Review

Topography and morphology of the Argyre Basin, Mars: implications for its geologic and hydrologic history

Harald Hiesinger*, James W. Head III

Department of Geological Sciences, Brown University, Providence, RI 02912, USA

Abstract

Argyre, located in the southern highlands southeast of Tharsis, is one of the largest impact basins on Mars and formed in Early Noachian time. We use Mars Global Surveyor (MGS) data to characterize the basin and its geologic features and units. It has been proposed that meltback of a south polar ice cap during the Noachian completely filled the basin with water, that the outflow channel in the north drained the basin, and that the water eventually entered the northern lowlands (Parker T.J., 1994.) If true, this would be the longest drainage system on either Mars or the Earth and would have immense implications for the hydrologic cycle and the evolution of the atmosphere on Mars. In order to address this question, we used topographic data from the Mars Orbiter Laser Altimeter (MOLA) and imaging data from the Mars Observer Camera (MOC). We also tested several alternative models proposed by previous workers (i.e., eolian, volcanic, mudflows, glaciers, fluvial/lacustrine) for the evolution of the Argyre basin. Based on our investigation we conclude that the Argyre basin went through a complex geologic history with several geologic processes contributing to its current appearance. Glacial and fluvial/lacustrine processes in conjunction with eolian modification were probably most important in the evolution of the interior of the Argyre basin. The Hesperian wrinkle ridged unit Hr was previously interpreted as volcanic in origin due to the occurrence of ridges. Based on our observations we conclude that ridges in Argyre Planitia are dissimilar to wrinkle ridges in other occurrences of unit Hr. The new data suggest that these are eskers and based on the occurrence of these esker-like features, we propose a model in which the floor of Argyre was covered by ice. There is evidence for areally significant amounts of water having ponded in the Argyre basin in its past history, but a complete fill to depths of ~ 4 km and overflow remains questionable. On the basis of our findings it is unlikely that Uzboi Vallis drained the basin to the north, because the basin would have to be completely filled with at least 2.1×10^6 km^3 of water and this is not consistent with current hydrologic models. Instead, new MOLA data show evidence for drainage into the basin from the north, south of crater Hale and Uzboi Vallis. We performed estimates of the available water and found that the amount of water that can be produced by meltback of a Hesperian ice cap appears insufficient to completely fill the Argyre basin. We propose that water that ponded in the Argyre basin would have sublimed, evaporated or migrated into the substrate rather than flowing through the northern outflow channel.

In summary, a significant input of sediments and a partial fill of Argyre basin with water during the Hesperian is suggested by several channels emptying into the Argyre basin from the south and north, signs of fluvial erosion on the southern basin floor, the formation of small deltas at the mouths of Surius Vallis and the valley at the north rim, the amount of available water, and the smoothness of unit Hr. The formation of esker-like features indicates that this body of water very likely froze over. Finally MOC images reveal evidence that eolian activity, that is deflation of floor material and accumulation of dunes, modified the basin floor. On the basis of the MOLA and MOC data and our observations we outline a scenario for the evolution of the Argyre basin. In our model, water, produced by a Hesperian meltback of the south polar ice sheet, entered the Argyre basin, partly filling the floor of the basin to form a temporary ice covered lake. A downward freezing front propagated faster than the ice could sublime, resulting in an increasing ice thickness with time. As influx of water continued, in shallower regions of the lake (i.e., close to the incoming channels), the ice was grounded and incoming water formed subglacial channels in which esker-like ridges were deposited. After the influx ceased, continued sublimation and migration of water into the substrate reduced the amount of water/ice in the basin. Throughout the entire geologic history, eolian activity played an important role in the Argyre basin, mantling or exhuming morphologic features, influencing sublimation rates, and contributing to the present day morphology.

* Corresponding author. Tel.: +1-401-863-3454; fax: +1-401-863-3978.
E-mail address: harald_hiesinger@brown.edu (H. Hiesinger).

Contents

1. Introduction

Argyre basin is one of the most prominent and best preserved impact basins on Mars (e.g., Wood and Head, 1976; Schultz et al., 1982; Schultz and Frey, 1990), is located at −51°S and 43°W, and has a diameter in excess of 1500 km (Tanaka et al., 1992) (Fig. 1). Several geologic histories have been proposed for the evolution of the Argyre basin (e.g., Hodges, 1980; Scott and Tanaka, 1986; Jöns, 1987; Kargel and Strom, 1992; Parker, 1994). Each of these models has distinctive geologic implications, predictions and consequences and we use MOLA and MOC data in order to test the plausibility of these hypotheses and to address new scenarios consistent with the new data.

In addition, MOLA data can be used to address several fundamental questions, which not only have implications for the Argyre basin, but for the entire planetary body. Was Argyre ever completely filled with water as proposed by Parker (1994) and Parker et al. (2000) and if so, where did all the water go? Do the presently exposed geologic units relate to such an event? Was there a throughgoing transport

of water from the south polar regions to the northern lowlands and is Uzboi Vallis a drainage channel from a completely filled Argyre to the northern lowlands as suggested by Parker et al. (2000)? Did glaciation dominate the evolution of Argyre as proposed by Kargel and Strom (1992) or did the history of Argyre involve a complex interplay of volcanism, tectonism, eolian and aqueous processes, rather than being dominated by any single process (e.g., Scott and Tanaka, 1986)? And finally, how does one account for the apparently very fresh nature of Argyre compared to other basins, such as Hellas?

Several geologic units are associated with the Argyre basin. In the geologic map of Scott and Tanaka (1986), the oldest unit (Nplh) in this region shows an Early Noachian crater age (N16 = 200–250), that means 200–250 craters larger than 16 km in diameter are exposed on a surface of 1 million km^2. Comparison of crater size–frequencies allows one to derive relative ages for geologic units because the longer a surface is exposed to the meteorite bombardment, the more craters it accumulates. The basin impact must be simultaneous to or predate the formation of this
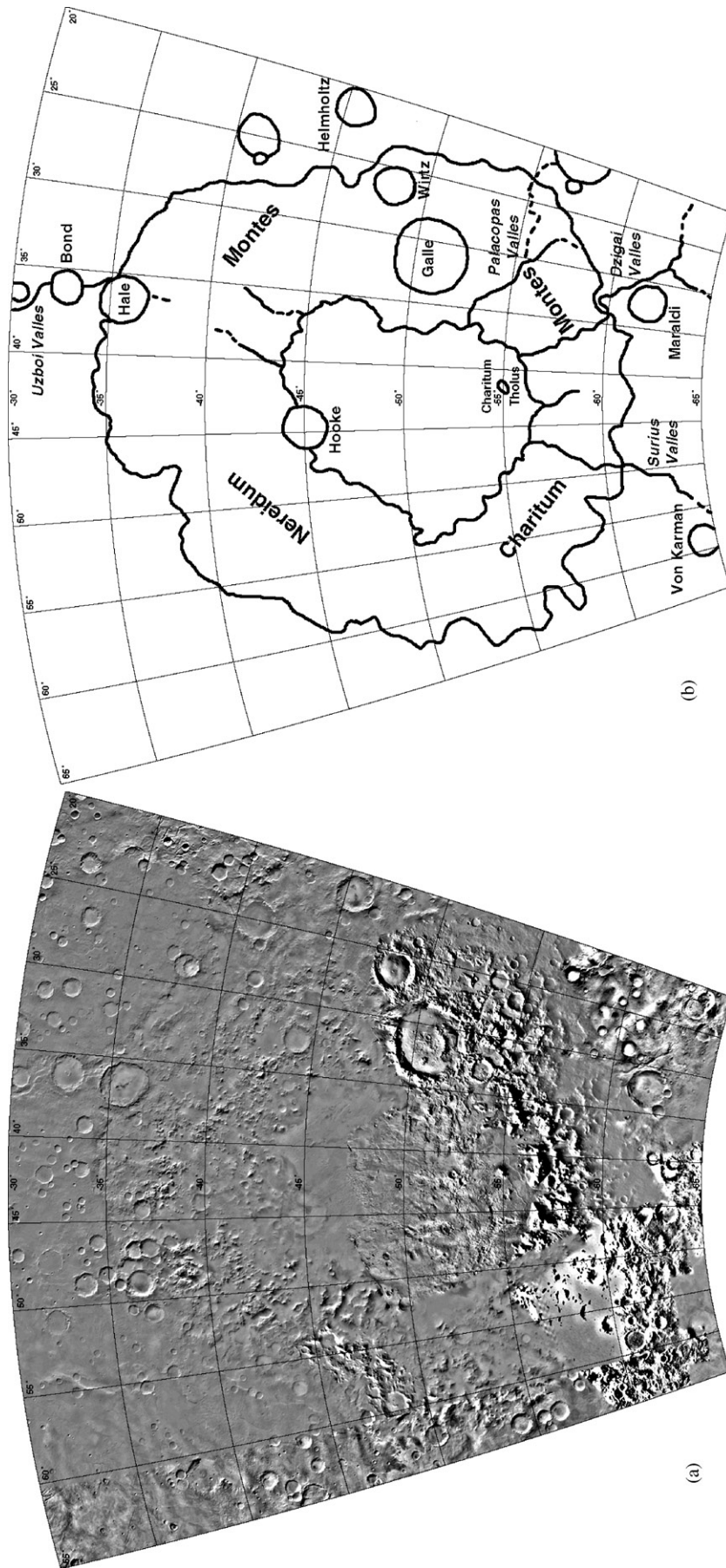
Fig. 1. The Argyre basin. (a) Viking MDIM mosaic with about 250 m spatial resolution; (b) sketch-map showing the location of major features associated with the Argyre basin. Lambert azimuthal equal-area map projection; centered at −51°S, 43°W, 1° latitude = 59.17 km. Covered area is from −30°S to −65°S and from 20°W to 65°W; 5° grid spacing.

unit and occurred in the Early Noachian (Scott and Tanaka, 1986). In the map of Scott and Tanaka (1986), the Argyre basin is slightly younger (N16= $\sim$ 210) than the Hellas and Isidis basins (N16= $\sim$ 240). At Viking resolution the Argyre basin appears very pristine with sharp morphology but despite its unique appearance there is no evidence that the Argyre basin is significantly younger than any other large impact basin on Mars (Parker, 1996a, b). Noachian units of the floor of the Argyre basin (Nple, Npld) are younger (N16=100–200; N5 > 400) and contemporaneous with the Noachian plains unit Npl_1, which is exposed north, west and south of the basin structure. Unit Npl_2, found east of the basin is younger (N16 = 25–100; N5 = 200–400). Contemporaneous in age with these two groups is the Noachian ridged unit Nplr with crater ages of N16 = 150–75 and N5 = 300–600. Three Hesperian units are exposed in the Argyre basin. The Hesperian plains unit Hpl_3 has a crater age of N5 = 120–200 and N2 = 700–1200, respectively. The ridged unit Hr formed more or less simultaneously during Hesperian times (N5 = 130–200; N2 = 800–1200) and the channels (unit Hch) mapped by Scott and Tanaka (1986) are also Hesperian in age (N2 = 400–900).

2. Previous models and outstanding problems

In the geologic map of Hodges (1980), which is based on Mariner 9 A-frame images, the interior of Argyre is mapped as smooth plains material. In her interpretation this unit Ps consists largely of eolian deposits but a partly fluvial origin is suggested by branching channels draining into Argyre, specifically from the south rim. She interpreted Ps material to be unconsolidated and thus subject to erosion and transport. Hodges (1980) reported that preexisting underlying topography is largely obscured and concluded that the deposits are of substantial thickness. A knobby plains unit Pk is confined to the lowlands within and at the inner margins of the Argyre basin rim. The knobs are interpreted as erosional remnants of rugged Argyre basin rim material or fallback ejecta, which protrude through the smooth plain unit. In this map, Charitum Montes and Nereidum Montes are made of blocky, irregular massifs, serrate ridges, and hillocks, arranged in radial and concentric patterns. Ridge crests and hilltops are sharp and angular. This unit Ar represents primitive crustal material, which was disrupted (faulted, brecciated, and uplifted) by the Argyre impact and subsequently deeply eroded. Broad valleys and knife-edge ridge crests led Hodges (1980) to conclude that this unit was modified by a possible glaciation. Thus in the interpretation of Hodges (1980), the geologic history of the Argyre basin is characterized by large-scale erosion and deposition of material by eolian and to a lesser extent by fluvial and glacial processes.

The geologic map of Scott and Tanaka (1986) shows several geologic units, which are associated with the Argyre basin. Representative Viking Orbiter views of each unit are shown in Fig. 2. The Charitum and Nereidum Montes are of

Noachian age (Nplh; Fig. 2d) and are interpreted as ancient highland volcanic rocks and impact breccia, which were uplifted by tectonism associated with impact basin formation. In the valleys of the Charitum and Nereidum Montes and on parts of the basin floor, unit Hpl_3 (Fig. 2c) is exposed. This is a smooth, relatively featureless unit and is interpreted as thick interbeded lava flows and eolian deposits that bury most of the underlying rock. Nple (Fig. 2e) is described as an etched unit and occurs in age between unit Nplh and Hpl_3 and is exposed in the central parts of the basin floor. This unit shows a rough, etched texture which is produced by deeply furrowed, sinuous, intersecting grooves. Scott and Tanaka (1986) suggest that this unit was formed by degradation of a cratered unit by wind erosion, decay and collapse of ground ice, and minor fluvial processes. Unit Npld (Fig. 2f), which is visible southwest of crater Galle, is of the same age as unit Nple. Npld is a dissected unit and is interpreted as a mixture of lava flows, pyroclastics and impact breccias that were heavily eroded by fluvial processes. Finally, in the southern and southeastern parts they map a unit that consists of Hesperian ridged plains material (Hr; Fig. 2b). Unit Hr is interpreted as extensive flows of low-viscosity lavas, which erupted from numerous sources at high rates. According to Scott and Tanaka (1986) the ridges are either volcanic or tectonic in origin. Based on the maps of Scott and Tanaka (1986) and Tanaka and Scott (1987), the geologic history of the Argyre basin was described in the following way. During the heavy bombardment in Early Noachian times an impact excavated the Argyre basin, causing uplift of fractured Noachian plateau material and ejecta to form the rim. In Middle Noachian times, the floor has been covered by several units, including an etched, cratered unit that is characterized by deep erosion due to wind, water and periglacial processes. During the Hesperian, volcanism or sedimentary processes deposited the ridged unit of the basin floor. Still in the Hesperian, but probably slightly younger, a smooth unit was deposited that may consist of interbeded lavas and windblown sediments. Finally, in the Late Hesperian channels formed at the southern and northern rim. During the Amazonian, smooth sloping debris aprons along the scarps of Charitum Montes were produced by mass-wasting and slow, glacier-like flow of ice-rich plateau material (Scott and Tanaka, 1986). Crater Hale postdates the Hesperian age Uzboi Vallis and is of Hesperian or even Amazonian age.

Kargel and Strom (1992) proposed that extensive glaciation influenced the Argyre basin and the regions south of it (Fig. 3). Morphologic features such as ridges, grooves, smooth plains, very steep mountain slopes, and features interpreted to be rock glaciers led Kargel and Strom (1992) to conclude that Argyre was glaciated in its past. They interpret ridges as eskers, the deposits of the basin floor to have formed within a proglacial lake, and the rough unit (Nple) as formed by collapse features of a retreating glacier. In their model, ice accumulated in the mountainous rim of Argyre, i.e. the Charitum Montes, and on adjoining cratered uplands and flowed into the basin. Erosional pro-
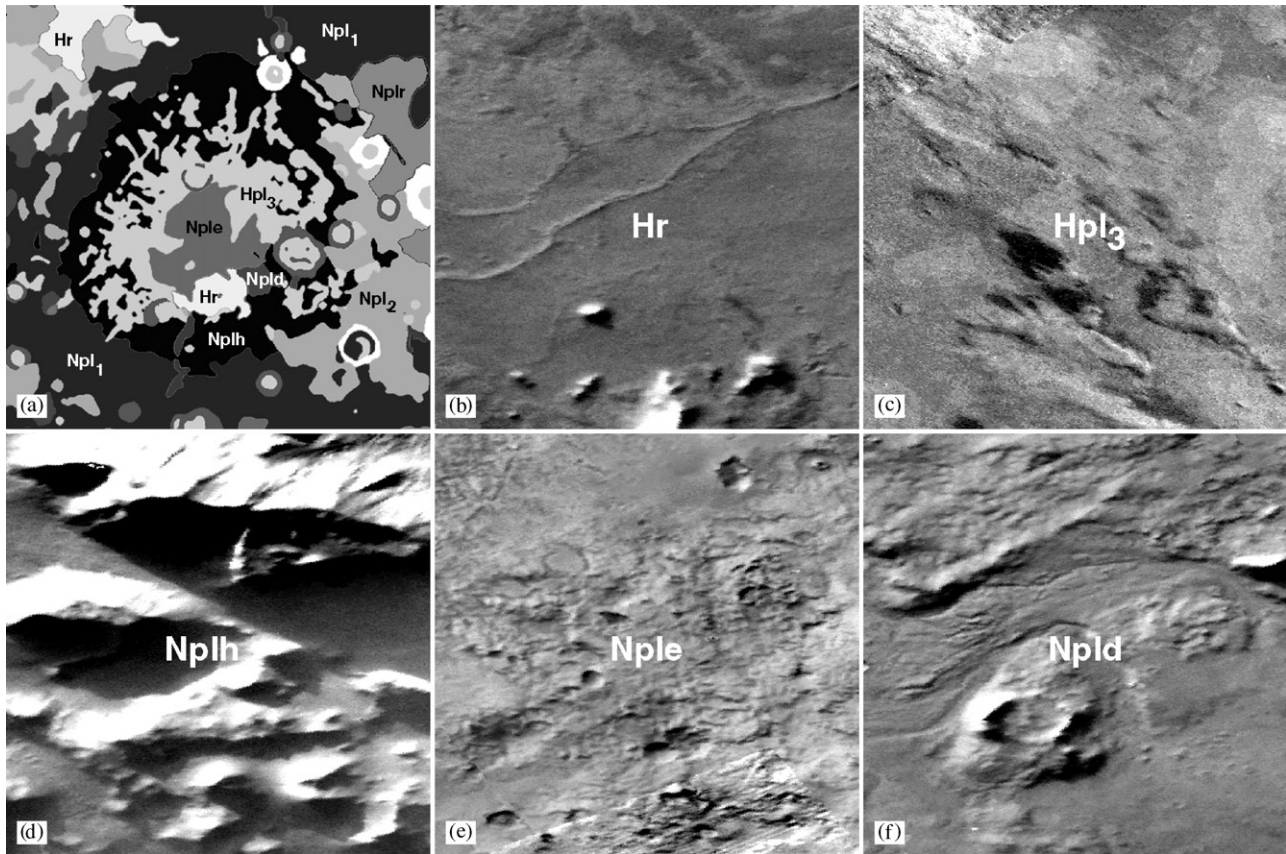
Fig. 2. Detailed views of geologic units of Scott and Tanaka (1986) in the Argyre basin. (a) Geologic map of Scott and Tanaka (1986), simple cylindrical map projection. Viking mosaics showing (b) unit Hr; (c) unit Hpl$_3$; (d) unit Nplh; (e) unit Nple; (f) unit Npld. Figures b–f are simple cylindrical map projections, box height is $1°(\sim 59$ km).

cesses associated with ice movement carved the steep slopes of Charitum Montes. Subsequently eskers and collapse features formed on the basin floor when large amounts of melt water were produced and the glacier rapidly retreated. According to Kargel and Strom (1992), meltwater accumulated in a proglacial lake and deposited smooth glaciolacustrine plains. Based on martian impact cratering models (Tanaka, 1986), Kargel and Strom (1992) concluded that glaciation may have taken place between 0.25 and 2.3 b.y. ago, but at least during the latter half of martian history.

Tanaka (1986) and Tanaka et al. (1992) correlated martian epochs with absolute ages. In their stratigraphy the Noachian lasts from 4.6 to 3.5 b.y., the Hesperian from 3.5 to 1.8 b.y. and the Amazonian from 1.8 b.y. to present. According to the Neukum and Wise (1976) stratigraphy the Noachian ranges from 4.6 to 3.8 b.y., the Hesperian from 3.8 to 3.55 b.y. and the Amazonian from 3.55 b.y. to present. The largest disagreement between these two stratigraphies occurs for the Hesperian epoch, being either less than 300 m.y. long (Neukum and Wise, 1976) or about 1.7 b.y. long (Hartmann et al., 1981; Tanaka, 1986). Based on the most recent work of Hartmann and Neukum (2001), the Hesperian is now considered to last from 2.9 to 3.7 b.y.,

with Neukum favoring a somewhat shorter Hesperian Period (3.3–3.7 b.y.) compared to Hartmann (2.9–3.5 b.y.). Despite these differences between the stratigraphies the latest glaciation of the Kargel and Strom (1992) model occured during the Amazonian.

Jöns (1987, 1999) suggested that two-thirds of Argyre Planitia are now covered with mud, which formed when the south polar cap melted. According to the map of Jöns (1987) the mudflow entered Argyre basin through Surius Vallis and Dzígai Vallis. Based on his observations of the orientation of the ridges in Argyre Planitia Jöns (1999) rejected an origin of the ridges due to glaciation. Instead he proposed that the mudflow spread out from the point of influx into all directions so rapidly that it formed tsunami-like shock waves during its emplacement. Simultaneously, instantaneous desiccation and freezing occurred, which solidified the waves and formed narrow ridges.

A fifth model was presented by Parker (1989, 1994) and Parker et al. (2000). According to Parker (1996a, b) the fresh appearance of Argyre basin is primarily caused by erosional "enhancement" during the Noachian and Hesperian, rather than a pristine state of preservation. The Argyre basin itself is a very ancient structure that has been broadened and filled
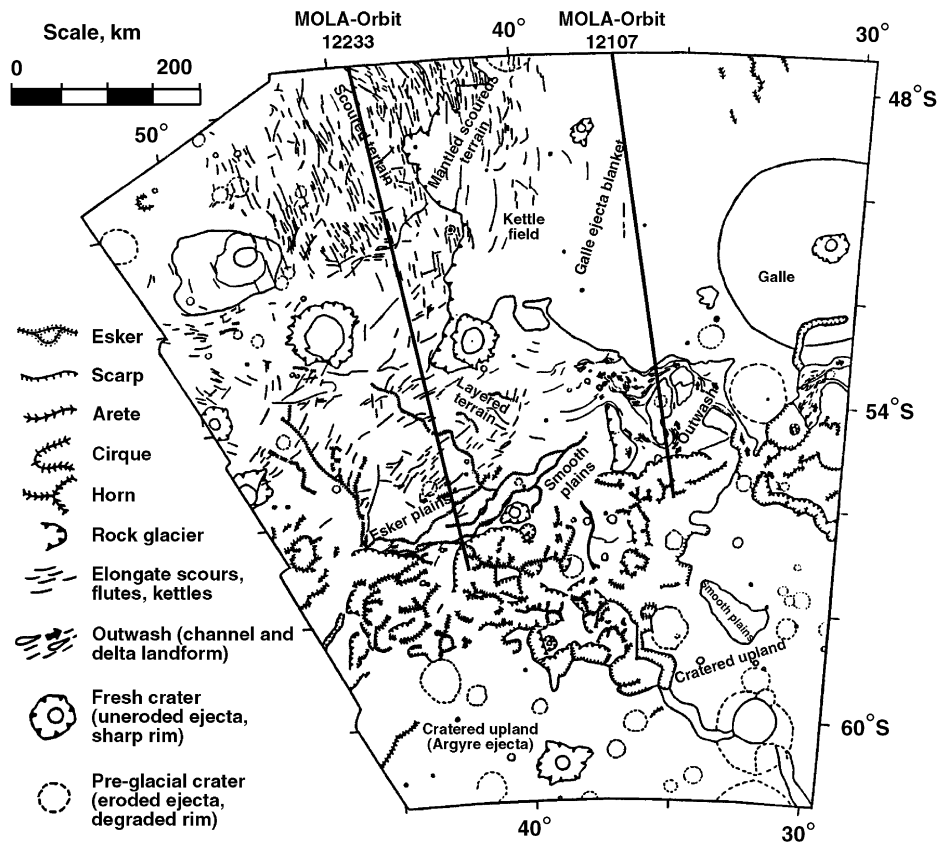
Fig. 3. Sketch-map of glacial features in the southern Argyre basin (Kargel and Strom, 1990). Thick black lines show the location of two MOLA orbits (12107 and 12233), which are shown in Figs. 16a and b.

in through mass-wasting, fluvial, lacustrine, and eolian erosion (Parker, 1996a, b). Parker (1996b) argues that many of the flat-topped Charitum and Nereidum rim mountains represent erosional remnants of the surrounding Noachian plateau. To produce the currently observed morphology of the Argyre basin several kilometers of material between the mountains were removed, probably by fluvial and lacustrine erosion (Parker, 1996b). Several channels empty into the Argyre basin from the south and east and there is a possible outflow channel, Uzboi Vallis, through which water could have flowed out of the basin to the north (e.g., Parker, 1989; Parker et al., 2000) (Fig. 1). Smith et al. (1999) showed that the Argyre basin has a drainage area of about 20×10^6 km^2, about 14% of Mars, which is similar in size to the drainage area of the much larger Hellas basin. In addition Argyre basin is located in the vicinity and downslope of the regions of ancient polar ice deposits (Dorsa Argentea) which apparently underwent extensive melting and retreat in middle Mars history (Head, 2000a; Head and Pratt, 2001). Thus, if there were ever large volumes of water flowing across the surface of Mars in its earlier history (e.g., see review in Carr, 1996), either through precipitation and runoff, groundwater sapping, or groundwater migration and drainage to topographic lows (Clifford and Parker, 2001), then the Argyre basin may have contained substantial quantities of water.

