The geological history of Northeast Syrtis Major, Mars

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As inferred from orbital spectroscopic data, Northeast Syrtis Major bears considerable mineral diversity that spans the Noachian-Hesperian boundary despite its small geographic area. In this study we use observations from the High Resolution Imaging Science Experiment, supplemented with Context Camera imagery, to characterize and map the lateral extent of geomorphic units in Northeast Syrtis Major, and constrain the geomorphic context of the orbital-identified mineral signatures. Using recent observations, we confirm previous mineralogy identified with the Compact Reconnaissance Imaging Spectrometer for Mars, and greatly extend the lateral extent of visible to near-infrared investigation utilizing the greater coverage. Analysis of Thermal Emission Imaging System observations reveals further physical properties and distribution of the geomorphic units. The stratigraphy, which spans the Noachian-Hesperian boundary, displays significant morphological heterogeneity at the decameter scale, but it is unifiable under five distinct geomorphic units. Our paired morphological and mineralogical analysis allows us to construct a detailed geological history of Northeast Syrtis Major. Several geological events that occurred in Northeast Syrtis Major—including the formation of the post-Isidis crust, the emplacement of an olivine-rich unit, the formation of sulfate minerals, and the emplacement of the Syrtis Major Volcanics—can be related to regional and global processes constraining the local chronology. Other mineralogical indicators, particularly the formation of Al-phyllosilicates, are difficult to place in the temporal sequence. They are observed in isolated patches on the post-Isidis crust, not as a distinct stratigraphic unit as observed elsewhere in Nili Fossae, suggesting their formation via isolated leaching or through alteration of initial compositional heterogeneities within the crust. Exposures of an olivine-rich unit are intermittently observed to form quasi-circular landforms, suggestive of emplacement in circular depressions, which may indicate a period of cratering between the formation of the Isidis basin and the deposition of the olivine-rich unit. We identify and discuss intriguing large linear features of the olivine-rich unit, reminiscent of dyke-fed volcanism, that have raised bounding ridges suggestive of contact metamorphism with the crust. We compile, review, and discuss many of the outstanding questions and running hypotheses relevant to our mapping area. A synthesis of our geomorphic mapping with recent literature reveals a well-defined geological history with extensive aqueous activity at Northeast Syrtis Major that is amass in a stratigraphic sequence spanning a time likely greater than 250 million years of geological history. Our geomorphic and spectral analyses confirm that Northeast Syrtis Major exhibits considerable geomorphic and mineralogic diversity within a relatively small geographic area that is representative of the geologic processes occurring throughout the broader Nili Fossae region during the Noachian and Hesperian. Northeast Syrtis Major adds to this sequence by exposing the diverse environmental history of this region as observed through the presence of alteration minerals not present in this fidelity or proximity elsewhere in Nili Fossae.

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1. Introduction

At the nexus of the northwestern border of the Isidis basin and the northeastern extent of the Syrtis Major volcanic province lies the region informally known as Northeast Syrtis Major (Fig. 1; ~ 17–18 °N and 76–77 °E), a diverse martian landscape with varied geology and mineralogy that spans the Late Noachian and Early Hesperian boundary (Ehlmann and Mustard, 2012). At Northeast Syrtis Major (henceforth NE Syrtis), four distinct aqueous environments were inferred via the presence of orbital-identified minerals: shallow crustal Fe/Mg-phyllosilicate-bearing terrains, carbonate-bearing olivine-rich terrains, Al-phyllosilicate-bearing terrains, and layered sulfate-bearing terrains (Mustard et al., 2007, 2009; Ehlmann et al., 2009; Ehlmann and...

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The stratigraphy of key mineral-bearing strata are interpreted to show a trend from early neutral-pH water environments in the Late Noachian to acidic conditions in the Early Hesperian (Ehlmann and Mustard, 2012), though the paradigm of alkaline mineralogy inferred from Fe/Mg-smectites has recently started to be questioned as these minerals have been shown to form at mildly acidic pH conditions (e.g., Peretyazhko et al., 2016). Previous investigators examined the mineralogy and stratigraphy at a regional scale (e.g., Ehlmann et al., 2009, 2011; Ehlmann and Mustard, 2012), but this left unexamined important geomorphic characteristics and stratigraphic relationships that can only be revealed through detailed orbital analyses at the meter to decameter scale.

Here, using the highest spatial resolution data available, we investigate the geomorphic context of the previously identified orbital mineral signatures to further our understanding of the relative age relationships and geomorphic textures. Our objective is to investigate the lateral extent of the mineral stratigraphy first identified in the area by Ehlmann and Mustard (2012) over the broader NE Syrtis region, and observe how the morphology and composition of units identified in NE Syrtis varies spatially and through time by correlating and characterizing multiple exposures throughout the region at a high level of detail. NE Syrtis has a complicated but rich geological history that is expressed over a large area (∼2500 km²) with a unique sequence of units. We aim to correlate stratigraphic contacts and mineralogy mapped in NE Syrtis to the surrounding Nili Fossae, including the Jezero crater watershed, as the spatial proximity of these analyses to our study region provide valuable points of comparison. Lastly, we aim to construct a detailed geologic history of NE Syrtis using the most comprehensive mapping of the region to date. Unraveling this history through the detailed, high-resolution analysis of the morphology and mineralogy presented here will further our understanding of the Late Noachian to Early Hesperian transition, and the context of NE Syrtis in the geological history of Mars.

