely dependent on which production curve is used. The 1981 production curve flattens in the 1- to 10-km-diameter range, and thus incorporates a distribution that has a "bump" in the curve at 10 km. The 1983 production curve is even more irregular in the 2- to 20-km-diameter range, and using this curve eliminates several of the additional populations that would be inferred from the use of more linear production curves.

To illustrate that determining resurfacing ages is model dependent, we have determined resurfacing ages for an area of Isidis rim (Fig. 2) using two different production curves (Fig. 3a), and by separation of crater populations using superposition (Fig. 3b). To obtain a minimum formation age for the surface, all craters were counted on the rim material (location shown in Fig. 1) and plotted as a cumulative distribution in Fig. 3a. Both the *Neukum and Hiller* (1981) and the *Neukum* (1983) curves were fit visually to the frequency distribution of all craters (solid circles), and the 5-km values read from the curves. As shown in Fig. 3, neither curve fits the data distribution very well because of the resurfacing that has reduced the number of craters <20 km in diameter. Craters smaller than 20 km were replotted as a cumulative distribution as done by *Neukum and Hiller* (1981), and again fit to both production curves (Fig. 3a), suggesting a resurfacing age of N(5) = 260 (1983 fit) or N(5) = 390 (1981 fit). The difference between these ages is significant.

In order to determine whether either the 1981 or 1983 resurfacing age was consistent with that determined stratigraphically, the resurfacing age was determined by counting only those craters that are postresurfacing, based on superposition relationships (solid circles in Fig. 3b). The age of N(5) = 240 read from the 1983 curve on Fig. 3b agrees very well with the age determined by curve splitting using the 1983 curve, but this is not always true. In addition, the replotted smaller craters in Fig. 3a suggest the possibility of a second resurfacing if the 1981 curve is used (cf. *Frey et al.*, 1987), but not if the 1983 curve is used. For these reasons, we believe that it is better to use superposition to sort craters into pre- and postresurfacing populations than it is to depend on production curves to do the sorting.

Finally, we have found that the 1983 curve provides a better overall fit for ages of upland resurfacing and most northern plains units. Thus, for internal consistency, we have used this curve throughout. Because many of our cumulative diameter-frequency plots do not deviate from this curve near D = 5 km (except for normal data scatter), many of our N(5) ages are essentially the same as other direct N(5) ages determined by estimating the 5-km density by using a D^{-2} line (*Tanaka*, 1986) or by fitting a line to the half dozen or so points closest to 5 km on the plot. Table 1 provides other crater ages determined from our plots for comparison with ages determined by other workers.



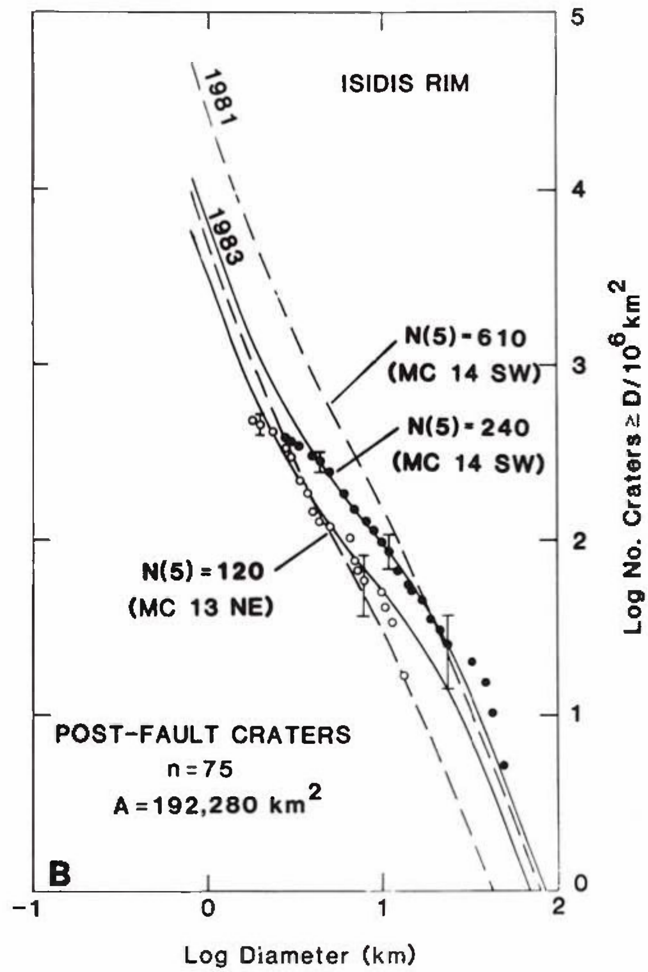


Fig. 3. Cumulative frequency plots of Isidis rim. (**a**) Total population fit to *Neukum and Hiller* (1981) production curve (dashed line) and *Neukum* (1983) curve (solid line). Solid circles are total population of craters, and open circles are remaining population after subtracting craters >20 km. (**b**) Postfaulting crater population on Isidis rim material (solid circles). This distribution is based on superposition rather than subtraction (Fig. 3a), and demonstrates the model dependence of the subtraction technique. Open circles are postfault craters on the northwest rim of the basin (from MC-13 NE).

