Formation of Ares Vallis (Mars) by effusions of low-viscosity lava within multiple regions of chaotic terrain

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Ares Vallis is one of the largest outflow channels on Mars, extending northward ~1500 km from the highlands of Margaritifer Terra into the Chryse impact basin. This outflow system developed primarily during the Hesperian and Amazonian as a result of voluminous effusions from the subsurface that took place within Iani Chaos, Aram Chaos, Margaritifer Chaos, and Hydaspis Chaos. Though Ares Vallis is widely interpreted as a product of catastrophic outbursts from aquifers, its basic attributes do not appear to support aqueous origins of any kind: aquifer outburst mechanisms lack meaningful solar system analogs, clear examples of fluvial or diluvial sedimentary deposits are apparently absent at Ares Vallis, and there is no mineralogical evidence along component channels and within terminal basins for extensive aqueous alteration or for deposition of thick evaporite units. Instead, as is the case at hundreds of ancient channels of the inner solar system, the nature of Ares Vallis is aligned with dry volcanic origins. Such origins are broadly consistent with the system’s relatively pristine mineralogy, the widespread mantling of component channels by lava flows, and the apparent presence of voluminous mare-style flood lavas within terminal basins. With assumed lava viscosities of 1 Pa s and temperatures of 1350 °C, discharge rates of ~97 × 10⁶ m³/s are estimated at Ares Vallis for 100-m-deep flows along channel reaches with widths of 25 km and slopes of only 0.2°. Mechanical and thermal incision are respectively estimated to be ~12.2 m/day and 2.3 m/day for 100-m-deep flows on these slopes. Formation of the main Ares Vallis channel and associated regions of chaos is likely to have required a minimum effused lava volume of ~1.8 × 10⁶ km³, and still greater lava volumes would have been necessary to form associated channel reaches including those located south of Margaritifer Chaos.

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1. Introduction

The outflow channels of Mars are mainly interpreted as products of catastrophic outbursts of water from aquifers confined by frozen ground (e.g., Carr, 1979; Baker et al., 1991; Clifford, 1993, 2017; Head et al., 2003, 2018; Rodriguez et al., 2005; Leask et al., 2006a; Komatsu, 2007; Carr and Head, 2010b, 2019; Grotzinger et al., 2011; Warner et al., 2011; Rodriguez et al., 2012; Baker et al., 2015; Larsen and Lamb, 2016; Durrant et al., 2017; Lapotre et al., 2016; Hamilton et al., 2018; Baker, 2018a; Zuber, 2018). Aqueous interpretations of the Martian outflow channels have led to inferences of enormous ancient and modern stores of water in the near subsurface, the past existence of large lakes and oceans within the terminal basins of outflow systems, and the past occurrence of major oscillations in global climate (e.g., Parker et al., 1989; Baker et al., 1991; Rotto and Tanaka, 1992; Moore et al., 1995; Gulick et al., 1997; Williams et al., 2000; Lucchitta, 2001; Parker and Currey, 2001; Jaumann et al., 2002; Carr and Head, 2010a, 2010b, 2019; Warner et al., 2013; Salvatore and Christensen, 2014a, 2014b; Barker and Bhattacharya, 2018; Citron et al., 2018; Rickman et al., 2018). Aqueous interpretations have also been used to help identify sites of possible astrobiological interest (e.g., Masursky et al., 1979; McKay, 1992, 1996; Oehler and Allen, 2012; Cabrol, 2018).

Problematically, aqueous interpretations of the Martian outflow channels do not appear to be consistent with the basic character of these systems (e.g., Leverington, 2004, 2011). For example, despite assumed sediment loads of up to 40% (e.g., Komar, 1980; Carr, 1996; Leask et al., 2006b, 2007; Carr and Head, 2015), deposits of obvious fluvial origin remain elusive along the outflow channels and within their terminal basins (e.g., Greeley et al., 1977; Burr and Parker, 2006; Ghatan and Zimbelman, 2006; Leverington, 2007, 2009a, 2018, 2019; Carling et al., 2009a; Hobbs et al., 2011; Leone, 2014, 2017; Rice and Baker, 2015). Aqueous minerals such as sulfates, carbonates, and clays are widespread on Mars, but exposures of these minerals are in many cases geographically limited and are spatially separated by apparently unaltered materials, and overall, the surface of Mars has been subjected to little alteration by water (e.g., Bibling et al., 2005, 2006; Hurowitz and McLennan, 2007; Christensen et al., 2008; Bibring and Langevin, 2008; Leverington, 2009a, 2011; Ehlmann, 2014; Leone, 2014, 2018). There
is little spatial correlation between hydrated minerals and Martian outflow channels (e.g., Birbring et al., 2006; Mangold et al., 2008; Carter et al., 2013; Wilson and Mustard, 2013; Ehlimann, 2014), despite the hypothesized occurrence of up to dozens to thousands of individual flow events for aqueous development of each outflow system (e.g., Manga, 2004; Andrews-Hanna and Phillips, 2007; Harrison and Grimm, 2008) and despite reliance of aquifer outburst models on saturation of the upper ~10 km of megaregolith by liquid and solid water over geological timescales (e.g., Baker et al., 1991; Clifford, 1993; Baker, 2001; Clifford and Parker, 2001; Wilson et al., 2009). Similarly lacking are the widespread aqueous alteration and thick evaporitic sequences that some workers expect within the terminal basins of outflow channels (e.g., Fairén et al., 2011; Mouginot et al., 2012; Pan et al., 2017). The aquifer outburst processes most commonly hypothesized to have driven formation of the outflow channels do not appear to have meaningful solar system analogs (Leverington, 2011) and may be inconsistent with the permeabilities expected of the Martian megaregolith (Marra et al., 2014).

The properties of the Martian outflow channels instead appear to be closely aligned with those of hundreds of ancient channel systems that developed on large rocky bodies of the inner solar system and that are interpreted as having developed as a result of volcanic processes (e.g., Leverington, 2004, 2011, 2014, 2019; Byrne et al., 2013). As with numerous volcanic channels preserved on the Moon, Venus, Mercury, and Earth, the Martian outflow systems show evidence for having acted as conduits for volcanic flows erupted at or near their heads, and their terminal basins are apparently mantled by extensive volcanic units including mare-styled flood basalts (e.g., Leverington, 2007, 2009a, 2011, 2018, 2019; Hopper and Leverington, 2014; Leone, 2014, 2017). Volcanic processes can realistically account for the existence and basic properties of the Martian outflow channels without the need to appeal to the past operation of exotic aqueous processes that, according to some workers, lack theoretical support and have apparently left no obvious traces (e.g., Schonfeld, 1977a, 1977b, 1979; Leverington, 2004, 2011, 2014, 2018, 2019; Hopper and Leverington, 2014; Leone, 2014, 2017, 2018; Baumgartner et al., 2015, 2017).

Ares Vallis is a prominent outflow system on Mars that extends northward from Margaritifer Terra into the northern lowlands. This outflow system is one of the largest on Mars, with typical channel widths of ~25 to 100 km and a total length in excess of 1500 km (Fig. 1). Ares Vallis has numerous attributes that seem to be inconsistent with development by aqueous processes, and instead shows substantial evidence for dry igneous origins. This paper presents a volcanic interpretation of Ares Vallis that involves the past effusion of large volumes of low-viscosity magmas at several major igneous sources associated with large regions of chaos. Estimates of possible flow conditions and total eruption volumes are presented, and potential implications for the nature of other channel systems on Mars are identified.

