Surface grain size of alluvial fans on Mars from thermal inertia, as an indicator of depositional style

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Keywords:
Geological processes; Infrared observations; Mars, surface; Terrestrial planets

Abstract

The depositional history of alluvial fans on Mars provides insight into the climatic conditions during the time of fan formation in the late Hesperian to early Amazonian. However, traditional stratigraphic analysis of the alluvial fan deposits is not possible across most of Mars. This study assesses the use of thermal inertia data as a tool for sedimentologic interpretation of 437 Mars alluvial fans. Based on previous work demonstrating the relationship between depositional style, grain size, and thermophysical properties, this study uses analysis of the thermal inertia of alluvial fan surfaces across the global population of fans on Mars to make an assessment of depositional styles that built the alluvial fans. The thermal inertia values across the global population of fans are indicative of sand- to pebble-sized sediment. The variability of grain sizes across the global population is more homogenous than expected based on comparisons to terrestrial alluvial fans. Nearly all Mars alluvial fans have an average thermal inertia that corresponds to pebble and smaller grain size, and < 1% of Mars alluvial fans have an average thermal inertia that corresponds to cobble-sized grains. Spatial patterns of thermal inertia variability on alluvial fan surfaces show a small number of fans with evidence for either downslope fining or channelization, but the majority of fans show no recognizable geologic patterns in surface thermal inertia. The interpretation of the thermal inertia-derived grain size suggests that either there is widespread mantling of unconsolidated sand across the surface, or that Mars alluvial fans were built by primarily sand-sized sediment, which may be indicative of lower energy sediment transport events.

1 Introduction

The depositional style and associated sedimentary characteristics of alluvial fans can be used to interpret environmental conditions of deposition, including water volumes, transport energy of runoff events, and potential climatic conditions. On Earth, alluvial fans are primarily built by a combination of bedload transport and sediment gravity flow processes (Blair, 1999; Ventra and Clarke, 2018). Determination of depositional processes in terrestrial fans is typically done through stratigraphic analysis of subsurface layers. Sediment gravity debris flows are poorly sorted deposits containing pebble- to cobble-sized or larger clasts suspended in a fine grain matrix, while deposits from bedload transport are typically dominated by sand- to pebble-sized sediment with very little matrix material (Blair and McPherson, 2009; Larsen and Steel, 1978; Ventra and Clarke, 2018). On the surfaces of terrestrial alluvial fans, the bimodality of debris flow deposits is rarely preserved in the long term due to winnowing of fine grained material, resulting in a concentration of larger clasts on the surface (Blair and McPherson, 1992; Nishiizumi et al., 2005). In alluvial fan sedimentology, the clast size on a fan surface can be indicative of depositional style and transport energy within a deposit. The two end-member cases can be described as A) a concentration of cobble- to boulder-sized clasts suggesting the presence of debris-flow deposits, and B) ubiquitous sand-sized sediment suggesting relatively low-energy bedload transport. Within that range a variety of mixed-case scenarios are possible, which we collectively interpret as uncertain depositional style within this study.

Grain size of sedimentary surfaces is not directly measurable across most of Mars due to the limited resolution of orbital visible image datasets and the small number of sites visited by landed missions. The available visible-image CTX data (~5 m/px) is too low resolution to detect individual clasts. Larger boulder-sized clasts are detectable in HiRISE image data (~30cm/px), but because multiple adjacent pixels are required to confidently resolve an object, smaller boulders (~25 – 90 cm diameter) along with the cobble and smaller clasts are still below the limit of resolution. The global coverage of HiRISE data is also too sparse to use as an analysis tool for a global population of alluvial fans. In comparison, there exists near global coverage of THEMIS infrared data and derived thermal inertia (TI) data products (Christensen et al., 2013; Fergason et al., 2006).

TI values derived from THEMIS nighttime infrared images can be used as a proxy for grain size on Mars (Edgett and Christensen, 1991; Edwards et al., 2009; Nowicki and Christensen, 2007). The quantitative relationship between TI values and sedimentary grain size has been confirmed with rover grain size observations in areas where the surface sediment characteristics are homogeneous over the scale of a THEMIS image footprint (Ahern et al., 2021; Edwards et al., 2018; McCarty and Moersch, 2020; Yingst et al., 2016). Previous studies of terrestrial alluvial fans have shown that thermophysical properties of terrestrial fan surfaces correlate to sedimentary characteristics of surface deposits, including grain size (Hardgrove et al., 2010, 2009).

