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FINAL TECHNICAL REPORT

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GEOLOGIC MAPPING OF ARGYRE PLANITIA

Submitted to

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(NASA-CR-197986) GEOLOGIC MAPPING
OF ARGYRE PLANITIA Final Technical
Report (University of Southern
California) 46 p

PROJECT SUMMARY

This report describes the results from the geologic mapping of the central and southern Argyre basin of Mars. At the Mars Geologic Mapper's Meeting in Flagstaff during July, 1993, Dave Scott (United States Geological Survey, Mars Geologic Mapping Steering Committee Chair) recommended that all four quadrangles be combined into a single 1:1,000,000 scale map for publication. It was agreed that this would be cost-effective and that the decrease in scale would not compromise the original science goals of the mapping. Tim Parker completed mapping on the 1:500,000 scale base maps, for which all the necessary materials had already been produced, and included the work as a chapter in his dissertation, which was completed in the fall of 1994 (see attached). Geologic mapping of the two southernmost quadrangles (MTM -55036 and MTM -55043; MTM=Mars Transverse Mercator) was completed as planned during the first year of work. These maps and a detailed draft of the map text were given a preliminary review by Dave Scott during summer, 1993. Geologic mapping of the remaining two quadrangles (MTM -50036 and MTM -50043) was completed by summer, 1994. Results were described at the Mars Geologic Mappers Meeting, held in Pocatello, Idaho, during July, 1994). Funds for the third and final year of the project have been transferred to the Jet Propulsion Laboratory, where Tim Parker will revise and finalize all maps and map text for publication by the United States Geological Survey at the 1:1,000,000 map scale.

RESULTS

The primary product expected from this mapping project will be a single 1:1,000,000 scale map sheet, corresponding to the original four 1:500,000 scale controlled photomosaic base maps of the MTM -50036, -50043, -55036 and -55043 quadrangles. This map will be published by the USGS. A companion scientific paper describing the geologic evolution of Argyre Planitia based on the work on these quadrangles, but including a discussion of the importance of the Argyre Basin to the geologic history of this part of the Martian highlands and its place in the paleohydrologic cycle of Mars is included as a chapter in Tim Parker's PhD dissertation, which was completed during Fall, 1994. The scientific paper is currently in preparation for publication in a peer-reviewed scientific journal.

PROPOSAL SUMMARY

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PROPOSAL TITLE: Geologic Mapping of Argyre Planitia

ABSTRACT: (Type single-spaced below line. Lettered paragraphs (a) through (d) should include: a. brief statement of the overall objectives and justification of the work; b. brief statement of the accomplishments of the prior year, or "new proposal"; c. brief listing of what will be done this year, as well as how and why; and d. one or two of your recent publications relevant to the proposed work.)

a.) **Objectives:** Investigate the morphology and distribution of the layered plains material and sinuous ridges in central and southern Argyre. Emphasis is placed on a careful analysis of their distributions relative to regional topography and features such as large channel systems radial to the basin. Further emphasis is placed on characterizing the process or processes likely to have been responsible for their formation and what they might suggest about the martian paleoclimate.

b.) **Progress.** MTM quadrangles -55036 and -55043 and map text were given a preliminary review at the USGS (map text is attached). At the Mars Geologic Mapper's Meeting, it was recommended that all four quadrangles, MTM-50036, -50043, -55036, and -55043, be combined into a single 1:1,000,000 scale map sheet when published. All map quadrangles and revised map text will be submitted for formal USGS review by the project anniversary date in July, 1995.

d.) Summary Bibliography:

- Parker, T. J., 1994. Geologic mapping of Argyre Planitia: A large highland sedimentary basin. In "Martian Paleolakes and Oceans", Dissertation Chapter Three, p. 59-83, and Appendices II and III, p. 185-196.
- Parker, T. J., and Gorsline, D. S., 1992. Preliminary geologic mapping of the MTM -55036 and -55043 quadrangles, southern Argyre Planitia, Mars, *Lunar and Planet. Sci.* - XXIII, Lunar and Planet. Inst., 2p.
- Parker, T. J., and Gorsline, D. S., 1993. Extent and Timing of Fluvial and Lacustrine Events in Argyre Planitia, Mars, *American Geophysical Union* Spring Meeting.

MARTIAN PALEOLAKES AND OCEANS

by

Timothy Jay Parker

A Dissertation Presented to the
FACULTY OF THE GRADUATE SCHOOL
UNIVERSITY OF SOUTHERN CALIFORNIA

In Partial Fulfillment of the
Requirements for the Degree
DOCTOR OF PHILOSOPHY
(Geological Sciences)

December 1994

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Timothy Jay Parker

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This dissertation, written by

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*under the direction of his..... Dissertation
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has been presented to and accepted by The
Graduate School, in partial fulfillment of re-
quirements for the degree of*

DOCTOR OF PHILOSOPHY

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Dean of Graduate Studies

Date

DISSERTATION COMMITTEE

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CHAPTER THREE
GEOLOGIC MAPPING OF ARGYRE PLANITIA: A LARGE
HIGHLAND SEDIMENTARY BASIN

General Statement

Argyre Planitia is the second largest well-preserved impact basin in the southern highlands of Mars and perhaps the best preserved large impact structure on the planet (Hodges, 1980). It is approximately 1400km in overall diameter and 2km deep (USGS, 1989). It is encompassed by a prominent rim of rugged mountains (Nereidum and Charitum Montes) between 300km and 500km wide. Several of the mountains in Charitum Montes are over 10km high, determined from shadow measurements.

Geologic mapping at a scale of 1:500,000 includes quadrangles MTM -50036, -50043, -55036 and -55043 (figures 17-20). These quadrangles are assembled primarily from the high-resolution (approximately 40m/pixel) Viking Orbiter images from orbits 567B through 569B of the central and southern part of the basin. Much of this data provides stereo pairs with good overlap and reasonable vertical exaggeration. The remaining area of the quadrangles are covered at a pixel scale of 250m or greater, though the image quality is generally quite good.

The purpose of this mapping effort is to characterize the timing and depositional environment(s) represented by the Argyre valley networks and outflow channels, the process or processes responsible for the evolution of layered plains materials and sinuous ridges identified on the basin floor, and infer what these processes might tell us about the Martian paleoclimate.

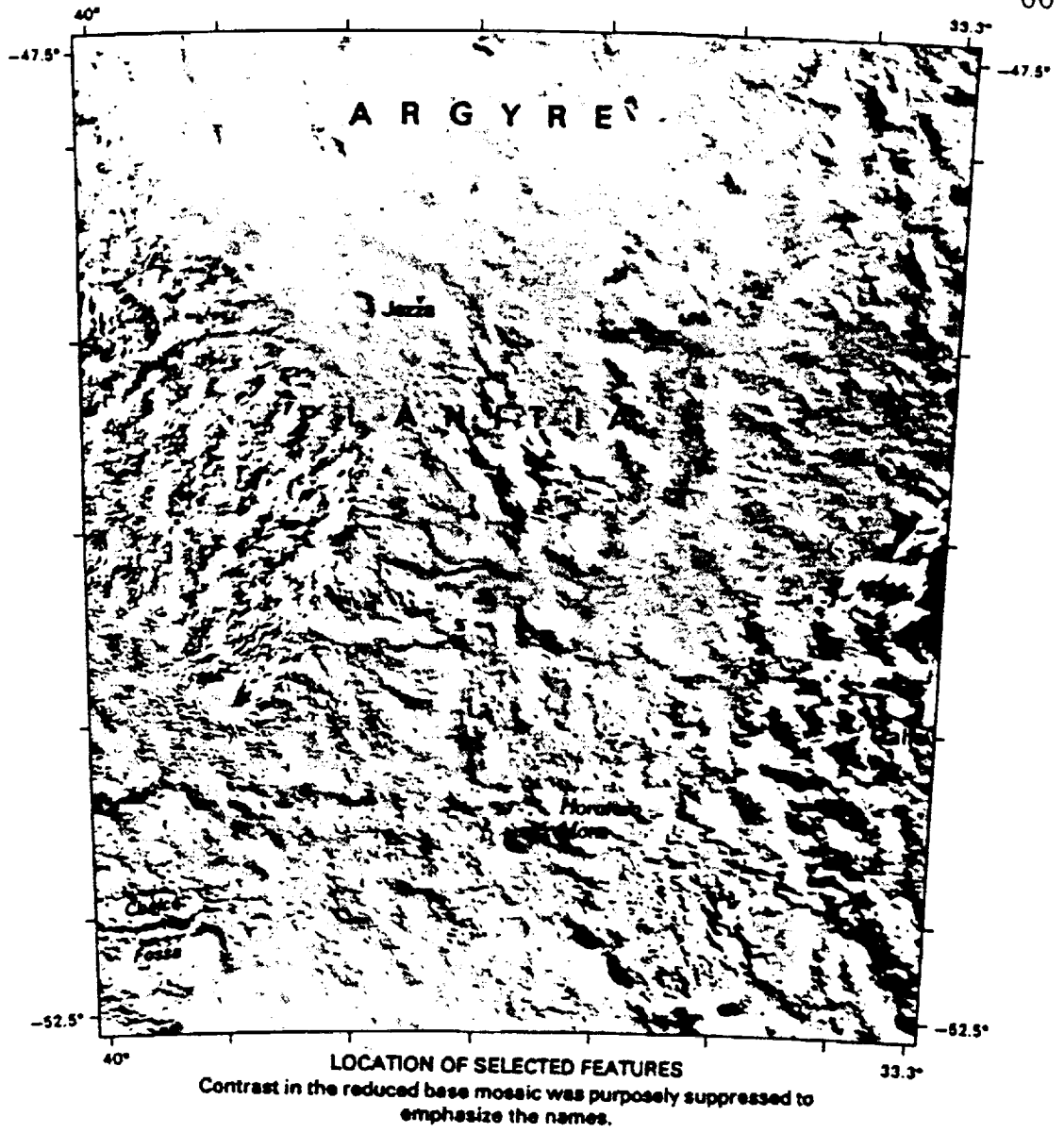


Figure 17: Quadrangle MTM -50036. a) Image base map, with nomenclature.