2. Overview of the Ares Vallis outflow system

The main Ares Vallis outflow system extends ~1500 km from the highlands of Margaritifer Terra into the lowlands of Chryse Planitia (e.g., Baker and Milton, 1974; Mutch and Saunders, 1976; Masursky et al., 1977; Carr, 1979, 1996; Baker, 1982; Lucchitta, 1982; Mars Channel Working Group, 1983; Rotto and Tanaka, 1995; Komatsu and Baker, 1997; Marchenko et al., 1998; Paci ci et al., 2009) (Figs. 1 to 4). The system heads at multiple sites of voluminous effusions from the subsurface, including those of Iani Chaos, Aram Chaos, Margaritifer Chaos, and Hydaspis Chaos (e.g., Carr, 1979; Komatsu and Baker, 1997; Tanaka, 1999; Glotch and Christensen, 2005; Rodriguez et al., 2005, 2011, 2014; Andrews-Hanna and Phillips, 2007; Harrison and Grimm, 2008; Massé et al., 2008; Coleman and Baker, 2009; Paci ci et al., 2009; Warner et al., 2009, 2010a, 2011; Neukum et al., 2010; Guallini et al., 2011; Sefton-Nash et al., 2012; Roda et al., 2014; Baioni and Tramontana, 2015; Rodriguez et al., 2015). On the basis of spatial associations with other highland features including Morava Valles and Ladon Valles, additional sources have previously been inferred for the Ares Vallis system as far south as the Arygrye impact basin (e.g., Parker, 1989; Clifford and Parker, 2001; Coleman, 2003; Grant and Parker, 2002; Pondrelli et al., 2005; Baker, 2007; Coleman and Baker, 2009; Salvatore et al., 2016; Wilson et al., 2018) (Figs. 1 and 2). The total eroded volume of the main Ares Vallis channel, not including related chaotic terrain, is estimated to be ~10^5 km^3 (Carr, 2012). The kilometer-scale longitudinal slopes typical of component channels are well under 1° (Fig. 3).

As with the other circum-Chryse outflow channels (e.g., Tanaka, 1986; Warner et al., 2009; Chapman et al., 2010a, 2010b), the Ares Vallis system is expected to have developed as a result of multiple flow episodes that took place primarily in the Hesperian but that also extended well into the Amazonian (Rotto and Tanaka, 1995; Robinson et al., 1996; Nelson and Greeley, 1999; Warner et al., 2009, 2010a; Neukum et al., 2010; Rodriguez et al., 2014, 2015). Early system development likely involved flow from sources associated with Iani Chaos and Margaritifer Chaos in the Late Noachian to Early Hesperian, ~3.6 Ga before present, but additional substantial development of the system is inferred to have involved these and other sources for time frames as recent as the Early Amazonian, ~2.5 Ga before present (Warner et al., 2009, 2010a; Roda et al., 2014). Less major periods of system development are likely to have occurred over intervals that collectively span much of the Amazonian Period (e.g., Neukum et al., 2010; Rodriguez et al., 2014, 2015).

The main Ares Vallis channel extends northward from Iani Chaos and has an approximate average width of 25 km, but the system’s overall width exceeds 100 km where the main channel divides into multiple conduits and enters Chryse Planitia (Masursky et al., 1977; Carr, 1979, 1980; Mars Channel Working Group, 1983; Komatsu and Baker, 1997; Costard and Baker, 2001; Baker, 2002) (Figs. 5 to 7). Within this basin, Ares Vallis is truncated by channels of the Tiu and Simud systems, which continue northward into Acidalia Planitia. Along the main Ares Vallis channel, floors are generally ~50 m to 2 km below adjacent uplands (e.g., Warner et al., 2009). Some of the most shallow channel reaches are located at higher elevations and are likely to have formed in earlier stages of system development, prior to the incision of narrower and deeper conduits (e.g., Nelson and Greeley, 1999; Warner et al., 2009, 2010a).

As with other large Martian outflow systems (e.g., Baker, 1982; Carr, 1996), the component channels of Ares Vallis are variously characterized by the presence of streamlined erosional residuals, longitudinal grooves, inner channels, hanging valleys, cataarcs, and patches of chaotic terrain (e.g., Masursky et al., 1977; Baker and Kochel, 1978; Lucchitta, 1982, 2001; Komar, 1983; Mars Channel Working Group, 1983; Komatsu and Baker, 1997; Parker and Rice Jr., 1997; Nelson and Greeley, 1999; Costard and Baker, 2001; Costard et al., 2007; Warner et al., 2009, 2010b; Paci ci et al., 2009; Moscardelli and Wood, 2011; Rodriguez et al., 2011, 2015) (Figs. 5 to 10). On the basis of widespread associations with mafic reflectance properties, high thermal inertias, and the presence of geomorphic features such as wrinkle ridges and flow fronts, volcanic mantling units are interpreted to exist along much of the Ares Vallis system (e.g., Robinson et al., 1996; Salvatore et al., 2010, 2016; Ody et al., 2011, 2012a, 2012b; Wilson and Mustard, 2013; Leone, 2014) (Fig. 10). Fluvial sedimentary features such as depositional bars and giant current ripples have been proposed, but clear examples have proven difficult to identify (e.g., Komatsu and Baker, 1997; Rice and Baker, 2015). Regions of chaos show the signs of disturbance and subsidence typical of Martian chaotic terrain located elsewhere, and contain features such as flat-topped plateaus, knobby remnants of highland terrain, and mantling units including interior layered deposits (ILDs) (e.g., Glotch and Christensen, 2005; Massé et al., 2008; Guallini et al., 2011; Warner et al., 2011; Sefton-Nash et al., 2012; Roda et al., 2014; Baioni and Tramontana, 2015) (Fig. 9). South of the main Ares Vallis system, the Uzboi–Ladon region contains fan deposits, including the
Eberswalde deposit, that are interpreted by many workers as possible lacustrine deltas that formed in association with fluvial activity during the Noachian Period and possibly as recently as the Amazonian Period (e.g., Grant and Parker, 2002; Malin and Edgett, 2003; Bhattacharya et al., 2005; Moore and Howard, 2006; Mustard et al., 2008; Pondrelli et al., 2008; Grant and Wilson, 2011; Irwin et al., 2015).

The main Ares Vallis channel terminates within the Chryse impact basin, though related channels continue northward into Acidalia Planitia (e.g., Masursky et al., 1977; Rotto and Tanaka, 1995; Komatsu and Baker, 1997; Tanaka, 1997; Golombek et al., 1997a, 1999; Tanaka et al., 2005) (Fig. 1). The Chryse basin is widely mantled by thick wrinkle-ridged volcanic units that have properties similar to those of the lunar maria (e.g., Greeley et al., 1977; Scott and Tanaka, 1986; Rotto and Tanaka, 1995; Head III et al., 2002; Pan et al., 2017). Truncation of Ares Vallis channels by those of the Tiu and Simud systems suggests that major development of Ares Vallis occurred prior to that of these systems (e.g., Costard and Baker, 2001; Ivanov and Head, 2001). Locations of ancient oceanic shorelines have been proposed for Chryse Planitia (e.g., Parker et al., 1993; Clifford and Parker, 2001; Ivanov and Head, 2001; Rodriguez et al., 2016; Citron et al., 2018), but clear evidence for the past ponding of water and development of related sedimentary deposits is absent here and within the other basins that form the northern lowlands (e.g., Masursky et al., 1977; Malin and Edgett, 1999; Chatan and Zimbelman, 2006; Leverington, 2007, 2018; Pretlow, 2013; Leone, 2014, 2017; Pan et al., 2017). Nevertheless, surface units of the Chryse and Acidalia basins have previously been

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**Fig. 1.** The main Ares Vallis outflow system extends northward into Chryse Planitia from several source regions including Hydaspis Chaos, Aram Chaos, Iani Chaos, and Margaritifer Chaos. Tiu Valles truncates Ares Vallis and extends further north into Acidalia Planitia. The Ares Vallis system is associated with sources located further to the south such as those that formed Uzboi Vallis and Ladon Valles. The areas depicted in Figs. 2, 3, and 4 are indicated. Equirectangular projection. Mars Orbiter Laser Altimeter (MOLA) data after Smith et al. (2003).
interpreted as possible sedimentary materials deposited during formation of Ares Vallis and the other circum-Chryse outflow channels (e.g., Rotto and Tanaka, 1995; Komatsu and Baker, 1997; Rice Jr. and Edgett, 1997; Tanaka, 1997; Marchenko et al., 1998; Wilson et al., 2004; Kleinhans, 2005; Tanaka et al., 2005).