According to the model of Parker et al. (2000) large volumes of basal meltwater may have been discharged from beneath the south polar cap. In their model Argyre basin is part of a more than 8000 km long drainage system from the Dorsa Argentea region near the south pole, to the lowlands in the northern hemisphere. According to Parker et al. (2000), the water would have flowed into the Argyre basin and would have completely filled the basin during the Noachian. Parker et al. (2000) argue that the basin was completely filled with water because there is no morphologic continuation of the channels on the basin floor. Once Argyre captured all the meltwater and was filled, flow through the northern outflow channel, Uzboi Vallis, occurred. According to Parker et al. (2000), Uzboi Vallis is a large Noachian outflow channel (it is mapped as Hesperian by Scott and Tanaka, 1986) and Parker et al. (2000) see evidence for at least two catastrophic flood episodes from Argyre. Even though Parker et al. (2000) do not specifically address the question when these two flood events took place, the implication of the Noachian age of Uzboi Vallis is that Argyre basin must have been filled with water up to the topographic level of the outflow channel early in Mars' history, that is, the Noachian (Parker, 1994). Based on present day topography, it also implies that the depth of this body of water was of the order of 3–4 km. In the model of Parker
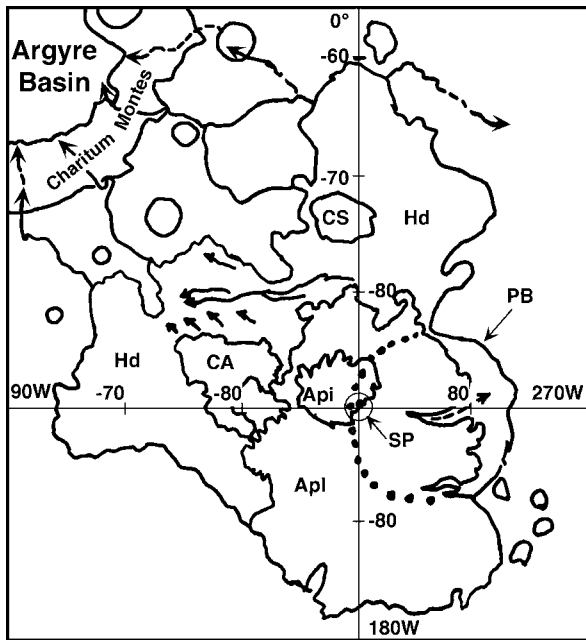
Fig. 4. Sketch-map showing the relationship between south polar deposits, channel formation and the Argyre basin (modified from Head, 2000c, d). Map shows the distribution of geologic units (Api, Apl, and Hd from Scott and Tanaka, 1986) and features associated with the south polar deposits. SP South Pole; PB Prometheus Basin; dotted line shows extension under cap, dashed line shows Chasma Australe; CA Cavi Angusti; CS Cavi Sisyphi; arrows within Hd are Dorsa Argentea esker-like ridges; arrows outside Hd are channels interpreted to be draining Hd. Polar stereographic map projection, 1° latitude= ∼ 59 km.

(1994), this water is derived from meltback of a south polar ice cap, which had to occur during the Noachian.

Finally, Head (2000a, c, d) and Head and Pratt (2001) proposed that water from the melting of an extensive south polar cap entered Argyre basin during the Hesperian. Using MOLA topography, Head (2000a–d) and Head and Pratt (2001) found evidence for a formerly larger ice cap (Fig. 4) and he identified four channels that originate at the distal parts of the Dorsa Argentea Formation. These channels wind their way several hundreds of kilometers northward, and finally terminate in the Argyre basin (Head and Pratt, 2001). The channels do not show tributaries, dendritic patterns or other associated features that would suggest runoff from regional precipitation or extensive ground water sapping. From the length (900–1600 km) and the large lateral separation (200–400 km) of individual channels, Head (2000d) and Head and Pratt (2001) concluded that basal melting and meltback of the south polar water–ice deposits were widespread, volumetrically significant and were likely the source of water that carved the channels that transported water to the low-lying Argyre basin.

To conclude, these six models for the evolution of the Argyre basin provide insight into the geologic history of the basin. One model involves mainly eolian deposition (Hodges, 1980), another model involves significant volcanic activity (Scott and Tanaka, 1986), a third model calls on

the emplacement of mud in large parts of Argyre Planitia in a catastrophic event (Jöns, 1987, 1999), and a fourth model suggests large-scale glaciation (Kargel and Strom, 1992). A fifth model suggests that the Argyre basin is completely filled with water during the Noachian (Parker et al., 2000), and a sixth scenario predicts the transport of significant amounts of water to the basin floor during the Hesperian (Head, 2000c; Head and Pratt, 2001).

3. Analyses and results

3.1. Database

We use MOLA data to characterize the Argyre basin and its deposits and to assess their origins and the questions outlined in the introduction. Compared to the previously published topographic map of the US Geological Survey (1976), which had a vertical accuracy of 1–2 km, MOLA offers an improvement of two orders of magnitude. In 1997 the Mars Observer Laser Altimeter (MOLA) on board the Mars Global Surveyor spacecraft (MGS) started to acquire high-precision topographic profiles along near polar groundtracks in the northern hemisphere. Since then the coverage of MOLA has been continuously expanded to southern latitudes, including the south pole. The instrument has a vertical shot-to-shot resolution of ∼ 30 cm and along-track spatial resolution of ∼ 300 m (Smith et al., 1998). The surface spot size in mapping orbit is about 130 m. The large number of orbit crossings ($\sim 2 \times 10^6$; Zuber et al., 2000) allows one to cross-correlate and to adjust orbits in order to enhance the vertical precision of the data. From $\sim 2 \times 10^8$ elevation measurements along these orbits a gridded topographic model with a spatial resolution of 15 km and an absolute vertical precision of < 5 m was generated (Zuber et al., 2000).

3.1.1. Topography

There are several topographic maps available for the Argyre region. Topography based on Mariner 9 and Earth-based radar data indicate that the rim of Argyre is approximately at 3 km above the datum (US Geological Survey, 1976). The datum is defined by a gravity field described by spherical harmonics of fourth order and fourth degree combined with a 6.1 mbar atmospheric pressure surface derived from radio occultation data. This datum is a triaxial ellipsoid with axes of 3394.6, 3393.3, and 3376.3 km. In this map the basin floor lies below 2 km and there are two distinctive hills on the basin floor east and south-southwest of crater Hooke. Summits of these hills reach absolute heights of more than 2 and 3 km, respectively. Interestingly, the implication is that the hill south-southwest of crater Hooke would be as high as the basin rim, which is between 3 and 4 km high.

The US Geological Survey (1993) topography is based on stereoscopic photogrammetry of Viking imaging data.
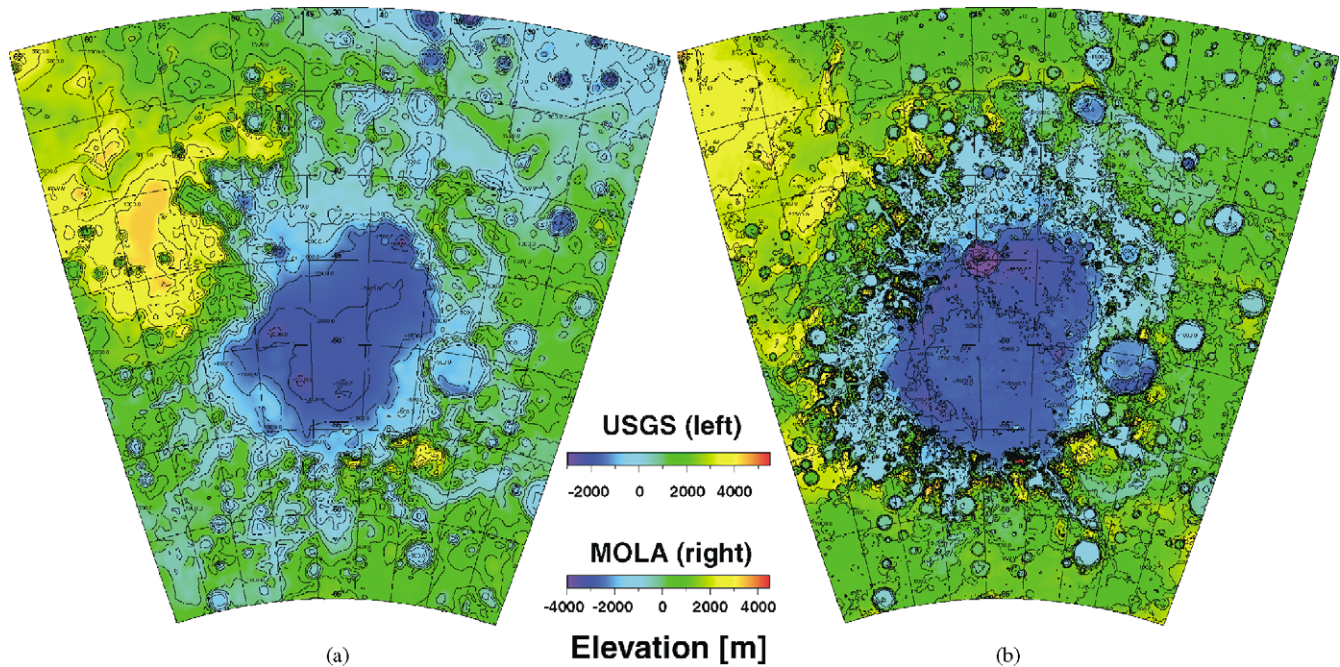
Plate 1. Comparison of US Geological Survey topography (a) and MOLA topography (b). Important differences are that the highest and lowest topographic points occur in different locations and that the floor of Argyre is tilted toward the N and W in the new data. Lambert azimuthal equal-area map projection; centered at −51°S, 43°W, 1° latitude = 59.17 km. Covered area is from −30°S to −65°S and from 20°W to 65°W; 5° grid spacing.

Digitized 1 km contour lines of the 1:2,000,000-scale series of topographic maps published by the US Geological Survey were used to produce a gridded topography (Plate 1a). The datum of this map is a gravity-level surface described in terms of spherical harmonics of fourth-degree and fourth-order combined with a 6.1 mbar pressure surface with a mean radius of 3382.9 km. In these data we see that the floor of Argyre is at about −2000 m; crater Hooke is not resolved in these data. The lowest point is within a sharp depression in the northeast of the floor at −3286 m. There are also at least two broader depressions in the southwest of the floor. The lowest points of these depressions occur at about −2500 to −2600 m. No tilting of the floor was observed but there are hints of a depression in the northeast of the floor and a second larger, elliptical depression in the southwest, which are separated by a low broad ridge. The terrain surrounding Argyre lies at about −500 m in the northeast, 2000 m in the southeast, 1200 m in the southwest, and 3300 m in the northwest. The highest point is located in the Nereidum Montes in the northwest and is 4604 m high.

Smith and Zuber (1998) re-determined the position of the 6.1 mbar atmospheric pressure surface on Mars with respect to MOLA surface topography. They found that the 6.1 mbar surface lies, on average, 1600 m below the geoid-defined zero level of MOLA topography, which occurs at an average pressure of 5.2 mbar at $L_s = 0°$. Zero elevation is defined as an equipotential surface whose average value at the equator is equal to 3396.0 km ± 300 m (Zuber et al., 1998). In Smith et al. (1999) the mean equatorial radius

is 3396.2 km ± 160 m. A 36th degree-and-order harmonic model, which was fit to MOLA data, was used to determine the best-fit ellipsoid. This reveals a triaxial ellipsoid with axes of 3398.627, 3393.76, and 3376.2 km.

Fig. 5 is a shaded relief map based on the new MOLA data. Superposed are the locations of profiles across the basin structure, which are shown in Figs. 6a–d. The new topographic data from MOLA (Plate 1b, Figs. 5, 6a–d) show that the deepest point in Argyre occurs within a small crater in crater Hooke at −5121 m. The highest point of the Argyre rim is at 5393 m and is located in the Charitum Montes southwest of crater Galle. Based on these elevations the total maximum topographic relief of the Argyre basin is in excess of 10 km. The summits of the Charitum and Nereidum Montes are generally higher than the surrounding terrain outside the basin rim and are separated by deeply incised valleys (e.g., profiles D*, G, H, I). These steep mountains and deep valleys form the rough annulus of the Argyre basin. Outside this annulus, the topography is usually much smoother (e.g., profiles A*, B*, J*, K*, L*, A, J, K). The basin floor also appears to be much smoother than the annulus (e.g., profiles E*, F*, G*, E, F, G, H). Profile H crosses the geologic unit Hr which is characterized by its extreme smoothness and flatness. MOLA data show that the basin floor of Argyre is tilted to the north and northwest and lies approximately at −2900 m. The surrounding terrain in the northeast of Argyre is at an elevation of 400 m; southwestern parts are generally higher and occur at about 800 m. Towards the Tharsis region the terrain is even higher.
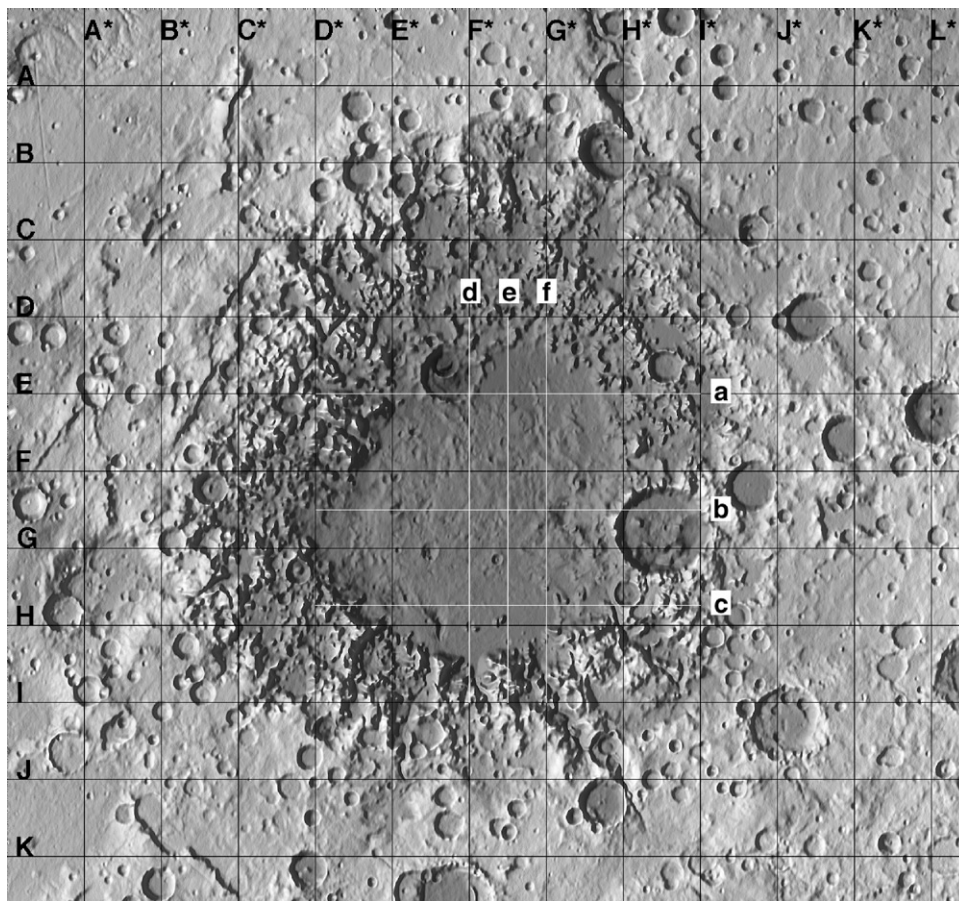
Fig. 5. Shaded-relief map of the Argyre basin based on gridded MOLA topography. Black lines and letters indicate the location of profiles shown in Fig. 6. Lambert azimuthal equal-area map projection; centered at −51°S, 43°W, 1° latitude = ∼ 59 km.

Numerous impact craters appear to be flat-floored, which might be an indication of infilling (e.g., profiles D*, K*, L*, A, D, E, F).

Profiles in Figs. 6b and d are detailed views of the floor of Argyre with the geologic units of Scott and Tanaka (1986) annotated. Unit Hpl$_3$ occurs over a wide range in elevation and is much rougher than one might expect from the imaging data. However, at the northern edge of the Argyre floor, unit Hpl$_3$ appears to be very flat and smooth. This exceptionally smooth area is located at the mouth of the large incoming channel where channel-transported sediments have been deposited, probably on top of unit Nple. Unit Nple is rough and appears to be partly covered by unit Hpl$_3$ and the much smoother unit Hr. The dissected unit Npld is tilted to the west. Debris aprons (unit As) are associated with the very steep topography along the floor/mountain transition but occur only in the southern Charitum Montes. The interior of crater Galle was mapped as "smooth crater floor" by Scott and Tanaka (1986), consistent with MOLA data that indicate a surface roughness similar to unit Hr.

Comparing the US Geological Survey topography from 1993 with the new MOLA topography (Plate 1a and b) we see significant differences. Major differences are that the

floor is not tilted in the US Geological Survey data and that the lowest and highest elevations occur in different locations.

3.1.2. MOC images

In addition to the MOLA data we made use of images obtained by the MOC experiment on board the Mars Global Surveyor spacecraft (e.g., Malin et al., 1992, 1998; Malin and Edgett, 2000). At the time of writing, about 450 narrow-angle images were available for the latitudes between −65° and −30° and the longitude range of 25°–60° (Fig. 1). The spatial resolution at the center of these narrow-angle images varies from 1.37 to 20.85 m/pixel.

3.2. Rings of Argyre

In Viking images the Argyre basin is an unusually pristine looking basin and its rings and structure have been investigated by several authors (e.g., Wilhelms, 1973; Wood and Head, 1976; Malin, 1976; Hodges, 1980; Thomas and Masson, 1984; Pike and Spudis, 1987; Schultz and Frey, 1990; Spudis, 1993). Based on our understanding of the literature on the Argyre rings, there is significant disagreement about the numbers, locations and the diameters of the
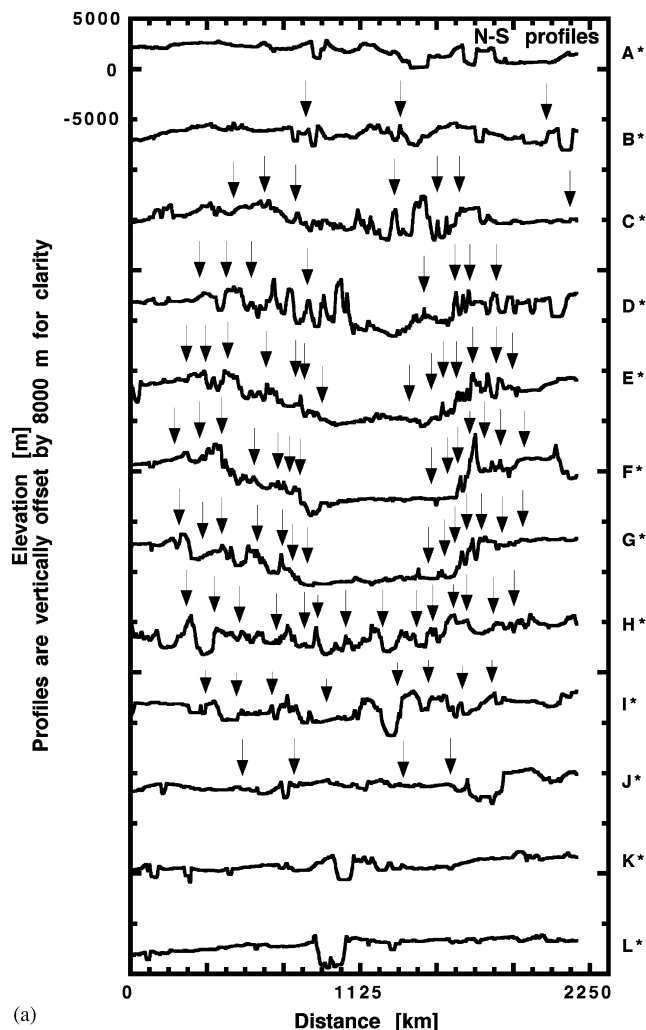
Fig. 6. Profiles across the Argyre basin based on MOLA gridded topography. (a) "N–S profiles"; north is to the left, south is to the right. Profiles have a vertical exaggeration (V.E.) of ∼ 50×. Black arrows indicate the approximate location of ring structures of Fig. 7a. As rings are not always continuous, morphologic features that define the ring do not show in each profile. (b) Detailed "N–S profiles" of the Argyre floor with superposed geologic units of Scott and Tanaka (1986). Profiles have a vertical exaggeration (V.E.) of ∼ 100×. (c) "W–E profiles"; west is to the left, east is to the right. Profiles have a vertical exaggeration (V.E.) of ∼ 50×. Black arrows indicate the approximate location of ring structures of Fig. 7a. As rings are not always continuous, morphologic features that define the ring do not show in each profile. (d) Detailed "W–E profiles" of the Argyre floor with superposed geologic units of Scott and Tanaka (1986). Profiles have a vertical exaggeration (V.E.) of ∼ 100×.

Argyre rings, as well as which ring represents the main ring. Based on Mariner images, Wilhelms (1973) identified three rings with 800, 1000, and 1200 km diameters and segments of even larger fourth and fifth rings. Wood and Head (1976) found a 560 km wide peak ring and a diameter for the basin of 1200 km. Based on principal analyses of lunar basins such as reported by Hartmann and Wood (1971), Malin (1976) determined a diameter of 800 km for what he called the most prominent, scarp-like ring. Hodges (1980) reported ring diameters of 900, 1200, and

1600 km. Thomas and Masson (1984) identified five or more outer discontinuous ridges but do not report their diameters. Pike and Spudis (1987) and Spudis (1993) identified six rings with 410, 630, 800, 1100, 1360, and 1900 km diameters. According to their interpretation, the main ring structure of the Argyre basin is represented by the 800 km wide ring. Schultz and Frey (1990) inferred ring diameters for Argyre of 540, 1140, and 1850 km, with the largest ring being the main ring. Melosh and Ivanov (1999) argued that due to extensive erosion neither the Hellas basin nor the Argyre basin show multi-ring scarps.

The definition of different ring structures necessarily results in differences in ring spacing. Based on his interpretation, Wilhelms (1973) found that the spacing increases outward by a ratio like that observed in lunar basins. However, lunar basins differ in a way that they (1) exhibit a more or less constant ring spacing of $2^{0.5}D$ (e.g., Fielder, 1963; Hartmann and Wood, 1971), and (2) that the spacing of the Argyre rings of Wilhelms (1973) is considerably smaller than for lunar basins. Pike and Spudis (1987) demonstrated that this $2^{0.5}D$ scaling law also holds for Mars and Mercury (99% confidence level). Contrary to Wilhelms (1973) and Pike and Spudis (1987), Schultz and Frey (1990) found that the ring spacing of several martian multiring basins, including the Argyre basin decreases outward. Based on their ring assignment, the spacing is much wider than that predicted by the $2^{0.5}D$ scaling law.

Not only is there confusion in the characteristics of the basin rings, but also in the comparison to multiringed structures on the Moon. Wilhelms (1973) argued that the Argyre basin is generally similar to the Orientale and Imbrium basins but differs in some respects. In his interpretation, the inner Argyre ring consists of isolated islands and is like the inner Imbrium ring. His second and third rings probably correspond to the second and third rings of the Orientale and Imbrium basins (Fig. 7b). Schultz and Frey (1990) argued that only martian basins smaller than Argyre (diameter of Argyre in their interpretation is 1850 km) are comparable dimensionally, morphologically, and structurally to the lunar Orientale basin. Basins larger than Argyre but smaller than Chryse ($D = 3600$ km) exhibit a rugged faulted annulus, central depression, and shallower topography relative to the basin diameter. These basins do not show clear analogs or identifiable remnants of an Orientale-like structure (Schultz and Frey, 1990). Thomas and Masson (1984) compared the Argyre basin with the lunar Orientale basin, the mercurian Caloris basin, and the Valhalla basin on Callisto. Based on morphologic, tectonic and stratigraphic evidence they concluded that despite evident similarities, the Argyre basin is different from the lunar counterparts. Spudis (1993) reported that the Argyre basin is similar in appearance to the Crisium basin in that the interior and troughs between the rings have been extensively flooded by volcanic plains material. He suggested that the Argyre basin has undergone a geologic history comparable to the Crisium basin.
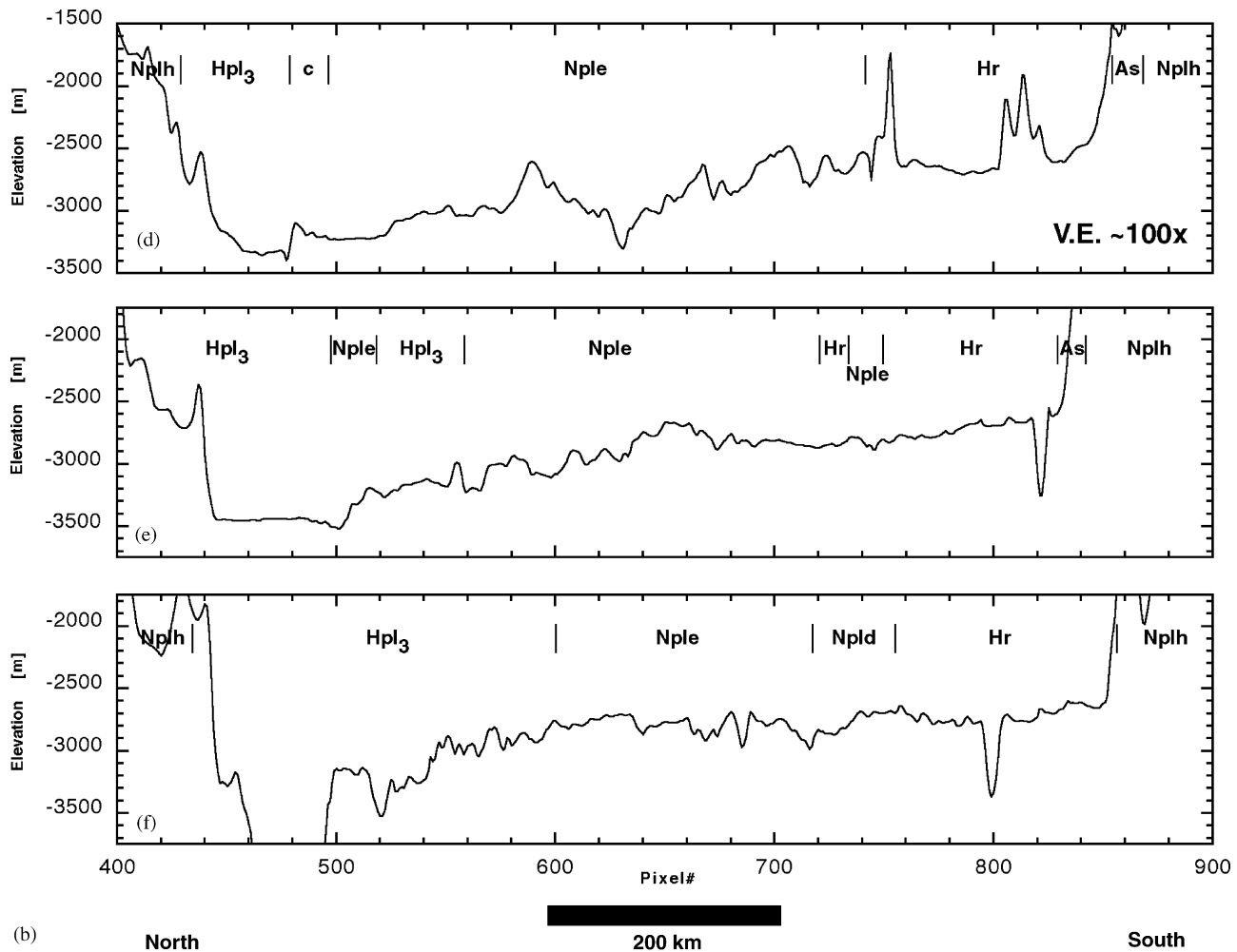
Fig. 6. *(Continued)*.