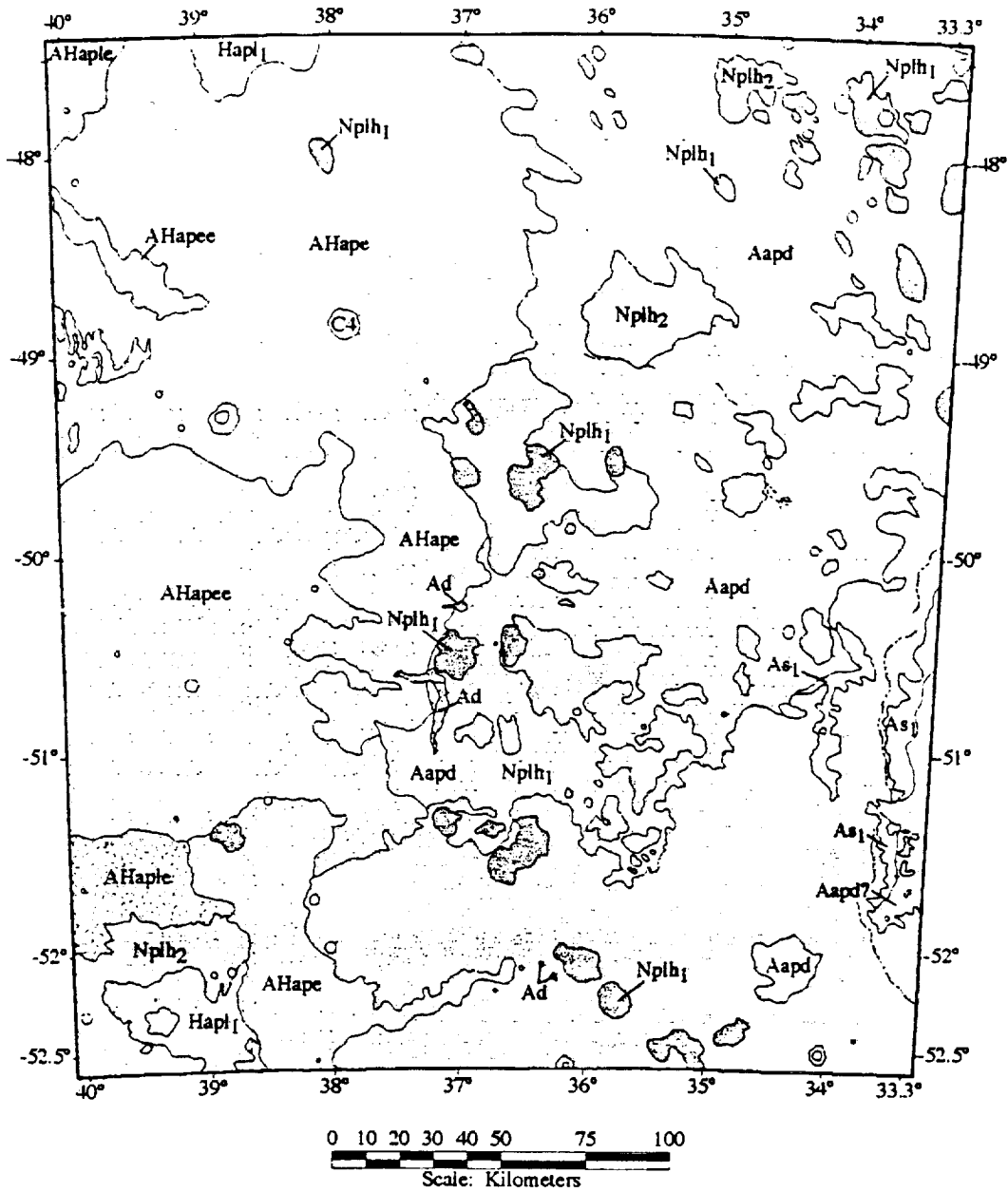


Figure 17 (continued): b) Geologic map of quadrangle MTM -50036. See text and Appendix II for explanation of map units and symbols.

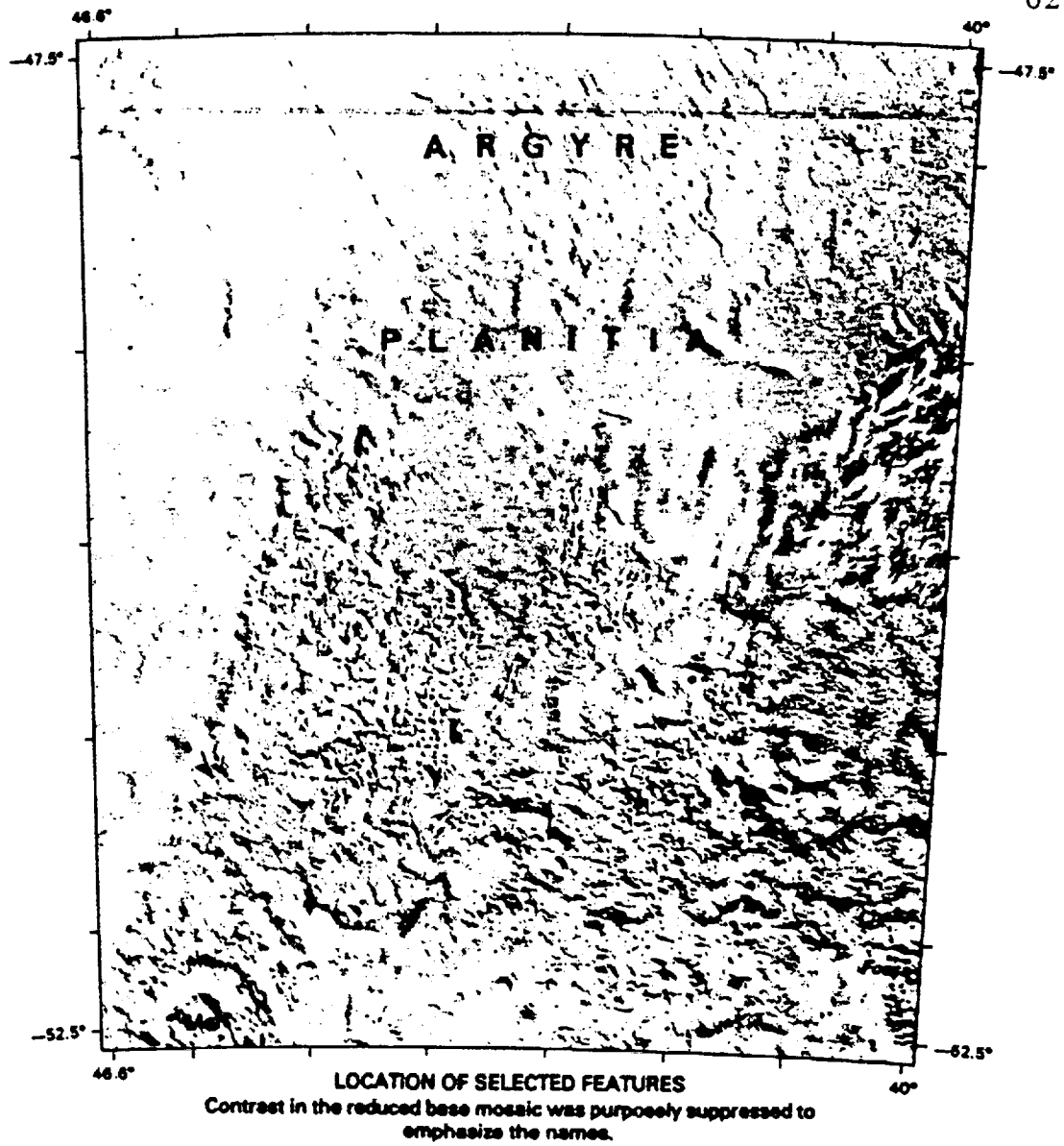


Figure 18: Quadrangle MTM -50043. a) Image base map, with nomenclature.

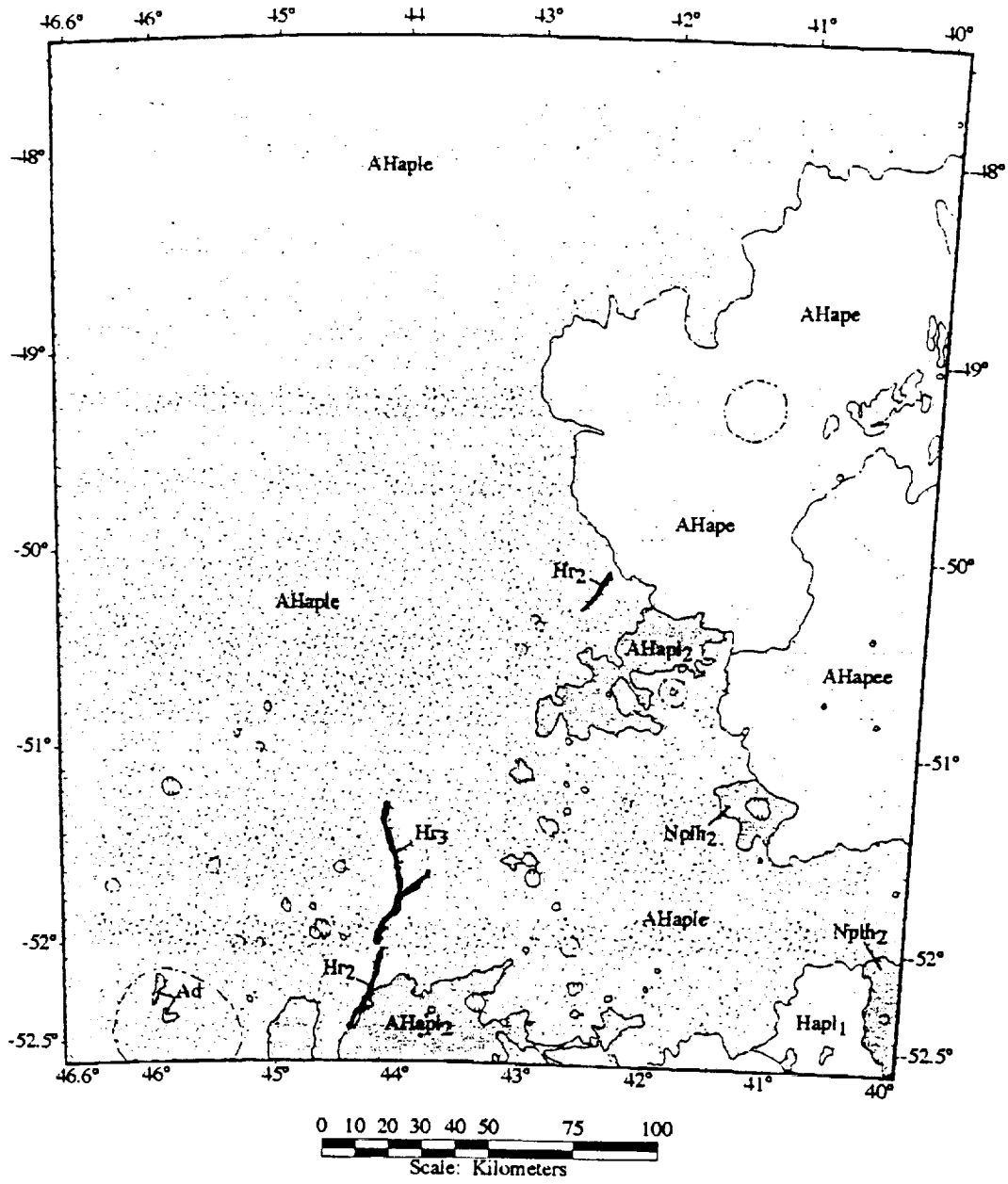


Figure 18 (continued): b) Geologic map of quadrangle MTM -50043. See text and Appendix II for explanation of map units and symbols.

