Table 2
Time constraints on major aqueous alteration environments on Mars. The type outcrops that show aqueous alteration on Mars are modified after Murchie et al. (2009) (his Table 3) and re-ordered in approximate chronological order based on our independent evaluation of the stratigraphic constraints on these outcrops from crater counts and local relationships. Most neutral-pH alteration is conceivably quite old (before the Late Noachian), which may pre-date valley network activity, or at least the termination of VN formation. Evaporite deposits/chemical precipitates may be more common late in Mars history (Bibring et al., 2006; Murchie et al., 2009).

Aqueous environments	Type area (s)	Timing of aqueous alteration for the type area (s)
Layered phyllosilicates	Nili Fossae	*Pre-Noachian or Early Noachian*. Most of the deep crustal alteration/ phyllosilicate is interpreted to be pre-Isidis (Mustard et al., 2007, 2009; Mangold et al., 2007). Exhumation is important
	Mawrth Valles	*Pre- or Early-to-Mid Noachian*. Age constraint on phyllosilicate bedrock is from craters in the Mawrth Valles region that appear to post-date the phyllosilicate-bearing material (Michalski and Noe Dobrea, 2007). Exhumation is important (craters turned into knobs; phyllosilicates are exposed from underneath an eroded caprock)
Deep phyllosilicates	Exposures by craters in the highlands	*Pre-Noachian or Noachian, Difficult to Constrain More Specifically*. Multitude of exposures in central peaks, rims, and walls are excavated crust, so limits on timing are hard to come by. Formation/alteration was conceivably at depth (e.g., Parmentier et al., 2008)
Carbonate-bearing outcrops Serpentine-bearing outcrops	Nili Fossae	*Early-to-Mid Noachian*. Outcrops are associated with olivine units (Ehlmann et al., 2008b, 2010) that are interpreted to be directly related to the Isidis basin-forming event (e.g., Mustard et al., 2009)
Intracrater clay-sulfates	Columbus Crater	*Mid-Noachian? (Late-to-Early)*. Rim of Columbus crater has $N(5) \sim 440 \pm 179$ ($N = 6$), implying a (uncertain) Mid-Noachian age for the interbedded clay and sulfates described by Wray et al. (2009)
Phyllosilicates in intracrater fans	Jezero Crater, Holden Crater, Eberswalde Crater	*Unconstrained*. Presumably detrital. In the case of Jezero crater (e.g., Ehlmann et al., 2008a), the source of sediments includes Early (or Pre?) Noachian phyllosilicates and Mid-to-Early Noachian carbonates in the watershed
Plains sediments (chlorides)	Terra Sirenum	*Late Noachian/Early Hesperian*. Crater counting of the type area suggests has a LN/EH-boundary age for the THEMIS 'glowing' terrain (Osterloo et al., 2008). Chlorides are presumably evaporitic in origin; associated phyllosilicates may be detrital
Meridiani-type layered deposits Valles-type layered deposits	Meridiani Planum Valles Marineris ILDs	*Late Noachian to Hesperian*. These sulfate-rich deposits retain craters rather poorly. In Meridiani, sulfate plains clearly embay highlands and have an Early Hesperian crater density, which is thus a minimum age for the observed water–rock interaction. ILDs are likely Hesperian in age based on stratigraphy and crater counting (Quantin et al., 2010)
Siliceous layered deposits	Plains above VM	*Hesperian to Amazonian*. Deposits are superposed on Late Hesperian to Early Amazonian surfaces
Polar gypsum deposits	Basal unit and surrounding dunes	*Unconstrained*. Sand in dunes and basal unit; period of alteration is unbounded

environments where these formed. From Murchie et al.'s (2009) classification of distinct aqueous environments, the most likely examples of outcrops with in situ aqueous mineral formation are (1) deep phyllosilicates (common highlands exposures usually in crater rims, central peaks, or ejecta; Mustard et al., 2008); (2) layered phyllosilicates (such as Mawrth Vallis; e.g., Poulet et al., 2005); (3) certain carbonate-bearing outcrops (and, more recently discovered, serpentine-bearing outcrops; Ehlmann et al., 2010) situated with their ultramafic precursors (Ehlmann et al., 2008b), and, (4) environments with chemical precipitates or evaporites (chloride-bearing plains sediments, Osterloo et al., 2008; hydrated silica deposits, e.g., Milliken et al., 2008; layered sulfates such as those found in Meridiani Planum and Valles Marineris; e.g., Gendrin et al., 2005; sulfates interbedded with phyllosilicates on a crater interior; e.g., Wray et al., 2009). For this final class in particular, chemical sedimentation may be a result of groundwater-driven interactions with the upper crust, rather than surface precipitation, runoff, and weathering; preservation of jarosite at these locations also suggests that long-term arid conditions existed after the emplacement of these chemical sediments (Elwood Madden et al., 2004, 2009).

Despite the fact that both valley networks and phyllosilicate clays are predominantly in Noachian terrains, evidence that demonstrates that valley networks and these alteration products are characteristics of the same environment and formed at the same time is limited. Water–rock interactions that formed clays may have mostly ended by the time of the Isidis impact in Nili Fossae (Mustard et al., 2007; Mangold et al., 2007), and much of the observed neutral-pH alteration may have occurred in very ancient times (Poulet et al., 2005; see also Table 2). If this is the case, the phyllosilicates may be older than the Late Noachian to Early Hesperian valley systems where clay-bearing sediments were transported and deposited, such as in Eberswalde, Holden, and Jezero craters (e.g., Ehlmann et al., 2008a; Milliken and Bish, 2010).

Along with broad global trends, there are also differences in the character of aqueous alteration around the youngest large impact basins Isidis (Mustard et al., 2007, 2009; Mangold et al., 2007; Ehlmann et al., 2009) and Argyre (Buczkowski et al., 2010). Buczkowski et al. (2010) observe that although iron/magnesium-bearing phyllosilicates are exposed within and by the Argyre basin structure, less mineralogical diversity is present than in a comparable setting at Isidis. Buczkowski et al. (2010) interpret the alteration minerals of Argyre as primarily pre-dating the basin-forming event, which acted to expose pre-existing alteration products in the Noachian crust. The greater diversity of alteration products in the Nili Fossae area associated with Isidis requires multiple alteration events in distinct weathering environments (Ehlmann et al., 2009). This distinction is consistent with Argyre being younger than Isidis (Section 2) and with a hypothesized global decline in neutral-pH, high-water–rock ratio aqueous alteration as a function of time.