In this study, we analyze the average and range of TI values within individual fan surfaces to interpret the sedimentary grain size of each alluvial fan deposit and investigate regional and global trends in grain size across a global population of alluvial fans on Mars. We also investigate common spatial patterns of TI distribution on alluvial fan surfaces to assess potential depositional trends. From the TI spatial patterns and TI-derived grain size we infer the likely depositional style of each alluvial fan and discuss the possible implications for Mars climate during the late Hesperian to early Amazonian, when alluvial fans are thought to have formed (Holo et al., 2021; Kite, 2019; Rodriguez et al., 2005; Warner et al., 2009).

2 Background

2.1 Alluvial fans on Mars

Alluvial fans are found on Mars concentrated across the cratered highlands and the high southern latitudes (Mondro et al., 2023; Wilson et al., 2021). Alluvial fans are formed by sporadic, high-energy sediment transport events interspersed with periods of inactivity (Beaty, 1990; Blair and McPherson, 1994; D'Arcy et al., 2017; McDonald et al., 2003). Previous work suggests that Mars alluvial fans formed during the late Hesperian to early Amazonian during the final stages of liquid water activity on the surface (Carr and Head, 2010; Holo et al., 2021).

Age dating of alluvial fans on Mars depends on an accurate assessment of the surrounding surface. Because the alluvial fan surfaces are typically too small to accurately date by crater counting, previous work has relied on an interpretation of cross-cutting and superposition relationships in crater floor deposits along with dating fan-hosting craters (Grant and Wilson, 2011; Holo et al., 2021; Palucis et al., 2014). Recent work has focused on refining the age dating of craters by crater counts on the ejecta of large craters, which in turn gives a more precise age for the upper limit of fan formation within those craters. At least some alluvial fans were found to be hosted in craters that are < 2.5 Ga, indicating fan formation conditions persisted into the Amazonian in at least some regions (Holo et al., 2021). This is consistent with findings from previous work which used cross-cutting relationships of crater floor deposits to date individual fans (Palucis et al., 2014) and small populations of fans (Grant and Wilson, 2011).

In the time since the cessation of water activity on the surface of Mars, alluvial fans have been exposed to aeolian erosional and impact processes which have altered the fan surfaces but not eroded them completely. Modern alluvial fan surfaces viewed in orbital data (Dickson et al., 2023; Fergason et al., 2006; Laura et al., 2023) show wind-scoured surfaces with remnant features which may be related to original depositional events (Figure 1). The example fans in Figure 1 contain a pattern of channel-like features detectable in CTX visible image data and also exhibit layered features, which may be sedimentary strata, exposed along the edges of these remnant channels.

2.2 Thermal Inertia as a proxy for grain size and depositional style

Surface temperatures inferred from thermal infrared spectral radiance measurements are used to calculate the thermal inertia of particulate material (Edgett and Christensen, 1991;

Kieffer et al., 1977; Nowicki and Christensen, 2007; Presley and Christensen, 1997a, 1997b). Thermal inertia values are related to the effective grain-size via a physical and analytical model of radiation transport (Kieffer et al., 1977). A material's thermal inertia is a measurement of how resistant the material is to changes in temperature. It is defined as

$$TI=(k\rho C)^{1/2},$$

where k is the thermal conductivity, ρ is the bulk density, and C is the specific heat capacity of the surface (Kieffer et al., 1977). The units of thermal inertia (TI) are $[J \cdot m^{-2} \cdot K^{-1} \cdot s^{-1/2}]$ although for simplicity, they are referred to as thermal inertia units (tiu) in this manuscript. For rock and regolith material, thermal inertia is primarily controlled by the thermal conductivity, which is dominated by variations in grain size (Presley and Christensen, 1997). The temperature of fine-grained sediment, which has a low TI and exhibits larger diurnal temperature changes, changes rapidly under insolation and cools down faster at night. Coarse-grained sediment or highly indurated surfaces, which have high TI, take much longer to heat up under insolation but are able to retain heat much more effectively at night, resulting in smaller diurnal temperature changes.

