Evidence for Deposition of Chloride on Mars from Small-Volume Surface Water Events into the Late Hesperian-Early Amazonian

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Peer Review Comments on 2021AV000534

Reviewer #1

Title: Evidence for deposition of chloride on Mars from small volume surface water events into the late Hesperian-early Amazonian
Authors: E.K.Leask and B.L. Ehlmann

Reviewer: Mikki Osterloo

General comments: The article details an update to the statistics of the global chloride survey offering new insights into possible formation mechanisms of these unique and somewhat perplexing deposits. Of importance is updated crater age-dating of the units upon which the chloride materials occur and detailed geomorphological assessments using higher resolution CTX and HiRISE imagery as well DEMs. Additionally, the work presented includes a comprehensive spectral investigation using CRISM to search for associated minerals (e.g., sulfates, carbonates, clays) to better understand the potential geochemical/geological relationships. The work adds to the previous research and
advances the community's understanding of chloride material formation. The proposed conceptual model invoking a process that occurs in the dry valleys of antarctica is new and the authors have collected data to support this new hypothesis. Additionally, updated crater-age dates suggest the mechanism that formed the chlorides could have operated, in select locations, into the Amazonian further supporting past results that suggest chlorides are among the youngest deposits to have recorded relatively large scale hydrologic activity on the surface. I have a few general comments as well as specific comments that I hope the authors will consider in order to improve the impact of the manuscript.

- In general, the manuscript somewhat overstates that previous work proposed that the chlorides were formed similarly to a playa lake environment on earth. From my perspective there have been a few studies (e.g., Hynek et al. 2015) that did stress the "deep lake, long lived water", however my own research (Osterloo et al. 2008, 2010, 2015) did not strongly hypothesize that the environment was exactly like one would find on earth. Additionally, some of my later work specifically stated that the chlorides formed via evaporitic processes from surface runoff given the correlation of chloride deposits with channels and incised valleys. (e.g., Osterloo and Hynek, 46th LPSC abstract #1054). Of course, this is an LPSC abstract from 2015, so the authors may not be aware of it. In my opinion there have been a plethora of plausible formation mechanisms with some being favored over others. I think being specific on which previous work strongly hypothesized a mechanism over another and adding citations would be helpful. I have made some suggestions below.

- The work presented has some really interesting new findings both in terms of ages of the deposits as well as a plausible formation mechanism. Stressing these over the previous formation mechanisms that are unlikely (e.g., volcanic outgassing) and perhaps even removing some of that text would help streamline the manuscript and aid in the readers overall understanding of "what's new about the chlorides" instead of revisiting old or out of date knowledge.

- It may help to provide in the supplemental text a list of which deposits had CRISM coverage, which were used for age-dating, how many had channels, etc. A summary database of the work would be very powerful for add on studies and would strength some of the statistics stated throughout.

Specific comments:

Line 68-70. Although it is somewhat true that chlorides and chloride mixtures were inferred due to the lack of spectral signature (e.g., rather spectrally featureless), there has also been modeling work that further constrains the most likely mineral(s) and abundances present in the chloride deposits. I would suggest modifying this to include the work of Jensen and Glotch 2011 (Jensen, H.B. and T.D. Glotch, (2011) Investigation of the near-infrared spectral character of putative Martian chloride deposits, JGR, doi:10.1029/2011JE003887)
Although Osterloo et al. 2010 (and 2008) used the map units to constrain the oldest ages of the chloride units, several studies have also undertaken crater age-dating to better understand the geologic ages of these materials. E.g., Osterloo et al. (2010) and Osterloo and Hynek (2015), Hynek et al. (2015) and potentially others. The authors do not discuss how their crater age dates compare with those completed previously. Although the LPSC abstract does not discuss specific areas that were used in the study, the general results are available for discussion. Several sites were presented in the 2010 study and Hynek (2015) also used crater age-dating for the site near Meridiani (and also inferred "late stage" formation). It would be useful if some of these previous sites were discussed in light of new crater age date estimates presented here.

Note- the updated work of Osterloo and Hynek (2015) found a much higher percentage of fluvial channels and sinuous networks associated with the chloride materials as well (using higher resolution imagery).

Osterloo et al. 2010 never stated that the most likely formation mechanism was similar to a playa lake on earth. In fact, the stated hypothesis is evaporation from ponded water either from surface runoff or ground water upwelling. In that work, the lack of accessory minerals such as sulfates was noted as inconsistent with this type of environment. Furthermore, Glotch et al. (2010) concludes that the chlorides likely formed during the late Noachian to early Hesperian as a result of groundwater discharge and evaporation. They go on to say that a later event, involving groundwater or perhaps surface water, led to the formation of the chloride-bearing unit. The main point here is that there has been a plethora of previous work on the chloride materials, few have invoked a mechanism similar to playa lake formation on Mars so the authors need to take care when lumping previous works together. If the other works cited do specifically state that all of the chloride materials were formed in a similar way to playas on earth, then make the case for differences observed here and those typical of playas on earth. Another way to go about this if none of the cited works concluded playa formation, then simply discuss that playa formation is one potential mechanism and go on to provide the reasons why these materials would not be consistent given the slopes, etc.

These sections are quite short. Combining to a single paragraph or summarizing with a table would be more useful to the reader. Additionally when lumping deposits into distinct regions, it would be helpful for the reader to understand the quantity of deposits (or total volume, etc).

Again, remind the reader here of what "all lines of evidence" are. And again, Osterloo and Hynek (2015) using higher resolution data also concluded that chloride formation via evaporitic processes from surface runoff was the dominant mechanism of formation.

Be specific and cite sources instead of referring to "prior literature" given that the literature here is varied. Specifically, here, Hynek et al. 2015 would likely be the
correct citation given that the work relied heavily on "thick chloride" deposits.

Line 443-448. Unless the authors have evidence that deliquescence is active on the martian surface, I think the discussion detracts from what is being proposed as the new idea of formation mechanism. The manuscript would probably be strengthened if the discussion simply focused on the new idea and not rehashing old ideas which the data do not support.

Ube 459-463. Same as above.

Line 505-507. Being specific here is key. How many are several? Adding a chart, table, or maybe graph showing the distribution of chloride units across the geologic units with age dates (from crater age-dating) overtop. Finding a single deposit on an Amazonian terrain is unique rather than the norm it would seem based on the data here. Certainly, it is plausible that these materials are much younger and they have simply formed on older terrains due to the geomorphology (and latitude range). However, as the authors state, it is not provable with current mechanism for age dating the materials. Nonetheless, we are constrained by what we have available so being as detailed as possible is important.

Supporting information:

I would suggest adding a table or chart detailing the results of the updated geologic age survey (using updated maps) as well as a table of how many deposits had crater age-dating analysis on them (and the results). Furthermore, it is not sufficiently clear if the crater age dates presented in the manuscript are examples of the analysis or the entirety of the analysis.

**Reviewer #2**

Review of "Evidence for deposition of chloride on Mars from small-volume surface water events into the Late Hesperian-Early Amazonian" by Leask and Ehlmann
Review by Tim Glotch

This paper presents an exciting new analysis of chloride-bearing deposits on Mars and presents substantial evidence that these deposits were formed as a result of evaporation of shallow ponds in the late Hesperian/early Amazonian. These deposits may represent the last gasp of aqueous mineralization on Mars.

The paper presents several important observations to support the main conclusions:
1) Substantially higher proportion of channels associated with chloride-bearing deposits than previously recognized.
2) Thin, draping textures of chloride deposits and absence of chlorides on slightly higher topographic rises.
3) Chlorides appear at a range of elevations in many areas, and in basins, occur at higher elevations close to the inlet channels.
4) Crater counting reveals late-Hesperian to early-Amazonian ages, substantially younger
than Tanaka et al. (2014) global map units on which they occur. Overall, the paper is well written and organized and the figures are clear and legible. I recommend publication of the manuscript after minor revisions. I have several comments, all related to the geochemistry/mineralogy of the deposits and the materials that they were derived from that should be addressed by the authors and numerous small suggestions in the appended annotated pdf.