2. Background

The age of the key geomorphic units around NE Syrtis are reasonably well constrained due to two stratigraphic markers: the Isidis basin and the Syrtis Major volcanic province. The region lies near the 1500 km ring of the Isidis impact basin (Frey et al., 2000), halfway between the 1100 and 1900 km diameter rings (Schultz and Frey, 1990), and the crater size-frequency distribution of impacts on the basin and ejecta generates a formation age of 3.96 Ga (Werner, 2005). An olivine-rich unit lies directly on the terrain excavated by the Isidis basin-forming event, establishing its age as contemporaneous with or immediately post-Isidis (Mangold et al., 2007; Mustard et al., 2007). The younger stratigraphic marker is the volcanics from Syrtis Major capping layered rocks that are sulfate-bearing. Crater retention ages date the lavas to the Early Hesperian, with an age range between ∼3.5–3.8 Ga (Hiesinger and Head, 2004; Ivanov et al., 2012). Additionally, the formation of the Nili Fossae fractures occurred after both the formation of the Isidis basin and the emplacement of the regionally-extensive olivine-rich unit, and before the emplacement of the Syrtis Major volcanic province (Mustard et al., 2009). This is well constrained as the fractures cut the olivine-rich unit but are emplaced by the Syrtis Major volcanic province (Mustard et al., 2009). Therefore, approximately 250 Myr of geological history is recorded between these two stratigraphic markers.

The regionally-extensive olivine-rich unit, which is well exposed in NE Syrtis, has been studied with multiple orbital spectroscopic instruments including the Thermal Emission Spectrometer

Fig. 1. Northeast Syrtis Major, Mars. North is up in all images. (a) The location of Northeast Syrtis Major at the nexus of the western edge of the Isidis basin, the northeastern Syrtis Major volcanic province, and the southeastern extent of the Nili Fossae. The mapping area is delineated by the black rectangle, and (b) is indicated with the dashed white rectangle. The background is MOLA colored topography overlain on the ∼100 m/pixel THEMIS global daytime infrared mosaic. (b) Local context for the mapping area (black rectangle). Jezero crater is immediately to the northeast, and the Syrtis Major volcanic province begins at the south and west of the mapping area. To the north is the watershed for the western fan of Jezero crater (Goudge et al., 2015). The background is the THEMIS mosaic as in (a), and the location of 1c is indicated by the dashed white rectangle. (c) Northeast Syrtis Major. The mapped area (black rectangle) is divided into three regions: the Plains, the Depression, and the Syrtis Major Volcanics. The unnamed 6 km crater discussed in the text is the topographic depression observed in the top-left quadrant. The basemap is a CTX-derived DEM overlain on a mosaic of CTX images. The CTX images comprising the mosaic are listed in the supplementary Table S2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Mustard 2012).
Many carbonate, relationships, diffusely fracturing region (vug) and elevated hydrothermal activity (OMEGA) (Mustard et al., 2005; Mustard et al., 2007; Ody et al., 2013), and the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) (Mustard et al., 2009). Two hypotheses have been proposed for the emplacement mechanism of the Nili Fossae olivine-rich unit. The first hypothesis is that the olivine-rich unit was emplaced as either basaltic volcanic flows in-place when Isidis formed (Hamilton and Christensen, 2005) or as picritic lava flows emplaced subsequent to the Isidis basin formation (Tornabene et al., 2008). The clear stratigraphic context for the olivine-rich unit emplaced post-Isidis precludes a pre-Isidis intrusive igneous origin (Hoenf et al., 2003). The second hypothesis is that the unit comprises impact melt produced during the formation of the Isidis basin (Mustard et al., 2007, 2009). Supporting evidence includes the observation that the spatially-extensive unit ranges across ~3 km of elevation (Hamilton and Christensen, 2005), drapes the post-Isidis topography, and is distributed across the ring structures of the Isidis Basin (Mustard et al., 2007), all of which are morphologically consistent with impact melt.

The olivine-rich unit is of significance because of its high olivine content (up to ~40%, Poulet et al., 2009), large areal extent (>113,000 km², Hamilton and Christensen, 2005; Mustard et al., 2009), and intimate association with Mg-rich carbonate (Ehlmann et al., 2008; Ehlmann and Mustard, 2012; Edwards and Ehlmann, 2015). The variable alteration to Mg-rich carbonate and isolated observations of serpentine are particularly intriguing aspects of the olivine-rich unit (Ehlmann et al., 2008, 2010; Murchie et al., 2009; Mustard et al., 2009; Ehlmann and Mustard, 2012; Mustard et al., 2014). Proposed carbonate formation mechanisms include hydrothermal alteration of the ultramafic host rock at slightly elevated temperatures, contact metamorphism, precipitation from transitory shallow lakes, or weathering of the olivine-rich rocks (Ehlmann et al., 2008; Brown et al., 2010; Viviano et al., 2013; Bramble and Mustard, 2016). The olivine-rich unit is observed throughout the western Isidis basin (Mustard et al., 2007, 2009) including on the floor of Jezero crater (Goudge et al., 2015), in the vicinity of the large Nili Fossae graben (Ehlmann et al., 2008; Mustard et al., 2009), to the north in a region informally called the Nili Fossae carbonate plains (Ehlmann et al., 2008; Edwards and Ehlmann, 2015), and in the southern Isidis basin at Libya Montes (Mustard et al., 2009; Bishop et al., 2013a). Furthermore, the carbonate-bearing unit is significant as it may be a potential reservoir of atmospheric carbon, though the degree to which carbonate-bearing rocks may have acted as a carbon sink is difficult to constrain from orbit (Wray et al., 2016), however recent efforts have begun addressing this question (Edwards and Ehlmann, 2015). The Nili Fossae olivine-rich unit has been hypothesized as a source region for the plumes of methane observed in the martian atmosphere (Mumma et al., 2009; Wray and Ehlmann, 2011) and the fracturing of the olivine-rich unit may allow methane, perhaps diffusely produced in the subsurface from serpentinization of the olivine-rich unit, to reach the surface.