STRUCTURAL CHRONOLOGY IN THE AMENTHES REGION

Upland Surfaces

The Isidis basin rim is one of the oldest exposed surfaces in the Amenthes region. Only rugged, massif-like rim materials still remain in the immediate vicinity of the basin, and no trace of an ejecta blanket exists in the surrounding terrain. According to the stratigraphic chronology proposed by *Tanaka* (1986), the basin is part of the Lower Noachian Series with a crater density N(16) = 120-300. The rim material is faulted by

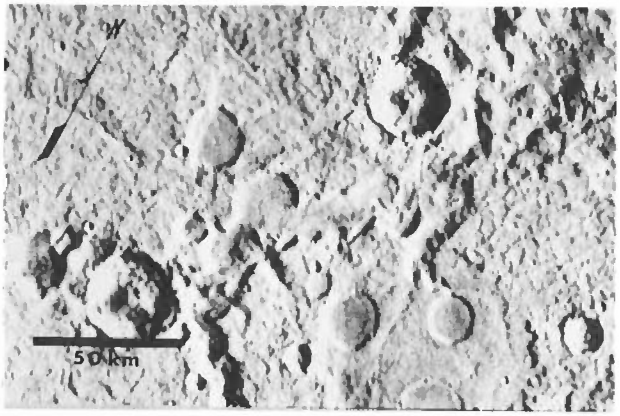


Fig. 4. Rimless, plains-filled craters in the cratered plateau material south of the cratered terrain boundary. The etched and sculpted appearance of the terrain suggests erosional stripping of rim materials rather than deposition of material up to the rim crest. (Viking Orbiter Frame 381S49 in quadrangle MC-14 SW)).

grabens circumferential to the center of the basin that are well developed on the northwest and southeast sides and infilled by plains material. Additional small north/northeast-trending faults cut the rim material and a few craters on the southeast side of the basin (Fig. 2), although most of the major faults occurred before emplacement of the plains. For the young crater population shown in Fig. 3b, all craters that were faulted or plains filled were omitted from the count. An additional crater count on the northwest rim of the Isidis basin yields an age of N(5) = 120 for the age of termination of circumferential faulting (Fig. 3b). Consequently, by crater number N(5) = 120-240, the circumferential faulting of the Isidis basin had ceased. The larger faults had ceased forming earlier, but statistics on the few craters that are cut by these large faults are so poor that it is unreliable to determine that age.

Stratigraphically, the next youngest upland unit has been mapped as cratered plateau material (*Hiller,* 1979) and occurs to the east of the Isidis basin. The surface is characterized by scattered dendritic drainage patterns, numerous north/northwest-oriented scarps, and has two morphologically distinct populations of craters. Numerous craters in the cratered plateau lack a raised rim and evidence for an ejecta blanket, and their interiors are commonly flooded with smooth plains material. As shown in Fig. 4, the surface surrounding these craters has an etched and lineated appearance implying erosional stripping of their rims and ejecta rather than deposition of material up to the rim crest. The maximum diameter for these modified craters is 40 km, which, based on Martian diameter/rim height curves (*Pike and Davis,* 1984), suggests removal (or deposition) of 300 to 600 m of material.

As would be expected from visual examination of the crater distribution on the cratered plateau, it is difficult to fit the frequency data by one curve (Fig. 5). The maximum age for the surface (all craters, Fig. 5) determine from the 1983 curve crossing is N(5) = 790, identical to that which would be obtained by reading a "direct" age from the crater distribution (Table 1). The "young" crater population yields an age of N(5) = 230, essentially identical to the postfaulting age determined for Isidis rim material (Fig. 5).

Structural deformation of the cratered plateau is present in two types of scarps. An older, highly degraded system of west-northwest oriented ridges and scarps occurs parallel to the cratered terrain boundary and radial to the Isidis basin. Fresher appearing scarps have orientations similar to the old ridges, but commonly deviate to more northerly trends (Fig. 6). These scarps are continuous across the old rimless craters, suggesting that structural modification continued to N(5) ~ 240, but did not affect the younger crater population.

