THE GEOLOGY OF MARE ACIDALIUM QUADRANGLE MARS

by

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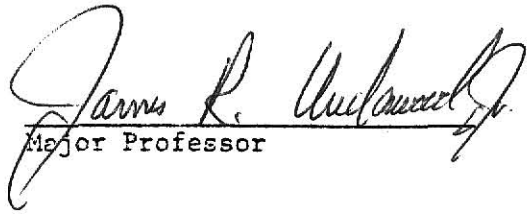

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CONTENTS

Page

INTRODUCTION 1

Area of Study 3

Purpose of Study 3

Methods of Investigation 6

Data Base 8

Mariner 9 8

Viking 8

Previous Mapping 10

GEOLOGY OF MARS 13

Planetary Dichotomy 13

Impact Craters 18

Permafrost 21

Meteorology and the Atmosphere 25

Wind Features 27

Channels 28

Volcanism and Ice 30

GEOLOGY OF MARE ACIDALIUM QUADRANGLE 31

Impact Craters 31

Plateau Province 32

Cratered Plateau 32

Dissected and Fractured Plateau Material 42

Rugged Plateau Material 45

Ridged Plateau Material 51

Fractured Plateau Material 57

Lower Plateau Material 58

Page

Plains Province 64

Mottled Plains Region 67

Mottled Plains Material - Undivided 68

Hummocky Mottled Plains Material 76

Patterned Mottled Plains Material 80

Subdued Patterned Mottled Plains Material 88

Fractured Plains Material 91

Knobby Plains Material 99

Smooth Plains Material 102

Patterned Smooth Plains Material 112

Variegated Plains Material 115

Other Material 119

Dark Material 119

Light Material 119

Channel Material 122

Knobby Terrain Material 122

GEOLOGIC HISTORY 126

Early Cratering 126

Outgassing 127

Early Volcanism 127

Scarp Formation 128

Scarp Retreat and Formation of Plains Units 128

Tectonism 131

Late Volcanism 133

Recent Processes 133

Page

SUMMARY AND CONCLUSIONS 134

REFERENCES 136

ACKNOWLEDGMENTS 146

APPENDIX 147

APPENDIX I - TEMPE PLATEAU REGION 150

Crater Material 153

APPENDIX II - CENTRAL PLATEAU REGION 156

Crater Material 158

APPENDIX III - CYDONIA REGION 161

Crater Material 168

Bamberg Deposits 169

APPENDIX IV - GEOLOGIC MAP OF MARE ACIDALIUM QUADRANGLE 171

Plateau Materials 171

Plains Materials 175

Other Materials 180

Crater Materials 181

ILLUSTRATIONS

Figure		Page
1.	Generalized geologic map of Mars	4
2.	Topographic map of Mare Acidalium quadrangle	5
3.	Location of terrains on which crater counts were made	9
4.	Location of Viking images and photomosaics shown in text	11
5.	All craters greater than 15 km in diameter	14
6.	Impact crater material	19
7.	Mean annual surface temperature for each latitude of Mars	23
8.	Cummulative crater size-frequency distributions for the plateau units	33
9.	Small channels on cratered plateau	35
10.	Floor-fractured crater on cratered plateau	37
11.	Cratered plateau - smooth plains boundary	40
12.	Dissected and fractured plateau materials	43
13.	Rugged plateau material	46
14.	Relative-height profiles of crater forms shown in Figure 13	48
15.	Ridged plateau material	52
16.	Flow fronts on ridged plateau	54
17.	Fractured plateau material	59
18.	Lower plateau material	61
19.	Streamlined remnants of lower plateau material	65

Page

20. Cummulative crater size-frequency distributions for the mottled plains units and knobby plains 70
21. Mottled plains material - undivided, example 1 71
22. Mottled plains material - undivided, example 2 74
23. Hummocky mottled plains material 77
24. Patterned mottled plains material 82
25. Patterned mottled plains - variegated plains boundary 86
26. Lava flows on subdued patterned mottled plains 89
27. Subdued patterned mottled plains material 92
28. Patterned mottled plains - subdued patterned mottled plains boundary 94
29. Fractured plains material 97
30. Knobby plains material 100
31. Smooth plains material 103
32. Cummulative crater size - frequency distributions for the variegated plains, smooth plains, and mottled plains - undivided 105
33. Ridges on the smooth plains, example 1 108
34. Ridges on the smooth plains, example 2 110
35. Patterned smooth plains material 113
36. Variegated plains material 117
37. Dark, light, and channel material 120
38. Knobby terrain material 123

Page

39. Photomosaic of the Tempe Plateau region 148

40. Geologic map of the Tempe Plateau region 149

41. Photomosaic of the Central Plateau region 154

42. Geologic map of the Central Plateau region 155

43. Photomosaic of the Cydonia region 159

44. Geologic map of the Cydonia region 160

Plate

1. Geologic map of the Mare Acidalium quadrangle of Mars .....Pocket

INTRODUCTION

Galileo, in 1610, was the first to observe Mars through a telescope. In 1659, Christian Huygens produced the first drawings of Mars showing the dark markings, maria, that early workers believed represented bodies of water. Father Secchi, in 1869, introduced the Italian word, "canali," which means channels, to describe some of the dark, streak-like martian markings. Unfortunately, the English language press translated the Italian word "canali" not as "channels," which has no necessary implication of intelligent design, but as "canals," (Hoyt, 1976). In 1877, Schiaparelli strengthened the idea that these streak-like features were canals by mapping their distribution. Percival Lowell, who established Lowell Observatory at Flagstaff in 1894 specifically to study Mars, suggested that Schiaparelli's channels were irrigation canals constructed by intelligent beings to bring water from the poles to the dry equatorial region (Hoyt, 1976). On the other hand, several scientists suggested that the polar caps were made up of frozen carbon dioxide, and therefore, subfreezing temperatures would make Mars uninhabitable. It was not until 1965 that some of these arguments began to be resolved.

In July, 1965, Mariner 4 flew by the southern hemisphere of Mars and sent back 22 close-up images that revealed a cratered, lunar-like surface. Four years later, in 1969, the Mariners 6 and 7 fly-by missions returned a total of 202 images from the southern hemisphere of Mars, confirming that relatively uninteresting lunar-like craters were indeed scattered over the martian surface. These later images also revealed that the craters were modified by erosion.

The atmosphere around Mars permits geologic processes that cannot occur on other planetary bodies such as the Moon and Mercury, e.g., wind erosion and deposition. It was not until the Mariner 9 orbital mission in 1971 that the scientists were able to see evidence of the diversity of geologic processes that have shaped martian geologic history. Processes that have been identified are impact, volcanic, tectonic, fluvial periglacial, and eolian.

Mariner 9 data revealed striking differences between the northern and southern hemispheres of Mars. This hemispheric dichotomy is expressed by an abrupt change from the high-standing, densely cratered terrain in the south, to low-lying, lightly cratered terrain in the north. The boundary separating these two terrain types is commonly expressed as a 1-2 km high, irregular scarp (Carr, 1980b), north of which the plains slope downward to elevations 5-6 km or more below the southern highlands.

The area involved in this investigation occurs along the boundary between the southern highlands and the northern plains. Several areas in the northern plains were selected on the basis of Mariner 9 data as potential landing sites for the Viking landers because the areas appeared to be relatively smooth. The 40° - 50°N latitude band was of special scientific interest because of the high atmospheric water content, moderate surface temperature, and the possibility of near-surface permafrost (Masursky and Cradbill, 1976).

When the Viking 1 orbiter arrived at Mars in June 1976, these areas were photographed in great detail in order to determine the safest landing

site, and eventually the Utopia Planitia site (48°N, 226°W) was selected. One of the alternative landing sites, Cydonia (44°N, 10°W), occurs within the area of this investigation. The Cydonia site was originally considered for the Viking 2 lander because the atmospheric pressure in this region was high enough to permit water to exist in a liquid state. The Cydonia site was rejected because it appeared to be too rough.

Area of Study

Mare Acidalium was one of the dark areas that appeared on Schiaparelli's map of Mars in the late 1800's (Schiaparelli, 1878). The area of this investigation is Mare Acidalium quadrangle (MC-4); Acidalia Planitia, the largest area of low albedo in the northern hemisphere, constitutes much of the Mare Acidalium quadrangle. This quadrangle lies between 30° - 65°N latitude and 0° - 60°W longitude (Fig. 1). Occultation data from Mariner 9 indicate that the elevation in the central area of Acidalia Planitia is more than 3 km below the 6.1 millibar datum, the elevation reference surface established for Mars corresponding to the pressure at the triple point of water (Fig. 2).

Purpose of Study

Mariner 9 data from Mars revealed the striking planetary dichotomy, i.e., southern highlands and northern lowlands. The low-resolution Mariner 9 images depicted the northern plains as flat to gently rolling hills with few topographic irregularities (Scott, 1978). A few scattered

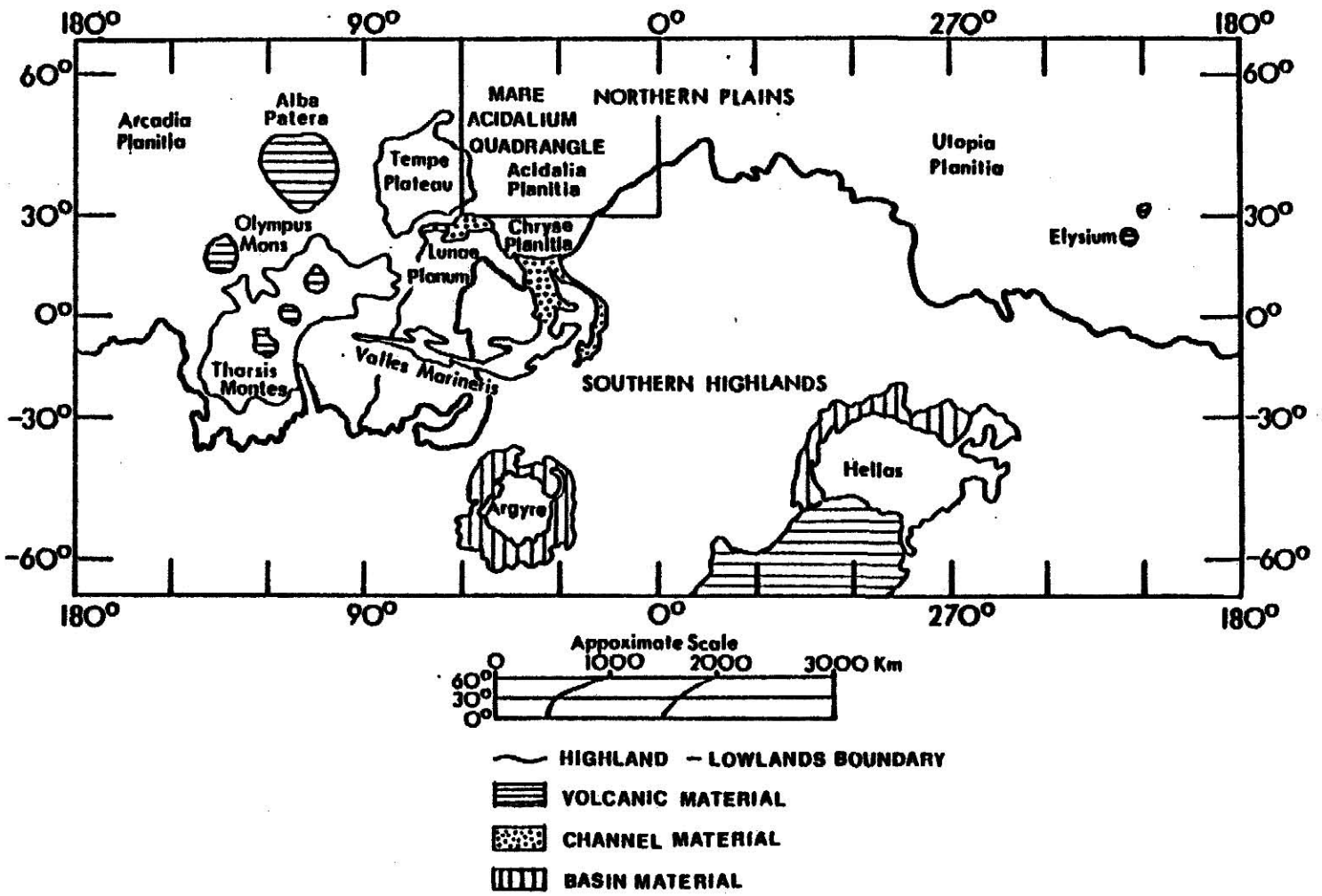


Figure 1. Generalized geologic map of Mars. Mare Acidalium quadrangle is indicated by the box; terrain units are based on Scott and Carr (1978).

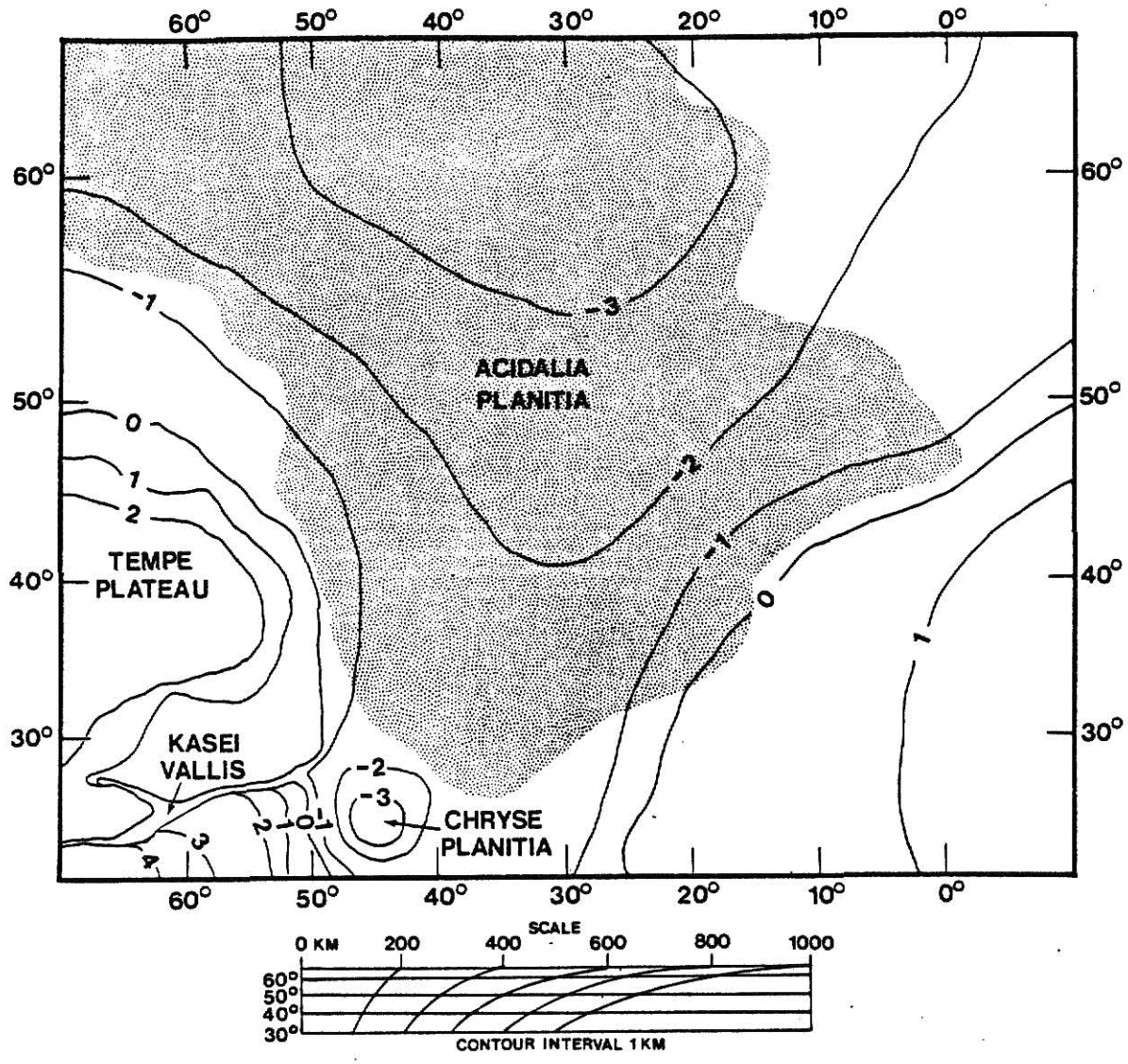


Figure 2. Topographic map of Mare Acidalium quadrangle. Stipple pattern indicates area of extremely low albedo; scale from the 1:25,000,000-scale Topographic Map of Mars (U.S. Geol. Survey, 1976).

high-resolution Mariner 9 images in this northern region hinted that the geology was more complex. The higher-resolution Viking orbiter images have revealed a variety of surface features that confirm the complexity of the geology in the area. Few detailed studies of this area have been done utilizing the high-resolution Viking orbiter data.

This investigation incorporates data from both the Mariner and Viking missions in an effort of identify the materials in, and to infer the most reasonable geologic history of, the Mare Acidalium region of Mars.

Methods of Investigation

Photogeology is defined as: "The identification, recording, and study of geologic features and structures by means of photography, specifically the geologic interpretation of aerial and space photographs and images and the presentation of the information so obtained" (Bates and Jackson, 1980).

On Earth, aerial photographs commonly reveal details of the geology that are not detectable on the ground. Both fieldwork and photogeology are often incorporated into making a geologic map. Because geologic maps of Mars are based only on photographic observations and other remote sensing techniques rather than on ground surveys, the various definable geologic units must be characterized by geomorphic and albedo features. Ideally, the geologic terrains that are delineated have stratigraphic significance; however, the surface processes have been intermittently active such that surfaces of many ages are exposed in many different

geographic areas. It is often difficult to distinguish between the age of a depositional or an erosional surface and the age of the material that immediately underlies it. The occurrence of surface features such as volcanoes, lava flows, impact craters, channels, dunes, and fractures are useful when interpreting the origin and geologic history of an area.

Mars has been divided into thirty quadrangles by the U.S. Geological Survey. The present investigation involves geologic mapping and interpretation of the plains and adjacent highlands in one of these quadrangles of the northern mid-latitudes. Materials that were used include Mariner and Viking single-frame images, stereopairs where available, and photomosaics. Preliminary geologic mapping was done on five 1:2,000,000-scale photomosaics and selected higher-resolution photomosaics. The data were then compiled on one sheet at a scale of 1:5,000.000 for presentation in this thesis. Also, included in the thesis are larger-scale maps and photomosaics of particularly relevant regions.

Early lunar workers developed a method based on statistics of impact crater populations to determine the relative ages of surfaces on the Moon and planets other than Earth. This method is based on the simple relationship between crater abundance and age, i.e., old surfaces are more densely cratered than young surfaces. The technique used for analysis of crater populations is to plot the crater diameter versus the abundance or frequency of craters. The early investigators found that the number of craters increases geometrically as the size of the crater decreases because the interplanetary debris is dominated by smaller-sized particles (Mutch et al., 1976).

To determine possible age relationships between surfaces with distinctive geomorphic and geologic characteristics, statistical analyses of crater frequencies were performed in accordance with the methods outlined by the Crater Analysis Techniques Working Group (Arvidson et al., 1978). These data are presented in cumulative size-frequency distribution plots. The locations of the crater counts are shown on Figure 3.

If every crater on a surface is younger than the surface material, this method will provide a minimum age of the surface material, as well as the exposure age of the surface itself (McGill, 1977). Caution must be used with this method of dating surfaces, because, as McGill (1977) pointed out, large craters have higher walls and deeper pits than small craters. Thin surface deposits such as lava flows, eolian materials, and air-fall materials, could completely obliterate the small craters, partially bury the intermediate size craters, but have little effect on the large craters.

Data Base

Mariner 9.--In 1971-1972, nearly 100 percent of the martian surface was photographed by Mariner 9. The vast majority of the 7,300 images returned by Mariner 9 have a resolution of 1-3 km (A-frames), whereas approximately 1-2 percent of the images have a resolution of 100-300 m (B-frames). Within the Mare Acidalium quadrangle, Mariner 9 transmitted to Earth 26 A-frames and 33 B-frames.

Viking.--Following their arrival at Mars in 1976, the two Viking orbiters acquired approximately 65,000 images of the martian surface. The

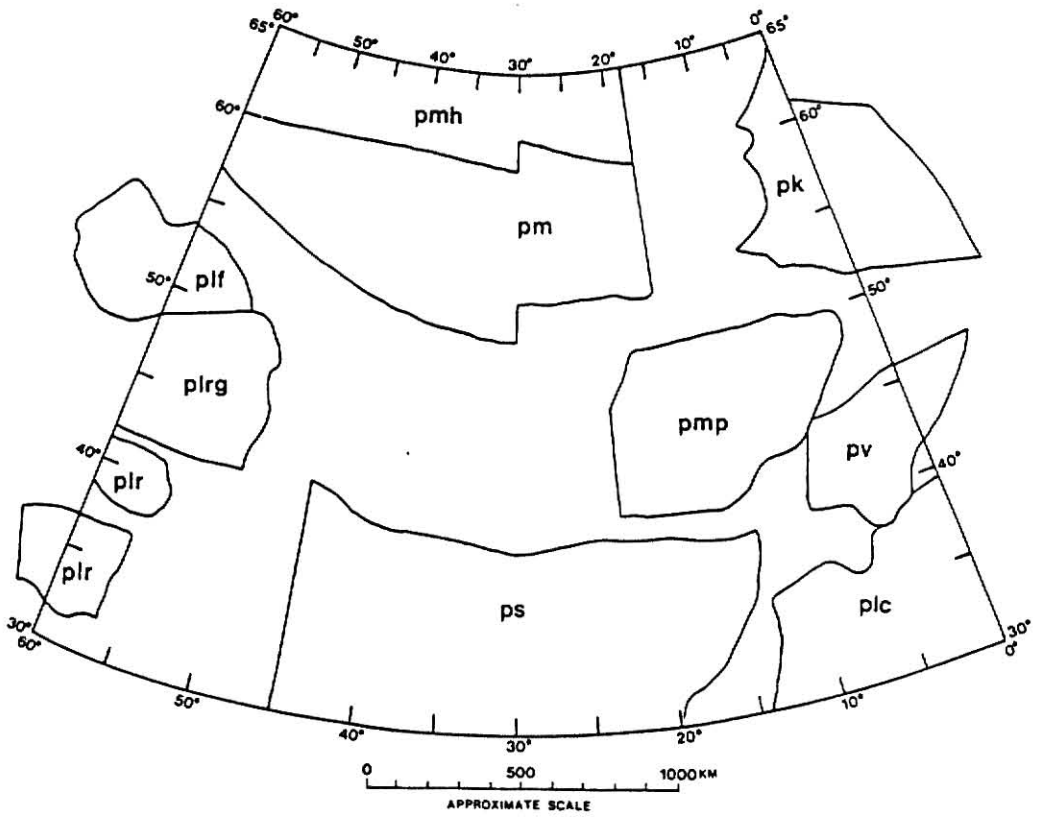


Figure 3. Location of terrains on which crater counts were made. Some areas extend into adjacent quadrangles; plateau units include: cratered plateau (plc), rugged plateau (plrg), ridged plateau (plr), and fractured plateau (plf), plains units include: mottled plains - undivided (pm), hummocky mottled plains (pmh), knobby plains (pk), patterned mottled plains (pmp), variegated plains (pv), and smooth plains (ps).

images are categorized into four groups:
(1) low resolution (average 70,000 km^2 per image, > 180 meters/pixel)
(2) medium resolution (average 40,000 km^2 per image, 130-180 meters/pixel),
(3) high resolution (average 10,000 km^2 per image, 35-130 meters/pixel), and
(4) very high resolution (average 2,500 km^2 per image, < 35 meters/pixel).
In Mare Acidalium quadrangle approximately 1,600 images of varied resolutions were acquired. Figure 4 shows the locations of the high-resolution strips within the quadrangle. Most of the high-resolution data were obtained from the Cydonia region, the area that was designated as a potential Viking landing site.

Previous Mapping

On the basis of Mariner 9 data, Underwood and Trask (1978) mapped the geology of Mare Acidalium quadrangle at a scale of 1:5,000,000. Mariner 9 images in the northern latitudes were of poor quality because of atmospheric dust and the high sun angle at which many of the images were acquired, and, as a result, only a few geologic subdivisions could be recognized within the lowland plains of the quadrangle. These divisions included: mottled plains material, plains material, plains and dissected plateau material, and channel material. The adjacent quadrangles were mapped by Wise (1979), Lucchitta (1978), Milton (1976), Wilhelms (1976), and Dial (1982) at a scale of 1:5,000,000. The Cydonia region of MC-4 was designated as a possible landing site for the Viking lander (Masursky and Cradbill, 1976), resulting in more detailed geologic mapping in this region (Scott, 1976).

Other cartographic products published by the U.S. Geological Survey

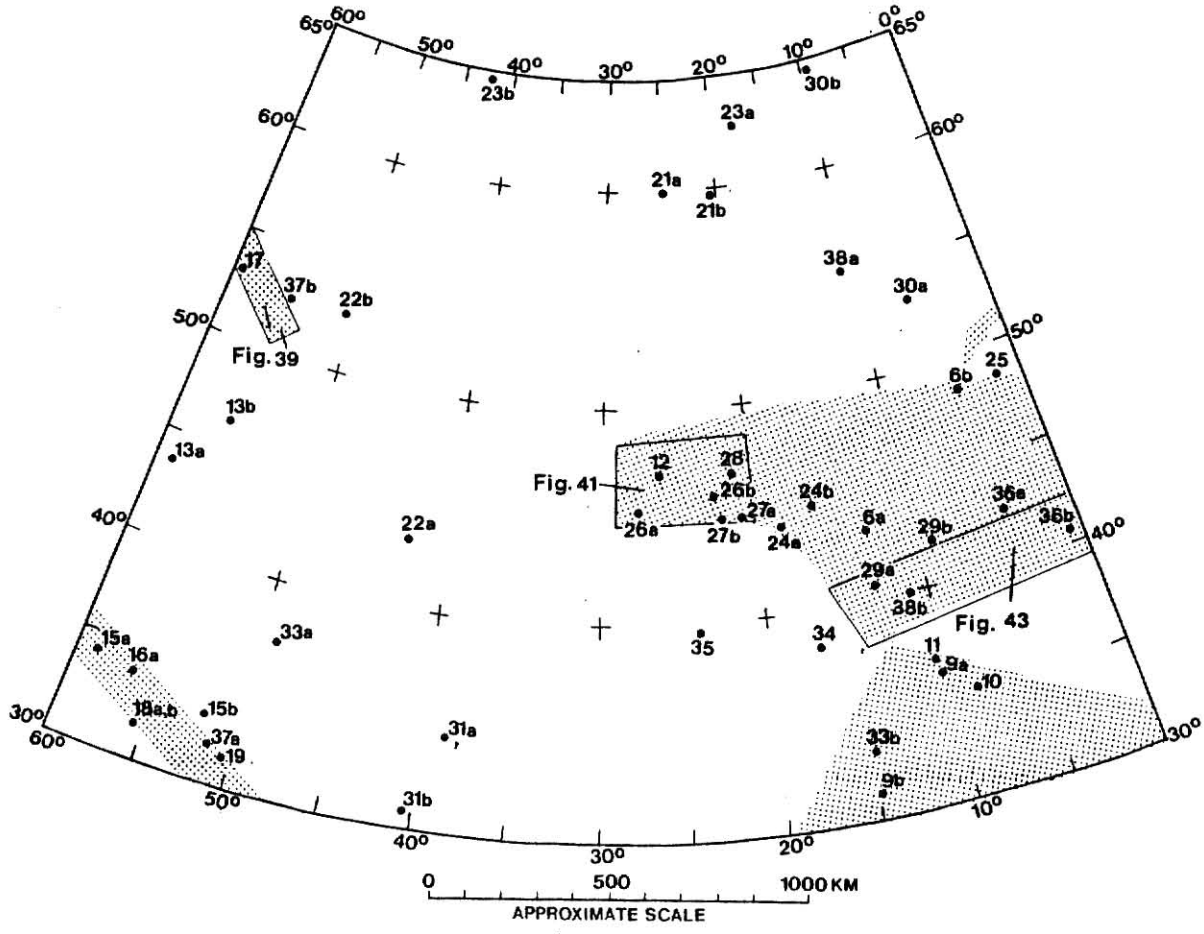


Figure 4. Location of Viking images and photomosaics shown in text. Numbers correspond to figure numbers in this report; dots locate center of images; boxes show locations of high-resolution photomosaics and geologic maps included in Appendix I-III; shaded areas are regions of high-resolution data.

include: 1:5,000,000 topographic map of MC-4 (1976); 1:5,000,000 shaded relief map of MC-4 (1975); 1:1,000,000 topographic map of the Cydonia region (1976); 1:250,000 high-resolution map of the Cydonia region (1976); and 1:2,000,000 controlled photomosaics of the northeast, northwest, southeast, south-central, and southwest sub-quadrangles (1981).

GEOLOGY OF MARS

A general overview of the planet Mars and martian geology is important for understanding the processes that affect the geologic development of a particular region. Several review papers and books have been published (Masursky, 1973; Mutch et al., 1976; Carr, 1980b, 1981). Scott and Carr (1978) published a geologic map of Mars that shows 24 geologic units. Also included on the map are tectonic features, the majority of which are extensional. A number of geologic features on Mars indicate a long period of horizontal tensional stresses acting on the lithosphere. Solomon and Chaiken (1976) and Toksoz and Hsui (1978) presented thermal history models suggesting that Mars has undergone a period of expansion that resulted in extensive systems of tensional fractures and volcanism.

Planetary Dichotomy

One of the most interesting discoveries of the Mariner 9 mission was the striking difference between the northern and southern hemispheres of Mars. There is an abrupt change from the high-standing, heavily-cratered terrain in the south, to the low-lying, lightly-cratered terrain in the north (Fig. 1,5). The boundary between the two hemispheres is approximately a great circle inclined 35° to the equator (Mutch et al., 1976). The northern plains slope to elevations > 3 km below the mean datum, that level where the atmospheric pressure is 6.1 millibars. The southern highlands generally stand 2-3 km above the mean datum.

The heavily-cratered terrain in the southern hemisphere includes the planet's oldest exposed surfaces. Superficially, these old surfaces

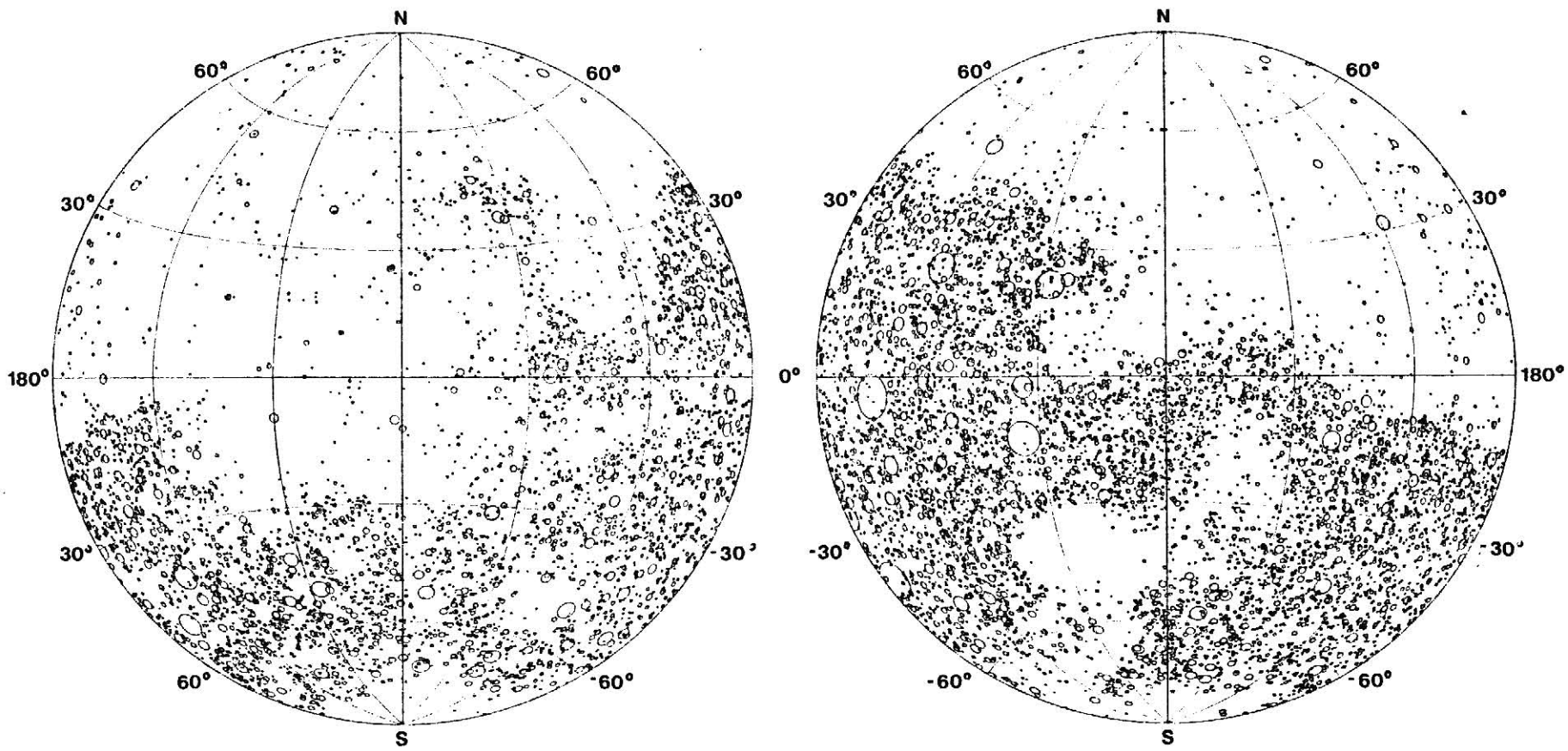


Figure 5. All craters greater than 15 km in diameter. Note the distinct difference in crater density between the northern and southern hemispheres. From Mutch et al. (1976).

resemble the lunar highlands. The two units are thought to be similar in age because of the abundance of large (> 30 km) craters on both units (Soderblom et al., 1974; Neukum and Wise, 1976). The ancient cratered terrain on Mars, however, records a far more complex history of depositional and erosional events. The larger martian craters tend to be highly degraded, and many of these large craters are channeled and gullied, indicating erosion by running water. Volcanic activity (Greeley and Spudis, 1978) and eolian activity (Carr, 1981) were important modifying agents. The old cratered terrain appears to represent a complex mixture of impact debris, volcanic rocks, and eolian and fluvial sediments.

In contrast, the northern plains include some of the youngest surfaces exposed on the planet. Some of the plains material in the Tharsis volcanic regions are almost devoid of impact craters (Scott and Carr, 1978). The low-latitude northern plains contain a number of overlapping volcanic units that have been modified to various degrees by fluvial and eolian processes (Carr, 1981).

The high-latitude northern plains are not as simple to understand as the low-latitide plains. The high-latitude northern plains appear to represent a complex history of erosion and deposition. The surface contains a wide array of topographic and albedo features such as polygonal fractures, pedestal and flow-ejecta craters, irregular depressions and hills of varied origin, and light and dark streaks.

Soderblom et al. (1973a) reported that many craters in the high northern latitudes were filled or partially filled with light material,

suggesting the presence of an old debris mantle that has been stripped away from the intercrater regions. Carr and Schaber (1977), Rossbacher and Judson (1981), and Lucchitta (1981) have indicated the possible importance of ice in shaping the northern terrain. To complicate things further, the northern plains are probably sites of accumulation of fluvial debris derived from the large outflow channels to the south (Carr, 1980b). The complex characteristics of the northern plains most likely result from the interaction of impact, volcanic, eolian, fluvial, mass wasting, and periglacial processes.

The boundary separating the heavily-cratered highlands and the sparsely-cratered lowlands varies. In some places the relationship is simple; the younger plains overlap the older, cratered surface. In these areas, islands of older, cratered terrain can be seen protruding through the plains material (Carr, 1981). In other areas, the boundary is expressed by a steep escarpment 1-2 km high. In many areas along the escarpment there are flat-topped mesas and rounded, equidimensional hills that have been interpreted as erosional remnants of highlands material left by scarp retreat (Scott 1978, 1979; Scott and Carr, 1978).

The origin of the planetary dichotomy is controversial. Soderblom and Wenner (1978) pointed out that extensive areas throughout the northern equatorial region appear to have been uniformly stripped to depths 1-2 km below the pre-existing surface. These areas vary in age and in absolute elevation. Soderblom and Wenner suggested that the southern highlands are underlain by an ice-laden zone and sections of this layer were removed from the region by such processes as eolian deflation, gravitational slump,

collapse, and fluvial transport. Erosion stopped at the liquid-ice interface because rocks below the zone of permafrost were cemented and much more resistant. Head et al. (1977) also concluded that the boundary between the cratered terrain and plains was the result of collapse and erosion at the north-facing escarpment.

Carr (1980a, 1981) and Wise et al. (1979) have argued that erosion by surface processes cannot fully explain the disappearance of the ancient crust from the northern hemisphere because there is no sink of sufficient size to accommodate the debris. Carr (1980a) and Mutch et al. (1976) suggested that differentiation produced a crust of varied thickness. The crust was thinner in the north and thicker in the south. The lack of a gravity anomaly along the plains-highlands boundary lends support to this view (Carr, 1980a).

Wise et al. (1979) discussed the possibility of subcrustal erosion by a convection cell operating beneath the northern plains region. The cell, rising beneath the northern plains, eroded the base of the crust and disrupted the remaining crust by fracturing. Subsequently, the northern region sank to maintain isostatic equilibrium (Phillips and Saunders, 1975) and was covered by volcanic material. The eroded basal-crustal material was eventually transported to the Tharsis region where slow transfer of heat from zones deep in the mantle produced an extremely long volcanic phase (Wise et al., 1979).

