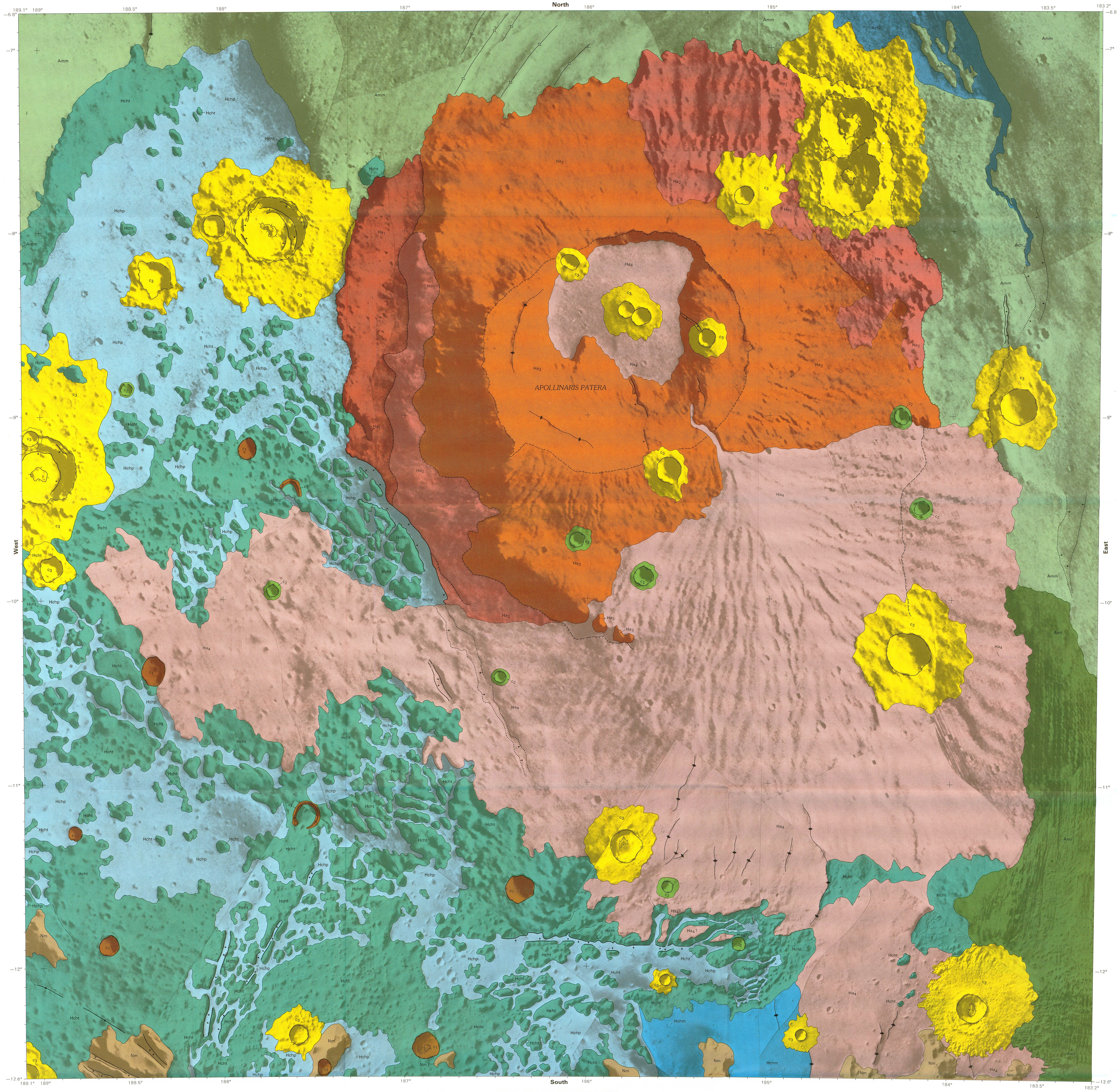
U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Prepared for the
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