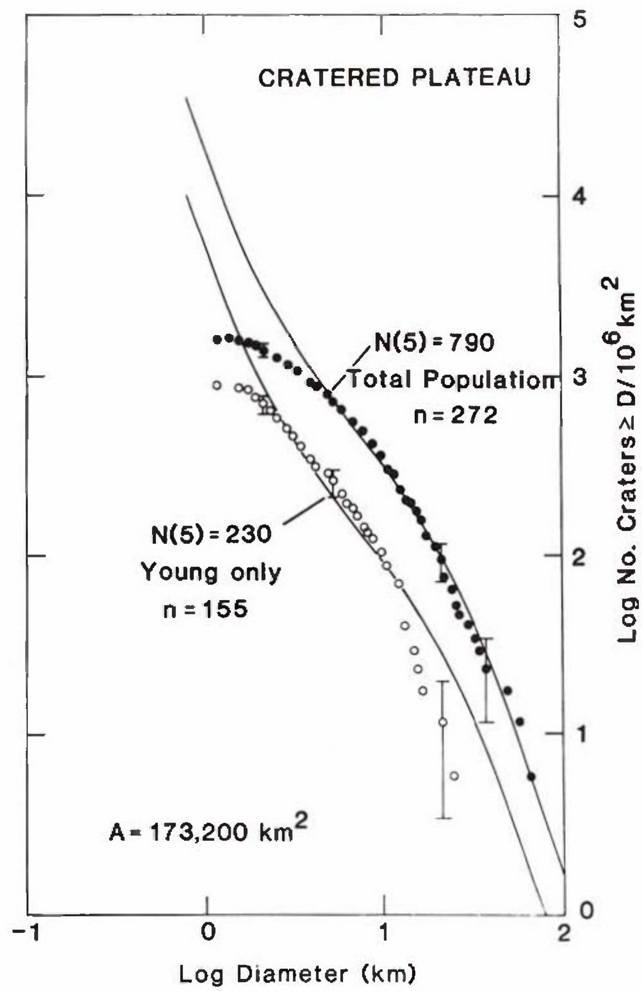


Fig. 5. Crater frequency plots for cratered plateau material south of the cratered terrain boundary in MC-14 SW. Total population of craters (solid circles) shows a fall-off at about 4 km, indicative of resurfacing of the unit. Young population of craters including only those with rims and ejecta (open circles) suggests stabilization of the surface by crater age N(5) = 230.

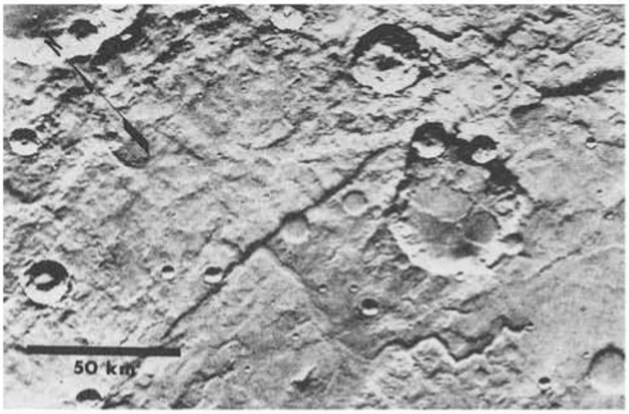


Fig. 6. Young west/northwest trending scarp in the cratered plateau material that crosscuts rimless crater. Faulting in the region occurred between N(16) = 135 and N(5) = 230, but did not continue into the time represented by younger craters in the region. (Viking Orbiter Frame 381S62 in quadrangle MC-22 NW).

Transition Zone

A 300-km-wide zone of scattered knobs and plateaus extends northward from the cratered terrain boundary into the northern lowlands where the density of knobs and mesas gradually decreases. Large mesas near the cratered plateau are most easily interpreted as remnants from backwasting of that unit, but the smaller isolated plateaus and knobby hills are subject to more uncertainty in interpretation. They have been interpreted as ancient terrain protruding through the younger plains material, resistant volcanic layers of once more extensive plains deposits, or as consolidated portions of a once widespread aeolian deposit (*Greeley and Guest,* 1978; *Scott,* 1978; *Hiller,* 1979). Like the crater counts of the Isidis rim and cratered plateau materials, our counts of this region were designed to determine whether the buried (?) unit north of the boundary was the same age as the cratered plateau, and hence, whether the knobs were remnants of that unit.

Within this zone (kt in Fig. 1) all possible craters, even vaguely circular arcs of knobs that may once have been a continuous crater rim, were counted to obtain the maximum age of the surface. As shown in Fig. 7, we have fit the production curve to the larger (>20 km) craters because of the deviation from the curve due to resurfacing by plains material. The maximum age thus derived is N(16) = 77; a 5-km age is not reliable because of the fall-off in crater frequency. The 16-km age read directly from the distribution is less than the maximum age of the cratered plateau, but within the range of the 1 sigma error associated with the crater diameters used to fit both curves. The large crater distribution (>20 km) of both units is indistinguishable when they are plotted on the same graph. Consequently, we believe the younger maximum age of the knobby terrain may be partially due to inherent difficulties in fitting the production curve to a crater distribution that has undergone resurfacing, although it is possible that some of the discrepancy is real if we are not seeing all of the craters on the buried surface because of their disruption by faulting.