Major comments:
1) Lines 440-442: The authors cite volcanic outgassing as a potential source of Cl for the deposits. It is probably likely that precipitation due to volcanic outgassing would also be rich in sulfur, and that the sulfur and Cl would be present as aerosols vapor deposit coatings on dust/soil rather than well crystalline oxychlorine or sulfate phases. It would be helpful to provide some idea of how chloride and sulfate are segregated in such a scenario.
2) Lines 489-492: It would be really helpful to be more quantitative here. Are there models in the literature that discuss the relative solubilities of chlorides and sulfates/carbonates that you can point to as supporting evidence? Could you run some relevant models in Geochemist’s Workbench or a similar geochemical modeling software? In addition, if the Martian dust is a major source for leaching the Cl, I don’t think it is clear what the Cl- and S-bearing phases are (aerosols/vapor deposits or crystalline phases?) or what their solubilities would be.
3) The manuscript does not address the known presence of other oxychlorine salts in the Martian regolith (perchlorate and likely chlorate; see Sutter et al., 2017 and references therein). What are the possible relationships, if any, between the known Cl-bearing salts in the Martian soil and the chloride deposits? In addition, what does the apparent presence of only anhydrous chloride salt say about the environmental conditions at the time of deposition? Hygroscopic and hydrated Mg-, Ca-, and Fe-bearing chlorides would likely be detectable by CRISM due to their hydration features, but are not apparent. Overall, the manuscript would be substantially strengthened by addressing some of the relevant geochemistry more quantitatively.


Reviewer #3 Evaluations:
Recommendation: Return to author for minor revisions
Significant: Yes, the paper is a significant contribution and worthy of prompt publication.
Supported: Yes
Referencing: Yes
Quality: Yes, it is well-written, logically organized, and the figures and tables are appropriate.
Data: Please Select
Accurate Key Points: Yes
Reviewer #3 (Formal Review for Authors (shown to authors)):

This paper provides a careful study of the context of chloride deposits on Mars, investigating both the non-chloride minerals associated with the deposits, as well as the topographic context and age of the underlying terrain. The work expands the range of likely standing water on Mars into the early Amazonian and presents a model for chloride deposit formation which can be tested by future work. Overall, I found the paper to be clearly written and well referenced. The arguments made in the paper are clearly supported by the data provided and the interpretations are well-reasoned. From my perspective, this is high quality research that is worthy of publication. Below, I've listed a few issues/questions that could be addressed to further strengthen the manuscript.

Lines 237-240 Chloride salts significantly decrease the freezing temperature, vapor pressure, and evaporation rate of liquid water. As ions become more concentrated, these effects are even greater. Therefore, the end-stage fluids responsible for precipitating these chloride deposits have very different thermodynamic properties that pure water. A discussion of the relative stability of near-saturated chloride brine would be a good addition here, as the addition of salts significantly expands the stability field of liquid water.

Figure 6 caption: typo in ejecta blanket.

Line 406-407: this sentence is very awkward - consider rephrasing to read: Our thickness estimates (<3m and typically <1m) are lower than those reported in the prior literature, but are also consistent with smaller volumes of water.

Lines 476-477. There is a disconnect in the math here, as a circle with a diameter of 10 km has an area of 78 km^2, which is <10% of the area needed in the mass balance calculations. This needs to be clarified or the argument reframed.

Line 495: typo - soilts

Figure 11. This is an interesting model which led me to wonder - do you observe more chloride deposits on the pole-facing slopes where snow/ice is more likely to accumulate?

Line 549 Calculates should be calculations

Line 556 Not clearer what you mean by "our update of the statistics of distribution". More specifics/explanation would be helpful here.

Line 559 crater counting "of" local units

[Please see attachment that begins on the following page.]
EVIDENCE FOR DEPOSITION OF CHLORIDE ON MARS FROM SMALL-VOLUME SURFACE WATER EVENTS INTO THE LATE HESPERIAN-EARLY AMAZONIAN

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Abstract

We determine the environmental setting and timing of enigmatic large-scale chloride deposits on Mars, examining all available high-resolution imagery globally, building digital elevation models, surveying targeted infrared images intersecting chloride deposits for accessory minerals (e.g., clay, carbonate, and sulfate), and performing crater counting for age-dating when possible. We find that chloride deposits are commonly draped atop underlying topography, often associated with channels, sometimes perched above deep craters in local topographic lows, and span a wide range of elevations. Where measurable, chloride deposit thicknesses are typically <3 m. The deposits range in elevation over tens of meters, inconsistent with previous hypotheses of playa-like environments, which are very flat. Chloride deposit elevations within larger basins are typically asymmetric with chloride deposits much higher on the inlet channel side, indicating that (a) surface water runoff was the most likely water source and (b) the basins were likely not filled completely with water in a deep lake setting but rather chlorides formed within a series of shallow ponds. Mass balance allows local sourcing from mobilization of cations and chlorine from dust/soil. Though prior global-scale studies report chloride deposits superimposed on Noachian terrains, crater-counting of local, stratigraphically-associated datable surfaces shows chlorides superimposed on 3.4-2.3 Ga volcanic terrain. This indicates that surface waters...
forming chloride deposits continued through the Hesperian and into the Amazonian, making them among the latest-formed, large-scale deposits of water-related minerals on Mars. Collectively, data suggest formation from meltwater from episodic ice/snow deposits continuing until 2.0-2.5 Ga.

Plain Language Summary

Chloride salt deposits on Mars are intriguing because they dissolve very readily and thus record the last stage of liquid water present at Mars’ surface. They are found across the ancient, clay-rich, southern highlands of Mars but also sometimes on top of younger volcanic regions, around the edges of the ancient terrain. As a result, we think that they are much younger than the underlying ancient terrains, continuing to form as recently as 2.3 billion years ago. These salt deposits are different from salt flats on Earth, because they occur over a range of elevations and sometimes on slopes, rather than in a single flat area. The chlorides are often found in small depressions, including perched above much deeper craters where no chloride is observed. They are also often found within channels. For these reasons, we think that the water source came from surface runoff, rather than deep groundwater welling up to the surface. The small amounts of water required are most likely from occasional melting of ice. Chloride could come from the top of the soil; clay-rich soils form a salt crust when evaporation pulls water and dissolved salt up from the top ~1 meter.

Key Points

- Large-scale Martian chloride deposits occur in local topographic lows, drape >10s m of pre-existing topography and have thicknesses <3m
- The chlorides formed in chains of shallow saline ponds, perched atop clay-bearing soils and/or permafrost, fed by meltwater from ice/snow
- Superposition on dateable surfaces of ages of 3.4-2.3 Ga, indicates large scale surface liquid water on Mars in the late Amazonian
Chloride deposits on Mars, first identified by Osterloo et al. (2008), are of particular interest because they record the last surface water present at a given location on the surface, as subsequent water events would dissolve them. These light-toned, indurated deposits (<1 km² - ~1000 km²) are found throughout the southern highlands, have been previously described as ancient (Noachian to early Hesperian in age; ~4.0-3.4 Ga), and are often found in local topographic depressions, sometimes with channel-like features (Osterloo et al., 2008; Glotch et al., 2010; Osterloo et al., 2010). In high-resolution imagery, many of these deposits appear to have polygonal fractures and/or ridges, which have been interpreted as salt polygons or desiccation features (Osterloo et al., 2010; El Maarry et al., 2013; Ye et al., 2019).