ATLAS OF MARS
1:500,000 GEOLOGIC SERIES
APOLLINARIS PATERA REGION
MTM -10186 G, 1993
MAP I-2351



Base (unpublished) by U.S. Geological Survey

SCALE 1:502 000 (1 mm = 502 m) AT 190° LONGITUDE
TRANSVERSE MERCATOR PROJECTION

10 0 10 20 30 40 50 60 70 80 90 100
KILOMETERS

INTERIOR—GEOLOGICAL SURVEY, RESTON, VA—1993

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GEOLOGIC MAP OF SCIENCE STUDY AREA 8, APOLLINARIS PATERA REGION OF MARS

(SPECIAL MTM -10186 QUADRANGLE)

By
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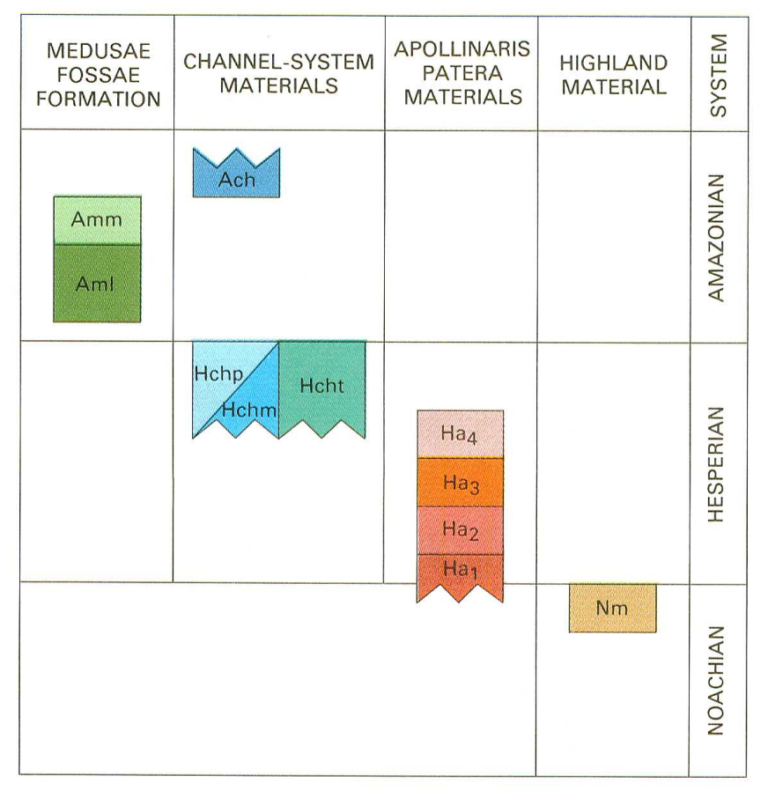
1993

CORRELATION OF MAP UNITS



DESCRIPTION OF MAP UNITS

MEDUSAE FOSSAE FORMATION

[The Medusae Fossae Formation has been interpreted to consist of ash-flow tuffs (Malin, 1979; Scott and Tanaka, 1982, 1986). Only a small part of the formation occurs in the map area]

Amm **Middle member**—Forms smooth, gently rolling surface with long, low, streamlined ridges (interpreted as yardangs) in northern part of map area. Overlaps Apollinaris lava flows, flood-plain deposits, and chaotic material; covered by younger channel deposits in northeastern part of map area; a moderate-size crater appears to be superposed

Aml **Lower member**—Surface darker and rougher than surface of middle member; deeply scoured into narrow ridges and grooves. Overlies youngest lava flow from Apollinaris and chaotic material

CHANNEL-SYSTEM MATERIALS

Ach **Younger channel material**—Occurs on floor of small channel cutting middle member of Medusae Fossae Formation and covers a low-lying area northeast of Apollinaris. *Interpretation:* Material deposited by flowing water surrounding ridges that are eroded remnants of Medusae Fossae Formation

Hchp **Flood-plain material**—Generally smooth surface; covers large, low area west of Apollinaris Patera; embays dissected hills and mesas of chaotic material. *Interpretation:* Channel and flood-plain deposits

Hcht **Chaotic material**—Forms irregular patches of hills and mesas rising above flood-plain material in western part of map area; hills and mesas have roughly uniform height but are lower than Noachian massifs. In places unit appears gradational with both massifs and lava flows from Apollinaris. *Interpretation:* A mélange of ancient highland rocks and Apollinaris lava flows disintegrated by melting of ground ice and dissected by flooding from channels in highlands and by earlier outflows from Ma'adim Vallis