The youngest age of materials within the transition zone is based on only those craters that are superposed on either the knobs and plateaus, or the intervening plains materials. The "young" crater distribution matches the 1983 production curve quite well (Fig. 7), resulting in an age of N(5) = 190 for stabilization of this surface.

Plains Materials

Four types of plains units occur both north and south of the cratered terrain boundary in the Amenthes region: Syrtis Major Planum (SM), ridged plains (pr), smooth plains (ps), and Isidis Planitia (IP). On the southwest edge of the Isidis basin, the Syrtis Major volcanic construct is surrounded by a

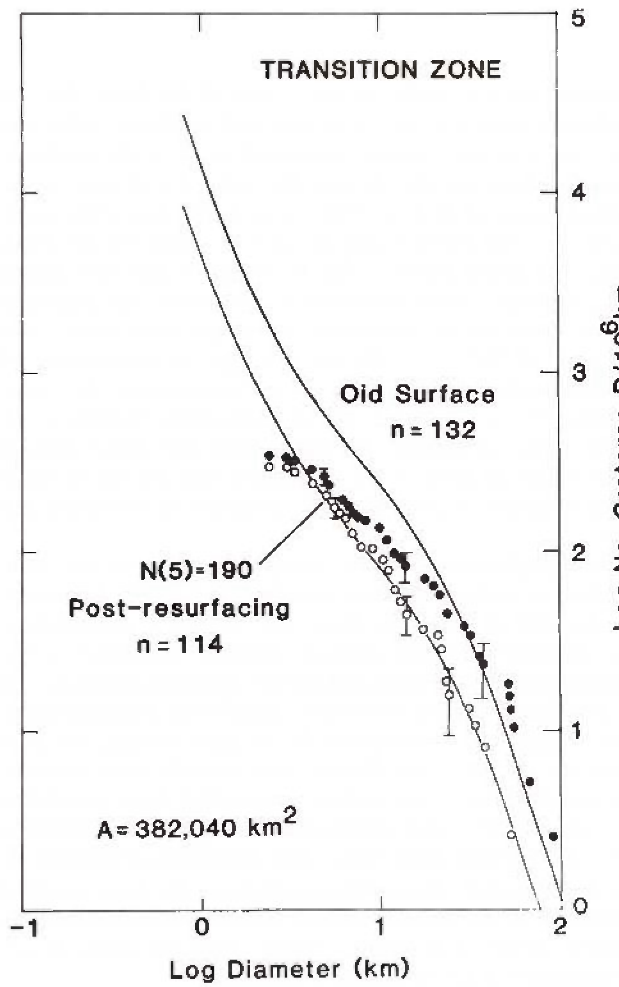


Fig. 7. Crater frequency plots for the transition zone between the cratered plateau and the northern smooth plains. Total population of craters including buried rims is shown by solid circles; open circles are craters superposed on knobs, mesas, and intervening plains units.

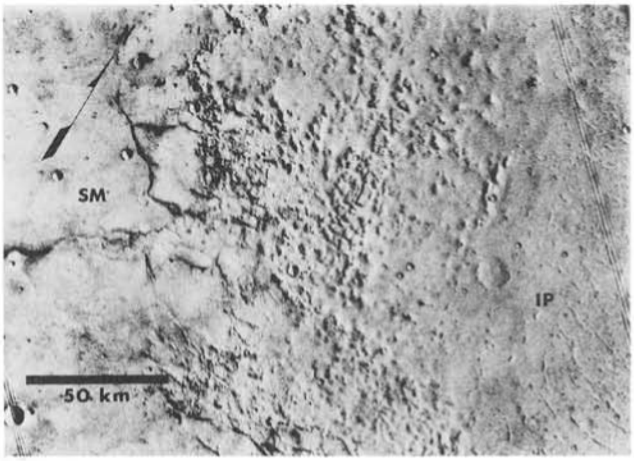


Fig. 8. Contact between plains of Syrtis Major Planum (SM) and Isidis Planitia (IP). Isolated plateaus and knobs extend beneath the smooth plains material of Isidis Planitia, and most erosional backwasting to produce mesas and knobs took place prior to emplacement of smooth plains that encircle the central part of the Isidis basin. (Viking Orbiter Frame 377S60 in quadrangle MC-13 SE).

complex of plains units that is elevated 3-4 km above the floor of Isidis Planitia (*Schaber*, 1982). The plains display prominent wrinkle ridges and scarps, and obscure the Isidis rim where they descend into the basin floor. Juxtaposed to the Syrtis Major plains units are the hummocky plains of the Isidis basin floor. These materials are characterized by small, semicircular arcuate ridges (not wrinkle ridges), and linear strings of isolated mounds that *Grizzaffi and Schultz* (1987) interpret as evidence for deposition and removal of a thick layer of material.