Impact Craters

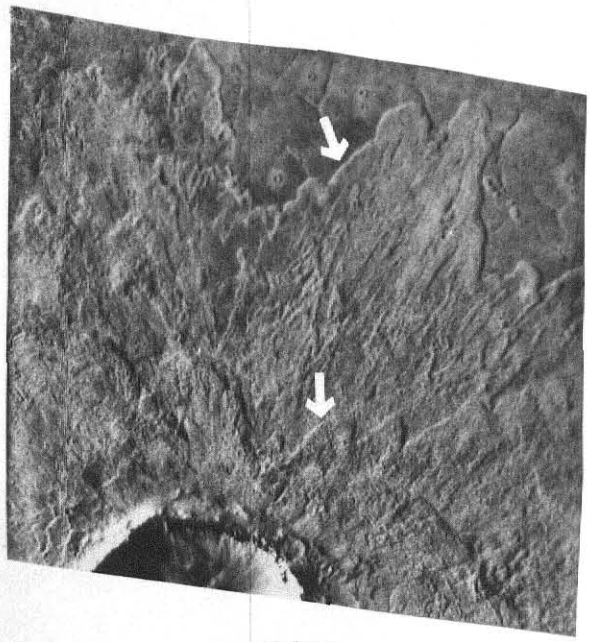
Circular depressions are a common landform on the surface of nearly every solid planetary body in the solar system. Most workers have interpreted these features as impact craters. Impact craters can be very important indicators of such things as surface material, erosional and depositional events, and relative ages of exposed surfaces (Carr, 1981).

The morphology of ejecta around most of the martian craters is different from that around lunar and mercurian craters. Lunar and mercurian craters are surrounded by a continuous ejecta blanket that commonly extends outward as bright rays and fields of secondary craters. Ballistic emplacement is the mode of deposition of ejecta around these craters. In contrast, many of the martian ejecta blankets appear to have been emplaced by surface flow (Fig. 6a). These craters have been identified by a variety of names such as rampart, fluidized, splosh, flower, flow-ejecta, and so on. They shall be referred to either as rampart or flow-ejecta craters in this study.

Craters having ejecta blankets with a distinct outer ridge or rampart were first recognized on Mariner 9 B-frames and are designated as rampart craters. McCauley (1973) and Arvidson et al. (1976) attributed their unusual morphology to wind erosion. Further investigation revealed fine details of the ejecta blankets that were primary features and not the result of subsequent modification (Head and Roth, 1976). Most workers presently believe that the presence of liquid water, water ice, or other volatile material in the ejecta was the cause of its fluid properties (Carr, 1981). These fluidized or rampart craters occur on almost every geologic unit on Mars, and they apparently formed thoughout a considerable span of time

Figure 6. Impact crater material. (a) Ejecta lobes of Arandas crater (30 km diameter); concentric flow-ejecta deposits are indicated by the arrows; the inner ejecta deposit was interpreted as part of the crater's overturned rim flap that was subsequently overridden by the more extensive outer ejecta deposit (Carr et al., 1977); shadow length estimates indicate that the inner ejecta unit rises 40-100 m above the surrounding material, and the outer ejecta unit rises 80 m above the surrounding plains (Mouginis-Mark and Carey, 1980); fine radial structure occurs on the lobes; Viking frame 9A42 (43°N, 14.5°W). (b) Small pedestal crater (< 2 km diameter); compare the pedestal crater (p) to the other non-pedestal impact crater (c) of similar size; note that the pedestal crater has a low platform that extends outward approximately three crater diameters; the surrounding unit is patterned mottled plains material (pmp); the small arrows indicate troughs; the larger arrow indicates a ridge; faint lines at eastern and western side are image artifacts; Viking frame 26A56 (47.5°N, 5.2°W).

a.



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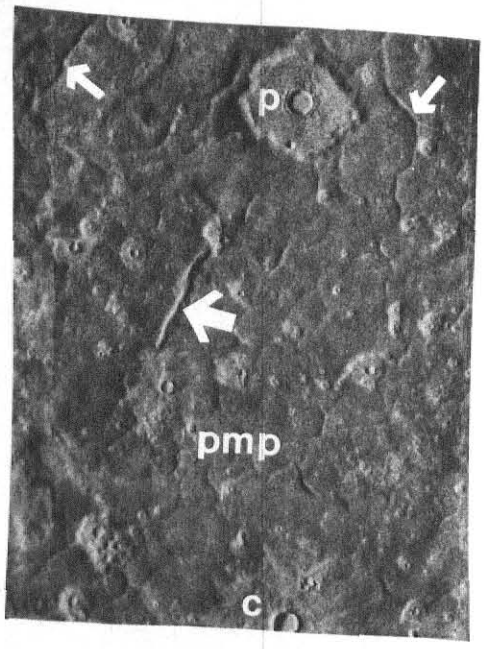
b.



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(Allen, 1979a).

Another type of martian crater with unusual morphology is the pedestal crater (Fig. 6b). These kinds of craters are common in the northern hemisphere between latitudes 30°N and 70°N (Carr, 1981) and are craters situated in the center of a low platform or pedestal that extends outward more than three crater diameters. McCauley (1973) suggested that ejecta from the impact armored the surface adjacent to the crater and subsequent deflation of the intercrater region resulted in the crater and its surrounding ejecta remaining as a platform or pedestal overlooking the lower intercrater area. Mutch and Woronow (1980) suggested that the pedestal craters represent viscous ejecta, i.e., too viscous to flow into lobes.

Permafrost

The presence of permafrost on Mars has long been suspected based on observations of the annual surface temperatures and the assumed outgassing history of the planet (Sharp, 1973, 1974; Anderson et al., 1967; Farmer and Doms, 1979; Fanale, 1976). Water vapor or water ice is indicated from infrared and water-vapor measurements over the polar caps (Kieffer et al., 1977; Farmer and Doms, 1979) and from soil analysis by the Viking landers (Biemann et al., 1977). Mariner and Viking orbiter data have reinforced the suspicion that permafrost has played an important role in the development of the martian landscape (Carr and Schaber, 1977).

Probably the most important consideration is that Mars is cold. The present mean annual temperature is approximately -60°C (Leighton and Murray, 1966) well below the triple point of water. The cold temperature favors

development of a zone of frozen ground everywhere beneath the surface of the planet (Carr and Schaber, 1977). Only between latitudes 70°S and 30°N do the summer, daytime temperatures exceed 0°C (Fig. 7) (Anderson et al., 1973).

Fanale (1976) showed that at latitudes > 40°, the mean annual surface temperature is low enough for subsurface ice to be in equilibrium with current levels of water vapor in the atmosphere. Below 40° latitude, water ice is unstable and could sublime and dissipate if exposed to the atmosphere. Observations of the atmospheric water vapor are consistent with the presence of a permanent reservoir of water ice buried at a depth of 10 cm to 1 m at all latitudes poleward of 40° (Farmer and Doms, 1979).

Approximately two-thirds of the study area lies north of 40° latitude. Fanale (1976) suggested that a regolith of unconsolidated material as much as two km thick may exist on Mars, and that within this regolith, permafrost could occur anywhere above the 273° K isotherm (ice-liquid water temperature boundary).

There have been a number of estimates made of the amount of water outgassed from Mars based on the elemental and isotopic composition of the atmosphere and on assumptions regarding the initial composition of Mars. These estimates include the use of the abundances of ^{36}Ar, ^{40}Ar (Anders and Owen, 1977; Owen and Biemann, 1976; Fanale, 1976), and N_2 (McElroy et al., 1977). These estimates predict that the thickness of a layer of water that could cover the entire surface of Mars ranges from 9 m (Anders and Owen, 1977) to 80-160 m (Pollack and Black, 1979). Presently, we observe water only as frost or ice of the polar caps and as water vapor in the atmosphere.

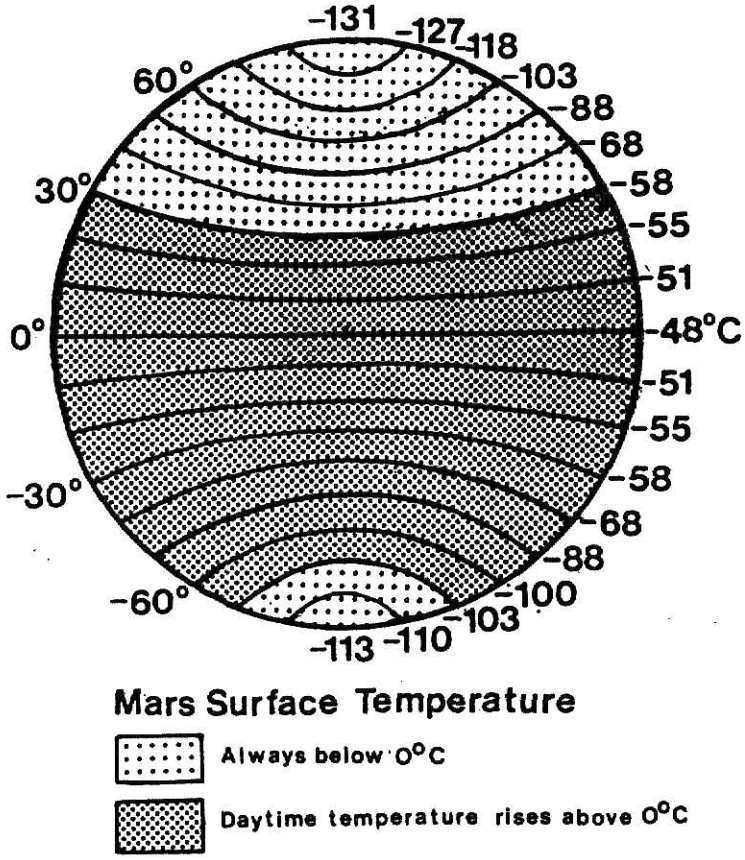


Figure 7. Mean annual surface temperature for each latitude of Mars. Temperatures are derived from the model of Leighton and Murray (1966); adapted from Fanale (1976) and Sharp (1974).

For the last two centuries, astronomers have observed the annual advance and retreat of the bright polar caps. Initially, these caps were regarded as comparable to a terrestrial polar ice sheet. Later it was realized that these masses could be little more than thin frost blankets (Sharp, 1974). Viking orbiter data indicate that frozen carbon dioxide advances and recedes from the polar caps seasonally, but the residual cap left in the summer is composed of water ice (Kieffer et al., 1977).

Estimates on the amount of water contained in the atmosphere, polar caps and surface frost, and the water lost through exospheric escape have been compared to the estimates of the amount of water originally outgassed (Rossbacher and Judson, 1981). These calculations indicate that much water is still unaccounted for and may be trapped as subsurface permafrost or chemically bound in the soil (Owen and Biemann, 1976).

A number of features have been interpreted by photogeologists as evidence for the presence of permafrost on Mars. Sharp et al. (1974) and Carr and Schaber (1977) suggested that permafrost may have been important in the formation of chaotic and fretted terrains and some channel features. Rampart or flow-ejecta depostis that surround many craters may be the result of impact into ice-laden regolith (Carr et al., 1977; Gault and Greeley, 1978). Patterned ground, similar to that seen in periglacial regions on Earth, characterizes extensive areas of plains in the 40° - 50°N latitude belt. Carr and Schaber (1977) and Gatto and Anderson (1975) interpreted scalloped scarps and irregular shallow depressions as thermokarst features, structures resulting from disturbances of the subsurface ice layers.

In summary, the conditions necessary for the formation of permafrost appear to exist on Mars. The mean annual temperature is well below freezing. Theoretical calculations on the outgassing history of the planet and current water-vapor measurements indicate the presence on Mars today of large volumes of water vapor or water ice, some of which may be stored in the subsurface. Geomorphological studies of Mars show many landforms that further reinforce the importance of permafrost on the planet.

Meteorology and the Atmosphere

An important factor in controlling martian surface conditions is the nature and activity of the atmosphere. Similar to Earth, the axis of Mars is tilted approximately 23° with respect to its orbital plane. As a result, the martian atmosphere undergoes seasonal changes analogous to those on Earth. The eccentricity of the martian orbit results in the southern hemisphere having a shorter but hotter summer than the northern hemisphere.

From Mariner 4 observations, scientists learned that the thin atmosphere of Mars was composed primarily of carbon dioxide and that the atmospheric pressure was much lower than had been previously assumed; Martian atmospheric pressure is an average of 7 millibars (Earth's average atmospheric pressure is 1,013 millibars (Carr et al., 1980). Goody and Belton (1967) recognized that such an atmosphere would respond strongly and quickly to variations in solar heating and radiative cooling during the day, thus, causing changes in pressure that would result in diurnal wind systems.

Because of the tenuous atmosphere of Mars, much stronger winds than those on Earth are required to set particles into motion. Arvidson (1972)

estimated that saltating grains of a given diameter will travel 20 times faster on Mars than on Earth. High-velocity winds combined with relatively low settling velocities permits fine particles to remain aloft in the martian atmosphere sufficiently long to result in global dust storms (Mutch et al., 1976).

Even before the Mariner and Viking missions, telescopic observations showed that major dust storms are fairly common on Mars. Antoniadi (1930) was the first to suggest that wind might be modifying the surface of Mars. He proposed that increased solar heating of the atmosphere during perihelion provided enough energy for wind to raise large amounts of dust.

Mars observers, for more than a century, have been able to distinguish between yellow clouds (i.e., dust clouds) and white clouds (Snyder, 1979). Several types of white clouds have been observed: morning and evening hazes, recurrent localized clouds (i.e., in the Tharsis, Olympus Mons, and Elysium regions), and polar hoods. Generally, most of these clouds are believed to be composed of water; however, some may consist of carbon dioxide (Briggs et al., 1977).

During the winters the polar regions cool to extremely low temperatures, forming an extensive cloud cover known as a polar hood. North of about 60° latitude, the polar hood is believed to be partially composed of carbon dioxide ice particles. This cloud cover disappears in late winter to reveal a surface covered largely with carbon dioxide frost or snow (Leovy and Briggs, 1974).

Wind Features

Mariner 9 arrived at Mars during one of the more intense planet-wide dust storms. After the dust settled, Mariner cameras revealed a wide variety of landforms that can be attributed to wind. These features include dune fields, yardangs, and varied light and dark markings that are interpreted as surficial wind streaks (McCauley, 1973). The Viking mission has provided additional information about the eolian regime.

The most common eolian features observed on Mars are wind streaks. These streaks are almost always associated with impact craters or other topographic obstacles. Although wind streaks occur in a variety of shapes, sizes, and topographic settings, most can be grouped into one of three categories: (1) bright depositional streaks, (2) dark erosional streaks, or (3) dark depositional streaks (Thomas et al., 1981). Presumably, the orientations of wind streaks relect both global flow patterns and slope-controlled winds.

A vast field of transverse and barchan dunes, several hundred kilometers across, surrounds the north polar cap (Tsoar et al., 1979). Smaller fields of transverse dunes occur in craters and in canyons and valleys all over the planet (Ward et al., 1982). Wind directions can be derived from dune shape and orientation of the slip faces.

Crater splotches are irregular, dark deposits that occur on the down-wind interior sides of craters. Many of these dark splotches have been resolved to be fields of dunes, through image enhancement. The occurrence of dark crater splotches increases with increased latitude (Thomas et al., 1981).

Yardangs are streamlined erosional landforms aligned with the strongest regional winds (Ward, 1978); other wind-erosion features on Mars include pits and grooves. Ward et al., (1980) considered these erosional features to be indicators of long-term wind trends. Most of the erosional landforms occur in the equatorial region of Mars, i.e., the area swept clean of eolian debris (Soderblom et al., 1973b).

The global wind pattern can be derived from systematic mapping of the orientation of eolian features (Ward et al., 1980). Of particular interest to this investigation is the circulation pattern in the northern hemisphere.

Coriolis-type winds appear to dominate near the pole (above 80°N). Between 80°N and 40° - 50°N, most streaks and dunes trend northwest-southeast showing no coriolis affect. Ward et al., (1980) suggested that the mid-latitude trend may be the result of storm winds locally generated form thermal contrast produced by the retreating ice cap during the spring. South of 40° - 50°N latitude the winds may be influenced by the coriolis effect as they change to a northeast-southwest orientation (Ward et al.,1980).

Channels

The channels on Mars have been the subject of considerable controversy since their discovery during the Mariner 9 mission; however, most workers have concluded that they are fluvial features. The main question is whether significant quantities of water could have existed in the past on the planet's surface (Mutch et al., 1976). Presently, the surface is too cold (Leighton and Murray, 1966), and the atmospheric pressure is too

low at the lower latitudes (Fanale, 1976) for liquid water to be stable at the martian surface. These problems led to the suggestion that different atmospheric and climatic conditions existed in the past (Mutch et al., 1976; Carr, 1980b).

The two types of channels that are important to the present study are the small runoff channels that occur in the cratered terrain and the large outflow channels that occur around the Chryse basin. Runoff channels are commonly simple gullies or troughs a few tens of kilometers long. Their number and length tend to decrease toward the high latitudes (Carr and Clow, 1981). Masursky et al. (1977) suggested that the water that cut the channels may have been derived from rainfall. Alternatively, Pieri (1980) concluded that sapping or seepage from the groundwater system was more probable. Several of these small channels occur in the old cratered terrain in Mare Acidalium quadrangle.

The outflow channels are very wide, have few, if any, tributaries, and commonly extend for more than 100 km (Fig. 1). Scour patterns and teardrop-shaped islands are commonly associated with the channels (Carr and Clow, 1981). These large outflow channels have been interpreted as having been formed by catastrophic flooding (McCauley et al., 1972; Masursky, 1973; Masursky et al., 1977; Milton, 1973; Baker and Milton, 1974; Nummedal, 1976; Carr, 1979; Baker, 1982).

Carr and Clow (1981, Fig. 7) mapped the planetwide distribution of the outflow channels, the largest of which are around Chryse Planitia. Scours from the channels that enter the Chryse region from the south extend

northward into Acidalia Planitia before they disappear between 35°N and 40°N. Channel deposits of Kasei Vallis occur in the southwestern part of Mare Acidalium quadrangle.

Volcanism and Ice

The effects of volcanism on surface ice have been investigated by Allen (1979b) and by Hodges and Moore (1978, 1979). Mesa-like structures on the martian surface resemble Icelandic tablemountains believed to be the result of volcanic eruption beneath an ice layer. Moberg ridges, thought to be subglacial fissure eruptions, have also been tentatively identified in the northern plains of Mars (Allen, 1979b). Frey et al. (1979) have identified what they believe to be pseudocraters in the Cydonia region. Pseudocraters are small domes with or without summit craters that develop from steam venting when lava flows over wet ground (Lucchitta, 1981).

GEOLOGY OF MARE ACIDALIUM QUADRANGLE

Impact Craters

In the present investigation, craters have been assigned to one of four morphologic categories based on crater preservation state according to the guidelines adapted for the Mars Geologic Mapping Program of the U.S. Geological Survey. A c_4 classification indicates young crater material; the rims are sharp, and the floors are deep. Small c_4 craters (< 10 km) generally have a bowl shape whereas the larger c_4 craters have central peaks. The ejecta blankets are fresh and extensive. Craters of c_3 classification are moderately fresh, although they have been somewhat modified. The crater rims are relatively sharp. The larger c_3 craters may or may not have a central peak, but the floor is still lower than the surrounding terrain. The ejecta blankets show somewhat less detail than c_4 craters. Moderately old or degraded craters are designated as c_2 craters. The crater rims are rounded, the floors are generally flat, and they have no central peak. The ejecta blankets may have been partly buried or stripped away. A c_1 crater is highly degraded; the crater rims are subdued, and the floors are flat and shallow and usually filled with younger material. The ejecta may have been completely obscured or removed, and only parts of the rim still exist. Greeley et al. (1977), in mapping the Chryse Planitia region, emphasized that the rate of degradation of craters is probably not uniform on a global scale but may be considered fairly uniform over a limited area.

To determine possible age relationships between units, crater counts

were made on all material units of sufficient size to provide a valid statistical sample. The cumulative crater size-frequency is defined as the number of craters per unit area with diameters equal to, or greater than, a specific diameter (Nuekum and Hiller, 1981). The data are presented on plots of log crater frequency (number per unit area) versus log crater diameter (Fig. 8). The frequency plots should shift to higher crater densities as the surface-rock units become older. The relationship is demonstrated in Figure 8; the cratered plateau unit is believed to be the oldest in the quadrangle based on the abundance of large (> 20 km) impact craters. Utilization of larger craters in size-frequency plots is preferable because large craters are less susceptible to destruction than smaller ones.

Plateau Province

The elevated plateau province contains the oldest exposed surfaces in the quadrangle based on the crater size-frequency distributions and marks the northern extent of the ancient southern highlands. Plateau material occurs in three areas: the southeast corner, containing cratered plateau material (302,000 km^2); the central region, containing dissected and fractured plateau material (25,000 km^2); and the southwest corner, containing rugged plateau material (270,000 km^2), ridged plateau material (95,000 km^2), fractured plateau material (46,000 km^2) and small patches of lower plateau material.

Cratered Plateau.--The surface of the elevated cratered plateau in the southeast corner of the quadrangle appears to be the oldest in the map

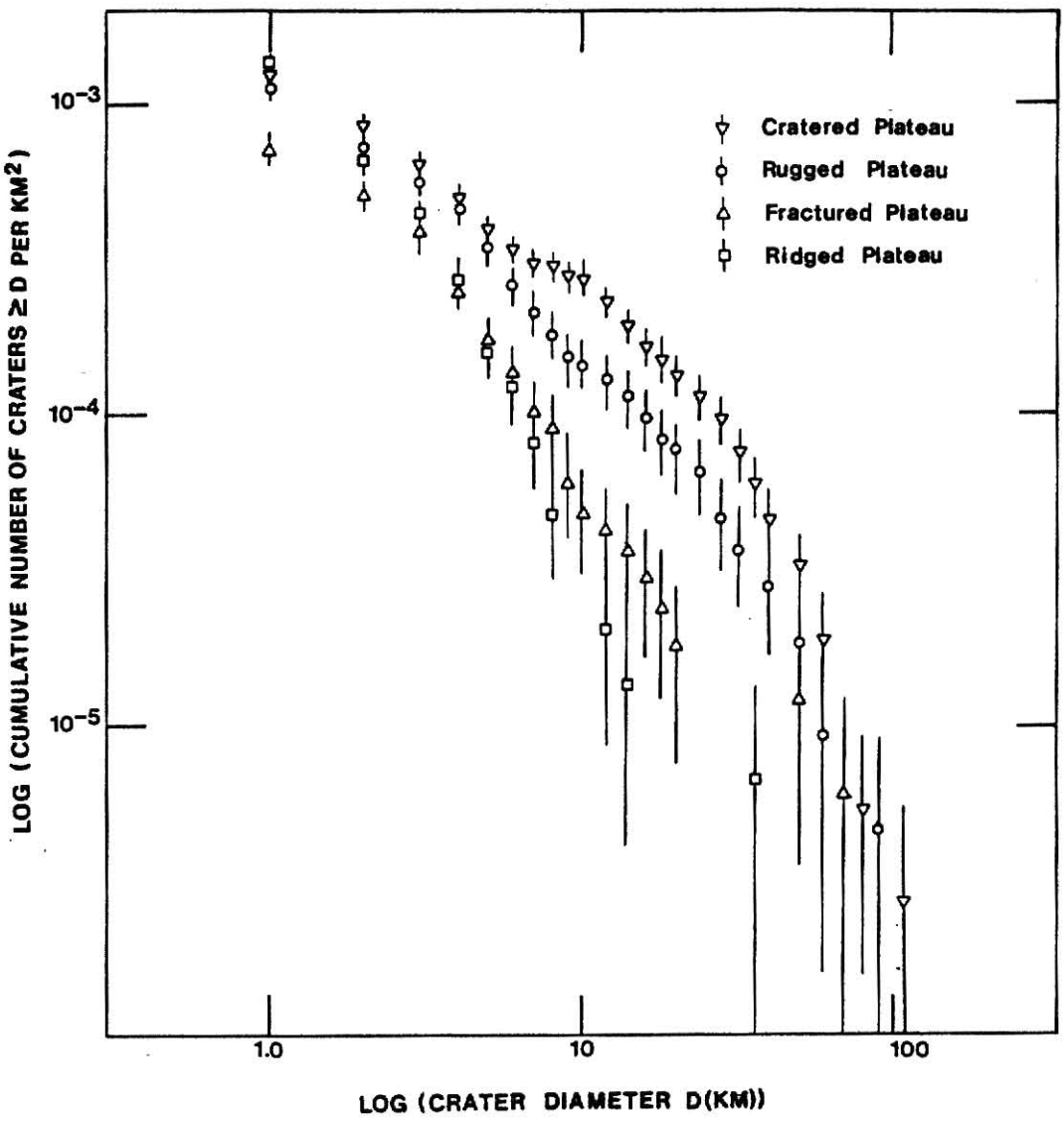


Figure 8. Cummulative crater size-frequency distributions for the plateau units. Number of craters are cummulated from largest to smallest size; vertical lines indicate one standard deviation, 1σ, confidence intervals for each data point plotted, calculated by assuming the crater populations are Poisson distributed. The 1σ is approximated by using $N = \pm \sqrt{N}$ where N is the number of craters (Arvidson et al., 1978).

area based on the abundance of large (> 20 km) impact craters (Fig. 8). The cratered plateau material is characterized by many flat-floored, degraded and partly buried c_1 and c_2 impact craters. Craters of c_3 age and younger are superposed on the cratered plateau surface. The age of the material forming the cratered plateau surface and burying the older craters must, therefore, be older than the craters of c_3 age. The lithology of these deposits is unknown but may comprise thin volcanic lava flows and eolian material.

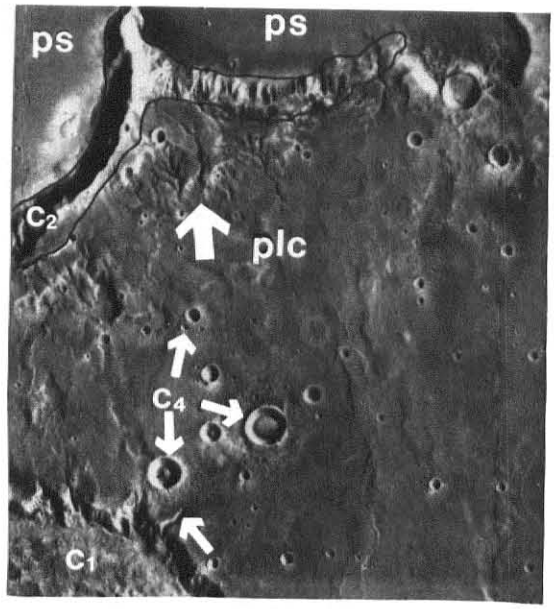
Processes of eolian deposition and erosion appear to be currently active. Dark material commonly occurs on the floors of larger craters, and in a few places the dark material seems to have been blown out of the crater interior, forming a dark plume downwind from the crater. Light streaks of light material also are present but are less common.

Several small sinuous channels occur on the cratered plateau surface (Fig. 9) and are included on Carr and Clow's (1981) global-distribution map. These authors use the term "valley networks" for these features. Pieri (1980) suggested that these features may imply immature drainage from restricted source regions as a result of mobilization of volatile material in the subsurface, e.g., through sapping or seepage from permeable strata.

Shultz and Glicken (1979) used the term "floor-fractured crater" to describe impact craters, commonly found along the plateau-plains boundary, that have apparently been heavily modified by processes restricted to the crater interiors. Several of these modified craters occur on the cratered plateau in MC-4 (Fig. 10). Because modification occurs only in certain

Figure 9. Small channels on cratered plateau. (a) Dendritic network of channels (large arrow) associated with rim material of the large c_2 craters near the plateau-plains boundary; small trough along the rim of old c_1 crater indicated by arrow; small c_4 craters occur with or without central peaks; several north-northeast trending ridges occur on the cratered plateau; compare the texture of the smooth plains (ps) and the cratered plateau (plc); see Figure 11 for regional setting; image artifacts occur along the eastern and western margins of the image; Viking frame 218S20 (36.4°N, 8.5°W).
(b) Sinuous channels at plateau-plains escarpment; channels on cratered plateau (plc) indicated by arrows; northeast channel discontinuous, partially covered in one area by small impact crater; channel originates from circular depression; irregular rimless depressions that may be thermokarst features occur on cratered plateau; knobby material (k) occurs on smooth plains (ps); image artifacts occur along east and west margins of the image; Viking frame 205A02 (30.9°N, 14.7°W).

a.



10 km

N

b.

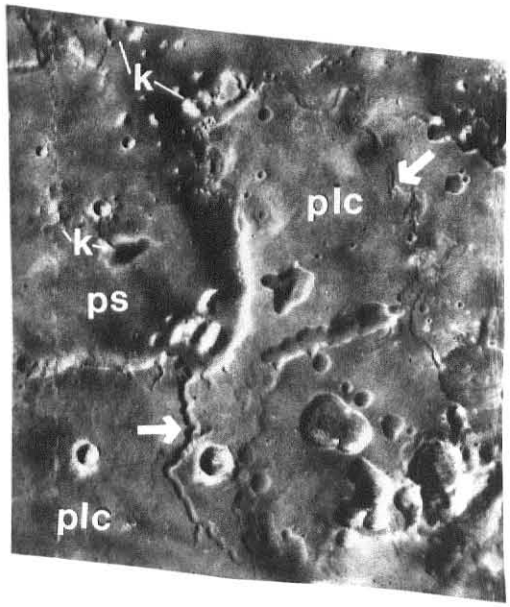


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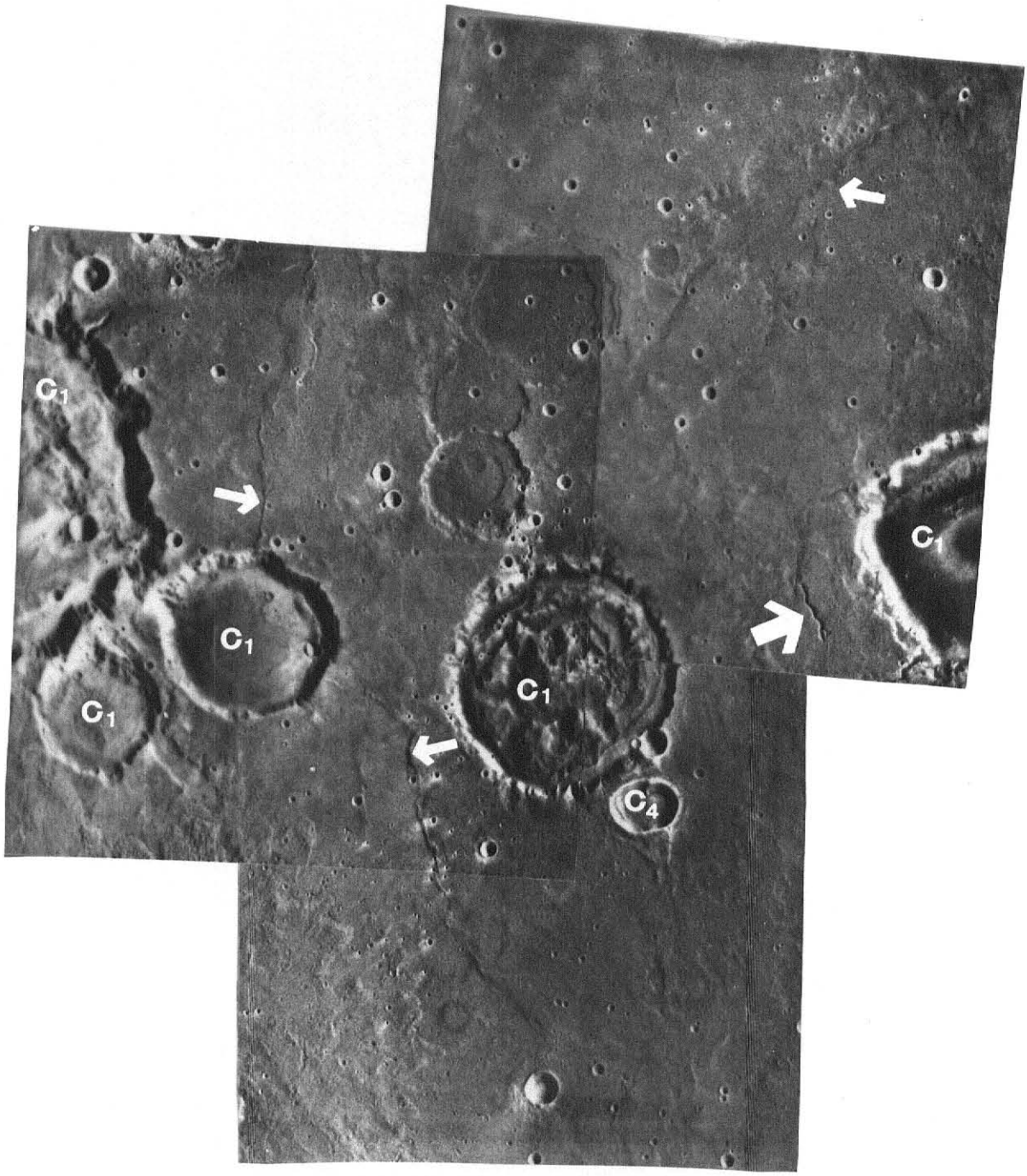
Figure 10. Floor-fractured crater on cratered plateau. See Figure 11 for regional setting; compare the floor morphology of the 20 km diameter c_1 floor-fractured crater in the center of the mosaic and the larger c_1 crater only partially shown along the western margin of the image with smaller c_1 craters to the west; small bowl-shaped c_4 crater occurs just south of the floor-fractured crater; note the three smaller (10 km diameter) craters north of the floor-fractured crater; a rim is still visible on the crater farthest south, whereas the two craters to the north exhibit only faint circular outlines; angularity of some crater outlines, e.g. western-most c_1 crater that is only partially shown, may be result of regional fracture pattern; low ridges and faintly visible irregular depressions (small arrows) give the intercrater surface a rough appearance; small sinuous channel indicated by the large arrow; image artifact occurs along the eastern margin of the mosaic; Viking frames 216S06, 218S19, 218S21 (35°N, 8.5°W).


C1
C1
C1
C1
C1
C4
10 km
N

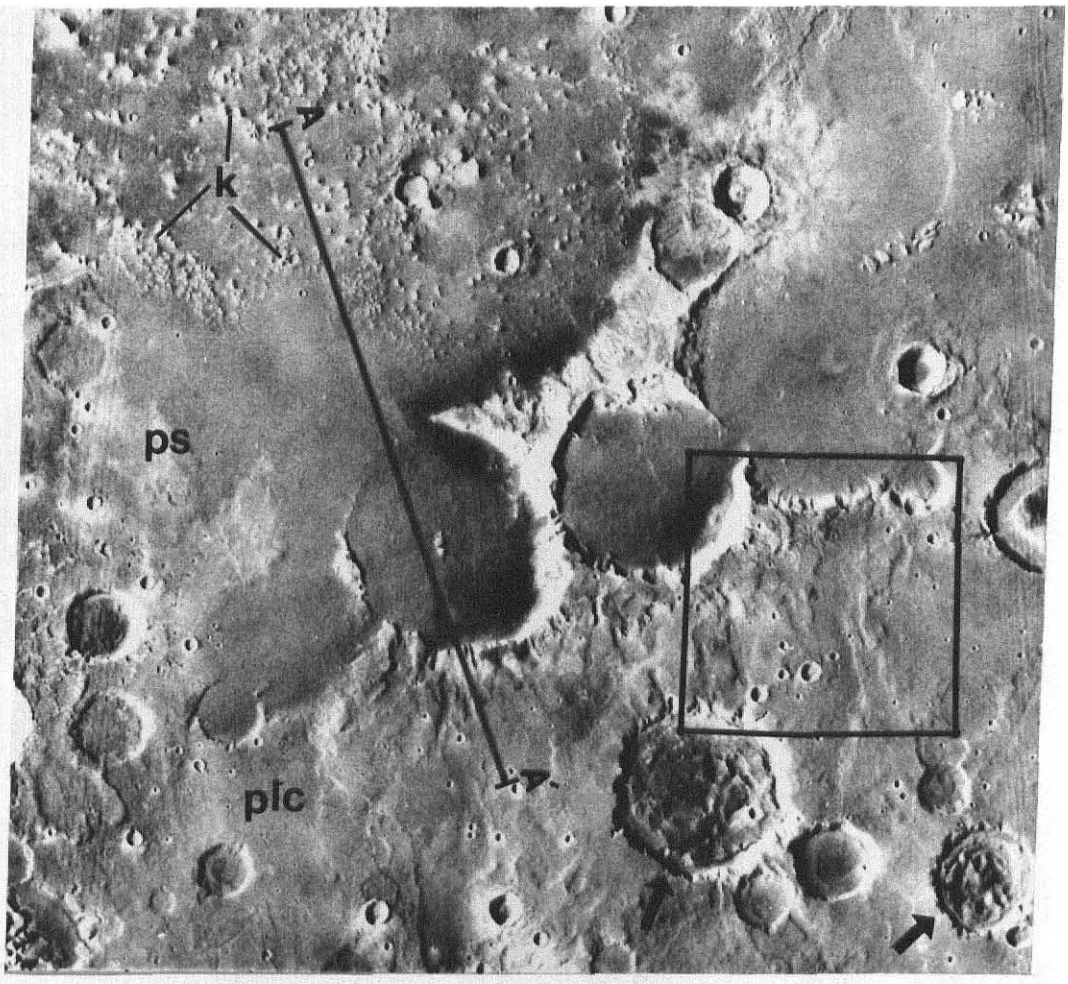
craters in a given region (Fig. 10) and affects craters of widely different formation ages, Shultz and Glicken suggested that modification of the craters is directly related to processes that are localized beneath certain crater floors and not necessarily related to the initial impact events. They suggested that these craters are sites of localized intrusions; the injection of the intrustion is assumed to lift the crater floor and cause fracturing and slumping of the wall material. During advanced stages of intrusion, concentric grabens surrounding the floor and polygonal fractures in the central floor plate may form. Heat released by the intrusion beneath the brecciated zone of the impact crater could thaw permafrost resulting in the release of water or vapor through the fractures. This release of water may result in further surface deterioration and modification (Shultz and Glicken, 1979).