Hchm **Channel material of Ma'adim Vallis**—Smooth, flat surface with few small ridges; in southeastern part of map area; albedo moderate to low. Material dissected in places at boundary with chaotic material. Channel partly blocked by crater ejecta south of map area. *Interpretation:* Fluvial deposits from Ma'adim Vallis. Local disintegration and collapse have contributed to formation of chaotic material

APOLLINARIS PATERA MATERIALS

[Apollinaris is a medium-size (about 200-km-diameter) volcano having morphologic characteristics of a shield-type structure in its lower part and a composite structure at its crest. The following four lava-flow units recognized from Apollinaris are distinguished on the basis of age; all are interpreted to be basaltic in composition]

Ha_4 **Unit 4**—Two occurrences: Smooth flow covers floor of caldera; fan-shaped flow covering south flank of Apollinaris is radially furrowed and ridged, contains wrinkle ridges in lower part; covers basal scarp and other scarps on flanks of volcano. *Interpretation:* Youngest lava-flow unit on Apollinaris; postdates all faults around volcano. Radial furrows may be due to fluvial erosion or may be overlapping, braided lava-flow lobes; wrinkle ridges may be surface expression of dikes

Ha_3 **Unit 3**—Forms upper flanks of Apollinaris; evenly spaced grooves extend down flanks of upper, steeper part of structure. *Interpretation:* Lower part of unit consists of lava flows, upper part of lava and pyroclastic material

Ha_2 **Unit 2**—Smooth to hackly surface; conspicuous valleys and ridges in northeastern exposure; scarp marks most of basal contact. Largest exposures appear more deeply eroded. *Interpretation:* Lava flow(s), deeply eroded in places, postdated by bounding fault; disintegration of unit may have formed chaotic material in places

Ha_1 **Unit 1**—Occurs at base of west flank of Apollinaris; underlies units Ha_2 and Ha_3. Surface appears smooth to hummocky. Low basal scarp separates unit from flood-plain and chaotic materials, but unit is gradational in places with chaotic material. *Interpretation:* Similar to unit 2

HIGHLAND MATERIAL

Nm **Massif material**—In southern part of map area; forms prominent mountains standing above all nearby units; contacts with adjacent materials locally marked by steep cliffs. *Interpretation:* Includes basement materials of highlands. Bounded by normal faults

Contact—Dashed where approximately located

Fault or graben—Dotted where buried; bar and ball on downthrown side. Forms contact in places

Wrinkle ridge—Mare type, forms contact in places

Yardang

Scarp—Dashed where buried. Line at base; ticks point downslope. Forms contact in places

Small channel

Caldera rim—Dashed where approximately located

Crater rim crest

Fresh crater, relatively young

Subdued crater, intermediate in age

Degraded crater, relatively old

Crater central peak

INTRODUCTION

Volcanoes are among the most imposing and geologically interesting features on Mars. Nearly 60 percent of the planet's surface is covered by volcanic rocks dating from the Early Noachian to Late Amazonian Epochs (Tanaka and others, 1988). This map of the volcano Apollinaris Patera and surrounding area is one of a series of large-scale (1:500,000) geologic maps initiated by the National Aeronautics and Space Administration to investigate areas of particular scientific interest. The areas selected for mapping contain candidate landing sites for future sample-return missions to Mars (fig. 1).

The map area is considered to be of special scientific interest for several reasons: (1) it includes the prominent volcano Apollinaris Patera, a type of volcanic edifice unusual on Mars in that it is not associated with significant faulting and is partly surrounded by a basal scarp similar to that of its much larger counterpart at the base of Olympus Mons; (2) it is located in a major transition zone between ancient highlands to the south and much younger lowland plains to the north; (3) rocks having different origins and a wide range of ages occur in the area; and (4) erosional processes associated with fluvial, volcanic, and eolian activity have shaped the terrain. The map area's potential as a landing site is increased by its extensive, relatively smooth areas at low elevation (0 to 1 km), which would permit access by an automated vehicle and atmospheric breaking by a landing craft.