The contact between plains units of Syrtis Major and Isidis Planitia is marked by plateaus and intervening smooth plains that encircle the hummocky plains of the central Isidis basin. Individual plateaus of Syrtis Major Planum materials gradually are replaced by more subdued knobs and hills, and eventually grade into the hillocks and hummocky plains of the central Isidis basin (Fig. 8). The fracturing that preceded mesa development must be younger than the Syrtis Major plateau, which has a formation age of N(5) = 150 (Fig. 9). The young limit on both fracturing and backwasting leading to mesa development is the age of the Isidis Planitia plains, N(5) = 60.

Northern lowland plains units similarly provide a young limit on mesa development adjacent to the cratered plateau material. Both smooth plains and ridged plains occur intermixed with isolated knobs in the transition zone and within depressions in the cratered plateau south of the boundary. North of the transition zone, contacts between these two types of plains are gradational. Counts on the ridged plains in MC-14 SE north of the transition zone indicate an age of N(5) = 190 (Fig. 10), identical to the age determined for postresurfacing within the transition zone. The smooth plains yield an age of N(5) = 70, slightly older but virtually indistinguishable from that determined for Isidis Planitia. Both ages provide a young limit on faulting that contributed to initial plateau development, but debris aprons that are superposed on plains adjacent to plateaus indicate that erosion and cliff retreat continued past these times.

Elysium Region

On the north flank of Elysium Mons, photogeologic evidence for a sequence of faulting, plateau formation, and cliff retreat of isolated mesas is similar to that seen in the western part of the Isidis basin. The northern part of the volcanic shield is cut by curved faults concave to the northern plains, which enclose polygonal plateaus separated by straight fault segments. Away from the shield, the plateaus are more widely spaced, and are mixed with knobby hills 1-5 km in diameter (Fig. 11). Because the sequence of structural disruption and modification appears similar to that observed in the Isidis basin,

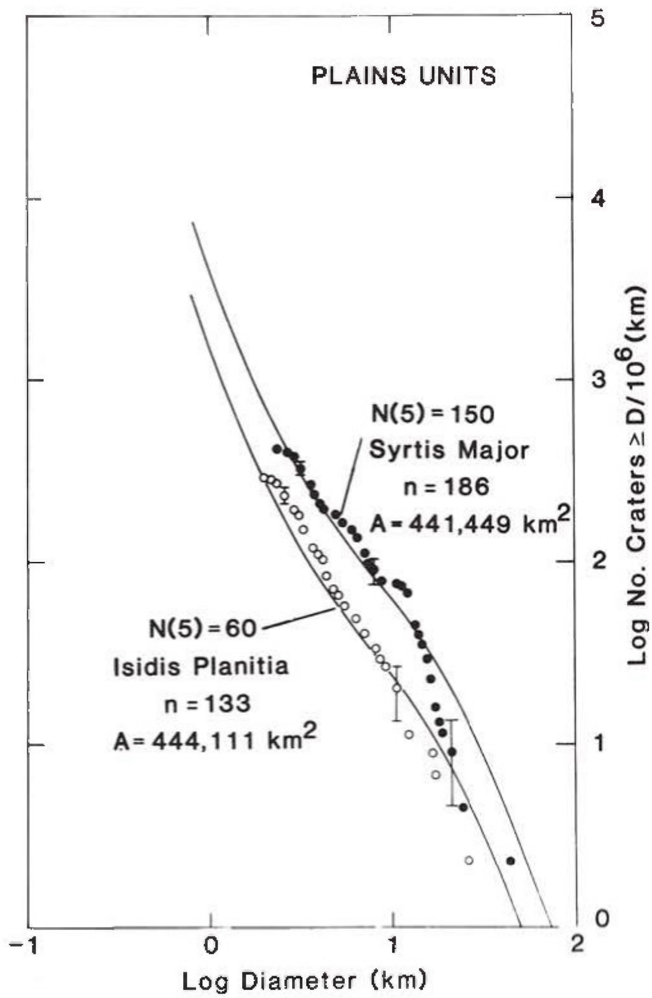


Fig. 9. Crater frequency plots for Syrtis Major Planum (solid circles) and the central part of Isidis Planitia (open circles).