Orbital visible to near-infrared spectroscopic investigations have identified varied aqueous alteration and igneous mineralogies in Nili Fossae and NE Syrtis. Based on regional-scale stratigraphic relationships, previous studies have deduced a sequence of aqueous mineral formation, suggesting it progresses from phyllosilicate, to carbonate, to kaolinite, and terminating with sulfate formation, as distinct layers rich in these minerals are isolated in well-defined ascending stratigraphic positions (Ehlmann and Mustard, 2012). Many phyllosilicate minerals have been identified (e.g., Mangold et al., 2007; Mustard et al., 2008; Ehlmann et al., 2009), with the dominant clay mineral in the region identified as Fe-rich smectites and observed to correlate with exposures of the Noachian crust (Mangold et al., 2007; Mustard et al., 2008; Ehlmann et al., 2009). Al-bearing clays were identified in NE Syrtis and were suggested as an alternative alteration pathway of the Noachian low-Ca pyroxene crustal materials (Ehlmann and Mustard, 2012). Serpentine was identified in conjunction with the Noachian plains olivine-rich unit that has been variably altered to Mg-rich carbonate (Ehlmann et al., 2010; Ehlmann and Mustard, 2012), and was suggested to be a product of serpentinization of the olivine-rich unit in a hydrothermal aqueous environment (Ehlmann et al., 2010), perhaps set up by the emplacement of hot olivine-rich material (Viviano et al., 2013), or by deep burial by Syrtis Major lavas (Michalski and Niles, 2010). Mechanisms under consideration for the formation of the crustal phyllosilicates for Mars in general and in our mapping region include formation as surface weathering products incorporated into the megaregolith by impact processes, hydrothermal alteration in the shallow crust (Ehlmann et al., 2011), magmatic precipitation (Munier et al., 2012), impact origin (Tornabene et al., 2013), and alteration in the presence of supercritical fluids during the cooling of the martian magma ocean (Elkins-Tanton, 2008; Cannon et al., 2016). Kaolin-group minerals may suggest that pedogenic-type leaching or hydrothermal alteration occurred (Gaudin et al., 2011), and these outcrops may be the result of formation under circum-neutral pH waters, or localized acidic leaching (Ehlmann et al., 2009).

Sulfates are observed at the boundary of NE Syrtis and the Syrtis Major volcanic province (Ehlmann and Mustard, 2012; Quinn and Ehlmann, 2014a, 2014b). They are hypothesized to record a transition in the aqueous environments towards bearing acidic waters in both a regional and global context (Bibring et al., 2006; Ehlmann and Mustard, 2012). Spectral analysis resolved diagnostic absorptions in multiple locations that were consistent with the jarosite, polyhydrated sulfates, and/or a mixture of jarosite with other hydrated phases (Ehlmann and Mustard, 2012). The sulfate-bearing unit is ~500 m thick and displays meter-scale layering (Quinn and Ehlmann, 2014a, 2014b). The morphology and structure of raised boxwork ridges, erosion-resistant ridges in a polygonal network confined to the sulfate-bearing unit, suggests formation via filled volume-loss fractures in a sedimentary setting (Quinn and Ehlmann, 2014b). Ehlmann and Mustard (2012) offered two formation hypotheses for the sulfates at NE Syrtis. First was a volcanic-hydrothermal hypothesis where acidic fluids circulate through layered volcanic flows altering the rock and precipitating sulfates. A variation on this hypothesis would be the deposition of the layers as ash flows or falls (Quinn and Ehlmann, 2014b). Second was a lacustrine-groundwater hypothesis where the layers are deposited as evaporite sediments in a geologic setting similar to those observed at Meridiani Planum (McLennan et al., 2005) or Terra Sirenum (Wray et al., 2011), and the circulation of fluids may be related to extensive groundwater aquifers (Andrews-Hanna and Lewis, 2011) or a hot volcanic layer leading to contact metamorphism of underlying sediments. The abundant carbonate and sulfate minerals in Nili Fossae and NE Syrtis corroborate the presence of diverse aqueous environments, as carbonates require neutral-neutral conditions and some sulfates, such as jarosite, require acidic conditions. The assemblages bearing phyllosilicate, carbonate, and sulfate minerals present in NE Syrtis illustrate that spatially and temporally distinct environments of aqueous alteration were active in the region (e.g., Poulet et al., 2005). This mineralogy is hypothesized to indicate a global trend in the planet's chemical history suggestive of the transition of waters from circum-neutral pH towards acidic conditions (Bibring et al., 2006; Ehlmann et al., 2011; Ehlmann and Mustard, 2012), and also shows that the stratigraphy of NE Syrtis spans the Phyllosian–Theiikan boundary (Bibring et al., 2006).
Additional intriguing geological observations in Nili Fossae and NE Syrtis generate further outstanding questions about the evolution of Mars. Unaltered crystalline igneous units in Noachian-aged crust, enriched in low-Ca pyroxene, would provide testable constraints on geochemical and petrological formation models for the early crust of Mars (Elkins-Tanton et al., 2005; Skok et al., 2012; Grott et al., 2013). Raised ridges in Nili Fossae and NE Syrtis are an outstanding question as running hypotheses for their formation includes mineralized fracture zones (Saper and Mustard, 2013), as well as breccia dykes and crater-related faults (Head and Mustard, 2006). Megabreccia bearing internal fabric, including layering and possible phyllosilicates, demonstrate active geological processes in the region prior to the basin-forming impacts, may bear geochemical remnants of the primitive and hydrothermally-altered crust of Mars, and provide access to the subsurface (Mustard et al., 2009; Tornabene et al., 2013). The question remains whether the altered megabreccia blocks originated as primary ancient crust, impact processes, or were produced by later igneous intrusions.

