evidence, if it ever existed, would be vulnerable to erasure by burial and erosion. Nevertheless, if during the Noachian, Mars had a large inventory of water and if ever warm condition prevailed, as is indicated by the valley networks, then bodies of water would have accumulated in lows such as the northern basin and Hellas.

### 2.4.3 Weathering

A distinguishing feature of the Noachian as compared with later eras is the widespread presence of phyllosilicates, such as nontronite, Fe-rich chlorites, saponite, and montmorillonite (Bibring et al., 2006; Murchie et al., 2008), minerals that all form by the aqueous alteration of basalts (e.g., Zolotov and Mironenko 2008). Weathering to form these minerals probably also occurred in the pre-Noachian but the evidence has been largely destroyed. In some places the phyllosilicates appear to be excavated from below the surface or are overlain by unaltered, olivine-rich rocks. Mustard et al. (2007) show, for example, that olivine-rich rocks overlie phyllosilicates in the Nili Fossae and suggest that they formed from impact melts produced by the event that formed the Isidis basin. The relations suggest that prior to the uppermost Noachian, conditions were such that phyllosilicates could form, but conditions changed toward the end of the era such that rocks that formed at the end of the Noachian retain their primary mineralogy. The presence of phyllosilicates in Noachian terrains and their absence in younger terrains suggest that near the end of the Noachian, surface conditions changed from warm wet conditions under which hydrous weathering could occur, at least occasionally, to colder, drier conditions under which hydrous weathering was suppressed.

### 2.4.4 Noachian Climates

The geomorphic evidence for lakes and rivers, the widespread presence of phyllosilicates in Noachian terrains, and the evidence for groundwater movement and surface water at Meridiani (Grozinger et al., 2005) all suggest at least episodic warm conditions during and at the end of the Noachian. Greenhouse models indicate that it is very difficult to raise global temperatures sufficiently to allow widespread precipitation on early Mars with only a $CO_2$–$H_2O$ atmosphere because of Mars' distance from the sun, the expected low energy output of the Sun, and formation of $CO_2$ clouds (Haberle, 1998; Kasting, 1991). In addition, we saw above that a thick $CO_2$ atmosphere is difficult to sustain against impact erosion and weathering. Although some carbonate rocks have been detected from orbit (Ehlman et al., 2008), failure to detect widespread carbonate deposits (Bibring et al., 2006) argues against a thick ($>$1 bar) $CO_2$ atmosphere during and particularly at the end of the Noachian, when the most prominent valleys formed. If surface conditions on Mars were at least episodic such as to stabilize liquid water near the end of the Noachian, some mechanism other than, or in addition to, warming by a $CO_2$-$H_2O$ greenhouse seems to be required. Possibilities include the presence of other greenhouse gases such as $SO_2$ and $CH_4$, or large-scale climatic perturbations resulting from large impacts or large volcanic events. Segura et al. (2002) suggest that large impacts would warm the surface and inject significant