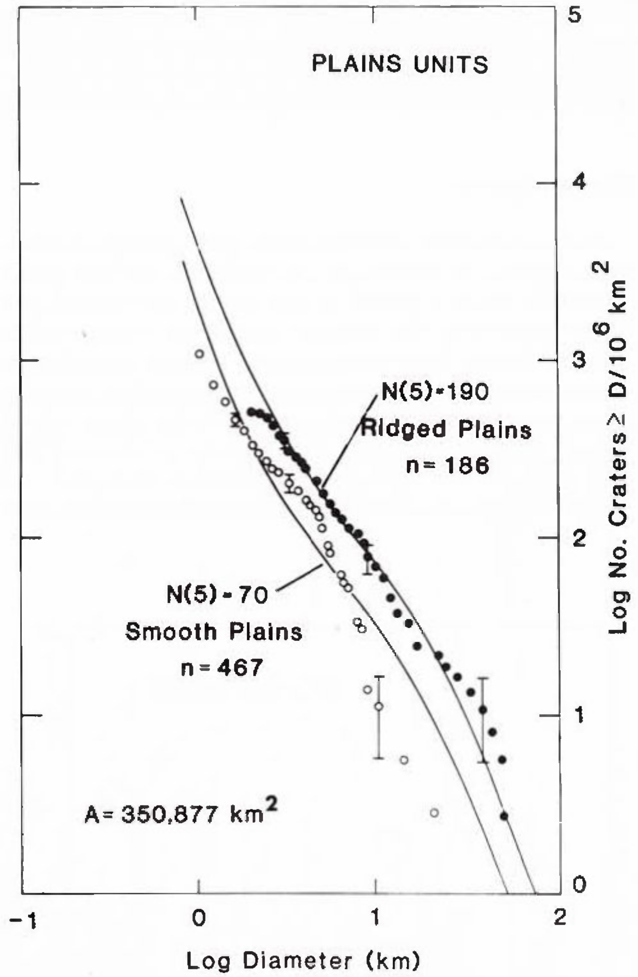


Fig. 10. Crater frequency plots for smooth and ridged plains of the lowlands north of the transition zone. Data for the ridged plains (solid circles) is well fit by the 1983 production curve, but that of the smooth plains (open circles) is not well fit, possibly due to a further resurfacing episode removing craters less than ~3-4 km (?).

we determined the age of the shield deposits and of the intervening plains surrounding the mesas to place upper and lower limits on the age of faulting.

Crater ages determined for the plains and shield materials (Fig. 12) are consistent with later infilling of plains units surrounding the shield. The crater frequency on volcanic flows on the shield itself are fit fairly well by the 1983 production curve, although both shield and surrounding plains counts show evidence for resurfacing by the fall-off in frequency at diameters <1.5 km. On the shield, this deviation could be attributed to resurfacing by younger flows, but there is no such similar evidence for resurfacing on the plains unit north of the shield. The age of the shield is N(5) = 140, essentially the same as that determined for Syrtis Major Planum [N(5) = 150], although the lower density of large craters alone suggests that the shield is younger than Syrtis Major, as found by *Tanaka* (1986). The age of the surrounding plains is N(5) = 80, which is also similar to that of the smooth plains to the southwest in MC-14. This is interpreted to be the time at which most of the plateau development ceased, except for minor continued cliff retreat.

DISCUSSION

Cratered Terrain Tectonics and Resurfacing

The oldest surfaces we have dated in the Amenthes region, the Isidis rim and cratered plateau material, are cut by faults and scarps, remnants of the earliest observed tectonism along the highland side of the cratered terrain boundary (Fig. 13). The time of formation of large grabens circumferential to Isidis is constrained by infilling of the grabens by ridged plains material, but more closely by dating of the crater population that includes plains-filled highland craters and those craters that are superposed on the faults themselves. Formation of these grabens ceased by N(5) = 240 at about the same time as cessation of the process that removed the rims from craters on the cratered plateau. *Comer et al.* (1985) preferred a model for concentric graben formation in which the superisostatic

Fig. 11. Faulted plateaus and isolated outliers on the northern flank of Elysium Mons. The shield was faulted and the isolated plateaus were created by cliff retreat before emplacement of the intervening plains deposits that surround the shield. (Viking 1:500,000 photomosaic MTM 35212).

load responsible for faulting extended to the edge of the volcanic fill of Isidis. If this model is correct, our results imply that this portion of the fill is now buried by more recent plains.

The old population of rimless craters in the cratered plateau can be used to constrain highland tectonic events regardless of the process that removed the rims. As shown below, however, the interpretation of that event(s) may also allow more precise dating of boundary faulting. *Wilhelms* (1974) preferred a depositional origin for what was then termed the plateau plains, based on analogy with lunar plains and images available at that time from Mariner 9. However, rimless craters in the cratered plateau material are not in all cases surrounded by smooth plains. Such craters also interrupt the contact between gullied uplands and smoother plateau material, and may also be completely surrounded by rugged plateau material. Deposition of highland plains material may have helped to subdue the rims but, because of the varied terrain exposed surrounding the craters, was not solely responsible for obscuring the rim. Consequently, we believe an erosional origin for rim and ejecta removal is supported by the geologic setting of these upland craters, and that the event(s) occurred well after the Isidis impact, since such craters are present on the Isidis rim.