The greater Nili Fossae region has recently been under intense analysis, indicative of the exceptional exposure of geologic units in this region, the unprecedented wealth of orbital data, and its importance in understanding the evolution of Mars. Immediately north of our study area is the watershed for the deltas observed in Jezero crater to the northeast (Goudge et al., 2015), further north are the carbonate plains with the planet’s largest exposure of carbonate-bearing rocks (Edwards and Ehlmann, 2015), and to the northwest is the Nili Fossae trough (Ryan et al., 2016). The spatial proximity of these analyses to our study provides valuable points of comparison for the discussion of NE Syrtis. In their geomorphic mapping of the Jezero crater and watershed, Goudge et al. (2015) demonstrated that the mineralogy of the fan deposits is detrital in nature and reflects the composition of their associated watersheds. They mapped 28 geomorphic units and observed a mottled olivine- and carbonate-bearing unit overlaying basement units bearing Fe/Mg-rich smectite, similarly reflecting broader mineralogical and morphological trends in Nili Fossae (Mangold et al., 2007). Edwards and Ehlmann (2015) performed a joint thermal infrared and visible to near-infrared analysis of the Nili Fossae carbonat e plains where several geomorphic units were identified and their mineralogy and physical properties constrained. They demonstrated that carbonate processes at low temperatures likely altered olivine-enriched basalts to compositions bearing at most ~20% Fe/Mg carbonate, which suggests carbonate-bearing rocks in Nili Fossae only sequestered <12 mbar of CO2.

The diverse geomorphic units in a stratigraphic sequence at NE Syrtis demonstrate the variety of testable hypotheses addressable via future exploration or return of samples to the Earth. These hypotheses are compiled in Table 1. It is beyond the scope of a single paper to address each of these hypotheses, but our geomorphic map and combined geomorphic and spectroscopic analyses presented here enable findings that constrain some of the above hypotheses. Additionally, our detailed mapping, which pushes the highest resolution orbital data available to its limits, helps to clarify what can and cannot be resolved with orbital analysis alone. Certain unavoidable limitations—image resolution or non-uniqueness of geomorphic indicators as observed in orbital data, for example—similarly limit the ability to address outstanding hypotheses with the investigation herein. In this contribution, we investigate the morphological characteristics of NE Syrtis and the stratigraphic setting of the multiple mineralogical signatures identified by orbital spectroscopy using the available high-resolution orbital imagery, in an aim to constrain the spatial, stratigraphic, and temporal relationships in NE Syrtis.

3. Data and methods

To investigate the characteristics and lateral extent of identified geomorphic units and the geomorphic context of the orbital-identified mineral signatures, a geomorphic map was created utilizing high-resolution image data. Tandem analyses in the visible to near-infrared (VNIR) and thermal infrared (TIR) further constrained the properties of the geomorphic units.

3.1. Morphological mapping and analysis

The foundation of the mapping of NE Syrtis was two basemaps, created using the high-resolution imagery of the region acquired by the Mars Reconnaissance Orbiter (MRO) spacecraft (Zurek and Smrekar, 2007). The first basemap was a mosaic of images from the Context Camera (CTX) (Malin et al., 2007) produced using the USGS Integrated Software for Imagers and Spectrometers (ISIS) software. HiRISE images were spatially referenced to the CTX mosaic prior to mosaicking. Digital Elevation Models (DEMs) were produced using CTX and HiRISE stereo image pairs with the NASA Ames Stereo Pipeline (Broxton and Edwards, 2008; Moratto et al., 2010). The DEMs were map-projected and referenced to the martian areoid.

The DEMs allowed for constraints on both regional and localized topographic and stratigraphic relationships, and for morphometric analysis of geologic units. The CTX and HiRISE images utilized in this analysis are listed in the supplementary Table S1 and Table S2, respectively.

The geomorphic mapping area was bounded to the north by the Jezero watershed and the region investigated by Goudge et al. (2015), to the east by the unnamed 7 km crater south of Jezero crater, and to the south and west by the first contact with the Syrtis Major volcanic flows (Fig. 1). The region investigated has near-contiguous HiRISE coverage allowing for the meter-scale geomorphology to be studied. In regions with HiRISE coverage, the surface was investigated at a mapping scale of 1:1000, and unit contacts were drawn at this scale. The mapped geomorphic units were initially characterized at HiRISE resolution, and the transition to regions without HiRISE coverage results in the loss of the fidelity required to accurately map these units. The contacts between these units occur below the resolution of CTX. In regions without HiRISE coverage, CTX images were investigated and unit contacts were drawn where geomorphic units were discernable at a mapping scale of 1:5000. Regions where the resolution was too low to identify the HiRISE-characterized units as the boundaries were below the resolution of CTX, or regions where multiple geomorphic units were in close spatial proximity hindering mapping at CTX resolution, were incorporated into the Undifferentiated Terrain (UNT) unit. Fig. 2a identifies the area in NE Syrtis where HiRISE imagery was used in the geomorphic unit mapping. The geomorphic mapping was performed without regard to the mineralogical analysis. An exception was made for regions without HiRISE coverage where CRISM spectral summary parameters for the mineral olivine were utilized to confirm suspected geomorphic units matching other spectrally-confirmed olivine-rich exposures. In general, geomorphic units were defined by their characteristics identifiable in the HiRISE images and derived DEMs. These characteristics include, but were not limited to, the qualitative albedo, overall two-dimensional geomorphic shape, texture and patterns internal to a unit, DEM topography, and stratigraphic position.
3.2. CRISM spectral analysis

The VNIR spectral characteristics of the identified geomorphic units were investigated using hyperspectral images from CRISM aboard MRO (Murchie et al., 2007). Full-resolution (~18 m/pixel) and half-resolution (~36 m/pixel) targeted observations made by the CRISM infrared detector (1.00 to 3.92 μm) were processed by dividing the I/F image by the cosine of the incidence angle, where I/F is the radiance at the sensor divided by the solar irradiance divided by π (Murchie et al., 2007). The image was divided by a scaled volcano scan observation empirically optimized for each observation as a first-order correction for atmospheric gases. Spectral summary parameters were calculated to guide the spatial identification of mineral signatures (Pelkey et al., 2007; Salvatore et al., 2010; Viviano-Beck et al., 2014). Images were map-projected and georeferenced to a Mars Orbiter Laser Altimeter (MOLA; Smith et al., 2001) digital terrain model to correlate with the geometric mapping. A vector image of the geometric map was overlain on the projected CRISM images to spatially compare the spectral features identified with the mapped units. To identify mineralogies of the mapped units, CRISM image pixels that displayed a strong signal in the parameter bands were collected from the map-projected images, spatially averaged within the mapped unit, and then the spectra were divided with in-scene, spectrally-bland spectra to diminish residual atmospheric and instrumental artifacts. For comparison with laboratory spectra of mineral samples, the map-projected pixels with the strongest spectral features were located in the non-projected camera-space images and the collected spectral pixels were divided by a spectrally-bland region spanning the same along-track detector width. CRISM observations utilized in this analysis are listed in supplementary Table S3 and their coverage of the mapping area is shown in Fig. 2b. The spatial locations of CRISM spectra presented in the figures below are listed in supplementary Table S4.