The boundary between the heavily-cratered plateau material and the lightly-cratered, smooth plains is varied. In the southern region, an escarpment several hundred meters high characterizes the boundary. There are many small channels, fractures, and irregular depressions on the plateau near the escarpment (Fig. 9b). These features may be the result of removal of water ice trapped in the plateau layers. This removal would result in collapse depressions and in scarp retreat. Franke et al. (1981) have begun a survey of slope features along the plateau-plains boundary and are applying standard equations and techniques for the analysis of slope stability. Their results, however, have not yet been published.

Along the northern boundary, dark plains materials that may consist of volcanic flows embay old c_1 and c_2 craters (Fig. 11), indicating that the

Figure 11. Cratered plateau - smooth plains boundary. (a) Compare the number of craters and the surface roughness of the cratered plateau (plc) and the smooth plains (ps); smooth plains materials embay the three large (40 km diameter) craters in the center of the image; knobby material (k), thought to be erosional remnants of the cratered plateau, can be seen scattered across the smooth plains in the northwest portion of the image; several of the intermediate-size craters in this region have linear sections of walls that may reflect a regional fracture pattern; the area shown in Figure 9a is delineated by the box; the floor-fractured craters shown in Figure 10 are indicated by arrows; image artifacts occur along the eastern and western margins of the image; Viking frame 561A07 (36.9°N, 11.0°W). (b) Schematic cross-section showing the smooth plains - cratered plateau boundary from A to A'.

a.



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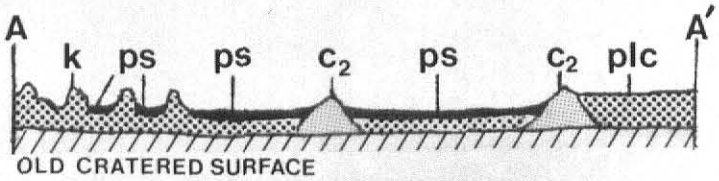
b.



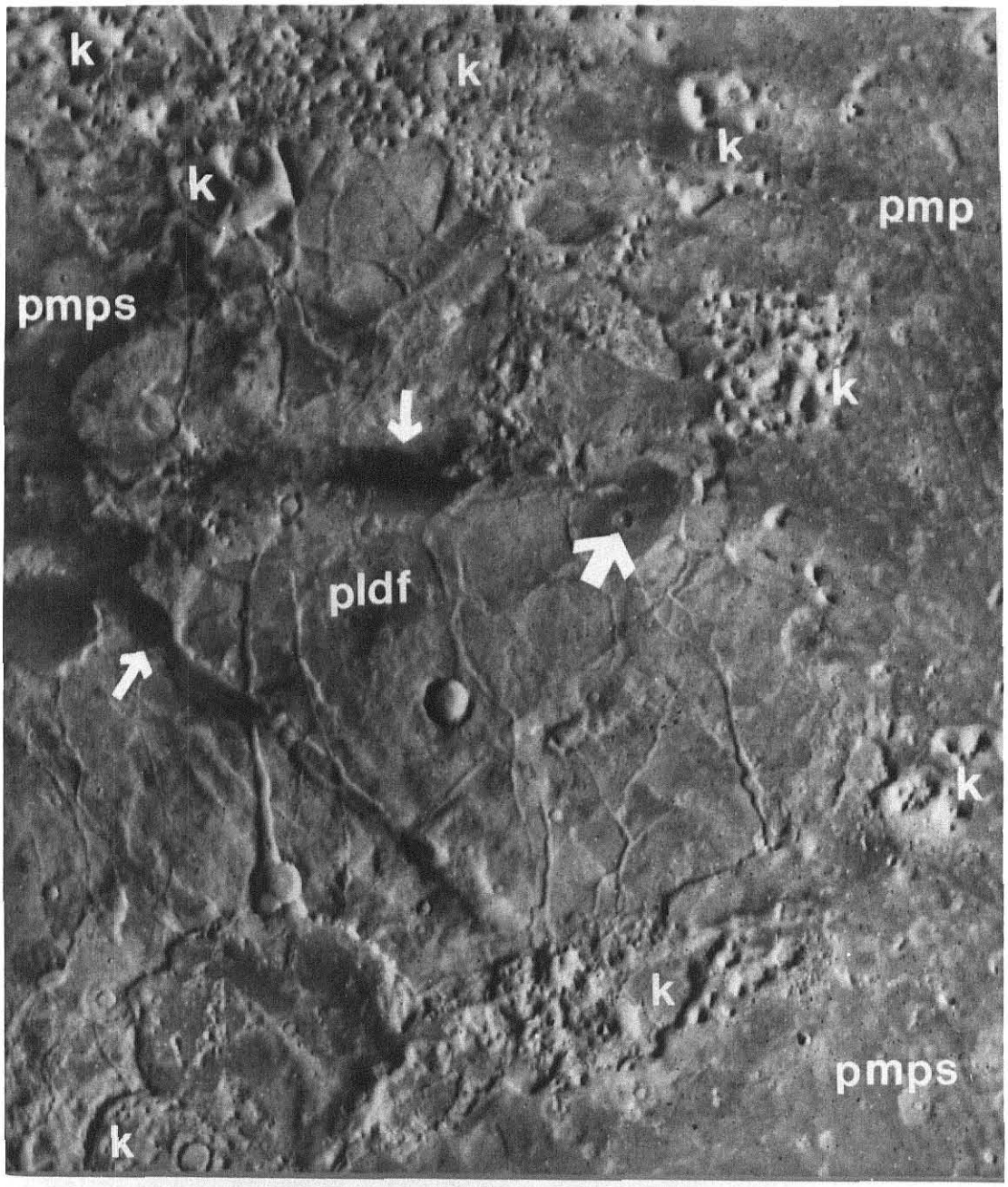
Schematic Cross-Section
Large Vertical Exaggeration

boundary in this region may be partly depositional. Numerous mesas and knobs, interpreted as erosional remnants of plateau material, occur along the entire plateau-plains boundary, indicating that the plateau material may have, at one time, covered much more of this region. Scott (1978) reported that, in many areas along the plateau-plains boundary, lava flows of the lowland plains embay older highland rocks, and remnants of the highland surface project as islands above the lava-covered plains. From the data of the Great Escarpment of Basutoland Plateau in Africa, Scott (1978) extrapolated a 0.16 cm/yr rate of scarp retreat for the martian escarpment. Scott estimated that a minimum of 200 million years would have elapsed between the beginning of lateral erosion of the highlands and the extrusion of lava in the lowlands.

Dissected and Fractured Plateau Material.--The dissected and fractured plateau material covers a small area in the center of the quadrangle. The plateau surface is smooth and is cut by a number of fractures and troughs that commonly trend north-south. This region was mapped in detail, and the geologic map is included as Appendix II. Only a few impact craters occur on the areally restricted plateau surface, thus crater statistics for relative age determination would be unreliable.

The remnants of degraded impact craters occur along the southern margin and are commonly embayed by dark plains materials (Fig. 12). The lack of ejecta or crater rims associated with these crater forms suggest that they were partially buried or that erosional stripping has left only the circular depressions. The plateau may consist of light eolian material

Figure 12. Dissected and fractured plateau material. Numerous fractures and troughs trend north, northwest, and northeast; patterned, and subdued patterned mottled plains materials (pmp, pmps) surround this isolated remnant of dissected and fractured plateau material (pldf). The small arrows indicate areas where subdued patterned mottled plains materials have filled depressions in the plateau. The two large circular depressions in the lower left corner may be old impact craters; small dome with summit knob (large arrow) occurs in the center of low-albedo material on the dissected and fractured plateau; knobby material (k) occurs to the north, east, and south of the plateau; image artifact occurs along eastern margin of image; Viking frame 670B16 (48°N, 24.5°W); for a more detailed map and cross-section, see Appendix II.



10 km

N

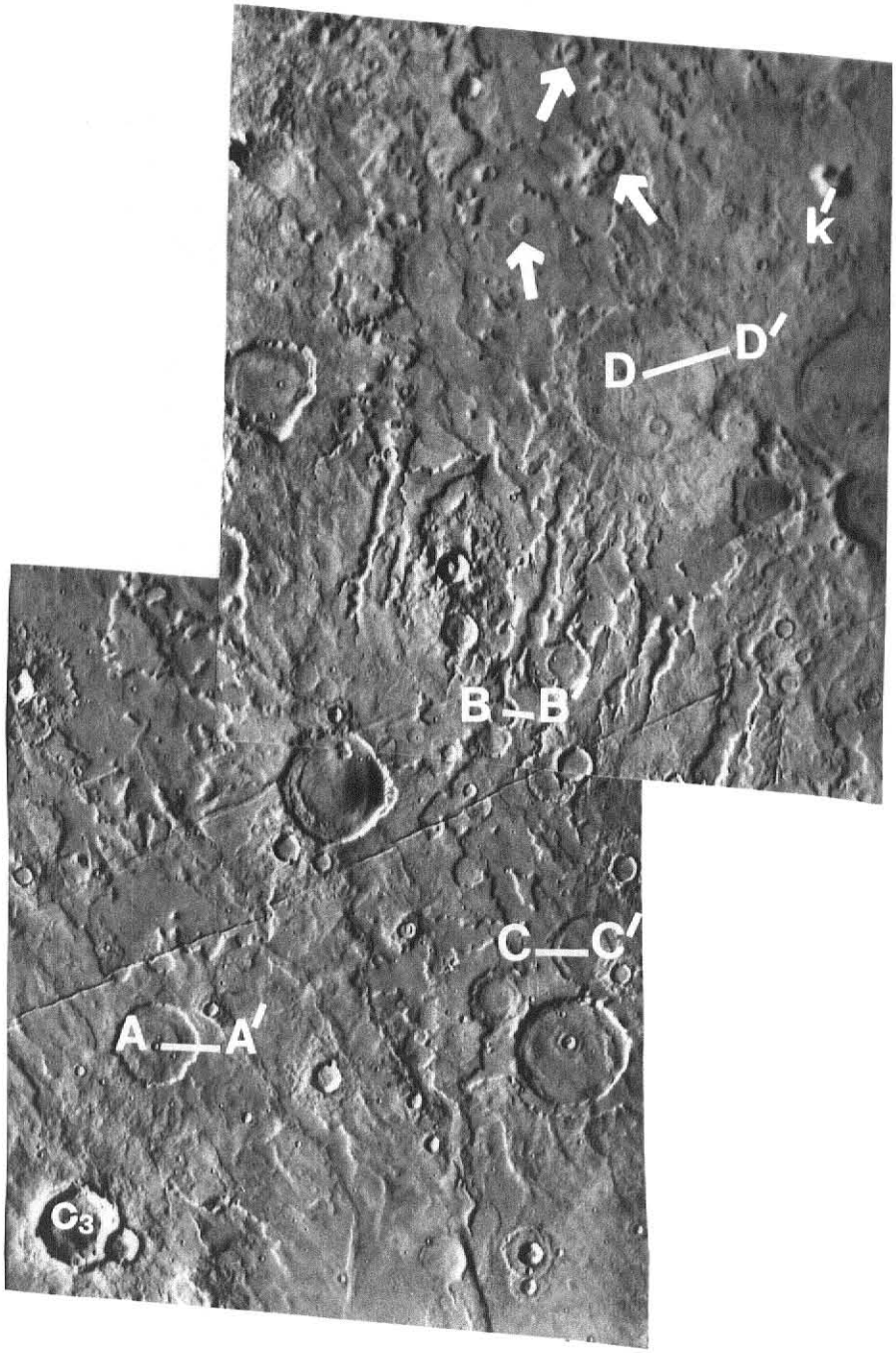
blanketing an older, cratered surface.

Along the northern boundary, there is a large region of knobby terrain; the knobs are interpreted as erosional remnants of a higher surface. Plains materials overlie and embay fractures and depressions in the plateau along the eastern and western boundaries. An escarpment marks the plateau boundary to the south. The knobs and isolated plateaus that occur near this escarpment are erosional remnants of plateau material.

Igneous processes have been active in this central region as indicated by the presence of several lava flows, a number of small domes with summit craters, and structures that have been interpreted by Allen (1979b) as tablemountains produced by volcanic eruptions beneath an ice sheet. The fractures that cut the plateau may, in some way, be tectonically related to this pulse of igneous activity. Alternatively, they may be the result of more regional stresses.

Rugged Plateau Material.--The rugged plateau material covers a large portion of eastern Tempe Plateau. The unit is characterized by many degraded flat-floored c_1 craters and crater ghosts. The intercrater area is rough, with many irregular scarps (up to 0.5 km in height), channels, and depressions (Fig. 13). Crater statistics (Fig. 8) indicate that the surface is older than the associated ridged or fractured plateau material but may be slightly younger than the cratered plateau material in the southeast corner of the quadrangle. The unit is interpreted to be volcanic and eolian material that has resurfaced the old, heavily-cratered terrain,

Figure 13. Rugged plateau material. The numerous irregular escarpments and depressions give the surface a rugged appearance; lettered bars indicate locations of topographic profiles shown in Figure 14; compare the interior morphology of the craters indicated by the lettered bars with the crater interiors seen in some of the other figures or with the c_3 crater seen in the southwest corner of the image; most of the craters seen on the rugged plateau have interior moats, although none of the crater interiors is exactly alike; small crater occurs in center of larger crater at A-A'; the channel-like depressions in the center of the image that may be somewhat radial to the circular mound at D-D' have been interpreted as thermokarst features; other irregular depressions on the rugged plateau may also be thermokarst depressions; the large circular mound shown at D-D' has been interpreted as a possible volcanic center (Scott, personal communication, 1981); ghost crater occurs to the east of the mound; small, unusual mesas (arrows) occur in the northern region; one of the mesas has an elongate summit depression; knob (k) may be volcanic intrusion or more resistant remnant of an underlying unit. Northeast trending fracture system occurs in the central region; mare-type ridges occur in the southeast corner of the mosaic; Viking frames 704B38-39 (45°N, 56.5°W).



10 km

N

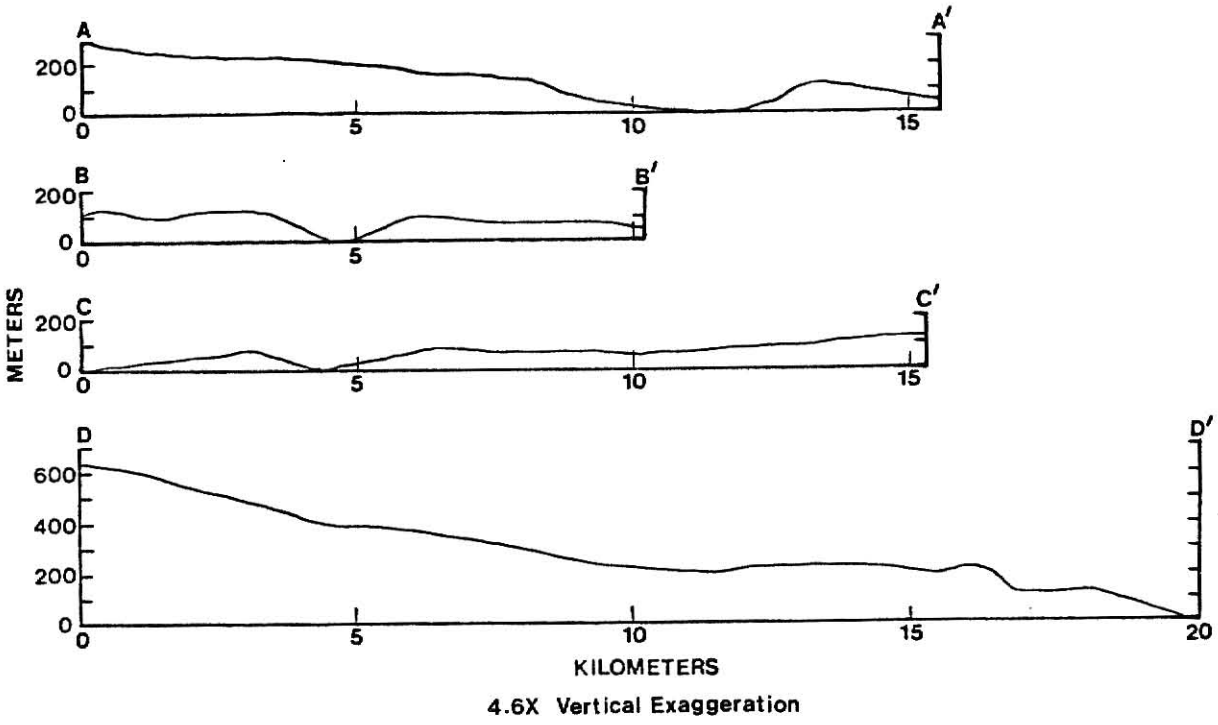


Figure 14. Relative-height profiles of crater forms shown in Figure 13. The profiles are constructed by computer from a program developed to extract topographic data directly from the Viking orbiter digital-image files. From Davis et al. (1981).

leaving exposed only the partially buried outlines of the larger craters. The region was subsequently disrupted by faulting.

Based on Mariner 9 data, a large volcanic center was recognized along the western border of Mare Acidalium quadrangle (Underwood and Trask, 1978) and the eastern boarder of Arcadia quadrangle (Wise, 1979). The radial etched-mountain material was described by Wise (1979) as radial, flat-bottomed, bifurcating, discontinuous valleys interspersed with steep-walled closed depressions and was interpreted as basaltic flows from a major volcanic center. High-resolution Viking images show that the radial channels do not extend into Mare Acidalium quadrangle, and thus the materials in this region are mapped as rugged plateau material.

Gatto and Anderson (1975) pointed out the similarity between the rugged intercrater region and terrestrial thermokarst topography. Thermokarst is produced by the melting of ground ice and accompanying collapse of the ground surface. On Earth, thermokarst topography consists of pits, dry gullies and valleys, small hummocks and closed depressions (Fairbridge, 1968). Gatto and Anderson (1975) suggested that the water produced during melting of ground ice continued to flow, forming the "stream" channels that are seen in the area. Subsequent wind erosion may have enlarged some of the depressions.

Other distinctive features of the rugged plateau surface are the circular structures with unusual interior morphology, that appear to be old, degraded impact craters. Several of these flat-floored depressions have an annular moat just inside the rim wall; other irregular depressions

contain circular ridges. Figure 13 shows examples of these unusual features. Relative-height profiles of three "moat" craters were plotted by Davis et al., (1981) and are shown in Figure 14a-c.

The circularity of these features strongly suggests that they are impact craters; the lack of sharp crater rims or ejecta blankets indicates later resurfacing or exhumation. The unusual morphology may be related to the target material. Roddy (1977) reported complex internal structure, including moat-like topography, from explosion experiments in unconsolidated alluvium overlying water-saturated clays. Alternatively, Fagen et al. (1981) suggested that these circular depressions result from surface subsidence rather than from impact onto the surface. These authors proposed that either the entire central region sank downward as one mass along fracture lines, or the central region broke into a number of small segments which eventually deteriorated leaving the depression. They do suggest, however, that the location of the collapse depression may depend on the existence of the impact craters and other topographic features of a more ancient terrain that underlies the plateau strata.

A large (40 km) circular feature with positive relief also occurs in this region, and a profile was produced by Davis et al. (1981) (Fig. 14d). Scott (personal communication, 1981) suggested that this feature may be the remains of an ancient volcanic center similar to the radially etched mountain material in MC-3 (Wise, 1979). Another alternative is that the feature is an exhumed, filled impact crater.

The boundary between the rugged plateau and the smooth plains is varied. To the south, the boundary is marked by a steep escarpment. This escarpment may partially be a result of fluvial erosion associated with Kasei Vallis. Farther to the north, the boundary appears to be depositional; smooth plains material overlies the plateau material, embaying or completely burying old craters. The boundary of the rugged plateau material with the other smoother plateau units is morphologically distinct.

Ridged Plateau Material.--The ridged plateau material occurs in the southern region of Tempe Plateau in MC-3 (Wise, 1979) and MC-4. This unit forms a relatively smooth surface with many north-northwest trending mare-type ridges (Fig. 15a, b). The crater size-frequency distribution curve for the ridged plateau material (Fig. 8) indicates that this unit is younger than the adjacent rugged plateau material and the cratered plateau material in the southeast corner of the quadrangle. The ridged plateau, however, may be similar in age to the fractured plateau material to the north inasmuch as their crater-density plots are similar.

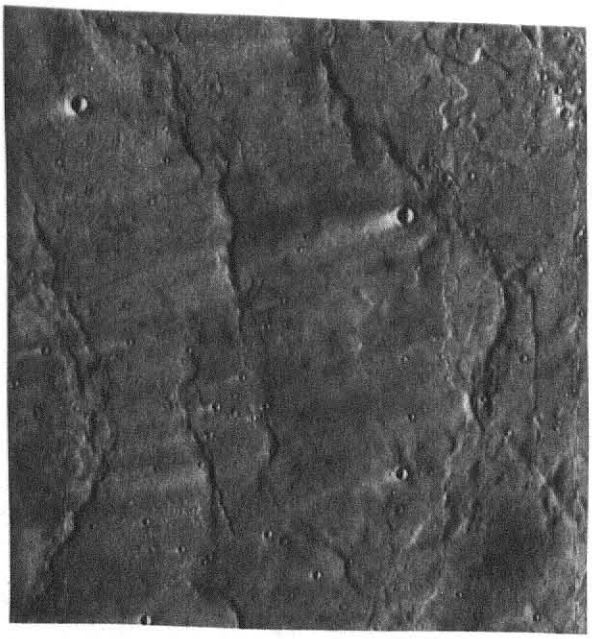
A possible flow front occurs on the ridged plateau surface near the boundary with the rugged plateau terrain (Fig. 16a). Other flow fronts have been reported on the ridged plateau surface in MC-3 (Fig. 16b) (Wise, 1979). These features led to the interpretation of this material as volcanic flow rock.

Many north-northwest trending mare-type ridges occur on this ridged plateau surface. Mare ridges were first observed on the Moon and were defined as broad, elongate arches or swells associated with narrower, steeper

Figure 15. Ridged plateau material. (a) High-resolution image showing several mare-type ridges; the ridges are asymmetric, with steeper flanks to the east, lunar mare ridges are commonly asymmetrical (Lucchitta, 1976); ridges trend approximately north-south; several of the small (< 1 km diameter) craters have distinct, high-albedo wind plumes indicating that the winds are from the east; image artifacts occur along the eastern and western margins of the image; Viking frame 668A06 (34.7°N, 58.7°W).

(b) Mare-type ridge cutting across the plateau-plains boundary (arrow); the difference in topographic expression of the ridge between the plateau (plr) and the smooth plains (ps) may be a function of material strength; the effects of differential erosion are apparent i.e. the ejecta blanket of the large c_3 impact crater in the center of the image is only visible on the plateau; the crater rim is particularly resistant to erosion; dark patches, interpreted as eolian material, are confined to low-lying areas on the upwind side of scarps and on the floor of the large crater (the wind is from the north-northeast); image artifacts occur along the eastern and western margins of the image; Viking frame 558A34 (34.6°N, 52.5°W).

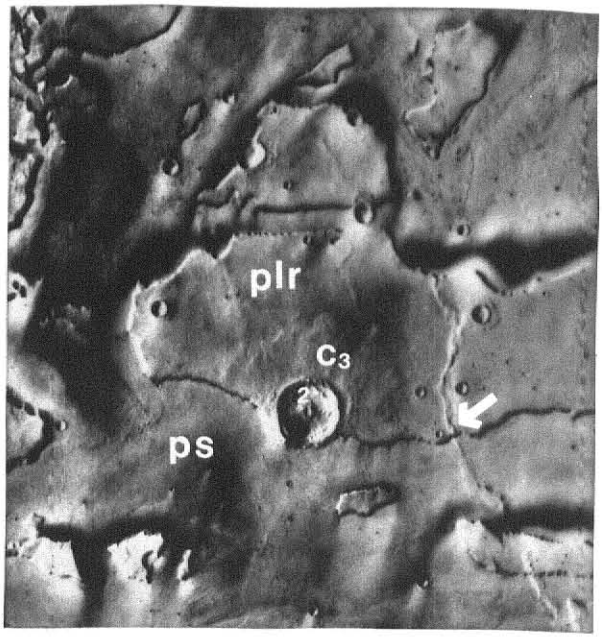
a.



10 km

N

b.



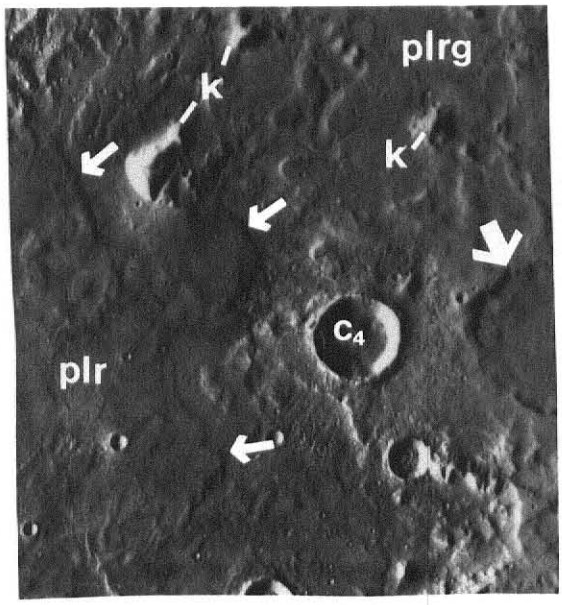
10 km

N

Figure 16. Flow fronts on ridged plateau. (a) Numerous flow fronts (arrows) on the ridged plateau (plr) along the boundary with the rugged plateau (plrg); fresh, bowl-shaped c_4 crater with radial, ballistic- and flow-ejecta deposits occur in the center of the image; knobby material (k) occurs in the northern portion of the image; relict crater indicated with large arrow; image artifact occurs along the western margin of the image; Viking frame 668A10 (33.9°N, 56.9°W).

(b) Flow fronts on the ridged plateau in MC-3; well-defined flow lobe are indicated by arrows; large impact craters at the top of the image obscure possible source areas for the two flows; both flows have been cut by en echelon grabens trending northeast-southwest; a few mare-type ridges can be seen in the southern region; Viking frame 704B58 (37.5°N, 65.6°W).

a.



10km

N

b.



10km

N

crenulated ridges or spines (Strom, 1972). Individual ridges on Mars may be as long as several hundred kilometers, ranging in width from 1-20 km, and as high as several hundred meters (Gifford, 1981).

The origin of mare ridges remains controversial. The two general hypotheses advanced to explain the origin of these ridges on the Moon involve igneous processes that produce such features as plutons, pressure ridges, squeeze-ups of lava, and fissure eruptions (Strom, 1972; Quaide, 1965; Hodges, 1973), or tectonic processes, such as faulting or folding (Lucchitta, 1976, 1977; Sharpton and Head, 1980; Howard and Muehlberger, 1973). The controversy is similar for Mars. From studying the mare-type ridges in Chryse Planitia (directly south of Acidalia Planitia), Greeley et al. (1977) favored the volcanic origin for the mare-type ridges because of their association with plains of volcanic origin and because none of the mare-type ridges truncated impact craters as would be expected if the ridges were tectonic. Alternatively, Lucchitta and Klockenbrink (1981) and Gifford (1981) found that the planet-wide trend of the ridges is predominantly north-south and concluded that the ridges were tectonic.

Although many mare-type ridges in MC-4 occur on the ridged plateau unit, they are not restricted to this unit. Some of the ridges extend into the rugged plateau material, a few ridges occur on the smooth plains, and one ridge can be traced across the higher ridged plateau unit and the lower smooth plains (Fig. 15b). This tends to support a tectonic origin for the ridges in this region. The occurence of the ridges on both plateau and plains material indicate that the ridges were formed after the development of the highlands-lowlands boundary.

The boundary between the relatively smooth ridged plateau material and the rugged plateau material is fairly distinct. Volcanic flow rock of the younger ridged plateau surface may have completely buried the older, rugged plateau surface. To the south, the ridged plateau - smooth plains boundary is erosional, with an escarpment separating the higher plateau material from the lower smooth plains. North of latitude 37°N, the boundary appears to be depositional with smooth plains material overlying and embaying grabens cut into the ridged plateau material. In some areas, a small channel filled with light, possibly alluvial material lies along the plateau-plains boundary (see Appendix I; see also Fig. 37).

Fractured Plateau Material.--Fractured plateau material occurs along the northern edge of Tempe Plateau in MC-4 and extends south and west into MC-3 (Wise, 1979). The unit forms a relatively smooth surface interrupted by numerous northeast-trending horsts and grabens. Individual troughs range in width from 1-10 km and are as long as 200 km. The grabens cut older c_1 and c_2 craters, but do not cut younger c_3 and c_4 craters. The crater size-frequency distribution curve for the fractured plateau material (Fig. 8) indicates that the unit is younger than the adjacent rugged plateau material but may be equivalent in age to the ridged plateau material to the south.

Wise (1979) suggested that the fractured uplands (fractured plateau material) consists of lava rock similar to the Lunae Planum material

(ridged plateau material) to the south. The material that makes up the fractured plateau is interpreted in the present study to be volcanic and eolian material that was later disrupted by faulting.

The fractures in this region cut all but the freshest impact craters indicating that the fractures are relatively recent features. To the west in MC-3, the faults extend north into the plains material. In MC-4, however, the fractures terminate at the plateau-plains boundary. Regionally, the fractures of the Tempe Fossae system are part of the semiradial fault system of the Tharsis province. This fault system may reflect an extensive zone of deep crustal weakness (Wise, 1979).

The boundary region between the fractured plateau material and plains material was mapped in detail and is included as Appendix I. Rim walls of degraded and embayed craters form the plateau-plains boundary in several places. Grabens that cut into the higher plateau surface terminate at the plains boundary and are also embayed by smooth, dark plains material.

A sinuous channel, oriented normal to the fracture trend, is cut into the plateau material (Fig. 17). In the same area, other sinuous channels within a graben deposited outwash or flood plain material onto the plains (Fig. 17). This indicates that there was drainage and a redistribution of material from the plateau.

Lower Plateau Material.--The lower plateau material occurs in small patches along the southeast margin of Tempe Plateau. This unit forms a rough surface at an elevation intermediate between the lower smooth plains material and the higher ridged or rugged plateau material (Fig. 18). A

Figure 17. Fractured plateau material. Boundary region between fractured plateau (plf) and smooth plains (ps); large (17 km wide) graben that cuts into the plateau trends northeast across the southeast corner of the image; smooth plains materials cover the floor of this large graben; debris also appears to bury fractured plateau material to the west of the large graben; smaller faults occur within the large graben; small arrows indicate smaller grabens cutting the fractured plateau; a sinuous 3-4 km-wide channel extends across the western portion of the image; the light-colored fan-shaped material (large arrow) on the smooth plains, has been interpreted as outwash or flood plain material from drainage of the plateau; compare the differences in the preservation of the craters and ejecta on the fractured plateau and on the smooth plains; especially note the c_3 flow-ejecta crater in the northern part of the image; Viking frame 61B52 (53.1°N, 60.5°W); for a more detailed map, see Appendix 1.

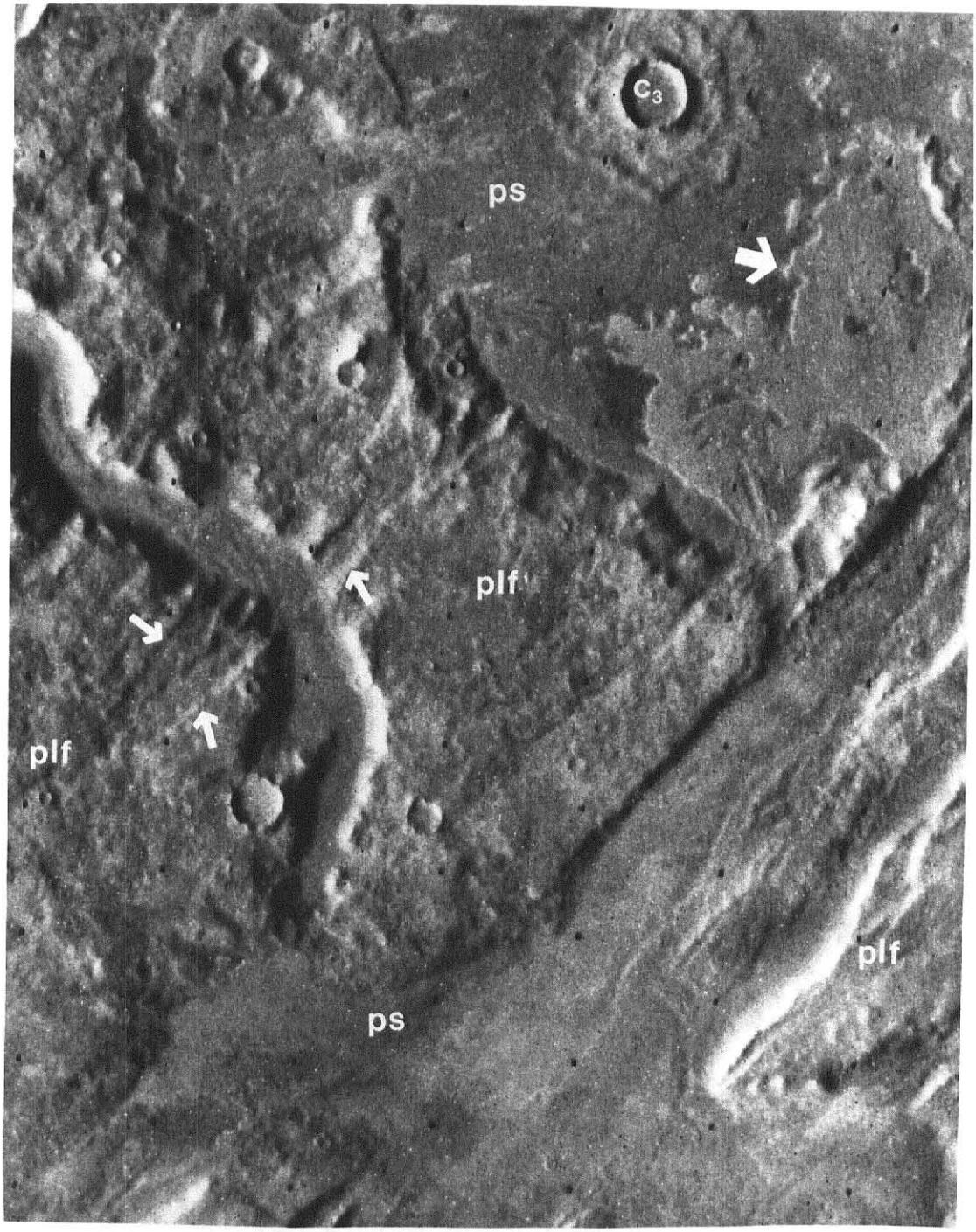
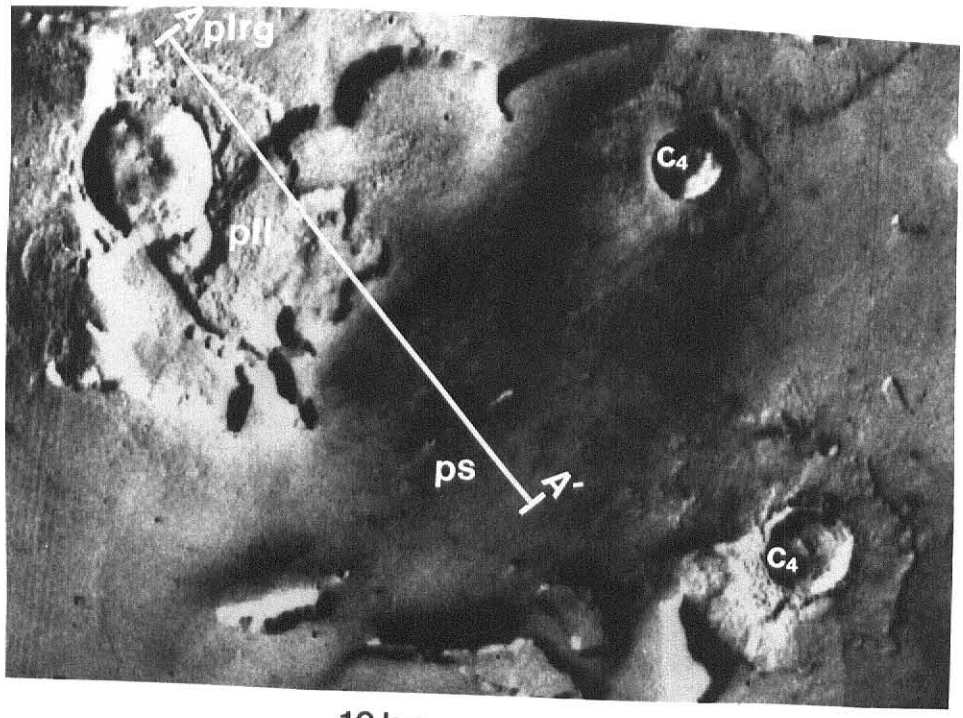

C_3
ps
plf
plf
plf
ps
10 km
N

Figure 18. Lower plateau material. (a) Lower plateau material (pll) at southwest margin of Tempe Plateau is bounded by higher rugged plateau material (plrg) and lower smooth plains material (ps); the lower plateau material appears to underly stratigraphically the rugged plateau material; alternatively, the lower plateau material here may be a down-faulted block of rugged plateau material; the dark patches on the smooth plains are thought to be eolian accumulations; notice that the ejecta blanket of the c_4 crater in the southeast corner of the image has been partially stripped away; image artifact occurs along the eastern and western margins of the image; Viking frame 558A17 (31.5°N, 55°W).
(b) Lower plateau material (pll) is shown in relationship to smooth plains material (ps) and an isolated remnant of ridged plateau material (plr); lobate flows of lower plateau material appear to embay a circular depression on the ridged plateau (arrow) indicating that the lower plateau material is a younger, possibly volcanic flow unit; compare the surface roughness of the lower plateau material with that of the smooth plains; north-south ridge is truncated by lower plateau material just west of isolated remnant of ridged plateau material; image artifacts occur along the eastern and western margins of the image; Viking frame 668A27 (31.1°N, 49.6°W).
(c) Schematic cross-sections A-A' and B-B' showing two possible stratigraphic positions of the lower plateau material.