The map area (fig. 2) includes parts of Mars Transverse Mercator (MTM) maps -10182, -10187, -05182, and -05187 (U.S. Geological Survey, 1986a, b, c, d). The base map (fig. 3) was compiled from these sheets. The Aeolis quadrangle, which includes the map area, was first mapped from Mariner 9 images at 1:5,000,000 scale (Scott and others, 1978). Later mapping based on higher resolution and better quality Viking images indicated the presence of possible ignimbrite or ash-flow materials (Scott and Tanaka, 1982). More recently, the Apollinaris region was included in the geologic map of the eastern equatorial region of Mars at 1:15,000,000 scale (Greeley and Guest, 1987) and in a study of fluvial valleys at 1:2,000,000 scale (Brakenridge, 1990). Our current mapping at 1:500,000 scale shows a greater diversity of materials and provides a more complete picture of the geologic history of the region.

About one-third of the images of the map area have resolutions of less than 75 m/pixel, while the other two-thirds have resolutions exceeding 200 m/pixel.

PHYSIOGRAPHIC SETTING

The highland-lowland boundary, which separates the two major physiographic and geologic provinces on Mars, extends across the southern part of the map area (figs. 2, 3). The two provinces make up a global crustal dichotomy whose origin is controversial; it has been attributed to phase changes in the mantle (Mutch and Saunders, 1976), erosional retreat of a fault scarp (Scott and Carr, 1978), mantle convection (Wise and others, 1979), a giant impact (Wilhelms and Squyres, 1984), overlapping impact basins (Frey and Schultz, 1990), and crustal thinning (McGill and Dimitriov, 1990). In the map area, the boundary is marked in places by many steep, cliff-forming scarps between Noachian massifs and younger materials of the plains; the plains consist of low-relief alluvial deposits, disordered assemblages of hills and mesas, and smooth-appearing members of the Medusae Fossae Formation (Scott and Tanaka, 1982, 1986). Small channels throughout the plains materials are part of a widespread system of fluvial valleys and their tributaries that traverse the highlands and empty into the Elysium basin to the north; this basin is believed to have been the site of a large paleolake that existed during the Amazonian Period (Scott and Chapman, 1991). Apollinaris Patera, the largest feature in the quadrangle and the most important geologically, is discussed in a separate section below.

STRATIGRAPHY

The Martian time-stratigraphic systems were first formally named and defined on the global geologic map of Mars (Scott and Carr, 1978). Later mapping using Viking images has allowed the original Noachian, Hesperian, and Amazonian Systems to be divided into eight series (Scott and Tanaka, 1986; Tanaka, 1986; Greeley and Guest, 1987; Tanaka and others, 1988). The stratigraphic ages of some rock units in the Apollinaris area were revised from the previous mapping and some new units were added on the 1:500,000-scale map.

NOACHIAN SYSTEM

Noachian rocks (unit Nm) are exposed along the south border of the map area where they form prominent massifs that protrude above the adjacent terrain; they are interpreted to consist of impact breccias and volcanic materials formed during an early period of high impact flux and uplifted by faulting (Scott and Tanaka, 1986). These block-faulted rocks, as well as some of the older crater material, are part of the plateau sequence of Early and Middle Noachian age mapped by Greeley and Guest (1987). In places it is hard to distinguish between Noachian massifs and other large blocks mapped as chaotic material (unit Hcht) of Hesperian age; generally, individual exposures of the chaotic rocks have less relief than the massifs and are characterized by mesas with broad, flat tops. These distinctions are largely arbitrary, however, and interpretations remain highly subjective.

Streams and sheetflooding from the highlands have dissected both the massifs and the chaotic material; the large outflow channel Ma'adim Vallis (fig. 2) contributed to the deep erosion and breakup of Noachian rocks within and south of the map area, probably during the Late Hesperian. Water outlets from this channel into the map area have been mostly covered by ejecta from a young, 30-km-diameter impact crater immediately south of the map area (fig. 4).

HESPERIAN SYSTEM

Hesperian rocks record extensive evidence of volcanism, tectonism, and canyon and channel development, but, compared with older materials, they are only moderately cratered by impacts (Scott and Tanaka, 1986). Hesperian lava flows, fluvial deposits, and chaotic material cover most of the map area. Four lava-flow units (Ha_{1-4}) are mapped at Apollinaris Patera. Crater counts indicate a middle Hesperian age for the youngest flow, but the Viking images do not have a good enough resolution to allow an unequivocal distinction between superposed craters and craters that may be partly embayed by the lava flow, especially craters having a rim-crest diameter of about 5 km or less. Thus, volcanic activity of Apollinaris may have started very early in Hesperian or possibly in Late Noachian time (see section on Apollinaris Patera).