Several authors noted the rugged appearance of the Argyre basin (e.g., Wilhelms, 1973; Schultz and Frey, 1990; Spudis, 1993). Despite this, detailed observations and their interpretations vary significantly. Wilhelms (1973) found that the rugged peaks of his second ring have mostly irregular outlines and subordinate concentric and radial elements. His third ring is bounded on the basin side by a steep scarp and on the outside by a plateau. He reported that this ring and the plateau exhibit numerous coarse and fine radial structures; large structures like Orientale's Vallis Bouvard occur in all but the northeast sector. The segments of his fourth ring are marked by discontinuous ridges with smooth convex upward profiles and his partial fifth ring is characterized by two long inward-facing scarps and a featureless plateau. Schultz and Frey (1990) described the morphology of the Argyre basin as characterized by a rugged annulus and concentric graben. Thomas and Masson (1984) found that the rugged appearance is due to isolated blocks and ridges that are separated by more or less rectilinear troughs. Similarly, Spudis (1993) reported that morphology of the Argyre rings is characterized by clusters of rugged massifs

that are not confined narrowly to concentric patterns such as those of the Outer Rook ring of the lunar Orientale basin. Despite his comparison to the Crisium basin, rings of which are formed by platform massifs, Spudis (1993) argued that in Argyre there is no platform topography evident. However, Parker (1996a) found that many of the Nereidum and Charitum rim massifs are flat-topped with knobby terraces several hundred meters below the highest peaks. He interpreted these features to be erosional remnants of the surrounding Noachian plateau material. In Parker's view erosional processes similar to the ones that formed the fretted terrain along the highland/lowland boundary caused the pristine appearance of the Argyre basin.

Pike and Spudis (1987) defined four criteria for the identification of mercurian multiringed impact structures and based on these criteria and the new MOLA topographic data we re-investigated the number and location of the rings associated with the Argyre basin. The four criteria are: (1) isolated massifs and massif chains in circular patterns; (2) arcuate ridges aligned with massifs; (3) scarps aligned with massifs or ridges; (4) anomalously high
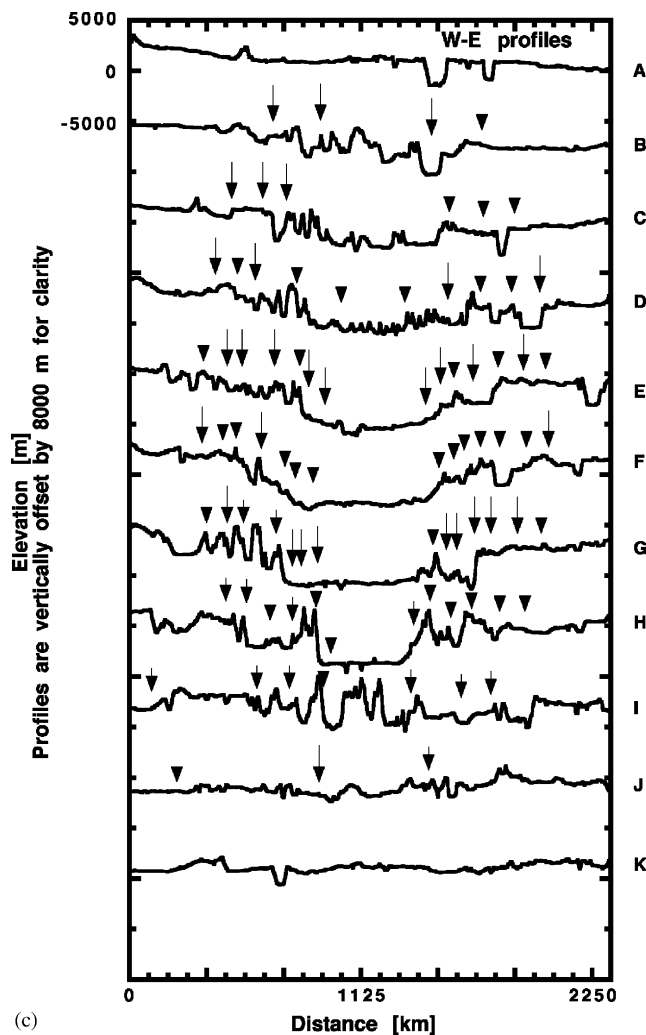
Fig. 6. *(Continued)*.

terrain. In addition to these criteria we also mapped concentric graben structures and the orientation of fluvial valleys that are concentric to the basin. The result of our mapping is shown in Fig. 7a.

In our interpretation, Argyre exhibits at least 7, probably even 8 rings with diameters of 650, 780, 870, 1050, 1290, 1470, 1700, and 2750 km, with the largest ring being the most uncertain structure (Figs. 7a, 6a and c). Based on these rings we obtain a ring spacing that is smaller than the $2^{0.5}D$ ($\sim$ 1:1.41) spacing of typical multiringed impact basins. Our average ring spacing ratio is 1:1.24 if we include all rings and 1:1.17 if we neglect the outermost ring. This smaller ring spacing might partly be due to the quality of MOLA data, which allows a better identification of ring structures than Viking imaging data. Interestingly, if we calculate the average spacing of every other ring, we obtain values that are very close to the $2^{0.5}D$ rule, that is, 1:1.38 for the inner seven rings and 1:1.46 for all rings, including the 2750 km ring. Calculating the ratio of Wilhelms' (1973) rings we found ratios of 1:1.25 to 1:1.2. Based on the rings identified by Pike and Spudis (1987) the average

spacing ratio is 1:1.37; using the rings of Schultz and Frey (1990), we obtained spacing ratios of 1:2.11 and 1:1.62. For the rings of Hodges (1980) we determined a ring spacing of 1:1.33. From this we conclude that none of the sets of rings proposed by various authors follows the predicted spacing of the $2^{0.5}D$ rule. However, Argyre is not the only basin in the solar system that possibly violates the $2^{0.5}D$ rule. Melosh (1989) pointed out that the Tolstoj basin on Mercury "badly violates" the $2^{0.5}D$ spacing rule. Ring diameter ratios of the Gilgamesh basin on Ganymede and the Valhalla basin on Callisto are also clearly far from $2^{0.5}D$ (Melosh, 1989). The physical significance of the $2^{0.5}D$ spacing is unknown but Spudis (1993) speculated that the spacing of rings is related to the physical conditions of the impact itself rather than target conditions. Melosh and McKinnon (1978) proposed that asthenospheric flow in response to transient cavity collapse could produce fault scarps with spacings of 1:1.2 to 1:2.

Looking at the MOLA morphology of the ring massifs, we found platform-like massifs as well as sharp-crested and peak-like massifs. Radially and concentrically dissected platform-like massifs occur preferentially in the southern and western parts of the basin. The occurrence of most prominent radial and concentric graben-like features is restricted to the region within the 1700 km ring. Platform massifs are absent in the northeast quadrangle. Rings in this part of the basin are outlined by isolated topographic peaks and wide flat intermountain areas. Some rings (e.g., the 1470 and 1700 km rings) are partially characterized by sharp basin-inward scarps and outward plateaus that are either level or sloping away from the basin. A similar morphology has been described for the Cordillera ring of Orientale (e.g., Moore et al., 1974; Head, 1974) (Fig. 7b). Similarly, our outermost ring is defined by a scarp/plateau morphology, best seen at the Argyre Rupes and in the east of the basin at about 5°W and 45°S. Based on the MOLA topography, our 1700 km ring is the most complete ring at highest elevations. Inner rings, especially the 780 and 870 km rings, are much more dissected and less continuous. Elevations of the massifs of these rings can locally exceed the elevations of the 1700 km ring but are generally somewhat lower.

On the basis of morphologic and topographic comparisons, Head (1974, 1977) and Bratt et al. (1986) suggested that the Orientale Cordillera ring was equivalent to a scarp marking the outer part of a collapsed megaterrace, the Outer Rook ring was the closest approximation to the transient crater rim, and the Inner Rook Mountains were equivalent to a peak ring. The innermost depression was related to thermal contraction of the cooling central basin uplifted geotherms. Starting from the interior of Argyre, the inner depression (rings 1–3) is similar to that of Orientale, the isolated mountains (rings 4–5) to the peak rings, and the main topographic scarp to the Cordillera Mountains (ring 7). The Outer Rook equivalent appears to be ring 6, or possibly a combination of rings 5 and 6. Ring 8 is very irregular and would lie beyond the Cordillera equivalent.
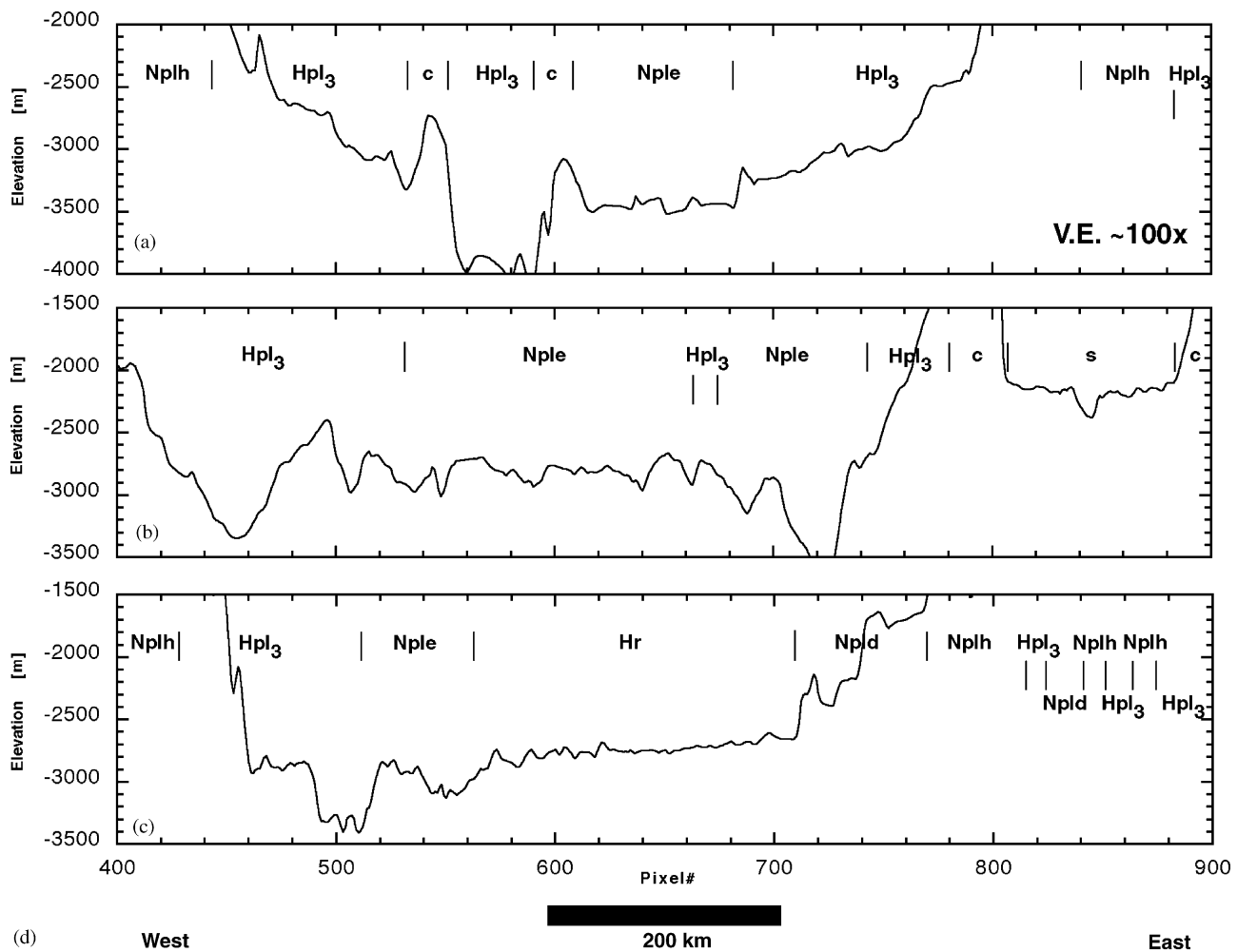
Fig. 6. *(Continued)*.

3.3. Eolian activity in Argyre

3.3.1. Previous observations, interpretations, and implications

Based on the interpretation of Mariner 9 A-frame images, Hodges (1980) concluded that the interior smooth plains of Argyre largely consist of eolian deposits. Smooth plains material in topographic lows were cited as suggesting a depositional origin, and wind streaks as evidence for unconsolidated debris (Hodges, 1980). On the basis of Mariner images she concluded that the floor material (unit Ps) is probably unconsolidated and thus subject to erosion and transport, especially during periodic planet-wide dust storms. Preexisting topography is largely obscured and from this Hodges (1980) concluded that the deposits are of substantial thickness. Hodges (1980) also mentioned that parts of the floor might be fluvial in origin as suggested by branching channels draining into Argyre, specifically from the south rim. Hodges (1980) further reported that the basin rim is subject to erosion, and likely erosional agents are water, wind, and ice.

3.3.2. Tests

We used MGS data to test this hypothesis of an eolian-dominated evolution of the Argyre basin. In a first test we looked at the distribution of smooth material and in a second test we investigated the morphology of ridges which are exposed in southern Argyre Planitia.

3.3.2.1. Distribution of smooth material.
Provided widespread eolian activity accumulated thick eolian deposits on the floor of Argyre basin, then we expect to see evidence for sand dunes and other eolian characteristics such as a smooth or mantled topography. At Viking resolution there are large areas of relatively featureless plains (unit Hpl_3 of Scott and Tanaka (1986); Fig. 2c) in Argyre which might be related to eolian activity. The smooth unit Hpl_3 occurs on the floor of the basin and occupies the valleys between the rim mountains. From MOLA data we know that this unit is exposed over a wide range of elevation (about 4 km). This result might be principally consistent with an eolian formation or modification of this unit because eolian deposits are not gravitationally confined to lower elevations as lava
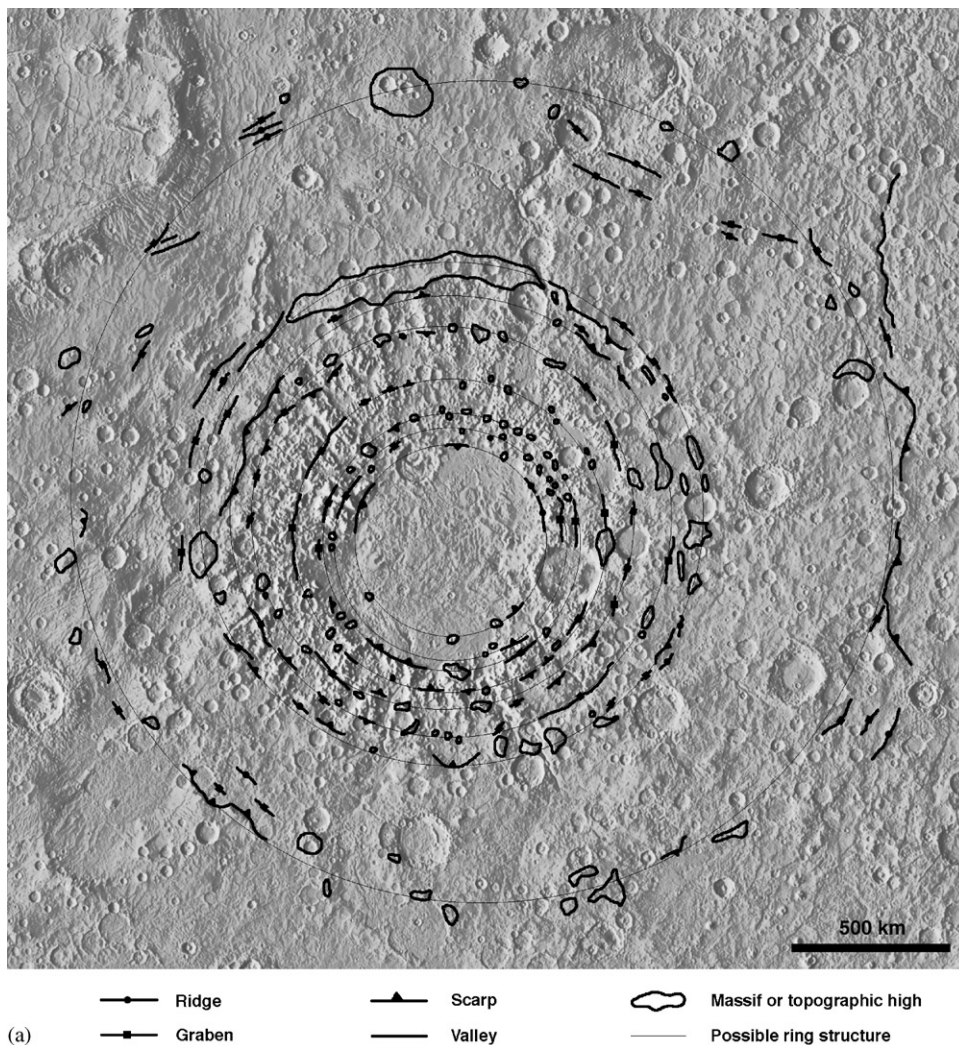
Fig. 7. (a) Shaded relief map of the Argyre basin and the surrounding terrain. Superposed is a map of basin elements (ridges, graben, scarps, channels, isolated massifs) based on MOLA data which were used to infer the locations, spacings, and diameters of ring structures associated with the Argyre basin. Lambert azimuthal equal-area map projection; centered at −51°S, 43°W, 1° latitude= ~ 59 km. (b) Clementine mosaic of the lunar Orientale basin. The black line indicates the location of the topographic profile. Note that the profile extends further to the north and south than shown in the image. Topography is based on Clementine LIDAR data of Zuber et al. (1994) with a spatial resolution of ~ 1 pixel/degree. Resolution is about a factor of 15 worse than the MOLA topography.

flows or lacustrine deposits (Parker, 1994). According to Parker (1994), eolian deposits drape older terrain rather than forming a topographically conformal boundary. Viking images show a variety of distinctive morphologic features in the basin center (unit Nple of Scott and Tanaka (1986); Fig. 2e) that appear fresh and not mantled. At Viking resolution no prominent dune fields were observed but MOC images reveal that dunes basically occur on all units associated with the Argyre basin. An example of a MOC image showing a dune field in Argyre Planitia is given in Fig. 8a. Investigating the distribution of dunes in MOC images in relation to the geologic units in more detail, we see that dunes preferentially occur on units with locally steep slopes, such as craters or channels. This might be related to changing wind speed across features with pronounced topography that favors accumulation and redistribution of fine-grained material. However, MOC images of the basin floor also indicate that almost every third image of unit Hpl_3 and every other image of unit Hr show rough surface textures that are probably related to deflation and/or sublimation (Fig. 8b). More than 70% of images of unit Npld, which is exposed on the floor of the Argyre basin, show such a texture. In addition, we see numerous mesas, especially in images of unit Hpl_3 and Hr, indicating significant amounts of erosion on the basin floor. Viking Infrared Thermal Mapper (IRTM) data of the Argyre and the Hellas basins show systematic differences in that the Argyre basin is characterized by a rougher floor compared to the Hellas basin (Christensen and Moore, 1992).
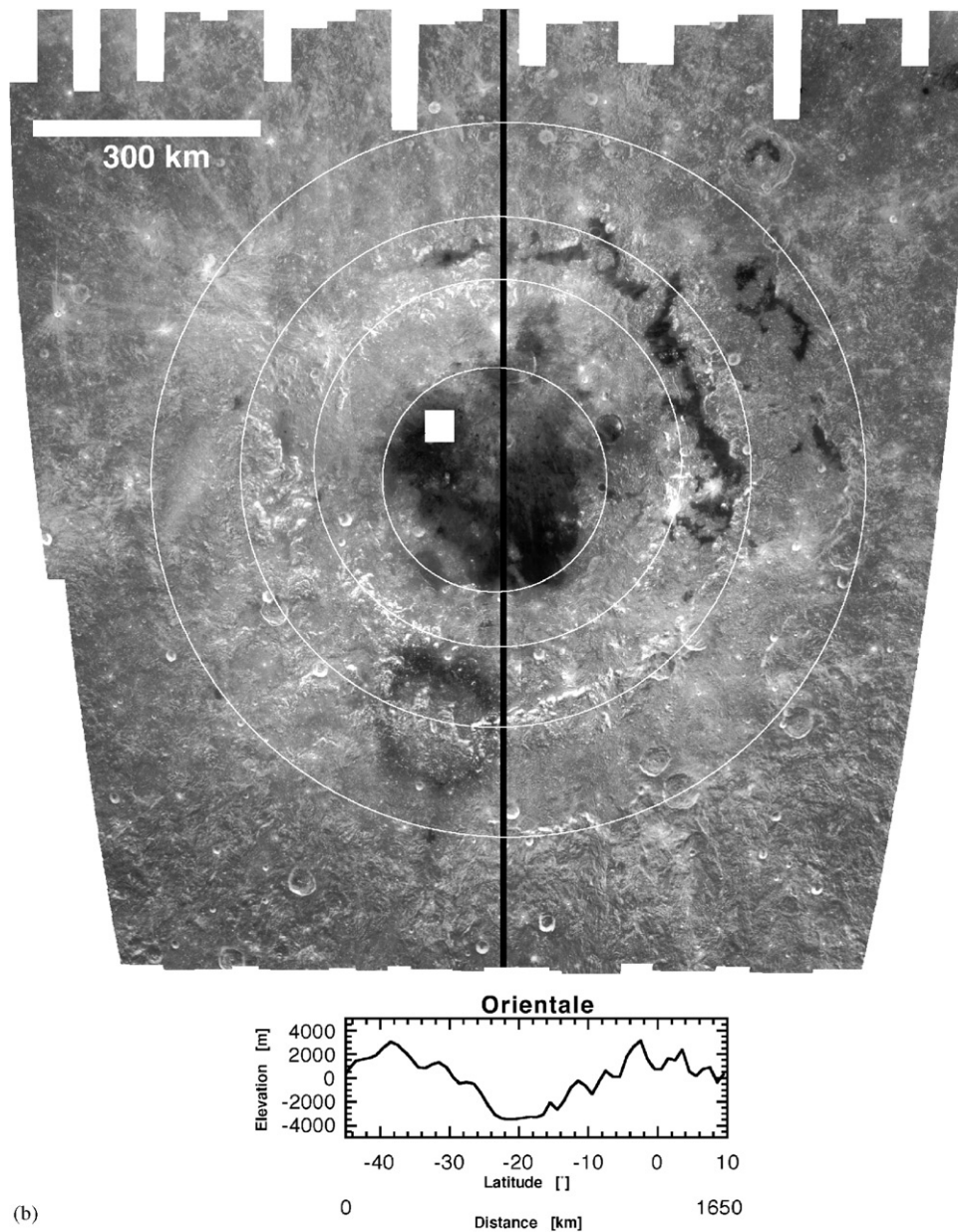
Fig. 7. *(Continued)*.

On the basis of IRTM data of the Hellas basin, Moore and Edgett (1993) concluded that eolian erosion removed several kilometers of dust leaving behind a coarser lag. They also concluded that within this lag, the abundance of rocks larger than sand size is very low. If this interpretation is correct then the thermal inertia data of the Argyre floor suggest an even coarser lag deposit compared to the Hellas basin. From our observations we conclude that the basin floor certainly was modified by eolian processes, eroding material in some areas and depositing it in other regions. However, based on the inspection of MOC images, we did not find strong evidence for an evolution of the basin floor solely dominated by eolian activity.