The Mars Pathfinder landing site, located at the mouth of Ares Vallis in Chryse Planitia (Fig. 7), was chosen in part so that the diverse range of highland materials transported during hypothesized aqueous flooding at Ares Vallis could be examined at a single location (e.g., Crumpler, 1997; Golombek et al., 1997a, 1997b, 1999; Mars Pathfinder Rover...
Topographic relief near the Pathfinder landing site is not uniquely diagnostic of fluvial landforms, but some local deposits have previously been interpreted as possible flood-related sediments, including materials in the lee of topographic features, various conglomerate and gravel units, and the extensive boulder fields that mantle the area (e.g., Mars Pathfinder Rover Team, 1997; Smith et al., 1997; Hobbs et al., 2011). Water and carbon were not detected in the soils of the Pathfinder landing site (e.g., Foley et al., 2003), and rocks examined by the Alpha Proton X-ray Spectrometer of the Sojourner rover consist of minimally-altered igneous materials (e.g., Smith et al., 1997; Wänke et al., 2001; Foley et al., 2003, 2008), including basalts and possibly basaltic andesites (e.g., Brückner et al., 2003; Farrand et al., 2008). Overall, weathering and erosion rates at the Pathfinder landing site have been extraordinarily low since the time of deposition of local units, up to ~3.5 Ga before present, implying the long-term persistence of dry and desiccating conditions here (e.g., Golombek and Bridges, 2000; Farrand et al., 2008).

Lithological and mineralogical mapping has been conducted for the Ares Vallis region using data generated from Mars orbit by instruments including the Thermal Emission Imaging System (THEMIS), Thermal Emission Spectrometer (TES), Observatoire pour la Minéralogie, l’Eau, les Glaces et l’Activité (OMEGA), and Compact Reconnaissance Imaging Spectrometer for Mars (CRISM). Crustal units exposed in the walls of Ares Vallis and along the surfaces of component channels, including mantling units that extend well into the northern lowlands, are predominantly mafic in composition (e.g., Rogers et al., 2005; Salvatore et al., 2010; Ody et al., 2011, 2012a, 2012b; Pan et al., 2017). Olivine-rich igneous units (consisting of up to ~25% olivine or more) exist along the floors and inner margins of parts of Ares Vallis, along parts of the upland plateaus adjacent to the channel system, within Aram Chaos and Iani Chaos, and at and beyond the mouth of Ares Vallis (e.g., Rogers et al., 2005; Koepfen and Hamilton, 2008; Salvatore et al., 2010, 2016; Leverington, 2011; Ody et al., 2011, 2012a, 2012b, 2013; Wilson and Mustard, 2013) (Fig. 11). The youngest olivine-rich units here are of Hesperian and Amazonian age, and the oldest such units form the Noachian uplands into which Ares Vallis was incised (e.g., Rogers et al., 2005; Wilson and Mustard, 2013). Within the Margaritifer Terra region, localized exposures of hydrated minerals including Fe-Mg-smectite clays have been identified, as have olivine-bearing basalts (e.g., Salvatore et al., 2016; Thomas et al., 2017). Exposures of hematite, phyllosilicates, sulfates, and carbonates exist within chaotic terrain associated with Ares Vallis, including at Aram Chaos and Iani Chaos, confirming the past aqueous alteration of geological materials here (e.g., Newsom et al., 2001; Glotch and Christensen, 2005; Glotch and Rogers, 2007; Massé et al., 2008; Sefton-Nash et al., 2012; Baioni and Tramontana, 2015; Thomas et al., 2017; Amador et al., 2018). However, despite the presence of hydrated minerals along isolated parts of Ares Vallis, there is little correlation between the spatial distribution of hydrated minerals and the spatial extent of this system or other Martian outflow channels, and the overall level of aqueous alteration here and at the other outflow channels is remarkably low (e.g., Rogers et al., 2005; Bibring et al., 2006; Mangold et al., 2008; Salvatore et al., 2010; Carter et al., 2013; Wilson and Mustard, 2013; Ehlmann, 2014; Amador et al., 2018). As in other regions of Mars, there is no special geographic correlation between hydrous mineralization and valley networks in the Ares Vallis region (e.g., Bibring et al., 2006; Ehlmann, 2014; Kaufman et al., 2019).
interaction of lava with surface snow and ice have been proposed for other Martian outflow systems (e.g., Cassanelli and Head, 2018, 2019).

Among aqueous hypotheses, groundwater outbursts have been favored for development of Ares Vallis, as well as for development of many other large Martian outflow systems, since alternative aqueous processes (involving e.g. the pooling and sudden release of meltwaters at system heads) are incapable of generating the floodwater volumes and discharge rates necessary for channel development (e.g., Carr, 1979, 2012; Mars Channel Working Group, 1983; Clifford and Parker, 2001; Andrews-Hanna and Phillips, 2007). Channel development at Ares Vallis is hypothesized by some workers to have possibly taken place beneath local or regional ice cover (e.g., Pacifi et al., 2009; Roda et al., 2014), and the most distal reaches of the system are widely expected to have been periodically subjected to submarine conditions related to the accumulation of floodwaters in terminal lakes or oceans (e.g., Parker et al., 1993; Ivanov and Head, 2001; Moscardelli and Wood, 2011). Channel incision and the formation of features such as cataracts are predicted to have been products of processes similar to those of terrestrial megafloods including those that formed the Channeled Scabland of Washington (e.g., Baker and Milton, 1974; Baker, 1982, 2009; Carling et al., 2009b; Warner et al., 2010a; Lamb et al., 2014; Larsen and Lamb, 2016; Lapotre et al., 2016).

The large areas of chaos at which Ares Vallis commences have been interpreted as the primary sites from which groundwater was catastrophically released during channel formation (e.g., Glotch and Christensen, 2005; Andrews-Hanna and Phillips, 2007; Harrison and Grimm, 2008; Warner et al., 2011), with some workers previously hypothesizing that these types of outbursts might have occurred in conjunction with explosive processes such as those related to the dissociation of gas hydrate (e.g., Komatsu et al., 2000; Max and Clifford, 2001). Some landforms at Ares Vallis are thought to have been formed by aqueous processes that may have been directly or indirectly related to hypothesized outbursts. For example, areas of irregular topography along Ares Vallis and within associated regions of chaos have been attributed to the possible development of thermokarst terrain during or after channel formation (e.g., Andrews-Hanna and Phillips, 2007; Warner et al., 2009, 2010b; Pacifi et al., 2009; Baioni and Tramontana, 2015). Some topographic basins of the Ares Vallis system, including impact craters and regions of chaos, are inferred to have been the sites of ancient lakes (e.g., Cabrol and Grin, 2001, 2002; Newsom et al., 2001; Glotch and Christensen, 2005; Guallini et al., 2011; Roda et al., 2014). The hydrous alteration of some chaos materials, including particular sections of interior layered deposits, has led to inferences of their past interaction with groundwater or with pooled surface waters (e.g., Glotch and Christensen, 2005; Sefton-Nash et al., 2012; Baioni and Tramontana, 2015).