Unlike many other minerals, identified on Mars by remote sensing of characteristic absorption and emission features (clays, sulfates, olivine, pyroxene, silicates), chloride minerals have no such features; instead, they are inferred by ruling out other possible materials with the same properties. Chloride deposits are bright-toned and brighter in the blue than red, relative to most Martian materials, have decreased water content as measured by the shortwave infrared OH/H₂O absorption at 3-μm, and no mid-infrared wavelengths with emissivity ~1 (Osterloo et al., 2008; Murchie et al., 2009). As noted in Osterloo et al. (2010), sulfides and diamonds could also have these properties, but sulfides rarely occur in km² exposures and would be darker, associated with volcanics, and accompanied by sulfate weathering products; large diamond exposures are geologically implausible. Though several types of chlorides are permitted by the spectral data, halite (sodium chloride) has been identified in martian meteorites (Bridges and Grady, 2000), detected in XRD data at Gale crater (e.g., Rampe et al., 2020), and elevated levels of correlated Na and Cl have been measured in situ on Mars, interpreted as halite (Ming et al., 2006 (Gusev); Knoll et al., 2008 (Meridiani); Thomas et al., 2019 (Gale)). Laboratory work shows that other potential secondary minerals (e.g. carbonate, sulfate, phyllosilicate) must be <1-5 wt.% in the chloride deposits, else they would be observed spectroscopically (Ye and Glotch, 2019).

Abundances of chloride are inferred to be 10-25%, in an otherwise spectrally non-distinctive mixture with Martian soils or dust (Glotch et al., 2016). Thus, while referred to in shorthand as “chloride deposits” herein and elsewhere in the literature, they are chloride-bearing Martian sediments, rather than pure salt deposits.
Chloride formation hypotheses include ponding and evaporation of surface water and/or upwelled groundwater (favored by Osterloo et al., 2010; Glotch et al., 2010; Reusch et al. 2012; El Maarry et al., 2013; Glotch et al., 2016; Melwani Daswani and Kite, 2017), diagenetic or hydrothermal brines (e.g., volcanic- or impact-related), or efflorescent crust. Strictly volcanic sources have been discounted due to lack of spatial association with volcanics and lack of the accessory minerals (sulfates, silica) expected for this setting. On Earth, evaporating lakes and playas tend to leave behind zoned salts (Eugster and Hardie, 1978), corresponding to progressively more soluble minerals (generally carbonates, sulfates, then chlorides), while hydrothermal brines will often deposit silica and sulfates and oxide minerals along with chlorides. Thus far, only phyllosilicates have been found in association with chloride minerals (Murchie et al., 2009; Glotch et al., 2010; Huang et al., 2018; Ruesch et al., 2012; El Maarry et al., 2013), reported at ~10% (Ruesch et al., 2012) to ~30% (El Maarry et al., 2013) of chloride deposits investigated. Origin in deep lakes, as interpreted by Hynek et al. (2015) and Melwani Daswani and Kite (2017), would require large volumes of water present at Mars’ surface; therefore, constraining both water depth and timing of chloride formation is important for our understanding of the evolving availability of water at Mars’ surface.

Since the initial detection of chloride deposits, they have been targeted for CRISM (Compact Reconnaissance Imaging Spectrometer for Mars) and HiRISE (High Resolution Imaging Science Experiment) images, and sufficient CTX (ConTeXt Camera) data is now available for a global mosaic that provides context for these deposits (Dickson et al., 2018). In previous global-scale studies, Ruesch et al. (2012) used OMEGA data with spatial resolution ~200-2.5 km/pixel. El-Maarry et al. (2013) investigated 43 chloride locations with CRISM images with >10x better spatial resolution, looking explicitly for Fe/Mg phyllosilicates. Here we use CRISM data to examine all previously reported chlorides with coverage, identify chloride deposits at smaller scale, and search for other associated minerals (e.g. sulfates, carbonates, clays) that might accompany chlorides to understand the water chemistry from which they formed. We then use high-resolution image data to study the morphology and cross-cutting relationships of the deposits as well as identify deposits to perform age-dating with crater counts. Finally, we compare results from Martian chloride deposits to proposed analogs on Earth and describe the formation conditions of the chlorides.
We exported 642 polygons that approximate chloride deposit locations from JMARS (Osterloo et al., 2010) into ArcGIS and used CRISM footprints (downloaded from NASA’s Planetary Data System (PDS)) to find all acquired CRISM targeted long wavelength (158 +8 nearby, covering 119/642 chloride deposits), HiRISE (273 images over 177 deposits), and HiRISE stereo images (29 pairs over 21 deposits) that intersected the chloride polygons (Fig. S1). Because there are often many small chloride deposit polygons clustered together, we used ArcGIS tools to draw a 10-km buffer around the polygons and aggregated those whose buffers intersected, assuming that they likely shared a genetic relationship due to spatial proximity (e.g. Fig. 1), resulting in 392 chloride deposit clusters (with CRISM coverage of 97 clusters, HiRISE color of 123 clusters, and HiRISE stereo of 17 clusters). 387/392 clusters have CTX coverage over the chloride deposit.

2.1 CRISM analysis

In its targeted mode, the CRISM instrument takes hyperspectral images of Mars’ surface at ~18-40 m/pix, covering a wavelength range of 0.36-3.9 µm (Murchie et al., 2007; Murchie et al.,

![Figure 1](image-url). Chloride cluster in the chaos terrain in Margaritifer Terra (20.74° W, 3.12° S). (A) Chloride deposits are perched above a crater and deep fractures that lie within a 10-km buffer. (B) Chloride deposit (blue tones) in THEMIS-875 decorrelation stretch image; channels are not visible at this resolution (100 m/pixel). (C) Same chloride deposit at CTX resolution (6 m/pixel), where fine channels are visible (white arrow). (D) The chloride deposit appears light purple in HiRISE color, which, when coverage is available, makes it possible to distinguish its boundaries with adjacent light toned fractured units (note greyscale (left) vs color (right) in D). A small chloride-filled channel is present in the lower right (white arrow). Chloride has a sharp contact with surrounding units and appears to drape SW-NE trending dune-like features.
We used a standard approach for secondary mineral detection. Targeted CRISM I/F images from the long wavelength sensor, which covers key absorptions for hydrated minerals, were downloaded from PDS, and processed using the CRISM Analysis Toolkit (Morgan et al., 2009) in ENVI (photometrically corrected (division by \( \cos(i) \)), atmospheric correction using the default 61C4 volcano scan, after McGuire et al. (2009)). Images were then ratioed using a simple column median denominator to remove residual atmospheric and detector artifacts. If ratioing artifacts due to absorptions in adjacent materials were suspected during analysis, a small spectrally bland area was instead manually chosen as a denominator to ensure that the features persisted using a different denominator. Because many of the CRISM image cubes covering chlorides were taken later in the mission after cooler set point temperatures were raised, these images are significantly noisier than those earlier in the mission, and so band depth calculations on unsmoothed data tend to show only noise. To mitigate this issue, we used an 11x11x11 spatial/spectral median filter to smooth the image before calculating band parameters. For each CRISM image, we used these band parameter maps calculated on smoothed data in tandem with ratioed, unsmoothed data to verify mineral detections. We focused on the band depths at 1.9, 2.1, 2.2, 2.3, and 2.5 \( \mu \text{m} \), in addition to the slope at 2.4 \( \mu \text{m} \). These wavelength ranges allow detection of hydrated minerals such as Fe/Mg clays (e.g. nontronite, saponite, chlorite), Al-clays (e.g. kaolinite, montmorillonite), serpentine, carbonate, and mono- and poly-hydrated sulfates, as well as water ice (e.g. Murchie et al. 2009a). For images where we found Fe/Mg clays, whose absorptions at 1.9 and 2.3 \( \mu \text{m} \) can overlap with carbonates, we also looked at the 3-4 \( \mu \text{m} \) part of the spectrum to look for features at 3.4 and 3.9 \( \mu \text{m} \) associated with carbonates. A known limitation is that the smoothing necessary to work with noisy images can also obscure deposits that are <100 pixels in size.