3.3.2.2. Morphology of ridges. Prominent ridges in the southern regions of Argyre Planitia (Fig. 2b) were interpreted as dunes (Ruff and Greeley, 1990; Parker et al., 1986). Average linear dunes on Earth have lengths from 2 to 3 km and widths of 30–150 m (Mainguet, 1984). They are often arranged in systems that can reach 30–40 km in length. Sand ridges in the Taklimakan desert in northwestern China, which can be distinguished from linear dunes by the dynamics of formation, are up to 1 km wide, up to 45 km long and 80–200 m high (Zhenda, 1984). Sand ridges are aligned parallel to the prevailing wind direction, sand dunes are aligned obliquely to the wind direction (Mainguet, 1984). Compared to the dimensions of the investigated
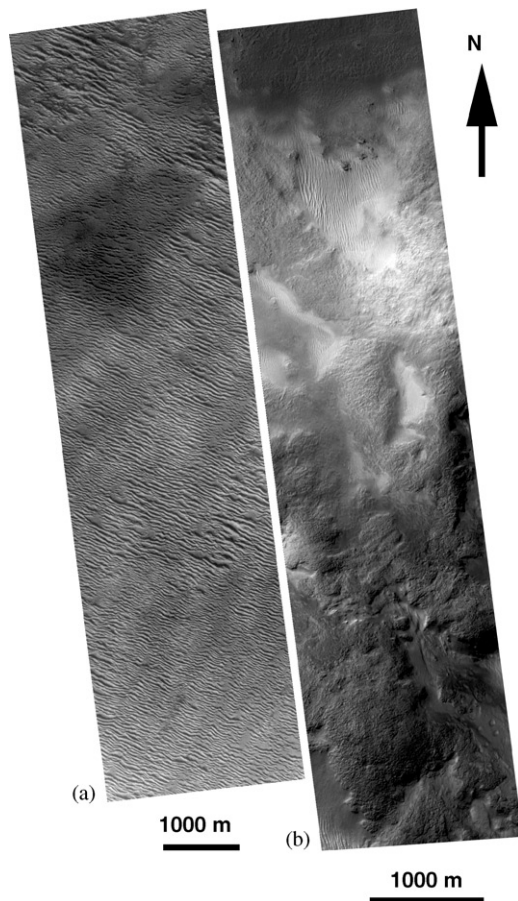
Fig. 8. MOC images of Argyre Planitia. (a) Dune field in MOC image M0203105 (50.95°W, 49.95°S). Dunes of unit Hpl₃ are much smaller than ridges of unit Hr. (b) Dunes and deflated terrain in MOC image M0100045 (35.32°W, 47.58°S, unit Hpl₃). Dunes occur preferentially in topographic lows. Circular and irregular depressions in the lower right corner could be collapse pits or old impact craters.

martian ridge (Fig. 9) derived from MOLA (300–350 km long, 3–9 km wide, 40–110 m high), terrestrial dunes appear to be much smaller. Martian dunes exhibit heights of 10–25 m and a wide range of crest-to-crest spacings (Greeley et al., 1992). The mean spacing of dunes in the north polar regions is of the order of 512 and 2400 m in the southern hemisphere (Greeley et al., 1992). In addition to these data, we identified all MOC images in the Argyre region, which contain dunes and measured the size of these dunes (Figs. 8a and b). Looking at about 100 MOC images, we found 40 images with dunes and our measurements show that typical dunes in the Argyre region are on the order of 100–1300 m long and about 10–100 m wide. We conclude that both terrestrial and Martian dunes seem to be too small to be good analogs to these ridges. Contrary to sand ridges, which often exhibit symmetric slopes, dunes often show asymmetric cross-sections with either higher or lower upwind slopes compared to downwind slopes. Profiles across the investigated ridge (Fig. 10) in Argyre Planitia do not show such an asymmetry of slopes.

On the basis of these observations we conclude that an eolian origin of the ridges in Argyre Planitia is not likely. We further conclude that the Argyre basin forms a depression that was a long-term trap for eolian material, and that eolian redistribution of floor material has certainly occurred. However, we find no strong evidence to support an eolian origin for the majority of the basin fill.

3.4. Volcanism in Argyre

3.4.1. Previous observations, interpretations, and implications

According to Scott and Tanaka (1986) the most extensive unit in the Noachian System is the cratered unit Npl₁ (Fig. 2a). They argue that the occurrence of lava-flow fronts in this unit, which is exposed outside the Argyre basin rim, and a profusion of impact craters, suggest that this unit consists of volcanic material interbeded with impact breccia. Areas where these materials have been mantled were mapped as Npl₂, areas that were heavily dissected by small channels were mapped as unit Npld. Similarly, regions where unit Npl₁ has been etched into irregular grooves and hollows were mapped as unit Nple. The most widespread Hesperian unit is the ridged plains unit Hr (Scott and Tanaka, 1986). Scott and Tanaka (1986) argue that this smooth unit is characterized by widely spaced, long, sinuous ridges similar to wrinkle ridges of the lunar maria and they conclude that unit Hr consists of lava flows.

3.4.2. Tests

With MOLA and MOC data at least three tests can be performed in order to assess the volcanic origin of the geologic units in Argyre Planitia.

3.4.2.1. Morphology of ridges. Lunar wrinkle ridges are hundreds of kilometers long, several kilometers to as much as 10 km wide, and 100 m or in some cases even 350 m high (Wilhelms et al., 1987). According to Lucchitta (1976) the elevation on either side of a wrinkle ridge can vary up to 50–100 m. A common characteristic of wrinkle ridges are narrow ridges superposed on top of the broad wrinkle ridge structure (e.g., Muehlberger, 1974; Golombek et al., 1999, 2000). Martian wrinkle ridges are similar in size and morphology. They are many tens to hundreds of kilometers long, up to a few tens of kilometers wide, and have a relief of a few hundred meters (Chicarro et al., 1985; Watters and Maxwell, 1986; Golombek et al., 1991, 1999, 2000). The elevation offsets are on the order of 50–180 m (Golombek et al., 2000).

According to Scott and Tanaka (1986) units Npld and Nple were highly modified after their deposition by subsequent erosional processes. Because MOLA data only show the current topography and morphology, i.e. after the modification, it is difficult to test the hypothesis of a volcanic origin of these units. However, unit Hr is less altered and
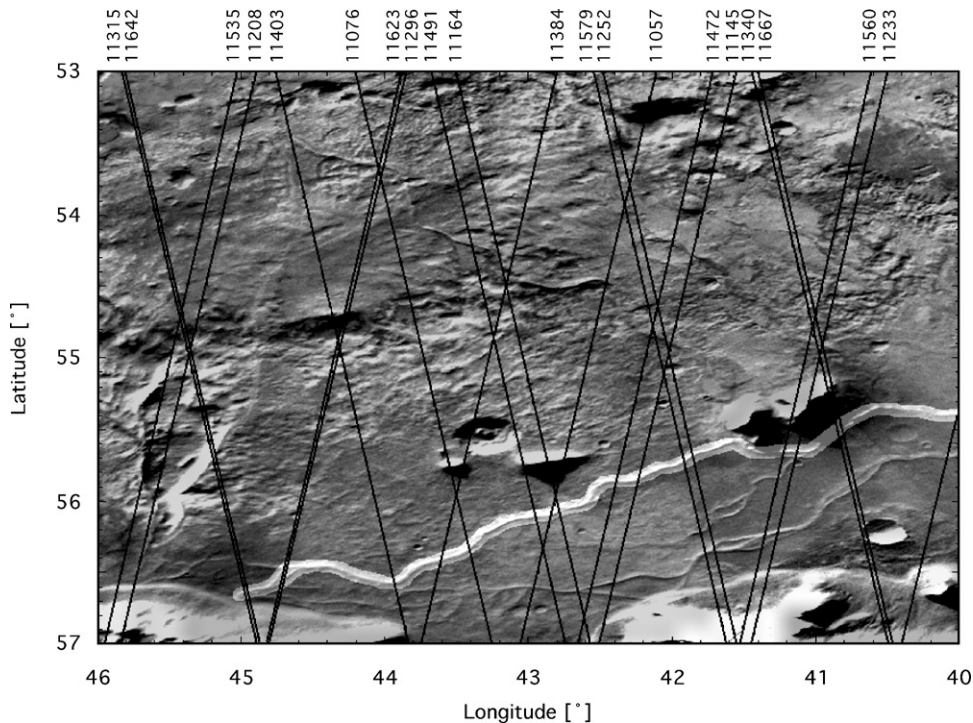
Fig. 9. Viking MDIM with superposed MOLA tracks of southern Argyre Planitia. The investigated ridge of unit Hr is highlighted. Simple-cylindrical map projection, 1° latitude = 59.17 km.

exhibits ridges that Scott and Tanaka (1986) found similar to wrinkle ridges of martian volcanic provinces, and thus were interpreted as evidence of volcanic deposits. However, examining the morphology of typical wrinkle ridges in Lunae Planum (Fig. 11a) and comparing them to the Argyre ridges (Fig. 11b), reveals significant differences. At equal image resolution, the Argyre ridges appear to be more sinuous, more braided, and we do not observe a small sharp ridge superposed on a broad ridge. Golombek et al. (2000) investigated wrinkle ridges of Solis Planum in detail and here we compare their results with our own findings for a prominent ridge in Argyre Planitia. Golombek et al. (2000) show MOLA profiles across wrinkle ridges that display plains surface at different elevations on either side of the ridge. Golombek et al. (2000) interpret these as indicating subsurface thrust faults underlying the ridge. It is mostly accepted that wrinkle ridges result from compressional folding and faulting of near-surface units (e.g., Golombek et al., 2000). Wrinkle ridges can be characterized by a sinuous or linear plan, asymmetric cross-sections, a smaller ridge superposed on a broad rise, an offset in elevation on either side of the ridge, lengths of tens to hundreds of kilometers, widths up to a few kilometers, and heights of a few hundred meters. Compared to the Argyre ridge we see significant differences in numerous characteristics of typical wrinkle ridges. The investigated Argyre ridge (Figs. 9 and 10) does not show a narrow ridge on top of a broad ridge, has numerous cross-sections that are symmetrical, exhibits smaller offsets in elevation between the left and right side of the ridge,

and appears less high than the wrinkle ridges studied by Golombek et al. (2000). This suggests that one of the main characteristics of the Hr plains unit used to infer a volcanic origin may be of different origin, and this decreases the evidence for the lava flow origin of these plains.

3.4.2.2. Source vents. Based on Viking images, Scott and Tanaka (1986) interpreted unit Hr as extensive flows of low-viscosity lava erupted from many sources at high rates. Unit Hr is a relatively small unit but 16 MOC images cover this area. Inspecting these images, we found no evidence for flow fronts, source vents, or other constructs that are clearly volcanic in origin. Although the surface units and structures do not appear to be of volcanic origin, plains of volcanic origin could underlie the presently observed surface deposits and it is not clear if layering seen in some MOC images is related to volcanic activity.

3.4.2.3. Surface roughness. A third test is the comparison of surface roughness of unit Hr with the roughness of well-known volcanic provinces and sedimentary units. Previous investigation of the roughness of geologic units in the northern martian hemisphere showed that unit Hr is significantly smoother than units Npl_1, Npl_2, Npld, and Nple (Kreslavsky and Head, 1999, 2000). We used the roughness map of Kreslavsky and Head (2000) which simultaneously displays the roughness at three different baselines, i.e. 19.2, 2.4, and 0.6 km in order to investigate unit Hr in detail. Each of these roughness maps is displayed as red,
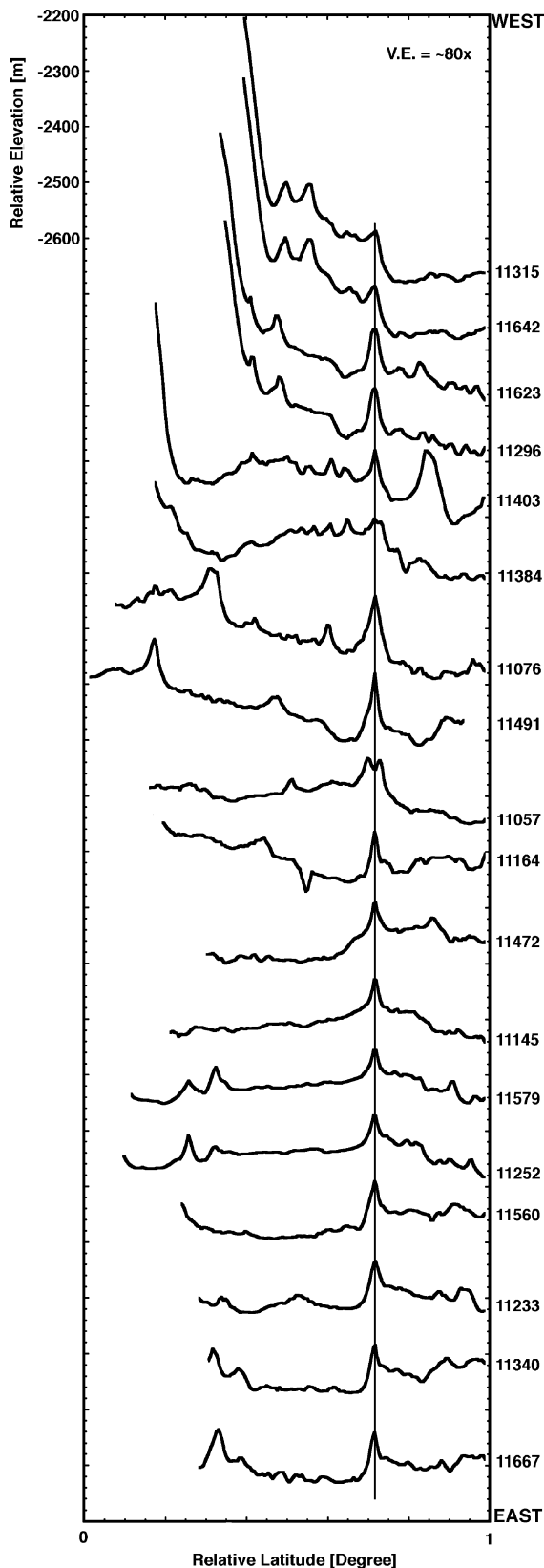
Fig. 10. MOLA profiles across the major ridge in southern Argyre Planitia. Profiles are 1° wide and are vertically offset for clarity. Numbers on the right are MOLA orbit numbers. Black vertical line shows position of ridge crest. Vertical exaggeration (V.E.) is ∼ 80×.
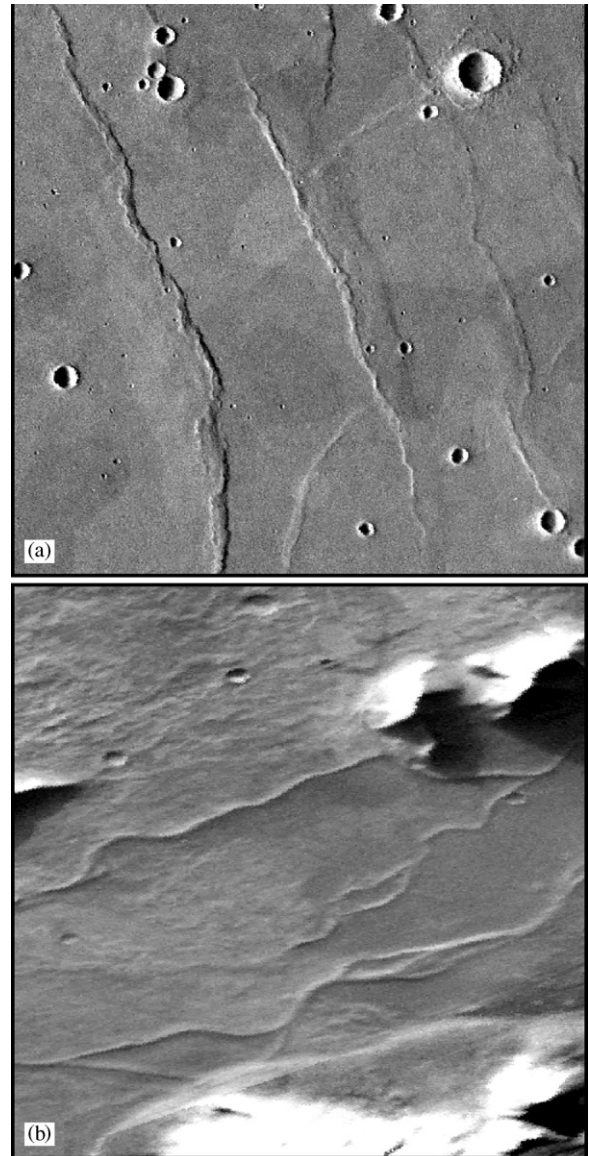
Fig. 11. Comparison of the morphology of wrinkle ridges in Lunae Planum (a) and the ridges in Argyre (b). Both images are Viking MDIMs at about 250 m spatial resolution. Wrinkle ridges appear less sinuous, show a small ridge on top of a broad rise, are not braided, and do not show diffluent and confluent branches.

green, and blue, respectively, with higher DN values indicating rougher terrain. Based on the data and global map of Kreslavsky and Head (2000), we determined the roughness of 130 globally distributed volcanic and sedimentary units, calculated the average roughness of each type of unit, and compared it to the roughness of unit Hr in the Argyre basin. Plotting the DN values for each baseline in a three-dimensional plot, volcanic and sedimentary units, to a first order, plot within a very narrow linear array (Figs. 12 and 13). The roughnesses of all volcanic units at each baseline are highly correlated, with older units generally rougher than younger units. This was also found by Kreslavsky and Head (2000) who explained this trend as being caused by

Fig. 12. Three-dimensional plot of mean roughness for geologic units at baselines of 0.6, 2.4, and 19.2 km derived from the roughness map of Kreslavsky and Head (2000). In this map, roughnesses at the three wavelengths are expressed as brightnesses in RGB space. In the map of Kreslavsky and Head (2000) rough areas are shown in bright (high DN values), smooth areas are shown in dark hues (low DN values), and color differences represent variations in roughnesses at the three investigated wavelengths. Based on this map we derived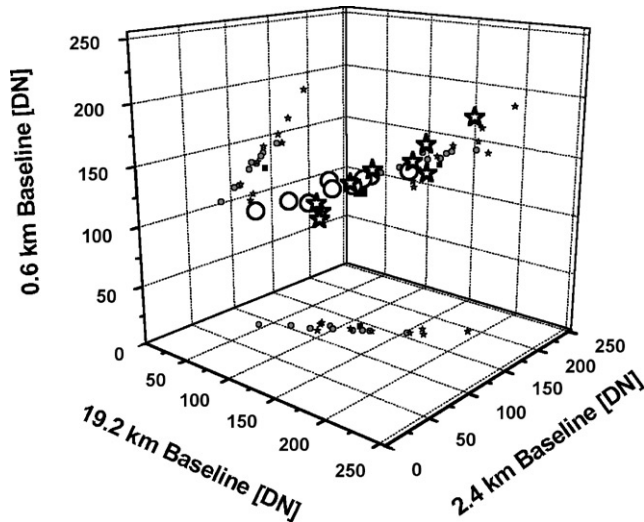 the mean surface roughness for a variety of geologic units. Open circles are volcanic units, open stars are non-volcanic units, and the solid square represents unit Hr in the Argyre basin. Larger symbols are data points, smaller symbols are projections of these data points to planes. Units are DN values. See Fig. 13 for unit identification.
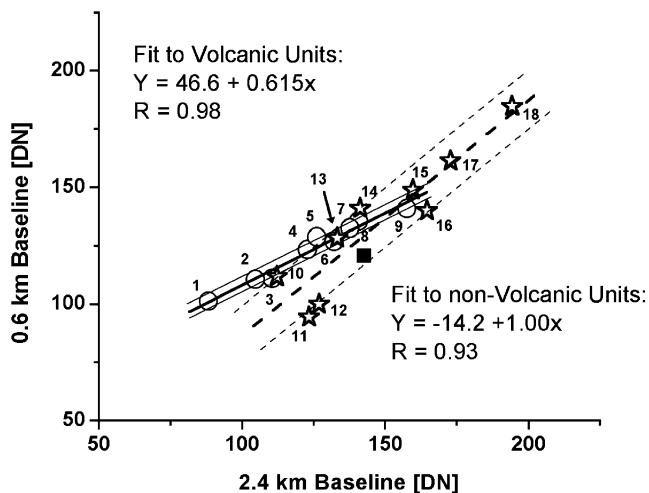

Fig. 13. Mean roughness of geologic units at baselines of 0.6 and 2.4 km derived from the roughness map of Kreslavsky and Head (2000). Symbols and units are the same as in Fig. 12. Note that all investigated volcanic units plot along a narrow line and that old volcanic units are systematically rougher than younger volcanic units. Thick lines are least square fits to the data (dashed for non-volcanic units), thin lines are 1σ standard deviations (dashed for non-volcanic units). Numbers indicate units: 1, Aa; 2, Aa$_1$; 3, At$_5$; 4, Ael$_1$; 5, Hal; 6, Hsl; 7, Hs; 8, Hr; 9, Nplr; 10, Aps; 11, Hvk; 12, Hvm; 13, Apk; 14, Hpl$_3$; 15, Npl$_2$; 16, Npl$_1$; 17, Nple; 18, Nplh.

accumulation of impact craters and tectonic deformation on older plains. For sedimentary units the roughness at the investigated baselines are also positively correlated, but the age/roughness relationship is much less obvious than for volcanic units. Projection of the data points to the surface planes defined by 0.6/19.2, 0.6/2.4, and 19.2/2.4 km roughness shows subtle differences between geologic units (Fig. 13). In the 0.6/19.2 plane and especially in the 19.2/2.4 km plane, unit Hr in Argyre is hardly distinguishable from other units investigated. However, in the 0.6/2.4 km plane, unit Hr shows many more characteristics of sedimentary than of volcanic deposits (Fig. 13). This is indicated by the observation that unit Hr in Argyre plots well within the 1σ standard deviation of the sedimentary units and outside the 1σ standard distribution of the volcanic units. In addition, unit Hr is located at the mouth of channels that enter the Argyre basin and the flows forming the channels quite likely deposited material. Finally, as discussed above we do not see source vents or flow fronts in southern Argyre Planitia, such decreasing the likelihood of a volcanic origin of unit Hr. We cannot exclude the possibility that a volcanic unit Hr was later mantled by sediments but based on our observations, that is, the surface roughness, the location at the mouth of incoming channels, the absence of source vents, and the characteristics of the ridges exposed on this unit, we conclude that it is very likely that unit Hr in Argyre is largely sedimentary in origin.

3.5. Mud in Argyre

3.5.1. Previous observations, interpretations, and implications

Jöns (1992) rejected large-scale glaciation of the southern hemisphere for a variety of reasons and proposed that a vast mud sheet entered Argyre Planitia when the south polar cap underwent melting (Jöns, 1987, 1999). His arguments against glaciation are that (1) older impact structures should be eroded, (2) ridges should be oriented parallel to the glacier flow, (3) there should be a moraine belt at the margins of the glacier, and (4) that spillways should occur immediately next to the glaciated regions (Jöns, 1992). The orientation of ridges in Argyre Planitia led him to conclude that they were not formed by a glacier but instead formed when mud waves instantaneously desiccated and froze. However, work Jöns and Mohlmann (2000) showed that for a 1 m thick layer of mud cooling by IR radiation would take about 2 days, and that cooling by conduction would last about 10^5 sec (2.78 h). On the basis of their calculations, they concluded that the derived cooling times are not consistent with the idea of an instantaneous solidification of a large mud sheet. According to Jöns (1999) the ridges form a delta-like, triangular-shaped structure with the vertex pointing "exactly" toward the mouth of Surius Vallis. The sides of this triangle are about 350 km long (Jöns, 1999). However, from his map (Jöns, 1987) we see that the mud-
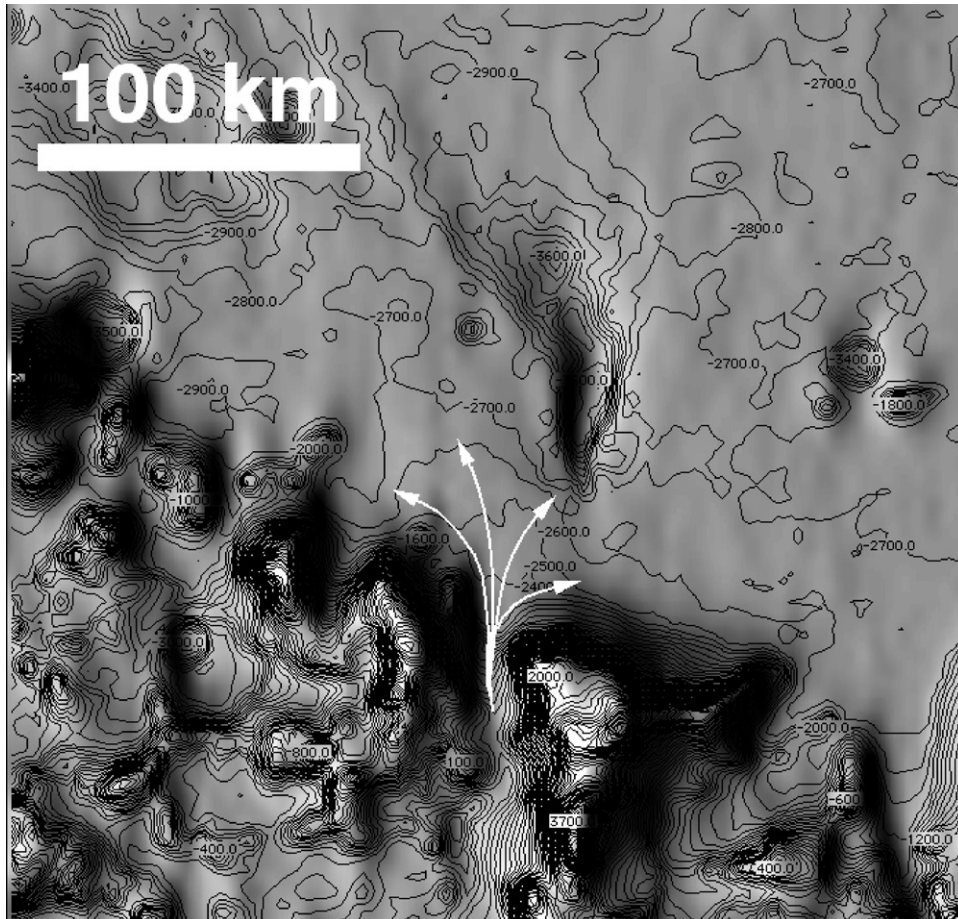
Fig. 14. MOLA topography of the mouth of Surius Vallis showing a small delta-like feature. Superposed are 100 m MOLA contour lines. Arrows start within Surius Vallis and indicate spread-out of transported sediments onto the floor of the Argyre basin in order to form a delta. Lambert azimuthal equal-area map projection; centered at $-51°$S, $43°$W.

flow spread out much farther to the north, covering about two-thirds of Argyre Planitia (Jöns, 1999).