Estimates of maximum discharge rates at Ares Vallis range between $-10^6$ and $5 \times 10^7$ m$^3$/s, with assumed water depths of $-20$ to 100 m (e.g., Masursky et al., 1977; Carr, 1979; Komatsu and Baker, 1997; Smith et al., 1997, 1998). Each source region is expected to have had its own discharge history driven by local igneous or impact processes. For example, a total of $-6$ to 49 floods, with discharges of $-10^6$ to $10^7$ m$^3$/s, are predicted to have developed as a result of aquifer effusions at Iani Chaos, with individual flood volumes of up to $-5000$ km$^3$ and with at least $-44$ years between these floods (Andrews-Hanna and Phillips, 2007). Under assumptions of average near-surface permeabilities of $-10^{-9}$ m$^2$, the modeling of outburst mechanisms has suggested the past occurrence of a minimum of $-160$ to 660 separate aqueous flood events at Ares Vallis (Harrison and Grimm, 2008). More generally, large outflow systems on Mars are expected to have possibly required up to thousands of flood events for development of each system (e.g., Andrews-Hanna and Phillips, 2007; Harrison and Grimm, 2008).

### 3. Aqueous interpretations of Ares Vallis

The Ares Vallis system is widely interpreted as having been formed by numerous catastrophic aqueous floods in the Hesperian and Amazonian (e.g., Carr, 1974; Masursky et al., 1977; Komar, 1983; Komatsu and Baker, 1997; Marchenko et al., 1998; Golombek et al., 1997a, 1999; Pacifi et al., 2009; Warner et al., 2009; Wilson et al., 2018). These floods are predicted to have primarily involved outbursts of groundwater resulting from the breaching of a globally-continuous cryosphere by igneous or impact processes (e.g., Carr, 1979; Baker et al., 1991; Clifford, 1993; Baker, 2001; Clifford and Parker, 2001; Glotch and Christensen, 2005; Andrews-Hanna and Phillips, 2007; Harrison and Grimm, 2008; Carr and Head, 2010a, 2010b; Warner et al., 2010a, 2011; Head et al., 2018). Some models of channel formation have also involved the hypothesized formation and later release of meltwater lakes (e.g., Masursky et al., 1977; Roda et al., 2014), the emplacement of debris flows (e.g., Chapman and Kargel, 1999; Tanaka et al., 2001), and/or the flow of glaciers (e.g., Lucchitta, 1982, 2001; Robinson et al., 1996; Chapman and Kargel, 1999; Costard and Baker, 2001; Pacifi et al., 2009). Flood models involving the production of melt by the

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**Fig. 4.** Geological map of the Ares Vallis region (Tanaka et al., 2014). Unit names: eNh, Early Noachian highland unit; mNh, Middle Noachian highland unit; Nh, Late Noachian highland unit; Nhu, Noachian highland undivided unit; HNt, Hesperian and Noachian Early Noachian highland unit; mNh, Middle Noachian highland unit; lNh, Late Noachian highland unit; AH, Amazonian highland unit; H, Hesperian transition unit; Hto, Hesperian transition out; Nhu, Noachian highland undivided unit; HNt, Hesperian and Noachian transition unit; Hto, Hesperian transition outflow unit; Ht, Hesperian transition unit; Ht, Late Hesperian transition unit; AHi, Amazonian and Hesperian impact unit. Robinson projection. The location of the depicted area is given in Fig. 1.
4. A volcanic interpretation of the Ares Vallis system

The basic attributes of the Ares Vallis system are arguably not consistent with its development by large aqueous outbursts. Though fluvial, glacial, lacustrine, and oceanic sedimentary deposits continue to be proposed for component channels and basins (e.g., Komatsu and Baker, 1997; Costard and Baker, 2001; Lucchitta, 2001; Cabrol and Grin, 2002; Costard et al., 2007; Pacifici et al., 2009; Warner et al., 2009; Moscardelli and Wood, 2011; Rodriguez et al., 2014; Salvatore and Christensen, 2014a, 2014b), clear examples of such features have proven difficult to identify at this or any other Martian outflow system (e.g., Greeley et al., 1977; Burr and Parker, 2006; Ghatan and Zimbelman, 2006; Leverington, 2007, 2009a, 2018; Carling et al., 2009a; Hobbs et al., 2011; Leone, 2014, 2017; Rice and Baker, 2015).

There is much yet to be learned about the detailed mineralogy of the Martian surface and subsurface, in part because of the paucity of ground truth data collected by landers and rovers on the surface. Nevertheless, as is the case at all other outflow channels on Mars, there is no evidence for extensive aqueous alteration of Ares Vallis, and the system is instead widely characterized by pristine igneous mineralogy (Bibring et al., 2006; Mangold et al., 2008; Carter et al., 2013; Wilson and Mustard, 2013; Ehlmann, 2014). The upper ~10 km of Martian regolith have been hypothesized to be highly porous and permeable and to have hosted large volumes of water over geological timescales, dynamically exchanging water with the surface at numerous points in the history of the planet (e.g., Baker et al., 1991; Clifford, 1993; Baker, 2001; Clifford and Parker, 2001; Wilson et al., 2009). Yet, the apparent preservation at Ares Vallis of large volumes of pristine olivine-rich materials, including those of the Noachian units that form the inner walls of component channels (e.g., Rogers et al., 2005; Salvatore et al., 2010, 2016; Ody et al., 2011, 2012a, 2012b, 2013; Wilson and Mustard, 2013), is arguably inconsistent with the past occurrence of dozens to thousands of aqueous outburst floods, and with the purported long-term existence of water in highly porous and permeable aquifers later exposed by channel incision (e.g., Leverington, 2009a, 2011, 2019). South of the main Ares Vallis system, the level of aqueous alteration along reaches such as the Uzboi-Ladon segment (e.g., Thomas et al., 2017) is similarly very low for channels purportedly formed by rainfall and/or outbursts from extensive aquifers. Depending on environmental conditions, Martian basalts subjected to wet conditions would become substantially altered over timescales of years to millennia (e.g., Oze and Sharma, 2007; Hausrath et al., 2008), producing materials characterized by distinct aqueous-absorption features in reflectance spectra (e.g., Noe Dobrea et al., 2003; Pommerol and Schmitt, 2008; Leverington, 2009b; Leverington and Moon, 2012; Leverington and Schindler, 2018; Wang et al., 2018). Thus, the existence at the outflow channels of vast tracts of little-altered materials is very difficult to reconcile with hypothesized channel development by aqueous floodwaters effused from enormous perennial aquifers (e.g., Leverington, 2009a, 2011, 2019; Leone, 2014, 2018).

Though alternative interpretations have previously been suggested (e.g., Salvatore and Christensen, 2014a), clear evidence for the pervasive hydrous alteration of geological materials exposed within the Chryse basin and other northern basins hypothesized to have held large Martian water bodies (e.g., Leverington, 2011), and for the thick sequences of evaporite minerals that some workers expect of the sites of former lakes and oceans (e.g., Leverington, 2011; see also e.g. Hills, 1984; Krijgsman et al., 1999; Zavialov et al., 2003), is missing in mineralogical maps generated using images acquired from orbit (e.g., Bibring et al., 2006; Christensen et al., 2008; Pan et al., 2017).
Consistent with this orbital view, the mineralogy of the Pathfinder landing site at the mouth of Ares Vallis is known to have been little altered by water (Smith et al., 1997; Golombek and Bridges, 2000; Wänke et al., 2001; Foley et al., 2003, 2008; Brückner et al., 2003; Farrand et al., 2008).

