equilibrating with the atmosphere. Nor do we know whether present loss rates of hydrogen are representative of the last 3.5 Ga. The average obliquity over the last 3.5 Ga is 40°, significantly higher than the current 25° (Laskar et al., 2004). At 40° obliquity, the water content of the atmosphere could have been higher than the present by a factor of 100 (Mellon and Jakosky, 1995), thereby leading to enhanced hydrogen losses from the upper atmosphere and the possibility of enriching a larger reservoir.

In view of all the uncertainties outlined above, we must conclude that modeling of accretion and atmospheric evolution does not place strong constraints on the amount of water available for geologic processes. In an alternative approach, Carr (1986) estimated that a global equivalent of roughly 500 m of water was required to transport the material eroded away to form the outflow channels, but this figure also has large uncertainties.

## 2.3 Early geologic events

How deep into the era of heavy bombardment can the geologic record be discerned from the surface topography is unknown. Part of the uncertainty stems from the cratering history: whether there was a late spike in basin formation around 3.9 Gyr ago (Tera et al., 1974) or a steady decline after accretion (Stöffler et al., 2006). Assuming a steady decline and using the Hartmann and Neukum (2001) estimates of the cratering rate in the late heavy bombardment period, Frey (2003) estimated that Hellas formed around 4.1 Gyr ago from the number of basin-like features superimposed on its rim. This number should, however, be viewed with considerable caution because of all the assumptions involved. Frey also suggested that Hellas be taken as the base of the Noachian and that the era from 4.55 to 4.1 Gyr ago be referred to as pre-Noachian.

Possibly the earliest geologic event recorded in the topography of the surface is the formation of the global dichotomy (Carr, 2006; Nimmo and Tanaka 2005; Solomon et al., 2005). The dichotomy is expressed in three ways that do not coincide everywhere: as differences in elevations, as differences in crustal thickness, and as differences in crater densities. The dichotomy results in a bimodal distribution of elevations, with a difference of 5.5 km between the two hemispheres (Aharonson et al., 2001). Neumann et al. (2004) estimate that the thickness of the crust averages roughly 30 km north of the dichotomy boundary and roughly 60 km to the south. As expected, the differences in crater densities across the boundary may be only a superficial difference for a densely cratered surface that is present at depths below the present Hesperian–Amazonian surface north of the dichotomy as indicated by remnants of old craters that poke up through the younger plains and by vague circular outlines in both the Mars Orbiter Camera (MOC) images and Mars Orbiter Laser Altimeter (MOLA) data. The low-lying, heavily cratered Noachian surface, north of the dichotomy boundary, is simply covered by younger deposits. A distinction must also be made between the time of formation of the depression and the time of formation of the fill. The number of craters superimposed on the fill yields little information about the age of the