3.5.2. Tests

This model is hard to test because only a few specific predictions were made. However, with MOLA data we can test for the existence of the proposed delta at the mouth of Surius Vallis. The shape of MOLA contour lines reveals a morphologic feature at the mouth Surius Vallis that can be interpreted as a delta (Fig. 14). However, the size of this delta is on the order of 30 km and therefore at least ~ 10 times smaller than the delta envisioned by Jöns (1987, 1999). In the MOLA data there is no evidence for a delta of the order of 350 km in dimension. Another prediction of Jöns (1992) is that ridges preferentially formed where the flooding material was dammed by escarpments and that in smooth areas without escarpments only a few, if any, ridges will occur. In the MOLA data we see no evidence for escarpments that might have dammed material. In addition, we see that the most prominent ridges are associated with unit Hr of the geologic map of Scott and Tanaka (1986),

which corresponds to the smoothest and flattest unit in our slope map. These observations are not consistent with Jöns' (1992) predictions.

In conclusion, in our opinion there is no need to postulate a catastrophic mudflow to explain morphologic features found in Argyre Planitia because they can be much more readily explained by other geologic processes.

3.6. Ice in Argyre

3.6.1. Previous observations, interpretations, and implications

Based on their investigation of the morphologic inventory of the Argyre basin and adjacent regions, Kargel and Strom (1992) concluded that Argyre underwent glaciation in its past (Fig. 3). According to their model, evidence for such a glaciation includes distinctive morphologic features which were interpreted as eskers (serpentine ridges formed by a stream flowing in or beneath a stagnant or retreating glacier), drumlins (low elongated hills of compact glacial till), moraines (ridges of unstratified glacial drift),
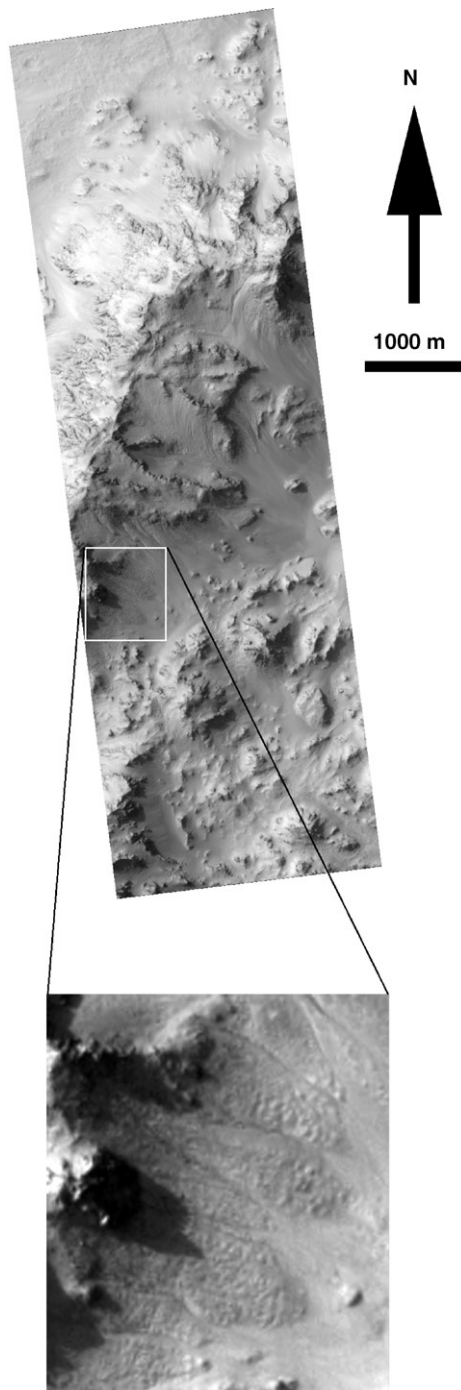
Fig. 15. Part of MOC image M0410179 ($\sim$ 36.74°W, $\sim$ 35.91°S) of the center of crater Hale. Detail shows debris avalanche from the steep mountain ridge, which can be interpreted as a rock glacier.

cirques (deep steep-walled recesses high on mountains and produced by glacial erosion), arêtes (rocky sharp-edged ridges above the snowline of rugged mountains formed by a glacier), horns (high pyramidal peaks formed by intersecting cirques), rock glaciers (masses of angular boulders and finer material with interstitial ice or an ice core), and kettles (depressions formed by melting of a detached block of stagnant ice that was buried in a glacial drift). Fig. 15

is a MOC image showing a morphologic feature that could be interpreted as a rock glacier. Figs. 16a and b are MOLA profiles across the floor of Argyre Planitia and its associated features that were interpreted as being formed by glacial processes by Kargel and Strom (1992) (see Fig. 3 for location of profiles). They proposed that ice accumulated in the mountainous rim of Argyre, i.e. the Charitum Montes, and on adjoining cratered uplands and flowed into the basin thereby sculpting the steep slopes of Charitum Montes. Once the glacier retreated, large amounts of melt water were produced and eskers and collapse features formed on the basin floor. The meltwater accumulated in a proglacial lake and deposited smooth glaciolacustrine plains (Kargel and Strom, 1992). According to Kargel and Strom (1992) this glaciation occurred late in martian history between 0.25 and 2.3 b.y. ago, that is within the Amazonian Period. Compared to the Hellas basin, another basin for which Kargel and Strom (1992) proposed a glaciation, the Argyre basin shows significant differences in morphology. These authors find deep erosional scouring at Malea Planum to be similar to glacial scouring in Canada and Antarctica and interpret ridges on the floor of Hellas as eskers, drumlins, recessional moraines and terminal moraines. In their Fig. 3a they also identify the shoreline of a proglacial lake. Provided that both areas, Hellas and Argyre, were once glaciated, then the inventory of glacial features is surprisingly different between these basins. Esker-like ridges and the postulated proglacial lakes are probably the only common morphologic features. On the other hand, Argyre is characterized by its rough annulus of mountains with deeply incised valleys, an etched/scoured unit on the basin floor with numerous collapse features, and possible rock glaciers along the southern floor/mountain boundary. There is also a difference in the location of Kargel and Strom's (1992) scoured terrain. In Argyre it is located on relatively flat basin floor, in Hellas we find the scoured terrain along the inward-facing slopes of the southern rim. For the Hellas basin Kargel and Strom (1992) argued that an extensional ice flow caused the erosion of scoured terrain on steeper slopes. Kargel and Strom (1992) argued that in the Hellas region, glacial erosion removed on average $\sim$ 200 m of material. If true, then this erosion must have been much more sheet-like in the Hellas region compared to the more localized erosion that formed the deep valleys of the Argyre basin. Thomson and Head (2001) used new MOLA data to test for a glaciation of the Hellas basin. They found that ridges in the Hellas basin, interpreted as moraines by Kargel and Strom (1992), are more similar to wrinkle ridges than to glacial features, and that the scoured terrain is unconnected to the south polar deposits, indicating that if glaciation occurred it was isolated (Thomson and Head, 2001). The occurrence of esker-like ridges is much more limited in the Hellas basin compared to the Argyre basin, and these ridges are much less extensive, continuous, and systematic (Thomson and Head, 2001). Layered terrain has been observed in MOC data on the northern basin floor of Hellas, which is possibly
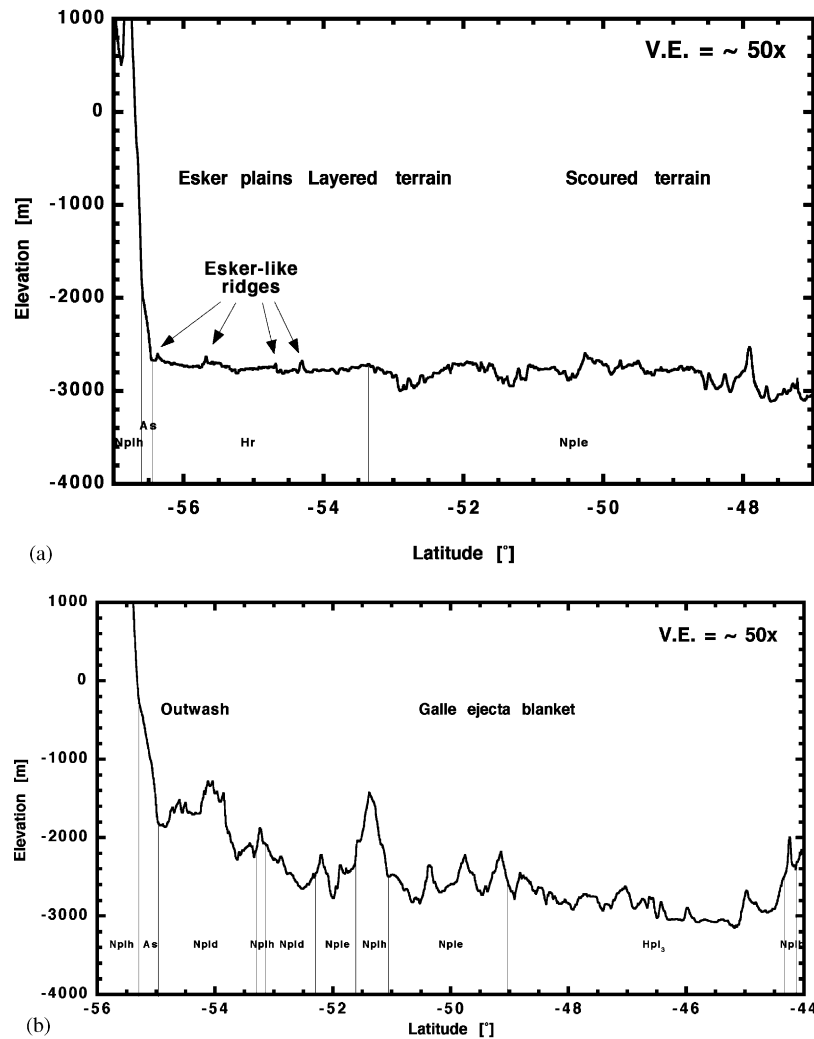
Fig. 16. MOLA profiles across the floor of the Argyre basin. Below the topographic profile geologic units of Scott and Tanaka (1986) are shown. Above the topographic profile terrain types of the map of Kargel and Strom (1990) are shown. (a) MOLA orbit 12233. Note how smooth unit Hr is compared to the etched unit Nple. Individual scour marks are of the order of 100–200 m deep. (b) MOLA orbit 12107. Note the prominent debris apron (As) at the base of the Charitum Montes and the rugged terrain of unit Nple. Unit Hpl_3 is somewhat smoother but still much rougher than unit Hr. See Fig. 3 for location of the profiles. Vertical exaggeration (V.E.) of both profiles is $\sim 50\times$. North in both profiles is to the right.

consistent with a deposition into a proglacial lake, although its formation could also be related to non-glacial lacustrine sedimentation. In summary, based on their observations of the occurrence of ridges, and scoured and layered terrain, Thomson and Head (2001) concluded that a glaciation is not required to explain the surface features within the Hellas basin.

3.6.2. Tests
There are several tests that can be performed with MOLA data in order to check the plausibility and consistency of the proposed glaciation.

3.6.2.1. Outline of a proglacial lake. Kargel and Strom (1992) postulated a "… vast proglacial lake and deposition of smooth glaciolacustrine plains" in the Argyre basin.

However, as they did not map this lake in detail, their prediction is not explicit enough to be tested rigorously (e.g., with MOLA data). We can address this problem only indirectly by making the following assumption. Provided that there was a proglacial lake in Argyre in which sedimentation smoothed the terrain and that the smooth unit Hpl_3 of Scott and Tanaka (1986) was deposited within this lake, then the outline of this unit should follow an equipotential line, which would basically correspond to a shoreline of this lake, assuming no modification or warping since that time. Similar tests have been proven useful to test for the existence of a large north polar ocean (Head et al., 1999).

Using MOLA data (Plate 1b, Figs. 5 and 6a–d) we can investigate at which elevations unit Hpl_3 is exposed and we can study the elevations of the contact between unit Hpl_3 and its neighboring unit Nple. We see that unit Hpl_3, which covers parts of the basin floor and is also exposed in the val-

leys between the rim mountains, occurs over a wide range of elevations (~ 4000 m) and its outline does not follow or approximate a single MOLA contour line. Parts of unit Hpl_3 cover the basin floor and approximately correlate with the lower regions within Argyre where a proglacial lake would be expected. However, parts of this unit are exposed in the valleys, which rise up to several kilometers above the basin floor, a level where the entire basin would have been filled and not just the region of the postulated proglacial lake. Parker (1996b) proposed that the smooth layered material in the basin interior is of Hesperian age whereas the surfaces in the reentrants into the rim mountains are late Noachian in age. Therefore it seems possible that two distinctive smooth plains units may exist, which are not distinguished in the map of Scott and Tanaka (1986). However, the contact between unit Hpl_3 and Nple in the geologic map of Scott and Tanaka (1986) does not always parallel MOLA contour lines as would be expected if unit Hpl_3 consists of deposits that were formed in a proglacial lake. In some areas the geologic contact is parallel to the MOLA contours, in other areas MOLA contours cut the geologic contact several times. We find that the contact between unit Nple and Hpl_3 varies in elevation from < -3400 m to > -2600 m. Provided that the contact was mapped correctly, we conclude from these observations that a formation of unit Hpl_3 solely from deposition of lacustrine sediments appears unlikely.

3.6.2.2. Slope of basin rim.
A second test is looking at the distribution of steep slopes because Kargel and Strom (1992) argued that an alpine-style glacier entered the Argyre basin from the south, sculpting Charitum Montes and thereby producing a topography with very steep slopes. They observed that the northern rim was fluvially modified but lacks evidence of glaciation as if it rained in the north at times, while it snowed in the southern regions of Argyre (Kargel and Strom, 1990). Following their logic, we would expect significant differences in the distribution of steep slopes between Charitum Montes (in the south) and Nereidum Montes (in the north), as well as differences in the shape of valleys.

These predictions are not consistent with observations based on MOLA data. In a slope map (Plate 2) based on the gridded topography (Head et al., unpublished data), Argyre is characterized by a very rough annulus with steep slopes of up to $15°$. We see that slopes are generally steeper in the NW, SW, and SE quadrangle but less steep in the NE. From this we conclude that slopes are largely similar for significant parts of Charitum Montes and Nereidum Montes. The slope data do not reveal that the slopes of Charitum Montes are significantly different from the slopes of Nereidum Montes, as was predicted by Kargel and Strom's (1990) scenario of glaciation in the south versus fluvial activity in the north. On the basis of MOLA data, a comparison of the shape of valleys did not show significant differences in cross-sectional shape between valleys from the northern parts of the basin and valleys in the south. Steepness of the slopes,

the shapes of valleys, and a feature that is plausibly interpreted as a rock glacier suggest significant amounts of ice in the northern parts of the Argyre basin.

3.6.2.3. Characterization of ridges.
A third test for the glaciation proposed by Kargel and Strom (1992) is to use MOLA data to investigate the origin of ridges which are exposed on the floor of the basin center, and interpreted by them to be eskers. Ridges in the Argyre basin and the south polar regions have previously been interpreted as wrinkle ridges (Scott and Tanaka, 1986), exhumed igneous dikes (Carr et al., 1980; Carr, 1984), exhumed clastic dikes (Ruff and Greeley, 1990), eolian ridges or linear sand dunes (Parker et al., 1986; Ruff and Greeley, 1990), fluvial spits and bars (Parker et al., 1986), inverted stream topography (Howard, 1981), and glacial eskers (Carr et al., 1980; Howard, 1981; Parker et al., 1986; Tanaka and Scott, 1987; Ruff and Greeley, 1990; Metzger, 1991; Kargel and Strom, 1990, 1992; Kargel, 1993; Head, 2000a, b; Head and Pratt, 2001). Some of these models for the origin of the ridges in Argyre and the south polar regions appear less likely due to a variety of reasons which are discussed by Ruff and Greeley (1990) and Parker et al. (1986). Kargel and Strom (1991) investigated eskers on Earth and concluded that martian ridges in the Argyre basin match the characteristics of terrestrial eskers in every aspect. They reported that martian esker systems are up to 800 km long, with single ridges being 100–200 km long, 600–2400 m wide and 40–160 m high. Terrestrial eskers vary in length from several meters to over 400 km, from a few centimeters to 200 m height, and from 25 cm to 6 km width. This is in good agreement with MOLA data of a ridge, interpreted as an esker by Kargel and Strom (1990), that show that the ridge varies in width from 3 to 9 km and in height from 40 to 110 m (Figs. 9 and 10).

Kargel (1993) argued that martian eskers of the Dorsa Argentea Formation and Argyre Planitia are symmetric in cross-section and wrinkle ridges are asymmetric. Therefore, the detailed morphology of these ridges provided by the MOLA measurements is potentially useful in order to test the glacial hypothesis. We investigated a ridge, which was mapped as an esker by Kargel and Strom (1990) (Fig. 3), and MOLA data (Fig. 10) indicate that the elevation of the terrain left and right of some parts of the studied ridge in Argyre Planitia are offset by 6–75 m, somewhat smaller than for wrinkle ridges of Solis Planum (Golombek et al., 2000). The mean offset is about 35 m with a standard deviation of 22. These asymmetric cross-section are often associated with ridge segments that are exposed on regional slopes. In Dorsa Argentea, asymmetric profiles have frequently been observed for ridges that are climbing up the side of a regional slope (Head and Hallet, 2001a, b) and this is consistent with our observations. MOLA data also show that the morphology changes significantly along the investigated ridge and there are numerous cross-sections which are sharp-crested symmetrical as is the case for eskers (Kargel, 1993), that is,
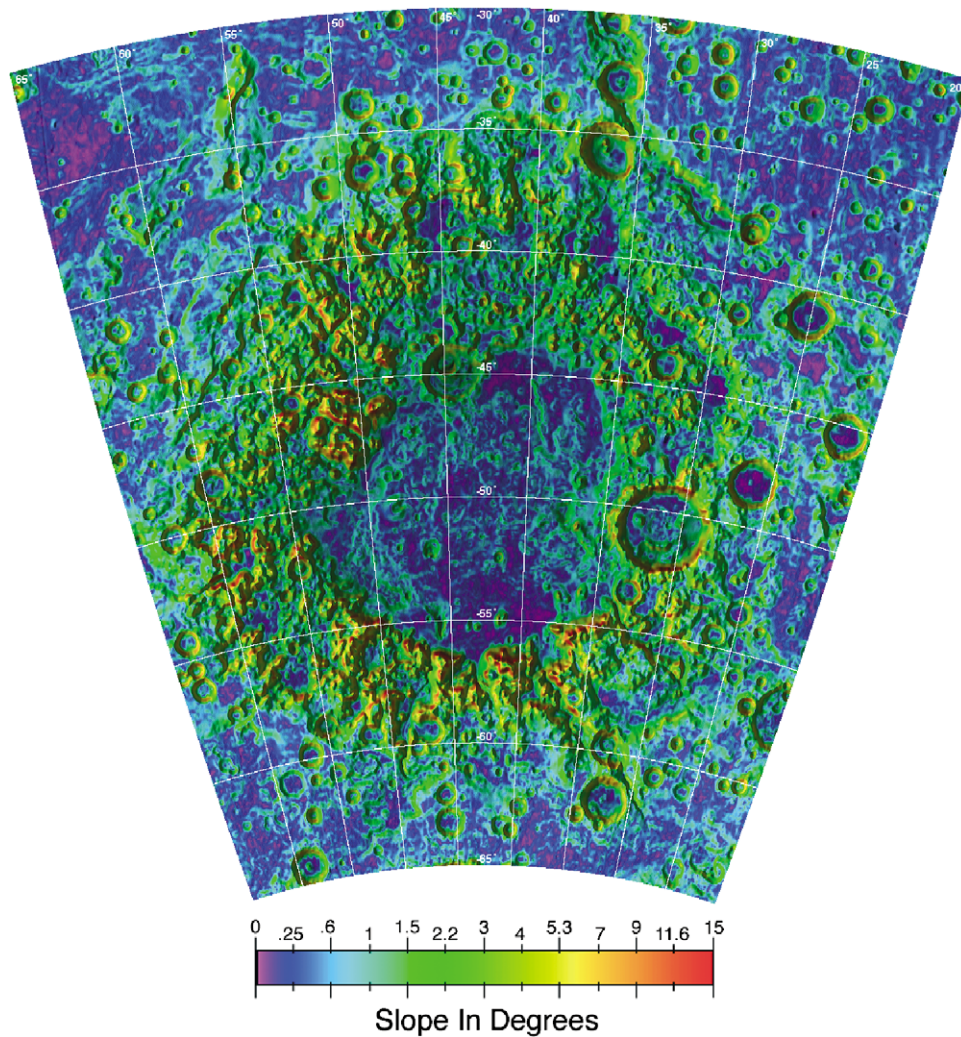
Plate 2. Slope map of the Argyre basin. Slopes of Nereidum Montes are very similar to slopes of Charitum Montes. Slopes in the NE quadrangle of the basin appear to be less steep than for the other quadrangles. Note that unit Hr shows very small slopes and that there is an equally flat area at the terminus of a valley at the northern margin of Argyre Planitia. Lambert azimuthal equal-area map projection; centered at −51°S, 43°W, 1° latitude = 59.17 km. Covered area is from −30°S to −65°S and from 20°W to 65°W; 5° grid spacing.

with only minor elevation offsets. We also observe multiple crested ridge segments similar to the ones described for ridges of the Dorsa Argentea Formation by Head and Hallet (2001a, b). Head and Hallet (2001a, b) compared the martian sinuous ridges of the Dorsa Argentea Formation with the terrestrial Katahdin esker system in Maine (Shreve, 1985). They found that in both locations, the cross-sections across the ridges vary from simple symmetrical (inverted-v) and flat topped to flat topped with median troughs and ridges. From Earth it is known that the cross-section of an esker is influenced by the ratio of the glacier-bed gradient to the ice surface gradient (Shreve, 1985). Sharp-crested eskers on Earth and on Mars are usually associated with nearly level or gently descending regions, multiple crested eskers occur in somewhat steeper terrain, and broad crested eskers are situated in the most steeply ascending reaches of esker paths (Head and Hallet, 2001a, b; Shreve, 1985). A relatively

sharp single crested morphology, as observed for most of the Argyre ridges, is predicted by the physics of esker formation on level surfaces (Shreve, 1985). Making use of the new MOLA data we see that the surface next to the ridges (unit Hr) is indeed one of the flattest surfaces on the Argyre floor. Summarizing our observations and the observations by Head and Hallet (2001a,b) for martian esker-like ridges and Shreve's (1985) observations for the Katahdin eskers, we conclude that a simple symmetry/asymmetry argument in order to distinguish between wrinkle ridges and eskers is inconclusive and might be misleading.

Another criteria to distinguish eskers from wrinkle ridges are small ridges that are superposed on top of a broad wrinkle ridge but are absent on esker-like ridges (e.g., Muehlberger, 1974; Golombek et al., 2000). Inspection of the MOLA profiles across the ridge in Argyre generally does not reveal such narrow ridges on top of the broad main
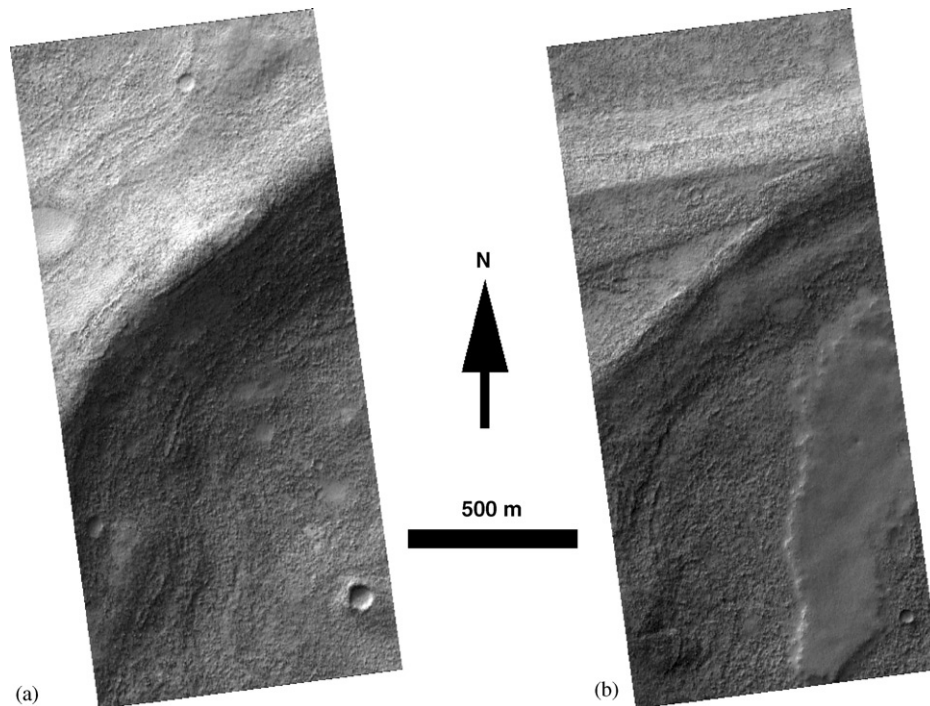
Fig. 17. MOC image (M0001511) of ridges associated with unit Hr in southern Argyre Planitia. MOC image M0001511 is a very long narrow strip and Figs. 17a and b show two details of this image. Fig. 17a is at ∼ −56°N 43.5°W, Fig. 17b is at ∼ 56.5°N 43.5°W. Ridges show layering and rounded morphology. Fig. 17b shows a unit with smooth surface that is probably removed by deflation to expose a more blocky/knobby surface texture. This is supported by the morphology of several impact craters that appear to be exhumed.

ridge as were reported for wrinkle ridges in Solis Planum by Golombek et al. (2000). In addition, MOC images that cover the ridges in Argyre Planitia (e.g., FHA01614, M0000028, M0001511, M0001842, M0002983, M0201680, M0202542, M0203544, M0300123, M0400320) reveal numerous very evenly spaced, continuous, and parallel layers of these ridges. In all these MOC images (e.g., M0001511; Figs. 17a and b), these layers can be traced across the entire field of view for at least several hundreds of meters, and we argue that such a pattern of undisturbed layering is rather inconsistent with a tectonic formation as a wrinkle ridge (Figs. 17a and b). The general morphology of the ridges in MOC images appears to be symmetrical, rounded, and we did not observe a small ridge on top of a broad rise, such confirming MOLA observations. From our observations we conclude that ridges in southern Argyre Planitia are not likely to be wrinkle ridges but eskers, hence supporting the interpretation of Kargel (1993) and Kargel and Strom (1992). On the basis of new MOLA data, similar ridges in the Dorsa Argentea region have been investigated by Head and Pratt (2001). Based on their observations of the morphology, topography, stratigraphy, stratigraphic and areal proximity to present polar deposits, they favored an interpretation of these ridges as eskers.