Channel deposits (unit Hchm) of Ma'adim Vallis appear to overlie the youngest lava flow from Apollinaris. The boundary between these two units is indistinct, but the channel deposits have a smoother surface with fewer impact craters than the lava flow.

Flood-plain material (unit Hchp) covers low-lying areas south and west of Apollinaris. It is interpreted to be deposits from many streams and rivers emanating from channel networks in the highlands south of the map area. These channels are commonly associated with collapsed terrains or faults, or they have morphologies similar to those of terrestrial channels produced by sapping processes. Water may have originated from large-scale melting of ground ice followed by rapid drainage and subsurface collapse (Squyres and others, 1987). These drainage networks probably coalesced on the lower, flatter slopes of the highlands to form broad expanses of shallow flood waters, which eroded and smoothed the older terrain with deposits of clastic sediments. Some of this water appears to have been partly responsible for the breakup of lava flows around the base of Apollinaris and their incorporation, along with disintegrated Noachian basement rocks, in the chaotic material (unit Hcht). This material consists of irregular clusters of hills and mesas projecting above the floodplains but at a lower level than the massifs. Along and near the south margin of unit 4 of the Apollinaris flows, the chaotic material may be a product of the disruption of the terrain by volcanic and ground-ice interactions, as has been proposed elsewhere on Mars (Allen, 1979, 1980; Mouginis-Mark, 1985, 1990; Squyres and others, 1987). Although chaotic material is probably composed mostly of Noachian and Lower Hesperian rocks, its age classification is based on the time of development of surface characteristics rather than the time of emplacement of the original rock materials (Milton, 1974).

AMAZONIAN SYSTEM

The Amazonian System as originally defined (Scott and Carr, 1978) contains the youngest rock units on Mars; it is represented in the map area almost entirely by members of the Medusae Fossae Formation that form gently rolling plains around the north and east sides of Apollinaris. Some of the materials now included in the formation were first recognized as possible ash flows by Malin (1979). Later studies by Scott and Tanaka (1982) supported an ash-flow or ignimbritic origin and subdivided the deposits into seven units. Subsequently, Scott and Tanaka (1986) named the materials the Medusae Fossae Formation and combined them into lower (unit Aml), middle (unit Amm), and upper (Amu) members. The geologic maps of the western (Scott and Tanaka, 1986) and eastern (Greeley and Guest, 1987) equatorial regions of Mars show the formation extending more than 5,000 km along an east-west corridor between the cratered highlands and lowland plains of Elysium Planitia. In our map area, only the lower and middle members of the formation have been recognized. The lower member, in the southeastern part of the map area, has a relatively dark surface and has been deeply furrowed by wind; it embays the youngest lava flow from Apollinaris. In contrast to the lower member, the middle member has a surface that is generally smooth and lighter in color. On the north flank of Apollinaris, the middle member overlaps older lava flows and buries the basal scarp of the volcano; in this area the formation has been sculpted by wind to form long, smooth-crested, northeast-trending yardangs. In places, subjacent topography, including ridges and grabens, is visible beneath the formation.

Young channel material (unit Ach) covers a low-lying area northeast of Apollinaris. It is interpreted to be channel floor and outwash deposits from a small channel incised in the middle member of the Medusae Fossae Formation.

APOLLINARIS PATERA

Apollinaris Patera is a dome-shaped volcano nearly 200 km across, rising about 5 km above the Martian datum; crater counts and stratigraphic relations (see Stratigraphy) suggest a middle Hesperian age for its youngest flow. Earlier mapping of Apollinaris (Scott and others, 1978) shows a large, complex summit caldera 75 km across consisting of at least three coalescing collapse depressions; the relatively gentle outer flanks of the volcano steepen abruptly toward the crest. Although Apollinaris has been classified morphologically as a shield volcano (Greeley and Spudis, 1981), recent photoclinometric profiles show a steeper upper slope, confirming the work of Scott and others (1978) and suggesting a change to a pyroclastic and effusive eruption style characteristic of composite volcanoes (Robinson, 1990).