### 2.2 Morphology and elevation

High resolution imagery (CTX and HiRISE) and digital elevation models (DEM) were used to understand the context and morphology of deposits and the stratigraphic relationships between geologic units. We use a global CTX mosaic (6m/pix) (Dickson et al., 2018) together with the gridded MOLA (Mars Orbiting Laser Altimeter) elevation product (463 m/pixel, e.g. Smith et al., 2001), available for almost all clusters. Within the 10 km buffer connecting all parts of each chloride cluster, we searched for: sinuous channels (e.g. Fig. 1C), whether they are filled with...
light-toned deposits, the range of elevation among chloride deposits in the cluster, and the
difference between the lowest chloride elevation and the lowest point in the 10 km buffer zone to
determine whether the chloride is perched relative to surrounding topography.

HiRISE color images (25 cm/pixel, with band centers at 536 nm (blue-green), 694 nm (red), and
874 nm (near infrared); McEwen et al., 2007; Delamere et al., 2010) are particularly useful
because in greyscale HiRISE images, fractured clay-bearing units can look morphologically
indistinguishable from the chlorides (also noted in El Maarry et al., 2013). HiRISE color in
conjunction with CRISM show a consistent pattern with mineralogy; chloride deposits appear as
bright light purple (low VNIR slope) and contrast with yellow-beige tones of the clay-bearing
units (Fig. 1D). We utilize HiRISE color imagery where available to ensure that we do not
misidentify clays as chlorides. In surveying the morphology of chloride deposits, we looked for
color variation, fracture patterns, thickness, concentric patterns, whether edges of the deposit
appeared sharp or diffuse, whether they appear to be draped or in stratigraphy, and whether they
were associated with other landforms, e.g. channels.

All HiRISE stereo pairs overlapping chloride deposits and a select subset of CTX stereo pairs
were made into DEMs using the Ames Stereo Pipeline (Beyer et al., 2018). These were used to
measure the thickness of chloride deposit (where possible), infer maximum and minimum water
depths, and measure the slope/asymmetry of deposits. We measured mostly in the middle of
chloride deposits (rather than the edges), as these are more likely to represent that typical
thickness and avoid the edges of potentially draping deposits. High resolution LiDAR DEM of
Death Valley for comparison with Earth playa topography at similar resolution was obtained
through OpenTopography (dataset: Snyder, 2005).

2.3 Age dating

We first used the Tanaka et al. (2014) global geologic map to update the approximate age
distribution of the terrains containing the chloride deposits, as the original Osterloo et al. (2010)
survey used Tanaka (1986) and Greeley and Guest (1987). For all of the sites, we also searched
for cross-cutting relationships that establish whether the chloride pre-dated, post-dated, or was
contemporaneous with nearby units to improve understanding relative to simple reporting of
occurrence in global-scale map units. We used crater counting to bound the age of the chlorides at all locales where stratigraphic relationships between sufficiently large units permitted it. We follow Warner et al (2015) who propose areas should exceed 1000 km² with preference for counts in >10,000 km² areas; all our count areas are >7000 km². Unit boundaries were determined based on breaks in slope and morphological similarities, and crater counting was performed using the CTX mosaic. Most bounds were oldest-possible age bounds, established by crater counting units that underly chloride deposits at select sites. In one instance, a youngest-possible age bound could be established from an overlying unit (see section 3.3.1). Craters that were entirely subdued (no topographic rim expression whatsoever) were excluded; those where the relationship with a unit was not clear were included, so as not to skew the count to young ages. The diameters were calculated in ArcMap and exported to Craterstats2 (developed by G.G. Michael, available: http://hrscview.fu-berlin.de/software.html), using the Mars production function of Hartmann and Daubar (2017) and chronology function of Hartmann (2005) updated by Michael (2013) to determine age dates.

3 Results

3.1 Relationship with other minerals and ice

3.1.1 Chlorides and Clays: Occurrence and contact relationships

No sulfates or silica were found in association with the chloride deposits, in agreement with Reusch et al. (2012)’s coarser spatial scale survey. We detect Fe/Mg clay deposits in 73/158 CRISM images of 39/97 aggregated chloride clusters (~40%) (Figure 2a; Fig. S2). Despite explicitly searching for other accessory minerals, we only found 4 locations with any other minerals in the same CRISM image as chlorides. Three of the four are small Al-clay deposits (Fig. 2a; Fig. S2), identified by absorptions at 1.4, 1.9, and a narrow absorption at 2.2 μm. In one of these locations (Fig. S2f), there is a shoulder at 2.4 μm that could be consistent with sulfate; however, the data are too noisy for certainty. In all three Al-clay instances, the dominant mineral identified is Fe/Mg clay (thousands of pixels), and far smaller Al-clay deposits are not in direct contact with the chlorides nor appear to be genetically related. Additionally, we find one location with a carbonate spectral signature in the same image as a chloride deposit (Fig. S3). This spectrum has paired strong 2.3 and 2.5 μm absorptions with positions consistent with MgCO₃(Fig. S3c). The carbonate appears to be part of the large Fe/Mg clay-bearing unit
underlying chlorides; it is indistinguishable morphologically from the clay-bearing unit in HiRISE (Fig. S3b), and the spectral mean for the clay-bearing unit throughout the image has a minor 2.5-µm absorption, consistent with intermixed carbonate.

El Maarry et al. (2013) proposed that a clay substrate might underlie all fractured chloride deposits, positing that clay desiccation might be responsible for the fracturing observed. In some instances, chloride deposits drape on top of clay-bearing units (notably in Terra Sirenum; e.g. Glotch et al., 2010). However, in other locations, a definitive genetic relationship is either inconclusive or the chlorides occur in underlying units (e.g. Knobel crater, Ehlmann and Buz, 2015; Huang et al. 2018). We find clays are in direct contact with or surround the chloride deposit in ~50% of instances (45/73 CRISM images with clays; 20/39 chloride clusters). In other cases, the clays are nearby, but appear unrelated to the chlorides. It appears that while chlorides occur around Fe/Mg clay-bearing terrains, they do not require direct contact with clays in order to form.

3.1.2 Water ice

In our search for hydrated minerals, we unexpectedly found spectral signatures for water ice in 8 CRISM images associated with chlorides (8 deposits, 7 clusters; Fig. 2b; Fig. S4). These ice deposits are found on pole-facing slopes between 42.8° S and 27.8° S. All of these images were taken during local winter (Ls 91-151); other CRISM images taken during other seasons, available for 3 clusters, did not show water ice. The ice is most likely a seasonal frost, consistent with the findings of Vincendon et al. (2010), who found seasonal water ice up to 13° S. While the current climate of Mars is too cold/low pressure for liquid water to occur seasonally today, seasonal deposits in the past may have been able to melt, providing a possible source of localized, small volumes of water across the southern hemisphere of Mars.

3.2 Morphology and Elevation

Chloride deposits are typically found either associated with sinuous features, draped in thin layers on top of underlying topography, or in local lows in intercrater plains that are often perched above nearby impact crater depressions (Fig. 2c, 2d). Investigation of individual
Figure 2. (A) Fe/Mg clays (green squares) are found with chlorides across Mars in ~40% of the images with targeted CRISM coverage. They can occur directly in contact with chlorides (dark green squares) or nearby within the same CRISM image (light green squares). Aluminum clays are only found with chlorides in the Terra Sirenum region, west of Tharsis. (B) Global distribution of water ice detected near chloride deposits (all on pole-facing slopes, poleward of 27.8° S). Where repeat CRISM images exist, these water ice deposits are only seen in southern hemisphere winter (Ls 91-151). (C) Global distribution of chloride deposits within channels at CTX (blue circles) and HiRISE (blue triangles) resolution. The distribution of chloride deposits is similar to the valley network density (red tones, after Hynek et al. (2010)); this could be due to a related water source for the features, or later chloride-bearing waters exploiting existing channel networks. (D) Perched chloride deposits—where there is a feature at lower elevation than the chloride (magnitude indicated by symbol shading) within a 10 km buffer—are found across the globe, with no obvious spatial trends. This pattern is consistent with surface runoff (rather than groundwater upwelling) as a primary source of water for the chloride deposits.
deposits shows chlorides are often found over a range of elevations in the same deposit and tend
to be at higher elevation on the side of a basin, where channels lead into the deposits.