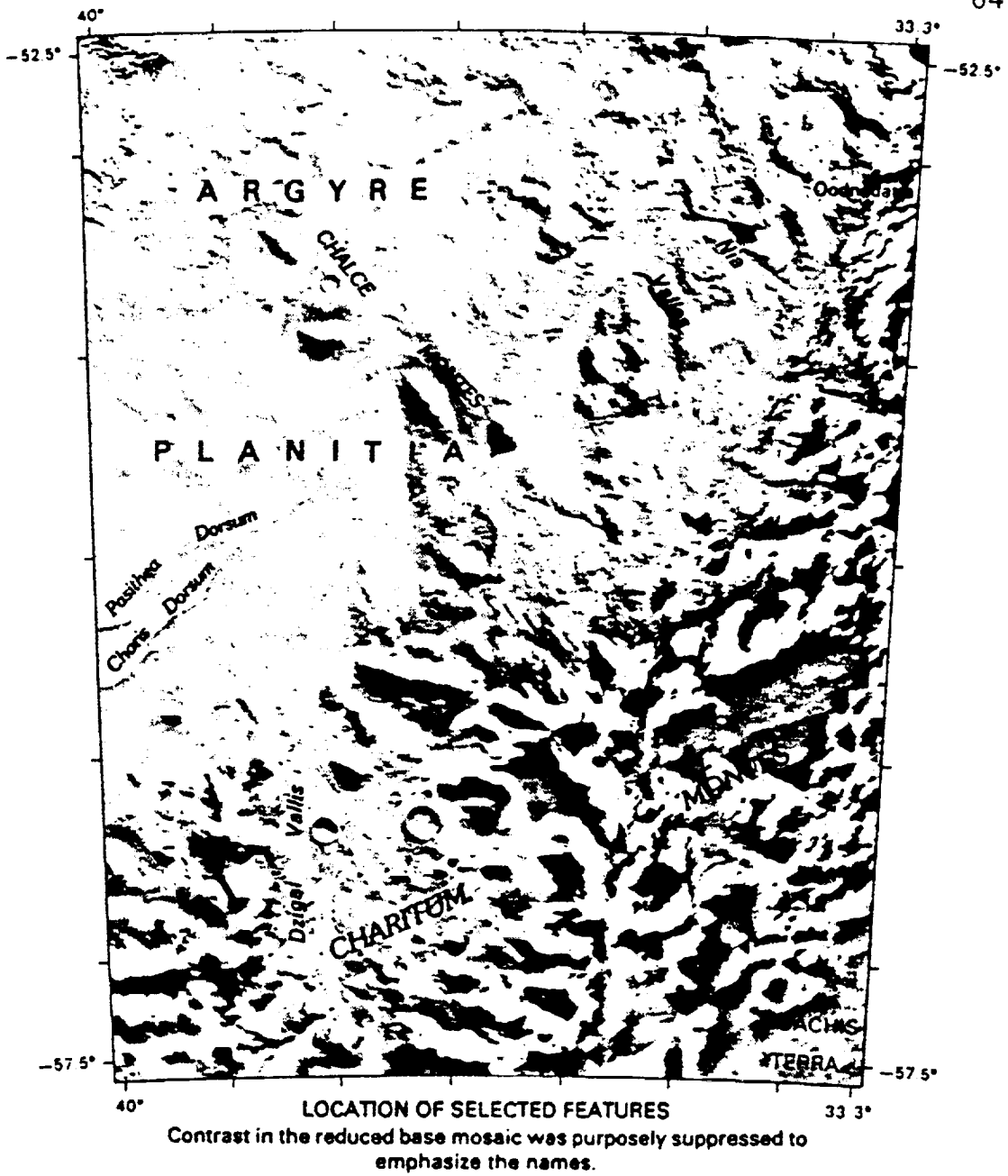


Figure 19: Quadrangle MTM -55036. a) Image base map, with nomenclature.

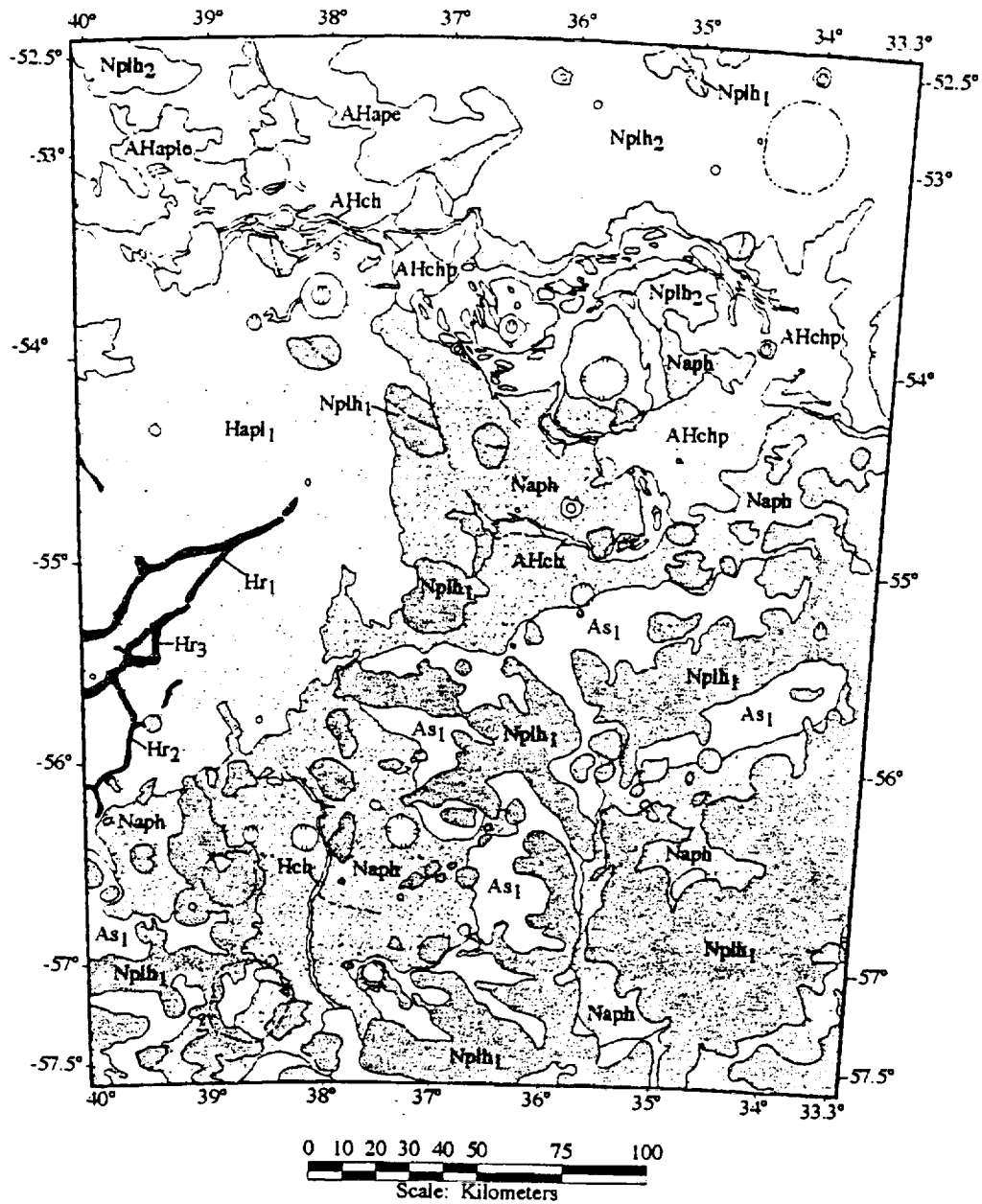


Figure 19 (continued): b) Geologic map of quadrangle MTM -55036. See text and Appendix II for explanation of map units and symbols.