Unlike most volcanoes on Mars, Apollinaris does not lie along large fault zones like those in the Tharsis region, nor is it associated with regional alignments such as the volcanic chain extending between Amphitrites and Tyrrhena Paterae and possibly on to Elysium Mons and Hecates Tholus (see Scott and Carr, 1978). Possibly Apollinaris is associated with faulting along the highland-lowland boundary that has been obscured by a cover of younger materials; other faults parallel this boundary but lie hundreds of kilometers to the north and south of the map area.

The south flank of Apollinaris is covered by a large, fan-shaped lava flow that appears to have been erupted from the summit caldera at a late stage in the growth of the volcano. The fan is highly dissected by radial troughs extending from its apex to the plains below; the morphology of the troughs suggests a mixed fluvial-lava flow origin (Gulick and Baker, 1990). Wrinkle ridges similar in appearance to those on ridged plains lava flows in other areas on Mars extend radially along the lower part of the flow; here the wrinkle ridges are probably the surface expression of dikes intruded on the flanks of the volcano. This younger flow locally buries a basal, cliff-forming scarp and other scarps around Apollinaris. These scarps may be the faces of concentric normal faults formed by magmatic intrusions, uplift, and subsequent doming and crustal extension of the volcano. Other, more complex hypotheses (tectonic or otherwise) are not needed to explain these scarps, for, unlike Olympus Mons (Morris and Tanaka, in press), Apollinaris has no circumferential trough, imbricate fractures and ledges on the scarp face, or other complicating features.

HISTORICAL SUMMARY

We know very little about the early history of Mars except that a period of intense meteorite bombardment produced a highly cratered surface consisting of breccias in overlapping ejecta blankets and interbedded volcanic flows. Large parts of this Lower Noachian surface are still exposed in the southern highlands, but only a few remnants occur in the map area, whose geologic history is best reconstructed from the stratigraphy and morphology of Hesperian and Amazonian rocks.

Volcanic (probably basaltic) eruptions at Apollinaris probably started very early in Hesperian or possibly in Late Noachian time and continued intermittently throughout the Hesperian Period. The initial effusive lava flows that formed the lower part of the dome were followed by more explosive eruptions of pyroclastic rocks and lavas to build the upper, steeper part of the structure. Depletion of the magma chamber by these eruptions or by withdrawal of the magma produced roof collapse and a large caldera. The last eruption from Apollinaris filled the caldera floor and overflowed from a narrow notch in the south wall of the crater; further magma withdrawal and subsidence lowered the floor to its present position. Throughout the growth of the volcano, magmatic heating by dikes and other conduits, as well as by lava flows, melted ground ice within the regolith. The resulting disintegration and collapse of the terrain continued into the Late Hesperian and formed clusters of chaotic hills and mesas. Floods from Ma'adim Vallis, a large channel south of the map area, contributed to the breakup of surface rocks, as did flows of water from many smaller channels in the highlands. This period of Martian history appears to have introduced flooding on a global scale, as shown by huge outflow channels around the Chryse basin, Mangala Valles, and other areas in the southern highlands (Scott and Tanaka, 1986; Greeley and Guest, 1987). As volcanism ceased at Apollinaris and flooding waned in the plains during the Late Hesperian, an interval of relative quiescence began that extended into Middle Amazonian time. This interval was probably interrupted by eruptions of ash-flow tuffs (Scott and Tanaka, 1982, 1986) that swept across the region for several thousand kilometers; in the map area they buried the east and north sides of Apollinaris. The sources of the pyroclastic materials are not known, but presumably they were discharged from fissures and calderas that subsequently were buried or partly buried by their vented materials (Scott and Tanaka, 1982).

Aside from impact-crater materials that accumulated throughout the history of the area, a channel of probable Late Amazonian age is the last evidence of important geologic activity in the map area.

CANDIDATE LANDING SITES IN THE QUADRANGLE

Outcrops of the Amazonian Medusae Fossae Formation, Hesperian lava flows and channel materials, and Noachian rocks may be readily accessible to a roving vehicle traversing the relatively smooth surface of the flood-plain material. Much higher resolution images from future missions, however, are required for selecting specific landing sites and for planning traverse routes to particular objectives.