3.2.1 Thin, draped chloride deposits

Estimating the thickness of chloride deposits on Mars is useful for mass balance calculations
(e.g. Melwani Daswani and Kite, 2017; Milliken et al. 2009) and to constrain plausible
depositional environments. Previous thickness estimates were typically 1-15 m on the basis of
unit topography (Glotch et al., 2010; Hynek et al., 2015; Melwani Daswani and Kite, 2017). We
made careful thickness measurements where chloride deposits have a “chipped” appearance, are
cross-cut by impact craters, or exposed in fractures (e.g. Fig. 3). The chloride thickness is often
below the vertical resolution of HiRISE DEMs, where available, <~3 m thick (Table S1).
Multiple locales have similar traits. Fractures cross-cutting chloride deposits reveal that they do
not extend into the subsurface (Fig. 3a-d), and small impact craters (≤10 m diameter, excavating
<3m) expose dark material from beneath the chloride (Fig. 3e). At Terra Meridiani, erosional
windows show thicknesses of <1.5 m (Fig. 4d), and a small impact crater excavating dark
materials from the subsurface similarly constrains thicknesses of chloride-bearing materials to

Figure 3. Examples where chloride thickness is exposed by fractures or impact craters. (A) Light
purple chloride fringes channel edge and is cross-cut by later fracture. (B) Close-up shows
polygonal fracturing in chloride, and that the chloride does not extend into the subsurface (white
arrow). (C) Light purple chloride is present on both sides of the fracture. Zoom in (D) shows that
the chloride layer is draped on top of underlying topography and does not extend into the
subsurface. (E) An impact crater has punched through a light purple, fractured chloride unit
(linear dunes present in bottom half of image). All ejecta from this ~15 m diameter crater are dark
toned, indicating that the chloride is only a thin layer at the surface, <~3-5 m.
<2-3m (Fig 4e). In the southwest part of the Tharsis region, chloride drapes lineations that are ~3m high, while taller features (black arrows) are left uncovered; where eroded, the chloride is a ~1 m thick (Fig. 5c,d,e), rather than the full volume of the landform. This is consistent with later, shallow water bodies depositing thin chloride precipitates on top of extant topography.

3.2.2 Sinuous features and chlorides in channels

Chloride appears in channels across the globe (Fig. 2c) and is mostly associated with locations of valley networks and, indeed, is often within the valley networks (e.g. Fig. 1c; Fig. S5). Chloride deposits follow small channels within a wider valley draining into Knobel crater, with larger deposits in localized depressions (Fig. 6), and in several volcanically resurfaced planum around the Tharsis region (Fig. 7-8). At the CTX scale, about 70% of chloride clusters (269/387) have sinuous channels that extend topographically lower toward the main deposit within the 10 km buffer, and ~20-25% of chloride deposit clusters (82/387 in CTX; 31/124 in HiRISE) have a light-toned unit consistent with chloride directly within channels (Fig. 2c). This occurrence rate is a significant increase from the lower resolution data available at the time of the Osterloo et al. (2010) survey, which found ~8% of the deposits to have sinuous or linear features.

3.2.3 Perched chloride deposits

While almost all chlorides are present in local lows (as noted in Osterloo et al., 2008, 2010), MOLA gridded data shows that the majority (228/392; 58%) are not actually at the lowest elevation within the 10 km buffer (e.g. Fig. 1). Of these perched deposits, about half (103/228) are >100m above the lowest elevation; ~7% (17/228) are >500m above (Fig. 2d). They are typically in intercrater plains between and topographically above ancient impact craters. There do not appear to be region-specific trends, i.e., perched chloride deposits occur throughout the southern highlands.

Osterloo et al. (2010) noted that while chlorides were widespread in the southern highlands, they were missing in major basins. Our findings are consistent with this, but also demonstrate that the trend holds at smaller scales: chlorides will often be found in intercrater plains but not in
Figure 4. Chloride deposit near Meridiani Planum (8.5 W, 3.1 S; CTX stereo pair P17 007770 1794 & P20 008917 1763). (A) Light-toned chloride unit (outlined in yellow) is present over ~ 50 m of elevation, including in channels leading into the main deposit. (B) HiRISE DEM (PSP 008917 1770 & PSP 007770 1770) shows a small stream leading into a higher elevation pond (top right), and a spill point into the deeper basin 15-30 m below. Chloride-covered basin floor elevation ranges by ~15 m. A mound at an intermediate elevation between the pond and the basin floor is chloride-free. (C) Concentric rings in a small crater suggest multiple stages of evaporation. (D) Chloride deposit thickness, measured near the centre of the deepest part of the basin is ~ 1.5 m. Fractures in chloride continue across minor topographic changes, indicating that it is a single layer draped on top of underlying topography. (E) A small impact crater punches through the chloride deposit, spreading dark ejecta (depth of crater < ~ 3 m). (F) Chloride deposits exist at a wide range of elevations (>50 m) and over slopes in contiguous parts of the deposit.
Figure 5. Chloride deposit in the southwest Tharsis region near Icaria Rupes (139.1 W, 38.8 S; Fig. 9 for age dating). (A) Light toned, ridged chloride unit is present in topographic low. Small, chloride filled channels lead into the main deposit (e.g., white arrow). (B) Context for (A). MOLA topography on CTX showing his chloride deposit is surrounded by channels, leading downhill from Noachian highlands onto flat volcanic plains. (C) Purple-white, fractured chloride is draped on underlying ridged topography, covering ridges up to ~3 m high, and sometimes appearing to chip away from the ridge crest (white arrows; thickness below HiRISE DEM resolution, <1 m). (D) While chloride covers some ridges, topography taller than ~ 3 m is not covered with chloride (white arrows), indicating that the water level was less than ~ 3m deep at the time of deposition. (E) Light-toned, fractured chloride deposit draped on underlying topography (e.g., ridge indicated by white arrow). Chloride here is <0.5-1m thick. (F) Chloride deposits exist at a wide range of elevations (>50 m) and over slopes in contiguous parts of the deposit.
adjacent crater bottoms, even when (a) craters are so degraded that there is not a significant crater rim to prevent spilling over, and (b) CRISM data show other minerals in crater floors, indicating dust obscuration is not precluding detection (e.g. Cross crater, Columbus crater).

3.2.4 Multi-elevation and asymmetric chloride deposits

Most deposits are at multiple elevations in highly localized topographic lows but taller ridges/knobs do not have chloride; examples are provided from four sites (Fig. 4-6; Fig. S5). In gridded MOLA elevation data, 171/392 (44%) of chloride deposit clusters range over >10m elevation between different parts of same deposit or cluster (median: 40 m, maximum: 300m) (Fig. S6). This is very different from playa salt deposits on Earth (Fig. S7), often invoked as a likely analog for martian chlorides (e.g. Osterloo et al., 2010; Glotch et al., 2010; Ye et al., 2019; Huang et al., 2018; El Maarry et al., 2013). On Mars, contiguous chloride deposits typically have slopes around 1% (~0.5-5%; Table S1), while terrestrial salt flats have slopes around 0.05% (one to two orders of magnitude flatter).