Eskers are the infillings of ice-walled stream channels and occur preferentially on rigid substrates, i.e. bedrock covered with coarse-grained high-permeability till, where deformation of the bed is inhibited (e.g., Flint, 1971; Clark

and Walder, 1994; Bennett and Glasser, 1996). Where water flows in pressurized conduits, the hydraulic gradient and direction of flow are controlled by ice surface topography and only to a lesser extent, the form of the bed (Benn and Evans, 1998; Shreve, 1985). Therefore a very distinctive characteristic of eskers is that they can be deposited across subglacial topographic divides. Correlating Viking MDIM data with MOLA topography we see that the investigated ridge does not strictly follow a topographic gradient but cuts across hills and valleys. In the MOLA data the crest of the investigated ridge, which was mapped as an esker by Kargel and Strom (1990), varies in elevation from −2680 to −2560 m, the variation of ∼ 120 m being well within the range observed for terrestrial eskers. The variation of the terrain immediately surrounding the studied martian ridge on the southern side is about 160 m; on the northern side it is ∼ 120 m. For comparison, terrestrial eskers have up-and-down long profiles which range in elevation up to 250 m (Flint, 1971). The Katahdin eskers in Maine, already mentioned earlier, cross passes more than 100 m higher than the intervening valleys, and one esker system west of the Hudson Bay ascends the regional slope to an elevation 275 m higher than its headwaters (Shreve, 1985).

The prominent ridges, which have been interpreted as eskers in Argyre Planitia (Kargel and Strom, 1990, 1992), occur close to and run parallel to the southern margin of the basin floor (Carr, 1984) but the distribution of ridges does not suggest any apparent relationship to regional or

basin-related structural trends (Parker et al., 1986). The orientation of the ridges in Argyre Planitia seems to contradict the glaciation hypothesis because the ridges run almost perpendicular to the flow of the glacier envisioned by Kargel and Strom (1992), which entered Argyre Planitia from the south. Besides other observations, the orientation of the ridges in Argyre Planitia led Jöns (1992) to reject the glaciation hypothesis. From terrestrial eskers it is known that they are usually aligned subparallel to the direction of former glacier flow. However, some terrestrial eskers are aligned transverse to former glacier flow, a situation most common for former ice-walled channels (Benn and Evans, 1998). In Argyre Planitia ridges are associated with unit Hr and MOLA data indicate that this unit correlates with a very flat lying area with very low slopes and that the ridges do not follow a prominent or steep slope (Plates 1b and 2). Therefore formation of ridges oriented even transverse to the hypothesized glacier flow appears possible and does not necessarily contradict the glaciation model.

The Katahdin eskers in Maine are $\sim$ 10–60 m high (Shreve, 1985). Based on this observation and his calculations of ice surface gradients and the basal shear stress, Shreve (1985) estimated the ice thickness that overlay these eskers to be on the order of 600–1200 m. The martian ridge is 40–110 m high. This comparison, together with the estimated maximum thickness of the Dorsa Argentea Formation ($\sim$ 3 km) suggests that the ice thickness could have been on the order of $\sim$ 2000 m. The crest of the investigated ridge is at an elevation of -2680 to -2560 m. Under the assumption that the ridge is an esker and that the overlaying ice is 2000 m thick, the upper surface of the ice would be at $\sim$ -600 m. Similarly, Moore and Wilhelms (2001) found evidence that the Hellas basin was once filled with an ice-covered lake; the ice carapace being roughly 1 km thick.

In addition, to the interpretation of the ridges as eskers formed within a glacier, we have to consider a formation at the terminus of a glacier. Terminal moraines on Earth, which accumulate at the down-flow margin of a glacier, are usually oriented transverse to its movement. Due to the close relationship to the ice margin, moraines are broadly arcuate, lobate, or irregularly winding in plan. End moraines such as push and dump moraines can merge or bifurcate, and often have asymmetric cross section. The ridge of end moraines is frequently discontinuous and broken by gaps, most of which mark the position of meltwater streams (Flint, 1971). Push moraines of advancing ice sheets have heights of up to 200 m, are < 5 km wide and up to 50 km long (Bennett and Glasser, 1996). According to Flint (1971) end moraines of ice sheets in North America and Europe rarely exceed 30–50 m heights, but end moraines of many valley glaciers in mountain regions are steeper and reach heights of 150 or even 300 m. We conclude that the height and the width of terrestrial end moraines are similar in dimension to the investigated ridge in Argyre Planitia.

The Argyre ridge is significantly longer than terrestrial end moraines and we do not observe gaps in the ridge that show characteristics of breaching water streams. In addition, if the Argyre ridge is an end moraine, lobateness should be more pronounced, especially in areas downslope of the large valleys where ice movement is expected to be largest and/or fastest. An independent argument comes from numerous MOC images (e.g., FHA01614, M0000028, M0001511, M0001842, M0002983, M0201680, M0202542, M0203544, M0300123, M0400320) which show that the ridges in the Argyre basin are layered or stratified, which is not consistent with an interpretation of the ridges as moraines because moraines are by definition not stratified (Figs. 17a and b).

3.6.2.4. Morphologies of valleys. On Earth a strong argument for or against a former glaciation is the shape of valleys. Terrestrial formerly glaciated valleys and fjords usually show a characteristic u-shaped cross-section with one steep and one gentler slope (Benn and Evans, 1998). Most glaciated u-valleys are formed by alteration of a v-valley originally cut by streams and mass wasting (Flint, 1971). If it is assumed that erosion rates of a v-valley are proportional to the sliding velocity, the most rapid erosion will occur on the sides of the valley. This causes broadening and steepening of the valley until an equilibrium profile is attained, which then continues to deepen over time (e.g., Harbor et al., 1988; Benn and Evans, 1998).

We compiled some terrestrial analogs for comparison. Based on the US Geological Survey (1958) topographic map at scale 1:24,000, we derived a profile from North Dome perpendicular across Yosemite Valley to Half Dome. This valley is an excellent example of a u-shaped valley and there is numerous evidence that this morphology was once formed by a glacier (e.g., Benn and Evans, 1998). We then compared the profile across Yosemite Valley with a profile of a valley at the western rim of Argyre (Fig. 18). It has to be kept in mind that the terrestrial valley is significantly younger than the martian valley and that erosional processes and rates may have influenced the shapes of the valleys in a variety of ways and extents. In Fig. 18 both valleys are shown at identical scale. We see that the Argyre valley is about 10 times wider than the Yosemite Valley. At the resolution of the MOLA topography we see a broad u-shaped valley cross-section with no sharp v-shaped incision, which would indicate a formation by fluvial systems. We also measured the slopes of the valley flanks and find that the slopes of Yosemite Valley are much steeper than the slopes of the valley in Argyre. While the general morphology of the Argyre valley is consistent with a previous glaciation, size and slope angles of the investigated valleys are significantly different. However, it is likely that the valleys of the Argyre basin follow radial tectonic structures initially formed by the basin-forming impact, and therefore could be quite large. Also, these valleys are old, giving erosional processes enough time to reduce or modify the slope
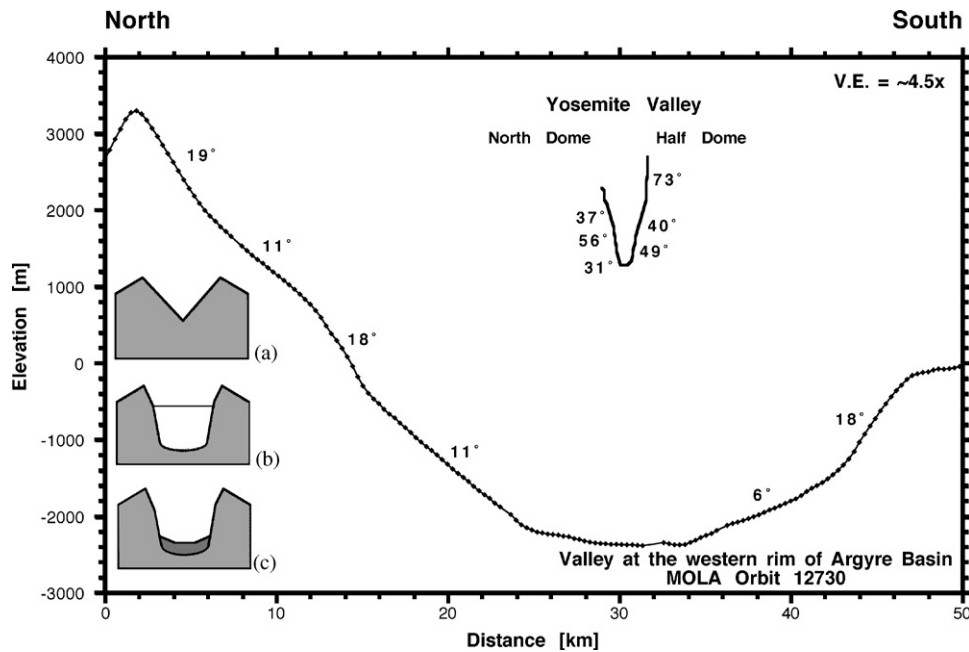
Fig. 18. Comparison of Yosemite Valley with a valley at the western rim of the Argyre basin at the same scale. Numbers along the profiles are slopes in degree. Vertical exaggeration (V.E.) is ∼ 4.5×. Inlet shows theoretical cross-sections (not to scale) of (a) an unglaciated valley, (b) a glaciated valley at times of maximum vertical ice extent, (c) and a valley after deglaciation.

angles. We conclude that simply investigating the shape of a terrestrial valley and comparing it to a martian valley does not give unambiguous results with respect to a former glaciation.

Kargel and Strom (1992) showed an example of a sharp-crested semicircular mountain ridge in Charitum Montes (their Fig. 2c). They interpreted this feature as a crater that had been modified into a cirque from which outwash emanated. This is not consistent with MOLA data because the new data show that the deepest point of this valley is within the crater, along the base of the proposed cirque, and that the flow direction is roughly from the NE to the SW and not the reverse, as predicted by Kargel and Strom (1992).

3.7. Water in Argyre: the case of a completely filled basin

Several hypotheses call on liquid water as an element in the evolution of Argyre basin (e.g., Parker, 1989, 1996a, b; Parker et al., 2000; Head, 2000c).

3.7.1. Previous observations, interpretations, and implications

Based on MOLA topography, the volume of the Argyre basin (4×10^6 km^3) is about 15 times smaller than the Hellas basin but its watershed, that is the drained area, is of similar size, i.e. 20×10^6 km^2 (Smith et al., 1999). Several channels, Surius Vallis, Dzígai Vallis, and Palacopas Vallis, breach the southern rim and empty into the Argyre

basin (e.g., Parker, 1989; Parker et al., 2000; Head, 2000c, d; Head and Pratt, 2001) (Figs. 1 and 19). Most of these channels can be traced back to the distal portions of the Dorsa Argentea Formation, which was interpreted to represent the extent of a formerly larger south polar ice cap. Numerous authors (e.g., Parker et al., 2000; Head, 2000c, d, Head and Pratt, 2001) argued that melting of the ice cap releases significant amounts of water and that this water would pond in the Argyre basin. In Parker's model the basin is interpreted to have been completely filled in the Noachian because he found evidence for two flood events in the outflow channel, Uzboi Vallis, which is of Noachian age (Parker, 1994, 1996a, b). Parker et al. (2000) proposed that once the basin was completely filled, water could have left the basin through Uzboi Vallis, a channel in the north of the basin and flowed down the Chryse trough (e.g., Saunders, 1979; Phillips et al., 2001) towards the northern lowlands (Fig. 19). The fill of the basin was probably derived from flow into the basin from three large channels in the south (Parker, 1994). According to Parker et al. (2000), additional evidence for a complete fill with water is that there is no morphologic continuation of the incoming channels on the basin floor.

What are the ages of the various channels and how are they related to the deposits in the interior of Argyre? The ages of the channels are not well constrained. Parker et al. (2000) proposed on the basis of their investigation of Viking images, that the incoming channels are of Early Noachian to Noachian age and that Uzboi Vallis is of Noachian age. In Parker (1996a, b), Surius Vallis, Dzígai Vallis, and Palaco-
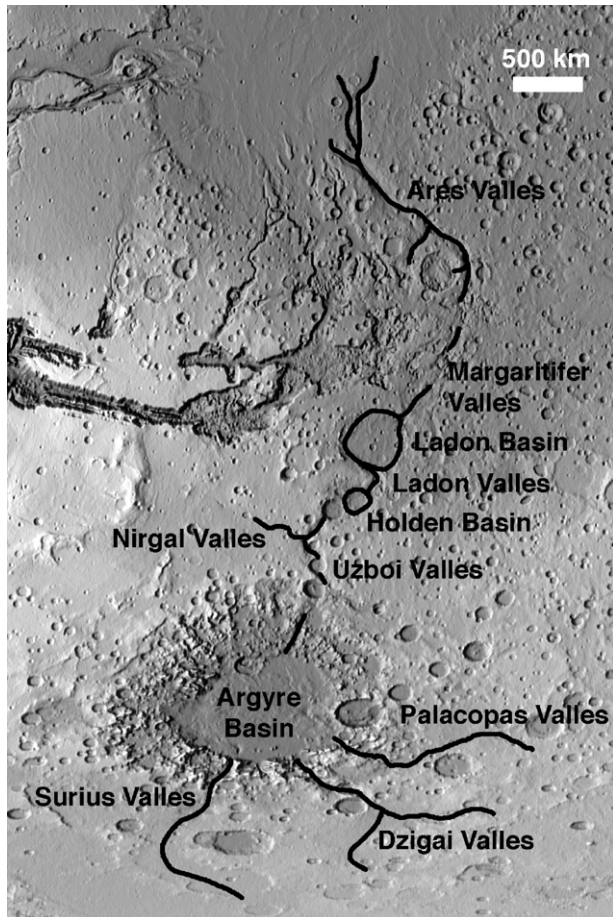
Fig. 19. Shaded relief map of the Argyre region and the Chryse trough. Alignment of several valleys and basins along the Chryse trough system were cited as evidence for water flow from the south polar regions, through the Argyre basin to the northern lowlands (e.g., Parker et al., 2000). Simple cylindrical map projection.

pas Vallis are designated as Hesperian in age but probably occupy valleys formed during the Noachian. Interestingly, in Parker (1996a, b), Uzboi Vallis is of late Noachian age and would therefore be older than the incoming channels. In the maps of Scott and Tanaka (1986) and Tanaka and Scott (1987) both valleys, Uzboi Vallis and Surius Vallis, are of Hesperian age, and the other two are not mapped.

3.7.2. Tests

To test the hypothesis that Argyre basin was once completely filled with water we made use of MOLA data. We performed several tests such as looking for terraces or possible shorelines, investigation of the surface roughness, flooding models, and estimation of water volumes required to fill the basin to different levels.

3.7.2.1. Search for shorelines. Clifford and Parker (2001) presented a model for the evolution of the Martian hydrosphere. This model is based on the assumption that permeability and porosity of the martian crust are high enough to allow the distribution of water to be governed by the effort

to reach hydrostatic equilibrium, responding to local perturbations (e.g., evaporation, precipitation, seismic and thermal disturbances) by flowing from regions of elevated hydraulic head to saturate the regions with the lowest geopotential. In response to the planet's declining geothermal heat flow, the formation and growth of the cryosphere is expected to have altered these conditions with time. During the Early Noachian the thickness of the cryosphere was insufficient to support an elevated water table. A consequence of this is that lower elevations at this time should have been flooded with water. Only later in martian history, i.e. the Late Hesperian, the cryosphere grew thick enough to confine a planet-wide groundwater system. Clifford and Parker (2001) concluded that the existence of a primordial ocean that covered the northern lowlands on Mars was inevitable, given the thermal and hydrologic conditions during the Early Noachian.

Parker et al. (1989, 1993) mapped several "shorelines" of such an ocean, i.e. Contact 1 and 2. Head et al. (1999) used MOLA data to perform a variety of tests of the ocean hypotheses and concluded that Contact 1 is not a good approximation of an equipotential line and that Contact 2 is most consistent with the idea of a large standing body of water in the northern lowlands. Provided that the distribution of water during the Noachian is governed by the effort to reach hydrostatic equilibrium as proposed by Clifford and Parker (2001), that the ocean in the northern lowlands existed at these times, and that Argyre was filled with water at these times, then we might expect to find "shorelines" in the Argyre basin at about the same elevation as Contact 1 and 2. Using MOLA data, Head et al. (1999) found that the global average elevation of Contact 1 is -1680 m ($1\sigma = 1.7$ km) and that Contact 2 is at -3760 m ($1\sigma = 0.56$ km). Edgett and Parker (1997) proposed a third shoreline in western Arabia and northern Sinus Meridiani. They used a topographic map of the US Geological Survey (1991) and found that this shoreline is at an elevation of $0-1$ km (± 1 km) and slopes westward 0.7 m/km over 3000 km. Due to the size of their Fig. 1 it is extremely difficult to locate the exact position of this shoreline. However, using the new MOLA topography, we find their shoreline falls at elevations that range from ~ -1400 m to ~ -1700 m. Parker et al. (2000) report that the elevation of the Meridiani shoreline is ~ -1500 m.

In an attempt to identify candidate "shorelines" that might exist at or near these levels we artificially flooded the basin to these levels (Fig. 20). MOLA data indicate that at -3760 m (elevation of Contact 2; Fig. 20b) only crater Hooke would have contained water, and that at -1680 m (elevation of Contact 1; Fig. 20g) the water level in Argyre basin is well below the elevation where the entire basin would have been filled and water would have flowed through Uzboi Vallis. Flooding the Argyre basin to the level of the third shoreline of -1500 m ("Meridiani shoreline"; Fig. 20h) would still not fill the basin high enough to allow water flow through Uzboi Vallis. We conclude that all of the investigated shoreline positions are below the elevation of the outflow channel of Argyre basin. If we assume that the basin is largely
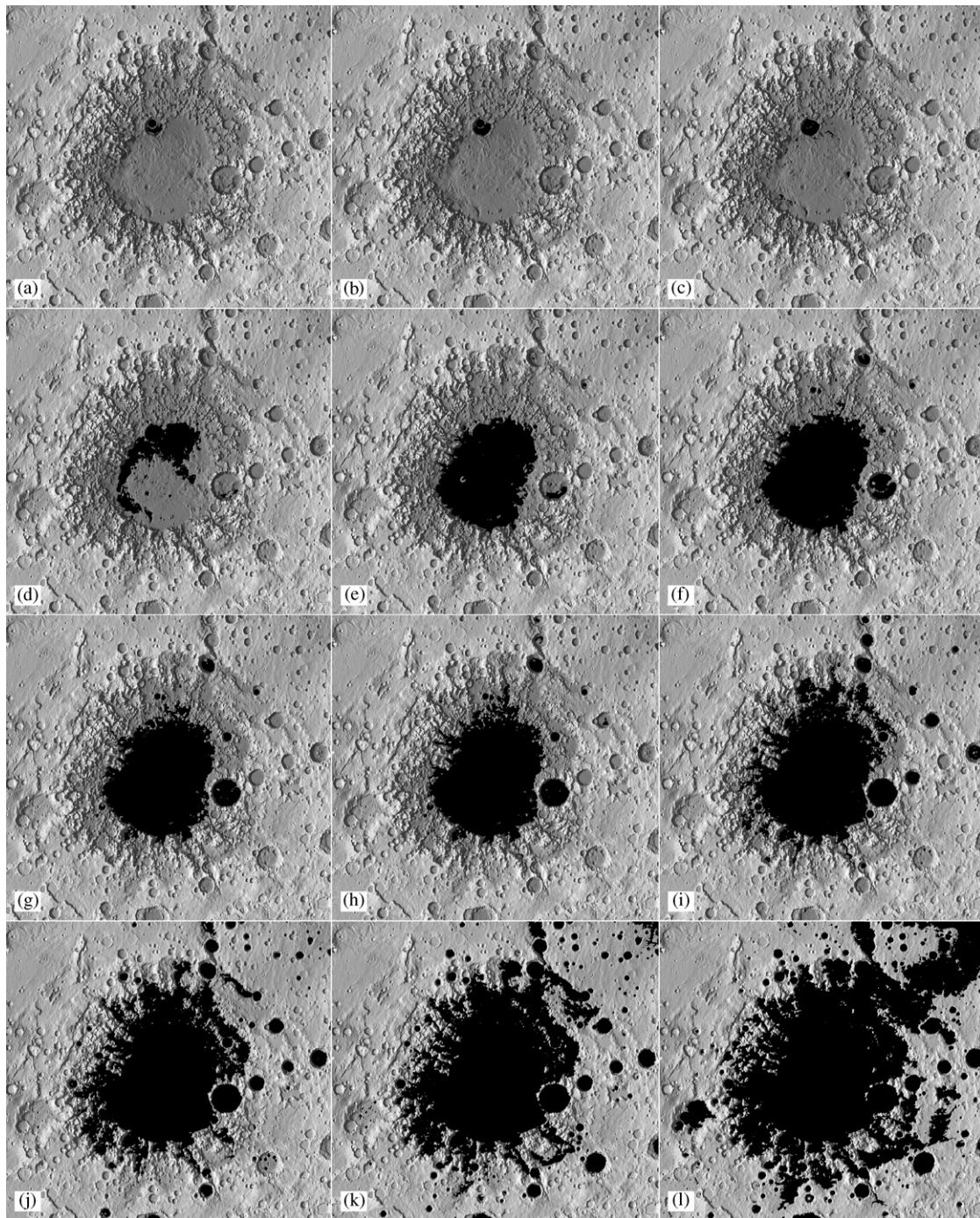
Fig. 20. Sequential flooding models of the Argyre basin superposed on MOLA shaded-relief map. (a) Flooded area at a water level of −4000 m; (b) −3760 m (elevation of Contact 2); (c) −3500 m; (d) −3000 m; (e) −2500 m; (f) −2000 m; (g) −1680 m (elevation of Contact 1); (h) −1500 m (elevation of the Meridiani shoreline); (i) −1000 m; (j) −500 m; (k) 0 m; (l) 500 m. Lambert azimuthal equal-area map projection; centered at −51°S, 43°W, 1° latitude= ∼ 59 km.

unmodified since that time and that the distribution of water in the martian crust is correctly modeled by the hydrostatic model of Clifford and Parker (2001), water would flow underneath the surface toward lower regions rather than accumulating in Argyre to a level where flow through Uzboi Vallis could occur. In this case, the only way we

could imagine filling the basin is by a very rapid input of large amounts of water, faster than water can evaporate, sublime, or percolate into the substrate. From our observations we conclude that either a complete fill of Argyre basin during the Noachian is unlikely, or alternatively, that the model of Clifford and Parker (2001) needs some revision. A

discussion of the amount of water that can be produced by meltback of the Dorsa Argentea Formation and the present south polar ice cap in relation to the amount of water that is needed to fill the basin completely is presented in Section 3.8.2.1.

In Viking images we did not identify morphologic features which would be evidence for a shoreline (e.g., equipotential terraces, benches, and albedo and texture differences that are traceable over significant lengths) at the level of drainage through Uzboi Vallis. We see terraces, benches, and differences in texture and albedo, but these occur at a wide range in elevation, mostly below the outflow level, could have been formed by a variety of processes (e.g., mass wasting), and are not unambiguous evidence for a lake within Argyre.

3.7.2.2. Termination and morphology of channels. As mentioned above, the ages of the channels are not well constrained and vary from Early Noachian to Hesperian. However, the age of the channels is crucial in order to address the hydrologic history of the basin. There are three possible scenarios: (1) the channels are early Noachian to Noachian in age (Parker et al., 2000); (2) the channels are Hesperian in age but occupy valleys formed in the Noachian (Parker, 1996a, b); (3) the channels are Hesperian in age (Scott and Tanaka, 1986; Tanaka and Scott, 1987).

If the channels, Surius, Dzígai, and Palacopas Vallis, are Hesperian in age, then this is inconsistent with the model of Parker (1994) that suggests a complete fill of the Argyre basin in the Noachian by water flow through these three large southern channels. In Viking data and in MOLA data, the channels can be traced down to the floor of the basin and this is consistent with the channels postdating the proposed complete fill. If the channels are early Noachian to Noachian, we face the problem of where the water came from. Parker et al. (2000) proposed meltback of a Noachian polar ice cap but Head and Pratt (2001) only found evidence for a Hesperian retreat of the ice cap and we will demonstrate that water volumes produced by such a retreat were probably insufficient to completely fill the Argyre basin. In addition, if the channels are early Noachian to Noachian in age, and the basin was completely filled at this time, then the channels should not be traceable down to the basin floor because they would have encountered a base level at a much higher elevation. If the channels are Hesperian in age but occupy Noachian valleys, this could explain the presently observed channel morphology and would leave the possibility of a complete fill of the basin during the Noachian. However, this scenario does not solve the problem of the Noachian water source.