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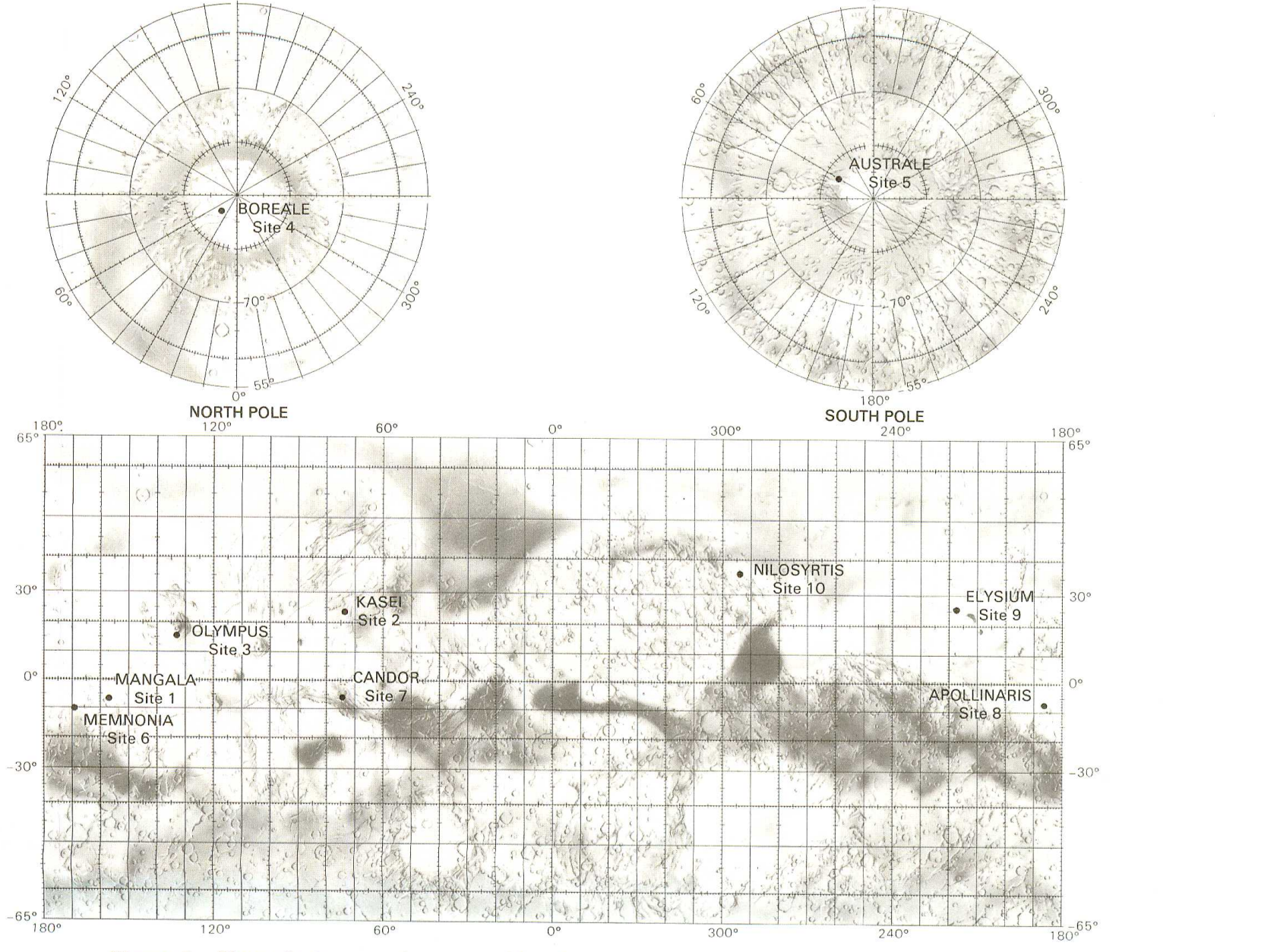

Figure 1. Planned science study areas on Mars that include 10 candidate landing sites for future sample-return missions.