Using the framework developed by previous studies of Mars (Edgett and Christensen, 1991; Nowicki and Christensen, 2007; Presley and Christensen, 1997a, 1997b) which confirm TI values that correlate to specific grain sizes, it is possible to relate the TI of alluvial fan surfaces to sedimentary grain size in Mars sedimentary environments. In terrestrial landscapes, apparent thermal inertia (ATI) is used as a proxy for relative TI (Gupta, 2018). An exact, quantitative relationship between grain size and TI is not applicable to terrestrial conditions due to the variability of weather, humidity, and presence of water in the atmosphere and at the surface, which drastically affects measurable TI of terrestrial sedimentary material because of its high heat capacity. However, previous work on terrestrial alluvial fans shows that there is a correlation between the relative thermophysical characteristics of alluvial fan surfaces and grain sizes of the sediment at the surface (Hardgrove et al., 2010, 2009). In a survey of alluvial fans in the Death Valley region, the total diurnal change in surface temperature ($\Delta T = T_{max} - T_{min}$) is highest for fine-grained material, while cobble- and boulder-covered surfaces and indurated features have low ΔT values (Hardgrove et al., 2010, 2009). Apparent thermal inertia is inversely correlated to ΔT in the equation for ATI when albedo variations are small across the region of comparison (Gupta, 2018). While these results do not provide a precise quantitative relationship between grain size measurements and ATI values in terrestrial settings, the demonstrated correlation supports the use of TI to determine depositional grain size on Mars alluvial fans based on the established quantitative framework of TI and grain size.

Debris-flow deposits are identified in outcrop as thick sections of matrix-supported material dominated by clasts that are cobble size up to the size of large boulders, with very little sand material (Blair and McPherson, 2009). Across the lateral exposure of alluvial fan surfaces, debris-flow deposits can be identified by accumulations of coarse (cobble or larger) clasts in lobe shaped deposits (Blair and McPherson, 1992). While debris flow sediment is typically bimodal, with coarse clasts suspended in a fine-grained, clay-rich matrix, the fine grained sediment has a shorter residence time on fan surfaces post-deposition, as fine grained material is more susceptible to winnowing and downslope transport from reworking (Beaty, 1990; Blair and McPherson, 1992; Nishiizumi et al., 2005).

Bedload transport deposits are identified in outcrop as planar layers 10s of cm thick, composed of sand- to cobble-sized sediment (Blair and McPherson, 2009). Laterally extensive bedload transport events that are not channel-confined are referred to as sheet floods (Blair and McPherson, 1994). Exposure of sheet-flood deposits across alluvial fan surfaces are identified by laterally extensive deposits of well- to moderately-sorted sand to pebble material (Blair, 2002, 1999). Downslope fining of grain sizes on alluvial fan surfaces is common on sheet-flood fans, as finer sediment requires less transport energy and is carried further (de Haas et al., 2014; Ventra and Clarke, 2018).

The alluvial fans on Mars are thought to be at least 2.5 Gy old and are hypothesized to have been depositionally inactive since then (Holo et al., 2021). Because of the combination of post-depositional reworking in the form of channelization and aeolian erosion of inactive fan surfaces, pristine sheet flood or debris flow features are unlikely to be recognizable on the modern surfaces of Mars alluvial fans. Traditional stratigraphic analysis of alluvial fan depositional history cannot be duplicated on Mars short of targeted rover exploration. As a proxy, we are assessing the sedimentary characteristics of alluvial fan surfaces from orbital data. While the surface analysis does not allow for detailed stratigraphic analysis of successive depositional events within a single fan, analysis of surface sedimentary grain sizes across the global population of alluvial fans still provides insight into global trends in the final stages of fan formation.

In analyzing modern alluvial fan surfaces, we are not necessarily characterizing the most recent fan deposits but instead, are characterizing what is currently at the surface after ~2.5 Gy (Holo et al., 2021) of non-deposition and erosion. The majority of alluvial fans are thought to have formed between the Early Hesperian and the Early Amazonian (Kite, 2019). However there is some evidence that alluvial fan formation overlapped with the formation of valley networks in the Late Noachian (Moore and Howard, 2005) and more recent work suggests that alluvial fan formation could have persisted into the middle Amazonian (Holo et al., 2021). With these uncertainties in mind, there are three possible interpretations we can make about what is currently exposed at the surface of the alluvial fans. Modern fan surfaces are either A) the final stage of fan deposition with no significant erosion since then, B) an eroded surface parallel to the original depositional layers, or C) an eroded surface cutting through different levels of previously-buried deposits (Table 1).