3.2.4.1 Chloride adjacent to Meridiani Planum

This deposit exists within a larger basin (Fig. 4a,b) and has chloride-filled channels leading into it from the east. Fractured chlorides on the basin floor have crust-like morphologies, similar to chlorides at Death Valley (Fig. S7). Around the edge of the deposit, a crater with a set of concentric rings likely records stages of evaporation (Fig. 4c). While chloride is present at a range of elevations (Fig. 4f), there is an asymmetry typical of Martian chloride deposits. Chloride occurs on the side of the basin where the channels are leading in; there is not matching chloride on the opposite side of the basin, as we would expect if the basin had been filled to the level of the highest chloride deposit. We see no trace of chloride on many mound/islands, despite being surrounded by chloride on all sides. This limits the maximum water depth to ~5-10 m at most; markedly different from the interpretation of Hynek et al. (2015) and Melwani Daswani and Kite (2017), who argue for lakes > 100m deep, based on the overall basin shape. Instead, the basin was likely carved during an earlier, wetter era; later, small briny water volumes then slowed into these existing depressions, not filling them completely.

3.2.4.2 Southwest Tharsis chloride
Channels lead into this deposit (white arrow, Fig. 5a; 5b), and a mostly contiguous layer of chloride fills the majority of a basin, atop a volcanic unit (Fig. 5b). Chloride is found atop topographic elements ≤~3 m high, while taller features are left uncovered (Fig. 5d-e). In cross section (Fig. 5f), chloride exists at a ~55 m range of elevations. Again, the elevation distribution is asymmetric, with the chlorides existing at higher elevations on the southern side of the deposit, where channels feed in. A flat-topped volcanic unit is present to the north, with no chloride detections on top of it (Fig. 5a, f), but chloride occurs at elevations up to 10 m higher than the flat top of the volcanic unit, indicating that this deposit was likely fed by surface water runoff from the south, and the basin never filled to capacity. The maximum water level was lower than the top of the volcanic unit, i.e., <~20 m.

3.2.4.3 Chloride adjacent to Knobel crater (near Gale)

This extensive, multipart chloride deposit (Fig. 6) is in a small basin, with an apparent channel leading into it from the southwest. Previous studies (Ehlmann & Buz, 2015; Huang et al., 2018) have interpreted chloride to be in stratigraphic layers with small patches of chloride in erosional windows. While chloride does appear to be in a layer, covered by ejecta in one part of the deposit (Fig. 6b), we also see small pond-like chloride deposits with crisp edges within the ejecta (Fig. 6c), and other patches consistent with ponds at a variety of elevations (~50 m over 8 km). In lower parts of the basin, we see a few chloride-free mesa tops, despite being surrounded by chloride (Fig. 6d, e, f). If these mesas were part of a capping unit overlying chloride, we would expect to see the same unit at similar elevations around the deposit edge. Instead, a contiguous layer of chloride slopes down to the basin from elevations well above the mesa tops. These observations of asymmetric elevation deposits are consistent with an existing chloride deposit upstream and within the topographic low, hit by an impact crater (providing a chloride source at high elevation around the crater rim), and reworked by small volumes of water to form the draped morphologies observed. Basin-filling volumes of water would have left behind chlorides on mesa tops, rather than only ~6 m up the sides as observed.
Figure 6. Chloride deposit adjacent to Knobel crater (132.0 E, 6.4 S; CTX DEM built from P20_008780 1727 XN and F22_044502 1732 XN). A) The light toned chloride unit is within a local low fed by a channel from the south, impacted by a small crater. Inferred stratigraphic relationships vary across the deposit. (B) a chloride deposit (purple in HiRISE color (ESP 044502 1735)) is in a layer exposed in small cliff edge and may pre-date the impact crater in the centre of (A). (C) Within the impact ejecta blanker are small, thin patches of chlorides (PSP 008780 1735), which appear to drape underlying topography; we interpret these as small ponds that occurred after the impact event. (D) Larger patches of chloride, with crisp edges corresponding to topographic lows, are also consistent with ponding (ESP 044502 1735). The purple chloride unit does not fully cover the topographic high (black arrow). (E) A flat-topped mesa is not covered by chloride, despite being surrounded by light toned, fractured chloride. Chlorides are found from the basin bottom up to ~ 6 m up the mesa. This mesa is at a lower elevation than nearby contiguous chloride deposits (see cross section F-F’); if the chloride were in a stratigraphic layer rather than draped, we would see other exposures of a non-chloride layer at this elevation, instead of contiguous chloride. (F) Cross section derived from HiRISE DEM (stereo pair: ESP 044502 1735 & PSP 008780 1735) showing chloride at a wide range of elevations, and in some cases following slopes; this could result from small volumes of briny runoff, carried downhill, ponding to a max water level of ~ 6 m in the lowest areas.
Osterloo et al. (2010), using published maps from 1986 (Tanaka) and 1987 (Greeley and Guest), found that most deposits were within Noachian terrains and ~24% within Hesperian terrains. Using the updated Tanaka et al. (2014) global map of Mars with unit ages, we find that only 7 deposits (/642) are in terrains mapped as Hesperian, near the edges of the Tharsis and Hesperia volcanic terrains. The rest are within Noachian terrains, consistent with work by Hill and Christiansen (2019). However, this type of analysis only provides an oldest-bound on the age. We found a number of sites where chloride was clearly on top of volcanic terrain, e.g. chloride in superimposed channels or on top of a surface with wrinkle ridges. When possible, we performed crater-counting to obtain more constrained oldest-bound ages, using the best local constraints. In one location, we obtained a youngest-bound age, using cross cutting fracture relationships (Fig. 9).

3.3.1 Icaria Fossae, South Tharsis

The Icaria Fossae region south of Tharsis hosts chloride deposits that are cut by the fractures (Fig. 10a-c), indicating that the chloride was deposited prior to fracturing but after the underlying terrain was formed. Nearby, a similar flat basin exists where the same suite of fractures that cut the chlorides are erased by deposition of a younger unit (Fig. 9d). This surface unit must thus be younger than the chloride deposits, providing both an upper and lower age bound to constrain chloride age in this location. The terrain underlying chloride (red) is dated at 3.3 Ga, while the nearby (blue) basin was resurfaced 2.0 Ga (Fig. 9e, f), meaning the chlorides were deposited between 3.3-2.0 Ga, Late Hesperian to Early Amazonian. By contrast, in the global scale Tanaka et al. (2014) map, these terrains are respectively classified as Late Noachian highlands and Early Hesperian volcanics.
Figure 7. Age of three chloride deposits near Thaumasia Planum and Bosporous Planum, East Tharsis. (A) Three regions with chloride are defined by topographic boundaries. (B) In the small purple region, light toned chloride deposit is found within a channel that cross-cuts a dateable surface (see also Fig. S7). (C) In the green region, the chloride deposit partially infills a channel at the surface on the wrinkle ridged dateable surface. (D) The magenta region in Bosporous Planum contains many chloride deposits, many of which are also in channels crossing the surface. (E) Purple region has a resurfacing age of ~ 3.3 Ga (resurfaced terrain ~ 3.7 Ga). (F) Green region has a resurfacing age of ~3.4 Ga, resetting craters smaller than ~ 10 km diameter, and an older age at 3.7 Ga. (G) Magenta region yields a uniform age of ~ 3.3 Ga.
Figure 8. Age of dateable chloride-bearing terrains on Mars. (A) Chloride deposits on the eastern edge of Hesperia Planum and in nearby Noachian highlands. (B) Chlorides are on top of Hesperian lava flow and occur within a channel (possibly a collapsed lava tube), indicating deposition after emplacement and resurfacing of the lava flow. (C) Crater counting results from the lava flow in the orange area in (A) show a resurfacing age of 3.4 Ga (and older age ~ 3.6 Ga). (D) Southwest Tharsis site (detail in Fig. 6) near Icaria Rupes has an underlying large, smooth unit, likely a lava flow. (E) The chloride deposit is present within channels incising the lava flow unit, indicating that the chlorides are younger than the volcanic unit. (F) Crater counting for the blue region in (D) yields an age of 2.3 Ga. (G) Cluster of chloride deposits on a volcanic unit in Noachis Terra. (H) Chloride is present within channels on top of this unit (white arrow) and deposits drape over a wrinkle ridge (black arrow). (I) Crater counting for cyan in (G) gives a resurfacing age of ~3.6 Ga (older surface ~3.8 Ga).
3.3.2 East Tharsis (Bosporos & Thaumasia Plana)

On volcanic units east of Tharsis, chlorides are present at three distinct elevations (Fig. 7a). In a small basin in Thaumasia Planum, chloride is deposited within a channel (Fig. 7b), immediately downhill from remnants of Noachian highlands with Fe/Mg clays (Fig. S8), and in an adjacent depression, a local depression has chloride-infilled channels cut into a volcanic unit (Fig. 7c). To the south, Bosporus Planum hosts a unit with many chlorides occurring within dissecting channels (Fig. 7d). At these three locales, terrains immediately under the chlorides were
resurfaced at 3.3-3.4 Ga (Fig. 7e-f), prior to chloride deposition. The two high elevation localities also record an older 3.7 Ga age. In the global scale Tanaka et al. (2014) map, these terrains are all classified as Late Noachian volcanics, corresponding to this oldest age, but local mapping establishes the oldest-bound on timing of the chlorides was Late Hesperian (<3.4 Ga).