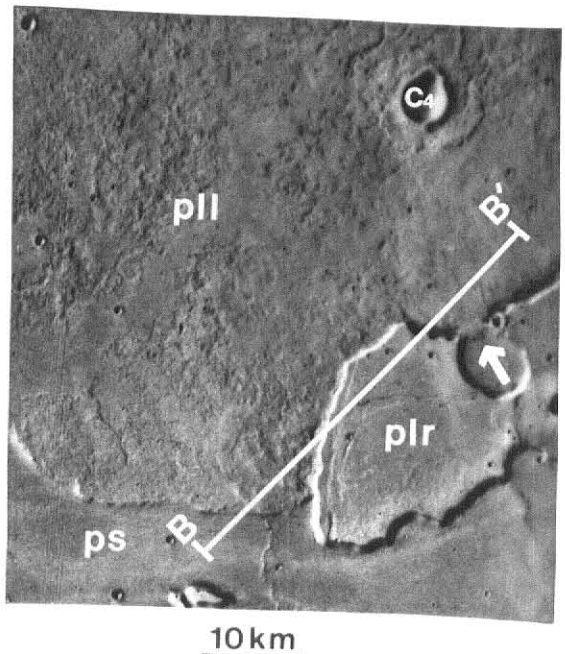
a.



10 km

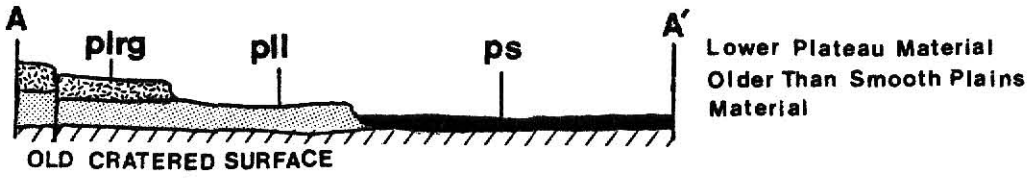
N

b.

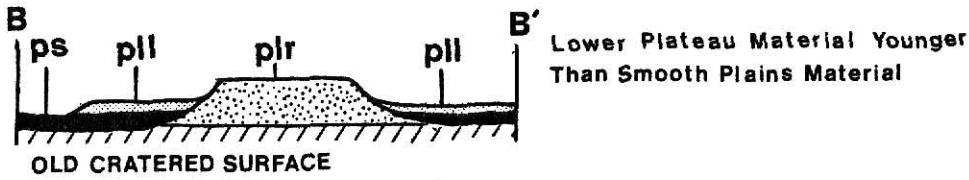


10 km

N



c. **Schematic Cross-Sections**
Large Vertical Exaggeration



few c_3 and c_4 impact craters (< 10 km) occur on this surface indicating that it is relatively young.

Exposures of lower plateau material, such as that seen in Figure 18a, indicate that stratigraphically the lower plateau material underlies the other plateau materials and has been exposed by erosion and scarp retreat. Other areas (Fig. 18b) show lower plateau material embaying a circular depression in the higher ridged plateau material, indicating that some of the lower plateau material was emplaced after the highlands-lowlands boundary developed and was subsequently modified by erosion.

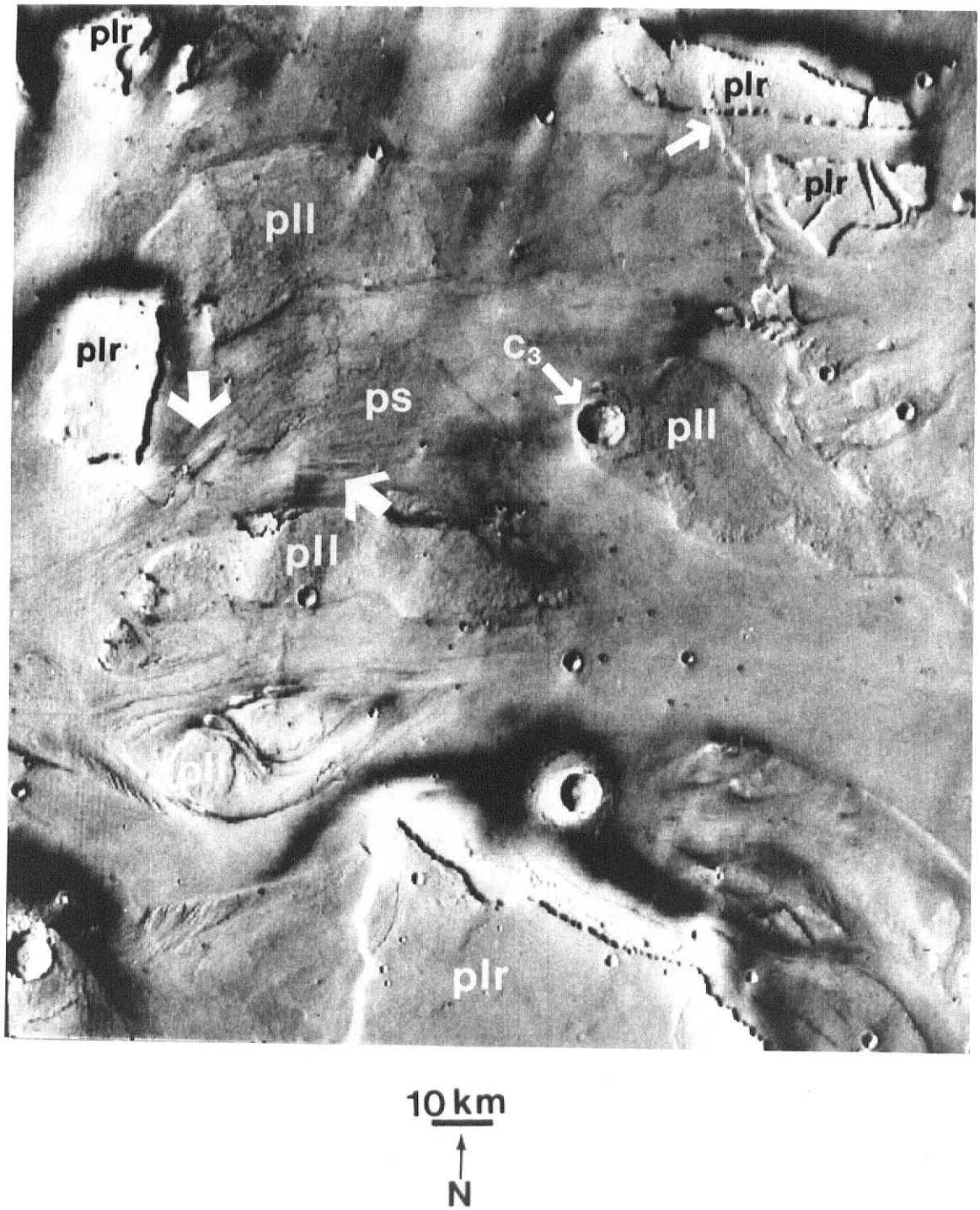
In several places small channels cut the lower plateau material, creating streamlined remnants up to 40 km long trending east-northeast (Fig. 19). Aqueous erosion is indicated by the presence in these channels of streamlined landforms.

The main channels of Kasei Vallis occur to the south and west between latitude 20° - 30°N, longitude 50° - 75°W (Fig. 1). Kasei Vallis has been interpreted as the site of catastrophic floods of great depths and high velocity (Baker and Milton, 1974; Baker and Kochel, 1979). The erosional and depositional effects associated with running water in Kasei Vallis appear to have extended into the southwestern region of MC-4 (Scott and Tanaka, 1980; Carr and Clow, 1981).

Plains Province

Lowland plains material covers approximately 80 percent of the area of MC-4. On the basis of Mariner 9 data, Underwood and Trask (1978)

Figure 19. Streamlined remnants of lower plateau material. Channels that cut into lower plateau material (pll) created streamlined landforms such as those seen in the southwest corner of the image; large arrows indicate possible fluvial bars or erosional grooves; the ejecta of a c_3 crater on the lower plateau has been partially stripped away; isolated remnants of ridged plateau material (plr) surrounded by smooth plains material (ps) do not appear to be streamlined; in many places, escarpments bounding the ridged plateau are linear and may be structurally controlled; dark material accumulates on the upwind sides of many topographic obstacles; light streaks associated with several of the small craters indicate that the wind is from the north-northeast; a continuation of the mare-type ridge seen in Figure 15b is indicated by the small arrow in the northeast corner of the image; image artifact occurs along the western margin of the image; Viking frame 558A15 (32.2°N, 52°W).


plr
plr
plr
pll
plr
C3
ps
pll
pll
pll
plr
10 km
N

subdivided the lowland plains into three basic geologic terrain types: mottled plains material, plains material, and plains and dissected plateau material - undivided. Results from the present investigation using Viking data indicate that nine subdivisions can be recognized within these lowland plains. Wherever possible, the descriptive modifiers used by Underwood and Trask (1978) were incorporated into the names of the units in the present investigation. These units are: mottled plains material - undivided (991,000 km^2), hummocky mottled plains material (386,500 km^2), patterned mottled plains material (458,200 km^2), subdued patterned mottled plains material (37,000 km^2), fractured plains material (23,000 km^2), knobby plains material (193,000 km^2), smooth plains material (1,162,400 km^2), patterned smooth plains material (60,000 km^2), and variegated plains material (128,000 km^2).

Mottled Plains Region.--The mottled plains extend almost entirely around the planet between latitudes 50° - 70°N (Scott and Carr, 1978). The term "mottled plains" was first used by members of the Mariner 9 imaging team (Carr et al., 1973). Soderblom et al. (1973b), in mapping the geologic terrain of the north polar region, described the mottled cratered plains as characterized at Mariner A-frame resolution ($\cong$ 3 km) by an abundant population of small craters (< 20 km) and a highly mottled appearance. The mottled pattern consists of a complex of streaks of bright material and concentrations of bright material highlighting the interior and exterior parts of crater rims and ejecta blankets. Soderblom et al. pointed out that

the mottled cratered plains has a lower average albedo than most of Mars and that it is one of the few regional units intrinsically characterized by its albedo.

The cause of the extreme albedo contrast between the ejecta blankets and the intervening plains is uncertain. Soderblom et al. (1973a) suggested that the bright materials are remnants of the debris mantle that, at one time, buried the mottled plains. Subsequently, the debris has been removed leaving patches of light materials trapped in the coarser-textured parts of the craters, such as their rims and ejecta blankets. High-resolution Viking data have commonly revealed fine detail on some of the ejecta blankets and bright crater rays, similar to those seen on the Moon. These fresh craters show little or no eolian modification, thus, it is difficult to interpret these bright-ejecta patterns as the result of trapped particles. Another explanation that was suggested by Carr (1981) is that impacting meteorites excavated higher-albedo material from below the dark surface.

The mottled plains occur in the northern two-thirds of MC-4. On the basis of variations in surface texture and detail, the mottled plains were subdivided into four units: mottled plains material - undivided, hummocky mottled plains material, patterned mottled plains materials, and subdued patterned mottled plains material.

Mottled Plains Material - Undivided.--The mottled plains material - undivided covers most of the northern region. The unit is characterized by

high-albedo zones surrounding many of the impact craters; the intercrater plains have very low albedo. The crater size-frequency distribution of craters $\geq$ 1 km (Fig. 20) indicate that the mottled plains material - undivided may be similar in age to the rest of the mottled plains units. The mottled plains material may consist of volcanic rock and eolian debris.

The western part of the mottled plains is characterized by a distinct northwest-southeast eolian grain. Many light streaks occur downwind from impact craters, and dark eolian material occurs in craters and forms splotches on the intercrater plains. Many of the smaller craters on these plains, north of latitude 45°N, appear to be filled or partially filled with light material (Fig. 21a). Soderblom et al. (1973a) reported that craters filled with light debris are common poleward from 30°N. These authors pointed out that it would be difficult to imagine a process that would fill only the crater interiors, so they suggested that the entire northern region was, at one time, mantled with light-colored debris thick enough to bury the craters. Subsequently, erosion has removed most of this mantle, leaving only materials protected within the crater interiors (Soderblom et al., 1973a).

The Vikings' data generally are superior to those obtained by the Mariner 9 spacecraft. However, the majority of Viking images north of approximately 40° are low- to-medium resolution (220 meters/pixel), equivalent to the Mariner B-frames. Many of the surface details are at the resolution point. One of these surface textures is a reticulate pattern that occurs in the intercrater region (Fig. 21b). It is difficult to determine the topographic

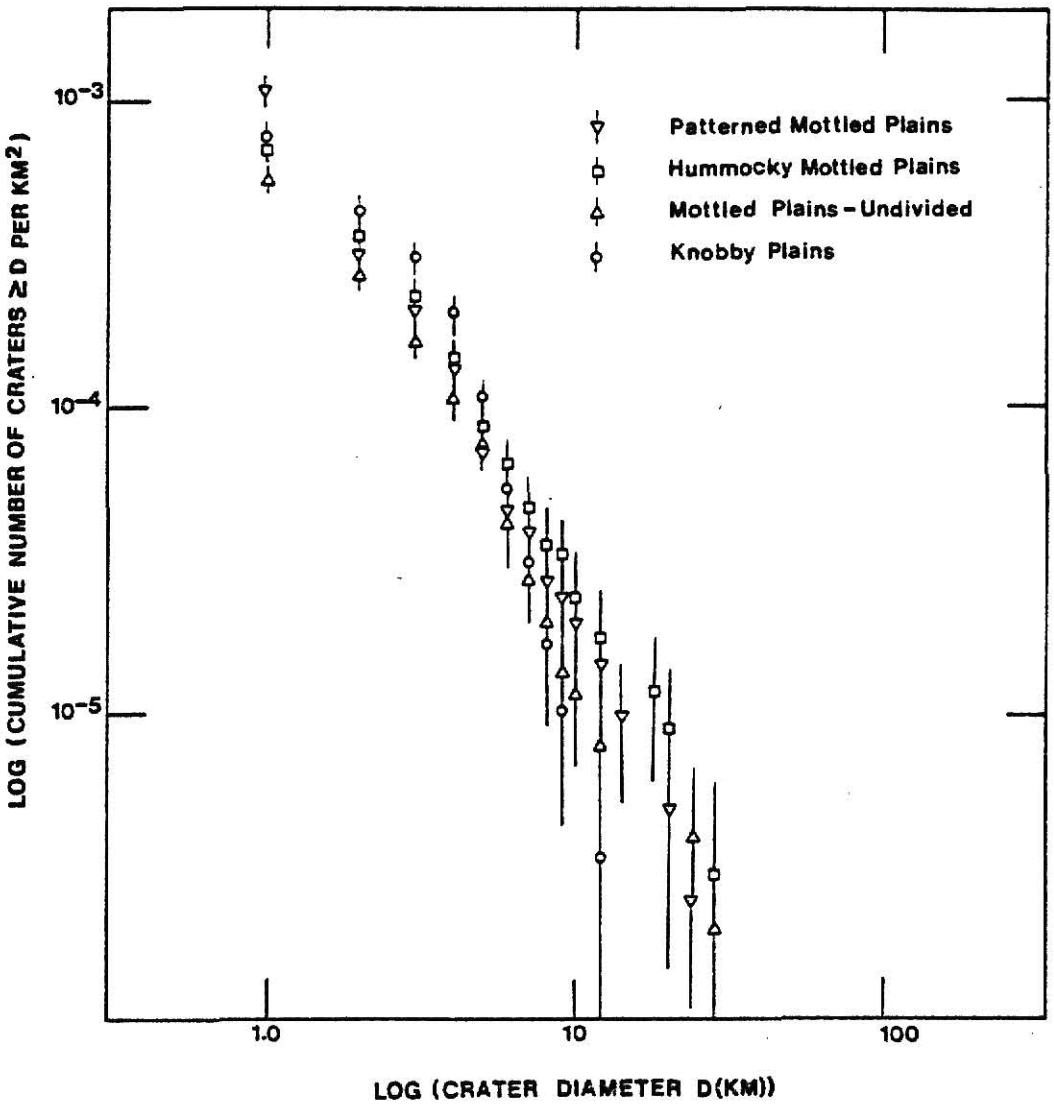


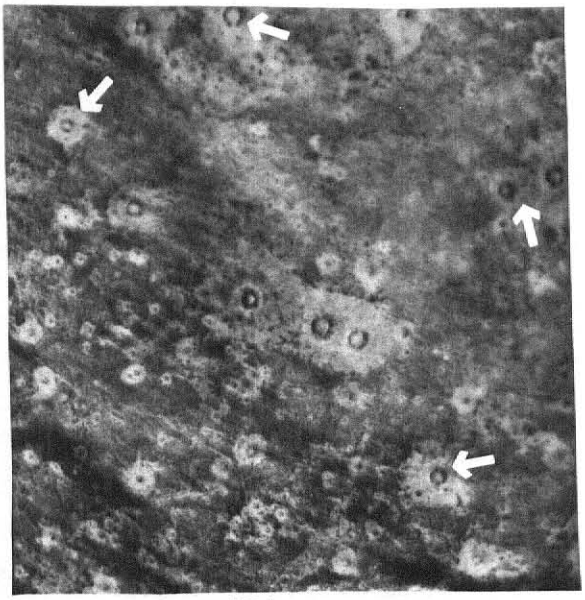
Figure 20. Cummulative crater size-frequency distributions for the mottled plains units and knobby plains. Numbers of craters are cummulated from largest to smallest size; vertical lines indicate one standard deviation, 1σ, confidence intervals for each data point plotted, calculated by assuming the crater populations are Poisson distributed. The 1σ is approximated by using $N = \pm \sqrt{N}$ where N is the number of craters (Arvidson et al., 1978).

Figure 21. Mottled plains material - undivided, example 1.

(a) Low-resolution image of the mottled plains material - undivided; high-albedo ejecta blankets extend outward 2-3 crater diameters and are surrounded by low-albedo plains; the arrows show some of the impact craters with interiors that appear to be filled with light-colored material; the light-colored material is believed to be the remnant of a debris mantle that, at one time, blanketed the northern region (Soderblom et al., 1973a); small-scale patterned ground occurs in the intercrater region; scattered dark hummocks occur in the north-central part of the image; dark streaks occur in the southern portion of the image; the wind is from the northwest; Viking frame 672B74 (60°N, 25.7°W).

(b) Enlargement showing the small-scale detail of the mottled plains material - undivided; faint reticulate pattern of varied scale occurs in the intercrater region; this pattern may be similar to that seen farther south in the patterned mottled plains or the fractured plains; compare the filled or partially filled impact craters in the southwest corner of the image with the fresh bowl-shaped crater indicated by the arrow; the fresh crater also has light-colored ejecta; scattered dark hummocks occur throughout the area; Viking frame 672B76 (60°N, 20.9°W).

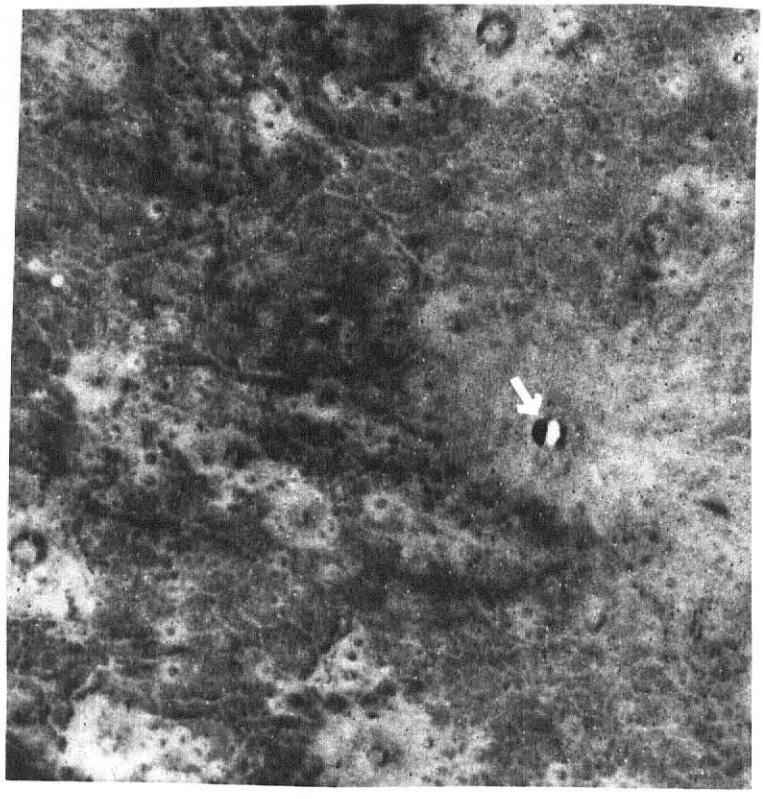
a.



10 km

N

b.



10 km

N

relief of these surface features that have produced this pattern, but it may be similar to that of the fractured plains and patterned mottled plains to the south.

Another pattern that is equally perplexing is a series of concentric arcs that occur near the mottled plains - smooth plains boundary (Fig. 22a). As with the reticulate pattern, the topographic relief cannot be determined. The pattern of arcs vaguely resemble the patterned ground that occurs in MC-5 at latitude 45°N, longitude 354°W. Carr and Schaber (1977) suggested that these arcuate features marked successive positions of the retreat of an escarpment during removal of a former mantle. Alternatively, Lucchitta (1981) suggested that the ridges resemble moraines. Rossbacher and Judson (1981) proposed that the "fingerprint" patterns may be solifluction lobes and ice-cored ridges similar to those observed in the Canadian arctic.

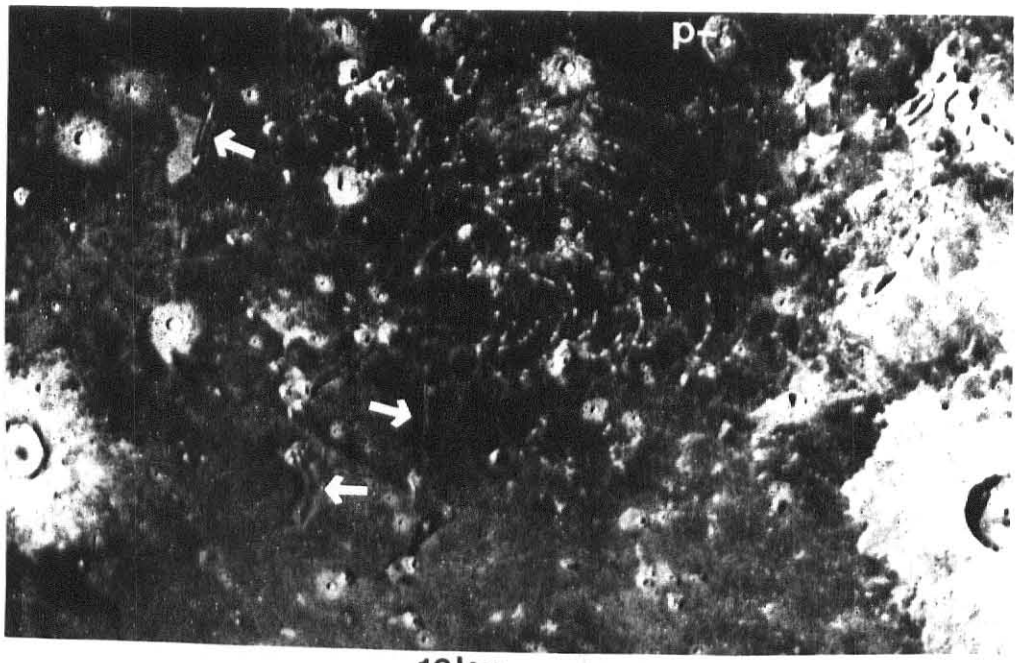
The boundaries with the other mottled plains units are gradational. The mottled plains - hummocky mottled plains boundary is marked by increased numbers of small, dark hills that characterize the hummocky mottled plains. The boundary between the mottled plains material - undivided and the patterned mottled plains has been placed at the first recognition of the polygonal troughs, the detection of which may be a result of resolution. The boundary with the lighter, dissected and fractured plateau material is generally recognized by contrasts in albedo and in morphology. The boundary between the mottled plains and smooth plains is commonly recognized by a textural and albedo variation: to the east, the smooth plains have higher albedo than the mottled plains; to the west, the

Figure 22. Mottled plains material - undivided, example 2.

(a) Faint curvilinear features of undetermined origin can be seen in the center of the image; these curvilinear features are located near the mottled plains - smooth plains boundary; unusual troughs with central ridges are indicated by the arrows; a pedestal crater (p) occurs in the northeast corner of the image; the extreme albedo contrast is a function of image processing; Viking frame 670B30 (43.7°N, 42.8°W).

(b) Boundary between the mottled plains material - undivided (pm) and the smooth plains material (ps) near Tempe Plateau; smooth plains are low albedo in this region; high-albedo line marks the boundary; high-albedo wind streaks associated with some craters indicate the wind is from the northwest; streak formation may be related to the topographic relief of the crater rims; note the narrow trough on the smooth plains (arrow); Viking frame 670B01 (53.1°N, 50.3°W).

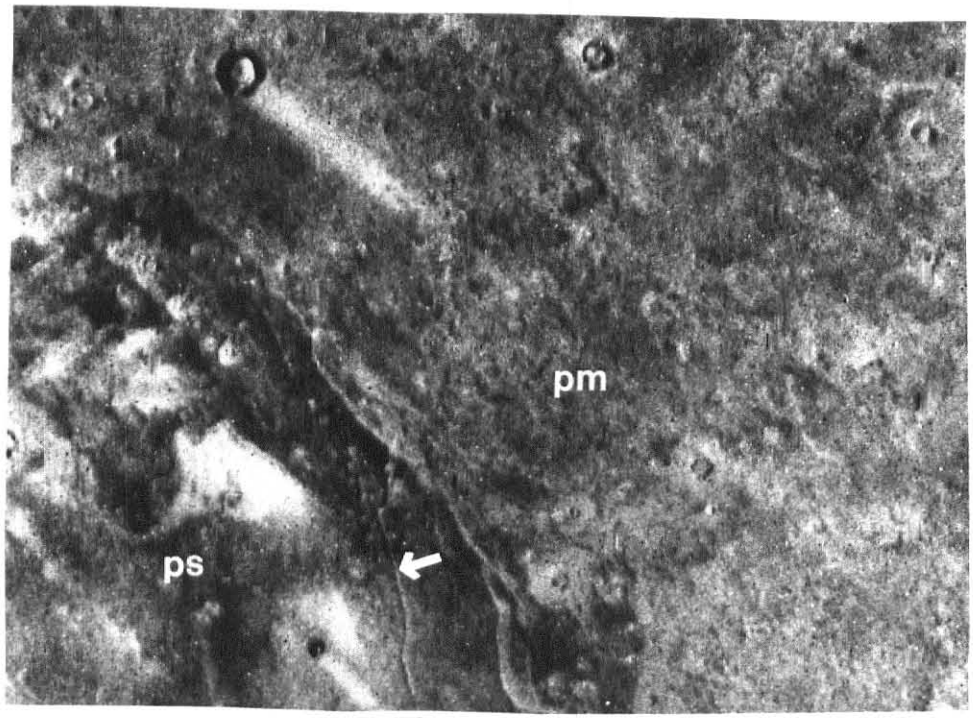
a.



10km

N

b.



10km

N

smooth plains have much lower albedo. A narrow, high-albedo line runs along the contact in places (Fig. 22b). To the west, a sinuous channel filled with light material runs along the mottled plains - smooth plains boundary.

Hummocky Mottled Plains Material.--The hummocky mottled plains material occurs along the northern border of MC-4 and extends north into MC-1. Botts (1980) used the name "bulbous plains" for a unit with similar characteristics that occurs at 70°N latitude. The hummocky mottled plains are characterized by many small (< 1 km) dark hills surrounded by lighter-colored material. These dark hills, in combination with high-albedo ejecta blankets, give the surface a mottled appearance (Fig. 23a). The crater size-frequency distribution (Fig. 20) indicates that the hummocky mottled plains may have a slightly greater abundance of large (> 10 km) craters than the other mottled plains units. Because the boundary between the mottled plains - undivided and the hummocky mottled plains is gradational, and because several of these large craters lie in this transition zone, this variation may not be significant. The light material that constitutes most of the surface is interpreted to be eolian. The darker material that occurs in the intercrater plains may be volcanic. Botts (1980) came to a similar conclusion for the origin of the bulbous plains in MC-1.

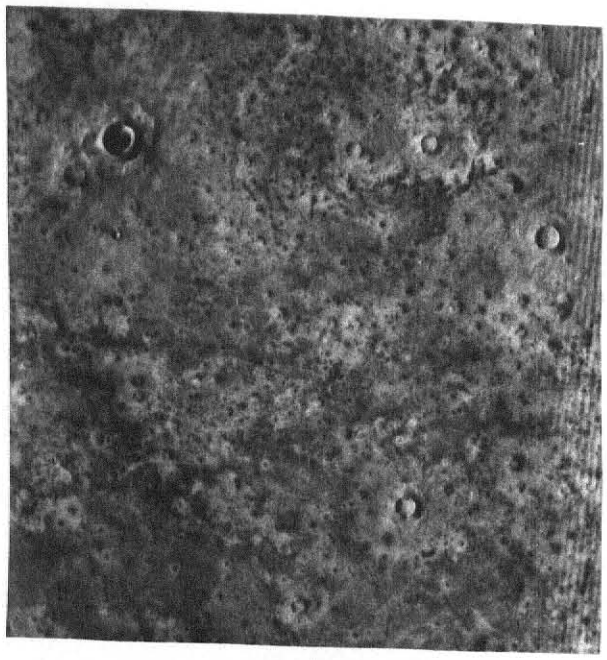
Similar to the mottled plains material - undivided, the hummocky mottled plains have many craters that are filled or partially filled with light material. There are also several large, fresh craters with high-albedo

Figure 23. Hummocky mottled plains material. (a) Dark irregularly spaced hills and knobs are scattered throughout the inter-crater region; the unit has a mottled appearance, with high-albedo ejecta blankets surrounded by low-albedo plains; the craters in the eastern part of the image are filled with light-colored material; the interior of the freshest crater in the northwest corner of the image contains a dark splotch presumed to be eolian material; compare this image with Figure 21a and notice that the eolian grain is not as obvious on the hummocky mottled plains; image artifact occurs along the eastern margin of the image; Viking frame 672B77 (62.7°N, 18.2°W).

(b) Large fresh impact crater on hummocky mottled plains shows little evidence of subsequent modification; two ejecta types surrounding this crater; thin, high-albedo, ray-forming ejecta extends out more than 5 crater diameters and thick flow-ejecta deposits occur close to the crater; compare this crater with the filled craters in the south-east portion of the image; the surrounding plains have a hummocky appearance; some of the dark hummocks appear to have summit depressions (small arrow) and, in places, the hummocks appear to coalesce (large arrow); image artifact occurs along the eastern margin of the image; Viking frame 669B30 (65.9°N, 43°W).

(c) Schematic cross section showing possible origins of the knobs or hummocks on the hummocky mottled plains.

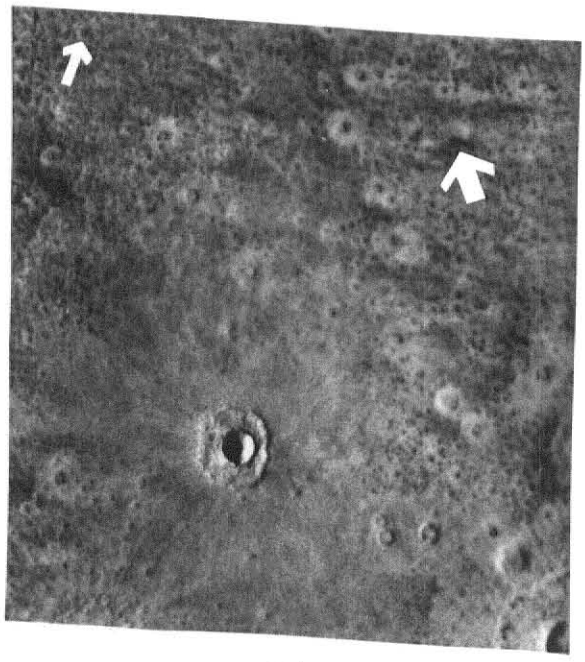
a.



10km

N

b.



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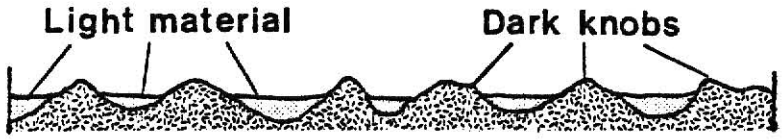
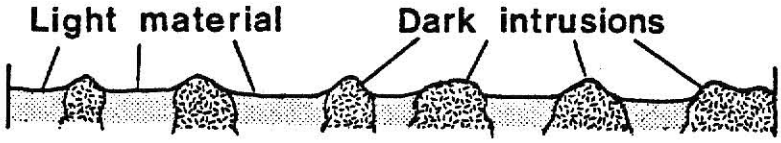


C. Schematic Cross-Sections
Large Vertical and Horizontal Exaggeration



ejecta blankets and rays (Fig. 23b). These larger, fresh craters commonly have deposits of dark material in the interior of the crater. The eolian grain, however, is not as apparent as in the mottled plains region to the south.

The features that characterize the hummocky mottled plains material are the small, irregularly spaced, dark hills and the low albedo crater rims. The knobs may be plutons, volcanic domes, volcanic necks, cinder cones, or permafrost features such as pingos. Alternatively, these knobs may represent a lower hummocky, cratered surface that has been mantled with lighter material leaving only the tops of the dark hills and crater rims exposed. This lower dark unit may or may not be volcanic. The presence of similar dark hummocks or knobs in the large c_2 crater, Lomonosov, weakens the hypothesis that the knobs may be high hills on a hummocky, low-albedo surface largely mantled with lighter material. There are no high-resolution images of this region, so no definite interpretations on the origin of the dark hummocks can be made.

The boundary with the mottled plains material - undivided to the south is gradational. The boundary between the mottled plains material and the lighter knobby plains is based on albedo, which may be the result of a thicker debris mantle covering the knobby plains.

Patterned Mottled Plains Material.--The patterned mottled plains materials cover a large part of east-central MC-4. The unit, as with other mottled plains units, is characterized by high-albedo ejecta blankets

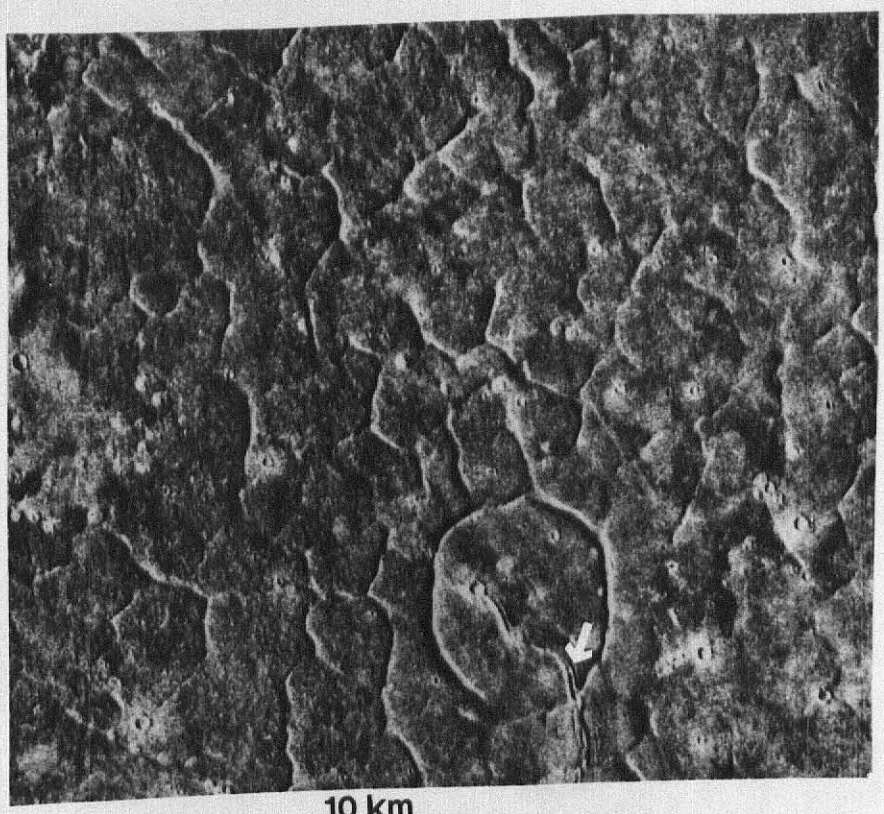
that extend out 2-3 crater diameters, surrounded by low-albedo intercrater plains. A polygonal pattern of troughs is superimposed on the low-albedo, intercrater plains. The impact crater density ($\cong$ 1000 craters $\geq$ 1 km/10^6 km^2) for this unit is slightly higher than that of the other plains units; however, the crater size-frequency curve (Fig. 20) is very similar to the other plains units indicating that there probably is little age variation between the units. The patterned mottled plains material probably consists of dark volcanic material that was subsequently disrupted to form the polygonal pattern of troughs (Fig. 24).

Patterned or fractured terrain occurs over extensive areas of the northern plains and has been the subject of considerable controversy since its discovery during the early stages of the Viking mission. Proposed mechanisms for the polygonal pattern include: permafrost activity, desiccation of water saturated sediments, cooling of lava, and tectonic deformation.