Option A is unlikely as it assumes that exposed surfaces experience minimal erosion over 2.5 Gy, which is not consistent with Mars observations. Option B assumes that wind erosion would deflate all fan surfaces precisely parallel to bedding so that only a single depositional layer is exposed at the surface which is inconsistent with Mars' wind-scoured landscape. Option C is the most likely scenario as it accounts for post-depositional wind erosion and allows for the most complexity within a large global system. Even if the style of alluvial fan deposition changed through time across the whole system, a global population of fans with a range of depositional grain sizes, observed as a variety of erosional states, would be expected to capture that variability. From the viewpoint of option C, if there were any significant variability in sedimentary characteristics and depositional style either spatially (across the population) or temporally (within the building of a single fan) we would expect to see a mix of grain sizes across the population of fans. If the alluvial fans across the global population were homogeneous in sedimentary characteristics and depositional style throughout the time of fan formation, then we would expect to see similar grain sizes on the majority of the alluvial fan surfaces.

3 Methods for analysis of Mars alluvial fans

3.1 Selection of alluvial fans

Earlier work produced a catalog of 775 alluvial fans on Mars (Mondro et al., 2023). We mapped the boundaries of each alluvial fan from visible CTX images (Dickson et al., 2023, 2018) and THEMIS day IR images. For the purposes of the mapping process, we defined the depositional boundaries of alluvial fans using visible changes in surface texture that follow an approximately radial pattern away from the identified fan apex location.

We assessed the availability and quality of THEMIS TI data coverage at each feature in the global catalog. We calculated the average dust cover index (DCI) value (Ruff and Christensen, 2002) for each alluvial fan surface and eliminated those features with an average DCI < 0.95, which is noted as the cutoff between "dust-covered areas" with high DCI and "dust-free areas" with low DCI in Ruff and Christensen (2002). As TI variations are most sensitive to grain size differences (Edgett and Christensen, 1991; Presley and Christensen, 1997a), abundant dust covering the fan surfaces will produce TI values that do not accurately represent the sedimentary characteristics of the alluvial fan deposits at the surface.

THEMIS-derived TI data coverage contains small gaps across the surface of Mars and is overall more sparse in high latitudes (Fergason et al., 2006). We eliminated alluvial fans that have no or partial TI coverage in the THEMIS-derived TI Global Mosaic (Fergason et al., 2006). We also eliminated alluvial fans for which the available TI data are unreliable or inconsistent. To determine data reliability, we assessed the TI data covering the fan in comparison to surrounding TI image images within the TI mosaic. We eliminated alluvial fans covered by outlier TI images. TI images were considered to be outliers if they contain nearly uniform TI values in either the highest (TI > 670 tiu) or lowest (TI < 50 tiu) TI grain size categories in contrast to all surrounding TI images. Alluvial fans were considered to have inconsistent TI data if the fan spanned more than one TI image where the adjacent pixel values across the boundary of adjacent TI images jumped by more than one TI grain size category.

3.2 Thermal inertia and grain size of alluvial fans

Previous work has established sedimentary grain size ranges that correlate to specific ranges of TI values on Mars (Edgett and Christensen, 1991; Nowicki and Christensen, 2007).

Based on the results of these previous studies, we defined sedimentary grain size categories by the associated TI value. Due to the uncertainties of the TI values used in the TI global mosaic, we also defined intermediate grain size categories. The derived TI values have an overall uncertainty of 20% globally (Fergason et al., 2006). For the TI values at boundaries between grain size categories, we calculated an uncertainty window from +10% to -10% of the boundary TI value. The resulting ranges of TI values are categorized as an uncertain grain size range; for example, "sand to pebble" for the uncertainty range between the "sand" TI category and the "pebble" TI category (Table 2).