3.3.3 East Hesperia Planum

At the eastern edge of Hesperia Planum, chlorides are detected atop volcanic terrain and in Noachian highlands nearby (Fig. 8a). The chloride in Hesperia Planum is located within a channel (Fig. 8b), indicating that it was emplaced after the volcanic unit. This unit has a resurfacing age of 3.4 Ga (older age is 3.6 Ga); chlorides must be younger than 3.4 Ga (Late Hesperian). In the global scale Tanaka et al. (2014) map, this unit is classified as Early Hesperian volcanic.

3.3.4 SW Tharsis

Chlorides are present on top of a smooth volcanic unit southwest of Tharsis, (Fig. 8d), where they are sometimes found in channels (Fig. 8e). This large, flat volcanic unit is dated at 2.3 Ga. Because the chlorides are on top of it, they must be younger than ~2.3 Ga, Early Amazonian. In the global scale Tanaka et al. (2014) map, this unit is classified as Early Hesperian volcanic.

3.3.5 Noachis Terra

Here, chlorides are on top of an older volcanic unit (flat area with wrinkle ridges; Fig. 8g), present in channels (white arrow in Fig. 8h) and draping over a wrinkle ridge (black arrow, Fig. 9h). This unit has a resurfacing age of 3.6 Ga (underlying terrain dated to 3.8 Ga). In the global scale Tanaka et al. (2014) map, this unit is classified as Late Noachian highland.

4 Discussion

4.1 Earth analogs for surface water-deposited Martian chlorides

In our analysis of Martian chlorides, all lines of evidence point to surface water runoff. We observe even more channels feeding into the deposits than reported previously. Evidence for
small volumes of water includes ponding at multiple elevations, asymmetry in deposits (high on one side, where channels lead in, and much lower on the other side), and draping textures where slightly higher topographic highs (>3 m) are generally not covered by chlorides. For a larger volume of water, deposits would have been more likely to form a flat layer rather than being influenced by underlying topography. Our thickness estimates lower than prior literature, <~3 m and typically <~1 m thick layers, are also consistent with small volumes of water.

On Earth, large-scale chloride deposits are most commonly associated with arid playa environments, such as the halite salt flats in Badwater Basin (Death Valley, California; Fig. S7). These environments have meter-scale polygonal ridges and/or fractures (Fig. S7d, e), similar to the characteristics of martian chlorides. However, these environments are extremely flat (<1 m elevation change over ~2.5 km; Fig. S7c; LiDAR data from Snyder, 2005), groundwater fills the basin and cycles of flooding and evaporation level the topography. As the last salt to crystalize in a sequence, playa chlorides are typically in the lowest topographic depressions and their chloride deposits many tens of meters-thick as they are zones of groundwater upwelling for local watersheds. This is very dissimilar to the martian chloride examples.

A more analogous terrestrial environment is paternoster lakes, glacial-fed lakes that are connected by streams, occurring at different elevation steps. A saline example is found in the Antarctic Dry Valleys (Fig. 10) (e.g., Meyer et al., 1962). Don Juan pond is in a local topographic low in the valley bottom with a bright white ring of salt around a shallow muddy pond (Fig. 10c). Salt crusts show a sharp contact at the edge (Fig. 10d) with salt encrusting short boulders (~< 10 cm). Both groundwater (e.g. Toner and Sletten, 2013) and deliquescence plus snowmelt (Dickson et al., 2013) have been proposed as water sources for Don Juan Pond. Dickson et al. (2013) observe seasonal flow of chloride-rich brines on top of a permafrost layer a few meters below the surface. Downstream in the valley is Lake Vanda, which has chloride-rich bottom waters (Angino and Armitage, 1963). The ~15 m elevation difference over 10-15 km is similar to martian chloride deposits; they do not exhibit the polygonal fracturing/ridges that we see in playa environments and on Mars, probably because they are still active/wet.
4.2 Water source for the chloride deposits

Meltwater runoff from snow/ice, either seasonal or episodic, likely supplied the overland water flow necessary for the chloride deposits. Today, we only see thin seasonal water frosts in the southern highlands of Mars (e.g., Fig. S4; Vincendon et al., 2010), which would likely not provide enough brine for the km²-scale chloride deposits, even if temperatures and pressures were high enough to allow for melting rather than sublimation. However, in the Hesperian and late Amazonian, such southern highlands surface ice deposits and subsurface ice or permafrost may have been more widespread, thicker, and able to melt and provide a water source, during certain obliquity regimes (e.g., Wordsworth et al., 2015). A few locations show concentric rings in chloride deposits (Fig. 4c, S5d), which might reflect multistage evaporation or repeated wet/dry cycles. Additionally, rare episodes of precipitation (e.g. due to volcanic outgassing)
could provide a source of surface runoff; such precipitation might be enriched in chlorine (e.g. Nekvasil et al., 2019) (see 4.3).

An alternative source for small volumes of water is deliquescence, where salt minerals present in the soil can adsorb water vapor from the air and form a concentrated brine when the relative humidity is high enough (as observed in Antarctica; Dickson et al., 2013). This may contribute to the observed deposits but does not seem likely to generate the overland flow seemingly required for 1-3 m thickness of chloride enrichment in some locales, although further modeling of deliquescence water volumes may be an avenue for future work.

4.3 Ion sources for chloride deposits

Our results concur with previous studies that have noted chloride deposits’ relationship with Fe/Mg clays as well as a lack of association with other salts (sulfate, carbonate) that are typically associated with large-scale chloride deposits on Earth (Ruesch et al., 2012; El Maary et al., 2013). Even using machine learning techniques (Dundar et al., 2019) and searching every targeted longwave CRISM image that intersects chloride, we were unable to find any small deposits of accompanying salt minerals. We do not observe phases other than Fe/Mg clay minerals when impact craters have broken through a chloride-enriched layer. Thus, it appears carbonate and sulfates may be effectively absent, or if present, be buried deeper than is typical for playa mineralization sequences with CO$_3^{2-}$, SO$_4^{2-}$, and Cl$^-$ ions.

Chloride ion sources include magmatic gases from volcanism as globally distributed atmospheric gases or from local fumaroles, leaching and alteration from igneous crust, or remobilization of older chloride deposits. In agreement with previous work (e.g. Osterloo et al., 2010; Ruesch et al., 2014), we do not believe that any local volcanic sources are likely or required, given the lack of observed fumarole structures and silica or sulfate accessory minerals.