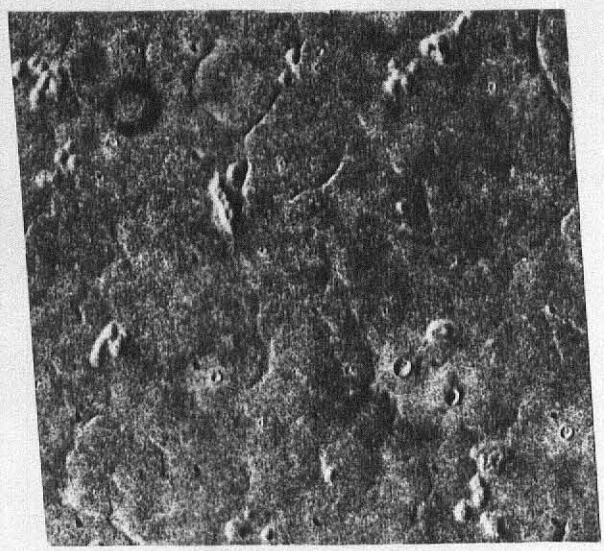
Carr and Schaber (1977), Coradini and Flamini (1979), Helfenstein and Mouginis-Mark (1980), and Helfenstein (1980) suggested that the fractures were created by ice-wedging processes such as those that occur in terrestrial periglacial regions. The major objection to the hypothesis is scale. The martian patterns are as much as two orders of magnitude larger than ice-wedge polygons on Earth. Morris and Underwood (1978) pointed out that the largest polygonal fractures on Earth ($\cong$ 1 km diameter) are associated with desiccation of thick, formerly water-saturated playa sediments. Helfenstein and Mouginis-Mark (1980) suggested that the smaller

Figure 24. Patterned mottled plains material. (a) Enlargement showing the crudely polygonal pattern of troughs superimposed on low-albedo plains; the sun is from the west; few of the polygons are closed; the large circular feature may reflect a buried impact crater; unusual ridge with summit trough (arrow) appears to eminate from a small crater and cuts across the circular trough; numerous small (< 1 km) craters can be seen on this image especially in the western region; Viking frame 32A18 (44.1°N, 18.3°W). (b) Numerous small (< 1 km) dome-like structures with or without summit craters are common throughout the patterned mottled plains; they may occur in clusters or chains as seen on this image; compare the morphology of the cratered domes with that of the small impact craters in the southeast corner of the image; the dark circle in the northwest corner is an artifact of the imaging system; Viking frame 9A44 (43.4°N, 13.6°W).

a.



b.



polygons (2-5 km diameter) were formed by ice-wedging and later desiccation processes caused some of the smaller polygons to coalesce, producing the 10-20 km polygons.

Morris and Underwood (1978) and Masursky and Cradbill (1976) suggested that the troughs may be large-scale lava cooling cracks. As with the ice-wedge hypothesis, the origin of the polygonal fractures by contraction and cooling of lavas faces a scale problem. Pechmann (1980) pointed out that few lava flows on Earth are thick enough to accommodate tension cracks that are hundreds of meters deep.

Pechmann (1980) investigated the possibility that the polygonal pattern of troughs was caused by deep-seated tension of tectonic origin that resulted in normal faulting. He reported that troughs in Acidalia Planitia locally exhibit preferred orientations. He compared the fractures on Mars to troughs of similar scale and morphology in the Caloris Basin on Mercury and suggested that both sets of troughs are grabens formed in response to a nearly isotropic horizontal tensional stress.

All of the proposed theories on the origin of the polygonal pattern have their limitations. It is possible that the troughs are polygenetic, that is, formed by more than one process. The larger fractures may be tectonic, whereas the smaller polygons closer to the pole may be the result of permafrost activity. Some of the troughs may have originally been formed by one or more processes and extended or enlarged, or both, by other processes.

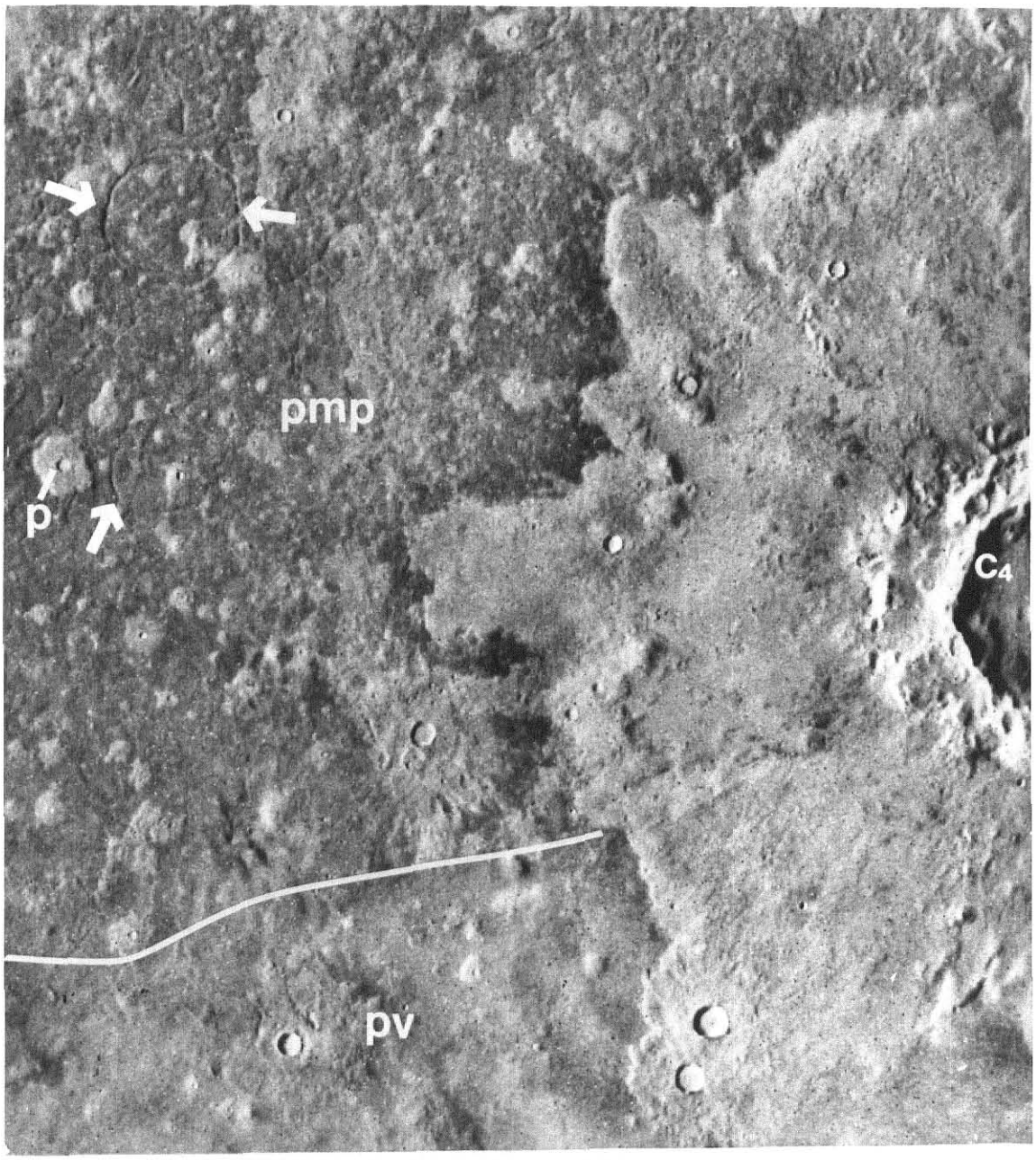
Common on the patterned mottled plains are numerous small, dome-like

structures with summit craters (Fig. 24b). Several origins have been suggested for these features. Wood (1979) and Hodges (1979) suggested that these features were products of volcanic activity, i.e., cinder cones; Frey et al. (1979) interpreted them to be pseudocraters produced by lava flowing over water-saturated ground. Lucchitta (1981) and Wood (1979) suggested that these domes resemble terrestrial pingos produced by the arching of frozen ground forced upward by the intrusion of water under pressure. Masursky and Cradbill (1976) and Carr (1981) offered yet another explanation; small impact craters were eroded to inverted relief.

Unlike those of the mottled plains units to the north, i.e., mottled plains material - undivided and hummocky mottled plains material, few of the impact craters on the patterned mottled plains are filled with light material. Fine detail is observed on the ejecta blankets, and there is little evidence for eolian modification. This suggests that the blanket of light-colored debris that once covered the mottled plains and knobby plains to the north did not extend southward into the patterned mottled plains region. The lack of the partly eroded debris mantle in this area may also explain the higher density of small impact craters, i.e., they have not been covered by the debris mantle as in the north.

Boundaries with all surrounding units are gradational. The boundaries with all the non-mottled plains units (variegated plains, fractured plains, smooth plains, patterned smooth plains) are based on albedo; the patterned mottled plains have much lower albedo than the other units (Fig. 25). In identifying the variegated plains and the smooth plains, the occurrence of

Figure 25. Patterned mottled plains - variegated plains boundary. Compare the texture and albedo change between the patterned mottled plains (pmp) and the variegated plains (pv); a white line marks the boundary; the large (40 km diameter) c_4 flow-ejecta crater covers the boundary in the eastern region; rugged ejecta occurs near the crater rim; a small pedestal crater (p) occurs on the west side of the image; large (30 km diameter) circular structure similar to that seen in Figure 24a is indicated by the arrows; a less distinct circular feature occurs to the right of the pedestal crater (arrow); the impact craters in this region appear fresher than those on the mottled plains to the north (Fig. 21); Viking frame 673B34 (47.3°N, 2.5°W).

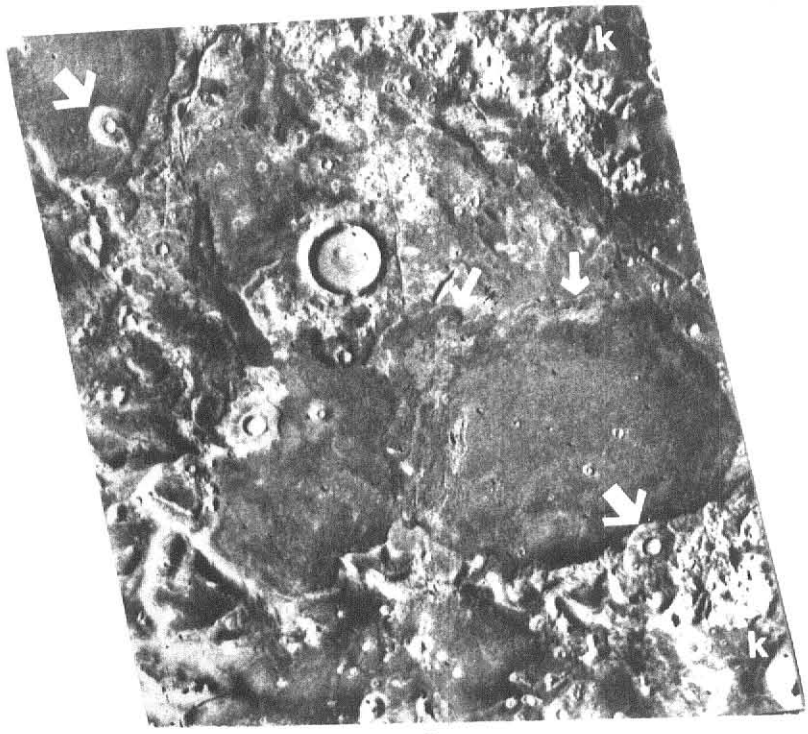

pmp
p
C4
pv
10km
N

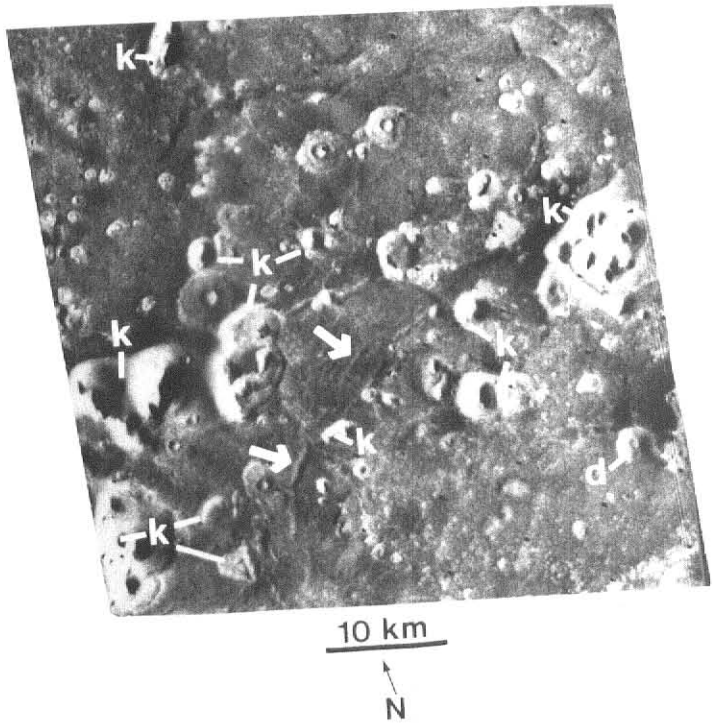
the polygonal trough pattern also was a criterion. The boundary with the mottled plains material - undivided was difficult to define because of the poor quality of the images, but the boundary is based on the occurrence of the polygonal troughs. The boundary between the patterned mottled plains and the subdued patterned mottled plains is placed where the troughs decrease in abundance, probably because they have been filled or partially filled by lava flows.

Subdued Patterned Mottled Plains Material.--The subdued patterned mottled plains material occurs in close proximity to the central plateau. The unit exhibits the same characteristics, at medium resolution, as the patterned mottled plains material. At higher resolution, however, the troughs are observed to be more discontinuous. Crater counts were not made on this surface because of its limited area, but the crater density is assumed to be slightly less than that of the patterned mottled plains material. The presence of flow fronts, pressure ridges, and possible volcanic cones led to the interpretation of this unit as volcanic flows that fill or partially fill pre-existing troughs.

A portion of the subdued patterned mottled plains was mapped in detail, and the geologic map is included as Appendix II. Figure 26 shows examples of lava flows that occur on this surface. The source of these lavas is somewhat uncertain. The flows may have originated from fissures that were subsequently buried, or from central vents. Several small, low-albedo domal structures that resemble pedestal craters, may, in fact, be small

Figure 26. Lava flows on subdued patterned mottled plains. (a) A large low-albedo lava flow can be seen in the center of the image; small arrows mark distinct flow lobes; another flow can be seen in the northwest corner of the image; the ejecta of the large impact crater in the center of the image may have been buried by older lava flows; lava flows may have originated from fissures that were subsequently buried, or from domal structures that are indicated by the large arrows; alternatively, these domal structures also resemble pedestal craters; smaller domes, seen as white dots in the southern part of the image, may be similar to those seen in Figure 24b; knobby material (k), from the breakdown of the plateau, occurs to the north and south of the large lava flow; two north-south trending fractures can be seen in the northeast corner of the image; Viking frame 35A32 (45.4°N, 28.4°W).
(b) Possible pressure ridges on a lava flow are indicated by arrows; a source for this flow is uncertain; note the clusters of small domes in the northeast corner and the larger dome (d) in the southeast corner of the image; if these domes are volcanic, they may be a local source for the flows; note the obscure pattern of troughs in the northeast corner of the image; isolated patches of knobby material (k) are scattered throughout the region; Viking frame 35A41 (46.5°N, 22.2°W).


k
k
10 km
N


k
k
k
k
k
k
k
k
10 km
N

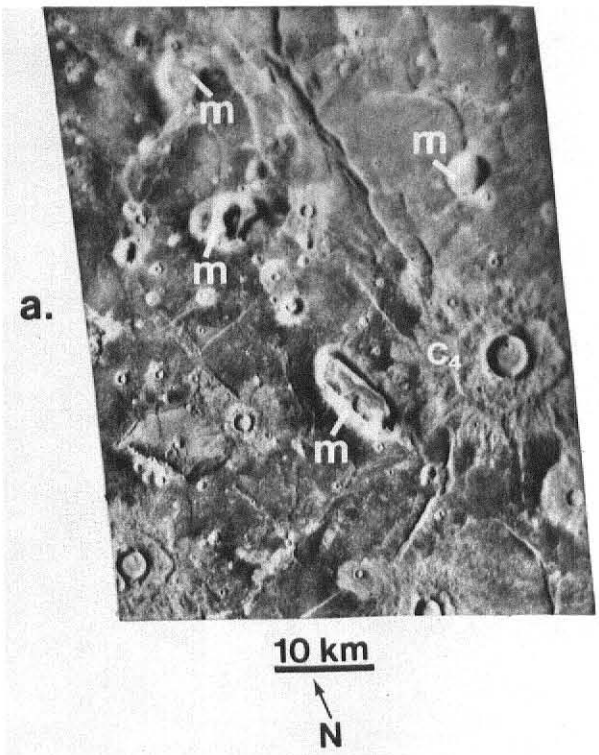
volcanoes (Fig. 26a). There are also numerous small, cratered domes, such as those that occur on the patterned mottled plains, that could be volcanic cones (Figs. 26, 27).

Hodges and Moore (1979) and Allen (1979b) believed that several of the small mesas and buttes in this region may be analogous to Icelandic tablemountains produced by subglacial central-vent eruptions and moberg ridges produced by subglacial fissure eruptions. These structures are commonly a few kilometers across and several hundred meters high (Fig. 27). If these martian features are true tablemountains and moberg ridges, then at one time this region must have been covered by a layer of ice, or possibly a combination of ice and rocky material, several hundred meters thick. Alternatively, these features could be erosional remnants of the dissected and fractured plateau material.

The boundary between the subdued patterned mottled plains and the dissected and fractured plateau boundary is commonly expressed by an escarpment with lava flows embaying incomplete impact-crater depressions on the plateau surface (Fig. 12). The boundary with the patterned mottled plains material is marked by an increase in trough abundance on the patterned mottled plains (Fig. 28).

Fractured Plains Material.--The fractured plains cover a small area between the patterned mottled plains and the cratered plateau in southeastern MC-4. The unit has a higher albedo than the mottled plains units and is characterized by wider troughs than those of the patterned mottled

Figure 27. Subdued patterned mottled plains material. (a) Small mesas (m) with or without summit knobs may be tablemountains or erosional remnants; many small cratered domes are at the limit of resolution; ejecta from the large c_4 crater is not cut by the arcuate fracture at the eastern side of the image, the smaller craters and ejecta blankets in the southern part of the image also are not cut by the fracture, indicating that the fractures are older than the c_4 craters; northwest-southeast and northeast-southwest fracture grid occurs; Viking frame 26A30 (44.8°N, 20.4°W); for a detailed map and cross-section, see Appendix II.
(b) The small mesa (m) in the northwest corner of the image is cited by Allen (1979b) as a possible tablemountain; from shadow-length measurements, Allen estimated that the mesa is 470 m high; numerous small cratered domes can be seen as white dots in the northern part of the image; a possible flow is indicated by arrows; the polygonal pattern of fractures is more obvious in this region than the region to the west (Figure 26b); Viking frame 26A28 (44.8°N, 21.7°W); for a detailed map and cross-section, see Appendix II.


a.
m
m
m
m
C4
10 km
N

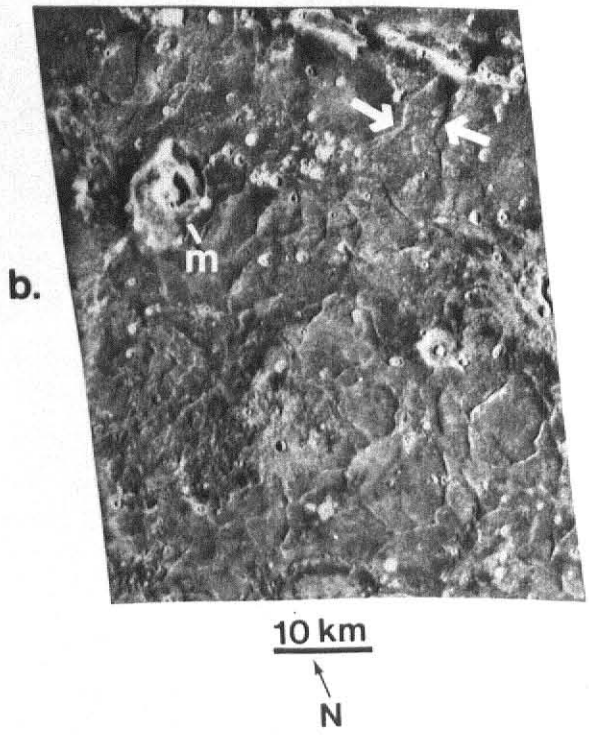
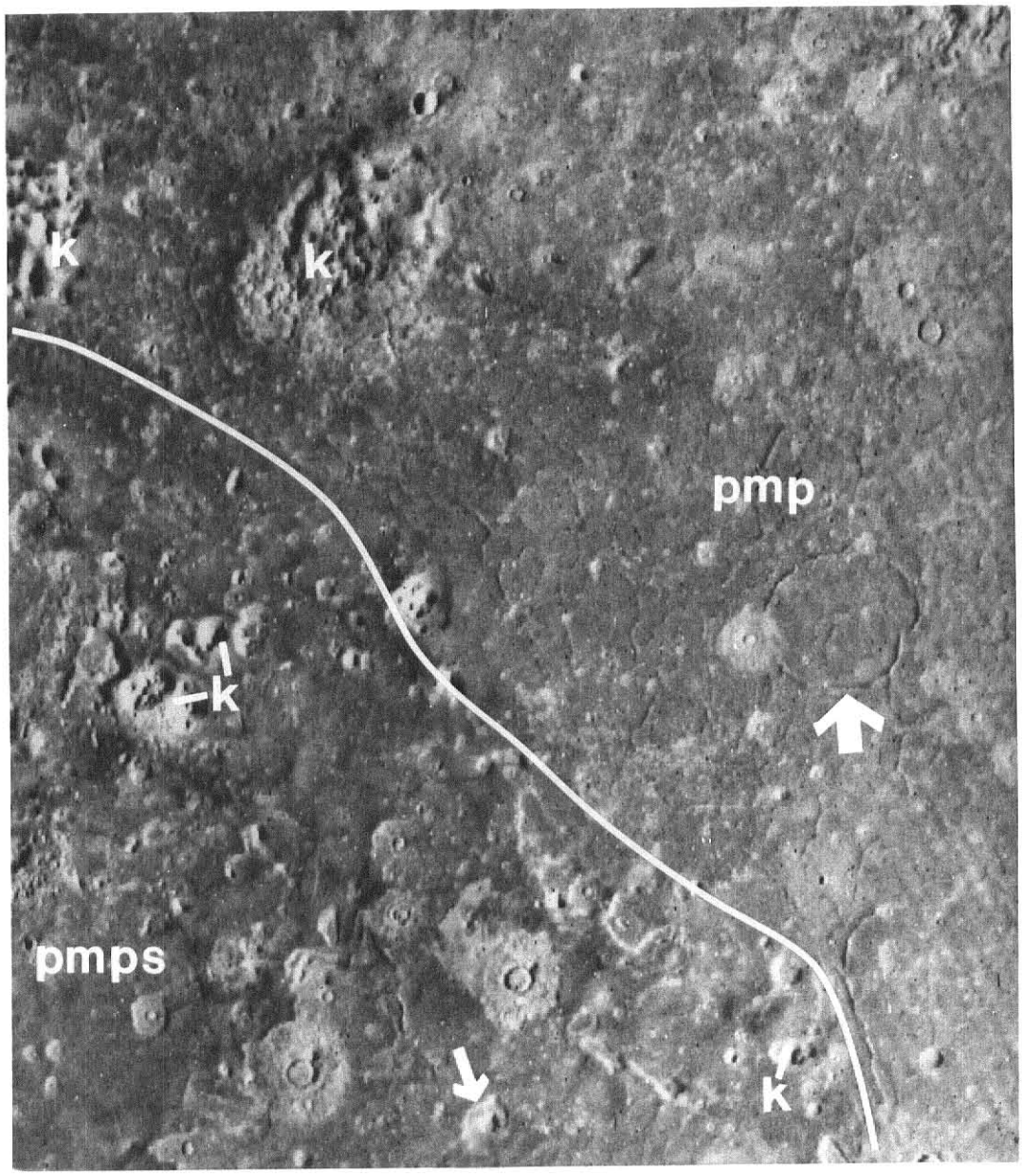

b.
m
10 km
N

Figure 28. Patterned mottled plains - subdued patterned mottled plains boundary. The boundary (white line) is marked by a rapid change in the abundance of troughs; also the subdued patterned mottled plains (pmps) may be slightly lower albedo; the image is too low in resolution to detect individual lava flows on the subdued patterned mottled plains, but the proposed tablemountain shown in Figure 27b is indicated by a small arrow in the southern part of the image; knobby material (k) is scattered throughout both the patterned mottled plains (pmp) and the subdued patterned plains (pmps); large circular trough on the patterned mottled plains occurs in the east-central portion of the image (large arrow); image artifact occurs along the eastern margin of the image; Viking frame 670B18 (47.2°N, 21.2°W); part of the area of this image was mapped in greater detail and is included as Appendix II.


k
k
pmp
k
pmps
k
10 km
N

plains and the patterned smooth plains. Crater counts were not made on this surface because of its limited area, but visual estimates indicate a fairly low crater density. No craters larger than 5 km in diameter exist on the fractured plains surface. The fractured plains material may consist of volcanic and eolian material.

The troughs of the fractured plains may be as wide as 2 km, as opposed to the troughs on the other patterned plains units that are generally less than 1 km wide. Commonly the troughs are shallow and have flat floors (Fig. 29). Pechmann (1980) reported that some of the troughs on the fractured plains have one or two smooth terraces along a portion of the wall. He also reported vertical offset in several of the troughs and concluded that these features were the result of normal faulting (Pechmann 1980; Figs. 1-3).

A small section of the fractured plains was mapped at higher resolution (Appendix III). In this region, the fractured plains nearest the large remnant of cratered plateau material (mesa material on the high-resolution map) may have been partially resurfaced by lava flows, as indicated by the presence of several possible flow fronts and by the subdued and discontinuous pattern of fractures.

The presence of a scarp forming the boundary between the fractured plains and the higher variegated plains and the presence of knobs and mesa material on the fractured plains led Guest et al. (1977) to conclude that the fractured plains material is an old unit that stratigraphically underlies the plateau material. Figure 29b shows a part of the scarp

Figure 29. Fractured plains material. (a) Compare these troughs with those seen on the patterned mottled plains (Fig. 24); troughs on the fractured plains can be as large as 2 km wide (troughs on the patterned mottled plains are generally less than 1 km wide); the wider troughs have flat floors and steep sides that Pechmann (1980) believed are consistent with either formation by downdropping of the trough floor or by separation of the trough walls followed by infilling; matching irregularities in some of the opposite walls of the troughs suggest tensional separation of the walls; arrow indicates the region where Pechman reported downward offset at the trough walls; numerous small domes occur in the southern portion of the image; knobby terrain (k) occurs in the southeast corner of the image; impact craters on the fractured plains unit do not have high-albedo ejecta blankets; Viking frame 35A64 (40.4°N, 13.9°W).

(b) Sinuous escarpment along the boundary between the fractured plains (pf) and the variegated plains (pv); the low albedo fractured plains material appears to terminate 2-3 km away from the escarpment; the arrow indicates a lobe-like structure that may be a thin lava flow; three fresh flow-ejecta craters can be seen in this image; several clusters of secondary craters occur in the southern and eastern regions; the knobs in the southwest corner of the image appear to be layered; image artifacts occur along the eastern and western margins of the image; Viking frame 35A73 (41.6°N, 8.7°W).

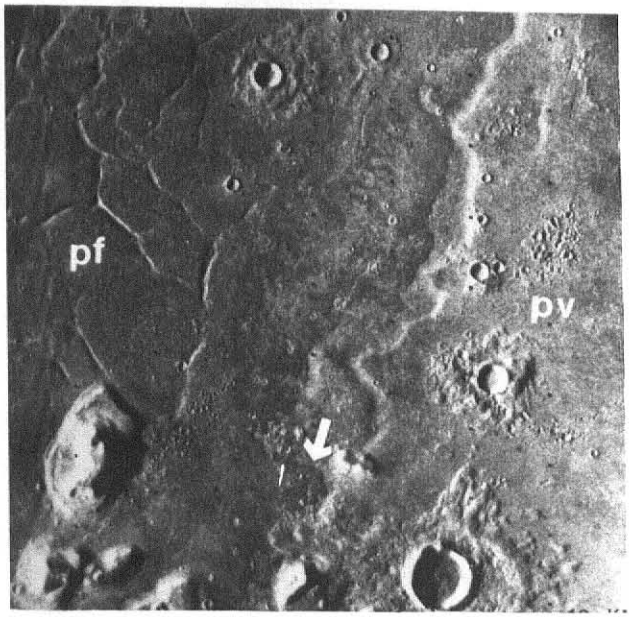
a.



10 km

N

b.



10 km

N

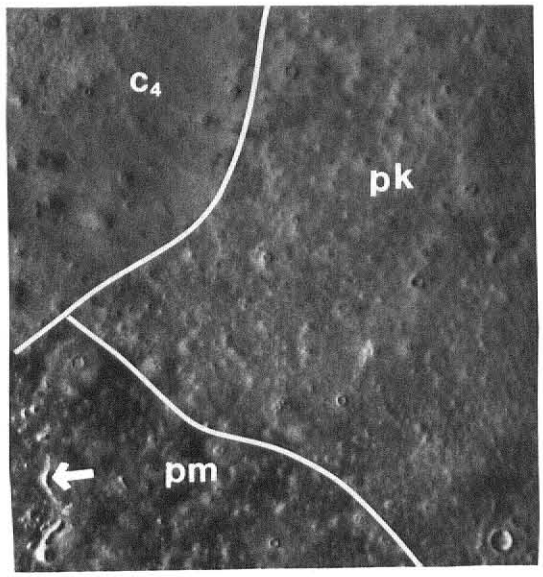
boundary. It appears as though the darker fractured plains materials do not always come in contact with the scarp. Guest et al. (1977) suggested that scarp retreat occurred by a breakdown of the rocks as a result of sapping and other ground ice activity and that as the scarp retreated, it left piles of lighter debris on the rocks stratigraphically below the smooth plains material. Alternatively, the lower fractured plains may have been partially resurfaced by thin lava flows, with the albedo boundary marking the extent of these flows.

In some areas a small escarpment marks the boundary of the fractured plains and the higher knobby terrain. If these knobs are erosional remnants of the higher cratered plateau material, then the escarpment boundary would suggest that the fractured plains lie stratigraphically underneath the cratered plateau and were exposed be erosion. The boundary with the darker mottled plains unit to the north is based on an albedo difference.

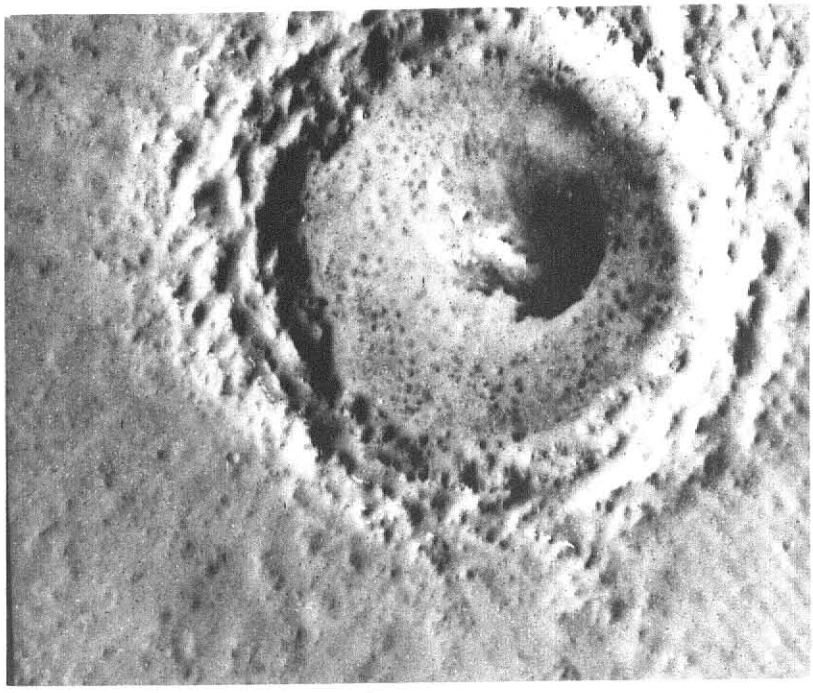
Knobby Plains Material.--The knobby plains material occurs in the northeast corner of MC-4 and extends eastward into the adjacent quadrangle, MC-5. The unit exhibits characteristics similar to those of the adjacent mottled plains including the filled and partly filled impact craters. The knobby plains, however, have much higher albedo (Fig. 30a). The crater size-frequency distribution curve for the knobby plains is very similar to that of the mottled plains units (Fig. 20), suggesting that the units are of similar age. The lithology of the knobby plains is interpreted to be eolian material blanketing a lower, possibly volcanic surface.

Figure 30. Knobby plains material. (a) Boundary between the knobby plains (pk) and the lower-albedo mottled plains (pm) (lower white line); the smooth light-colored material in the northwest corner of the image is ejecta from a large c_4 crater to the northwest; the knobby plains do not exhibit the same albedo contrast between the plains and ejecta blankets as do the mottled plains; a sinuous ridge on the mottled plains is indicated by the arrow; image artifact occurs along the eastern margin of the image; Viking frame 673B08 (54.3°N, 5.2°W).
(b) Large (130 km diameter) c_2 impact crater, Lomonosov, occurs on the knobby plains near the northern boundary of MC-4; small (< 1 km) dark hills occur on the floor of the crater; these knobs are similar to those seen in the inter-crater region of the knobby plains and hummocky mottled plains (Fig. 23); the large patch of dark material on the crater floor may be a field of dunes; the wall of this large crater consists of a complex of short ridges; the striped pattern in the lower right corner is an image artifact; Viking frame 672B56 (65.1°N, 9.8°W).

a.



b.



Knobs similar to those on the hummocky mottled plains are common on the knobby plains. These dark hummocks are present on the floor of the large crater Lomonosov (64°N, 9°W) (Fig. 30b). These darker knobs may be volcanic or permafrost features. It is not likely that they represent a lower, darker unit that has been partially mantled with lighter material.

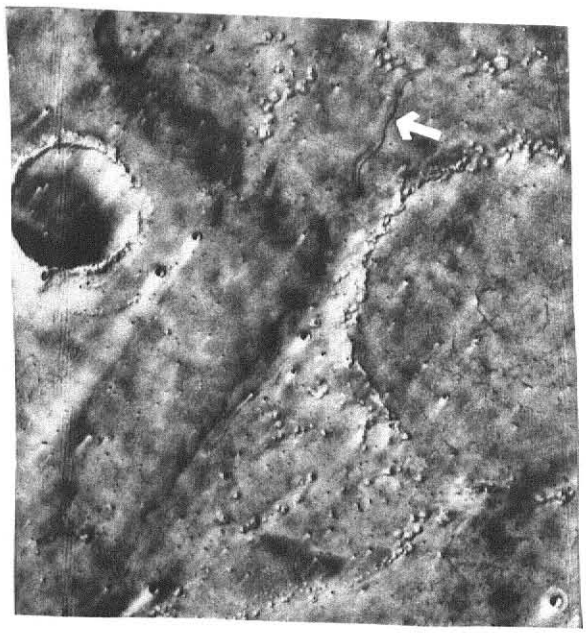
The knobby plains - mottled plains boundary is a sharp albedo contrast (Fig. 30a). This contrast may be the result of a thicker layer of debris that still mantles the knobby plains, i.e. has not been eroded as completely as it was in the mottled plains region. Alternatively, the albedo contrast may be the result of variations in surface lithologies.

Smooth Plains Material.--The smooth plains cover a large portion of the southern region of MC-4 and are relatively featureless at medium resolution. Patches of knobby terrain are scattered throughout the smooth plains region, including several places where the knobs form a circular outline (Fig. 31a). The albedo varies; in the east, the smooth plains are intermediate to high albedo, whereas to the west, especially along the northern and southern margin of Tempe Plateau, the smooth plains are low albedo. Bright and dark wind streaks are common throughout the smooth plains region. The crater size-frequency curve for the smooth plains (Fig. 32) is very similar to those of the mottled plains units, suggesting they may be equivalent in age. The smooth plains are believed to consist of eolian and alluvial deposits that buried an older, cratered surface.

In two areas, small sections of smooth plains were mapped at high

Figure 31. Smooth plains material. (a) Circular outlines of knobby material mark the positions of partly buried impact craters; the varied albedo pattern is caused by a shifting eolian mantle; both the light and dark wind streaks are scattered throughout the region; the arrow shows a discontinuous sinuous ridge and trough, many of which are scattered throughout the smooth plains; image artifacts occur along the eastern and western margins of the image; Viking frame 524A15 (34.5°N, 38.4°W).
(b) Streamlined remnants of an old impact crater; crater rim material is often much more resistant to erosion than is other, less well-compacted material; the streamlining of this feature is in a direction opposite to the wind; two unusual curvilinear troughs can be seen in the southern portion of the image (arrows); the mouths of several large outflow channels occur to the south of this region; the wind direction is from the northeast as indicated by the numerous light streaks formed downwind from impact craters; Viking frame 558A07 (32.7°N, 40.5°W).

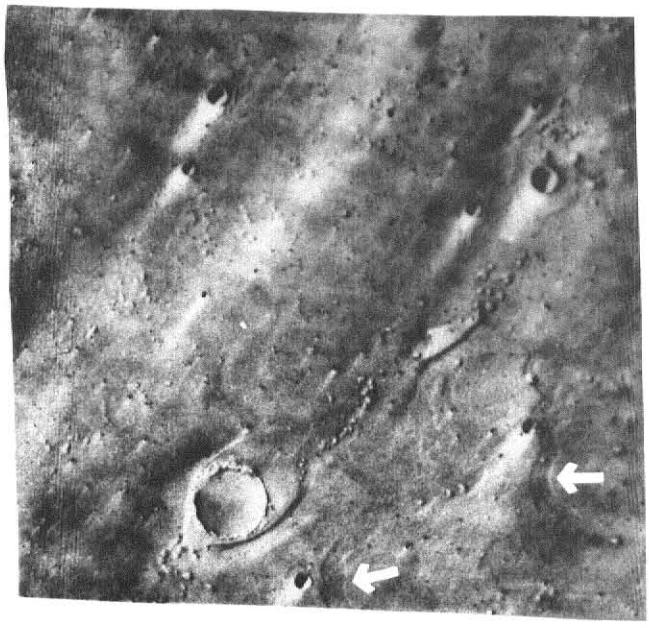
a.



10 km

N

b.