If water flowed through the channels into a lake within Argyre during the Hesperian, we can use MOLA data to test for such a lake. Of course, all channels having an Hesperian age does not necessarily mean that they were active at the same time, because the Hesperian Period lasted from about 3.8–3.55 b.y. (Neukum and Wise, 1976) or from 3.5–1.8 b.y. (Hartmann et al., 1981; Tanaka, 1986). Very recently

this wide range in age of the Hesperian period has been narrowed to 2.9–3.7 b.y. (Hartmann and Neukum, 2001), with Neukum favoring a somewhat shorter Hesperian Period (3.3–3.7 b.y.) compared to Hartmann (2.9–3.5 b.y.). Parker (1996a) argued that the channels were fed by polar cap melt and runoff and Head (2000c, d) and Head and Pratt (2001) found evidence for extensive polar cap meltback. As Head (2000c, d) and Head and Pratt (2001) also showed that the channels originate at the margin of the formerly larger ice cap, it seems very likely that all three channels transported significant quantities of water at about the same time, that is, when the ice melted during the Hesperian. However, this was much later in martian history than the proposed complete fill of the Argyre basin in the Noachian (Parker, 1994). According to Parker (1996b), lakes in Argyre may have existed intermittently from the Noachian to the Early Amazonian. If there was a lake in Argyre during the Hesperian, the age of the incoming channel in the geologic map of Tanaka and Scott (1987), and if the channels were active at about the same time, as indicated by the discussion above, then the incoming channels might all intersect this body at a common base level. Consequently we would expect the channels to terminate at about the same elevation, that is, close to the water level of this lake. We traced the channels as far down into the basin as they are visible in the MOLA topography. We find that Palacopas Vallis can be identified down to ~ -2170 m, Dzígai Vallis down to ~ -2500 m, and Surius Vallis down to ~ -2350 m. Thus the maximum difference in elevation of the channel termini is on the order of 330 m, or about a tenth of the entire basin depth. Parker (1989) reported that Palacopas Vallis is the most degraded valley relative to the basin's interior plains, followed by Dzígai Vallis and Surius Vallis as the least degraded valley. If this reflects subtle differences in age between the channels, and the water level of the lake continuously dropped, then the youngest channel should be traceable further down toward the basin floor than the older channels. This is not what we observe in the MOLA data. From this we conclude that the water level of the lake was probably subject to changes in elevation of the order of 300 m. Such changes in elevation could be caused by catastrophic release of melt water from the ice cap, similar to terrestrial jökulhlaups. Alternatively, the channels did not encounter a common base level at the time the channels were carved down to the basin floor, that is, there was no lake in Argyre at this time.

The elevation where water would flow through Uzboi Vallis, the outflow channel in the north is about 140 m. Provided that Argyre basin was filled up to this level, then the incoming channels must have continued to be active much later in order to leave still visible morphologic features, that is, after most of the water sublimed, evaporated or percolated into the substrate. As the termini of the incoming channels are ~ 2000 m below the level of spillover, Argyre basin would have to lose at least 2000 m or $\sim 1.4 \times 10^6$ km^3 of water.

This is about 3/4 of the entire volume that can be held in the Argyre basin. From this we conclude that the incoming channels and Uzboi Vallis are not related in time and origin.

Looking at the morphology of each channel, we see distinctive differences between Surius Vallis and Dzígai Vallis on one side and Palacopas Vallis on the other side. Both, Surius and Dzígai Vallis are characterized by a prominent narrow channel that is incised in a broader valley (Figs. 21a and b). Palacopas Vallis shows much less of a narrow, well-defined channel morphology over long distances. Generally, within the Argyre region, this feature appears as a broad flat lying valley that only exhibits a narrow channel where the valley breaches the inner mountain ring (Fig. 21c).

What is the nature of the channel (Uzboi Vallis; Fig. 21d), proposed by Parker (1994, 1996a, b) to be an outflow channel from Argyre to the north into the northern lowlands during the Noachian? Although it is generally accepted that water flowed from the southern highlands toward the northern lowlands (e.g., Smith et al., 1999; Head et al., 1999; Hynek and Phillips, 2001), the flow direction within Uzboi Vallis is not immediately obvious (Parker et al., 2000). On the basis of his examination of the topographic maps of northern Argyre Planitia, Parker (1994) reported that the floor of Argyre Planitia is at about 1000 m±1500 m, that the north rim is 3000 m ± 1500 m, and that the surface north of Argyre dips northward. He concluded that the topography supports a northward-draining Uzboi Vallis. We traced the floor of Uzboi Vallis, Ladon Valles, and an unnamed channel within the Argyre basin from −45° to −10° latitude and used MOLA data to derive a topographic profile along the channel system (Fig. 22). East of crater Hale we find a water divide. Water north of this divide would flow away from the basin towards the northern lowlands, would carve the prominent channel of Uzboi Vallis and would pond in several craters and basins along its way to the northern lowlands. Water south of the divide, that is the basin rim, would flow into the Argyre basin. Crater Hale postdates Uzboi Vallis formation and its ejecta blanket has certainly influenced the present day topography. However, the main topography in this region is caused by the basin rim and even removal of significant amounts of Hale ejecta would not drastically alter the flow of significant amounts of water into the basin. The morphologic expression of this incoming water is a well-defined channel on the lower slopes of the northern basin interior, south of Uzboi Vallis. The very distinctive channel morphology starts at a flat-lying region south of crater Hale and the channel probably predates crater formation. The channel then dissects some mountains and reaches down to a very low-lying region of the basin center where it forms a small delta-like feature. Similar to the channel entries in the south, we find a very smooth, flat lying region on the basin floor at the mouth of this channel. Both the channel and the smooth region are Hesperian in age and are mapped as unit Hpl_3 (Scott and Tanaka,

1986). The channel morphology close to the basin rim is less prominent than at the lower parts of the basin where the channel already collected more water and could erode more material. Cutting of this channel indicates that significant amounts of water flowed from the northern basin rim towards the basin center and this flow must have occurred after most of the water postulated by Parker et al. (2000) in the Argyre basin vanished. If Uzboi Vallis formed by spillover from the Argyre basin (Parker et al., 2000), then it also indicates that Uzboi Vallis must be much older than the channel on the inner slopes of the basin. Alternatively, there was never a complete fill of the Argyre basin and the channel, like the southern channels, eroded material all the way down to the floor.

Parker (1996a, b) suggested that valley networks that flowed outward from a drainage divide, that is the basin rim, may have been captured by inward-draining systems during the Noachian. This implies that both channel systems were active over significant periods of time. However, extended periods of water flow in Uzboi Vallis are not consistent with the idea of two distinctive catastrophic floods as envisioned by Parker et al. (2000).

3.7.2.3. Flooding models. Is there any evidence that the basin was once filled with significant quantities of water? To assess this, we used MOLA data and performed several sequential flooding models in order to study where potential water would pond within the basin (Fig. 20). If we flood the basin to a level of −4000 m, water would pond only in the deepest parts of crater Hooke (Fig. 20a). At the elevation of Contact 2, that is, at −3760 m, water still only ponds within crater Hook (Fig. 20b). Flooding up to −3500 m shows that water would be confined to crater Hooke and some small ponds in the SW of the basin floor and W of Galle. Most of these ponds occur along the border between the etched unit Nple and the smooth unit Hpl_3 (Fig. 20c). Further flooding to −3000 m indicates that water would pond in an arc in the NW, mainly covering unit Hpl_3 and surrounding unit Nple (Fig. 20d). Following the regional topography, water from the channel which enters the basin at 45°W/ − 53°S could have flowed along the western floor and ponded in the lowest region in the northwest. The average depth of water at this elevation would be ∼ 280 m, the volume on the order of 38,670 km^3. At a level of −2500 m the basin floor would be completely flooded with water, yielding an average depth of water of ∼ 450 m and a volume of 1.77×10^5 km^3 (Fig. 20e). Raising the water level to −2000 m only slightly enlarges the flooded area (Fig. 20f). Fig. 20g shows the flooded area at −1680 m, the elevation of Contact 1. At −1500 m, the elevation of the proposed Meridiani shoreline, the water enters the numerous small valleys of Charitum and Nereidum Montes, producing a radial dendritic pattern (Fig. 20h). This dendritic pattern is even more evolved at −1000 m (Fig. 20i). Galle and numerous larger craters in the NE are filled with water. Some larger ponds occur in the channel to the North, i.e. Uzboi Vallis. At −500 m the
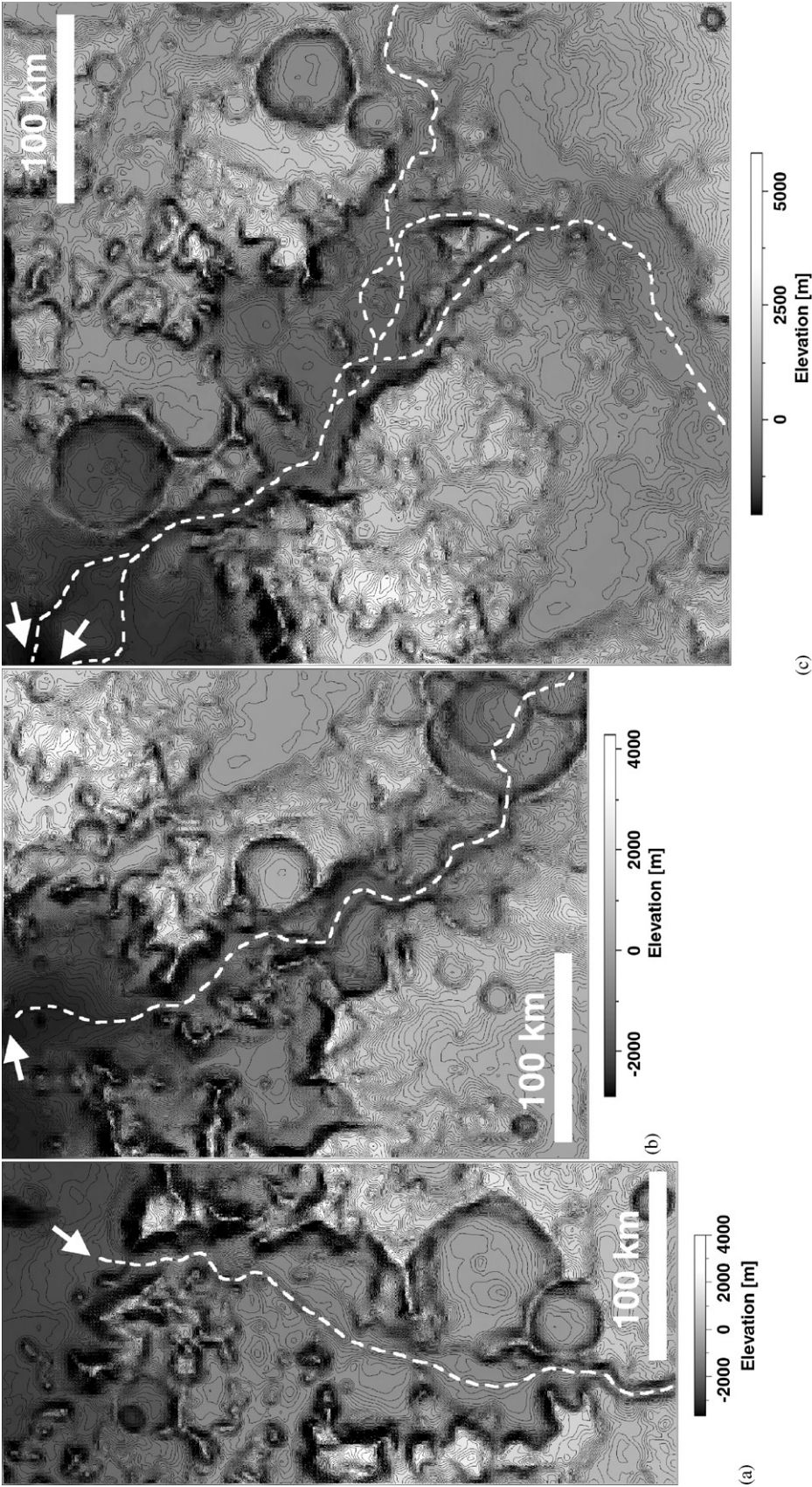
Fig. 21. MOLA topography of the mouths of channels associated with the Argyre basin. (a) Surius Vallis; (b) Dzígai Vallis; (c) Palacopas Vallis; (d) unnamed Valley on the inner northern slopes of Argyre. High topography is indicated by bright tones, low topography is shown as dark tones. Superposed are 50 m MOLA contour lines. White dashed lines in a, b, c indicate the channel, white arrows show its approximate termination on the basin floor. In addition to the topography, Fig. 21d shows a sketch map of the area with the location of features discussed in the text. Arrows indicate potential water flow on the basis of present topography. Lambert azimuthal equal-area map projection; centered at −51°S, 43°W.

Fig. 21. *(Continued)*.

dendritic pattern is fully evolved, the ponds in Uzboi Vallis become interconnected and numerous small craters in the NE are flooded (Fig. 20j). At 0 m Galle, a partially buried impact crater, is connected to the basin center (Fig. 20k). A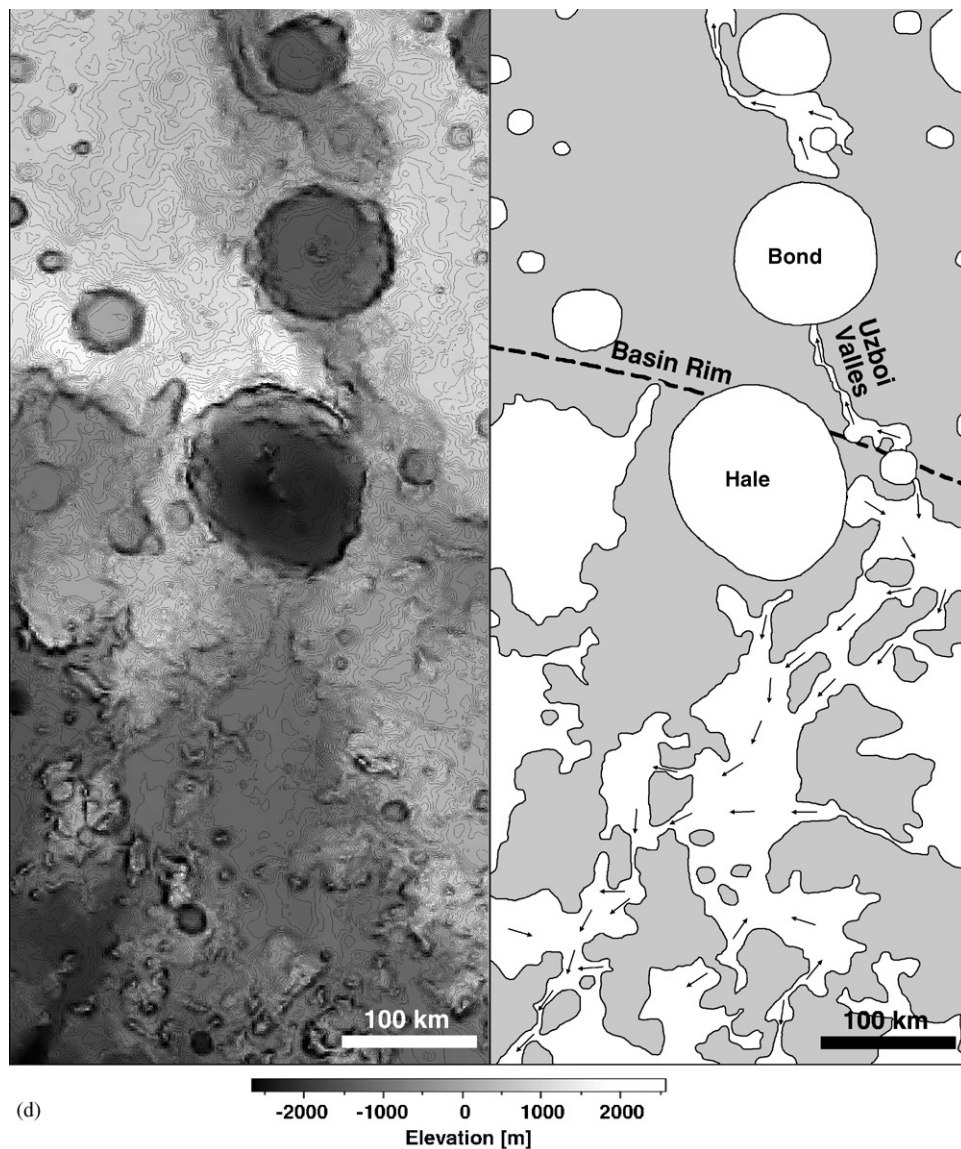t this water level the outflow channel, Uzboi Vallis, is still separated from the center of the basin. However, crater Hale postdates the channel and has certainly modified the original channel topography. At 500 m the channel is connected to the basin center but there also occurs a broad spillover in the NE (Fig. 20l). From our flooding models we conclude that Uzboi Vallis is at such a high elevation that the entire basin has to be filled before spillover would occur.

3.7.2.4. Volume estimates. The question then is, how much water is actually necessary to initiate spillover? Sequential flooding models based on present MOLA topography not only show where water would pond, but also

allow detailed investigation of volumes of water that could accumulate in the Argyre basin. Fig. 23 shows the volume of water in the Argyre basin in relation to the height of flooding. We flooded the basin in 500 m intervals from −6000 to 500 m. In addition we flooded the basin to elevations that correspond to the proposed shorelines of Parker et al. (1989, 1993) and Edgett and Parker (1997). Based on this approach we see that below −5500 m no water would pond in Argyre. At −5000 m only a very small volume of water of ~ 10 km^3 occurs at the lowest parts of the basin floor, that is, within crater Hooke. The volume grows steadily (−4500 m: ~ 200 km^3; −4000 m: ~ 1520 km^3) and at −3760 m, the global mean elevation of Contact 2, Argyre basin contains 3310 km^3 of water. Further flooding yields volumes of ~ 5970 km^3 at −3500 m, $\sim 38,670$ km^3 at −3000 m, and $\sim 1.77 \times 10^5$ km^3 at −2500 m. At −2000 m Argyre contains 3.96×10^5 km^3 of water and
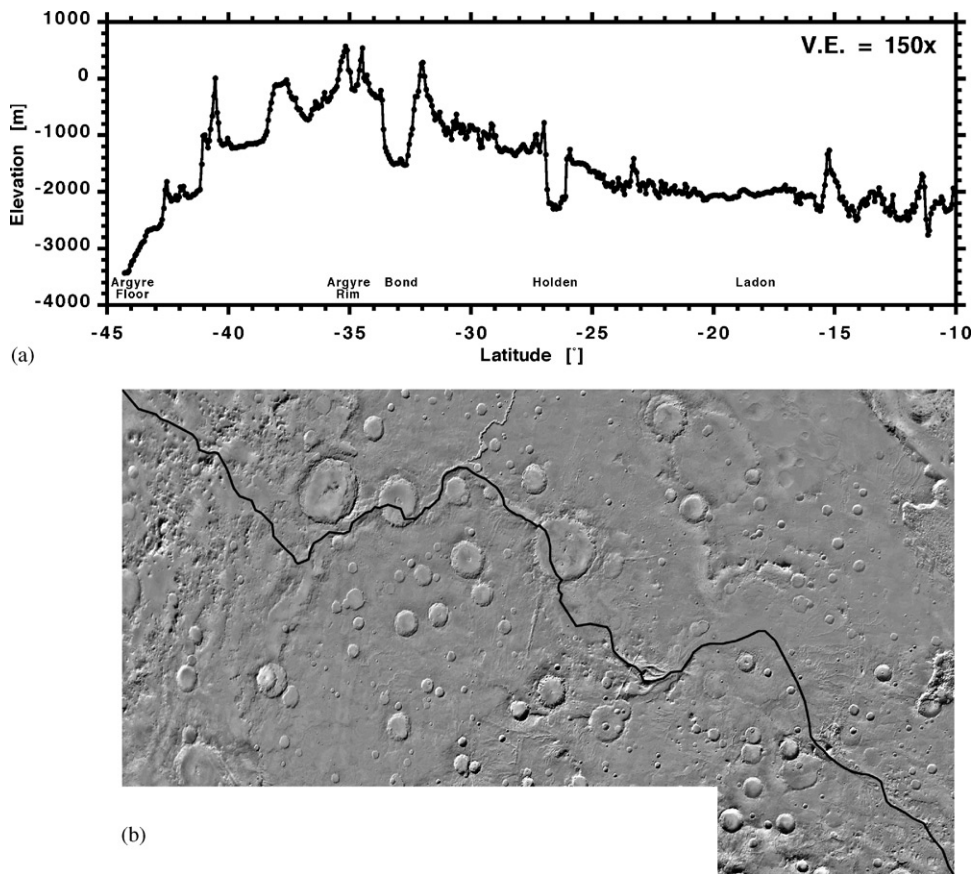
Fig. 22. (a) Profile along Uzboi Vallis and Ladon Valles on the basis of MOLA gridded topography. Vertical exaggeration (V.E.) is about 170×. (b) Viking MDIM is showing the location of the profile. Simple cylindrical map projection, North is to the right.

at −1680 m, the elevation of Contact 1, Argyre holds as much as 5.71×10^5 km^3 of water. The Meridiani shoreline is at about −1500 m (Edgett and Parker, 1997), equivalent to about 6.61×10^5 km^3 of water. At −1000 m the water volume is of the order of 9.94×10^5 km^3, at −500 m it is approximately 1.43×10^6 km^3, and at 0 m Argyre contains 1.98×10^6 km^3 of water.

Compared to previously published volumes of Argyre of $\sim 4 \times 10^6$ km^3 (Smith et al., 1999), we find that the amount of water that could have been stored within the basin is smaller and on the order of 2.1×10^6 km^3. This volume is based on flooding the basin up to 140 m, the elevation where water would start flowing out of the basin through Uzboi Vallis. At 500 m large-scale spillover would occur in the NE and we conclude that the basin cannot hold more than $\sim 2.7 \times 10^6$ km^3 of water. Thus the Argyre volume lies somewhat between the volume of the Sea of Japan (1.7×10^6 km^3) and the Mediterranean (3.7×10^6 km^3) (Smith, 1981). From our investigation of flooding models we conclude that (1) the basin has to be filled with at least 2.1×10^6 km^3 of water before flow through Uzboi Vallis could occur, and (2) once this hypothetical spillover through Uzboi Vallis stopped, one would be left with an enclosed lake approximately half the vol-

ume of the Mediterranean. We argue that such a lake or sea should have left morphologic evidence (terraces, texture and albedo differences that can be interpreted as shorelines), but such evidence has not been observed. Parker et al. (2000) proposed that the water that is necessary to completely fill the Argyre basin originated from basal melting of a once larger south polar ice cap. Using new MOLA data, Head and Pratt (2001) estimated the volume of such an ice cap and their data indicate that there is probably not enough water to completely fill the basin structure to a point where spillover would occur. We will discuss this in greater detail in Section 3.8.2.1.

3.7.2.5. Characteristics of ridges. Parker et al. (1986) proposed that the ridges in Argyre Planitia were formed during the Hesperian as lacustrine barriers or spits constructed of channel sediments which were deposited by wave-generated drift. Parker (1994) argued that the position of the ridges east of Surius Vallis might indicate a dominant wind direction toward the southeast, with wave energy deflecting the channel deposits toward the east along the basin floor. The wind direction in the Argyre region is not very well known. However, bright depositional wind streaks, mostly found in low- to mid-latitudes, indicate a
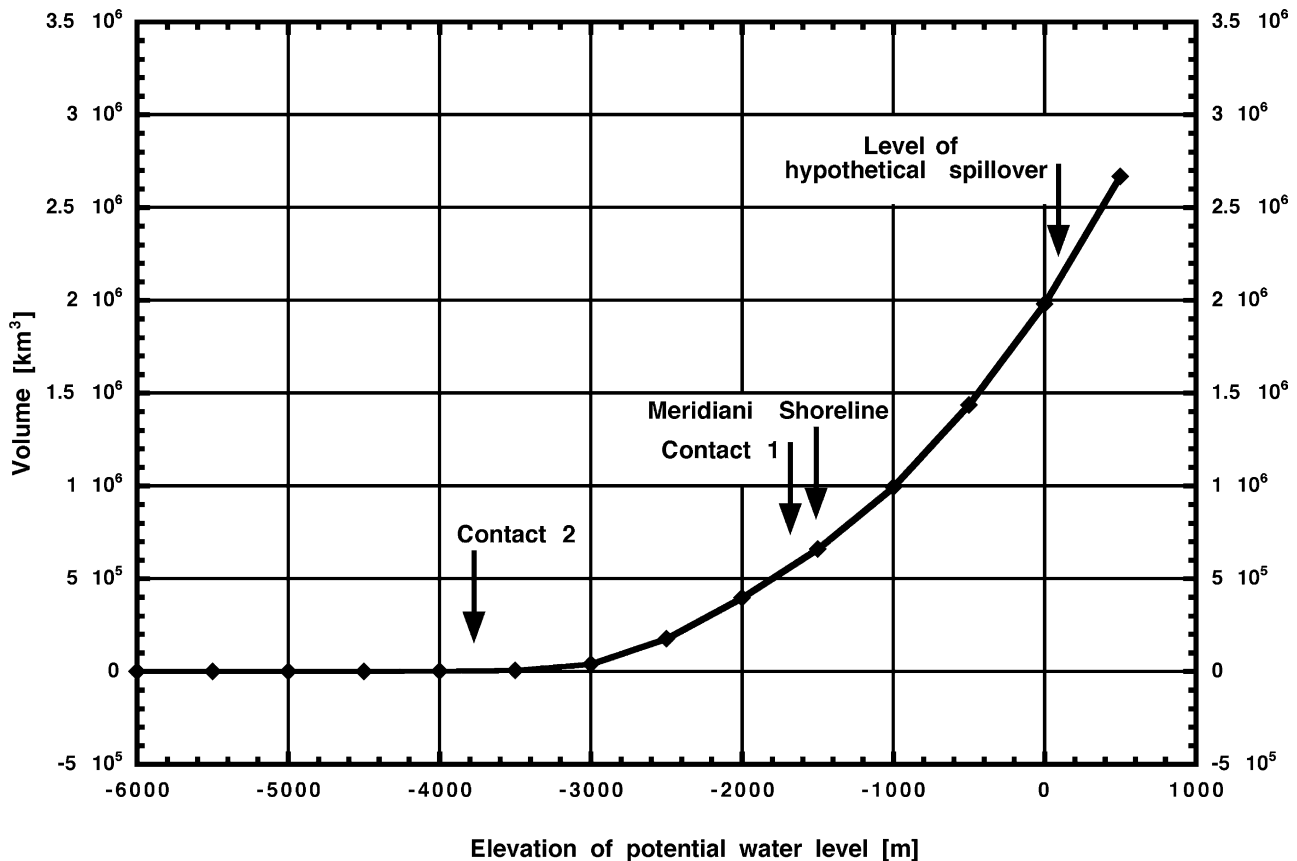
Fig. 23. Plot of water volumes (km^3) in relation to the elevation of the potential water level. Volumes are based on present topography from MOLA. At the level of Contact 2 only very small amounts of water occur within the Argyre basin. At the level of Contact 1 and the Meridiani shoreline the basin is partly filled and to initiate spillover through Uzboi Vallis significantly larger volumes are required.

general north to south wind direction, and dark erosional streaks, concentrated in the low southern latitudes, indicate winds mostly from east to west (Thomas et al., 1984). This is not consistent with the idea of Parker (1994) that northwest winds formed these ridges.