Absorption features observed in the CRISM spectra were characterized by their shape and wavelength position and were compared to a suite of laboratory-measured mineral spectra. Laboratory VNIR spectra of pyroxenes display broad absorptions centered near ~1.1 and ~2 μm, and the centers of these features vary primarily as a function of the mineral’s Ca content, with increasing Ca content shifting these absorptions towards longer wavelengths (Adams, 1974; Burns, 1993; Klima et al., 2007, 2011). Olivine has a prominent ~1 μm feature composed of three absorptions produced from octahedrally coordinated Fe2+ that varies its band center with changes in olivine Fe2+ content (King and Ridley, 1987; Burns, 1993).

Fe/Mg-smectites, including Fe-rich nontronite or Mg-rich saponite, bear prominent vibrational absorptions at ~1.4 (first OH stretching overtone and H₂O structural combination tone), 1.9 (structural H₂O combination tone of OH bend and H–O–H stretch), and 2.29–2.31 μm (combination tone of OH stretch and Fe/Mg–OH bend; Clark et al., 1990; Bishop et al., 1999, 2002; Frost et al., 2002). A suite of absorptions at ~1.4, 1.9, and 2.2 μm suggest the presence of a kaolin-group mineral, with the first two absorptions matching similar sources to those in Fe/Mg-smectites and the 2.2 μm doublet absorption resulting from a OH stretch and
Al-OH bend combination tone (Clark et al., 1990). The mineral talc has a sharp and deep 1.39 μm absorption from OH vibration and a broader 1.44 μm absorption (Clark et al., 2007). Narrow talc absorptions at 2.32 and 2.39 μm are of comparable width and the latter is ~50% the depth of the former (Clark et al., 2007). Similarly, an absorption at 2.47 μm is ~50% the band depth of the 2.39 μm absorption. Talc does not have H₂O in its crystal structure and therefore is lacking an absorption at ~1.9 μm.

Narrow absorptions observed at ~2.3 and 2.5 μm can match fundamental vibrational mode overtones of the CO₂ in the carbonate mineral structure, and paired band centers observed at ~2.31 and 2.51 μm or 2.32 and 2.52 μm are indicative of Mg-rich carbonate (Hunt and Salisbury, 1971; Gaffey, 1987). Orbital carbonate identifications on Mars also bear an absorption at ~1.9 μm (e.g., Ehlimann et al., 2008; Ehlimann and Mustard, 2012), which may indicate the Mg-rich phase is hydrated (Calvin et al., 1994) or is mixed with another hydrated phase, such as a smectite (Bishop et al., 2013b).

Sulfate minerals have been identified in NE Syrtis (Ehlimann and Mustard, 2012) and the particular phases identified were jarosite, based on the identification of a Fe-OH asymmetric doublet centered at 2.21 and 2.26 μm (Swayze et al., 2008), and polyhydrated sulfates, identified by structural H₂O absorptions at 1.4 and 1.9 μm and a diagnostic inflection at 2.4 μm.

3.3. Thermal infrared analysis

Thermal infrared (TIR) data from the THEMIS aboard the Mars Odyssey spacecraft (Christensen et al., 2004) were investigated in the mapping of NE Syrtis to analyze variations in the thermal inertia (TI) as well as broad trends in the dominant surface mineralogy, which influences the shape of the primary Reststrahlen features in the TIR wavelength region (Christensen et al., 2004). THEMIS images I27043003, I37820004, and I44288005 were the focus of our analyses and together these images cover the entire mapping area. For compositional analyses, THEMIS TIR data were processed using the techniques described by Salvatore et al. (2016). Summarized here, the data were collected by THEMIS with 10 spectral bands located between 6.8 μm and 14.9 μm and a surface spatial resolution of 100 m/pixel. These data were calibrated to top-of-atmosphere effective emissivity (Christensen, 1998; Rogers et al., 2005) and atmospherically corrected (Bandfield et al., 2004) to produce surface emissivity data. Windowed decorrelation stretch (DCS) images were produced using THEMIS radiance data (Edwards et al., 2011), and THEMIS DCS images with red-green-blue combinations of band 8 (11.79 μm), band 7 (11.04 μm), and band 5 (9.35 μm), respectively, were utilized in the mapping and the corroboration of geometric units identified using HiRISE and CTX images. Decorrelation stretch images using this particular band combination have been shown to be effective in differentiating spectrally distinct surface units, especially variations in mafic compositions (e.g., Hamilton and Christensen, 2005; Rogers et al., 2005; Edwards et al., 2008, Edwards et al., 2011).

Quantitative TI measurements, which indicate surface properties including the effective particle size and induration of the geomorphic units, were collected from the mapped geometric units using a global TI map (Fergason et al., 2006; Christensen and Fergason, 2013). Modeled effective particle sizes for each unit were generated as relationships between TI and the effective particle size of materials have been shown to be applicable on Mars (e.g., Kieffer et al., 1973). TI is related to the degree of induration and the grain size properties of the surface; for example, competent rock outcrops have a high TI while surfaces covered in fine-grained dust have low TI. As a means of minimizing dust cover and quantifying only the best exposures, measurements of the TI were made within each of the mapped units at locations exhibiting the highest TI values and in an area large enough to be confirmed within the bounds of the mapped unit.