10 km

N

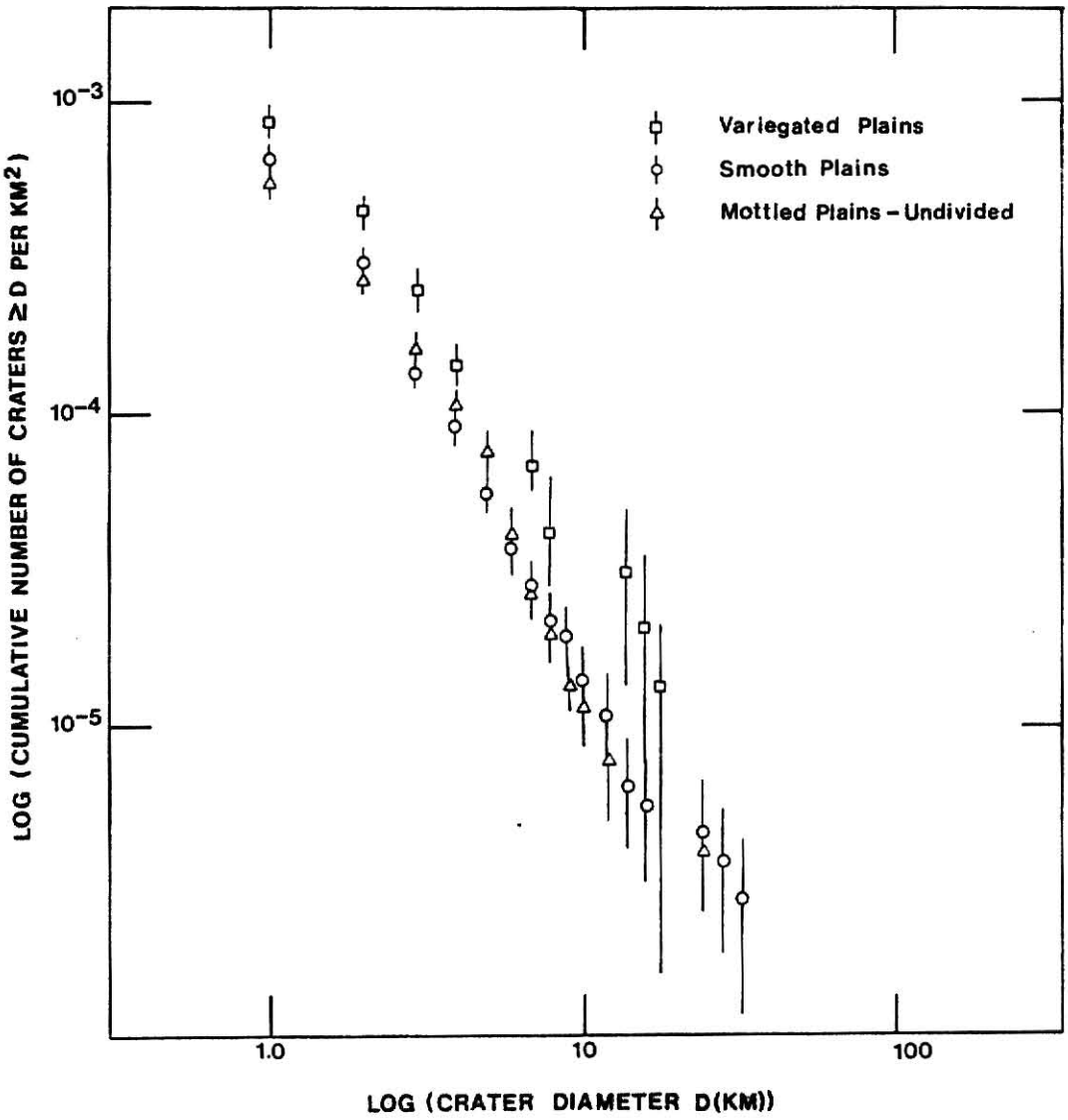


Figure 32. Cummulative crater size-frequency distributions for the variegated plains, smooth plains, and mottled plains - undivided. Number of craters are cummulated from largest to smallest size; vertical lines indicate one standard deviation, 1σ confidence intervals for each data point plotted, calculated by assuming the crater populations are Poisson distributed. The 1σ is approximated by using $N = \pm \sqrt{N}$ where N is the number of craters (Arvidson et al., 1978).

resolution (Appendix I, III). One area occurs along the northwest margin of the cratered plateau in the southeast corner of the quadrangle (Appendix III). Numerous small (< 1 km) cratered domes similar to those that occur on the patterned and subdued patterned mottled plains and on the variegated plains are scattered across the smooth plains surface in this region. Frey and Jarosewich (1981) discovered a definitive bimodal distribution of cratered dome diameters on the smooth plains. They suggested that if the domes are pseudocraters, the bimodal distribution may be the result of variations in the thickness of lava flows. Alternatively, the bimodal distribution may indicate that these domes have formed from more than one process. If these domes are volcanic edifices (Wood, 1979) or pseudocraters (Frey et al., 1979), the smooth plains in this region may consist partly of volcanic material.

The other area that was mapped using high-resolution data occurs along the northern margin of Tempe Plateau. In this region, smooth plains material embays troughs and channels that are cut into the higher plateau. Scott (1978) recognized lobate scarps and small convex cones and suggested that the smooth plains in this region are basalt flows. In the present investigation, most of the "small convex cones" are interpreted as impact craters, and the lobate scarps were not recognized. As a result, the smooth plains in this region have been interpreted as alluvial sediment from erosion and drainage off the highland block and as eolian material.

Scours and streamlined features oriented northeast occur in the southern smooth plains region (Fig. 31b) and disappear near 35°N. These features

have been interpreted to be the result of erosion associated with the release of water from the large outflow channels to the south (Carr and Clow, 1981). Much of the smooth plains material in this southern region may consist of debris deposited during the flooding.

Several mare-type ridges occur on the smooth plains in the southwestern region. Figure 33a shows one of these ridges that was cut by faults that are aligned with the faults of Tempe Plateau. Another mare-type ridge cuts across both the higher plateau and lower smooth plains material (Fig. 15b). The occurrence of these ridges on units with varied lithology and different elevation supports the hypothesis that the mare-type ridges in this region are tectonic.

Other unusual ridges of more uncertain origin occur throughout the smooth plains (Fig. 33b, 34). The sinuous ridges near the plateau plains boundary in the southeast region show no preferred orientation and can be more than 60 km long (Fig. 33b). Several of these ridges subdivide into two or more branches. Figure 34a shows a meandering pattern of troughs with ridges running down the center. Less well-preserved examples of this pattern occur as far north as 40°N. Scott (personal communication, 1982) suggested that these may be meander scrolls from shifting stream channels. A wider and more subdued pattern of ridges or swells occurs on the smooth plains around 37°N, 17°W (Fig. 34b). These subdued swells form a more regular pattern of branches.

Light wind streaks and patches of dark eolian material are common throughout the smooth plains region. The streaks record north and northwest

Figure 33. Ridges on the smooth plains, example 1. (a) A mare-type ridge on the smooth plains near Tempe Plateau is truncated by east-west trending faults; faint traces of the ridge (arrow) extend to the impact crater; isolated remnants of plateau material can be seen along the western margin of the image; dark patches are interpreted as eolian material; well preserved c_4 flow-ejecta crater occurs in the center of the image; image artifacts occur along the eastern and western margins of the image; Viking frame 558A31 (37.0°N, 49.1°W).

(b) A sinuous ridge near the plateau-plains boundary in the southeastern region; the ridge bifurcates at the knobby material then continues on the other side; a smaller ridge (arrow) cannot be seen as well because it runs parallel to the sun angle, and thus, no shadow is formed; the sun is from the top right; the mesas (m) and knobs (k) are believed to be erosional remnants of cratered plateau material; well-preserved c_4 bowl-shaped crater occurs in the northeast corner of the image; Viking frames 218S01-02 (33.0°N, 14.5°W).

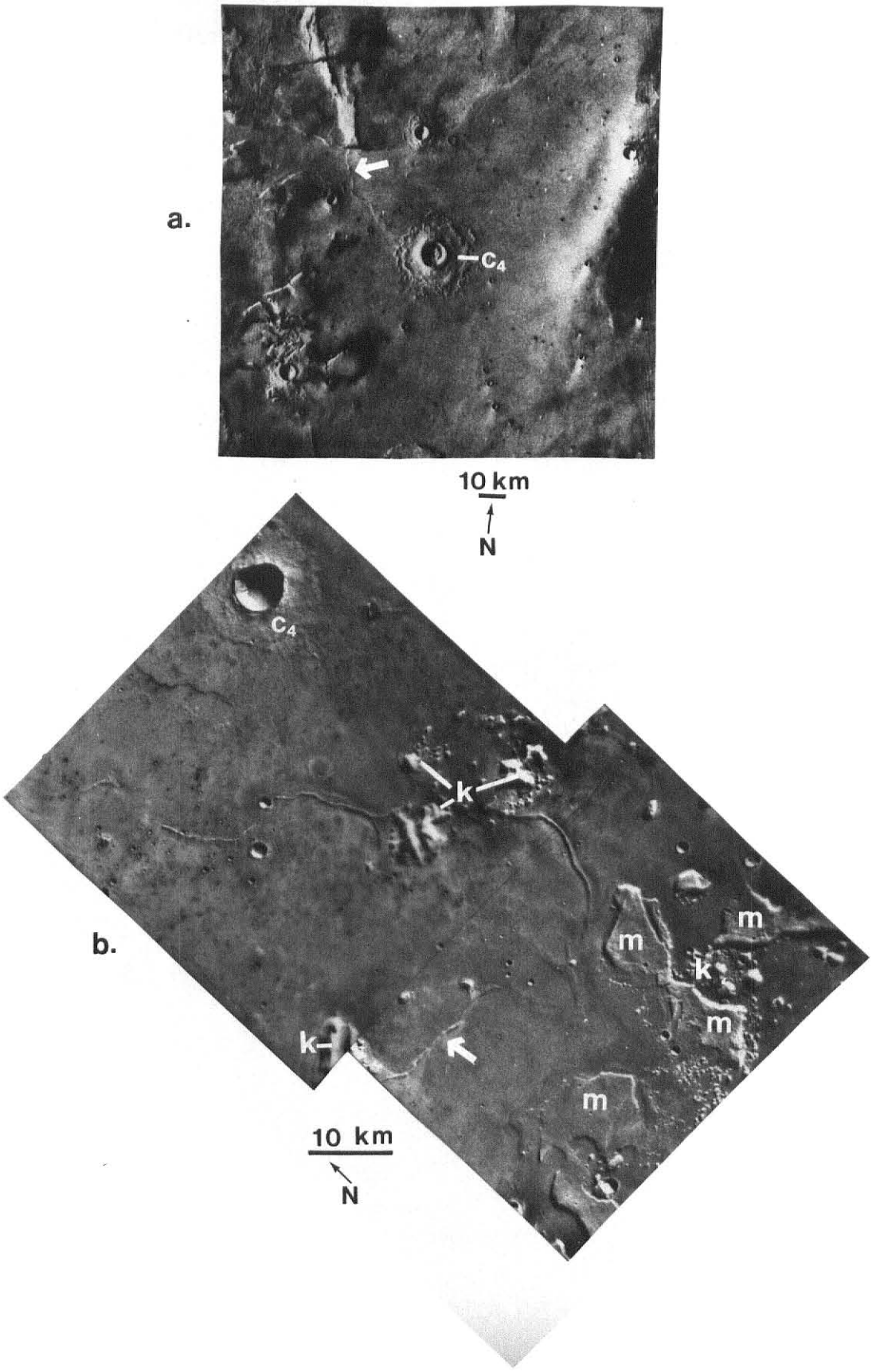
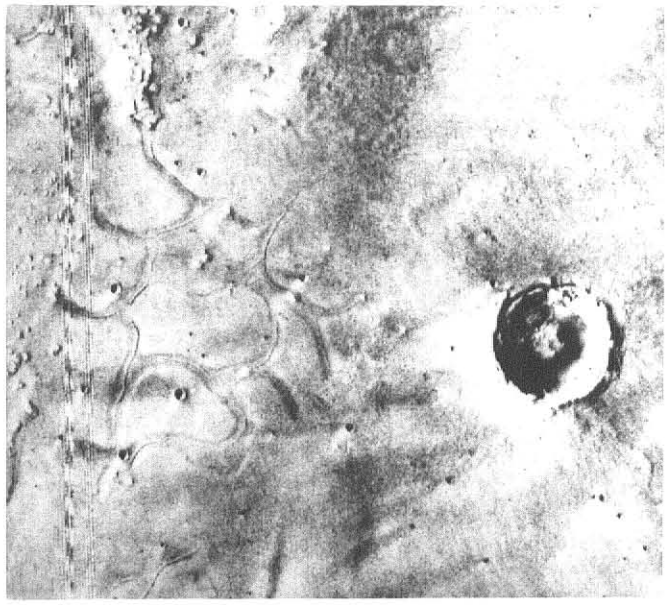

a.
C4
10 km
N
b.
C4
k
k
m
m
k
m
m
10 km
N

Figure 34. Ridges on the smooth plains, example 2. (a) Meandering pattern of troughs with ridges; the shallow troughs can be as large as 2 km wide; narrow ridges appear to run down the center of these troughs; Scott (personal communication, 1982) suggested that these are meander scrolls, however orthogonal intersections are atypical of meander scrolls; a large (20 km diameter) impact crater occurs on the eastern side of the image; dark patches and streaks of eolian material occur in the central region; the striped pattern on the west side is an artifact of the imaging system; Viking frame 524A28 (29.1°N, 28.0°W).
(b) Enlargement showing a subdued pattern of wide ridges or swells; some of these swells are 3-4 km wide; many of these swells subdivide into two or more branches; isolated knobs are scattered throughout the region; Viking frame 597A12 (37.5°N, 17.4°W).

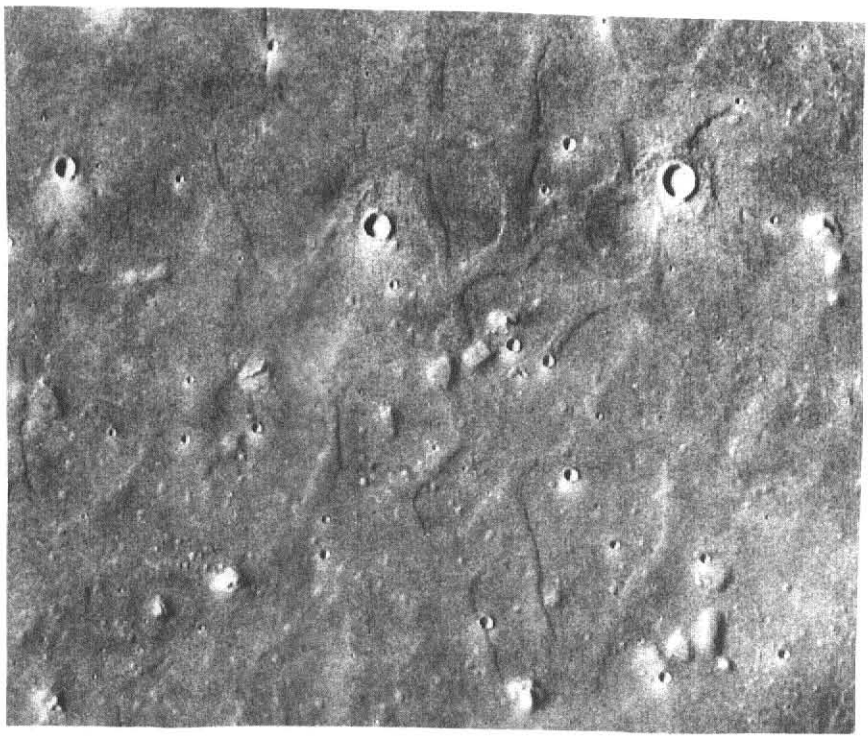
a.



10 km

N

b.



10 km

N

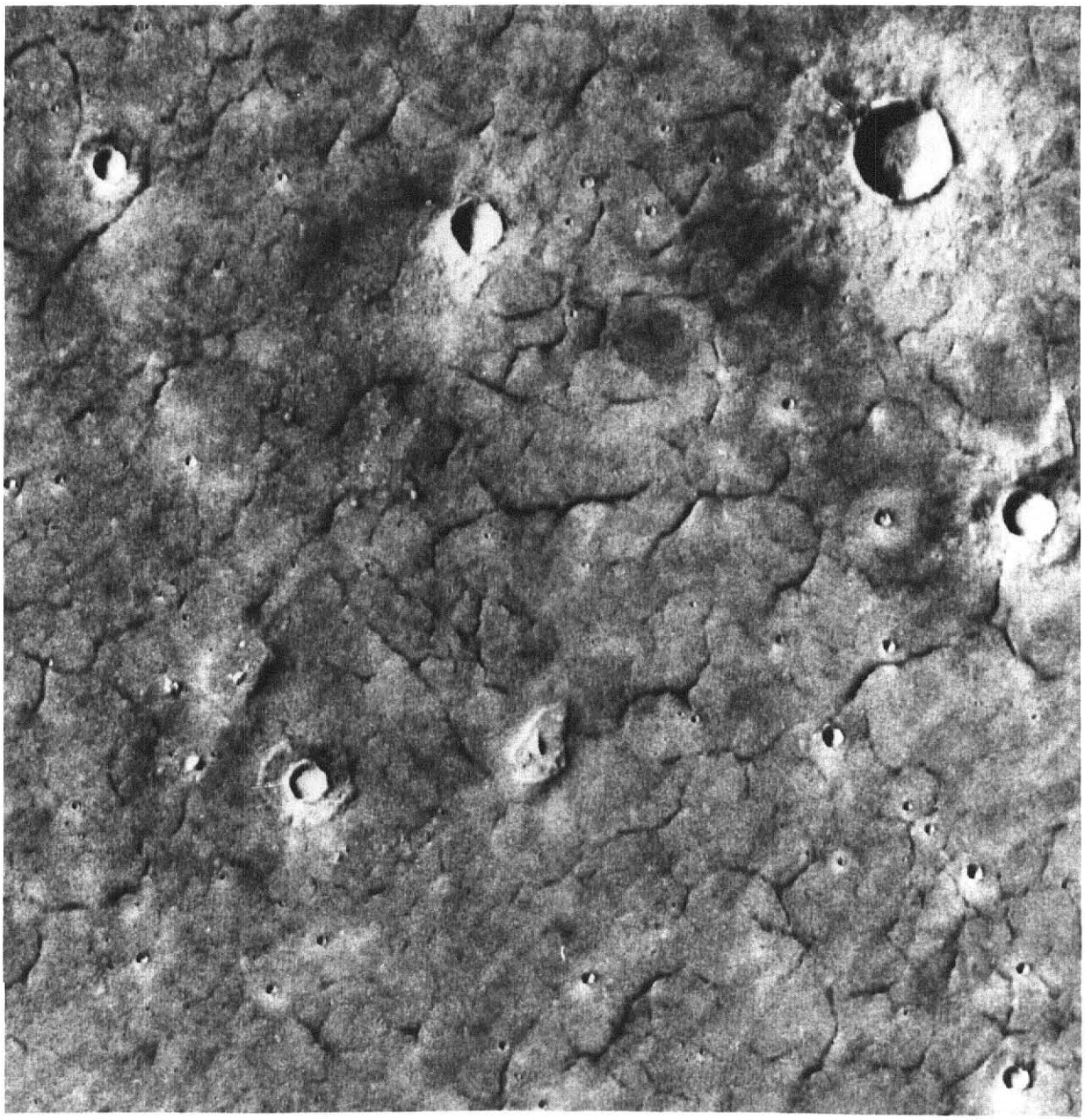
winds at north latitudes greater than 40°. Farther south, the streaks record a more northeasterly wind direction.

The boundary of the smooth plains with the darker mottled plains units to the north is based on albedo. The smooth plains - patterned smooth plains boundary is more gradational and is placed where trough abundance increases. To the southeast and southwest, the boundary between the smooth plains and the higher plateau units is a steep escarpment. Farther northwest, the escarpment is not always present, and smooth plains material embays and rests on the plateau units.

Patterned Smooth Plains Material.--The patterned smooth plains material occurs in the central region adjacent to the patterned mottled plains. The unit is characterized by a crudely polygonal pattern of troughs that is approximately the same size as that which occurs on the patterned mottled plains. The lack of high-albedo ejecta blankets and the overall higher albedo distinguishes the patterned smooth plains unit from the patterned mottled plains. No crater counts were made on this unit because of its limited extent and gradational boundary with the smooth plains, but crater density is assumed to be similar to that of the smooth plains. The lithology of the patterned smooth plains material is thought to be similar to that of the smooth plains material to the south, i.e., predominantly eolian material blanketing an older cratered surface (Fig. 35).

There are several possible explanations for the presence of the troughs on the smooth plains. Patterned mottled plains material may have, at one time, extended farther south and been subsequently blanketed with

Figure 35. Patterned smooth plains material. This enlargement shows the subdued pattern of troughs superimposed on the intermediate-albedo smooth plains; compare this image with Figure 24, which shows a similar pattern of troughs that bound polygons of slightly larger size; few of the troughs form closed polygons; circular forms are less common than on the patterned mottled plains; the albedo contrast between the crater ejecta blankets and the surrounding plains is not as extreme as on the mottled plains; Viking frame 597A05 (39.6°N, 24.2°W).


10 km
N

a thin mantle of lighter smooth plains material that slightly obscured the trough pattern. More feasible is the hypothesis that the smooth plains materials were subjected to the same mechanisms that produced the troughs on the adjacent mottled plains, i.e., permafrost activity, desiccation, or tectonism.

The boundary of the patterned smooth plains with the darker mottled plains material to the north is based on albedo. The occurrence of the trough pattern marks the smooth plains - patterned smooth plains boundary.

Variegated Plains Material.--The variegated plains material occurs along the eastern border of MC-4 and extends into MC-5. These plains are smooth, relatively featureless, and at medium resolution display a patchy albedo pattern. The crater size-frequency distribution (Fig. 32) for the variegated plains indicates that this unit may have a slightly higher number of larger craters, but the standard error bars are large and the difference may not be significant. The variegated plains are believed to be composed of volcanic and alluvial material (the latter only occurs near the plateau-plains boundary). These plains are blanketed by a thin mantle of shifting eolian material that forms the patchy albedo patterns.

A small section of the variegated plains around Bamberg crater (40°N, 3°W) was mapped using high-resolution data, and the map is included as Appendix III. On the geologic map the variegated plains are subdivided into the rough plains, hilly plains, and variegated plains. The rough plains are located adjacent to the ejecta deposits from Bamberg crater. The rugged texture is produced by the presence of many small

(< 1 km diameter) depressions that are believed to be secondary impact craters. The hilly plains are characterized by small (< 1 km wide) domes with summit craters similar to those that occur on the patterned and subdued patterned mottled plains and in places on the smooth plains. Clusters of these cratered domes are scattered throughout the variegated plains.

There are several small streamlined features on the variegated plains near the plateau-plains boundary along the eastern edge MC-4. Small channels occur on the cratered plateau near the plains boundary. The variegated plains material appears to blanket a portion of the ejecta deposits from Bamberg crater. These features suggest that the variegated plains in this region may consist of alluvial material deposited by channels draining the plateau to the south. Alternatively, the streamlined features may have been produced by wind erosion, and the variegated plains in this region may consist of eolian material.

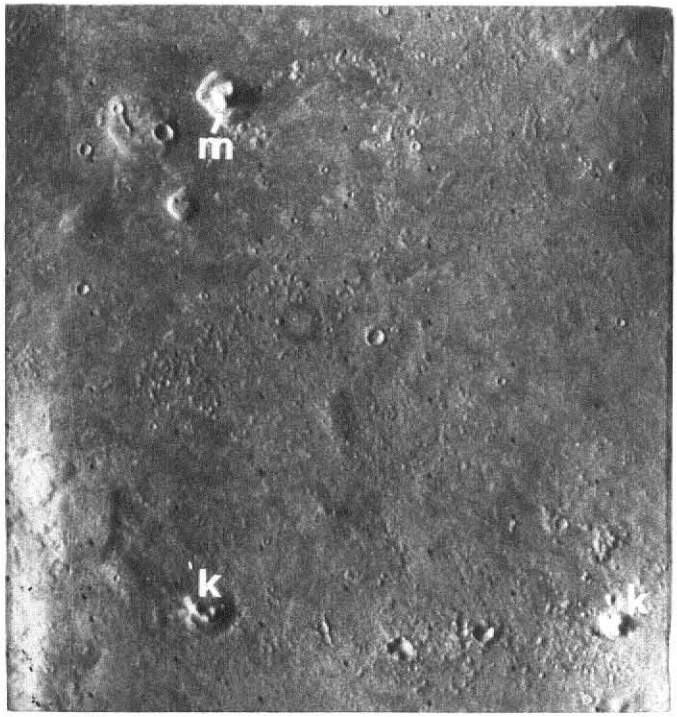
Structures resembling Icelandic tablemountains occur in several places on the variegated plains. Figure 36a shows one of these steep-sided, flat-topped mesas with a summit knob. Alternatively, the features have been interpreted as erosional remnants of a higher, probably layered surface (Guest et al., 1977).

The variegated plains - cratered plateau boundary is in many places expressed as a low escarpment. In other areas the boundary is textural, between the relatively rugged, highly-cratered plateau unit and the smoother, variegated plains unit (Fig. 36b). A small irregular escarpment marks the

Figure 36. Variegated plains material. (a) Smooth, featureless plains with few topographic irregularities; two small irregularly shaped secondary craters from a large crater occur in the southeast corner of the image; a small mesa with a summit knob (m) resembles Icelandic tablemountains (Allen, 1979b); alternatively, the mesa may be an erosional remnant of layered plateau material; two smaller knobs (k) occur in the southern region; dark circle in the center of the image is an image artifact; Viking frame 36A44 (43°N, 4.2°W).

(b) Boundary between the cratered plateau (plc) and the variegated plains (pv); compare the differences in crater densities between the two units; an escarpment (large arrow) marks the plateau-plains boundary; to the west of the escarpment, the circular outline of two old impact craters can be seen; many irregular depressions occur on the cratered plateau (small arrows) and are believed to be collapse features from the breakdown of the plateau; Bamberg, a c_3 crater approximately 50 km in diameter, occurs along the left side of the image; numerous secondary craters occur east of Bamberg; Viking frame 673B60 (40.5°N, 0.9°W); part of this region was mapped in greater detail and is included as Appendix III.

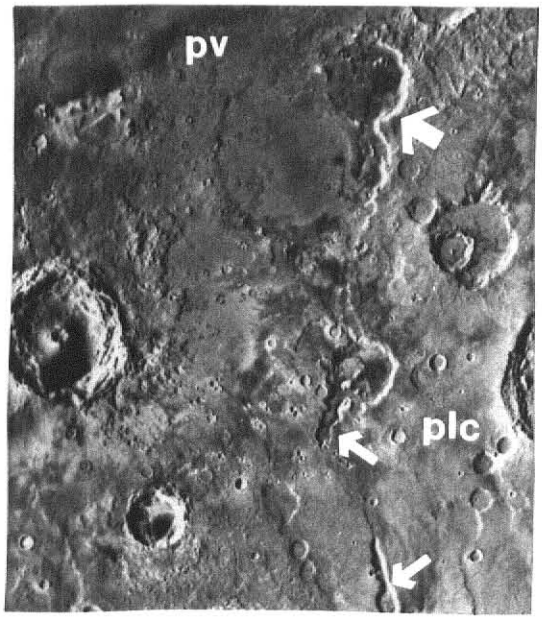
a.



10 km

N

b.



10 km

N

boundary with the lower fractured plains materials (Fig. 29b), suggesting that the variegated plains material may be younger and, therefore, overlie the fractured plains material (Guest et al., 1977). The boundary between the variegated plains and the darker patterned mottled plains is based on albedo and the presence of the polygonal pattern on the mottled plains (Fig. 25).

Other Material

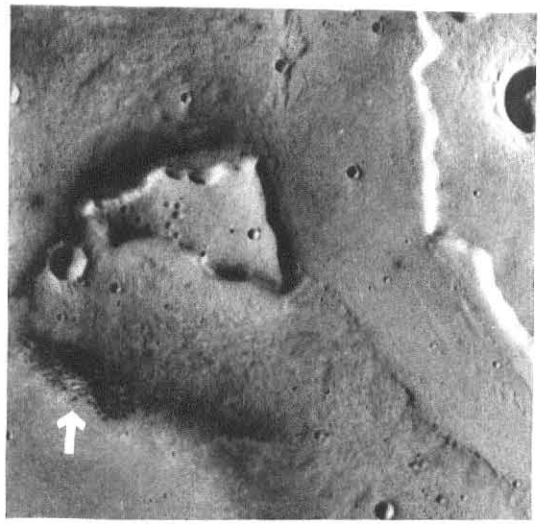
Dark Material.--Dark material occurs in patches through the quadrangle but is particularly abundant on the smooth plains near the southern margin of Tempe Plateau. Commonly these dark patches are associated with some sort of topographical barrier. Dark material occurs in and around craters on the plateaus and the plains (Figs. 15a, 30a), in valleys (Fig. 37a), along escarpments (Figs. 15a, 19), and in the inter-crater regions of the plains (Figs. 21a, 31a). These low-albedo materials are believed to be accumulations of eolian debris that reflect the present wind direction. In certain areas these dark patches have been resolved as fields of transverse dunes (Fig. 37a).

Light Material.--Light material is not as abundant as dark material. It occurs only in two areas: (1) along the northern margin of the southeast cratered plateau, and (2) along the northern margin of Tempe Plateau (Fig. 37b). A fan-shaped deposit of light-colored material is seen on the smooth plains adjacent to the fractured plateau (Fig. 17). The northern Tempe Plateau region was mapped in greater detail and is included as

Figure 37. Dark, light, and channel material. (a) Dark material occurs on the smooth plains between two plateaus; the small field of transverse dunes is indicated by the arrow; other dark material has accumulated on the upwind side of the small isolated plateau; this region is included on the low-resolution image shown on Figure 15b; Viking frame 668A17 (33.2°N, 53.6°W).

(b) High-albedo channel material (ch) can be seen along the boundary between the smooth plains (ps) and the mottled plains (pm); fractured plateau material (plf) occurs in the southwest corner of the image; patchy light material (lt) can be seen on the mottled plains in the northwest corner; several high-albedo wind streaks associated with some small craters indicate that wind is from the northwest; the smooth plains in this region are lower albedo than the mottled plains; the pattern on the east side of the image is an artifact of the imaging system; Viking frame 669B76 (53.9°N, 53.4°W); high-resolution map and cross-section of this area are included as Appendix I.

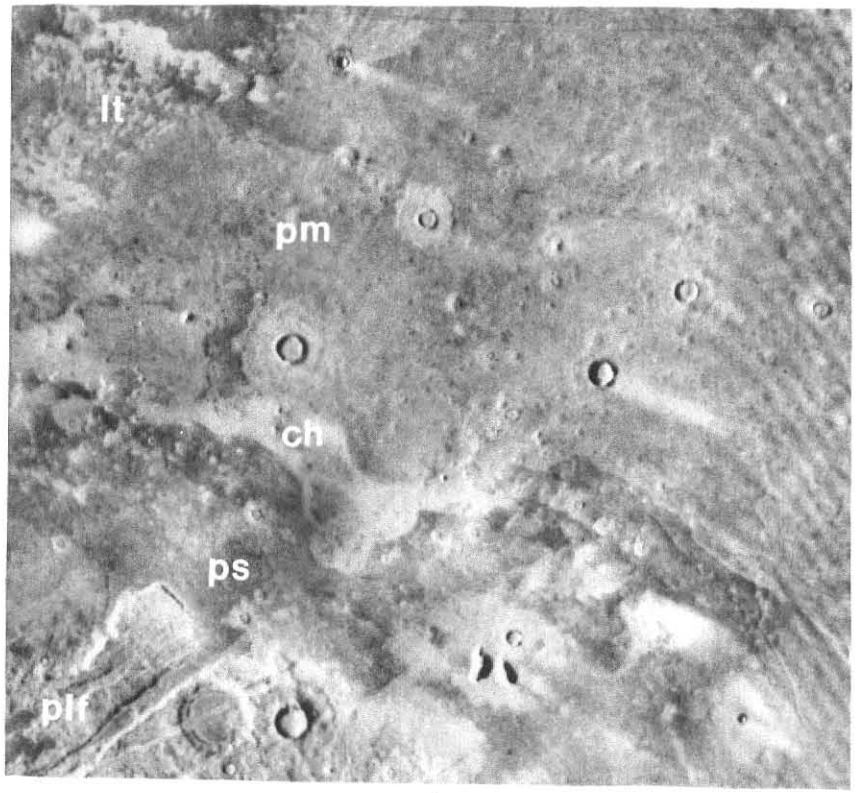
a.



10 km

N

b.



10 km

N

Appendix I. This unit is interpreted as eolian material and alluvial material from drainage of the highland block.

Channel Material.--High-albedo channel material occupies an elongate, sinuous depression along the smooth plains - mottled plains boundary north of Tempe Plateau (Fig. 37b). The channel ranges in width from 10-25 km and extends approximately 200 km. A very narrow trough can be traced another 100 km before it pinches out. This region was mapped in detail and is included as Appendix I. The unit is interpreted as alluvium filling an old stream channel (Scott and Tanaka, 1980).

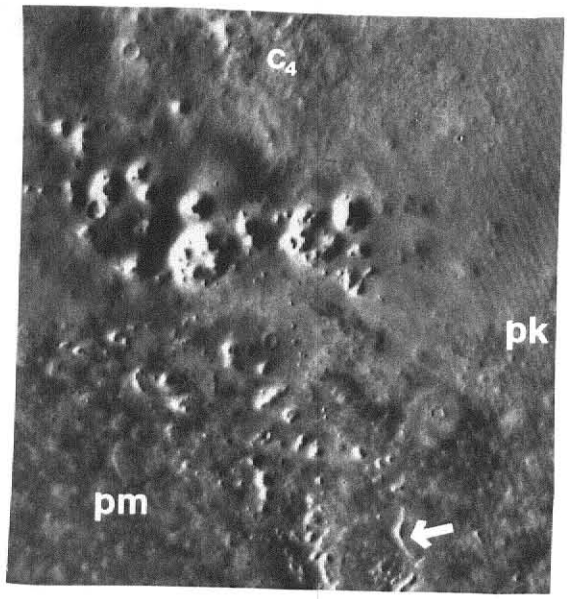
Knobby Terrain Material.--Knobby terrain material occurs throughout the lowland plains but is particularly common in close proximity to the cratered plateau in the southeast region and the dissected and fractured plateau material in the central region. The terrain consists of irregular hills of knobs that rise above the level of the plains. These knobs vary in size; the largest are 15 km across and are approximately 3000 m high (Fig. 38a). Most of the knobs are much smaller.

The origin of the knobs is varied and depends on the location. Knobs and mesas that occur close to the highlands probably are erosional remnants of the plateau material left by scarp retreat. Many of the knobs in this region appear to have basal debris accumulations (Fig. 38b). Squyres (1978) suggested that these debris flows may be similar to terrestrial rock glaciers.

Numerous patches of knobs occur on the smooth plains. In several areas, the knobs form a circular outline (Fig. 31a). These knobs are

Figure 38. Knobby terrain material. (a) Largest knobs in the quadrangle occur near Kunowsky crater, a large c_4 crater on the boundary between the knobby plains (pk) and the mottled plains (pm); these knobs are as much as 15 km across and more than 3000 m high; smaller knobs lie south of the large knobs; this image overlaps with the image in Figure 30b; a sinuous ridge is indicated by the arrow; pattern at the right side of the image is an artifact of the imaging system; Viking frame 673B06 (54.7°N, 9.2°W). (b) Knobby terrain near the plateau-plains boundary in the Cydonia region; many of the knobs appear to have basal debris accumulations; the arrow marks apparent flow lobe; Squyres (1978) interpreted the striations on the flow as the result of compression and contraction from movement; the knob with a summit crater (C) may be a cinder cone; stratification of the knobs is obvious in a few places; subdued pattern of troughs occurs on the plains; Viking frame 70A09 (40.4°N, 11.0°W); this area was mapped in greater detail and is included as Appendix III.

a.



10 km

N

b.



10 km

N

believed to represent more resistant remnants of an underlying heavily cratered terrain.

A few of these knobs in the Cydonia region have summit craters (Fig. 38b). West (1974) and Frey et al. (1979) interpreted these features as cinder cones.

GEOLOGIC HISTORY

Before concluding with an interpretation of the geologic history of the quadrangle, it is important to mention a point that was brought up by Milton (1976) and re-emphasized by Guest et al. (1977). Milton indicated that it is often difficult to distinguish between the age of an erosional surface and the rock units exposed on that surface. From mapping in the Cydonia region, Guest et al. (1977 p. 4119) concluded: "The northern 'plains' are composed of an intricate mixture of young rock units, young surfaces cut in old rocks that have been modified by surface processes such as wind, permafrost, etc., and old exhumed rock surfaces probably equivalent in age to units exposed in the southern cratered highlands of Mars."

Early Cratering

The process that dominated throughout the early history of the Mare Acidalium quadrangle was undoubtedly impact cratering. The oldest surfaces exposed in the quadrangle, as indicated by crater density, are the cratered plateau to the southeast and the slightly younger rugged plateau to the southwest. Both units have many large (up to 120 km) degraded craters of c_1 and c_2 age. Many of the old craters, however, were subsequently buried or partly buried by volcanic or eolian material or both. This resurfacing took place before the craters of c_3 age were formed inasmuch as c_3 craters are superimposed on the surface and show little evidence of modification.

Outgassing

Soderblom and Wenner (1978) suggested that during planetary outgassing water was injected into the upper few kilometers of the crust by subsurface igneous activity, surface volcanic eruptions, and lateral migration of liquid and vapor. Many geomorphic features that occur on these older plateau surfaces such as the small channels, irregular depressions, and floor-fractured craters, suggest that the materials that make up these two surfaces were rich in volatile substances.

Early Volcanism

Sometime after the rugged plateau surface was formed, the lavas and eolian materials that formed the fractured plateau and the ridged plateau were emplaced. The faults of the fractured plateau are a part of the Tempe Fossae system that extends to the southwest. This fault system is relatively old because it predates the emplacement of the smooth plains material. Other faults to the south that are oriented in a more east-west direction cut both plateau and plains materials, and, therfore, are considerably younger. Wise (1979), based on mapping of the adjacent MC-3 quadrangle stated: "The cause for localization of the older fault system of Tempe Fossae is unknown, although the alignment of three younger giant volcanoes of Tharsis southwestward along this line suggests that the fault system may reflect an extensive zone of deep curstal weakness."