On each alluvial fan for which we confirmed TI data coverage, we extracted TI values from all pixels within the mapped boundary of the fan from the TI global mosaic. For each alluvial fan TI raster, we calculated the mean and standard deviation of TI values within each fan outline. We define "meanTI" as the average of all TI pixel values within the mapped outline of each alluvial fan and "StDv" as one standard deviation of the range of TI pixel values that are used to calculate meanTI. We designated grain size categories for the mean TI value of each alluvial fan, along with grain size categories for the TI values one standard deviation above and below the mean. The standard deviation of TI values on an alluvial fan surface shows the range of TI values and functions as a representation of large-scale heterogeneity in grain size across the surface. We used both the meanTI of the fan surface and the range of TI, defined as +/- one StDv around the meanTI, to interpret the likely depositional style.

We visually assessed the spatial variability of TI values across each fan surface and qualitatively described each alluvial fan based on common TI spatial patterns that are seen within the global population of alluvial fans. Five general patterns are used to describe spatial variability of TI on alluvial fan surfaces. "Gradational" and "channelized" patterns are descriptive of geologic features that have been identified on terrestrial alluvial fans (de Haas et al., 2014; Ventra and Clarke, 2018). "Regional" and "distinct" patterns describe the fan's TI values in comparison to the surrounding surface material when there is no clear spatial pattern within the fan boundaries. The fifth category is used to describe fans with no clear pattern of spatial variation within the fan or relative to its surroundings. We also visually surveyed the full global population of alluvial fan TI values to assess whether there are any global patterns in the distribution of alluvial fan grain sizes or TI spatial patterns correlated to specific geologic regions.

4 Results and Discussion

4.1 Thermal inertia and grain size of alluvial fans

Of the 437 alluvial fans analyzed in this study, 362 have a meanTI that correlates to sand-sized sediment (Figure 2). A total of 25 alluvial fans have mean TI values corresponding to a finer-grained, dusty to sandy surface, and 13 alluvial fans have mean TI values suggesting pebble to cobble-sized sediment (Table 2). The highest mean TI of an alluvial fan correlates to the "pebble to cobble" grain size category. The number of alluvial fans in each grain size category, as categorized based on the average TI, forms a narrow normal distribution with sand-sized sediment as the mean and small numbers of outliers above and below.

The distribution of TI values within each fan, described by the grain size category of the mean TI +/- one standard deviation, rarely spans more than two grain size categories within a single fan (Figure 2). A histogram of standard deviation values of each fan across the global population shows that most fans have a small range of TI values across the surface (Figure 3), often encompassing only one or two grain size categories. There are 309 alluvial fans that have surface TI values where the mean and +/- 1 standard deviation TI values for the fan surface all fall within the range of sand-sized grains, indicating general homogeneity in the TI-derived grain sizes of the alluvial fan surfaces across the global population. The resolution of THEMIS TI data (~100m/pixel) means that there exists the possibility of grain size heterogeneity within a single pixel. The TI values are derived from THEMIS nighttime data (Fergason et al., 2006) which means that the TI of a single pixel is biased towards the warmer, in this case coarser-grained, material within the scene. Changes in sorting or dominant grain size between pixels would result in more variability in TI values across a fan surface, with an increased proportion of coarse-grained material resulting in an increase in TI values (McCarty and Moersch, 2020). In light of the TI bias towards larger grain sizes, the global prevalence of sand-sized TI-derived grain size is somewhat surprising and is perhaps indicative of more uniform global processes.

Dusty fans, as indicated by TI-derived grain size, are few in number (Table 2) because most of the dust-covered fans were eliminated by DCI. The 5 alluvial fans which have an average TI that falls in the dust grain size category were likely not captured by the DCI filter due to some overlap between the cutoff of high dust coverage in the DCI, which is derived from lower-resolution TES data, and TI-derived sediment grain size, which is derived from relatively higher-resolution THEMIS data.