4. Results

Despite NE Syrtis bearing great morphologic heterogeneity at meter to decameter scales, the geology of the area is unifiable under five distinct units of paired morphology and mineralogy (Fig. 3, Table 2). Ascending the stratigraphic column (Fig. 3) they are: (1) a Basement Unit (BAU) that exposes areas of low-Ca pyroxene and Fe/Mg-smectite and is observed in a range of morphologies including crustal mounds, smooth and knobby plains, and raised linear ridges; (2) an extensive Fractured Unit (FRU) that bears olivine-rich VNIR and TIR spectra, is variably altered to carbonate, and tapers off into Large Linear Features (LLF) that appear to descend downslope; (3) a Capping Unit (CAU) with an unremarkable VNIR spectrum that preserves craters and sheds boulders; (4) a 100s of meters thick slope unit (FSU) exposing layered sulfates and raised boxwork ridges; and (5) the dated Syrtis Major Volcanics unit (SMV) bearing a mineralogy of high-Ca pyroxene. Isolated and distributed outcrops in the Basement Unit display spectral signatures
Table 2
Geomorphic units mapped in Northeast Syrtis Major.

<table>
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<th>Unit</th>
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<td>Aeolian Debris Cover</td>
<td>Patches of dune fields obscuring contacts of other geomorphic units. Dune crests track approximately north-south.</td>
<td></td>
<td></td>
<td></td>
<td>Surfacial debris, mobilized by aeolian processes in a general east-west motion (downslope towards Isidis basin).</td>
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<tr>
<td>CRY</td>
<td>Crater – Young</td>
<td>Crater with circular rim and a discernable ejecta blanket obscuring contacts of other geomorphic units.</td>
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<td></td>
<td></td>
<td>Geologically-recent crater formed subsequent to the extensive regional erosion.</td>
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<tr>
<td>SMV</td>
<td>Syrtis Major Volcanics Unit</td>
<td>Elevated, flat, relatively smooth surface preserving craters.</td>
<td>high-Ca pyroxene 238.98 +/− 11.15</td>
<td>~200 μm</td>
<td></td>
<td>Lava flows from the Syrtis Major volcanic province halting in the vicinity of Northeast Syrtis Major.</td>
<td>3, 21</td>
</tr>
<tr>
<td>FSU</td>
<td>Feature-bearing Slope Unit</td>
<td>Steep slopes off of the SMV variably exposing light-toned layers, crustal knobs, or FRU high-standing above the smooth cover.</td>
<td>polyhydrated sulfate, jarosite, natrojarosite 304.64 +/− 30.11 (high TI) / 207.43 +/− 11.39 (low TI)</td>
<td>~560 μm (high TI) / ~100 μm (low TI)</td>
<td></td>
<td>Layered sediments deposited in an aqueous or volcanic system, underwent sulfate precipitation, then eroded and covered giving smooth appearance.</td>
<td>3, 21</td>
</tr>
<tr>
<td>RBR</td>
<td>— Raised Boxwork Ridges</td>
<td>Raised ridges meters wide and 10s-100s meters long in a boxwork texture high-standing above a smooth basement with interspersed light-toned outcrops.</td>
<td></td>
<td></td>
<td></td>
<td>High-standing ridges formed as filled volume-loss fractures (Quinn and Ehlmann, 2014b).</td>
<td>3, 21</td>
</tr>
<tr>
<td>CAU</td>
<td>Capping Unit</td>
<td>Unit with an uppermost crater-preserving surface and a variably-exposed lower layer of light-toned fractured blocks.</td>
<td>unremarkable 276.9 +/− 18.5</td>
<td>~375 μm</td>
<td></td>
<td>Volcanic flow or ash-fall deposit (volcanic or impact-generated). Lacking abundant Fe2+ in mafic minerals or poorly crystalline and/or glassy. Current expression governed by extent and mechanical properties of underlying FRU.</td>
<td>3, 5, 6, 9–11, 13, 15–18</td>
</tr>
<tr>
<td>SSM</td>
<td>— Smooth Sloped Mounds</td>
<td>CAU variant lacking crater-preservation, and bearing smooth, gradual, darker-toned slopes.</td>
<td>high-Ca pyroxene</td>
<td></td>
<td></td>
<td>Variant of CAU with weaker mechanical properties or erosional history producing smooth slopes and covered with dark-toned high-Ca pyroxene-bearing deposits.</td>
<td>5, 9</td>
</tr>
</tbody>
</table>

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Table 2 (continued)