Beyond inconsistencies between the expected and actual mineralogy of the Ares Vallis system, the catastrophic release of groundwater pressurized by the downward propagation of a freezing front (e.g., Carr, 1979; Baker, 2001; Clifford and Parker, 2001; Carr and Head, 2010a, 2010b; Head et al., 2018) is a very different process from the dam failures that drove the largest known terrestrial floods (e.g., Bretz, 1969; Leverington et al., 2000, 2002; Leverington and Teller, 2003), and is yet to be validated as a realistic mechanism for development of the Martian outflow channels (e.g., Hanna and Phillips, 2005; Marra et al., 2014). Indeed, though alternative perspectives exist (e.g., Manga, 2004; Andrews-Hanna and Phillips, 2007), recent work suggests that expected megaregolith porosities are insufficient for the formation of large outflow channels without the generation of extraordinarily large chambers in the subsurface through crustal flexure (Marra et al., 2014), a process normally associated with the high lava pressures of igneous plumbing systems (Leverington, 2011, 2019).

The subsidence of regions of chaos at Martian outflow channels has previously been attributed to processes such as excavation by aqueous outbursts, depressurization of aquifers, and the melting of subsurface ice (e.g., Carr, 1996; Rodriguez et al., 2005; Leask et al., 2006a). Processes involving outbursts from pressurized aquifers are arguably not consistent with the areas of anhydrous mineralogy in chaos regions. The melting of large volumes of ground ice appears to similarly be incongruous with exposed mineralogy and, in addition, may not be consistent with expected ice volumes at depth. Both the formation and melting of ice in the subsurface would presumably have involved the subsurface existence of water in the liquid state, and this water should have had the capacity to chemically alter the geological materials with which it was in contact prior to freezing and after melting; furthermore, the adsorbed and other water that can coexist with frozen geological units (e.g., Patterson and Smith, 1981; Williams and Smith, 1989) might have similarly allowed for the alteration of materials with which it was in contact. The thermokarst-like subsidence of hundreds of vertical meters would arguably be expected to involve massive ice rather than pore ice, the latter of which generally does not involve substantial subsidence during melting (e.g., Smith, 1984; Williams and Smith, 1989). This massive ice could conceivably occur in the form of relict ice (i.e., buried ice; e.g., Zegers et al., 2010) or segregated ice (which would be expected to form relatively small ice bodies in geological materials located very near the surface where associated heave can be accommodated during freezing; e.g., Murton et al., 2006). There is no special reason to expect that substantial volumes of buried glacial ice have existed in regions of chaos, nor is there reason to expect that enormous bodies of segregated ice formed at considerable depth within bedrock units such as the Noachian-aged materials widely exposed along the margins of many Martian outflow channels, chasmata, and chaos regions; formation of such segregated ice would have required heave of up to hundreds of meters during formation, for which there is no apparent evidence. If ice were present at all within the bedrock units of chaos regions, it would instead be expected to predominantly take the form of pore ice, and its melting would not generally be expected to produce the large amounts of subsidence seen at chaos regions since its original development would not have produced substantial amounts of ground heave.

Fig. 6. Toward its northern reaches, the main channel of the Ares Vallis outflow system generally shallows and increases in width. The location of the depicted area is given in Fig. 2. Associated areas depicted in Fig. 10 are indicated. THEMIS daytime infrared mosaic courtesy of Arizona State University.
In contrast to aqueous mechanisms, dry volcanic processes can readily account for the formation and basic attributes of the Ares Vallis outflow system. Though exotic by modern terrestrial standards (e.g., Leverington, 2014, 2018), such processes resulted in the development of hundreds of volcanic channels on rocky bodies of the inner solar system, including bodies with anhydrous surfaces such as the Moon, Mercury, and Venus (e.g., Greeley, 1971; Gornitz, 1973; Carr, 1974; Wilhelms, 1987; Baker et al., 1992, 1997; Head III et al., 1992; Head et al., 2011; Komatsu et al., 1993; Komatsu, 2007; Hurwitz et al., 2013a; Byrne et al., 2013; Williams et al., 2001, 2011; Baker et al., 2015; Roberts and Gregg, 2019). Under appropriate eruptive conditions, low-viscosity lavas have a clear capacity for thermomechanical erosion that can result in the incision of large channel systems (e.g., Peterson and Swanson, 1974; Hulme and Fielder, 1977; Hulme, 1982; Huppert et al., 1984; Lesher and Campbell, 1993; Greeley et al., 1998; Williams et al., 2000, 2011; Barnes, 2006; Houé et al., 2008, 2012; Jaeger et al., 2010; Hurwitz et al., 2012, 2013b; Stockstill-Cahill et al., 2012; Gole et al., 2013; Baumberger et al., 2015, 2017; Staud et al., 2016, 2017; Lesher, 2017; Vetere et al., 2019), including the development of scabland features such as cataracts (e.g., Dundas and Keszthelyi, 2014) and streamlined erosional residuals (e.g., Baker et al., 1992, 1997; Leverington, 2004). Large volumes of lava erupted at high rates of effusion and with low viscosities should be emplaced rapidly and with high levels of turbulence (e.g., Jaeger et al., 2010; Dundas and Keszthelyi, 2014; Cataldo et al., 2015; Baumberger et al., 2017; Vetere et al., 2019), allowing for the development of channel systems in part through the filling and overflow of local topographic basins. Lava levels within individual basins could conceivably become reduced over time as a result of processes such as outlet incision, loss of volatiles from lava, contraction during lava solidification, and drainback into magmatic plumbing systems (e.g., Leverington, 2009a).

The capacity of silicate lavas for the erosional development of channels is substantially a function of viscosity (e.g., Hulme, 1982; Williams et al., 2001, 2011; Jaeger et al., 2010; Leverington, 2014, 2018, 2019; Hopper and Leverington, 2014; Dundas and Keszthelyi, 2014), which varies with factors including silica content, temperature, and the abundances of crystals, bubbles, and xenoliths (e.g., Williams et al., 1998, 2000; Hurwitz et al., 2012; Chevrel et al., 2013; Robert et al., 2014; Cataldo et al., 2015; Takeuchi, 2015; Vetere et al., 2017, 2019; Pistone et al., 2016; Vona et al., 2016; Lesher, 2017; Klein et al., 2018). In contrast with the ~50–5000 Pa s typical of the minimum viscosities of modern silicate lavas on Earth (e.g., Shaw et al., 1968; Murase and Mcbirney, 1973; Self et al., 1997), mafic or ultramafic lavas involved in the formation of ancient volcanic plains and large channel systems had minimum viscosities at least as low as ~0.5 Pa s on the Moon (e.g., Murase and Mcbirney, 1970, 1973; Weill et al., 1971), ~4.5–7.5 Pa s on Venus (e.g., Kargel et al., 1993), ~0.02–14.2 Pa s on Mercury (e.g., Stockstill-Cahill et al., 2012; Byrne et al., 2013; Vetere et al., 2017), ~0.1–1 Pa s on the Earth (e.g., Williams et al., 2001, 2011; Lesher, 2017), and ~0.5 Pa s on Mars (e.g., Chevrel et al., 2014). Since lava temperatures decrease with distance from eruptive centers as a result of radiative and conductive cooling as well as substrate assimilation, the overall capacity for channel incision should tend to be greatest along reaches that are relatively close to eruptive centers and least along the most distal reaches of channel systems (e.g., Williams et al., 2001, 2011; Jaeger et al., 2010; Hurwitz et al., 2012; Cataldo et al., 2015; Baumberger et al., 2017; Leverington, 2018).
As is evident at the volcanic plains that form the floors of some lunar craters (e.g., Schultz, 1976; Jozwiak et al., 2012; Wilson and Head, 2018), igneous intrusions can fracture and undermine geological units in a manner superficially similar to that seen in Martian regions of chaos (Leverington, 2019), and the subsidence that helps to form chaotic terrain on Mars is hypothesized here to be a product of igneous processes including: 1) the fracturing and melting of country rock by igneous intrusions; and 2) magma drainback into plumbing systems during the latter stages of eruptions. Chaos regions on Mars are in numerous cases associated with features such as cones and flows (e.g., Meresse et al., 2008; Berman and Rodriguez, 2016; Berman et al., 2017, 2018; Leverington, 2019), landform types that are not uniquely the product of volcanic processes (e.g., Farrand et al., 2005; Skinner and Mazzini, 2009; Komatsu et al., 2016) but are consistent with volcanic interpretations. The Aram Chaos region contains candidate igneous source features (Fig. 9d) that are similar in character to the large updomed plates of lava present near the head of Kasei Valles, the largest outflow channel on Mars (Chapman et al., 2010a, 2010b; Leverington, 2018). Component channels of Ares Vallis are widely mantled by units interpreted by many workers as lava flows (e.g., Robinson et al., 1996; Salvatore et al., 2010; Ody et al., 2011; Wilson and Mustard, 2013; Salvatore et al., 2016) (e.g., Fig. 10), and the system terminates in the Chryse impact basin, which many workers interpret as being covered by wrinkle-ridged mare-style flows (e.g., Carr et al., 1976; Greeley et al., 1977; Scott and Tanaka, 1986; Rotto and Tanaka, 1995; Frey et al., 2002; Head III et al., 2002; Salvatore et al., 2010; Ody et al., 2012a, 2012b; Leone, 2014; Pan et al., 2017). The existence of what must be relatively young volcanic mantles along parts of Ares Vallis and within its terminal basin does not itself preclude the possible existence of fluvial deposits along Ares Vallis (e.g., Salvatore et al., 2016), and does not preclude formation of the main channel system by the past operation of aqueous processes. Nevertheless, as at other Martian outflow channels (e.g., Leverington, 2004, 2011, 2014), the overall mineralogical and geomorphological characteristics of the Ares Vallis system are consistent with dry volcanic origins.