All 4 of the alluvial fans that have a meanTI in the “pebble to cobble” range occur within THEMIS images where the TI values are anomalously higher than the surrounding THEMIS images. The THEMIS images that cover these alluvial fans were not different enough from the surrounding images to be eliminated as outliers (Section 3.1), however, they do show some evidence that the high TI values are regional artifacts in the data acquisition or processing and are not limited to the alluvial fans or confined to particular sedimentary features, suggesting that the “pebble to cobble” grain size designation may be larger than the actual sedimentary grain size of the surface. Of the 9 alluvial fans with average TI values that fall into the “pebble” range, 5 also within THEMIS images showing anomalously high TI, similar to the settings of the “pebble to cobble” alluvial fans. The other 4 “pebble” alluvial fans are found in craters where the entire crater floor has relatively high TI values. Uniformly high TI values across the full extent of a crater floor could be indicative of coarse-grained crater fill material, or could be a result of induration or other alteration processes.

4.2 Spatial patterns of TI

The spatial patterns of TI values across individual alluvial fan surfaces are qualitatively defined by whether TI appears to vary in a systematic way and whether the pattern of variation appears to correlate with visible surface features (Figure 4). “Channelized” and “gradational” categories both represent patterns in spatial TI variation that are interpreted to be representative of geologic features on the surface. On channelized fans, variations in thermal inertia values follow visible channel features on the alluvial fan surface (Figure 4B), and the channels have a slightly lower TI compared to the surrounding fan surface, indicating that the channels contain finer grained material. Fluvial channelization, which is common across alluvial fan surfaces, functions primarily as a secondary reworking process (Blair and McPherson, 2009; de Haas et al., 2014) and, therefore, is not directly indicative of primary depositional style.

Alluvial fans with gradational TI patterns have one of two related patterns (Figure 4A). Some of the gradational patterns show a fining downslope, evidenced by TI values gradually decreasing downslope along the fan surface. A downslope fining of surface grain sizes is also observed on terrestrial alluvial fans and is indicative of deposition from bedload transport as fine-grained material is carried further as transport energy levels drop (Blair and McPherson, 2009; Ventra and Clarke, 2018). Gradational patterns where grain size decreases downslope are often seen on sheet-flood dominated fans as a result of the different transport distances of different grain sizes through bedload transport of sediment during sheet flood events (Blair, 2002). However, downslope fining is also observed on debris-flow dominated fans which experience surface reworking of debris flow sediment (de Haas et al., 2014). Other fans with gradational patterns show a coarsening downslope with TI values gradually increasing along the surface of the fan. This may be a result of post-depositional erosion exposing lower sedimentary layers, which happen to be coarser than the most recent deposits, at the toe of the fan. The increasing TI downslope may also be a result of increasing levels of induration approaching the floor of the crater.

Spatial TI patterns that are described as “unclear” (Figure 4E) have some variability of TI across the fan surface that is not correlated with any visible surface feature and that may not be confined to the fan. It may instead be a part of a more regional pattern of variation with no clear source. Spatial TI patterns that are described as “distinct” (Figure 4D) have overall TI values which are different from the surrounding crater floor by at least two grain size categories, but which do not show any recognizable variation within the alluvial fan surface. The TI patterns described as “regional” (Figure 4C) have TI values with no distinct variation within the fan surface and show little to no contrast with the TI of the surrounding crater floor material. The “regional” TI patterns could indicate that either a) the source material and sediment transport processes filling the crater are similar all around the crater rim with no clear distinction between individual alluvial fans, or b) the alluvial fans and crater floor alike are covered by modern aeolian transported sand.

All five TI spatial patterns are found throughout the global population of alluvial fans (Figure 5). The TI spatial patterns show no clear correlation with mean TI or inferred grain size of the fan surfaces (Figure 6). The alluvial fans with average TI in the lowest (dust, meanTI <

170 tiu) and highest (pebble and pebble to cobble, meanTI > 484 tiu) grain size categories (Table 2) have TI patterns that are described as distinct, or regional, which are not related to any diagnostic depositional characteristics or sedimentary interpretations. There is also no clear correlation between fan size and mean TI or spatial TI patterns (Figure 6).

Channelized TI spatial patterns are only seen between 30°N and 30°S (Figure 5). Channelized fan surfaces are observed in visible morphology at all latitudes (Mondro et al., 2023) but do not always show a corresponding TI surface pattern. The alluvial fans that have channelized TI spatial patterns show lower TI values within the channels, indicating finer-grained channel fill. Channelized fans with no corresponding TI variations may be lacking the finer grained channel fill, or could have experienced either post-depositional diagenesis of the surface sediment that alters the TI or mantling of the surface with unconsolidated sediment that obscures original TI variations. It is unclear why these processes would not affect the lower latitudes as strongly. It is also possible that the concentration of channelized TI patterns in the lower latitudes is coincidental, as there is a higher concentration of all alluvial fans within that region.