Spits are depositional features built along the shore, ending in one or more landward hooks (Bird, 1969; Komar, 1976). On Earth, spits are most common on irregular coasts, where they grow across bay mouths, sometimes completely closing them (Komar, 1976). We studied Viking imaging data and MOLA topography data but our investigation did not reveal such hooks, nor do we see that the ridges in Argyre grow across a bay. In addition, the ridges in Argyre Planitia form anastomosing systems with both confluent and diffluent branches. They cross one another and are significantly longer than terrestrial spits (Bird, 1969). From these observations we conclude that a formation of the ridges as lacustrine spits or barriers appears unlikely.

A second model of formation related to aqueous processes was proposed by Rhodes (1980), who compared morphologic ridges in the Mangala region of Mars with Stanislaus Table Mountain in California. This discontinuous chain of hills is more than 95 km long and was formed by exhumation of an old riverbed, which was filled by latite lavas. The latite flow was exhumed from the surrounding pyroclastic debris and the topography was inverted around it. The terrestrial ridge is in places up to 90 m high and shows a flat-topped, steep-sided morphology. Howard (1981) discussed the possibility that ridges in Dorsa Argentea and Argyre are results of channel deposits with inverted relief. MOLA and MOC data indicate that the ridges in Argyre Planitia are characterized by rather rounded cross-section and not by flat-topped, steep-sided morphology. In addition, the ridges in Argyre have up and down long profiles which are consistent with a hydraulic head driving force, in contrast to simple surface flow (Flint, 1971; Head and Hallet, 2001a, b). From this we conclude that the ridges in Argyre were probably not formed by open-channel flow, a conclusion similar to that of Howard (1981).

3.7.2.6. Surface roughness. Kreslavsky and Head (1999, 2000) showed that geologic units in the Northern lowlands are characterized by distinctive kilometer-scale surface roughness and that surface roughness provides useful information on the origin and evolution of the geologic unit. Parker et al. (1989, 1993) postulated a north polar ocean

and argued that the formation of such an ocean should be accompanied by sedimentation, smoothing submarine terrain below the shoreline. Head et al. (1999) tested the northpolar ocean hypothesis and showed that the average surface below the shoreline is indeed smoother at all scales (from a few hundred meters to several tens of kilometers) than the surface above. We used the map of Kreslavsky and Head (2000) to investigate the roughness of the interior of Argyre basin and related terrain. MOLA data indicate that unit Nplh, which forms the mountains of the rough Argyre annulus, is rougher at all baselines than any other unit associated with the Argyre basin. On the basis of our observations of the roughness of individual geologic units, we find that all investigated Argyre units (Hpl$_3$, Hr, Nple, and Nplh) are on average systematically rougher at all baselines than units Hvm and Hvk, which are exposed in the northern lowlands, an area which was supposedly covered by a former standing body of water. While this could indicate a subsequent modification of the terrains after the water in Argyre disappeared, it can also be caused by smaller amounts of water with less sediments transported into the basin, a shorter existence of the lake with less sedimentation, or by influx of coarse material from the steep slopes of the basin.

3.8. Water in Argyre: the case of a partly filled basin

3.8.1. Previous observations, interpretations, and implications

A second model involving water in the evolution of Argyre basin was proposed by Head (2000c). However, there are significant differences between this model and that of Parker et al. (2000) concerning the timing and the amount of existing surface water in Argyre basin. On the basis of their investigation of the present south polar ice cap and its related geologic units, Head (2000c) and Head and Pratt (2001) concluded that a much larger polar cap existed during the Early Hesperian. They argued that the Argyre basin is located north of the Dorsa Argentea Formation for which they present evidence that it was covered by the south polar ice sheet in middle Mars history (Head and Pratt, 2001; Head, 2000c). Meltback or stagnant retreat of this ice sheet during the later Hesperian formed distinctive morphologic features such as cavi and eskers. Cavi, the surface manifestations of subglacial melting, show that at least parts of the meltwater reentered the subpolar cap aquifer. However, eskers and sinuous channels emerging from the distal margins of the former extent of the ice sheet indicate that significant amounts of water flowed towards the north, i.e. the Argyre region.

3.8.2. Tests

We used MOLA data in order to estimate the water volume that could have been derived from meltback of the south polar ice cap and that could have ponded in the Argyre basin.

3.8.2.1. Volume estimates.
The major question we try to answer with this test is whether meltback of the polar ice cap can produce enough water to fill the Argyre basin to significant levels, that is, how do the volume estimates of the Argyre basin compare to volumes that can be derived from meltback of a polar ice cap? Head and Pratt (2001) found evidence for extensive melting and retreat of a Hesperian-aged south polar cap. On the basis of MOLA topographic data they concluded that it is likely that the Dorsa Argentea Formation, which has been interpreted as volatile-rich south polar deposits, underlies the present ice cap. MOLA data show that the maximum thickness of the Dorsa Argentea Formation and the present ice cap is < 3 km (Head and Pratt, 2001). Assuming that the entire area of the Dorsa Argentea Formation was once covered with a maximum of 3 km of ice, Head and Pratt (2001) estimated a maximum volume of $\sim 8.82 \times 10^6$ km^3. If we subtract the volume of the present-day ice cap, which is of the order of 2.19×10^6 km^3 (Head and Pratt, 2001), the volume of the removed polar deposits would be $\sim 6.63 \times 10^6$ km^3. This is a maximum estimate as it is rather unlikely that the ice cap had a constant thickness of 3 km over the entire surface area of the Dorsa Argentea Formation. A more likely scenario would be a decreasing ice thickness toward the margins of the ice cap, significantly reducing the volume. If we further assume sediment/volatile ratios between one-third and one-half (e.g., Komar, 1980; Thomas et al., 1992; Herkenhoff, 1998), the amount of water that could be produced by melting would be of the order of 2.21–3.32×10^6 km^3, a volume sufficient to entirely flood the Argyre basin. However, it has to be kept in mind that this is a maximum estimate because the ice cap certainly becomes thinner towards its margins, and that only a portion of the meltwater would flow across the surface in order to pond in the Argyre basin. Significant amounts would enter the groundwater system, as indicated by cavi, and significant amounts would remain in the pore space of the present Dorsa Argentea deposits (Head and Pratt, 2001). Also, it appears likely that large portions of the ice cap's volatiles sublimed, evaporated, or migrated into the atmosphere, and thus never underwent melting or took part in surface run-off. In addition, regional MOLA data indicate that not all of the melt water would flow into the Argyre basin, and that some portion of the water could end up in the Hellas basin (Head et al., 2001). Another important issue is the timing of the melting. In order to completely fill the Argyre basin, the necessary water has to be available within a short period of time, that is, the influx has to be faster than the loss due to sublimation, evaporation or percolation into the substrate. If these processes are more efficient in removing water from the basin than influx can replenish, the residence time of a standing body of water would be rather short (e.g., Kreslavsky and Head, 2001; Carr, 1996; Moore et al., 1995). According to these authors lakes would very quickly freeze over, consistent with recent climate models which indicate that at present conditions temperatures in Argyre would be below freezing for most of the time (e.g., Haberle, 1998;

Haberle et al., 2000). Moore et al. (1995) and Moore and Wilhelms (2001) estimated that lakes at latitudes of Hellas could remain liquid beneath an ice cover for only $\sim 10^5$ years, assuming that the climate was similar to the present one.

Our volume estimates do not account for replenishing of the ice caps due to snow accumulations. Such a replenishing and continuous melting over long periods of time could significantly increase the amount of melt water that ended up in the Argyre basin.

Independent evidence for a partial fill of Argyre comes from our estimates of the ice thickness, which overlay the esker-like ridges in Argyre. We estimated the ice surface to be at ~ -600 m, at least several hundreds of meters below the elevation at which flow through Uzboi Vallis would occur. Fig. 20i shows the Argyre basin filled up to -1000 m, in Fig. 20j the Argyre basin is flooded to -500 m. Clearly at -600 m the water/ice level is well below the elevation of Uzboi Vallis. The volume of this frozen lake would be on the order of 1.4×10^6 km^3 (Fig. 23).

From numerous terrestrial and planetary examples it is well known that emplacement of thick basaltic lavas, large bodies of water or ice sheets cause subsidence of the floor of a basin or crater (e.g., Strom et al., 1975, Schultz, 1976; Solomon and Head, 1979). With MOLA data we observe the present day topography which is the result of a complex interplay between subsidence and rebound in dependence of the amount and timing of emplaced loads. Based on current topography we have shown that for a number of reasons it is unlikely that the Argyre basin was completely filled and spilled over. If we assume that Argyre was once completely filled with water, as suggested by Parker et al. (2000), the depth of the proposed lake was much larger than the maximum thicknesses of the Laurentide (~ 300–3000 m) and the Scandinavian ice sheets (~ 3000 m) (Flint, 1971). Since the load has been removed from these terrestrial areas by a retreat of the ice, rebound of the depressed terrain has been up to several hundreds of meters (e.g., Flint, 1971; Mörner, 1980). Based on these observations of terrestrial analogs we argue that flooding of the entire Argyre basin with a lake several kilometers deep would have depressed the floor, probably hundreds of meters, hence making it even harder to initiate spillover in the past compared to today.

From our observations we conclude that a complete fill of the Argyre basin due to meltback of a polar cap during the Hesperian is unlikely and that partly filling the Argyre basin with water derived from polar cap meltback is more likely. Such a partial fill is also consistent with Hesperian channels cutting far down into the basin. In summary, we found numerous evidence for water playing an important role in the geologic history and evolution of the Argyre basin. However, this evidence does not necessarily point to a complete fill of the basin. If there was such a complete fill, probably more than 3 b.y. ago, it is not easily tested for because subsequent modification of the basin has destroyed most of the evidence. Based on the evidence that is left, we pro-

pose that the Argyre basin was partly filled with a frozen lake during the Hesperian. In our model, Hesperian meltback of the south polar ice sheet released water, which entered the Argyre basin (Fig. 24). The meltwater partly filled the basin floor to form a lake, which froze over. Ice thickness increased with time until the entire lake was frozen to the ground or at least until the ice became grounded in the shallower regions of the lake (i.e., close to the incoming channels). Meltwater or incoming water formed subglacial channels in which esker-like ridges were deposited. After the deposition of eskers, continued sublimation and migration of water into the substrate removed the water/ice in the basin and the eskers became visible. Eolian activity contributed to the evolution of the Argyre basin throughout its entire geologic history, mantling or exhuming morphologic features, influencing sublimation rates, and contributing to the present day morphology. A similar geologic history has been proposed for the other large impact structure at southern latitudes, the Hellas basin (Moore and Wilhelms, 2001).

4. Discussion

The formation of the northern outflow channel is crucial for describing the geologic and hydrologic history of the Argyre basin. Here we discuss three possible scenarios: (1) Uzboi Vallis was formed by spillover of a completely filled Argyre basin, (2) precipitation and/or sapping along the basin rim caused surface run-off which formed the channel, and (3) a basin existed north of the Argyre basin which ponded water up to an elevation where it could spillover into Argyre. These scenarios differ significantly in the direction of the water flow. In scenario 1 water flowed northward, in scenario 2 water simultaneously flowed northward and southward depending on which side of the rim the water was located, and in scenario 3 water first flowed southward and later northward.

4.1. Spillover

Ponding of water in the Argyre basin and drainage to the north is a simple and logical way to transport meltwater from the south polar cap to the northern lowlands. However, there are some caveats. In order to initiate water flow through Uzboi Vallis, it is required that Argyre is completely filled with water. Based on new MOLA data it appears ambiguous whether meltback of a Hesperian south polar ice cap could possibly have provided enough water to fill the basin to a level where spillover could occur. However, because of the high elevation of the point of spillover, it is impossible that the outflow channel drained the basin completely; it would leave a standing body of water ~ 4 km deep. The point of spillover is at a high elevation and once the water level dropped below this elevation, the basin would still contain $\sim 2 \times 10^6$ km^3 of water. We conclude that Uzboi Vallis can only have contained water for a relatively limited
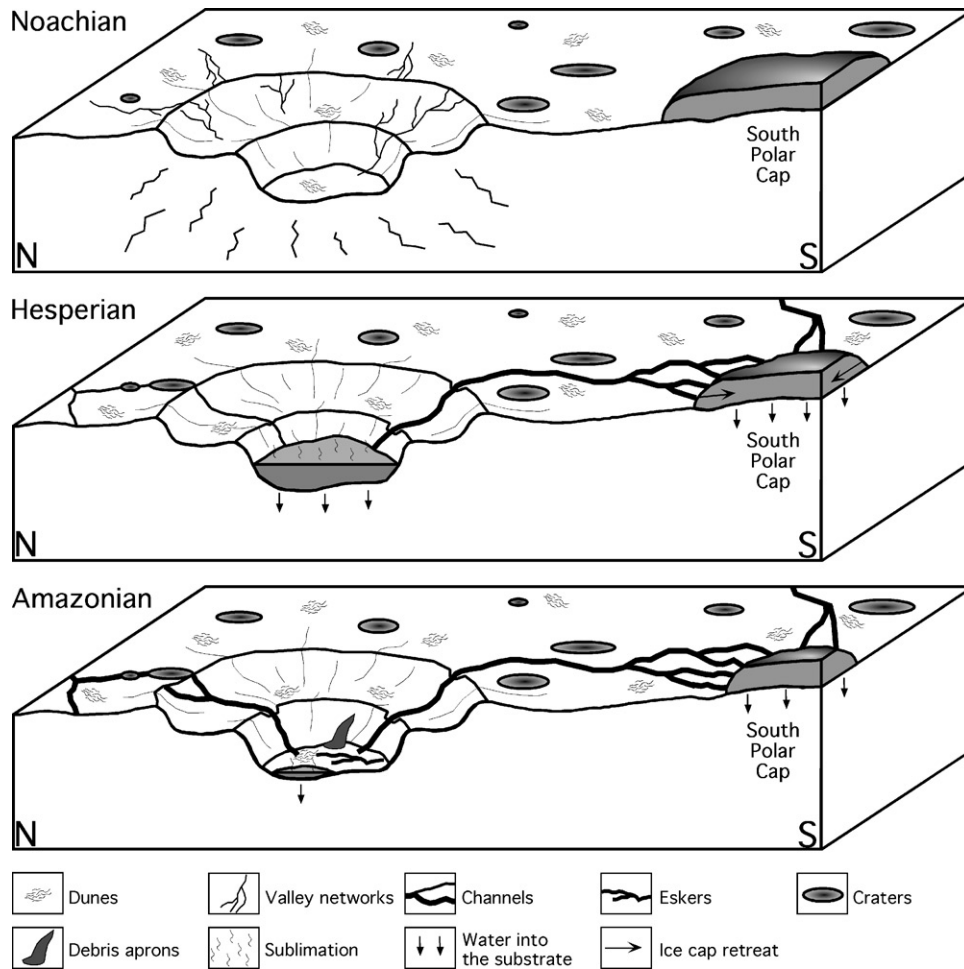
Fig. 24. Sketch diagram of the geologic history of the Argyre basin. During the Early Noachian, the Argyre basin was formed by a meteor impact, which fractured the crust and excavated the basin. During the later Noachian the basin was modified by tectonic and erosional processes. If the climate was warmer and wetter, than it is likely that valley networks were associated with the Argyre basin, as elsewhere on Mars. We assume that the south polar ice cap was in place and that eolian processes redistributed material across the surface. During the Hesperian the south polar ice cap retreated (Head and Pratt, 2001), releasing large amounts of water. Portions of this water went into the substrate, other portions ran across the surface towards the north and into the Argyre basin, carving prominent channels. Within the Argyre basin the incoming water formed a lake, which froze over. Some water of this lake sublimated, some water percolated into the substrate. The channel in the north appears to have entered from that direction, in contrast to the hypothesis of Clifford and Parker (2001) that the basin was filled from the south and overflowed to the north. By the Amazonian, the ice in the Argyre basin had been removed, eskers became visible, and debris aprons formed at the base of steep mountain slopes. Eolian processes continued to be active as indicated by numerous dune fields visible in MOC images.

period of time when the entire basin was filled and spillover occurred. Assuming $\sim 2 \times 10^6$ km^3 of water left after the water ceased to flow through Uzboi Vallis, we would expect to see evidence of such a lake/ocean for example in form of shorelines or differences in roughness. We could not identify morphologic features that resemble shorelines in MOLA, MOC or Viking data. Instead we see that several channels entering the Argyre basin can be traced down to the basin floor. The implication is that the basin has never been completely filled or that the now observable channels were formed after the hypothetical basin fill was removed. Another issue is the timing of the complete fill. Parker et al. (2000) considered Uzboi Vallis to be a large Noachian outflow channel. This implies that the basin has been com-

pletely filled in the Noachian, presumably by water derived from meltback of a south polar ice cap. However, recent studies (e.g., Head and Pratt, 2001) did not find evidence for a Noachian meltback but for a Hesperian meltback.

4.2. Precipitation/sapping

Is it possible that Uzboi Vallis and its extension into the Argyre basin were formed by surface run-off and/or sapping? Such a process requires substantial precipitation or a water-rich substrate at high elevations, i.e. the starting points of the channels. Dohm and Tanaka (1999) argued that the uplift of the Thaumasia plateau during the Noachian and Early Hesperian resulted in outward-verging fold-and-thrust

plateau margins. Uplift and deformation of the Thaumasia plateau could have lifted potentially water-rich substrate to high elevations and may have played an important role by providing subsurface water along fracture systems to the Argyre region. In this scenario the rim of Argyre would act as a drainage divide with water north of the rim flowing northward and carving Uzboi Vallis and water south of the rim flowing southward into the basin, carving the extension of Uzboi Vallis. Inspection of Viking images reveals numerous small fluvial valleys along the northern rim that start close to the rim crest. These valleys drain in both directions, depending on which side of the rim crest they are located. Based on Viking images we see significant differences in the distribution of small-scale fluvial valleys. These valleys occur more often at the northern rim (north of −43–45°) compared to the southern rim. A possible explanation could be that in the north temperatures were above freezing, allowing for fluvial run-off or sapping. In the south temperatures were below freezing, resulting in more glacially dominated landforms. On the basis of greenhouse models global mean surface temperatures early in Mars' history are thought to differ little from today's (Haberle, 1998). Recent climate models indicate that at present conditions temperatures in Argyre would be below freezing for most of the time (Haberle et al., 2000) but they do not resolve differences between the northern and the southern rims. Other examples of high elevation valleys are located in the northwest and northeast of the basin. Compared to other regions around Argyre, craters immediately northwest of Argyre more often show fluvial valleys on their upper inner walls, suggesting that precipitation or sapping processes from a high water table occurred. West of crater Hale is a large theater-shaped source region for an inward draining channel that merges with the extension of Uzboi Vallis near the basin floor. The source region of this channel is located at the basin rim, and there is no incision in the Argyre rim that would suggest external sources for the water that carved this channel. From this we conclude that the water was either derived from precipitation or from sapping. As this channel is of similar size as the extension of Uzboi Vallis, the amount of water that formed the channel might have been comparable. The implication is that it is possible to form a channel similar in size to Uzboi Vallis by surface run-off or sapping from high source areas. In this scenario a complete fill of the Argyre basin is not required because it could be shown that large channels can be produced by alternative processes.

4.3. Nirgal lake

In a third scenario we explore the possibility that water entered the Argyre basin from the north. A possible source region could have been Nirgal Vallis that drained a large area northeast of Argyre. As the Argyre rim is higher than the present day mouth of Nirgal Vallis, this scenario requires ponding of water north of Argyre to an elevation

where it could flow into the Argyre basin. Based on MOLA topography we found a topographic ridge north of the mouth of Nirgal Vallis that is only breached by Uzboi Vallis. If we assume that this breach was originally not in existence then water from Nirgal Vallis could have formed a lake whose water level was high enough to allow flow into Argyre. If this lake existed and drainage occurred before the ejecta deposits of crater Hale and Bond modified the channel topography, the elevation of the channel might have been lower than today, hence facilitating the flow of water into the basin. In this model, the inflowing water carved the extension of Uzboi Vallis, which can still be traced down to the Argyre floor in MOLA and Viking data. Later, once the northern ridge was breached, probably by an impact event, the lake drained towards the north, the water level dropped, and flow into Argyre ceased. Evidence for a late stage northward flow of water from Nirgal Vallis is a sediment fan that is deflected to the north at the conjunction with Uzboi Vallis. In this scenario the impacts of Hale and Bond modified the pre-existing Uzboi channel. Water collected from precipitation and or sapping along the Argyre rim also modified Uzboi Vallis and contributed to the present day channel topography. The implications of this model are that most of the Uzboi Vallis topography was created by a Noachian flow into the basin and that lesser amounts of water, originating at high sources, are required for the formation of the now observed channels compared to scenario 2. This scenario does not require a complete fill of the Argyre basin but influx from the north, in addition to the water that entered the Argyre basin in the south due to a meltback of a south polar cap, would contribute to the amount of water that ponded in Argyre.

5. Conclusions

We investigated the Argyre basin with new data from the MOLA and MOC experiments on board the Mars Global Surveyor spacecraft. Based on the results of our investigation we conclude:

(1) The Argyre basin exhibits several concentric ring structures with diameters of 650, 780, 870, 1050, 1290, 1470, and 1700 km. Argyre Rupes and a scarp at about 5°W and 45°S could mark an additional ring of about 2750 km in diameter. Initial investigation of the basin shape and comparison to Orientale indicates similarities in morphology between the Cordillera ring and the 1700 km ring of Argyre.

(2) The Argyre basin went through a complex geologic history and we see evidence that several geologic processes contributed to its current appearance. Based on our study we conclude that glacial and fluvial/lacustrine processes and to a lesser extent eolian modification were most important in the evolution of the Argyre basin.

(3) We find no strong evidence for an evolution of the Argyre basin solely dominated by eolian activity. However, numerous dunes indicate that eolian processes were active recently or are still active. Surface textures, which indicate deflation/sublimation and dune fields argue for a redistribution of fine-grained material within the basin. Sinuous ridges in Argyre Planitia are orders of magnitude larger than typical dunes and cannot be explained as eolian deposits.

(4) We see no evidence for a mud-delta as predicted by the model of Jöns (1999). In addition, predictions of the model that ridges would preferentially form where the flooding material was dammed by escarpments and that in smooth areas without escarpments only a few, if any, ridges would occur, are not consistent with MGS data.

(5) Unit Hr, previously interpreted as volcanic in origin (Scott and Tanaka, 1986) appears on the basis of the new data to have a sedimentary origin. Evidence for this is (1) the roughness of this unit which is much more similar to the roughness of sediments, (2) the location of the Hr unit at the mouth of incoming channels, (3) the absence of source vents, and (4) the characteristics of the ridges exposed on this unit. Ridges exposed in this unit share numerous morphologic characteristics with eskers rather than wrinkle ridges, suggesting that one of the main characteristics of the plains used to infer a volcanic origin may be of different origin.

(6) Glaciation may have influenced the area, but not to the large scale and style envisioned by previous authors (e.g., Kargel and Strom, 1992). Based on our investigation we conclude that formation of some of the units on the floor of Argyre (e.g., Hpl_3) solely from deposition of lacustrine sediments in a proglacial lake appears unlikely. Ridges in southern Argyre Planitia are of similar size to terrestrial eskers and show horizontal layering. They do not strictly follow the topographic gradient but have up-and-down long profiles. Compared to wrinkle ridges, they do not show a narrow ridge on top of a broad ridge, they exhibit smaller offsets in elevation between the left and right side of the ridge, and they appear less high. From these observations we conclude that ridges in Argyre Planitia are most likely eskers.

(7) We find evidence for water in the Argyre basin but a complete fill remains questionable. Evidence for water in the Argyre basin is the formation of channels which can be traced to the basin floor, the morphologies at their mouths which suggests a fluvial origin, and the availability of large amounts of water generated by the meltback of the south polar ice cap. In order to initiate flow through Uzboi Vallis, the basin has to be completely filled with at least 2.1×10^6 km^3 of water and this is not consistent with current hydrologic models. In addition, Head and Pratt (2001) investigated the south polar cap and its related deposits and they found no evidence for meltback of a formerly larger ice cap in the Noachian, which was proposed as a source for the water. On the basis of their volume estimates of the south polar cap, we calculated that the amount of water that can be produced by meltback of a Hesperian ice cap and that would end in the Argyre basin is probably insufficient to completely fill it. However, our volume estimates did not account for replenishing of the ice cap and continuous melting over long periods of time.

(8) We propose that the basin contained water, and that it was partly filled during the Hesperian. The source of this water is meltback of a formerly more extensive south polar icecap (also see Head and Pratt, 2001). Water that ponded in the Argyre basin would have sublimed, evaporated or migrated into the substrate rather than flowing through the outflow channel of Uzboi Vallis. The body of water in the Argyre basin very likely froze over. Subsequent retreat of the ice is indicated by the formation of esker-like ridges and eolian modification of the basin floor is seen in numerous MOC images.

(9) A comparison with terrestrial esker systems together with the estimated maximum ice thickness of the Dorsa Argentea Formation suggests that about 2000 m of ice overlay the esker-like ridges in Argyre; a total volume of ice on the order of 1.4×10^6 km^3. This volume is significantly smaller than the volume to initiate spillover of the basin through Uzboi Vallis.

(10) In summary, a concise geologic history of the Argyre basin is as follows. In our model, water produced by a Hesperian meltback of the south polar ice sheet entered the Argyre basin. The meltwater partly filled the basin floor to form a temporary ice covered lake. In the shallower regions of the basin, the ice was grounded and meltwater formed subglacial channels in which esker-like ridges were deposited. Continued sublimation and migration of water into the substrate finally reduced the amount of water/ice in the basin and the eskers became visible. Throughout the entire geologic history, eolian activity contributed to the evolution of the Argyre basin, mantling or exhuming morphologic features, influencing sublimation rates, and contributing to the present day morphology. Our geologic history of the Argyre basin is consistent with a very similar model that has been proposed for the other large impact structure at southern latitudes, the Hellas basin (Moore and Wilhelms, 2001).

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