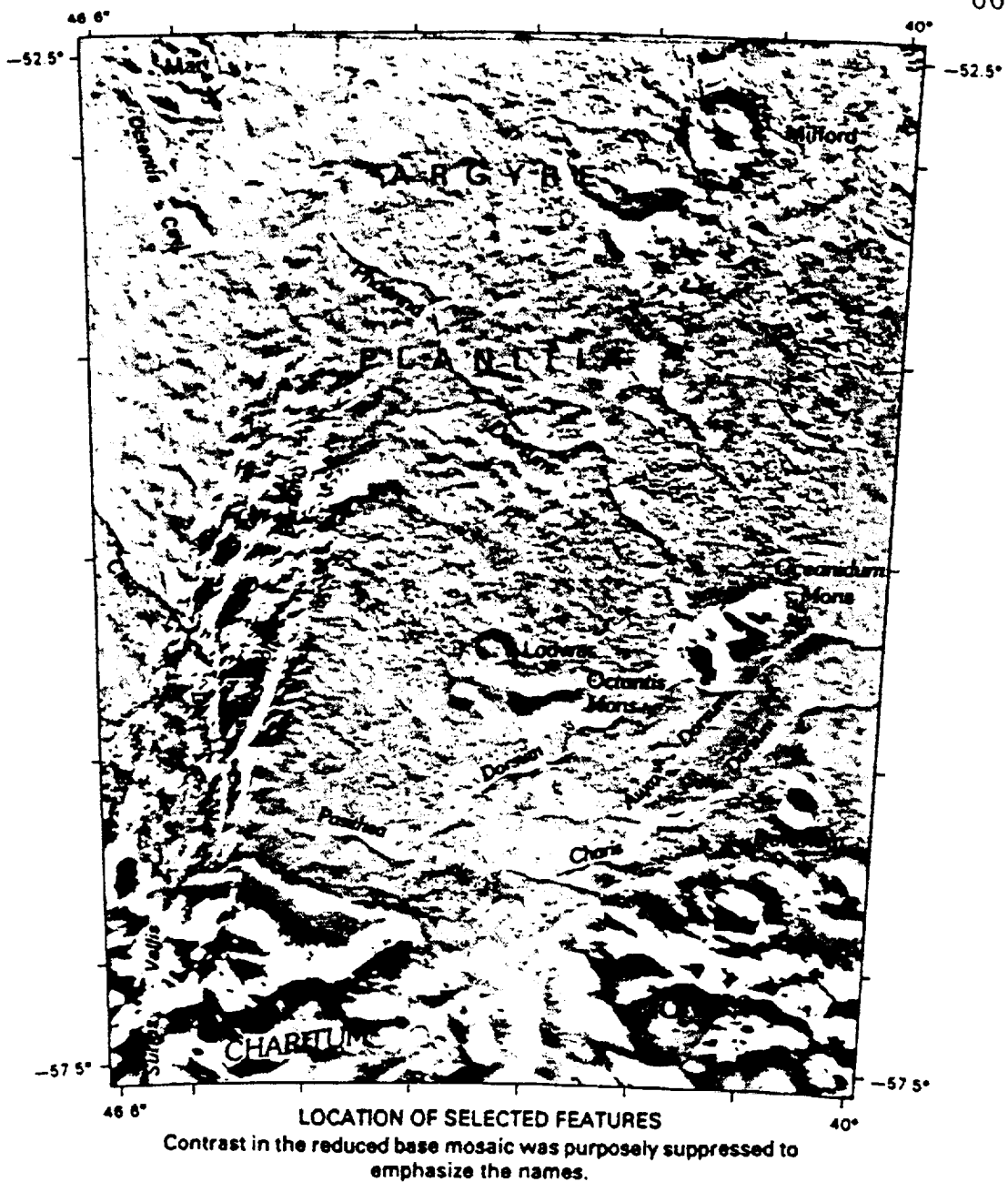


Figure 20: Quadrangle MTM -55043. a) Image base map, with nomenclature.

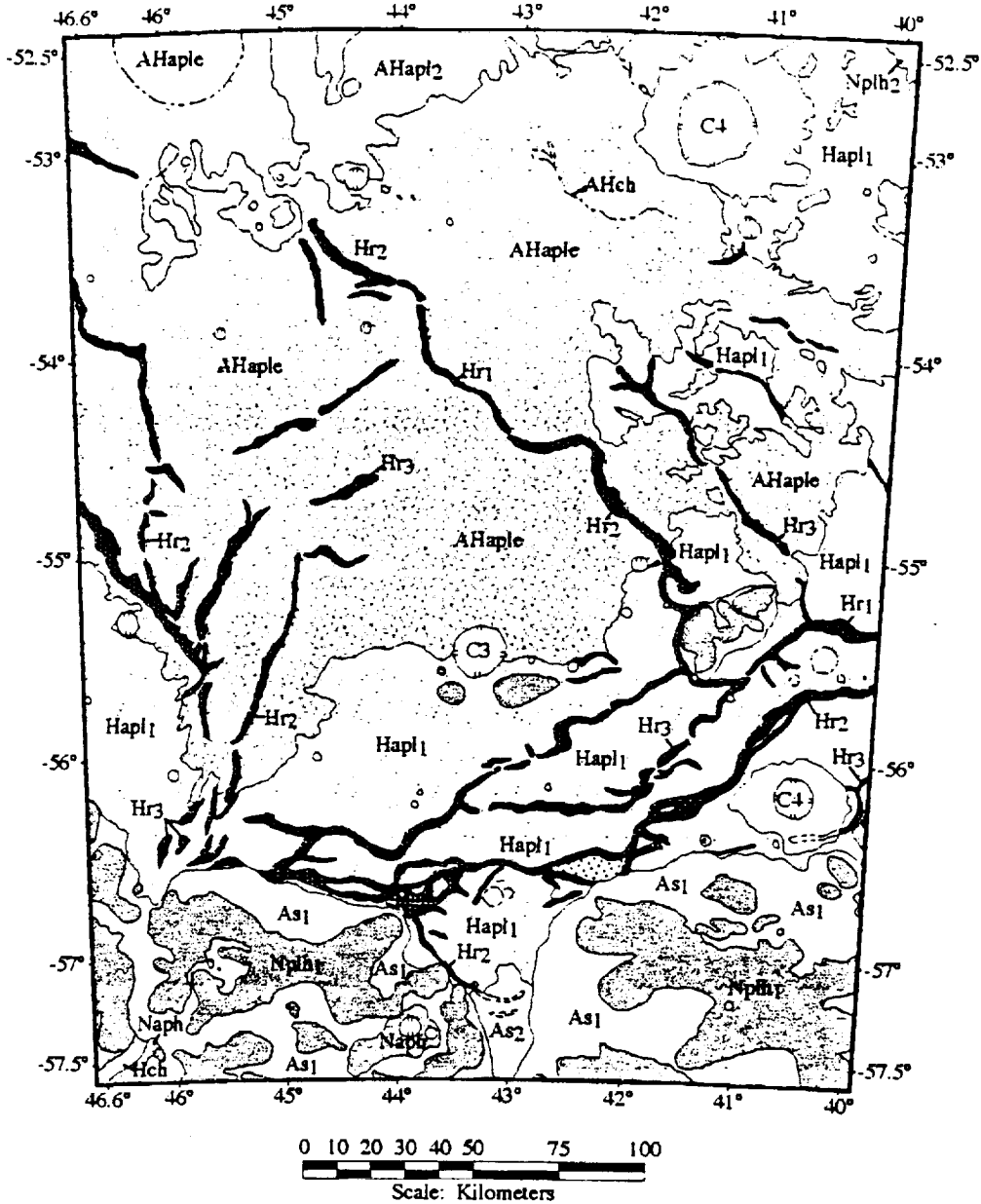


Figure 20 (continued): b) Geologic map of quadrangle MTM-55043. See text and Appendix II for explanation of map units and symbols.

Physiographic Setting

Argyre lies at the southern end of the Chryse Trough (Saunders, 1979) which dips gently northward from Nereidum Montes to Chryse Planitia (figure

21). Three valley networks and one of the outflow channels flowed into Argyre from the south and east (see *Atmospheric Sources?* above). These channels and valley networks exhibit different states of degradation and superposition relative to the basin's interior plains materials that suggest activity at different times.

The floor of Argyre is between 650 and 800km across and consists of layered material that has been partially etched, reminiscent of eolian deflation in arid lakebeds on Earth. The layering is identifiable as well-developed, regularly spaced alternate light and dark bands exposed in etched pits or hollows. The remaining unmodified surface appears smooth and flat to slightly hummocky. These deposits cover most of the interior floor of Argyre, including many of the reentrants into the circum-basin mountains on Argyre's north and west sides. The eastern basin rim topography is dominated by ejecta from the crater Galle.

Also present on the floor of the basin is a system of long (up to 200km), sinuous ridges of problematic origin occurring in association with the layered plains (figure 22). These ridges represent a type of ridge that is common to several basins elsewhere on Mars. The most notable examples of similar ridges are those in Dorsa Argentea (75°S lat., 40° lon.), where they are most numerous. They can also be found elsewhere within the Mare Australe quadrangle (MC-30), in the Prometheus (South Polar) Basin (80°S lat., 305° lon.) and in Terra Sirenum (at 72°S lat., 105° lon., and at 78°S lat., 120° lon., south of Lau crater). Elsewhere, at least one poorly preserved sinuous ridge can be seen at 40°S latitude, 308° longitude, in the west Hellas Basin. Another well-defined sinuous ridge can be seen at 4°S latitude, 210° longitude in northwest Aeolis (Carr, 1984), precluding high southern latitudes

Figure 21: Regional map view, from south pole to 30°N lat., of Argyre Planitia and radial channel systems (adapted from Scott and Tanaka, 1986; Tanaka and Scott, 1987).



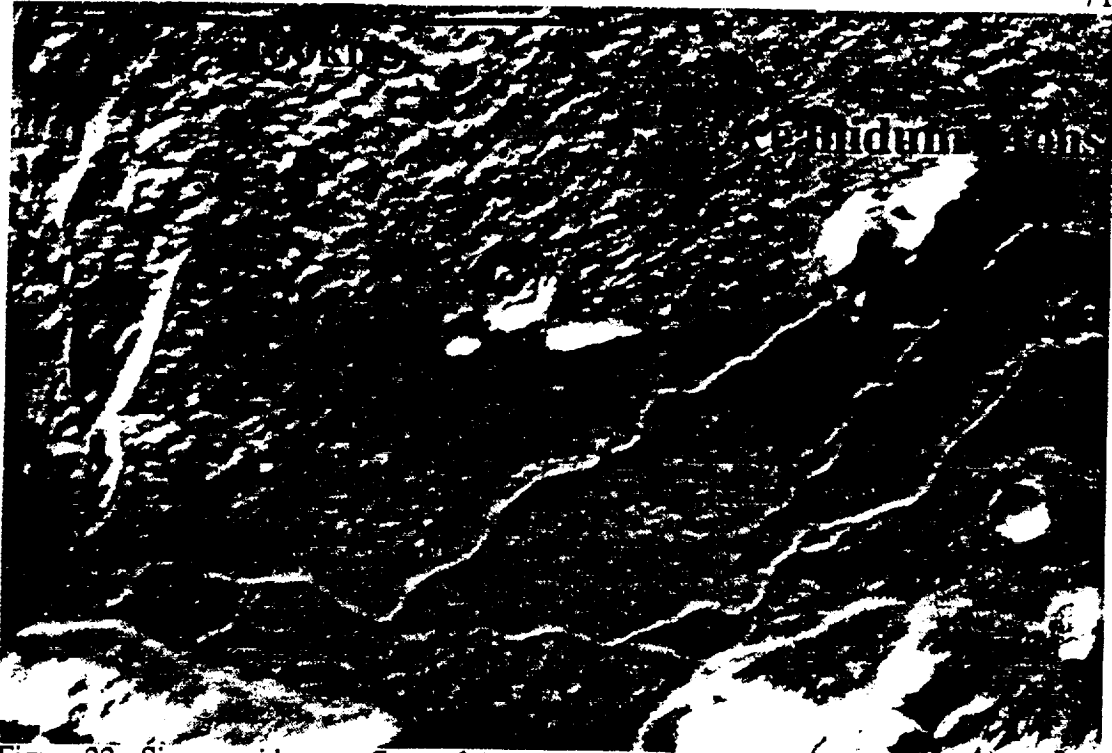


Figure 22: Sinuous ridges on floor of Argyre Planitia. Mission to Mars CD-Rom: Digital Image Map Volume 6: Portion of File MI55S043, 231m/pixel, USGS.

as a requirement for their origin. The ridges in central and southern Argyre represent the best-imaged examples of this ridge type by the Viking Orbiters.