4.3 TI implications for grain size and depositional style

The TI analysis of this global population of alluvial fans indicates that most alluvial fan surfaces on Mars are composed of sand-sized sediment. Interpretation of TI of sedimentary surfaces on Mars can be contextualized by two different scenarios: either the TI values are representative of depositional grain size from alluvial processes or the TI values are not representative of original depositional grain size. The overall fine-grained alluvial fans and the relatively small range of average grain sizes represented in the global population of fans on Mars have different implications depending on the framing in which TI values are assessed.

If the TI values of the alluvial fan surfaces are not representative of the original depositional grain size, then the most likely interpretation of the overall fine grain size of alluvial fans and small range of grain sizes is that the surface is mantled with aeolian sand deposits or in situ post-depositional breakdown of material across fan surfaces. The analysis of alluvial fans excluded features with high dust coverage, eliminating dust mantling as a likely explanation. The global trend of alluvial fan TI-derived grain size may be indicative of global, long-term, in-place regolith generation, which is breaking down coarser material into sand-sized sediment on a slow timescale. It is also possible that the TI values indicate widespread mantling of aeolian sand across the surface outside of recognized dune fields. As aeolian-transported sand would be unlikely to be constrained to only alluvial fan surfaces, this would affect all Mars surface investigations using TI.

If the TI values are representative of the original depositional grain sizes, the TI values provide insight into possible sediment transport processes. Based on TI-derived surface grain size, we interpret likely sheet flood deposits as finer grained (meanTI of “sand to pebble” or smaller) with a smaller range of grain sizes (TI values +/- one StDv that span two or fewer grain size categories) and interpret likely debris flow deposits as coarser grained (meanTI of "cobble" or larger) with a larger range of grain sizes (TI values +/- one StDv that span 3+ grain size categories. Because of the inherent uncertainty in defining the grain size cutoffs of specific depositional styles, alluvial fans in which the meanTI is in the range of "pebble" and "pebble to cobble" grain sizes are categorized as a possible mixed style fan and are generally interpreted as uncertain depositional history.

All but 13 of the alluvial fans included in this study are categorized as likely sheet-flood dominated fans based on the mean TI grain size categories. The other 13 alluvial fans are categorized as possible mixed depositional style fans based on the mean TI grain size categories. There are no alluvial fans with a mean TI in the range of cobble or larger grain size. The sediment making up these alluvial fans was sourced from the catchment areas located along crater rims. The vast majority of the alluvial fans in this study are found across the cratered highlands in craters that are older than 2.5 Gy. The Mars crust across the cratered highlands is primarily volcanic, mostly basaltic (Ehlmann and Edwards, 2014), which suggests that alluvial fan catchments were most likely eroding into volcanic bedrock exposed in the topography of the crater rims. Ongoing degradation of the oldest craters has produced low-relief or absent crater rims in the modern day (Forsberg-Taylor and Howard, 2004; Kreslavsky and Head, 2018), which has resulted in the original full extent of many of the alluvial fan catchments being severely degraded. A better understanding of the sediment preserved in alluvial fans, generated by aqueous erosion processes, will help to further constrain the models of crater rim degradation and the conditions under which different erosion processes occur.

4.4 Implications for depositional environment and Mars climate

Sheet-flood dominated fans are formed primarily by sediment transported as bed load or suspended load. The specifics of sediment transport in these conditions are affected by flow velocity, bed sheers stress, hydraulic roughness, channel morphology, and other parameters that can vary widely in a range of surface flow conditions (Kleinhans, 2006). Sediment size and sediment volumes can be used to more accurately define bedload sediment transport conditions to inform calculations of flow parameters and water volumes (Stucky de Quay et al., 2019). This global assessment of alluvial fan grain size and depositional style will provide important constraints on future models of surface water activity and analysis of the controls on sedimentary depositional systems. The sediment grain size results presented here can also be combined with modeled flow parameters to develop more precise estimates of sediment discharge and depositional rates for specific alluvial fan systems.

