In summary, a transition in the character of aqueous alteration from widespread neutral-pH aqueous alteration to more localized acidic aqueous alteration is suggested by observations of hydrated minerals on Mars (Bibring et al., 2006; Bibring and Langevin, 2008; Murchie et al., 2009). This paradigm of high-water–rock ratio alteration followed by more water-limited alteration later in Mars history (Bibring et al., 2006; Hurowitz and McLennan, 2007) seems borne out by new data even as many new alteration minerals have been recognized on the surface of Mars.

6. Magnetic anomalies and cessation of the magnetic field

Observations from the Mars Global Surveyor magnetometer experiment demonstrated that there are crustal magnetic anomalies observed over much of the surface, with the strongest anomalies concentrated in the southern highlands (Acuña et al., 1999). These crustal anomalies imply the existence of a core dynamo on Mars early in its history. The existence of this magnetic field may have played an important role in arresting the loss of the early Mars atmosphere by solar wind sputtering (e.g., Jakosky and Phillips, 2001), as well as shielding the surface from energetic cosmic rays (e.g. Molina-Cuberos et al., 2001).

There are two compelling constraints on the timing of the Mars magnetic field. First, crustal magnetic anomalies are largely absent in the interiors of Hellas, Argyre, Isidis, and Utopia, as well across most of Tharsis and most volcanic edifices on Mars, with the exceptions of Hadriaca Patera (Lillis et al., 2006) and Apollonaris Patera (Hood et al., 2010). The simplest explanation for the lack of magnetization in these basins and volcanoes is that they post-date the cessation of the magnetic field. If this interpretation is correct, the core dynamo must have ended in the pre-Noachian before the formation of Hellas (Lillis et al., 2008a,b; see Schubert et al. (2000) and Hood et al. (2010) for alternative interpretations of the timing of the magnetic field). It has been suggested that the formation of large earlier basins that are now buried, such as Utopia, may have contributed to this termination (Roberts et al., 2009).

Second, a further possible constraint on the timing of the magnetic field comes from ALH84001, which has remanent magnetization consistent with acquisition in a magnetic field caused by a core dynamo with strength 0.1–10$\times$ the present Earth dynamo (Kirschvink et al., 1997; Weiss et al., 2002). This interpretation is preliminary, however, as it is not entirely clear whether the magnetization in this meteorite was acquired from a dynamo or from pre-existing crustal fields (Gattacceca and Rochette, 2004). If it was from a core dynamo, and the age of ALH84001 is 4.091 ± 0.03 Gyr as recently suggested (Lapen et al., 2010), this would provide direct evidence of the persistence of a magnetic dynamo until $\sim$4.09 Gyr.

If these suppositions are correct, and ALH84001 preserves a core field and Hellas formed after the dynamo ended on Mars, this also bounds the formation of Hellas to after 4.09 Gyr (consistent with crater counting model ages, Table 1). Regardless of the evidence from ALH84001, the lack of magnetization within Hellas strongly suggests termination of the magnetic field before the basin formed, well before the end of valley network formation. The termination of the magnetic field before the valley network activity in the Late Noachian/Early Hesperian is consistent with: (1) crater counting results, which are imprecise but suggest a potentially long gap between Hellas and the end of valley formation and (2) stratigraphy, which irrefutably demonstrates that valley formation continued after Hellas, but provides no information about the length of time between Hellas and the end of valley formation. Thus, if a magnetic dynamo was playing an important shielding role for the surface and/or atmosphere, the shield may have been removed well before water stopped playing an important geomorphic role on the martian surface (in contrast to the timeline in Jakosky and Philllips (2001)).

One observation that complicates this scenario is the apparent complex magnetization that is observed in other Mars meteorites (e.g., Collinson, 1986; Collinson et al., 1997). Because the shergottites ($\sim$180 Ma) and nakhlites ($\sim$1.3 Ga) are much younger than Hellas (e.g., McSween, 1994), this requires that when magnetization is observed in these younger meteorite samples, it was not acquired by cooling in the presence of a dynamo. Other processes that are plausible include shock magnetization (Cisowski and Fuller, 1978), acquisition from the Mars crustal field, or by contamination by terrestrial fields. The alternative is that the interpretation that Hellas and other non-magnetized basins formed in the absence of a core dynamo is wrong. Given our understanding of the spatial distribution of magnetic remanence on Mars, the post-dynamo acquisition of magnetization in these samples is the simplest explanation, consistent with a scenario where the "SNCs [were] more likely magnetized during or after impact than during the initial magmatic cooling" (Rochette et al., 2005). Recent measurements of the nakhilite Yamato 000593 support this interpretation, consistent with the absence of a global magnetic field on Mars when Yamato 000593 formed, $\sim$1.8 Gyr (Funaki et al., 2009).

Complicating the interpretation of the magnetic record further is the fact that the observed pattern of crustal magnetization is heterogeneous, with virtually all of the strong remanent crustal magnetism observed in the southern hemisphere and with only weak magnetic signatures north of the dichotomy boundary. One explanation for this heterogeneity is that hydrothermal alteration may have been critical in establishing where magnetization in the crust is observed today (Solomon et al., 2005). If hydrothermal alteration of the crust was preferentially concentrated in low-lying regions, such as the largest impact basins and northern lowlands, the lack of magnetic signatures in the large, young impact basins may be a result of this demagnization process, even if the active dynamo persisted after their formation (Solomon et al., 2005).

Alternatively, the hemispheric difference in observed crustal remanence may reflect a single-hemisphere dynamo (Stanley et al., 2008), perhaps resulting from degree-one convection (e.g., Zhong and Zuber, 2001). A hemispheric dynamo does not affect the overall constraints on timing, since Hellas and Argyre are surrounded by crust with strong remanent magnetization, so the single hemispheric dynamo should still have affected these basins. Thus, in the absence of other modifying influences, the lack of magnetization in these basins would still imply that they post-date the cessation of the magnetic field, even if the remanent magnetization was a result of a one-hemisphere dynamo.

Lower-altitude measurements of the Mars crustal magnetic field would be very useful to help test which scenario is the best explanation for the observed magnetic anomalies (Langlais and Amit, 2008).

7. Atmosphere and possible atmospheric loss

Direct constraints on both the density of the early Mars atmosphere and its loss are somewhat limited. Some invocations of higher atmospheric pressure early in Mars history have been based simply on the need to explain valley network formation (e.g., Pollack et al., 1987). Many such modeling efforts assume that surface conditions when valley networks were formed must have been above 273 K (averaged over a Mars year), and investigators have built various models with different atmospheric pressures and constituents to explore how such a requirement might be met (see, e.g., Haberle, 1998 and references therein).

Isotopic measurements provide the strongest indication that the early atmosphere was substantially denser than today, perhaps