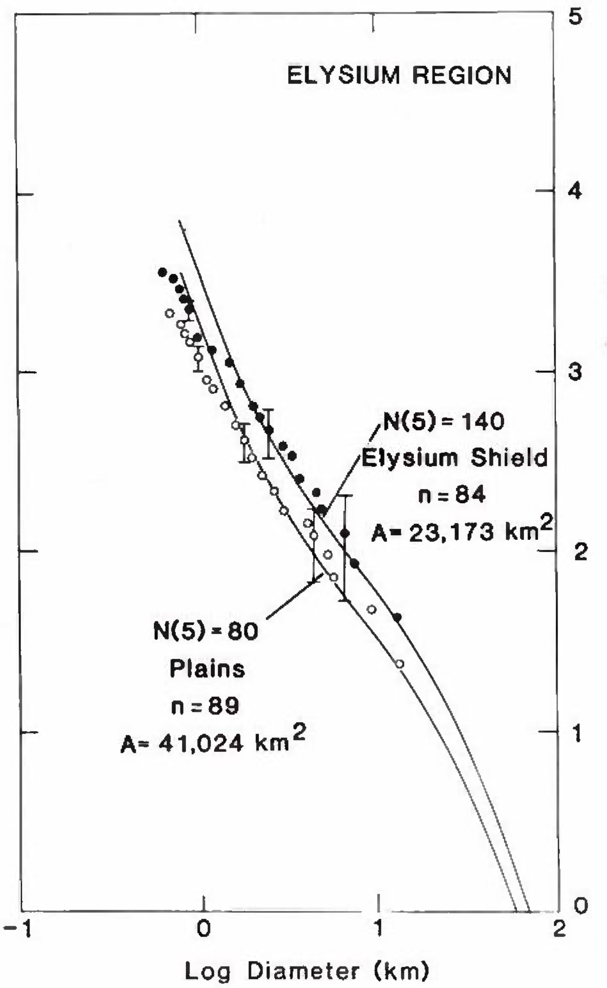


Fig. 12. Crater frequency plots for the northern shield of Elysium Mons (solid circles) and surrounding plains (open circles). Fall-off in shield crater population at diameters <1.5 km is probably due to resurfacing by multiple flows on the north flank of the volcano.

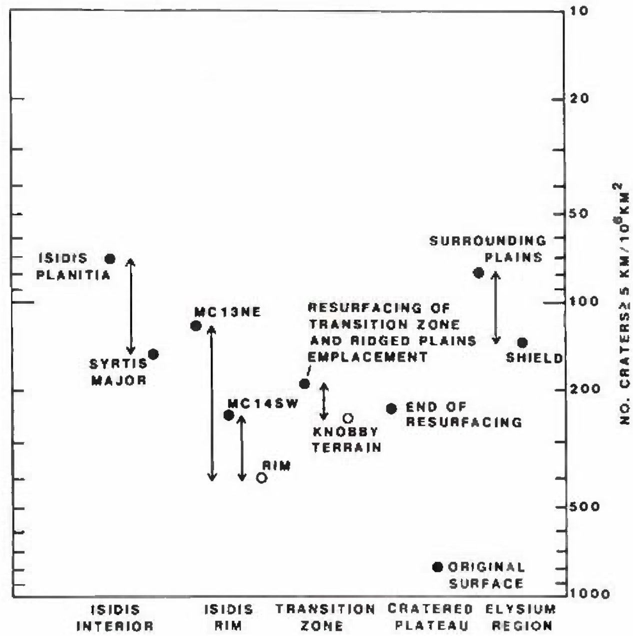


Fig. 13. Summary of resurfacing and tectonic events in the Isidis-Amenthes-Elysium region. In areas of volcanic plains emplacement, a similar sequence of faulting, erosion, and younger plains deposition is seen, but the timing of individual events in the sequence varies with location, as shown by double headed arrows indicating age ranges during which fracturing occurred. Open circles represent ages determined directly (see footnotes in Table 1).

Based on crater dating alone, it is not possible to tell whether the erosional process operated for a long time period (as would be expected from enhanced atmospheric conditions accelerating erosion), or was a function of the substrate (volatile-rich material that lost cohesion due to climate change). Our estimate of 300-600 m of removal is similar to the 300 m of removal estimated by *Grizzaffi and Schultz* (1987) for the interior of Isidis Planitia. A further suggestion of burial of this terrain was made by *Wilhelms and Baldwin* (1987), who proposed that both the uplands and preplains knobby terrain were covered by ice-rich deposits of varying thickness, which created the gullied uplands and interknob deposits when later eroded. If the erosion of this transient material was the same process that removed crater rims, then both deposition and erosion of such material occurred between N(16) = 135 and N(5) = 230, the postresurfacing age of the cratered plateau material.

Although the exact cause of planation remains unspecified, the timing of planation does place a constraint on the time of border faulting. If the faulting occurred after planation (as is suggested by the smooth-topped character of mesas adjacent to the uplands), then faulting had to occur after N(5) = 230, the resurfacing age, but before N(5) = 190, the age of the adjacent unfaulted plains.