5. Constraints on the effusive volcanic eruptions that formed Ares Vallis

If the Ares Vallis system was formed by the eruption of voluminous low-viscosity lava flows, what flow conditions, incision rates, and total lava volumes might have been involved? The precise manner in which low-viscosity lava flows are emplaced and incise into substrates is not yet well understood (e.g., Dundas and Keszthelyi, 2014; Cataldo et al., 2015; Baumgartner et al., 2017), partly because the most voluminous examples of these types of flows were erupted in much earlier stages of solar system history when the internal temperatures of large rocky bodies were considerably greater than at present (Leverington, 2014). Nevertheless, useful quantitative models are available for constraining basic flow parameters including rates of mechanical incision (involving the removal of substrates by kinetic energy) and thermal incision (involving the melting of substrates). This study utilized flow and incision equations previously applied to the study of lunar and Martian volcanic channels (Hurwitz et al., 2010, 2012) and derived from quantitative relationships described in numerous earlier volcanic and fluvial studies (e.g., Hulme, 1973; Huppert and Sparks, 1985; Williams et al., 1998, 2000; Keszthelyi and Self, 1998; Sklar and Dietrich, 1998). The specific software implementation of the flow model was previously...
applied in several recent studies of terrestrial and Martian volcanic channels (Leverington, 2014, 2018, 2019; Hopper and Leverington, 2014).

Mechanical incision associated with the flow of lava is given by (Sklar and Dietrich, 1998; Hurwitz et al., 2010, 2012):

$$\frac{d}{dt}\left[h_{\text{chan}}\right]_{\text{mechanical}} = K \rho g Q_w \sin \alpha$$

where $K$ designates the erodibility of substrates in Pa$^{-1}$, $\rho$ is lava density, $g$ is gravitational acceleration, $Q_w$ is the discharge of lava per meter of channel width (given in m$^2$/s), and $\alpha$ is the channel slope in degrees. The physical processes involved in mechanical lava erosion are not well understood at present, and therefore the results generated using Eq. (1) should be treated with caution (Dundas and Keszthelyi, 2014). The range that defines appropriate values of the erodibility constant ($K$) is poorly constrained for lava, and it’s not yet clear that the plucking and abrasion processes of lava are sufficiently similar to those of water to allow for the use of this form of mechanical erosion law in the study of channelized lavas (Dundas and Keszthelyi, 2014).

For slopes of $< 10^\circ$, the velocity of lava is given by (Hurwitz et al., 2010, 2012):

$$v_{\text{lava}} = \frac{g d_{\text{lava}} \sin \alpha}{C_f}$$

where $g$ is gravitational acceleration, $d_{\text{lava}}$ is lava depth, $\alpha$ is the channel slope in degrees, and $C_f$ is the friction factor, which is given by (Keszthelyi and Self, 1998):

$$C_f = \left(\frac{1}{32}\right) \left[\log_{10} \left(\frac{2Re + 800}{41}\right)^{0.92}\right]^{-2}$$

The Reynolds number ($Re$) is given by:

$$Re = \frac{\rho v d_{\text{lava}}}{\mu}$$

where $\rho$ is the density of magma, $v$ is the velocity of magma, $d_{\text{lava}}$ is the lava depth, $\alpha$ is the channel slope in degrees, and $\mu$ is the dynamic viscosity of lava.

Thermal incision associated with the flow of lava is given by (Hulme, 1973; Huppert and Sparks, 1985; Williams et al., 1998, 2000; Hurwitz et al., 2012):

$$\frac{d}{dt}h_{\text{chan}} = h_f(T - T_{mg})$$

where $h_f$ is the coefficient of heat transfer, $T$ is the lava temperature, $T_{mg}$ is the temperature at which the substrate materials melt, and $E_{mg}$ is the...
energy required to melt the substrate materials (Hulme, 1973; Huppert and Sparks, 1985; Williams et al., 1998, 2000):

\[ E_{mg} = \rho_g c_g (T_{mg} - T_g) + f_{mg} L_g \]

where \( \rho_g \) is the density of the substrate materials, \( c_g \) is the specific heat of the substrate materials, \( T_{mg} \) is the temperature at which the substrate materials melt, \( T_g \) is the initial temperature of the substrate materials, \( f_{mg} \) is the fraction of the substrate materials that must be melted prior to mobilization, \( L_g \) is the latent heat of fusion of the substrate materials, and \( h_T \) is the coefficient of heat transfer, which is given by (Hulme, 1973):

\[ h_T = \frac{0.017 k R e^3}{Pr^2 d_{lava}^4} \]

where \( k \) is the thermal conductivity of lava [2.16 – (0.0013 T)] (Williams et al., 1998), \( Re \) is the Reynolds number, \( Pr \) is the Prandtl number \([\rho c_d \mu/k]\), and \( d_{lava} \) is the lava depth.