<table>
<thead>
<tr>
<th>Unit map symbol</th>
<th>Unit name</th>
<th>Unit description</th>
<th>Interpreted CRISM signatures</th>
<th>THEMIS Thermal Inertia</th>
<th>Modeled effective particle sizes</th>
<th>Unit interpretation</th>
<th>Relevant figure(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRU</td>
<td>Fractured Unit</td>
<td>Corrugated surface of light-toned, fractured blocks surrounded by dark-toned material. Sparsely cratered.</td>
<td>olivine, Mg-rich carbonate, ~1.9 μm hydration feature, Fe/Mg-smectite</td>
<td>420.29 +/- 20.74</td>
<td>&gt; 1 mm</td>
<td>A coarsely-crystalline olivine-rich unit emplaced as impact melt or volcanism, rapidly covered by the CAU. It has been variably altered to carbonate.</td>
<td>3, 5, 6, 9–13, 15–19</td>
</tr>
<tr>
<td>LLF</td>
<td>— Large Linear Features</td>
<td>Linear features 10s-100s meters wide and 1000s of meters long composed of light-toned fractured blocks surrounded by dark-toned material.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3, 5, 13, 14</td>
</tr>
<tr>
<td>BAU</td>
<td>Basement Unit</td>
<td>Low-Ca pyroxene, Fe/Mg-smectite, kaolin-group mineral</td>
<td></td>
<td>255.11 +/- 18.05</td>
<td>~260 μm</td>
<td>Remnants of ancient crust. Expression governed by topography formed by Isidis impact and distribution of FRU. Highly eroded and variably covered with debris.</td>
<td>3, 5–7, 9, 11, 13–16</td>
</tr>
<tr>
<td>CMD</td>
<td>— Crustal Mounds</td>
<td>High relief peak, plateau, or elevated ridge from which lineations fan away.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5, 6, 9, 13, 15</td>
</tr>
<tr>
<td>RLR</td>
<td>— Raised Linear Ridges</td>
<td>Rectilinear features high-standing above smooth basement. Meters in width and 100s of meters in length.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3, 19</td>
</tr>
<tr>
<td>KNP</td>
<td>— Knobby Plains</td>
<td>Expansive smooth surface with many interspersed knobs, mounds, and ridges.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5, 6, 9, 13, 15</td>
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<tr>
<th>Unit map symbol</th>
<th>Unit name(^a)</th>
<th>Unit description</th>
<th>Interpreted CRISM signatures</th>
<th>THEMIS Thermal Inertia</th>
<th>Modeled effective particle sizes</th>
<th>Unit interpretation</th>
<th>Relevant figure(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMP</td>
<td>– Smooth Plains</td>
<td>Smooth, dark-toned surface. Heterogeneous internal structure. Abundant, but dispersed, decimeter light-toned blocks.</td>
<td></td>
<td></td>
<td></td>
<td>Surface exposing ancient basement. Large blocks likely megabreccia or accumulation and erosion of materials when showing a circular appearance. Planar flows of volcanic or erosion products may be present.</td>
<td>5, 9, 13, 15</td>
</tr>
<tr>
<td>LCM</td>
<td>– Large Crustal Mounds</td>
<td>Similar morphology to CMD but with elevations of 100s of meters.</td>
<td></td>
<td></td>
<td></td>
<td>Mounds formed near-contemporaneously with Isidis. Heavily eroded but maintaining high topography.</td>
<td></td>
</tr>
<tr>
<td>CRE</td>
<td>Crater – Eroded</td>
<td>Crater of significant size (≥ 1 km) with no discernable ejecta blanket dominating the local morphology.</td>
<td></td>
<td></td>
<td></td>
<td>Ancient craters formed during the early heavy bombardment. Subsequently eroded and slightly deformed by minor tectonic movements.</td>
<td></td>
</tr>
<tr>
<td>UNT</td>
<td>Undifferentiated Terrain</td>
<td>Mixed expressions of the above units. Unit contacts below CTX resolution.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>21</td>
</tr>
</tbody>
</table>

\(^a\) Geomorphic units are indicated in bold, subunits of the geomorphic units are indicated in italics, and minor units not significant to the text are indicated in plain letters.
of a kaolin-group mineral, and while these locations are at the surface of the Basement Unit they are not a significant stratigraphic unit as seen elsewhere in Nili Fossae (Ehlmann et al., 2009).

Raised linear features that are meters in width are observed in the mapping area and in two stratigraphic positions. Some of these ridges have been previously mapped by Saper and Mustard (2013) as raised ridges. Ridges meters in width are observed at the edges of the olivine-rich Fractured Unit descending into the downsection Basement Unit. Raised Linear Ridges (RLR) are observed in coherent outcrops in the Depression region (see below), are mapped as a subunit of the Basement Unit, and are most comparable to those discussed by Saper and Mustard (2013). Raised Boxwork Ridges (RBR) are stratigraphically equivalent to the ∼500 m thick Feature-bearing Slope Unit (FSU), and are high-standing above light-toned outcrops (Fig. 3).

From the geomorphic mapping and spectral analysis of NE Syrtis (Fig. 4) we identify three regions (Fig. 1c): (1) the Plains region, consisting of the relatively flat-lying region from 17.6–18.0° N and 76.8–77.3° E, (2) the Depression region to the south and west of the Plains region that transitions from the Plains region towards the Syrtis Major Volcanics, and (3) the Syrtis Major Volcanics region. Our mapped geomorphic units are discussed in detail below and summarized in Table 2.

**4.1. The plains of Northeast Syrtis Major**

The topographically subdued region outside the southwest rim of Jezero crater is termed here as the Plains region of NE Syrtis (Fig. 5). The Plains region has a dynamic topographical range of < 100 m, and a shallow regional slope towards the south and east, away from a topographically-high large crustal mound. The Plains region is additionally differentiated via the large contiguous area of HiRISE coverage, where ∼30 × 30 km of HiRISE stereo images have been acquired and used to generate high-resolution topography.

**4.1.1. Basement Unit**

The stratigraphically lowest geomorphic unit identified in the mapping area is the Basement Unit (BAU), which is differentiated into five geomorphic subunits (Table 2). No unit is identified underlying the Basement Unit, and therefore it is of undetermined thickness. The Crustal Mounds (CMD) subunit of the Basement Unit is observed as mounds exhibiting significant vertical relief with a peak, plateau, or elevated ridge from which lineations on the slopes fan away (Fig. 6a). The slopes are slightly darker in tone and do not exhibit boulder shedding. A subunit differentiation is made for Large Crustal Mounds (LCM), which share many morphological similarities with the Crustal Mounds, with the exception of their heights reaching of 100s of meters of elevation. These mounds are light-toned with lineations fanning away from the topographic high. The Crustal Mounds are more sparsely cratered than the Fractured Unit or Capping Unit (see below), likely due in part to a combination of its physical properties and amount of debris cover.

