Table 1
Crater measurements of the Hellas, Isidis, and Argyre. $N(X)$ is the cumulative number of craters $\geqslant X$, normalized to an area of 10^6 km^2; errors in $N(X)$ are from $\pm\sigma = \sqrt{N}/A$. The basins are clearly distinguishable from each other on the basis of the relative density differences for craters larger than 20 km. Age estimates are model ages from Hartmann (2005) isochrons (A_H) and Neukum isochrons (A_N) (reproduced in Ivanov (2001)). The computed 'model ages' are very insensitive to changes in crater frequency because of the high flux of impacts assumed in these absolute age models early in Mars history (as can be seen by comparing the frequencies and derived ages for Hellas and Argyre). Statistical fit errors for given model ages are ~±0.01 Gyr. In reality, the age is not known nearly this well; uncertainty in age estimates is dominated by the systematic uncertainty in the absolute age calibration/impactor flux (see, e.g., Hartmann and Neukum, 2001; Werner, 2008). Count areas are shown in Fig. 1 along with the crater size-frequency distributions for Hartmann and Neukum isochrons.

Basin	Count area (km^2)	$N(20)$	$N(64)$	A_H	A_N	Period
Hellas	7.3×10^5	151 ± 14	27 ± 6	4.02	4.04	Base of the Noachian
Isidis	4.7×10^5	117 ± 16	11 ± 5	3.96	3.97	Mid-to-Early Noachian
Argyre	1.6×10^6	88 ± 7	10 ± 2.5	3.92	3.94	Mid (to Early?) Noachian

Frey, 2008). The recognition of quasi-circular depressions and ghost craters has been particularly important for inferring that beneath the upper few hundred meters of the northern plains, there is an older (Hesperian?) ridged plains unit that is not deeply buried (Withers and Neumann, 2001; Head et al., 2002) and that below this surface, the basement of the northern plains are as old as the Noachian-aged highlands (Frey et al., 2002).

More recently, Frey (2008) and Lillis et al. (2008a) suggested that the combined population of possible QCDs and CTAs may provide the best data for considering the age of the largest basins (using features of 300 km and more in diameter). However, we are cautious about relying on this approach, since their data would imply that Argyre is older than Isidis by an appreciable margin, and that Isidis is as young as the beginning of the Late Noachian (~3.8 Gyr).

This sequence of basins (Hellas, Argyre, Isidis) is in direct disagreement with the measured population of visible craters (Table 1 and Fig. 1). Across a wide range of visible crater diameters (Table 1 and Fig. 1), there are fewer superposed craters on Argyre than Isidis, and fewer craters on Isidis than Hellas. Moreover, the rim region of Isidis (the Libya Montes) has a crater population dating to the Mid-to-Early Noachian boundary, which is inconsistent with a Late Noachian formation for the basin. Finally, the inferred sequence of these youngest fresh impacts is inconsistent with the relative preservation state of the basins (Schultz, 1986). We suggest that possible reasons for this discrepancy include one or more of the following factors: (1) small number statistics: since these young and well-preserved basins never had many >300 km craters to begin with (visible, degraded, QCDs or CTAs), inferring their relative age from craters of this size may lead to errors, (2) some QCDs or CTAs may not be impact structures, and/or (3) there may be different degrees of basin floor filling that affects the number of QCDs/CTAs that can be recognized (Isidis is potentially more filled than Argyre) (Head et al., 2002; Howenstine and Kiefer, 2005).

In summary, for the youngest, well-exposed basins on Mars, we prefer to rely on the superposed visible crater population for assessment of their timing and relative sequence – first Hellas, then Isidis, then Argyre.

3. Valley networks and surface erosion

Valley networks provide morphological evidence for fluvial activity, erosion, sedimentary transport, and a hydrological cycle on early Mars (Carr, 1996). Valley networks have numerous tributaries (Hynek et al., 2010), often begin near drainage divides (Craddock and Howard, 2002), and were interconnected across great distances, at least during their period of peak activity (see, e.g., Irwin et al., 2005; Fassett and Head, 2008a). Paleo-lakes on Mars appear to have been relatively common features (e.g., Fassett and Head, 2008a, and references therein), and certain valleys such as Ma'adim Valles, which initially appeared to come from localized sources (e.g., Gulick, 2001), appear to have formed as these paleo-lakes overtopped confining topography (Irwin et al., 2002). Groundwater-driven valley erosion alone seems inconsistent with many valley characteristics, particularly the dendritic, high-order tributaries that extend to drainage divides (Hynek et al., 2010). Even if some valleys formed as the result of groundwater discharge, precipitation-based recharge seems to have been necessary to close the hydrological cycle, as basic calculations suggest that subsurface water reservoirs would need to be recharged many times to erode the valley networks observed (Goldspiel and Squyres, 1991; Gulick, 2001). The characteristics of valley networks thus seem to require, at minimum, time periods when precipitation on the surface was possible, water was cycled through the early Mars atmosphere, and water was stable or metastable at the martian surface (Craddock and Howard, 2002; Hynek et al., 2010).

Several independent studies have attempted to estimate when the most extensive period of valley network formation occurred (e.g., Pieri, 1980; Carr and Clow, 1981; Fassett and Head, 2008b; Hoke and Hynek, 2009), using stratigraphic and crater counting analysis to date the termination of valley network activity. These studies suggest that regional-to-global-scale valley formation persisted until approximately the Noachian/Hesperian boundary or into the Early Hesperian at the latest (Fassett and Head, 2008b; Hoke and Hynek, 2009). Note that this 'regional-to-global' scale formation excludes certain regions that are thought to be local exceptions, such as valleys on certain volcanoes (e.g., Gulick and Baker, 1990; Fassett and Head, 2006, 2007), in association with glaciation (Dickson et al., 2009; Fassett et al., 2010), and within, or in the vicinity of, young, large craters (e.g., Williams and Malin, 2008; Tornabene et al., 2008; Morgan and Head, 2009).

In our study (Fassett and Head, 2008b), we suggested that two possible interpretations were consistent with our craters statistics: either (1) global termination of valley activity near the Noachian/Hesperian boundary or (2) persistence of some valleys into the Early Hesperian.

Increasing evidence has been put forth for erosion in at least some major valley networks were active well into the Early Hesperian or possibly the Late Hesperian (e.g., Mangold and Ansan, 2006; Ansan and Mangold, 2006; Bouley et al., 2009, 2010). In some of this work, a younger period of activity is derived than in Fassett and Head (2008b), primarily due to differences in analytical choices, particularly: (1) how count regions are aggregated, (2) different stratigraphic interpretations and, most importantly, (3) the effective diameter used to compare observed crater populations with isochrons. At some level, these factors are coupled, since larger diameter craters require greater aggregation of area to achieve meaningful statistics, at the expense of the ability to discern real local variation if it exists (as noted by Bouley et al. (2010)). As described above, reliance on smaller craters may result in younger ages due to crater retention. In summary, age data continue to support the idea that regional to global-scale valley network formation terminated in the Early Hesperian, although new evidence has bolstered the interpretation that valley formation lasted into this period (Bouley et al., 2009, 2010).