The above equations are functions of each other and are solved iteratively until variables converge upon specific values. Except with regard to certain flow depths and channel widths, the parameters used to model flow conditions are the same as those utilized in recent studies (Leverington, 2018, 2019), and are given in Table 1. Maximum lava flow depths at large volcanic channels of the inner solar system are expected to have typically been at least tens of meters and are likely to have been as great as hundreds of meters (e.g., Jaeger et al., 2010; Byrne et al., 2013; Dundas and Keszthelyi, 2014; Leverington, 2014, 2018, 2019; Hopper and Leverington, 2014). Water depths of up to ~100 m have been previously hypothesized for Ares Vallis (e.g., Masursky et al., 1977), and lava flow depths of 50, 75, and 100 m were therefore considered in flow modeling in the present study (extending the 25 and 50 m results presented in Leverington, 2019). Formation of large volcanic channels on rocky bodies of the inner solar system is expected to have involved minimum lava viscosities at least as low as ~0.01 to 10 Pa (e.g., Hulme, 1982; Kargel et al., 1993; Lesher and Campbell, 1993; Williams et al., 2000, 2011; Barnes, 2006; Houlé et al., 2008, 2012; Jaeger et al., 2010; Hurwitz et al., 2012, 2013b; Stockstill-Cahill et al., 2012; Gole et al., 2013; Baumgartner et al., 2015, 2017; Staude et al., 2016, 2017; Lesher, 2017), and this study utilized an intermediate lava viscosity of 1 Pa s that is close to the 0.5 Pa s viscosities known for lunar basalts recovered by the Apollo program (e.g., Murase and McBirney, 1970, 1973; Weill et al., 1971) and for Martian basalts examined geochemically by the Spirit rover at the mouth of the Ma’adim Vallis channel system (Chevrel et al., 2014). The temperatures of ancient maﬁc and ultramaﬁc lavas of relevance to the past development of large volcanic channels are likely to have approached or exceeded 1400 °C at the time of eruption (e.g., Burns and Fisher, 1990; Nisbet et al., 1993; Grove and Parman, 2004; Filiberto et al., 2008; Williams et al., 2011; Baumgartner et al., 2015, 2017; Cataldo et al., 2015; Vetere et al., 2019), and a magma temperature of 1350 °C was used here. The insulating effects of lava crusts can limit cooling effects to as little as 1° per 30 km for flows with depths of 20 to 30 m (e.g., Keszthelyi et al., 2006), potentially allowing voluminous lavas to flow for distances of up to...
thousands of kilometers (e.g., Leverington, 2018). Kilometer-scale slopes along Ares Vallis are predominantly well under 1° (Fig. 3), with much higher slopes locally associated with relatively young features including superposed impact craters and late-stage lava flows. This study considered slopes of 0.0 to 1.0°, recognizing that slopes closer to −0.2° or less are likely to be especially relevant to the study of relatively mature Martian volcanic channels that have incised hundreds of meters into their substrates (e.g., Dundas and Keszthelyi, 2014; Leverington, 2014, 2018, 2019; Hopper and Leverington, 2014; Baumgartner et al., 2017; Dundas et al., 2019).

Extending the 25 and 50 m results of Leverington (2019) that were determined for Ravi Vallis, the flow conditions and incision rates predicted for channelized lavas of the type expected to have formed Ares Vallis are summarized in Fig. 12 for flow depths of 50, 75, and 100 m. Flow velocities predicted for lava depths of 50 m and 100 m respectively reach as great as ~61 m/s and 92 m/s for slopes of up to 1°. On more relevant slopes of 0.2°, flow velocities of 25 m/s and 39 m/s are respectively predicted. For a channel width of 25 km, which is typical of much of the main Ares Vallis system north of Iani Chaos, discharge rates as great as ~75 × 10^6 m^3/s to 230 × 10^6 m^3/s are respectively estimated for 50-m-deep and 100-m-deep flows on slopes of up to 1°. On slopes of 0.2°, these discharges are estimated to be ~31 × 10^6 m^3/s to 97 × 10^6 m^3/s. For 50-m-deep and 100-m-deep lavas, flow is predicted to be fully turbulent on all slopes, with Reynolds numbers of ~7.1 × 10^5 and 2.1 × 10^5 respectively estimated on slopes of only 0.01°, and much larger Reynolds numbers of ~8.5 × 10^6 and 25 × 10^6 respectively predicted for flows on slopes of 1°.

Mechanical incision for 50-m-deep and 100-m-deep flows on slopes of 0.2° is estimated to be ~4 m/day and 12.2 m/day, respectively, and for slopes of 1° is estimated to be a remarkable 47 m/day and 144 m/day (Fig. 12). Consistent with earlier findings (e.g., Hurwitz et al., 2012), thermal incision for 50-m-deep and 100-m-deep flows on slopes of 0.2° is estimated to be more modest than mechanical incision, at ~1.9 m/day and 2.3 m/day, respectively. For slopes of 1°, thermal incision is respectively estimated to be 3.8 m/day and 4.7 m/day for 50-m-deep and 100-m-deep flows. The capacity of lava for incision will diminish with distance from an eruptive center, as lava temperatures decrease and as viscosities increase (e.g., Williams et al., 2001, 2011; Jaeger et al., 2010; Hurwitz et al., 2012; Cataldo et al., 2015; Baumgartner et al., 2017; Leverington, 2018). A decrease of −1° per 30 km would enable voluminous lavas to maintain their capacity for incision for distances of up to thousands of kilometers, and more voluminous flows will generally maintain their temperatures better than less voluminous flows (e.g., Keszthelyi et al., 2006).

Total effused lava volumes can be crudely estimated for large Martian volcanic channel systems on the basis of parameters such as channel widths, incision depths, estimated discharge rates, and estimated incision rates (e.g., Leverington, 2007, 2009a, 2018, 2019; Hopper and Leverington, 2014). For example, respective total effused lava volumes of ~1.35 × 10^9 km^3 are predicted for lavas with depths of either 50 m or 100 m on the basis of: 1) the above predicted discharge rates of ~31 × 10^6 m^3/s and ~97 × 10^6 m^3/s, involving reaches of 25 km width and 0.2° slope; 2) assumed incision depths below adjacent uplands of 1000 m; and 3) conservative overall combined mechanical and thermal incision rates of 2 m/day and 6 m/day (roughly half those predicted above for mechanical incision alone). These lava effusions involve total event lengths of ~500 days and 167 days, respectively, if system development is simplistically assumed to have only involved periods of maximum discharge. More realistically, channel formation is likely to have involved lava effusions of a wide range of volumes and rates, including some lower-volume effusions that are more likely to have constructively mantled the system rather than incised into substrates, reducing the overall efficiency of channel incision. The Ares Vallis system is known to have formed over an extended period of geological history, and thus channel development must have involved multiple individual eruptive episodes separated by extended periods of little to no volcanic activity.

Based on thermal principals that conservatively ignore the independent action of mechanical processes, the minimum volume of erupted lava required for removal of a particular volume of substrate can be crudely estimated as roughly ~8 to 25 times the volume removed (e.g., Leverington, 2007, 2018, 2019; Hopper and Leverington, 2014; Cataldo et al., 2015). Thus, for the approximate system volume of ~10^9 km^3 (Carr, 2012), a value that ignores chaos regions and applies only to the main channel of Ares Vallis north and immediately south of Iani Chaos, a total minimum erupted lava volume of ~8 × 10^10 to 2.5 × 10^10 km^3 is predicted. This range is broadly consistent with the ~1.35 × 10^9 km^3 volume predictions made above on the basis of discharge estimates and conservative incision rates. Formation of the full Ares Vallis system, including regions of chaos and related channel reaches, is expected to have involved a greater lava volume. The volumes of missing materials at the four key chaos regions associated with Ares Vallis are not easily estimated, since the original form of local terrain prior to disruption and subsidence is unknown; nevertheless, the approximate volume of missing materials at these chaos regions is estimated on the basis of MOLA data to be ~130,000 km^3, which exceeds the assumed volume of the main Ares Vallis channel by ~30% (individual estimated volumes of missing materials are as follows: Iani, ~60,000 km^3; Margaritifer, ~45,000 km^3; Aram, ~14,000 km^3; and Hydaspis: 12,000 km^3). For the combined volumes of the main Ares Vallis channel and the four related regions of chaos, a total minimum erupted lava volume of ~1.8 × 10^9 to 5.8 × 10^9 km^3 is predicted under the simplifying assumption that formation of chaos volumes involved mechanical and thermal processes related to those that operated at the channels. A still greater minimum erupted lava volume would be required if the reaches near Margaritifer Chaos and north of the Argyre impact basin, outside of the main Ares Vallis channel and chaos regions, were also considered. Such reaches are interpreted here as having developed volcanically, and include, for example, the Uzboi, Ladon, and Nigral components of the broader Ares Vallis system.

