Given the observations on the timing of valley network formation, three key questions remain to be definitively addressed: (1) how active was the period of valley network formation in the Noachian to the Early Hesperian, (2) how common/continuous were the periods when valleys were forming on early Mars, and (3) was water required to be stable over an extended period of time?

Estimates from modeling of valley network-associated sedimentary deposits imply emplacement times that are geologically quite short, of order 1–1000 years (Jerolmack et al., 2004; Kleinhans, 2005; Lewis and Aharonson, 2006; Kraal et al., 2008; Kleinhans et al., 2010). However, these estimates are based on continuous activity and sediment transport; estimates that assume terrestrial-like intermittency or sediment supply unsurprisingly infer much longer periods of time (Moore et al., 2003; Fassett and Head, 2005).

Drainage basin characteristics provide some of the strongest arguments for valley network formation over an extended period of time ($\sim > 10^5$ years) (Barnhart et al., 2009). Barnhart et al. (2009) synthetically reconstructed pre-erosion topography of the Parana drainage basin, and applied a variety of erosion scenarios to examine their consistency with the topography we actually observe. They found that an intense period of fluvial erosion and precipitation lasting $\sim 10^3$–10^4 Earth years would be sufficient to erode the valleys that are observed. However, these intense erosion scenarios resulted in a pattern of erosion far more integrated (with more crater rims breached) than what we observe on the surface. Thus, models that have greater episodicity, with runoff distributed over $\sim 10^5$–10^6 Earth years, are interpreted to be more consistent with the drainage pattern observed in the Parana region (Barnhart et al., 2009).

4. Volcanism

Volcanism is known to be a major factor in the long-term climate evolution of Mars, as eruptions liberate volatile species from the planetary interior to the atmosphere (e.g., Jakosky and Philllips, 2001; Phillips et al., 2001; Craddock and Greeley, 2009). For this reason, volcanism has commonly been inferred to be closely linked to changes in the surface environment. The formation of the mass of Tharsis in particular has been implicated in a transition from a phyllosilicate-forming era (phyllosian) to a sulfate-forming era (theiikian) (Bibring et al., 2006; Bibring and Langevin, 2008).

Constraining the timing of Tharsis volcanism is critical to understanding whether this conclusion is reasonable. On the basis of the fact that its emplacement and load on the Mars lithosphere influenced the orientation of Late Noachian/Early Hesperian valley networks, Phillips et al. (2001) argued that the bulk of the Tharsis volcanic was emplaced during the Noachian. Further evidence that Tharsis construction is ancient also comes from mapping, crater counts, and analysis of the tectonic record (Plescia and Saunders, 1982; Anderson et al., 2001), as well as from observations that portions of Tharsis are magnetized, even at high elevations ($\sim$7 km) (Johnson and Phillips, 2005).

On the other hand, the interpretation that the bulk of Tharsis is Noachian has been disputed by Craddock and Greeley (2009), who point out that the lack of craters on much of Tharsis means that most of its surface is Hesperian or Amazonian, and requires significant post-Noachian resurfacing. Craddock and Greeley (2009) estimate that lava deposits up to $\sim$10 km in thickness are required to remove a sufficient number of craters to reset the terrain age.

It is plausible that these two views can be reconciled in a scenario where the majority of the crust at Tharsis is constructed in the Noachian (crustal thickness $\sim$50–100 km; Neumann et al., 2004), but where extensive volcanic resurfacing persists through Hesperian and Amazonian times (see also Solomon and Head, 1982). However, the observation that a substantial amount of Tharsis-building is ancient (e.g., back to the Mid-Noachian or before) remains credible, as the existence of ancient, Noachian regions is clear, particularly in the Thaumasia highlands (Plescia and Saunders, 1982). Given that the magnetization of parts of Tharsis (Johnson and Phillips, 2005), early volcanism in these regions may pre-date Hellas (see Section 6). The interpretation that the construction of Tharsis near the end of the Noachian led to secular changes which caused Mars to transition from a planet where phyllosilicate formation was common to one dominated by sulfate formation (Bibring et al., 2006; Bibring and Langevin, 2008) may not be consistent with the fact the bulk of Tharsis may be old.

Hesperian and younger volcanism on Mars is also important regardless of the timing of Tharsis. In particular, volcanic plains emplacement, particularly focused in the northern lowlands, resurfaced $\sim$30% of the surface of Mars in this period (Head et al., 2002). Estimates from Viking mapping suggests that more than half of the volcanic resurfacing on Mars is Early Hesperian or younger (Tanaka et al., 1987; Greeley and Schneid, 1991); higher resolution observations with recent data would imply that this is conservative, because small patches of volcanic plains have been increasingly recognized in the highlands (Fassett and Head, 2008a).

In summary, the volcanic history of Mars should be closely correlated with a number of other conditions on the planet, including the density of the atmosphere, atmospheric chemistry and volatile inventory. As far as it can be determined however, the timing of volcanism (e.g., Tanaka et al., 1987) does not imply a one-to-one link between volcanism and surface conditions. No evidence exists that a declining volcanic fluxes correlates well with atmospheric loss, or that periods of Noachian volcanism helped facilitate transient clement conditions. Instead, the Hesperian volcanic deposits that resurfaced 30% of Mars are volumetrically significant and strikingly uneroded. Based on our current understanding of the timing of volcanic deposits, secular changes in volcanism or major volcanic events can not be directly connected to transitions in surface conditions.

5. Aqueous alteration

The recognition of alteration products on Mars has been revolutionized by observations in the last decade across the electromagnetic spectrum, first in the thermal infrared by TES and THEMIS (e.g., Christensen et al., 2001; Wyatt and McSween, 2002; Osterloo et al., 2008), and more recently, in the visible to near-infrared, by OMEGA (Gendrin et al., 2005; Poulet et al., 2005; Bibring et al., 2006; Bibring and Langevin, 2008) and CRISM (Milliken et al., 2008; Mustard et al., 2008; Ehlmann et al., 2009; Wray et al., 2009).

These data have resulted in the recognition of at least ten distinct environments where aqueous alteration products are observed (Murchie et al., 2009). Based on observations of hydrated minerals, particularly Fe–Mg phyllosilicates, it appears that neutral-pH alteration on Mars was an important process in the Noachian (Bibring et al., 2006). Murchie et al. (2009) examined the stratigraphic constraints on these deposits; we independently have reexamined these environments from a crater counting and stratigraphic perspective (Table 2). The time-stratigraphy of mineral formation in many of these environments is complicated. One of the major issues is that in some of the outcrops where phyllosilicates are observed, they are likely to be detrital (e.g., Ehlmann et al., 2008a; Murchie et al., 2009; Milliken and Bish, 2010). The timing of the aqueous alteration that resulted in the formation of these clays is thus not preserved – their present state could reflect Early Noachian formation and Late Noachian physical weathering, transport, and deposition.

Where minerals remain in situ (authigenic alteration), it is easier to make inferences about the timing of the geochemical