Sheet floods and ubiquitous sand-sized sediment also suggest a lack of matrix-forming material (i.e. phyllosilicates) in the alluvial fan source catchments. Previous work on terrestrial alluvial fans has shown that generation of matrix-supported sediment-gravity flows is typically associated with a significant source of clay minerals in the catchment, either from physical weathering of clay-rich sedimentary rocks or alteration of igneous or metamorphic bedrock

(Blair and McPherson, 1994; Levson and Rutter, 2000; Nichols and Thompson, 2005; Ventra and Clarke, 2018). Lack of evidence for debris-flow deposits across this global population of alluvial fans indicates that the fan source catchments do not contain high quantities of phyllosilicates. Spectral evidence for the widespread alteration of basaltic crust into phyllosilicate minerals is primarily seen in Noachian units (Ehlmann and Edwards, 2014), during the proposed "warm and wet" conditions of early Mars (Craddock and Howard, 2002; Ramirez and Craddock, 2018; Wordsworth, 2016). If clay mineral alteration at the surface had continued into the era of alluvial fan formation, or if remnant clay minerals were present in the original catchment areas, we would expect to see more evidence for coarse debris-flow sediment on the alluvial fan surfaces rather than the ubiquitous sand-sized sediment that the TI data indicate.

Alluvial fans are built by repeated episodes of surface water runoff that transports sediment to the fan surface. Alluvial fan formation continuing into the Amazonian (Holo et al., 2021) indicates that liquid water was flowing at the surface at least sporadically as recently as 2.5 Ga. Amazonian climate is generally thought to be dominated by more glacial conditions (Dickson et al., 2012; Fassett et al., 2010). However, the hypothesized occurrences of sporadic surface water flow during intermittent warmer periods within the hypothesized "cold and wet" climate models of the Noachian to Hesperian period (Bishop et al., 2018; Fairén, 2010; Segura et al., 2002; Wordsworth et al., 2017) would have persisted for longer than initially proposed, into the early Amazonian (Adeli et al., 2016; Hauber et al., 2013), to support alluvial fan depositional environments.

5 Conclusions

Thermal inertia analysis of alluvial fan surfaces on Mars provides a way to make a high-level assessment of the sediment grain size that makes up the alluvial fans. Across the global population of alluvial fans on Mars, mean TI values of individual fan surfaces indicate that the vast majority of fan surfaces consist of sand-sized sediment. If the TI values are not representative of the original depositional grain size, this may be indicative of widespread regolith generation or aeolian mantling across the surface of Mars. If the TI values are representative of the original depositional grain size, the global catalog of alluvial fans represents a surprisingly homogeneous population of depositional environments. These results would indicate that the vast majority of alluvial fans on Mars were primarily formed by bedload transport of sediment in sheet flood or fluvial conditions. Finer grained sediment in alluvial fans is indicative of lower energy bedload transport and an absence of debris-flow events.

This global survey of alluvial fan thermophysical properties will enable future work to further investigate the sedimentary characteristics of individual alluvial fan surfaces using additional datasets and analytical methods. A future analysis of HiRISE image data across the full alluvial fan population, including requesting HiRISE data for the features that have no coverage, would provide additional insight into larger surface features that may be associated with depositional events or the observed TI spatial patterns. The climatic and geologic controls on alluvial fan depositional style in terrestrial systems is a useful starting point for Mars sedimentary analysis but more work still needs to be done to investigate and validate the precise relationships between controlling factors in Mars depositional systems.

Data Availability

A table of alluvial fan location used for this study, along with a summary of thermal inertia values and associated grain size categories, is made available in a publicly accessible online data archive (https://doi.org/10.22541/essoar.167768127.72084291/v2). The FanID identifier included in this table links this database to a previously published database (https://doi.org/10.5061/dryad.qjq2bvqk0) of alluvial fans on Mars (Mondro et al. 2023). The FanID identifiers in both databases refer to the same features, allowing for further exploration of fan characteristics.

Funding Acknowledgement

This work was partially funded by J. Moersch's Mars Odyssey Participating Scientist grant (Arizona State University Subaward #10-254).

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