I am considering a range of sedimentary processes to explain the development of the ridges and layered plains. Three favored interpretations (which seem to make the most sense) include glacial (Howard, 1981; Kargel and Strom, 1990; 1991), fluvial and lacustrine (Parker et al., 1986b), and eolian (Ruff and Greeley, 1990; Ruff, 1991) processes. Of these three, the first two seem to explain the Argyre ridges best, because they appear directly associated with the mouth of Surius Vallis, a large valley network emptying into Argyre.

As glacial analogs, the ridges resemble eskers (e.g., Howard, 1981, Kargel and Strom, 1990, 1991), evidenced by one or two examples of anastomosing

or braided segments. However, no outwash deposits can be identified with the termini of any of the ridges. In addition they trend, for the most part, along the southern margin of the basin east of *Surius Vallis*, rather than into the central, presumably lowest part of the basin. For this reason, I favor a lacustrine model, in which the ridges are wave-generated barriers sourced from *Surius Vallis*. The ridges radial to *Surius Vallis* begin east of the channel mouth and all form broad counterclockwise arcs across the basin floor. This might indicate a dominant wind direction toward the southeast, with wave energy tending to deflect channel outwash sediments toward the east along the basin margin.

The difficulty in applying either a glacial or lacustrine model to the sinuous ridges is emphasized by considering their distribution around the planet, as outlined above. In other words, while it might be reasonable to expect glaciation at moderate to high latitudes on Mars, the sinuous ridge in *Aeolis* is nearly equatorial and at a low elevation, implying a need for global glaciation. Likewise, while lakes might have been stable on Mars at low to moderate latitudes at various times in its past (the *Aeolis* ridge lies within the gradational boundary "shoreline" described by Parker et al., 1989, 1993), sinuous ridges in the South Polar Basin would imply a need for global temperatures above freezing, difficult to do with even the most "optimistic" paleoclimate models. Perhaps in the final analysis, emplacement of the layered plains and sinuous ridges in *Argyre* involved both processes, possibly even a cycling from one to the other as the planet's climate changed over time.

Stratigraphy and Structure

Stratigraphic placement of the mapped units is based primarily on superposition relationships identified in the Viking images. These relative age determinations were then supplemented by crater size-frequency measurements of the major units in the two southern quadrangles, which allow placement of the units in the Martian time-stratigraphic systems. The reader is directed to Appendix I for a comparison of the Martian time-stratigraphic systems to those of Earth and the moon, and to Appendix II for the cumulative crater size-frequency distribution plots for six of the major basin interior units in Argyre Planitia.

Craters were classified based on their state of preservation and inferred stratigraphic position relative to surrounding units. Determining the stratigraphic position of craters within Argyre is complicated by erosional processes that may have been active over geologic time, particularly within the basin interior units. In addition, all four map quadrangles in this region experience advance and retreat of the seasonal ice cap, and therefore are likely to have been subjected to slow surface frost creep over geologic time. The depth of erosional pitting within the interior plains appears to indicate that the basin interior units are relatively thick, so that it is likely that craters smaller than about 1-2km in diameter postdate, at least, the initial emplacement of the interior plains materials, regardless of their state of preservation. For this reason, even moderately degraded craters less than about 2 km in diameter within these plains were included in crater size-frequency determinations.

Two types of crater counts were made in order to compare the degrees and styles of crater degradation from one unit to another: (I) Total cumulative

populations - all craters visible, including ghosts; and (II) superposed craters, to the extent that their relationship to the unit counted could be determined. Total cumulative plots, while they cannot give absolute ages for surfaces that have undergone multiple degradational events, may be useful for highlighting the degradational history of a unit as well as its efficacy at obliterating old, large craters.

Crater counts were made of the most areally extensive units in MTM -55036 and -55043 and compared with superpositional relationships to determine unit ages. These will be combined with counts of MTM -50036 and -50043 upon completion of mapping in those quadrangles. Other units may be too limited in area or too steep (dominated by a talus) to give reliable counts, but exhibit clear stratigraphic relationships to counted units.

Noachian System (From 4.6Ga to 3.5-3.8Ga)

The oldest exposed materials in the southern Argyre region are hilly to mountainous units Nplh₁ and Nplh₂. These units are comparable to the hilly unit of the plateau sequence (Nplh) described by Scott and Tanaka (1986) and Tanaka and Scott (1987) in the Western Hemisphere and Polar Regions 1:15,000,000 scale geologic maps. Earlier, Hodges (1980) mapped the Argyre rim mountains as unit ar, for Argyre Basin Rim Material. She also separated the Galle crater rim and ejecta as a crater unit, c₁ (Hodges, 1980). Separation of the Nplh units corresponds, for the most part, with Hodges' (1980) delineation, with the inclusion of parts of her unit pk included in unit Nplh₂. These rugged units comprise ancient crater rim material associated with the southern rim of the Argyre basin (Charitum Montes) and superposed large, degraded impact craters (Nplh₁) and the rim and ejecta material from the crater

Galle (Nplh₂). Unit Nplh₂ exhibits occasional longitudinal pits with raised rims oriented radial to Galle (e.g., Chalce Fossa, 52°S lat., 39.5° lon., MTM -50036), supporting the inference that the unit consists, at least in part, of Galle ejecta not buried by younger plains units due to local topographic relief.

Several interior massifs protruding through the plains in southern Argyre (e.g., Oceanidum Mons = Charitum Tholus on earlier maps, Octantis Mons) may be part of a discontinuous or poorly developed inner basin ring. An arc of similar massifs (Chalce Montes, 53.5°S-54.5°S lat., 36.5°-38.5° lon.) appears to be the highly degraded remnants of a 140km crater superposed on Argyre. This crater and other large degraded craters elsewhere within the Argyre basin (e.g., Hooke Crater at 45°S lat., 45° lon.) attest to the advanced state of degradation or burial of nearly all but the smallest craters within the basin interior.

Next in age is the first of the basin-filling plains materials that comprise the Argyre Planitia Assemblage (unit Naph), defined as Argyre Planitia hummocky plains; the unit is exposed within the southern rim mountains and along the margin of the interior of the basin. It exhibits a moderately high density of superposed craters, suggesting an upper Noachian age (see Appendix II), with older massifs of Charitum Montes protruding through it in places. It appears to dip gently basinward beneath the younger plains materials in the basin interior. This unit is comparable to unit pk, or Knobby Plains described by Hodges (1980) as "sparsely cratered deposits grading into smooth plains material... ..but with numerous small hillocks". The much higher resolution Viking Orbiter image data used to compile the present base maps has enabled us to further delineate this unit from the much less cratered basin interior units

and debris aprons within the southern rim mountains, thereby revealing its relatively high crater density.

Hesperian System (From 3.5-3.8Ga to 1.8-3.55Ga)

Channel materials. Unit Naph is cut in at least two places by large valley networks that flowed into the basin from the south, probably during Hesperian time (Tanaka and Scott, 1987). These valley networks are Surlus Vallis (57.5°S lat. 46.5° lon., MTM -55043) and Dzigai Vallis (56°S-57.5°S lat., 38° lon., MTM -55036). A third, unnamed valley network appears to have drained into the basin from the southeast at 54.2°S latitude, 33.3° longitude (MTM -55036), southwest of the crater Galle. This third channel is superposed in the map area by a much younger, small outflow channel (Nia Valles), that will be described below. The valley networks all lie within deeply incised, relatively narrow rectangular or U-shaped valleys where they cut through the basin's rim mountains and inter mountain plains. This suggests modest discharges into the basin for sustained periods of time, or multiple episodes of discharge, or both.

The mouth of Palacopas Vallis lies entirely outside the map area. Because the younger Nia Valles and its outwash deposits obscures the mouth, it is difficult to assess this channel's age relative to the other two valley networks. The mouth of Dzigai Vallis simply fades into the basin interior plains, with no evidence of either fan or delta deposits exposed at the surface within the basin. Dzigai Vallis is therefore interpreted to predate emplacement of the basin interior plains surface materials, though it may have contributed to their emplacement at an earlier time. Surlus Vallis appears to be the most recently active of the three valley networks. Many of the unusual sinuous ridges on

the basin floor appear to emanate from near the mouth of this valley and the plains in the vicinity exhibit a "fabric" that is radial to the mouth of the channel (see Hapl₁, below).

Plains Materials. Next youngest of the plains units of the Argyre Planitia Assemblage is unit Hapl₁, for layered Argyre Plains unit 1. Hodges (1980) designated this unit (and units AHaple and AHape, below) as unit ps, or smooth plains material, composed of unconsolidated eolian and fluvial deposits (from Surlus and Dzigai Vallis) of substantial thickness. Unit Hapl₁ consists of relatively flat to slightly undulating plains containing prominent sinuous ridges in map quadrangles MTM -50036, -55036, -55043. This unit appears to be equivalent to similar material embaying the Nereidum Montes rim mountains on basin's north and west sides. The plains surface exhibits a subtle pattern of radiating albedo markings from the vicinity of the mouth of Surlus Vallis, suggesting a direct link between sediment discharge from the channel and accumulation of the layered material comprising unit Hapl₁. This fabric is most evident in the local radial distribution of the large sinuous ridges in this part of the basin. This association between the layered plains and Surlus Vallis suggests a fluvial and/or lacustrine origin for the plains materials. Crater size-frequency plots (Appendix II) suggest a late Hesperian to early Amazonian age for the near-surface materials of unit Hapl₁, somewhat younger than the proposed source deposits in Tanaka and Scott's (1987) unit Hd1.

Amazonian System (From 1.8-3.55Ga to 0Ga)

Plains and Channel Materials. The Etched Layered plains, designated unit AHaple, is the most extensive unit in the Argyre interior. This unit

consists of a surface that appears to have developed through the erosional etching of unit Hapl₁ and, to a lesser extent, the etching of unit AHapl₂ (described below). The margins of the etch pits are sharply-defined, very irregular, and often exhibit prominent layering within their walls (figure 23). Abundant wind streaks, dunes, and possible yardangs in the northern half of basin suggest that this etching is produced through eolian deflation of friable materials. This inference is supported by observations by ground-based observers and by the Viking Orbiters that some modern planet-encircling dust storms appear to originate within Argyre. Crater ages (Appendix II) and examination of the shape of the total cumulative curve suggest initiation of deflation during upper Hesperian time, with continued but reduced activity continuing well into the Amazonian and perhaps to the present day.

Unconformably overlying this etched plains surface is a second layered unit, or Layered Plains Material 2, designated AHapl₂. This unit is an areally restricted unit in quadrangles MTM -50043 and -55043, near the center of the basin. It occurs as patches of relatively very smooth, planar surfaces stratigraphically overlying the etched layered plains surface. Several large, rimless pits in Octantis Cavi (53°S lat., 46° lon., MTM -55043) exhibit good evidence of layering. In addition, the unit also appears etched or deflated at its margins (figure 23). I have interpreted this unit as lacustrine sediments from Nia Valles influx into the lowest part of the basin's interior, based largely on its very smooth, planar expression and its location beyond the last detectable reach of Nia Valles (53°S lat., 42-43° lon., MTM -55043).