Scarp Formation

The formation of the boundary between the intensely cratered southern hemisphere and the lightly cratered northern lowlands must have occurred sometime after the emplacement of the youngest plateau material. This boundary may be the result of collapse and erosion of an ice-rich layer in the northern region (Soderblom and Wenner, 1978), the result of more global processes such as differentiation that produced a crust of varied thickness (Mutch et al., 1976; Carr, 1980a), or sub-crustal erosion and subsidence of the northern region (Wise et al., 1979). The large depression of Acidalia Planitia was suggested to be the result of crustal subsidence caused by uplifting and volcanism of the Tharsis region to the southwest (Carr, 1974; Phillips and Saunders, 1975).

Scarp Retreat and Formation of Plains Units

The knobby terrain materials that occur in large patches near the southeast plateau-plains boundary have been interpreted as erosional remnants of the higher plateau material that were left by erosion and scarp retreat. Dissected and fractured plateau materials and associated knobby terrain exist 800 kilometers northwest of the southwest cratered plateau and 1000 kilometers east of the southwest plateau province. These materials may also be erosional remnants of the plateau suggesting that the highlands material, at one time, extended over much of the plains region. This supports the mechanism of deterioration of an ice-rich layer and concomitant scarp retreat proposed by Soderblom and Wenner (1978) for the formation of the plateau-plains boundary. Much of the material that

forms some of the plains units may have been derived from the breakdown of the plateau.

The age relationships between the plains material are difficult to determine for several reasons. Boundary escarpments or embayment relationships are rare. The boundaries between the units are commonly gradational, reflecting only albedo or textural variations, or both.

Crater size-frequency distributions for all the plains units tend to follow the same general trend suggesting that most of the plains surfaces were exposed or emplaced during the same general time interval. Alternatively, the crater statistics may not represent accurate age relationships because of the complexity of the depositional and erosional events that have occurred. Almost all of the craters that occur on the plains are c_3 or younger.

Although the mottled plains occur some 1,000 km north of the highlands, Scott (1979, p. 3052) proposed that the plains may be a part of this surface. He stated:"Possibly the mottled plains unit represents lower, more deeply eroded remnants of the highlands that have survived an ancient episode of crustal separation caused by drifting or downfaulting and followed by volcanism with flood basalts filling the intervening region and forming smoother plains between the segregated parts of the crust." It is apparent that the mottled plains - undivided and the hummocky mottled plains have been blanketed with a light-colored debris mantle that has been partially stripped away. Whether the underlying darker material is an old erosional surface or younger, volcanic material is uncertain. The knobby plains resemble these northern mottled plains units in that the

knobby plains are rocks of uncertain age that have subsequently been blanketed with a layer of light material.

The patterned mottled plains are more likely to represent younger plains material rather than old rock exposed by erosion. The low albedo and the presence of many small, cratered domes suggest that these may be vast volcanic plains that were subsequently fractured by tectonic, desiccation, or permafrost processes. The pattern, however, appears to be fairly old because few of the superimposed impact craters were affected by the fracturing.

The subdued patterned mottled plains represent a more recent period of volcanic activity that caused lava flows to bury partially some of the troughs of the patterned mottled plains. These flows embayed and partially buried parts of the dissected and fractured plateau material that occurs in this central region.

The fractured plains are another example of the problem of material age vs. surface age. Guest et al. (1977) suggested that the fractured plains material is an old unit stratigraphically underlying the plateau material. The fractured plains surface was exposed by erosion and scarp retreat, with the fractures forming after the surface was exposed. The present investigation suggests that part of the fractured plains surface may consist of younger volcanic or eolian material. Boundary escarpments, where the fractured plains form the lower surface, indicate that the fractured plains are old in relation to some of the adjacent units.

The pattern of troughs on the smooth plains adjacent to the patterned

mottled plains and in close proximity to the fractured plains suggest that some of the smooth plains material was emplaced at approximately the same time as the patterned mottled plains. Part of the material that makes up the smooth plains may have been derived from the breakdown of the plateau. The presence of relics of large circular structures suggest that the smooth plains material in the central region buried a lower, more heavily cratered surface.

To the southwest, large-scale flooding and erosion associated with Kasei Vallis and other large outflow channels to the south were occuring either during or shortly after the emplacement of the majority of the plains material. This flooding may have contributed a large quantity of alluvial material to the smooth plains. Fluvial erosion created streamlined landforms, scours, and channels, and exposed layers of lower plateau material along the plateau-plains escarpment.

Tectonism

Tectonic stresses, probably the result of the Tharsis-related stress system, created north-south trending mare-type ridges that occur on both the plateau and the smooth plains in the southwestern region. Later, more tectonic activity resulted in east-west trending fractures that occur on both the plateau and the plains, as these fractures also extend across the mare-type ridges.

Farther north, the plateau-plains escarpment, streamlined landforms, erosional remnants, and tectonic features do not occur. Smooth plains material covers a narrow region between northeast Tempe Plateau and the

mottled plains. Circular outlines on the smooth plains together with the embayment of grabens on the plateau by smooth plains materials, suggest that the smooth plains material buried the older plateau material in this region. Perhaps the smooth plains material was deposited in a gentle depression that existed along the plateau - mottled plains boundary. Also occurring in this region are sinuous channels and fan-shaped deposits of light material. These features are believed to be the result of subsequent small-scale drainage and deposition of material from the highland block.

In the Cydonia region, the smooth plains differ from those to the west. A high density of small cratered domes and the gradational boundary with the subdued fractured plains, which are believed to be lava flows that partially fill the troughs, suggest that the smooth plains in this region may consist of volcanic material.

The origin of the variegated plains to the east is probably similar to that of the smooth plains, i.e., some of the material that constitutes these plains may be volcanic, whereas the variegated plains along the plateau-plains boundary may be partly alluvial and colluvial material deposited from drainage of the highland block. The emplacement of the variegated plains is believed to postdate the creation of the fractured plains because of the escarpment boundary; however, the age-relationship between the variegated plains and the patterned mottled plains to the north is uncertain.

Late Volcanism

Many of the volcanic features, i.e., lava flows, pressure ridges, and domes, that are scattered throughout the plains region appear to have formed recently because they show little subsequent modification. The proposed tablemountains and moberg ridges are associated with these young volcanic features and require the presence of an ice-rich unit to form. Clifford (1980) and Hodges and Moore (1979) proposed that a primitive ice sheet may have, at one time, covered a significant portion of the planet's surface. The ice sheet subsequently retreated in response to climatic changes, and the water from this ice sheet is presently stored in the groundwater system and in the polar caps. If this hypothesis is correct, then many of the unusual surface textures and features that occur on the lowland plains could be explained by the breakdown and removal of this ice-rich layer.

Recent Processes

Currently eolian erosion and deposition and mass wasting are the dominant processes within this region. Although many other processes are active, they do not play the determining role they once did. The margins of the plateaus and the knobby terrain are areas where permafrost decay and mass movement processes are creating collapse pits and debris flows. Freezing and thawing of the surface continue to produce small-scale permafrost features such as pingos and ice-wedge polygons. Tectonism and volcanism may also be active geologic processes.

SUMMARY AND CONCLUSIONS

High-resolution Viking orbiter images show the geology of the Mare Acidalium quadrangle to be much more complex than previously had been suspected from the lower-resolution Mariner 9 images. Two major terrain types exist within the quadrangle; the higher, heavily-cratered plateau province, and the lower, lightly-cratered plains province. Both provinces can be subdivided into a number of material units. The plateau province consists of six units: (1) cratered plateau material, (2) dissected and fractured plateau material, (3) rugged plateau material, (4) ridged plateau material, (5) fractured plateau material, and (6) lower plateau material. The plains province consists of nine units: (1) mottled plains material - undivided, (2) hummocky mottled plains material, (3) patterned mottled plains material, (4) subdued patterned mottled plains material, (5) knobby plains material, (6) fractured plains material, (7) variegated plains material, (8) smooth plains material, and (9) patterned smooth plains material.

The oldest surfaces in the quadrangle occur in the southeast and southwest plateau regions. These surfaces record an early period when large impacts were extremely common. Subsequently, these regions were partially or completely buried by younger materials. To the west, the Tempe Plateau region was disrupted by faulting, possibly related to an early stage of Tharsis tectonism.

The central part of the quadrangle may have subsided in response to uplift of the Tharsis region to the southwest. Plateau material that once

covered a large portion of the quadrangle began to break down and erode, leaving only erosional remnants of the higher surface scattered throughout the lowland region.

Volcanic, eolian, and alluvial sediments resurfaced a large portion of the lower plains. Processes such as wind, permafrost, mass movement, and tectonism created unusual and varied surface textures. Episodic floods of water from the large outflow channels to the south and west modified the surface in the southwest region, creating streamlined landforms and exposing the lower units of the plateau. Also, in this southwest region, tectonic activity associated with Tharsis-related stresses created mare-type ridges and east-west trending fractures. At the present time, wind erosion and deposition are the major processes active at the surface, although other processes such as tectonism, volcanism, mass movement, and periglacial activity may still play a role in molding the martian surface.

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Finally, I would like to thank Joseph M. Boyce at NASA Headquarters for originally informing me of this project and his continued encouragement throughout the project.

APPENDIX

Three areas were mapped using high resolution photomosaics, and these maps are included as Appendices I - III. These areas are: (1) the Tempe Plateau region (centered at 52°N, 58°W); (2) the Central Plateau region (centered at 46°N, 26°W); and (3) the Cydonia region (centered at 40°N, 7°W). See Figure 7 for locations of high-resolution maps. Caution must be used when comparing the photomosaics with maps because the maps are larger scale to enable more detail to be shown. Appendix IV contains descriptions of all the units on the 1:5,000,000-scale quadrangle map that is in the back pocket. For reference purposes, representative Viking frame numbers are included in all map unit descriptions. Some of these images are included in the text and are so indicated. For reasons of space and cost, not all of the representative images could be included.

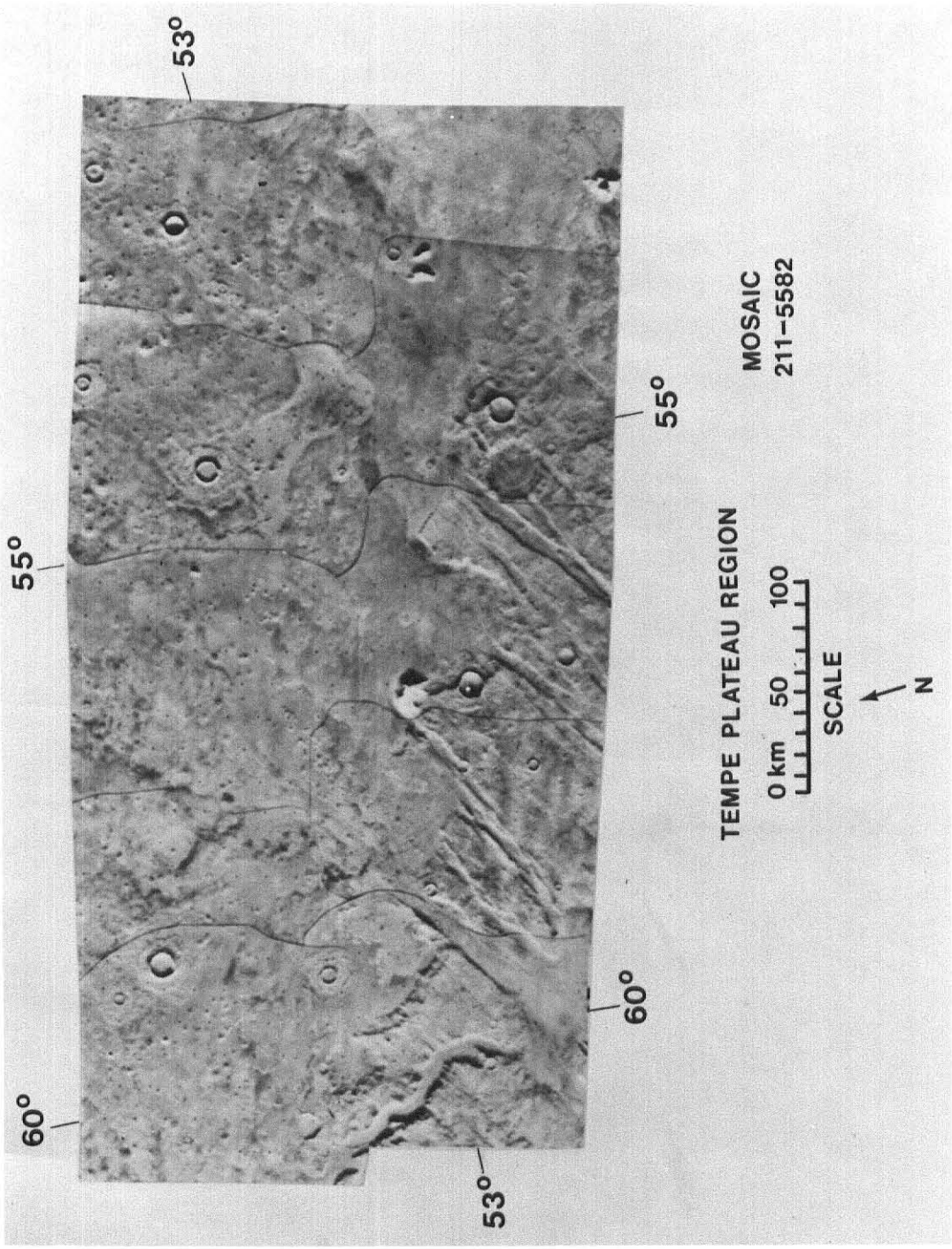


Figure 39. Photomosaic of the Tempe Plateau region.

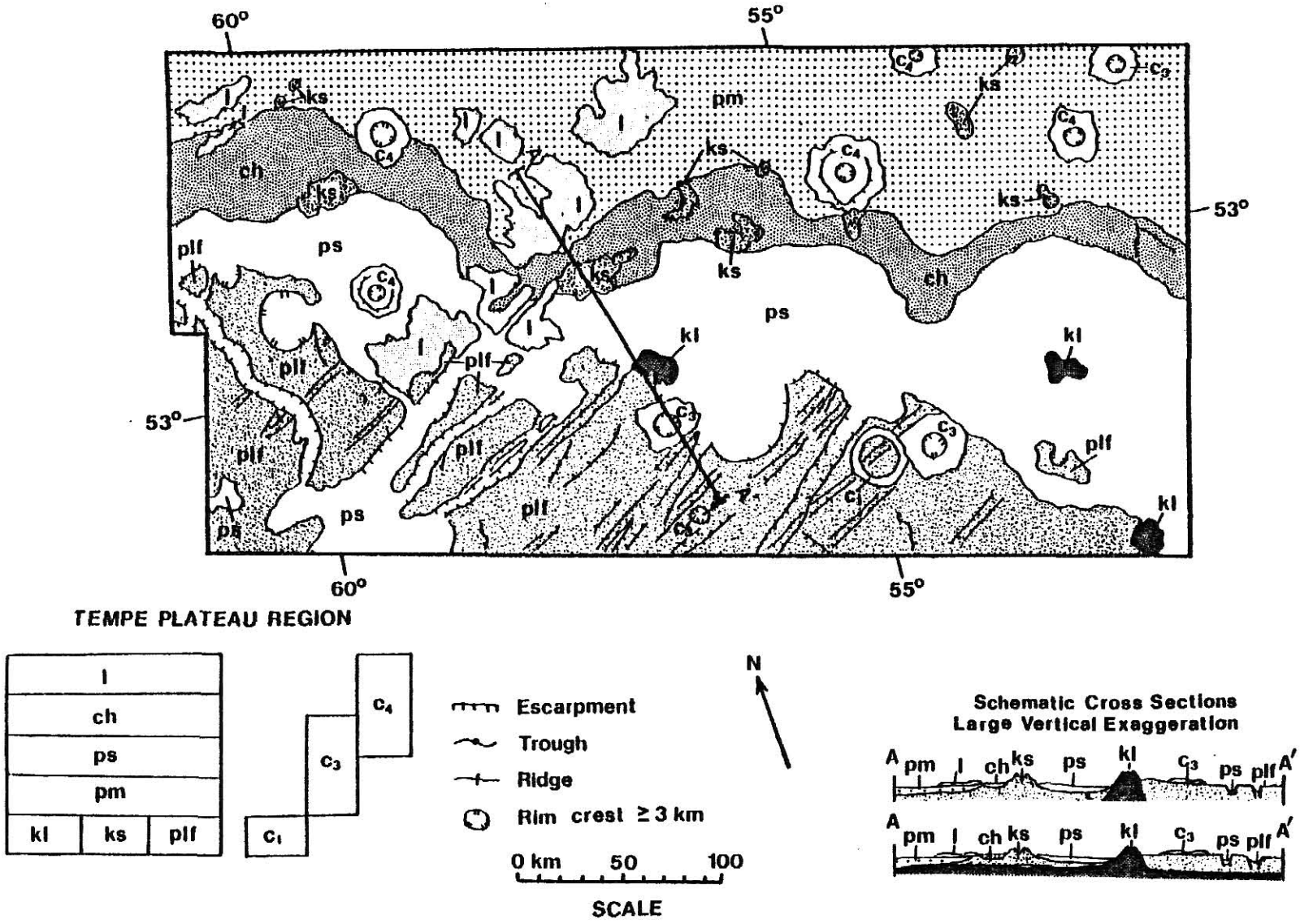


Figure 40. Geologic map of the Tempe Plateau region.

APPENDIX I - TEMPE PLATEAU REGION

plf FRACTURED PLATEAU MATERIAL - Occurs in southern half of region; intermediate albedo; moderate crater density; forms high surface cut by numerous faults trending northeast-southwest; northwest-southeast trending sinuous depression cuts fractured plateau material at 53°N, 60°W (Fig. 17); boundary with lower smooth plains materials marked by escarpment; smooth plains materials embay grabens cut into fractured plateau material; representative image 61B56.

INTERPRETATION: Volcanic and eolian material covering ancient crustal deposits; subsequently disrupted by Tempe Plateau faulting; faults cut older (c_1) impact craters.

kl LARGE KNOBBY MATERIAL - Occurs in three locations close to, or at, the boundary between fractured plateau and smooth plains; forms small, elongate and equidimensional, steep-sided mountains (largest ≅ 10 km across) that rise above both plains and plateau material; representative image 61B56.

INTERPRETATION: Volcanic material; alternatively may represent resistant volcanic, or other, material underlying fractured plateau *and smooth plains material.*

ks SMALL KNOBBY MATERIAL - Occurs in small patches on plains north of fractured plateau; forms small (< 1 km across), rounded hills or knobs that stand above surrounding plains materials;

representative image 61B55.

INTERPRETATION: Erosional remnants of higher surface material.

pm MOTTLED PLAINS MATERIAL - Occurs in northern part of area; low albedo; moderate crater density; relatively smooth plains with variegated-albedo pattern; ejecta blankets surrounding craters are generally higher albedo than surrounding plains; pedestal craters common; older c_3 craters partially filled with material; boundary with channel material marked by abrupt change to higher albedo; representative image 61B57.

INTERPRETATION: Volcanic and eolian plains; some small hills with summit craters may be volcanic; craters filled with eolian material suggest earlier existence of widespread eolian mantle, now largely deflated.

ps SMOOTH PLAINS MATERIAL - Occurs between fractured plateau and channel material; low albedo; low crater density; forms smooth plains; smaller craters (< 1 km diameter) partially filled with debris; small hills with summit craters at limit of resolution; escarpment commonly marks boundary with higher fractured plateau material; albedo change marks boundary with high-albedo channel material; representative image 61B52.

INTERPRETATION: Alluvial, eolian, and volcanic deposits; small hills with summit craters may be volcanic (Scott, 1978); plains materials fill sinuous channel cut into plateau and deeply embay

grabens in fractured plateau; eolian material partially buries small impact craters.

ch CHANNEL MATERIAL - Occurs between mottled and smooth plains (Fig. 37b); high albedo; low crater density; fills elongate, sinuous, gentle depression ranging in width from 10 - 25 km; representative image 61B57.

INTERPRETATION: Stream channel containing alluvium (Scott and Tanaka, 1980).

lt LIGHT MATERIAL - Occurs in patches close to fractured plateau in western region; high albedo; very low crater density; light-colored material appears to overlie plains materials; fan-shaped deposit at 53.2°N, 58.8°W; representative image 61B52 (Fig. 17)

INTERPRETATION: Outwash of flood-plain deposits, the result of drainage of higher plateau surface.

Crater Material

All craters mapped believed to have been produced by impact; subdivisions based on morphologic characteristics believed to reflect relative age.

c_4 YOUNG CRATER MATERIAL - Sharp, complete rim crests; steep walls; deep, rough floors; bowl shape; extensive ejecta deposits; representative image 61B59.

INTERPRETATION: Relatively recent impact-crater material.

c_3 MODERATELY YOUNG CRATER MATERIAL - Rim crest high, complete; walls relatively steep; floor may be rough and lower than adjacent terrain; ejecta deposits less extensive than c_4 craters; representative image 61B56.

INTERPRETATION: Moderately young but slightly degraded impact-crater material.

c_1 OLD CRATER MATERIAL - Rim crest low, incomplete or nearly absent; shallow flat floors generally filled with younger material; commonly forms rugged and partially buried ring; little or no ejecta deposits; representative image 61B58.

INTERPRETATION: Oldest, degraded impact-crater material.

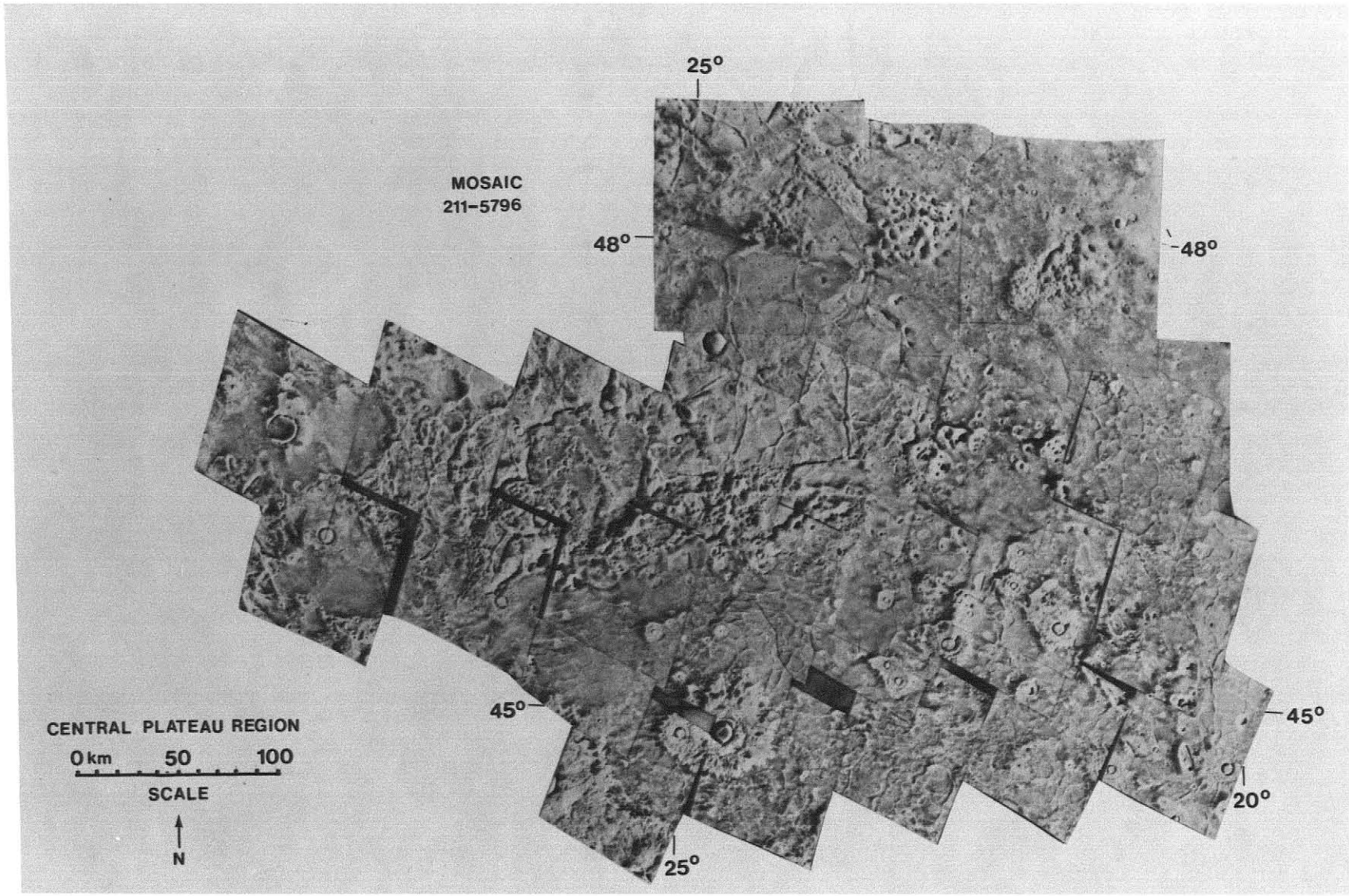


Figure 41. Photomosaic of the Central Plateau region.

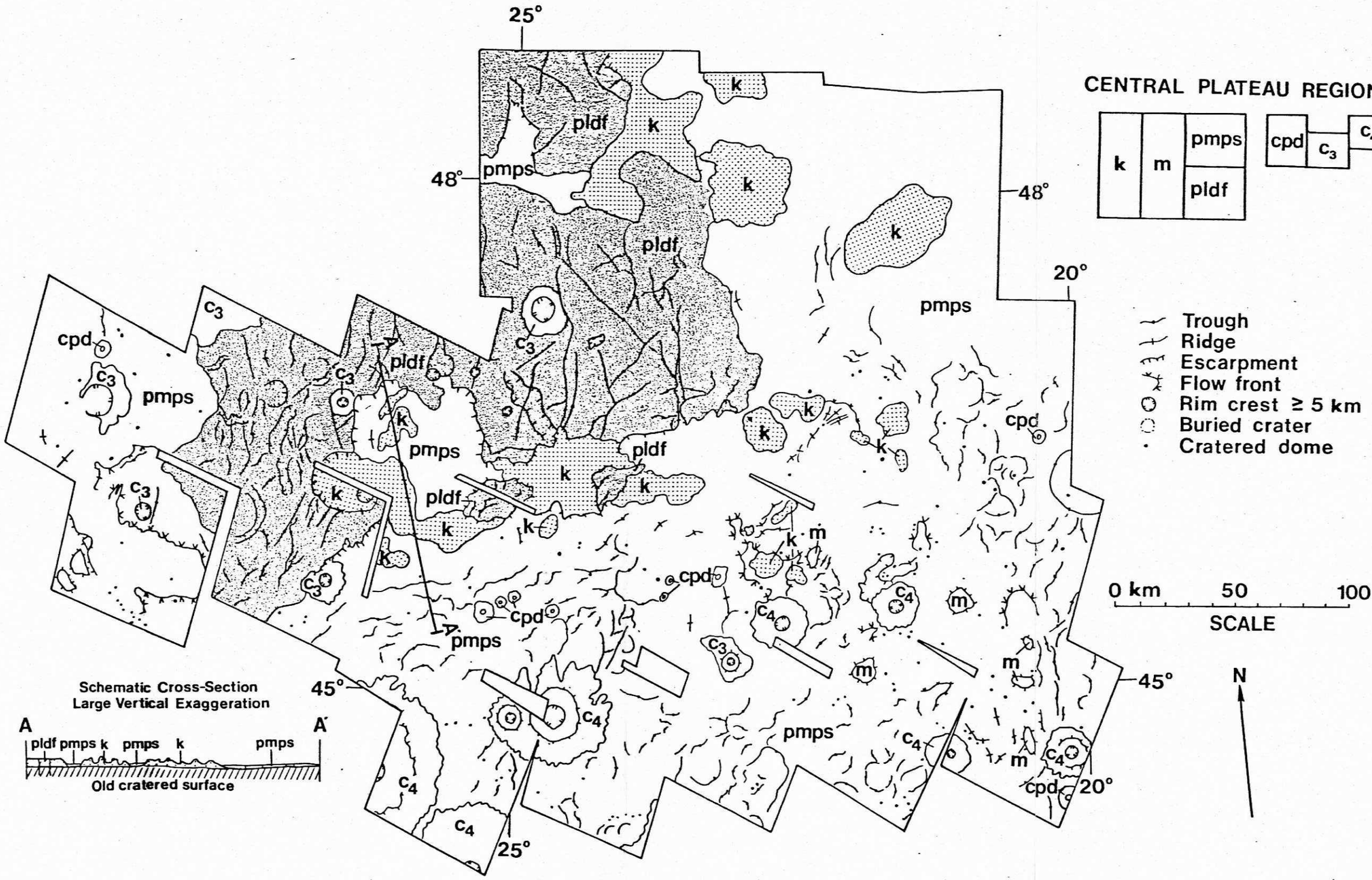


Figure 42. Geologic map of the Central Plateau region.

APPENDIX II - CENTRAL PLATEAU REGION

pldf DISSECTED AND FRACTURED PLATEAU MATERIAL - Forms high surface between 46° - 49°N and 22° - 28°W; intermediate to high albedo; low crater density; relatively smooth surface cut by many fractures that generally trend N - S; fracture width ranges from few hundred meters to more than 2 km; very few impact craters; escarpment characteristically marks the boundary of the plateau material with surrounding plains materials; representative image 35A35. INTERPRETATION: Remnants of higher unit that may have, at one time, covered region; circular depressions mark locations of large degraded craters; resurfaced by eolian and volcanic material; subsequently disrupted by faulting.

k KNOBBY MATERIAL - Occurs adjacent to fractured and dissected plateau and in scattered patches on plains; low crater density; knobs are small, irregularly shaped hills (average 2 km across) similar in height to that of plateau; knobs occur individually and in clusters and stand above plains material; some conical hills have summit craters; representative image 35A41 (Fig. 26b). INTERPRETATION: Erosional remnants of plateau material; locally may be small volcanoes.

pmps SUBDUED PATTERNED MOTTLED PLAINS MATERIAL - Surrounds dissected and fractured plateau and occupies circular depression bounded

by plateau and knobby material; very low albedo; moderate crater density; relatively smooth, dark plains cut by many discontinuous arcuate troughs generally < 1 km wide; pedestal craters common; high albedo flow-ejecta craters superimposed on plains; small (< 1 km wide) domes with summit craters common; representative image 26A27.

INTERPRETATION: Volcanic flow rock; possible flow fronts and pressure ridges occur in several areas (Figs. 26a, b); domes may be cinder cones; low dark hills with summit craters may be small shield volcanoes; volcanic material fills or partially fills pre-existing pattern of troughs.

m MESA MATERIAL - Forms isolated plateaus in region of subdued patterned mottled plains materials; low albedo; low, steep-sided, flat-topped mesas generally < 8 km across and several-hundred-meters high; several mesas have small knob or ridge on top; representative image 26A28 (Fig. 27b).

INTERPRETATION: Tablemountains resulting from subglacial volcanic eruptions; may have small cinder cones on top; alternatively may be erosional remnants of dissected and fractured plateau material.

Crater Material

All craters mapped believed to have been produced by impact; subdivisions based on morphologic characteristics believed to reflect relative age.

c_4 YOUNG CRATER MATERIAL - Sharp, complete rim crests; steep walls; deep rough floors; bowl shape; extensive ejecta deposits; representative image 26A24.

INTERPRETATION: Relatively recent impact-crater material.

c_3 MODERATELY YOUNG CRATER MATERIAL - Rim crest high, complete; walls relatively steep; floors may be rough and lower than adjacent terrain; ejecta deposits less extensive than c_4 craters; representative image 26A26.

INTERPRETATION: Moderately young but slightly degraded impact-crater material.

cpd PEDESTAL CRATER MATERIAL - Small (< 5 km diameter) bowl-shaped crater; ejecta extends outward 2 - 3 crater diameters; ejecta forms platform that stands above surrounding terrain; representative image 35A36.

INTERPRETATION: Impact-crater material with associated viscous ejecta flow; flow too viscous to form lobes (Mutch and Woronow, 1980).

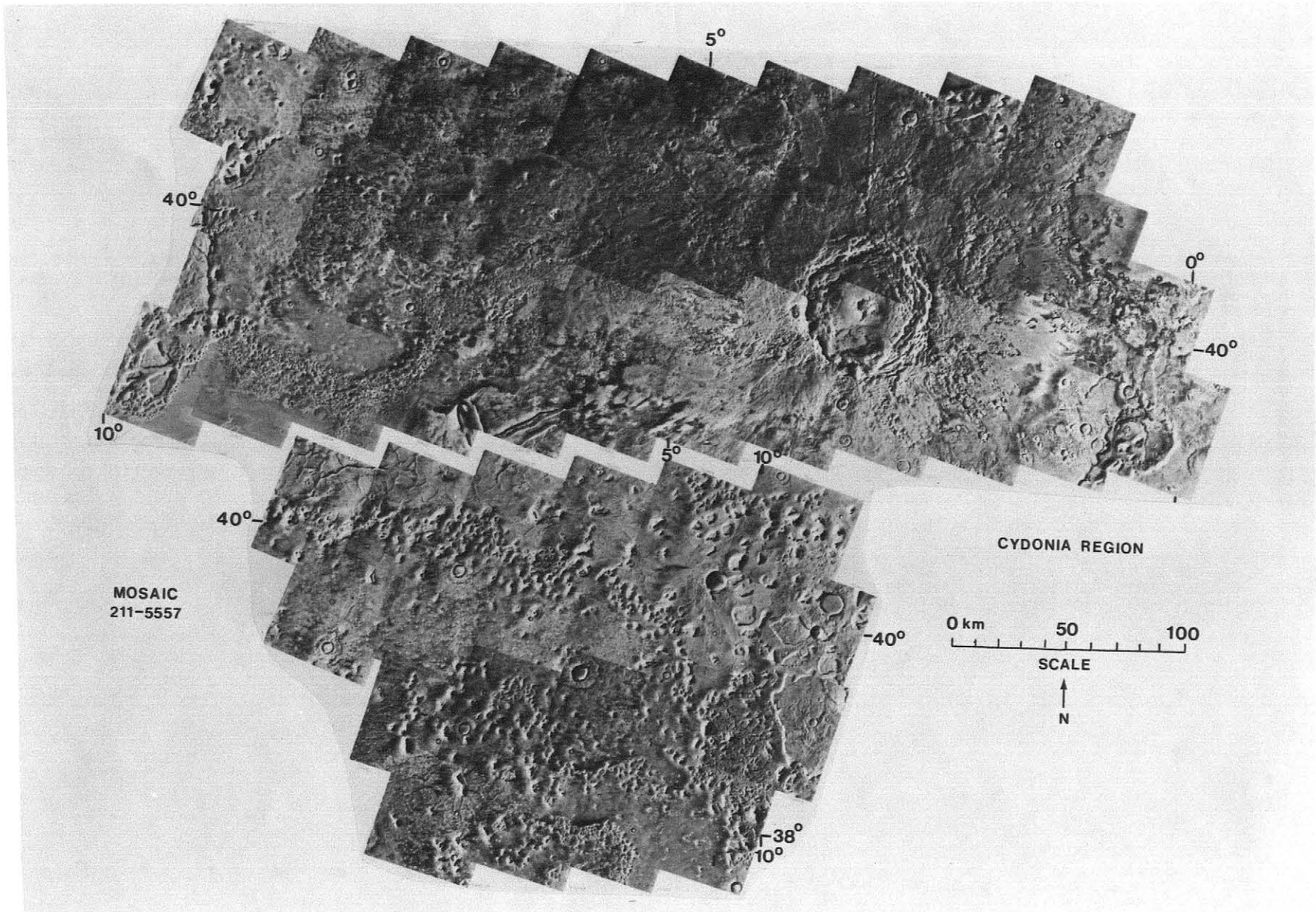


Figure 43. Photomosaic of the Cydonia region.

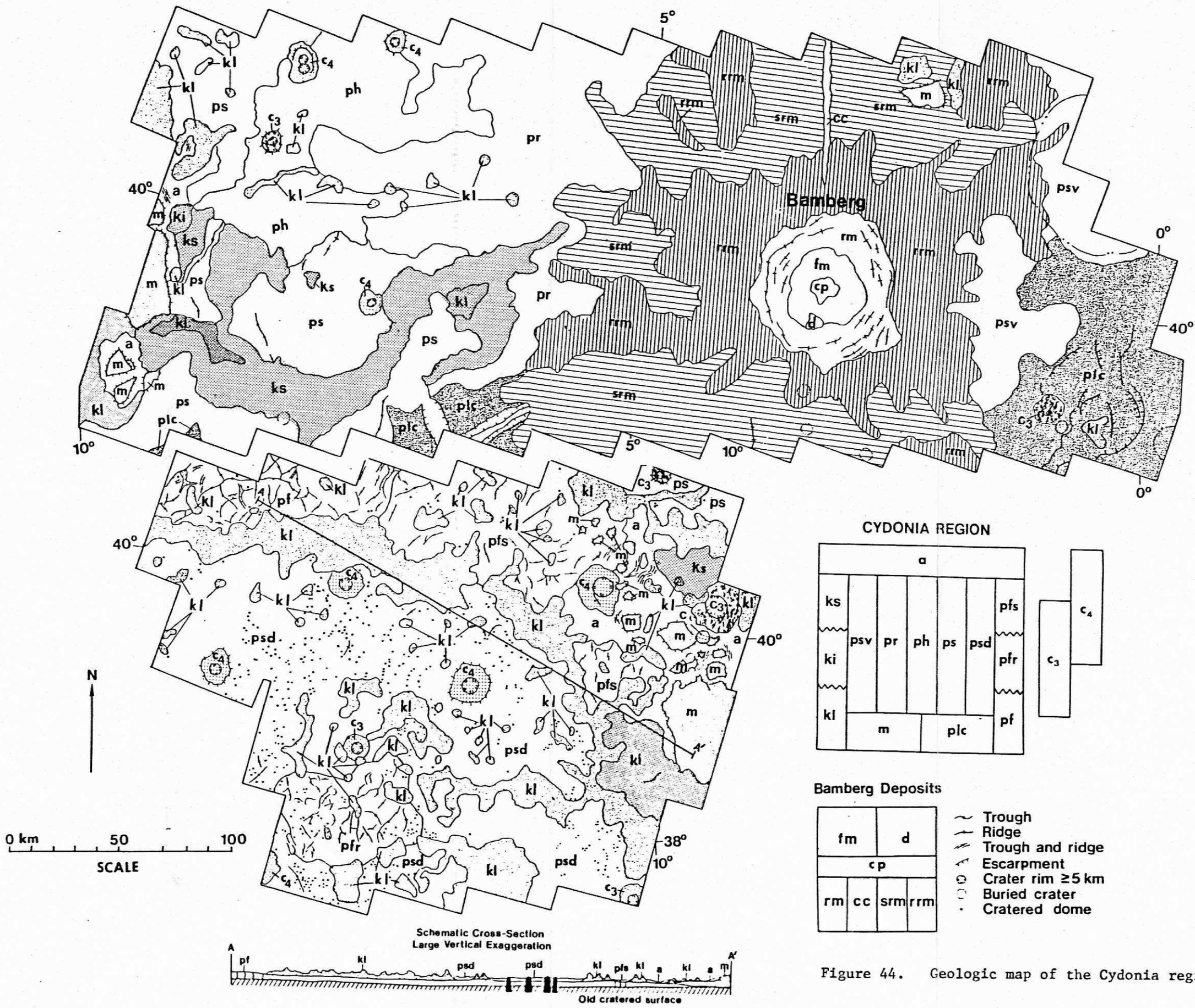


Figure 44. Geologic map of the Cydonia region.