Plateau Formation and Cliff Retreat

Based on age determinations reported here and additional dating of tectonic events in eastern Utopia Planitia, the same sequence of events occurred in MC-5 SW and MC-13 NE as in the Amenthes region (*McGill,* 1987). Dating indicates a rapid sequence of border zone formation that involved: (1) planation of the upland surface, (2) downfaulting of transition zones as separate blocks rather than continuous terraces, (3) erosion to produce mesas along the northern edge of the transition zone, and (4) flooding by ridged plains materials.

In the fretted terrain north of the flank of Elysium Mons, the complex plains surface has an age of N(5) = 80. The scattered mesas on these plains surfaces were present as discrete, isolated landforms before the intervening plains units formed, as indicated by two lines of evidence.

1. Wherever age relationships can be determined, the craters used to date the plains formed after the mesas existed in their present form; crater ejecta lies on plains surfaces between mesas, and clear evidence exists locally for obstruction of the flow of fluidized ejecta by mesas.
2. Plains lavas commonly terminate near groups of mesas so that it appears as if many of the mesas occur within or between younger lava flows. This relationship makes sense if the preplains surface near older mesas was slightly higher than in intervening areas where all of the older plateau material had been eroded away, and where younger plains lavas have ponded.

Thus, the lava capped plateau surface of Elysium was faulted and eroded in a relatively short time interval between N(5) = 140 and N(5) = 80, an interval almost certainly larger than the actual one because flow lobes younger than N(5) = 140 are faulted, and the N(5) = 80-age plains lavas need not have formed immediately after cessation of mesa erosion. These events occurred after the final volcanic eruptions of the north flank of Elysium, since there is no evidence for recent flows extending beyond or over the escarpment of the Elysium shield (*Mouginis-Mark et al.,* 1984).

The polygonal terrain material of Adamas Labyrinthus was deposited in the same time interval (*McGill,* 1986) as faulting and erosion of the cratered terrain boundary and the northern plateaus. Between Elysium Mons and Adamas Labyrinthus are numerous channels on a terrain characterized by mixed smooth and intricately eroded surfaces referred to as "disordered plains" by *Carr* (1981, pp. 82-83). It thus is not unreasonable to infer that materials eroded from the plateau peripheral to Elysium Mons were deposited as what is now polygonal terrain, an origin for these materials consistent with the mechanically most reasonable hypothesis for large-scale patterned fracturing (*McGill,* 1986), and consistent with large-scale patterns of channels and northern hemisphere topography (*Lucchitta et al.,* 1986).

CONCLUSIONS

1. Dating of surfaces and tectonic events in the eastern hemisphere of Mars, where there is independent stratigraphic control on periods of resurfacing, indicates that crater frequency ages determined by subtraction where crater frequency deviates from production curves are highly model dependent. Often they are not equivalent to ages determined from separate crater populations isolated by superposition and cross-cutting relationships.

2. The oldest structural event in the Amenthes region is the formation of grabens concentric to the Isidis basin (Amenthes Fossae), which ceased forming before final emplacement of the uppermost plains units of Isidis Planitia or the northern plains.

3. The planation process that removed crater rims from old craters in the upland cratered plateau ceased by N(5) = 240, suggesting that border faulting in the Amenthes region took place in a very short time period, post-planation of the cratered plateau, but pre-deposition of the plains at N(5) = 190. Relationships in the transition zone suggest that the true age of border faulting is very close to N(5) = 190.

4. Erosion of plateaus in the Elysium region took place at the same time as the deposition of the uppermost surface of the polygonal northern plains, consistent with the hypothesis of a sedimentary origin for that terrain.

5. Different areas of volcanic plains and upland surfaces have undergone similar sequences of tectonic detachment, faulting, and infilling by younger plains. Although the same sequence of events occurred at these different localities, the dating reported here indicates that faulting and plateau formation occurred at different times.

6. Both the "megaimpact" (*Wilhelms and Squyres,* 1984) and the "mantle overturn" (*Wise et al.,* 1979) models proposed to explain the Martian crustal dichotomy imply a single major structural disruption of the crust, and a "multiple impact" model (*Frey et al.,* 1986) requires numerous scattered disruptions early in Martian history. Our results indicate that fracturing and associated resurfacing in and around the Amenthes region was an ongoing process, and also apparently of different ages in different places. Although this result by itself is not strong enough to eliminate any of the models, it is not favorable to them, and suggests that a search for a more protracted origin for the dichotomy may be in order.

Acknowledgments. This paper has benefitted from the useful review comments of K. Tanaka and J. Zimbelman. Part of this work was done while one of us (GEM) was a Visiting Scientist at the Center for Earth and Planetary Studies, Smithsonian Institution. This research was supported by NASA grants NAGW-129 (at the Smithsonian Institution) and NGR-22-010-076 (at the University of Massachusetts). We are also indebted to the Smithsonian Office of Fellowships and Grants for support through the Short-Term Visit Program.

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