Nia Valles comprises two map units: Channel Material and Channel Floodplain Material. The Channel material consists of longitudinally scoured

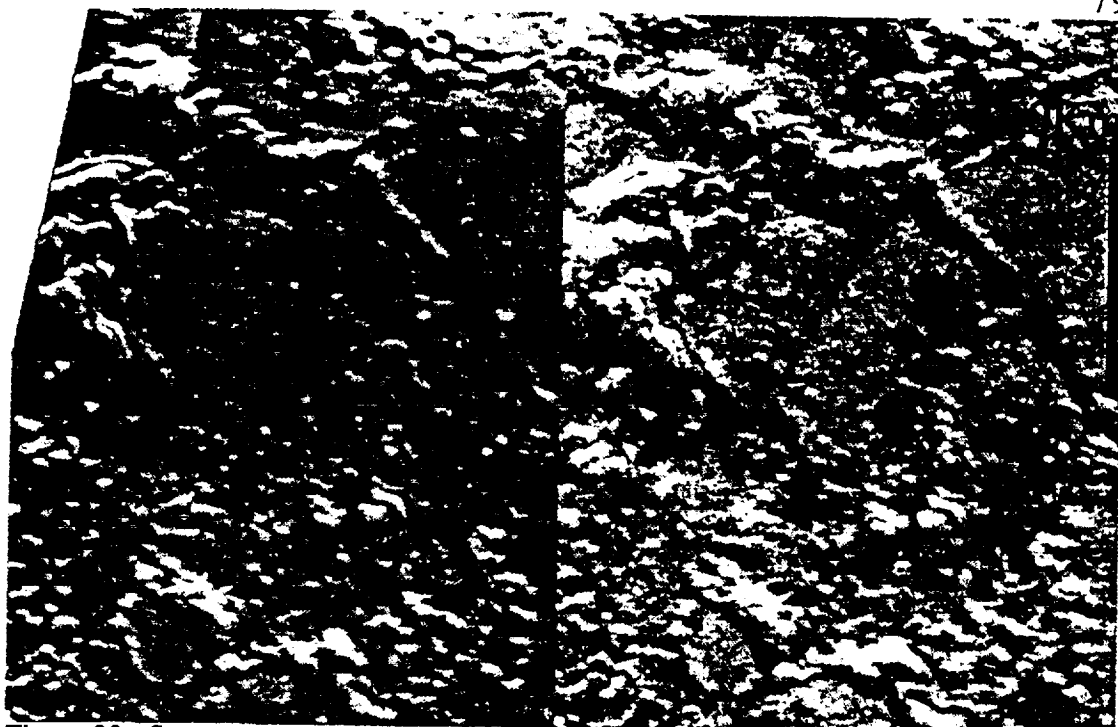


Figure 23: Stereo image pair of etched layering within unit Hapl1 and AHaple, central southern Argyre Planitia. Note terracing in large pits at left of scene. Viking Orbiter images 567b36 and 568b03. North is toward bottom right.

surfaces and streamlined structures that are usually confined to a distinct channel. This small outflow channel breaches a complex topographic barrier (53-55°S lat., 34-36° lon., MTM -55036) in at least four places, with major flows being deflected both to the north and south of it. Upstream from the barrier, the floodwaters appear to have been temporarily ponded, locally forming a broad, shallow lake (unit AHchp). Expansion reaches downstream from the barrier and streamlined structures that appear to be depositional bars were delineated as unit AHchp as well. In these reaches, channel scouring appears minimal or absent, suggesting local shallow depressions or downstream barriers to flow. Scour morphology can be easily seen in disconnected reaches westward to at least 39° longitude (MTM -55036) though faint relics, subject to the same etching that produced the AHaple

surface, are mapped as far west as 43° longitude in MTM -55043. Crater size-frequency plots of the Nia Valles materials and unit AHap12 (Appendix II) appear similar and suggest an upper Hesperian to lower Amazonian age for these units, but the errors are large due to its limited area.

An additional plains unit, AHape, for Elevated Plains material (AHapee, for etched Elevated Plains material) was mapped in MTM -50036, MTM -50043, and MTM -55036. This plains unit is slightly elevated relative to the neighboring layered plains and etched layered plains (most evident in MTM -50036 and MTM -50043). It has a largely featureless surface, but exhibits some evidence of linear to arcuate dark striae (at $49.5\text{-}50.5^\circ\text{S}$ lat., $41\text{-}43^\circ$ lon., MTM -50043). It also occasionally exhibits pitting, similar to that seen in unit Hap1 in southern MTM -55043, where etching of that unit is not so advanced as it is toward the basin center. It is unclear whether this unit stratigraphically overlies and is therefore younger, or is an earlier, thick unit that is overlapped by layered plains material at its margin (crater counts have not been made of this unit to date). Unit AHape may consist of eolian material blown out of deflation hollows elsewhere in Argyre if it is demonstrably younger than those plains. Alternatively, it may be some kind of thick lava flow unit, in which case it could predate the other plains surfaces.

Surficial Deposits. Four mappable surficial deposits were identified. These are defined as Slide Material and Gently-Sloping Slide Material (As1 and As2), Draped Plains material (Aapd) and Dune material (Ad). The slide material units are specific local materials equivalent to global unit As in Scott and Tanaka (1986) and Tanaka and Scott (1987). Unit As1 consists of prominent debris aprons surrounding massifs in Charitum Montes south of about 55°S latitude. The largest aprons are associated with the innermost,

tallest rim mountains. Southward (toward the outer Charitum Montes rim), they decrease rapidly in size and extent, until the outermost massifs appear to lack debris aprons altogether.

The As₁ debris aprons exhibit well-defined radial striations, pointing to a downslope flow or creep process, and an apparent parabolic toe profile. These surface morphologies suggest a rock-glacier or other similar periglacial origin for the debris aprons. Small, sharply defined craters, though rare, are present on several debris apron surfaces. Crater size-frequency counts point to an upper Amazonian age for unit As₁ (Appendix II).

The smaller surficial slide unit, As₂, occurs as a single local unit in MTM -55043 extending from beyond the base of unit As₁ for about 30km across the interior plains surface in a reentrant of the plains into Charitum Montes (at 57-57.5°S lat., 43° lon.). This unit is interpreted as a possibly more fluidized flow than the material comprising unit As₁.

The Draped Plains unit is so designated because it appears to blanket older terrain, including hilly terrain in the MTM -50036 quadrangle. This unit is very lightly cratered, and may be partially composed of modern eolian material blown out of deflation hollows elsewhere in the basin.

Recognizable dunes are relatively uncommon in the southern part of Argyre, though there are several fields within craters and against obstructions in the northern half of the basin. Small patches of dunes can be seen in quadrangles MTM -50036 and MTM -50043.

Geologic History

The geologic history that I have inferred for the southern Argyre region from superposition and age relationships from this and surrounding units is

punctuated by several key events (see also Correlation Chart, Appendix II).

These are, from earliest to most recent:

1. The oldest recorded event in the map region is the impact that formed the Argyre Basin during Noachian time.
2. Initial filling of Argyre interior with volcanic and sedimentary materials - unit Naph. Formation of crater Galle and other large craters during upper Noachian time.
3. Drainage of large lake within Argyre during upper Noachian and lower Hesperian time is indicated by evidence of flow from basin northward through Uzboi Vallis. Topographic barrier to flow appears to have been restored by formation of 100km crater Bond.
4. Earliest preserved evidence for channel flow into Argyre from three large valley networks through southern rim of Argyre seems to indicate a lower to upper Hesperian age, based on crater ages of basin-wide layered deposits. This water may have been derived through basal melting of a relatively thick and more extensive ancestral south polar ice cap than the present cap, or surface melting and runoff, or both. Large lakes may have been present in Argyre at this time. These may have been either ephemeral or permanent and possibly ice-covered.
5. Eolian deflation of layered plains occurs while basin interior is dry and unprotected by an ice cover during upper Hesperian to lower Amazonian time. These conditions may have increased in duration at this time as influx from valley networks decreased to below the loss rate due to evaporation/sublimation and percolation within the basin, modulated by the planet's Milankovitch climate cycles, which are more extreme than are those on Earth (e.g., Toon et al., 1980).

6. Small Scale catastrophic flood through Nia Valles into basin interior and onto partially etched layered plains occurred probably during lower Amazonian time, but possibly as early as upper Hesperian time.

7. Eolian deflation of layered plains, including lacustrine sediments from Nia Valles, continued throughout Amazonian time to the present day, where modern dust storms have been observed. Elevated Plains and Draped Argyre Plains units may be material blown out of deflation hollows in central and southern Argyre.

8. Formation of debris aprons, probably rock glaciers in southern Argyre, particularly around tallest massifs in inner portion of Charitum Montes rim mountains, during upper Amazonian time.