APPENDIX III - CYDONIA REGION

plc CRATERED PLATEAU MATERIAL - Occurs east of Bamberg crater at eastern edge of mosaic area; intermediate to high albedo; high crater density; characterized by many large degraded impact craters with flat floors; intercrater area relatively smooth with varied albedo; many small (< 1 km diameter) craters and crater clusters; boundary with variegated smooth plains expressed by rapid increase in density of craters and in places, a gentle escarpment; representative image 72A30.

INTERPRETATION: Ancient crustal deposits partially resurfaced by volcanic and eolian depostis; removal of volatile substances trapped in mantle deposits may have caused collapse depressions and debris flows; many small craters and crater clusters may be secondary craters from Bamberg.

m MESA MATERIAL - One large mesa and several smaller mesas lie near 39.5°N, 10°W; intermediate albedo; low crater density; size of mesas range from 10 km^2 to 1400 km^2 and mesas may be several-hundred-meters high; rough texture superimposed on larger mesas; irregular pits occur on mesa centered at 39.85°N, 9.8°W; representative image 72A09.

INTERPRETATION: Outliers and erosional remnants of cratered plateau material that occur approximately 150 km south; breakdown of lenses of layers of ice produced irregular collapse pits.

kl LARGE-KNOB MATERIAL - Occurs mainly to west between 10° - 15°N and 39° - 42°N; irregular knobs and ridges generally 1 - 2 km across; heights of knobs similar to heights of mesas; spacing between knobs ranges from 0.5 - 4 km; low crater density; conical knobs with summit craters occur (Fig. 38b); some knobs appear layered or resting on top of lower mesa; small domes (< 1 km wide) with summit craters occur throughout knobby region; inter-knob area smooth, low albedo; discontinuous, low escarpment forms boundary of knobby terrain with fractured plains material to north; smooth plains material surrounds knobs; representative image 70A05.

INTERPRETATION: Small volcanoes or erosional remnants of cratered plateau material, or both; embayed by smooth plains material.

ki INTERMEDIATE-KNOB MATERIAL - Occurs along west side of large mesa at approximately 39°N, 10°W; forms low irregular hills and knobs; width of knobs ranges from 0.5 - 1.5 km; heights of knobs generally < 500 m, and lower than surrounding large-knobs; inter-knob spacing ranges from 0.2 - 1.5 km; low crater density; representative image 72A09.

INTERPRETATION: Erosional remnants of cratered plateau-material; intermediate size and apparently lower height represent erosion to a lower unit or layer of cratered plateau material.

ks SMALL-KNOB MATERIAL - Occurs primarily in arc east of mesa material at 38.5°N, 8.5°W; forms low, small hills and knobs

ranging from 0.1 - 0.8 km across; spacing between knobs very close, generally < 0.1 km; circular pattern of knobs occurs at boundary with smooth plains material; low crater density; representative image 72A14.

INTERPRETATION: Erosional remnants or debris from breakdown of overlying cratered plateau material; locally may represent more resistant remnants of crater rims.

pf FRACTURED PLAINS MATERIAL - Occurs north of large-knob material to west; moderately-high albedo; low crater density; characterized by crudely polygonal pattern of troughs cutting smooth plains; troughs range in width from 0.2 - 1.5 km and are 5 - 10 km apart; depth ranges from 30 ± 10 m to 100 ± 10 m (Pechmann, 1980); wider troughs commonly have flat floors; in some areas, boundary of large-knob material with lower fractured plains material characterized by escarpment (40°N, 12.6°W); escarpment not present in other areas (40°N, 13°W); fractures terminate abruptly at contact with low-albedo inter-knob plains material; representative image 70A03.

INTERPRETATION: Fractured material may be old unit stratigraphically underlying cratered plateau and mesa material (Guest et al., 1977); overlying units subsequently stripped away; alternatively, may be younger plains material; fractures may have occurred after erosional stripping or after deposition and may be result of permafrost activity (Carr and Schaber, 1977), desiccation (Morris and Underwood, 1978), or tectonism (Pechmann, 1980).

pfr RADIALLY FRACTURED PLAINS MATERIAL - Occurs only in southwest, centered at 38°N, 13°W; low albedo; low crater density; fractures range in width from 0.2 - 0.8 km and extend radially outward approximately 25 km from 2 x 6 km ridge; two fracture traces aligned from one side of ridge to the other; numerous small (< 1 km) domes with circular summit depressions occur on radially fractured plains; fractures do not cut knobby material; gradational boundary with surrounding smooth plains; representative image 72A02.

INTERPRETATION: Ridge may be moberg ridge (Allen, 1980) or erosional remnant of plateau material; domes probably volcanic (Allen, 1980; Frey et al., 1979; Wood, 1979); fractures may be tectonic and may have influenced location of intrusions of igneous material.

pfs SUBDUED FRACTURED PLAINS MATERIAL - Occurs north of, and surrounding large knobs west of mesa material between 39.5°N - 41°N and 10° - 12°W; moderately-high albedo; very low crater density; fractures narrow, generally < 0.5 km wide and discontinuous; some small domes < 1 km wide with summit craters; gradational boundary with smooth plains and fractured plains; representative image 70A07 (Fig. 38b).

INTERPRETATION: Volcanic flow rock that fills or partially fills fractures; cratered domes may be small volcanoes.

psv VARIEGATED SMOOTH PLAINS MATERIAL: Occurs only at east margin adjacent to cratered plateau material; high and low albedo; low crater density; smooth, featureless surface; several small (≅ 5 km long) dark streamlined features oriented SE-NW occur close to boundary with cratered plateau material; boundary with cratered plateau marked by rapid decrease in crater density on smooth plains; in places boundary is expressed as gentle escarpment overlooking lower smooth plains; boundary with rough radial material of Bamberg crater is abrupt textural change; representative image 72A29.

INTERPRETATION: Sedimentary blanket and channel deposits originating from highlands to the south during plateau breakdown and scarp retreat.

pr ROUGH PLAINS MATERIAL - Occurs between 39° - 42° N and 5° - 8° W; low albedo; high density of small craters < 1 km diameter; surface appears rough at high resolution; gradational boundaries with adjacent hilly plains material and rough radial material; more distinct textural boundary with smooth radial material; representative image 70A21.

INTERPRETATION: Plains of unknown origin with many secondary craters from adjacent c_3 impact crater, Bamberg; presence of many secondary craters makes crater counts unreliable.

ph HILLY PLAINS MATERIAL: Occurs between 39° - 41.5°N and 7° - 9°W; low albedo; low crater density; characterized by high density (30 - 40/100 km^2) of small (< 500 wide) hills; many hills appear

to have summit craters although craters are at limit of resolution; boundary with smooth plains is distinct albedo and morphologic change; gradational with rough plains; representative image 70A15.
INTERPRETATION: Volcanic plains with small cinder cones (Wood, 1979) or pseudocraters (Frey et al., 1979; Lucchitta, 1981); alternatively, hilly plains may represent fields of pingos (Wood, 1979).

ps SMOOTH PLAINS MATERIAL - Occurs in several regions between 38° - 40°N and 7° - 11°W; intermediate albedo; very low crater density; smooth, featureless plains; most impact craters < 1 km diameter; 6 conical hills approximately 2 km diameter occur on smooth plains between 38.8° - 39.2°N and 8.5° - 9°W; some hills appear to have summit craters; in same area a 25 km-long, ≅ 500 m-wide, straight trough oriented NW-SE traverses smooth plains; another more sinuous trough of similar width oriented approximately parallel occurs 30 km west; trough originates from 2 km-wide conical hill with summit depression and meanders northward approximately 60 km through narrow region of smooth plains bounded on both sides by knobby terrain; boundary with knobby terrain in most places gradational; representative image 72A12.
INTERPRETATION: Volcanic and eolian plains; conical hills may be small volcanoes; troughs may be collapsed lava tunnels or tubes analogous to lunar sinuous rilles (Greeley and Spudis, 1981).

psd SMOOTH PLAINS MATERIAL WITH DOMES - Occur mainly west of mesa material between 38° - 40°N and 10° - 13°W; low albedo; moderate crater density; relatively smooth plains with many small

(< 1 km across) domes with summit craters; gradational boundary with subdued fractured plains and with radially fractured plains; dark smooth plains material and domes surround knobs; representative image 70A04.

INTERPRETATION: Volcanic and eolian deposits; small domes may be cinder cones, pingos (Wood, 1979), or pseudocraters (Frey et al., 1979; Lucchitta, 1981).

a APRON MATERIAL - Surrounds knobs and occurs at base of mesa escarpments; intermediate albedo; very low crater density; valley fill between knobs and mesas commonly has ridges and troughs parallel to escarpment; distal margins of apron material lobate; representative image 70A11.

INTERPRETATION: Lobate debris flows from escarpment; ridges and troughs parallel to escarpment are compressional features from flows (Squyres, 1978); young age indicated by scarcity of impact craters.

Crater Material

All craters mapped believed to have been produced by impact; subdivisions based on morphologic characteristics believed to reflect relative age.

c_4 YOUNG CRATER MATERIAL - Sharp, complete rim crests; steep walls; deep rough floors; bowl shaped; extensive ejecta deposits; representative image 70A02.

INTERPRETATION: Relatively recent impact-crater material.

c_3 MODERATELY YOUNG CRATER MATERIAL - Rim crests high, complete; walls relatively steep; floors may be rough and lower than adjacent terrain; ejecta deposits less extensive than c_4 craters; representative image 70A12.

INTERPRETATION: Moderately young but slightly degraded impact-crater material.

Bamberg Deposits

cp CENTRAL PEAK MATERIAL - Peak centrally located in Bamberg crater; diameter approximately 10 km; summit pit diameter approximately 6 km; no stratification observed, representative image 72A25.

INTERPRETATION: Formed by elastic rebound following impact; central pit may be collapse pit created by release of trapped volatile material.

fm FLOOR MATERIAL - Smooth and relatively featureless; varied albedo; no impact craters; terminates at ridges of rim material; representative image 72A25.

INTERPRETATION: Eolian or slumped material fills interior of crater.

d DUNE MATERIAL: Series of dark parallel ridges; occurs near south margin of floor material; representative image 72A25.

INTERPRETATION: Small field of transverse dunes.

rm CRATER RIM MATERIAL - Consists of many ridges and hills; rim material may be as wide as 18 km with very low crater density; representative image 72A25.

INTERPRETATION: Rim formed during impact process.

cc CRATER CHAIN MATERIAL - Extends north of Bamberg crater for approximately 70 km; maximum width 3 km; consists of 40 small craters or depressions (Mouginis-Mark, 1979); representative image 70A27.

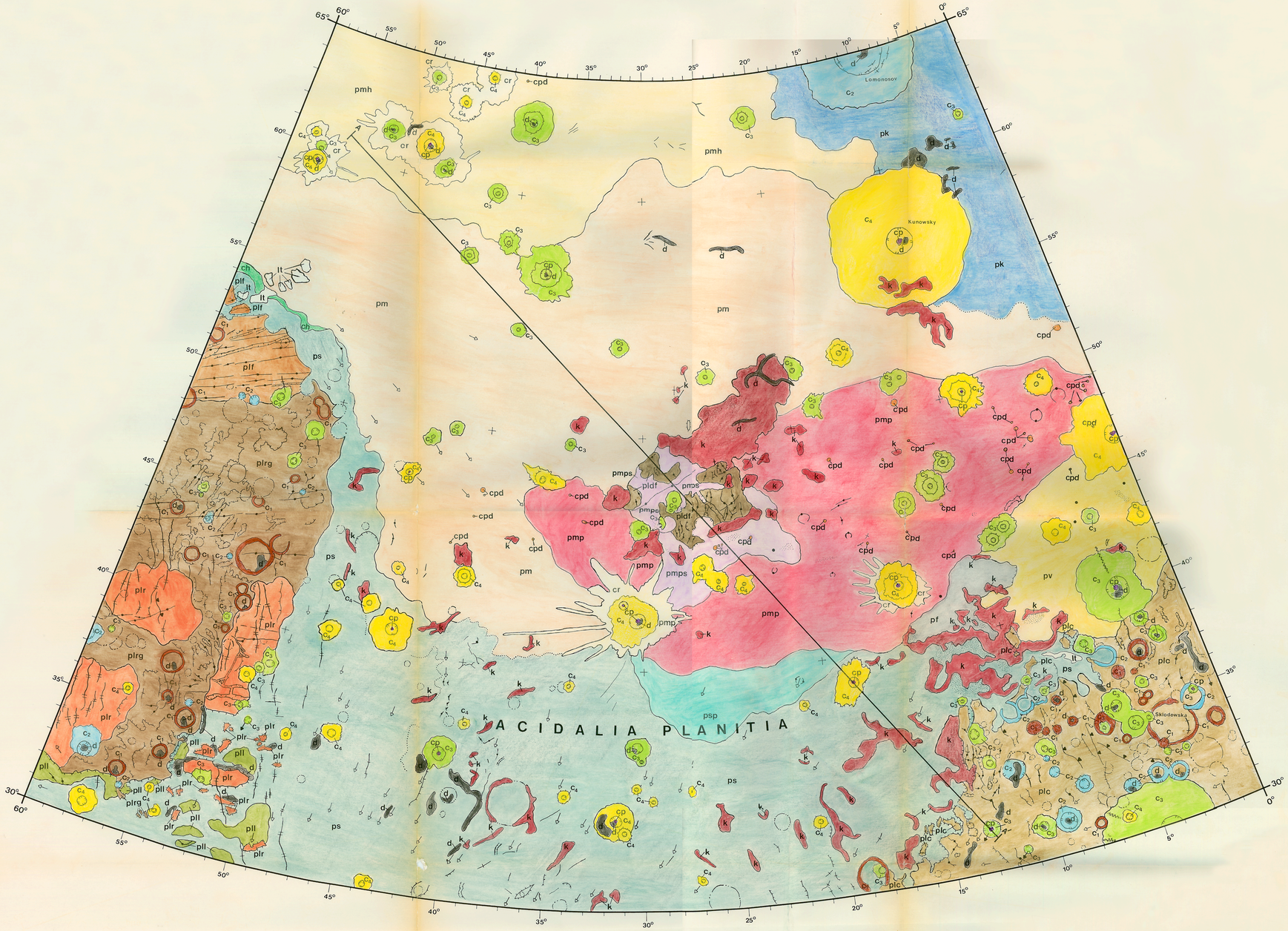
INTERPRETATION: Chain of secondary craters formed during impact.

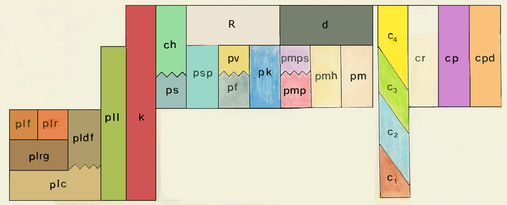
rrm ROUGH RADIAL MATERIAL - Forms rough surface radial to Bamberg crater; extends outward up to 3 crater diameters from rim material; many closely spaced pits and depressions; boundary with smooth radial material is abrupt textural change; representative image 70A25.

INTERPRETATION: Ejecta deposit of Bamberg crater; some flow lobes; many secondary craters and crater clusters produced by impact.

srm SMOOTH RADIAL MATERIAL - Forms relatively smooth surface radial to Bamberg crater; extends outward 2 - 3 crater diameters from crater-rim material; varied albedo; low crater density; representative image 70A27.

INTERPRETATION: Ejecta deposits of Bamberg crater possibly more volatile-rich than rough radial material and thus with a smoother surface.





MAP UNITS

PLAINS MATERIALS

- pv — Variegated Plains Material
- psp — Patterned Smooth Plains Material
- ps — Smooth Plains Material
- pk — Knobby Plains Material
- pf — Fractured Plains Material
- pmps — Subdued Patterned Mottled Plains Material
- pmp — Patterned Mottled Plains Material
- pmh — Hummocky Mottled Plains Material
- pm — Mottled Plains Material – Undivided

PLATEAU MATERIALS

- plf — Fractured Plateau Material
- plr — Ridged Plateau Material
- plrg — Rugged Plateau Material
- pll — Lower Plateau Material
- pldf — Dissected and Fractured Plateau Material
- plc — Cratered Plateau Material

OTHER MATERIALS

- d — Dark Material
- lt — Light Material
- ch — Channel Material
- k — Knobby Terrain Material

CRATER MATERIALS

- c_4 — Young Crater Material
- cr — Crater Ray Material
- c_3 — Moderately Young Crater Material
- cp — Central Peak Material
- cpd — Pedestal Crater Material
- c_2 — Moderately Old Crater Material
- c_1 — Old Crater Material

SYMBOLS

- Contact; albedo contact dotted
- Steep scarp; used as contact in places; hachures point downslope
- Gentle scarp; barb points downslope
- Narrow depression; graben, channel, trough
- Low ridge
- Mare-type ridge
- Lineament; topographic or tonal
- Sharp albedo variation
- Light wind streak; arrow shows orientation of streak
- Dark wind streak; arrow shows orientation of streak
- Dune field
- Mesa with ridge or knob; may be tablemountain
- Region with cratered domes < 1 km diameter; domes may be volcanic cones
- Crater rim crest ≥10 km diameter; hachures point toward center of depression
- Partially buried or highly degraded crater rim crest
- Secondary crater chain
- Irregular, rimless depression; hachures point toward center of depression

N

Scale 1:4,336,000 at 30° Latitude
Lambert Conformal Projection

100 50 0 KILOMETERS 100 200 300 400 500 600 700 800 900 1000

GEOLOGIC MAP OF THE MARE ACIDALIUM QUADRANGLE OF MARS

By
Nanci E. Witbeck

APPENDIX IV - MARE ACIDALIUM QUADRANGLE

Crater densities are given for units for which crater counts have been made. Number refers to the cumulative number of craters 1 km in diameter and greater per 10^6 km^2 as determined from crater size-frequency distribution curves. All numbers were derived directly from the size-frequency curves and not extrapolated. Crater densities > $1{,}000/10^6$ km^2 are considered moderate; crater densities $\leq$ $1{,}000/10^6$ km^2 are considered low.

Plateau Materials

plc CRATERED PLATEAU MATERIAL - Occurs in southeast corner of quadrangle between lat 30° - 40°N, long 0° - 20°W; low albedo, moderate crater density (1460 craters $\geq$ 1km/10^6 km^2); characterized by many large (up to 120 km diameter), flat floored, c_1 and c_2 craters; intercrater areas contain irregular depressions and low escarpments; irregular depressions are common near plateau-plains boundary; escarpment commonly marks boundary with lower plains units; representative image 561A07 (Fig. 11).

INTERPRETATION: Ancient crustal deposits partially resurfaced by volcanic and eolian material that also fills large craters.

pldf DISSECTED AND FRACTURED PLATEAU MATERIAL - Occurs between lat 46° - 49°N, long 22° - 28°W, intermediate to high albedo; low crater density (few craters observed); relatively smooth surface cut by numerous fractures and troughs trending north-south; fracture widths up to 2 km; fracture lengths up to 50 km; escarpment marks the boundary of plateau unit in some places; other areas, sharp change from high-albedo plateau material to low-albedo plains material; representative image 670B16 (Fig. 12).
INTERPRETATION: Remnants of a higher unit that earlier may have covered the region; large circular depressions mark the location of degraded and filled craters; resurfaced by eolian and volcanic materials; subsequently disrupted by faulting.

plrg RUGGED PLATEAU MATERIAL - Occurs in western region between lat 31° - 52°N, long 50° - 60°W; intermediate albedo; moderate crater density (1150 craters $\geq$ 1 km/10^6 km^2); forms rough surface with numerous shallow, flat-floored c_1 craters up to 90 km diameter; intercrater area contains many rimless, irregular depressions and escarpments; several channel-like depressions trending north-south with openings to the north; northeast trending fractures; boundary with surrounding smoother units generally morphologically distinct; representative image 704B38-39 (Fig. 13).
INTERPRETATION: Volatile-rich volcanic flow rock and eolian material resurfacing ancient crustal deposits; melting of ground ice caused local collapse and formation of depressions that were later modified by the wind; local disruption by faults of the Tempe Plateau.

plr RIDGED PLATEAU MATERIAL - Occurs between lat 31° - 40°N, long 50° - 60°W; intermediate albedo; moderate crater density (1300 craters $\geq$ 1 km/10^6 km^2); forms smooth surface with north-northwest trending mare-type ridges, oriented similarly to those ridges in MC-10; few fracture traces; boundary with rugged plateau material is morphologic change from smooth, ridged plateau surface to rough, rugged plateau surface; representative image 668A06 (Fig. 15a).

INTERPRETATION: Volcanic flow rock with mare-type ridges; locally disrupted by faults of the Tempe Plateau.

plf FRACTURED PLATEAU MATERIAL - Occurs in western region between lat 48° - 52°N, long 52° - 60°W; intermediate albedo; low crater density (700 craters $\geq$ 1 km/10^6 km^2); relatively smooth surface cut by many northeast trending flat-floored depressions up to 17 km wide; escarpment generally forms boundary with lower plains material; distinct morphologic boundary between relatively smooth fractured plains material and rugged plains material; representative image 61B52 (Fig. 17).

INTERPRETATION: Volcanic flow rock and eolian material cut by many faults of Tempe Plateau.

pll LOWER PLATEAU MATERIAL - Occurs in small patches between lat 30° - 36°N, long 49° - 60°W; varied albedo; few craters observed; forms rough surface at elevation intermediate between smooth plains and plateau units; cut by channels creating mid-channel, streamlined,

erosional remnants up to 40 km long; boundary with smooth plains commonly marked by low escarpment with lobate pattern in places (Fig 18b); escarpment marks boundary with higher plateau units; representative image 668A27.

INTERPRETATION: Remnants of a lower, more resistant plateau layer exposed and eroded by fluvial activity; may also be eroded lava flows or plains material.

Plains Materials

pm MOTTLED PLAINS MATERIAL - UNDIVIDED - Covers large area between lat 40°N - 63°N, long 15° - 60°W; varied albedo; low crater density (550 craters $\geq$ 1 km/10^6 km^2); high-albedo zones extend out 2-3 crater diameters; low-albedo intercrater plains; small craters filled or partially filled with light material; distinct northwest-southeast eolian grain indicated by wind plumes and streaks; boundary with other mottled plains units gradational; boundary with smooth plains marked by change from intermediate-albedo smooth plains material to low-albedo mottled plains material; representative image 672B74 (Fig. 21a).

INTERPRETATION: Volcanic and eolian material; former blanket of light material now being stripped away by wind; ejecta blankets may act as trap for fine-grained windblown particles.

pmh HUMMOCKY MOTTLED PLAINS MATERIAL - Occurs in northern part of quadrangle between lat 58° - 65°N, long 5° - 60°W; extends northward into MC-1; varied albedo; low crater density (675 craters $\geq$ 1 km/10^6 km^2); high albedo zones surround impact craters; intercrater plains characterized by low dark hummocks or knobs (generally < 1 km wide) surrounded by lighter material; many craters are filled or partially filled with light material; gradational boundary with all surrounding units; representative image 672B77 (Fig. 23a).

INTERPRETATION: Volcanic and eolian plains; small dark knobs or hummocks are volcanic, plutonic, or permafrost features such as

pingos; alternatively, knobs may represent a lower hilly, irregular surface mantled with light material leaving only dark summits of once-buried hills exposed; ejecta blankets may act as trap for fine-grained, light-colored windblown material.

pmp PATTERNED MOTTLED PLAINS MATERIAL - Occurs between lat 40° - 50°N, long 0° - 30°W; varied albedo; low crater density (1000 craters $\geq$ 1 km/10^6 km^2); high-albedo ejecta blankets extend outward 2-3 crater diameters; intercrater region very low albedo; crudely polygonal pattern of troughs; troughs generally < 10 km long, < 1 km wide, and $\cong$ 100 m deep; pedestal craters common; small (< 1 km wide) domes with summit craters common; boundary with all surrounding units gradational; representative image 32A18 (Fig. 24a).

INTERPRETATION: Volcanic plains; domes are small cinder cones; high-albedo zones surrounding impact craters are result of impact excavating lower material having high albedo; troughs originated through permafrost (Carr and Schaber, 1977), desiccation (Morris and Underwood, 1978), or tectonic (Pechmann, 1980) processes.

pmps SUBDUED PATTERNED MOTTLED PLAINS MATERIAL - Occurs around dissected and fractured plateau near center of quadrangle; crater density observed to be similar to patterned mottled plains; low albedo; relatively smooth dark plains cut by many discontinuous, arcuate troughs generally < 1 km wide and averaging 5 km long;

small (< 1 km) domes with summit craters common; boundary with patterned mottled plains gradational; boundary with higher dissected and fractured plateau marked by escarpment; representative image 35A41 (Fig. 26b).

INTERPRETATION: Volcanic flow rock; flow fronts and pressure ridges occur in several places; domes are small cinder cones; volcanic material fills or partially fills pre-existing troughs.

pf FRACTURED PLAINS MATERIAL - Occurs between lat 40° - 43°N, long 10° - 15°W; intermediate albedo; no craters larger than 5 km; characterized by crudely polygonal pattern of troughs cutting smooth plains; trough widths range from 0.2-2.0 km, are as long as 20 km, and are 5-10 km apart; depth of troughs range from 30-100 m (Pechmann, 1980); wider troughs mostly have flat floors; decrease in trough abundance marks boundary with surrounding units; representative image 32A36.

INTERPRETATION: Fractured materials may be old unit stratigraphically underlying the plateau materials exposed by scarp retreat; alternatively, may be young volcanic and eolian material; fractures are post depositional and are the result of tectonism (Pechmann, 1980), desiccation (Morris and Underwood, 1978), or permafrost activity (Carr and Schaber, 1977).

pk KNOBBY PLAINS MATERIAL - Occurs in the northeast corner of quadrangle, lat 52° - 65°N, long 0° - 15°W; extends eastward into MC-5; intermediate to high albedo; low crater density (750 craters $\geq$ 1 km/10^6 km^2); small craters (< 2 km) mostly filled with light material; ejecta blankets of 2-10 km craters obscured by light

material; numerous small (< 1 km) irregularly spaced knobs give surface rough appearance; boundary with mottled plains material marked by distinct albedo change from high-albedo knobby plains to low-albedo mottled plains; representative image 673B08 (Fig. 30a).

INTERPRETATION: Volcanic plains blanketed with light-colored eolian material; knobs are eroded volcanic material or partially buried impact craters.

ps SMOOTH PLAINS MATERIAL - Covers large portion of southern region between lat 30° - 40°N, long 10° - 50°W; intermediate to high albedo; low crater density (760 craters $\geq$ 1 km/10^6 km^2); patches of knobby terrain material are scattered throughout smooth plains; large (up to 120 km) circular features are outlined by knobs; grooves and streamlined features oriented east and northeast are common to the southwest; boundary with higher plateau units marked by escarpment, boundary with mottled plains marked by albedo change form intermediate- to high-albedo smooth plains to low-albedo mottled plains; representative image 558A07 (Fig. 31b).

INTERPRETATION: Eolian fill and, especially to south, alluvial fill from large outflow channels to south and west; locally may be volcanic material; overlies older cratered surface; shifting eolian material results in varied albedo.

psp PATTERNED SMOOTH PLAINS MATERIAL - Occurs between lat 37° - 40°N, long 18° - 31°W; intermediate albedo; low crater density assumed to be similar to smooth plains materials; characterized by subdued pattern of discontinuous troughs only a few hundred meters

wide and averaging 5 km long; high-albedo wind streaks associated with many craters; decrease in fracture abundance marks boundary with smooth plains material; change from intermediate albedo to low albedo marks the boundary with mottled plains; representative image 597A05 (Fig. 35).

INTERPRETATION: Thin mantle of light-colored eolian material blanketing patterned mottled plains, partially filling troughs; mantle thickness increases to the south; alternatively, fractures may be result of permafrost activity (Carr and Schaber, 1977), desiccation (Morris and Underwood, 1978), or tectonic activity (Pechmann, 1980) and may have occurred after smooth plains materials were emplaced.

pv VARIEGATED PLAINS MATERIAL - Occurs between lat 38° - 46°N, long 0° - 10°W; varied albedo; low crater density (880 craters $\geq$ km/10^6 km^2); smooth, featureless plains; patchy albedo pattern; scattered occurrences of small (< 1 km wide) domes with summit craters; small patches of knobs and mesas occur; boundary with patterned mottled plains occurs where troughs begin; boundary with cratered plateau changes from rough plateau material to smoother plains material; representative image 36A44 (Fig. 36a).

INTERPRETATION: Volcanic plains; domes may be cinder cones; alternatively, these plains may consist of alluvial and eolian material; small knobs and mesas erosional remnants of plateau material to south.

Other Materials

d DARK MATERIAL - Very low-albedo material; forms patches in and around craters, in valleys, along escarpments, and on plains units; representative image 558A15 (Fig. 19).

INTERPRETATION: Eolian material aligned with present wind circulation; locally may be small dune fields.

lt LIGHT MATERIAL - High-albedo material; forms patches near plateau-plains boundary; representative image 669B76 (Fig. 37b).

INTERPRETATION: Eolian and alluvial material.

ch CHANNEL MATERIAL - Occupies elongate depressions near plains-plateau boundary in western region; high albedo; very few craters; representative image 669B76 (Fig. 37b).

INTERPRETATION: Alluvial deposits of former streams.

k KNOBBY TERRAIN MATERIAL - Irregular hills or knobs rising above level of plains; may be up to 15 km across and 3000 km high but generally smaller; locally knobs form circular pattern; at high resolution, some knobs appear to have summit craters; representative image 70A09 (Fig. 38b).

INTERPRETATION: Erosional remnants of higher surface of plateau material; in some areas may represent crater rims and more resistant facies of lower cratered unit; locally may represent exposed igneous intrusions or small volcanic cones or mountains.

Crater Materials

All craters mapped believed to have been produced by impact; craters with diameters < 10 km not mapped; subdivisions based on morphologic characteristics believed to reflect relative age.

c_4 YOUNG CRATER MATERIAL - Sharp, complete rim crest; central peak; steep walls; deep rough floors; extensive ejecta deposits; representative image 558A31 (Fig. 33a).

INTERPRETATION: Relatively recent impact-crater material.

cr CRATER RAY MATERIAL - High-albedo material that surrounds several large (> 20 km) c_4 craters on mottled plains (units pm, pmh, pmp); representative image 670B36.

INTERPRETATION: Fine-grained, light-colored primary and secondary ejecta material.

c_3 MODERATELY YOUNG CRATER MATERIAL - Rim crests high, complete; may have central peak; walls relatively steep; floor may be rough and lower than adjacent terrain; ejecta deposits less extensive than c_4 craters; representative image 673B60 (Fig. 36b).

INTERPRETATION: Relatively young but slightly degraded impact-crater material.

cp CENTRAL PEAK MATERIAL - Rugged, irregular peaks centrally located in c_3 and c_4 craters; representative image 597A46.

INTERPRETATION: Formed by rebound following impact.

cpd PEDESTAL CRATER MATERIAL - Small (generally < 5 km) bowl-shaped craters; ejecta extends outward 3 crater diameters; ejecta forms platform that stands above surrounding terrain; convex slope at distal edge of ejecta blanket; representative image 26A56 (Fig. 6b).

INTERPRETATION: Impact crater with associated viscous ejecta flow (flow too viscous to form lobes; Mutch and Woronow, 1980); alternatively may represent preferential retention of eolian debris in and around craters as intercrater debris is eroded away (Carr, 1981).

c_2 MODERATELY OLD CRATER MATERIAL - Rim crests low, rounded, complete or imcomplete; no central peak; floors generally flat; may be partially flooded or filled with younger material; ejecta deposits show little or no surface texture, or are partially stripped away; representative image 672B56 (Fig. 30b).

INTERPRETATION: Moderately old and partially degraded impact-crater material.

c_1 OLD CRATER MATERIAL - Rim crest low, incomplete, or nearly absent; no central peak; shallow flat floors generally filled with younger material; commonly forms rugged and partly buried rings; little or no ejecta deposits; representative image 218S19 (Fig. 10).

INTERPRETATION: Oldest, highly degraded impact-crater material.

THE GEOLOGY OF MARE ACIDALIUM QUADRANGLE MARS

by

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ABSTRACT

Mare Acidalium quadrangle lies between 30° - 60°N latitude and 0° - 60°W longitude. Materials that were used in mapping the quadrangle include Mariner and Viking single-frame images and photomosaics. Preliminary geologic mapping was done on five 1:2,000,000-scale photomosaics and selected higher resolution photomosaics. The data were then compiled on one sheet at a scale of 1:5,000,000.

The Mariner 9 mission revealed a striking planetary dichotomy; high-standing, heavily-cratered terrain in the south that contrasts with low-lying, lightly-cratered terrain in the north. Both of these terrain types occur in Mare Acidalium quadrangle. The boundary separating the elevated cratered plateau from the lower plains is, in many places, an escarpment 1-2 km-high, however, in a few places where there is no escarpment, plains materials embay and overlap the heavily-cratered plateau material.

Plateau materials cover approximately 20 percent of the quadrangle and occur in three areas in the southern region. The plateau province consists of six units: (1) cratered plateau material (302,000 km^2). (2) dissected and fractured plateau material (25,000 km^2), (3) rugged plateau material (270,000 km^2), (4) ridged plateau material (95,000 km^2), (5) fractured plateau material (46,000 km^2), and (6) lower plateau material (small patches).

The cratered plateau and rugged plateau materials, believed to be the oldest in the quadrangle, are characterized by many ancient flat-floored, degraded and partially buried impact craters. The

younger ridged plateau and fractured plateau materials contain mare-type ridges and NE-trending grabens, respectively. The dissected and fractured plateau material is characterized by many N-S trending fractures and ghost craters and occurs near the center of the quadrangle. Lower plateau material occurs in small patches along the plateau-plains boundary in the southwest region. The unit may represent resistant material underlying the older plateau units and is exhumed, or material that was deposited on top of the smooth plains.

Lowland plains materials cover the remaining 80 percent of the quadrangle. The plains province consists of ten units: (1) mottled plains material - undivided (991,000 km^2), (2) hummocky mottled plains material (386,000 km^2), (3) patterned mottled plains material (458,000 km^2), (4) subdued patterned mottled plains material (37,000 km^2), (5) fractured plains material (23,000 km^2), (6) knobby plains material (193,000 km^2), (7) smooth plains material (1,162,000 km^2), (8) patterned smooth plains material (60,000 km^2), (9) variegated plains material (128,000 km^2), and (10) knobby terrain material (small patches).

The mottled plains units are characterized by high-albedo zones around impact craters that are surrounded by low-albedo intercrater plains. To the north, crater floors are commonly filled with light material, and there is a distinct NE-SE eolian grain. Gradiational boundaries exist between all mottled plains units. Boundaries between mottled plains units and other plains units commonly have distinct morphologic and albedo contrasts. The NW-SE eolian grain is most apparent on the mottled plains material - undivided. The

hummocky mottled plains and the higher-albedo knobby plains are characterized by numerous, randomly distributed, small, dark hills or hummocks that may be volcanic. The patterned mottled plains, subdued patterned mottled plains, fractured plains, and patterned smooth plains are characterized by a polygonal pattern of troughs that may be the result of permafrost, desiccation, or tectonic activity. Lava flows partially obscure the trough pattern on the subdued patterned mottled plains. The troughs on the fractured plains are much larger than those on other plains units. Troughs on the patterned smooth plains may be slightly smaller than those on other plains units.

The vast smooth plains and variegated plains have few impact craters. Streamlined landforms and channels on the smooth plains indicate fluvial erosion and deposition. The variegated plains contain features that may be volcanic. Knobby terrain material occurs in patches throughout the lowland plains and may represent erosional remnants of plateau material, more resistant remnants of an underlying cratered surface, igneous intrusions, or volcanic constructs.

The heavily-cratered plateau materials in the southern region record an early period when the impact of large bodies was common. Later, these regions were partially or completely buried by younger volcanic and eolian materials and disrupted by faulting. The central region may have subsided and plateau material that once covered a large portion of the quadrangle began to break down and erode, leaving only erosional remnants of the higher surface scattered throughout the lowland region. Volcanic, eolian, and alluvial materials resurfaced a large portion of the lower plains. The distinctive and varied surface

textures in Mare Acidalium quadrangle have been created by impact, tectonic, fluvial, eolian, periglacial activity and mass movement processes.