6. Discussion

Formation of the main Ares Vallis channel and the four largest associated regions of chaos is conservatively estimated to have required eruption of a minimum lava volume of ~1.8 × 10^10 km^3. In comparison, formation of Kasei Valles, the largest outflow system on Mars, is predicted to have required eruption of a lava volume of at least ~5 × 10^9 km^3 (Leverington, 2018). Smaller Martian outflow systems are expected to have involved eruption of proportionately lower total lava volumes. For example, formation of the Hrad Vallis system, a 1450-km-long system that heads on the distal flanks of Elysium Mons and which is characterized by widths of only several kilometers, is predicted to have required eruption of as little as ~11,000 km^3 of lava (Hopper and Leverington, 2014). The Ravi Vallis outflow system, located north of Valles Marineris, is deeply incised into its substrate despite its preserved channel length of only ~215 km, and is predicted to have required a minimum erupted volume of ~64,000 km^3 in order to form its main channel and adjacent Aroratum Chaos (Leverington, 2019). The Athabasca Valles outflow system, located in the Cerberus Plains region, is very shallowly incised into its substrate and is associated with only ~7500 km^3 of basalt flows (Jaeger et al., 2010; Keszthelyi et al., 2017).

The outflow systems of Mars are characterized by a wide range of sizes (e.g., Baker, 1982; Carr, 1996; Leverington, 2011, 2014). In the present study and in recent work (Leverington, 2018), the largest of these outflow systems are individually predicted to have formed as a result of minimum total lava effusions in the millions of cubic kilometers. On the basis of thermal principles applied above, a global outflow-channel and chasmata volume of ~6 × 10^9 km^3 (Carr, 1996) implies
associated lava effusions on Mars of at least \(-50 \times 10^6\) to \(150 \times 10^6\) km\(^3\), under the simplifying (and unlikely) condition that all chasmata were formed volcanically. On Earth, individual large igneous provinces (LIPs) of the Phanerozoic had original volumes of hundreds of thousands to tens of millions of cubic kilometers (e.g., Coffin and Eldholm, 1994). The largest known LIP on Earth is the \(-120\) Ma Ontong-Java plateau, which may have a total volume (including both intrusive and extrusive units) of \(50 \times 10^6\) km\(^3\) or more (e.g., Coffin
and Eldholm, 1994). Thus, formation of all Martian outflow channels and associated chayms might have involved a total minimum lava volume approaching, and possibly exceeding by several times, the entire volume of this especially large terrestrial LIP. Notably, the largest known terrestrial volcanic channels did not form in association with LIPs of Phanerozoic age, and instead formed during the Archean and Proterozoic, when the voluminous effusion of turbulently-flowing lavas was more common (e.g., Leverington, 2014). Correspondingly, it is unlikely that the Martian outflow channels could have been formed by the mere effusion of voluminous lavas. Such lavas had to also be characterized by the remarkably low viscosities and high effusion rates most typical of the initial 1–2 billion years of solar system history (Leverington, 2011, 2014).

The origins of the Martian outflow channels are pertinent to our broader understanding of the basic characteristics and history of Mars. Aqueous interpretations of the Martian outflow channels have previously suggested near-surface water volumes that represent at least several hundred meters of globally-averaged water (even while assuming remarkably high sediment loads of ~40% by volume), which far exceeds the several tens of meters commonly estimated on the basis of ground observations or from geochemical considerations (e.g., Carr, 1986; Scambos and Jakosky, 1990; Carr and Wänke, 1992; Wänke and Dreibus, 1994; Beatty et al., 2005; Christensen, 2006; Carr and Head, 2015; Breuer et al., 2016). Carr and Head (2015) brought estimates of near-surface volatiles closer to agreement by assuming that the canyons of Valles Marineris are mainly tectonic features with origins that did not involve substantial erosion by effused fluids, and that the ice contents of hypothesized global cryospheric seals were less voluminous than previously hypothesized; and by not including the groundwater volumes that must necessarily have been left behind in aquifers during and after effusions to the surface (e.g., Leverington, 2011). Aqueous interpretations of the outflow channels have frequently led to the characterization of Mars as a “water world” that has, in contrast to the cold and dry conditions of the present, repeatedly experienced periods of wet surface conditions and correspondingly high atmospheric pressures (e.g., Baker et al., 1991; Baker, 2001, 2018b). A volcanic origin for Ares Vallis and the other Martian outflow channels would bring the total predicted volatile contents of Mars back in line with the lower estimates derived from surface observations and geochemical inferences, by greatly reducing the need to hypothesize the current or past existence of enormous long-lived aquifers of global extent, the early or periodic existence of thick atmospheres capable of supporting the widespread presence of wet surface conditions that could have led to the development of giant aquifers, and the past existence of large bodies of standing water including geographically extensive oceans (e.g., Leverington, 2011, 2014).

The aqueous paradigm that has dominated the past half century of Mars exploration is based largely on aqueous interpretations of the Martian outflow channels. Yet, the mineralogical and geomorphological properties of the Martian surface near outflow channels, including those of the landscapes that variously comprise the Ares Vallis outflow system, strongly suggest dry channel origins and the predominance of relatively cold and dry surface conditions over most or all of the history of the planet. Although Mars possesses significant confirmed water reservoirs in the form of perennial ice caps and near-surface stores of ice at middle and high latitudes (e.g., Smith et al., 1999; Christensen, 2006), corresponding water volumes are far smaller than those previously hypothesized by some workers to have been required for formation of Martian channel systems, and are modest relative to the size of the planet (Leverington, 2011). Incongruities between the assumptions of the prevailing aqueous paradigm and the surface properties of Mars suggest that this paradigm should be replaced by a more realistic research framework that better recognizes the importance of dry surface processes in the development of Martian landscapes.

### 7. Conclusions

Ares Vallis is widely interpreted as having formed as a result of catastrophic outbursts of groundwater at several associated regions of chaos, but aquifer outburst mechanisms do not appear to have meaningful solar system analogs, and aqueous origins are arguably not consistent with the sedimentological and mineralogical characteristics of this system. Obvious examples of fluviatile or shoreline deposits, or of extensive areas of hydrous alteration or the deposition of evaporites, are not known for component channels and basins. The preservation at Ares Vallis of large exposures of olivine-rich materials, including those of the Noachian units that form the substrates into which channels were incised, does not appear to be compatible with the hypothesized past occurrence of dozens to thousands of aqueous outburst floods here, and with the long-term existence of highly porous and permeable aquifers later exposed by channel development. Consistent with orbital perspectives, the Pathfinder landing site at the mouth of Ares Vallis is dominated by volcanic lithologies that have been little altered by water.

The basic properties of the Ares Vallis outflow system suggest dry volcanic origins analogous to those of hundreds of other ancient channel systems on bodies including the Moon, Earth, Venus, and Mercury.
Such origins are in accord with the largely pristine mineralogy of Ares Vallis, and with the widespread association of component channels and terminal basins with voluminous lava flows. Plausible assumptions regarding low-viscosity lavas allow for incision rates of up to 10 m per day or more for flows with depths of 100 m. Formation of the Ares Vallis system, including four large regions of chaos, is estimated to have required a minimum effused lava volume of $\sim 1.8 \times 10^6$ km$^3$, with greater lava volumes required for formation of associated channels such as those located south of Margaritifer Chaos (e.g., the Uzboi, Ladon, and Nirgal components of the broader Ares Vallis system). Volcanic development of Ares Vallis is consistent with volcanic origins for all Martian outflow channels, and with the predominance of dry surface conditions over most or all of the history of Mars.

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