9. Localized dune deposits probably are modern.

APPENDIX I - CHRONOLOGY FOR THE EARTH, MOON, AND MARS
 COMPARED

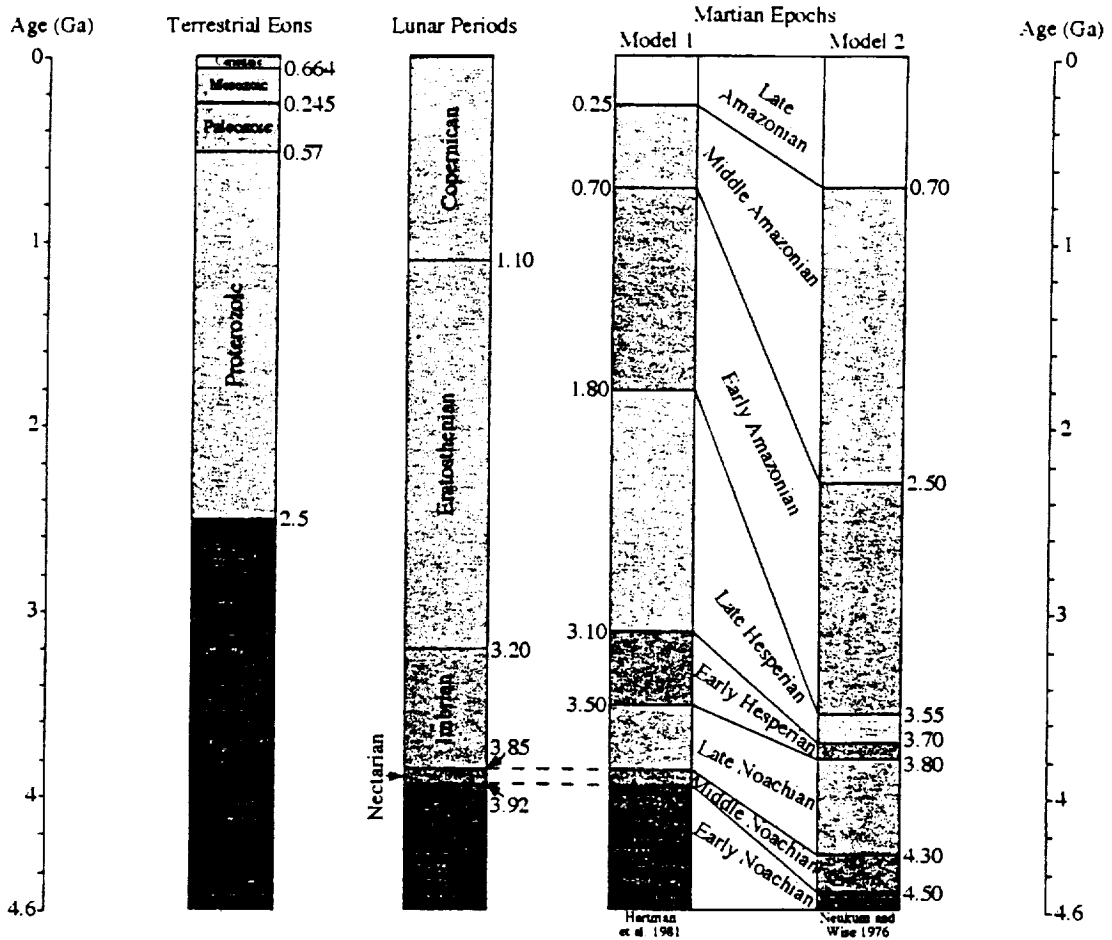



Figure 48: Chronologies for the Earth, moon and Mars (adapted from Tanaka, 1986).


APPENDIX II - DESCRIPTION AND TIMING OF MAP UNITS, ARGYRE
PLANITIA


Description of Map Units

Following are unit descriptions for the four quadrangles (figures 17-20).


Surficial Materials



 Ad - Dune material. Localized dunes and dune fields in quads MTM -50036 and -50043. Individual dune forms indistinct. material may be either light or dark. *Interpretation:* Modern eolian transport of sand-size material.


 As₁ - Slide material. Prominent debris aprons surrounding massifs in Charitum Montes in quads MTM -55036 and -55043. Exhibit radial striations and apparent parabolic toe profile shape. *Interpretation:* Radial striae and apparent parabolic toe profiles suggest rock-glacier or other similar periglacial origin.


 As₂ - Gently-sloping slide material. Single local unit in quad MTM -55043 at base of unit As₁. *Interpretation:* More fluid material flow than unit As₁. Alternatively, it may represent a local eolian blanket.

Plains Materials: Argyre Planitia Assemblage


 Aapd - Draped Argyre Plains Material. Expansive unit northwest of crater Galle in MTM -50036. Lightly cratered, exhibits "draped" appearance of older plateau and mountain materials. *Interpretation:* Draped appearance suggests air-fall or eolian origin. May be eolian material derived from deflation of plains interior deposits.

 AHapee and  AHape - Etched Elevated Argyre Plains and Elevated Argyre Plains material. Slightly elevated plains unit relative to neighboring layered plains and etched layered plains. Unit is most extensive in quadrangle MTM -50036, with small occurrences in MTM -50043 and -55036. Largely featureless, but with some evidence of linear to arcuate dark striae and pitting in MTM -50036. Stratigraphic position relative to layered plains material (Hapl₁ and AHaple, below) is unclear. Unit may overly layered plains or it may predate them, with the layered plains onlapping its elevated margin. *Interpretation:* Unit may represent eolian material blown out of deflation hollows in central and southern Argyre if it is demonstrably younger than the layered plains materials. Alternatively, unit may be a flow unit emplaced onto or onlapped at its margin by the layered plains materials. However, no source vent can be found to support this interpretation.

 AHapl₂ - Layered Argyre Plains material 2. Areal restricted unit in quads MTM -50043 and -55043. Occurs as patches of relatively very smooth, planar surfaces unconformably overlying etched layered plains material (AHaple, below). The unit exhibits several large, rimless pits with good evidence of layering in the pit walls and appears deflated at its margin. *Interpretation:* Lacustrine or fluviolacustrine deposits from Nia Valles influx into topographically lowest part of basin and onto partially etched unit AHaple. Etching of unit AHapl₂ may indicate eolian deflation of sediments after cessation of discharge from Nia Valles.

 AHaple - Etched Layered Argyre Plains material. Areal extensive unit throughout much of Argyre interior. Margins of etched pits are sharply-defined, very irregular, and often exhibit prominent layering within

their walls. Appears to have developed by etching of unit Hapl₁ and, to a lesser extent, etching of unit AHapl₂ unit (above). *Interpretation:* Abundant wind streaks, dunes, and yardangs in this unit in the northern half of the basin suggest that this surface developed through eolian deflation of friable materials comprising unit Hapl₁ (below). Some modern planet-encircling dust storms appear to originate within Argyre, so evolution of this surface has likely continued to the present.

 Hapl₁ - Layered Argyre Plains material 1. Relatively flat to slightly undulating plains containing prominent sinuous ridges in quads MTM -50043, -55036, and -55043. Appears equivalent to similar unit embaying Nereidum Montes on basin's north and west sides. *Interpretation:* Lacustrine or glaciolacustrine sedimentary unit derived from large valley networks radial to basin.

Subunit Hr - Sinuous ridges integral with surrounding units Hapl₁ and AHaple. Ridges can be as much as 200km or more long and typically 1 or 2km wide and a few tens of meters high. They exhibit etching similar to surrounding plains materials and also display layering contiguous with surrounding plains. Most of the ridges in Argyre appear to radiate from just east of the mouth of Surlus Vallis, with the more prominent ridges tending to follow the southern margin of the basin's interior. These appear to branch and rejoin or anastomose in some places. A second set of ridges is found north of Oceanidum Mons and trends northwest across the interior of the basin, with individual ridges trending subparallel to one another. No obvious depositional fans or outwash regions have been identified with any of the ridges. *Interpretation:* Sedimentary structures emplaced contemporaneously with plains layered sediments from Surlus Vallis. Possibly lacustrine barriers,

glaciofluvial eskers, or a unique type of structure produced through a combination or cycling of the two processes.

The ridges have been subdivided into three classes based on their apparent state of preservation. This classification includes both positive relief structures and "inverted" structures where etching of a ridge appears more advanced than that of the surrounding plains.



Hr1 - Well defined sinuous ridges exhibiting sharp outlines and crests.



Hr2 - Moderately defined sinuous ridges, rounded or exhibiting indistinct crests and/or partly etched. May also occur as topographically inverted troughs (etched) grading into positive relief ridges. Where they are etched, they display layering similar to or continuous with that of the surrounding plains.



Hr3 - Poorly defined sinuous ridges exhibiting very indistinct outlines and typically low profiles and indistinct crests. Commonly occur as topographically inverted troughs within etched layered terrain.




Naph - Hummocky Argyre Plains material. Plains along southeast basin margin within inner Charitum Montes massifs in quads MTM -55036 and -55043. Elevated slightly above and sloping into and beneath basin interior plains materials. *Interpretation:* Initial basin filling plains unit or erosional surface. Possibly consisting of eroded flood lavas or fluvial sediments.


Valles Materials



AHchp - Channel floodplain material. Plains material in expansions of Nia Valles. May occur as unscoured surfaces between


segments of clear channel or as expansions beyond the lateral margins of the channel. Several streamlined structures within the channel were also so mapped where they appeared to be depositional features associated with the channel rather than erosional remnants of older surfaces. *Interpretation:* Fluvialacustrine plains and depositional bars emplaced during small-scale catastrophic flood that formed Nia Valles. Fluvialacustrine plains likely formed as channel encountered shallow depressions in pre-flood topography or topographic barriers downstream.


 AHch - Channel material. Scoured terrain exhibiting longitudinal striae and streamlined structures indicative of channelized fluid flow in Nia Valles. *Interpretation:* Relatively small-scale (for Mars) catastrophic flood channel that flowed into and across the interior of Argyre Basin.

 Hch - Channel material. Large-scale valley networks radial to Argyre. 1) Collectively includes wall and floor materials of Surius Vallis, a large, incised valley network entering the Argyre interior from the south in quadrangle MTM -55043. No channel scour morphology is visible on the valley floor (typical of Martian valley networks). Mouth of Surius Vallis appears to have been source for large sinuous ridges within basin. *Interpretation:* Channel of modest-scale, relatively long duration discharge into Argyre Basin, sourced near south polar plains materials. Association of sinuous ridges with mouth of Surius Vallis suggests that it was the most recently active of the valley networks draining into the basin interior. 2) Narrow, shallow terminus of Dzigai Vallis entering Argyre Basin interior in south-central portion of quadrangle MTM -55036 and cutting unit Naph. No fan or delta deposits can be identified within Argyre interior plains at the mouth of Dzigai Vallis. *Interpretation:* Channel of modest-scale, relatively

long duration discharge into Argyre Basin, sourced near south polar plains materials. Lack of fan or delta materials at valley mouth suggests Dzigai Vallis ceased being active prior to emplacement of uppermost layers of unit Hapl₁.


Plateau and Mountain Materials

 Nplh₂ - Hilly to mountainous material. Occurs primarily south and west of Galle Crater in quads MTM -50036 and -55036. Contains longitudinal pits with raised rims radial to Galle Crater. *Interpretation:* Unit probably represents ejecta from Galle and other large, ancient impact craters that were not buried by later plains units because of local topographic relief. Relatively softened appearance locally may reflect eolian mantling.

 Nplh₁ - Mountainous material. Southern Argyre Basin rim massifs (Charitum Montes) in quads MTM -50036, -55036, and -55043.

Interpretation: Erosional remnants of Martian lithosphere disrupted during Argyre-forming impact. Several interior massifs within Argyre (for example, Oceanidum Mons) may be part of a discontinuous inner basin ring. Others (Chalce Montes) may be highly degraded remnants of a large crater superposed on Argyre.