Chloride contents of soils, dust, and sedimentary rocks on Mars range from ~0.3-3 wt. % with unaltered igneous rocks sometimes lower (Berger et al., 2016; Haskin et al., 2005; Thomas et al., 2019). We assume halite and estimate how much material would (1) have to be fully leached to generate all chloride deposits observed and (b) how much material contains enough chloride to account for a median chloride deposit (~10 km$^2$, ~1m thick). Across the southern highlands, the
total area of the chloride deposits is ~14,000 km$^2$ (Osterloo et al., 2010). Assuming a layer ~1 m thick of 25% halite (Glotch et al., 2016), this translates to ~1x10$^{14}$ mols Cl. For a density of typical rocky materials (3000 kg/m$^3$), this amount of chlorine would be present in a layer 0.7-7 mm thick across the southern highlands (area ~6.5 x10$^7$ km$^2$). But the chloride deposit-forming processes appear to be more locally controlled, involving small amounts of water moving through local topographic lows, so as a more appropriate metric, we find that chloride derived from the top 3-30 cm of typical martian materials would need to be leached over a 1000 km$^2$ area to create a median chloride cluster. Indeed, ~1000 km$^2$ is the typical area included within the 10 km buffer zone around a deposit and is the size of several of the larger basins in which small chloride deposits are found (e.g. Fig. 1a). Since we know capillary action can access the top meters of porous media, these calculations mean leaching from the top soil layer is a plausible chlorine source, if the fluid and rock chemistry and duration enables leaching.

We propose a conceptual model that explains the observed characteristics of chloride deposits (Fig. 11). Either large-scale volcanic processes or chemical weathering enrich Cl in Martian dust, soils, and sedimentary rocks (e.g. Settle, 1979; Clark and van Hart, 1981; Nekvasil et al., 2019). Widespread Fe/Mg clays across the Noachian highlands are an indication that chloride ions may already have been released into more mobile phases by significant earlier alteration of igneous rock (Milliken et al., 2009). To generate large-scale areas of concentrated chlorides, capillary action with small water volumes derived from melt dissolves Cl-bearing phases in the top ~1 meter of soil and generates surfaces/near-surfaces enriched in chloride precipitated during water evaporation/sublimation. Small volumes of low temperature water preferentially dissolve just the most soluble salts (chlorides), providing a mechanism for separating chlorides and retention of less-soluble sulfates like Ca sulfates in the subsurface, where they are hidden from remote sensing. Such mobility has been observed in soils at Gusev crater where both Cl and S are enriched in soils but Cl is more enriched at the surface relative to S (Haskin et al., 2005). Small volumes of meltwater—likely repeatedly—then mobilize small salt deposits and aggregate them in local topographic lows. Clay-bearing soils (e.g., Warren et al., 2003) or permafrost (Dickson et al., 2013) may serve to inhibit infiltration of meltwaters into the subsurface.
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Figure 11. Schematic diagram for chloride formation (A) At end of a surface water epoch, evaporation/capillary action form a salt crust in regions with impermeable clays. (B) Water ice accumulates (e.g. at elevation, or on pole-facing slopes). (C) Ice melts, sending small volumes of meltwater downstream. Previously deposited salt crusts may be dissolved, creating briny waters, redepositing in local topographic lows. Clays or permafrost prevent infiltration of the transported surface waters. (D) Freezing/evaporation occurs, leaving perched and/or asymmetric salt deposits (rather than basin-filling rings of salt).

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4.4 Timing

Although chloride deposits are found overwhelmingly in Noachian and early Hesperian terrain (3.9-3.6 Ga) when considered at Tanaka et al. (2014) map scale (e.g. Osterloo et al., 2010), because the chlorides drape on these surfaces, this only provides a no-older-than bound. Where crater counts on local units with clear stratigraphic relationships are possible, these typically indicate much younger oldest bounds. Hynek et al. (2015) date the Meridiani chlorides to be <3.6 Ga, while Ehlmann and Buz (2015) and Huang et al. (2018) date the underlying Knobel terrain to ~3.7 Ga and the overlying capping rock to 1.1 Ga. Here we show several chloride deposits must be younger than ~3.3-3.4 Ga (Hesperian), one must have formed between 3.3 Ga and 2.0 Ga, and there is even one that is on top of Amazonian terrain (younger than 2.3 Ga).
Taking into account both our age dates and those of previous studies, we conclude that chloride deposits might have started to form in the Noachian, but the processes creating these deposits continued until at least the Early Amazonian ~2.3 Ga. Given the crisp, fresh appearance of these deposits in spite of being within erodible deposits in dusty regions, we hypothesize that a significant proportion of them may even be on the younger side of the age range, though dateable units are not nearby to prove. The persistence of episodes of small volumes of water into the Amazonian is consistent with other recent observations in Gale crater of young small valleys and Amazonian age dates of diagenetic minerals (e.g. Ehlmann and Buz, 2015; Grant et al., 2019; Martin et al., 2017).

4.5 Explaining the global spatial distribution of chloride deposits

A long-standing, puzzling fact about the chloride deposits has been that they are almost all in highlands south of the equator and not in highlands regions north of the equator (e.g. Mawrth Vallis, NE Syrtis). This is a clue about Martian paleoenvironmental conditions and not merely a detectability issue as many other alteration minerals are found in these terrains (Ehlmann and Edwards, 2014). Prior work has suggested chloride deposits follow the same approximate distribution as the valley networks (Hynek et al., 2010; see Fig. 2a). We agree but also conclude that the fact that valley networks north of the equator lack the chloride deposits detectable at THEMIS resolution (Fig. 2a) is important to understanding chloride deposit origin and timing. Bouley et al. (2016) propose that the valley networks formed prior to true polar wander, induced by reorientation of the volcanic Tharsis bulge to the equator. They demonstrate that the densest valley networks line up with a ~0°-30°S zone of maximum modelled precipitation in Mars’ expected pre-Tharsis orientation. We note that the chloride deposits align with the ~0°-30°S zone of maximum expected precipitation in the present orientation of Mars, thus indicating that the chloride deposits likely formed after this true polar wander was complete (Hesperian or later). That is, the chlorides do indeed occur in locations with prior valley networks—and highlands clays deposits that indicate paleoweathering—but, importantly, only where precipitation is favored in the modern climate regime. Future work with climate models should focus on modeling conditions that enable late Amazonian surface waters to form large-scale chlorides with the minimum water quantities needed to reproduce the thin, perched, draped deposits.
5 Conclusions

Chloride deposits found across the southern highlands of Mars likely represent small volumes of surface water, deposited in existing topographic lows such as old channels and resurfaced lake basins. Chloride deposits tend to be draped on top of underlying topography, and at a range of elevations, unlike playa environments or evaporites from deep lakes on Earth. The deposits are thin (<3 m) and asymmetric with greater thicknesses near inlet channels. Despite being found in local topographic lows, many chloride deposits are within 10 km of even deeper lows with no signs that groundwater upwelling is responsible for these deposits. Instead, surface runoff is the most likely water source, from sources like seasonal or episodic melting of ice or permafrost. Their distribution south of the equator is coarsely consistent with predictions for ice deposition as snow on Amazonian Mars over obliquity cycles. Saline paternoster lakes in the Dry Valleys, Antarctica are an analogous terrestrial analog environment.

Weathering of basaltic materials to clay minerals releases cations. Mass balance calculations show sufficient chloride anions to generate the observed deposits could be leached from the top layer (<1 m) of soil/dust in the highlands surrounding the topographic lows. Supply of Cl in volcanic aerosols may also contribute. The deposits are self-consistently explained by chloride sourced in observed nearby clay-bearing Noachian highlands—by leaching of rocks and sediments or remobilizing earlier-formed salt deposits—transport of small volumes of meltwater downhill leading to deposition atop younger terrains.

While our update of the statistics of distribution relative to the latest global-scale geologic maps shows the vast majority (97%) of chlorides are superimposed on Noachian terrains, these are simply oldest-bounds on the age of the chlorides. Those sites that allow detailed age-dating by crater counting with local units with superposition relationships show, in multiple cases, chloride deposit formation between 3.4-2.3 Ga. Thus, we conclude that Mars’ chloride deposits record the last large-scale waters on Mars and continued to form into the Amazonian by surface liquid water flow.

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site < doi link TBD – to be populated at revisions >.

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