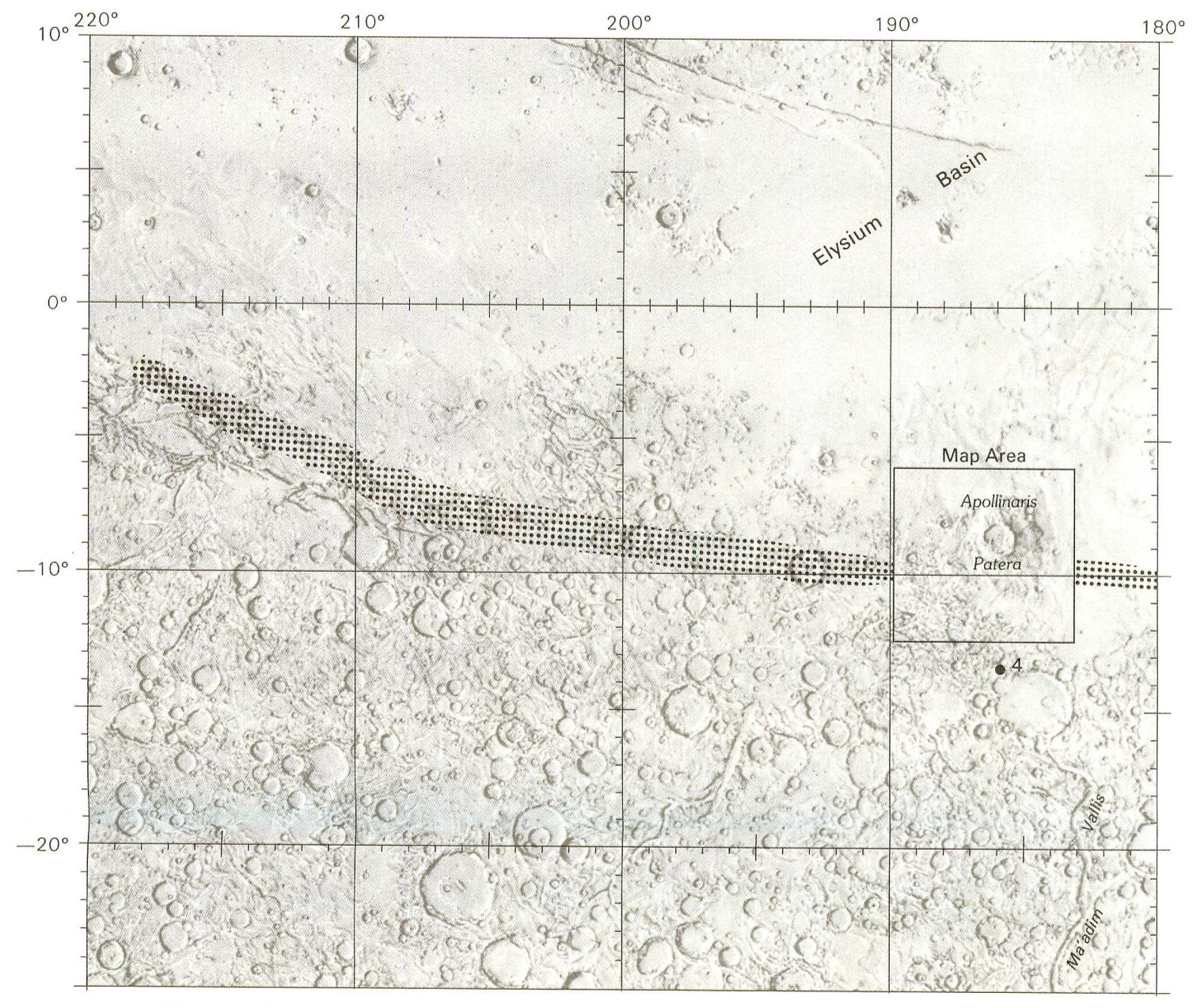

Figure 2. Index map showing locations of major physiographic features in Apollinaris Patera region of Mars. Highland-lowland boundary (stipple pattern) extends across southern part of map area (for clarity, not shown within map area). Approximate location of figure 4 (just south of map area) shown. Scale 1:15 million.

Figure 3. Photomosaic base of map area. Highland-lowland boundary marked in places by steep, cliff-forming scarps between Noachian massifs and younger plains materials. Scale 1:2 million.

Figure 4. Ejecta from large, young impact crater covering most water outlets from Ma'adim Vallis into map area. Viking Orbiter image 435S02.

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