Crater Materials

 Craters were classified into four categories based on their state of preservation and inferred stratigraphic position relative to surrounding units (greatly simplified in figures 17-20). These classifications were made for all recognizable craters for the purpose of unit age determinations based on size-frequency distributions. Determining the stratigraphic relationships between craters and plains units within Argyre is complicated by the etching of the

layered material and by modern eolian activity within Argyre and the implication that this likely has continued over geologic time. In addition, all four map quadrangles in this region experience advance and retreat of the seasonal ice cap, and therefore are likely have been subjected to slow surface frost creep over geologic time. Etching of the interior layered terrain has produced deep pits throughout much of the map area, particularly in quadrangles MTM -50043 and -55043, that suggest even moderately degraded craters less than a few kilometers in size within the plains must be included in crater size-frequency determinations. Craters larger than about 5km diameter (and their ejecta where recognized) are indicated by class on the associated maps.

All craters visible within the map units were counted, classifying them as C1-C4 based on their state of preservation. Only the freshest craters (C3 and C4) were used to compile the cumulative plots and making age determinations, except in the case of the three interior plains units, which often exhibit pitting to an apparent depth greater than that of small craters within them. Each crater was then counted or not counted on an individual basis, depending on whether local pitting appeared to indicate that the crater was beneath or on top of the interior plains units (presumably some layered sedimentary deposit). Eolian modification of the interior of Argyre is extensive, particularly toward the basin center, so it is important to try to both date the emplacement of layered plains materials, which may be fluvial, glacial, or lacustrine, and also provide some sense of the eolian etching history of those materials. And this is why the Etched Basin Interior Plains unit (AHaple) is mapped as a separate unit from Basin Interior Plains units 1 and 2,

though it is probably composed of the same materials, because its surface represents the eolian erosional history of those materials.

C4 - Well preserved crater materials. Craters exhibit pronounced, raised rims and rugged surface textures relative to surrounding materials. Ejecta blankets often are sharply delineated flow-margin deposits. Large craters may exhibit prominent central peaks (e.g., Milford Crater at 53°S lat., 41.5° lon., MTM -55043, ~20km diameter). *Interpretation:* Freshest craters, likely indicative of relative youth, but preservation is probably, in part, a function of crater diameter and local geologic processes. Small C4 craters are likely very young, particularly those within the basin interior, as these are subject to the etching of the interior plains materials, including modern eolian activity, as well as seasonal cap advance and retreat.

C3 - Moderately-preserved crater materials. Craters with or without raised rims, generally with flat floors, yet still distinct from surrounding units. Limits of ejecta seldom discernible. Crater Lodwar (55.5°S lat., 43.5 lon., MTM -55043, ~15km diameter) is unusual in that it exhibits a central peak but lacks a raised rim or recognizable ejecta deposits. *Interpretation:* Craters of moderate age or small, young craters in relatively erodable materials that have experienced a fair amount of plains etching and/or seasonal cap advance and retreat, and local fluvial or lacustrine burial or reworking.

C2 - Poorly-preserved crater materials. Craters without raised rims. Flat floors may be only slightly depressed relative to surrounding surface. Nevertheless, C2 craters are easily recognizable as craters. *Interpretation:* Generally old large craters or young to moderate age small craters that have been subjected locally to fluvial, glacial/periglacial, lacustrine, and eolian burial and reworking.

C1 - Highly degraded crater materials. Extremely degraded, or ghost craters. Rims tend to be level with surrounding surface and/or are incomplete. Larger ghost craters may exhibit rims comprised solely of broken chains of hills or mountains (above several kilometers in diameter). Floors tend to be level with surrounding units, making recognition of the crater difficult unless subsequent processes work to enhance the crater's outline (e.g., the crater Mari, 52.5°S lat., 46° lon., MTM -50043 -55043, has been pronounced by formation of Octantis Cavi). *Interpretation:* Generally very oldest craters, or small, moderate-age to old craters that have undergone extensive erosion or burial over much of Martian geologic history. Large C1 craters (several tens of km diameter) likely rank among the oldest craters on the planet.

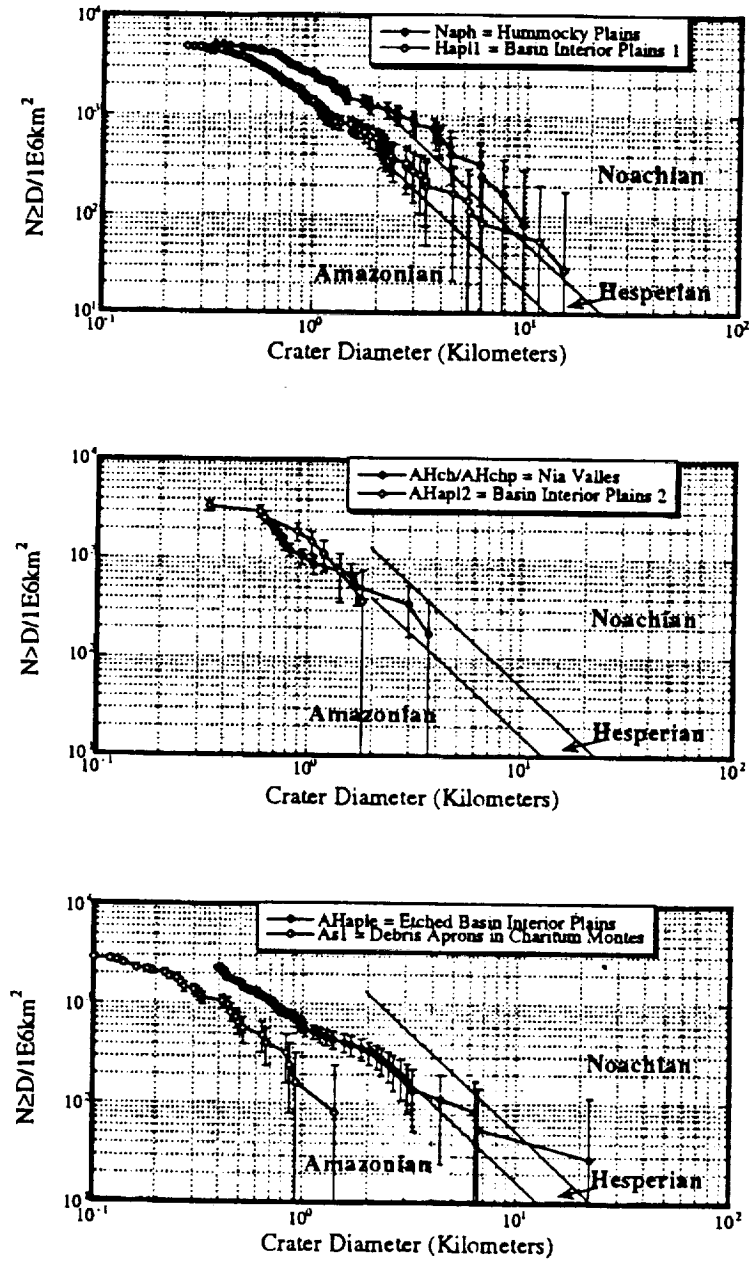


Figure 49: Cumulative crater size-frequency distributions for the major Argyre plains interior units. Time systems after Tanaka (1986).

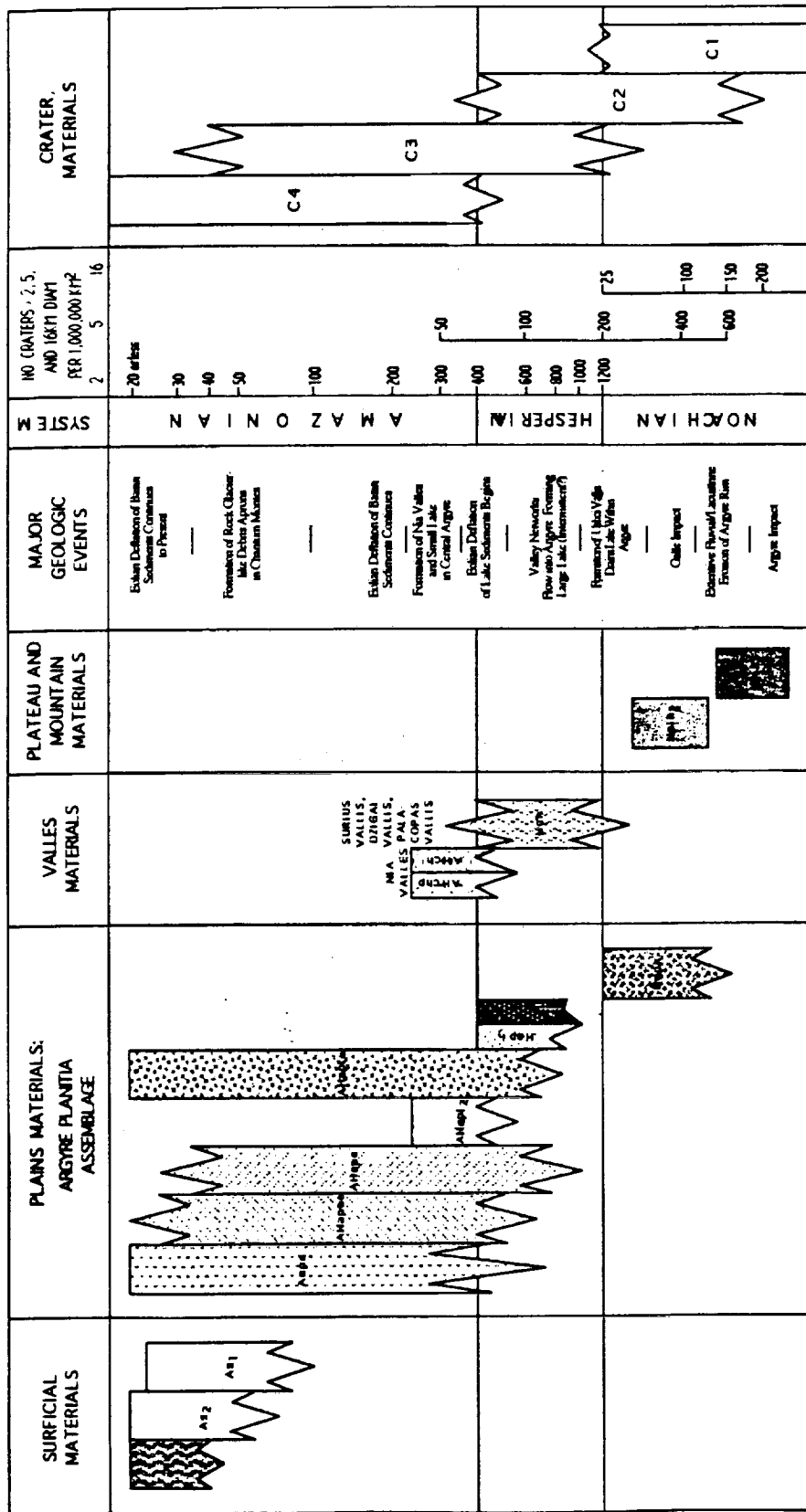


Figure 50: Correlation of Map Units, Argyre Planitia.