Two plains units are mapped in NE Syrtis: Smooth Plains and Knobby Plains, both subunits of the Basement Unit. Smooth Plains are characterized by an expansive, relatively dark-toned smooth surface. Isolated ridges or spatially-insignificant mounds akin to the Crustal Mounds or other mapped units are observed in the Smooth Plains but are relatively uncommon. Knobby Plains are extensive smooth regions interspersed with frequent ridges or mounds akin to the Crustal Mounds or other mapped units imparting a knobby texture in the HiRISE and CTX data. The Crustal Mounds, Knobby Plains, and Smooth Plains may be indicative of an erosional progression, with the Crustal Mounds being the most intact and the Smooth Plains representing the greatest amount of degradation. An intermediary step would be the variably dissected exposures of the Crustal Mounds that are spatially related in seemingly coherent structures with light-toned surfaces and dark-toned smooth gradual slopes.

Dispersed exposures of massive blocks or megabreccia are observed in the subunits of the Basement Unit. The megabreccia or massive blocks exhibit a diversity of morphologies including both angular and rounded textures, internal structure including possible layering, and disaggregation into seemingly drawn-out filaments. The megabreccia are up to 10s of meters in diameter, and are of similar characteristics to those observed elsewhere in Nili Fossae (e.g., Mustard et al., 2009; Goudge et al., 2015). The megabreccia are spatially distributed throughout the Basement Unit as small, isolated occurrences of light-toned blocks that are meters in size with no topographic signature. Multiple surface textures are observed within the Smooth Plains, where the lowermost is a dark-toned plain bearing abundant megabreccia, and meters above is a smoother, lighter-toned plain (Fig. 6b and c). These textures and the megabreccia are not mapped as separate units as they are not spatially significant at the mapping scale.

CRISM pixels displaying strong signals in the parameter images were analyzed from the Basement Unit. Narrow absorptions at approximately 1.4, 1.9, and 2.3 μm are observed in isolated patches of the Basement Unit (Fig. 6e) where the dust cover is low. These absorptions are consistent with the prominent vibrational absorptions of Fe/Mg-smectite, including Fe-rich nontronite or Mg-rich saponite, and are interpreted as such. Broad absorptions are observed at ∼2 μm consistent with the presence of low-Ca pyroxene (Fig. 6g). Low-Ca pyroxene is common and pervasive in the Basement Unit and subunits via this feature identified in several exposures.

Distinct absorptions at ∼1.4, 1.9, and 2.2 μm correlated with isolated light-toned features 10s of meters in size are diagnostic of the presence of a kaolin-group mineral (Fig. 7). Outcrops exhibiting these absorptions are only observed in small and isolated patches in the two plains subunits, and are associated with light-toned features on the surface that are qualitatively among the lightest-toned
features in a given HiRISE scene. The light-toned surfaces display a massive texture with no internal fabric at the highest resolution apart from dark-toned fractures and cover (Fig. 7b and c). No positive or negative topographic irregularities are observed correlating with these light-toned features using a HiRISE DEM, and the features appear part of the basement and not a separate stratigraphic unit eroded to its current exposure. As the geomorphic units were identified independently of CRISM data, outcrops bearing a kaolin-group mineral could not be identified on morphology alone and therefore were not mapped as separate subunits. While some of the circular light-toned massive blocks could be interpreted as rounded megabreccia, they may also be interpreted as circular depressions formed by small craters filled with light-toned materials that were later eroded to form a level surface (Fig. 7b).

TIR investigation of the Basement Unit produced a Tl value of 255.11 ± 18.05 K m⁻² K⁻¹ s⁻⁰.⁵, which generated a modeled effective particle size of ~260 μm. These values likely correlate more closely to the regolith and debris observed covering the Basement Unit, rather than inherent thermophysical properties of the base-

ment itself, consistent with the patchy distribution of strong CRISM signatures of low-Ca pyroxene, Fe/Mg-smectite, and a kaolin-group mineral. The Basement Unit is predominately green in the THEMIS DCS mosaic (Fig. 8a). The green color is indicative of generally higher values in band 7 than the surrounding materials due to more silica-rich compositions shifting the main Reststrahlen features towards shorter wavelengths. Green units in this THEMIS DCS band combination are generally consistent with basaltic compositions with alteration phases present (Salvatore et al., 2016), and this observation is corroborated here by the identification of Fe/Mg-smectites and Al-phyllosilicates in CRISM pixels correlated with the Basement Unit.

4.1.2. Fractured Unit

The Fractured Unit (FRU) is a spatially extensive unit with a hummocky, corrugated surface of light-toned blocks on the scale of 10s of meters seen closely packed in a darker supporting material stratigraphically above the Basement Unit (Fig. 9). The dark-toned material forms polygonal shapes around the light-toned
blocks giving this unit a fractured appearance, and a fractal pattern of smaller fractured blocks is observed within the larger blocks (Fig. 9). A sharp contact is seen between this unit and the Basement Unit, and the Fractured Unit is observed to embay the Basement Unit (Fig. 6a). Fields of light- and dark-toned boulders are observed, and interspersed are small crater-preserving mesa mounds and small mounds resembling the other units identified but not spatially significant. The Fractured Unit is commonly covered with patches of aeolian cover forming dune fields with an approximate north-south dune orientation. The dune fields are commonly located in the topographic lows and craters of the Fractured Unit.

Parallel lineations are occasionally observed in the Fractured Unit. The lineations most frequently observed are a variable banding that is concentric and parallel to the upslope Capping Unit (Fig. 10a). This banding appears to occur on a relatively flat surface. Other less-frequently observed lineations are suggestive of layering. These lineations are most commonly found in the Depression region (see below) and display alternating light- and dark-toned bands (Fig. 10c). The bands are not of uniform thickness and display a wavy appearance. The bands can span 20 to 30 m of elevation when outcropping on slopes.

The Fractured Unit conforms to the underlying topography on both local and regional scales. The unit follows the topographic gradient and, over 100s of meters, remnants are observed in linear topographic lows and form circular features (Fig. 11). The Fractured Unit embays the slopes of large mounds with the underlying unit often exposed at the crest. The unit is also observed to conform to, or drape, the larger-scale regional topography, being observed at elevations from −2000 m (relative to the MOLA datum) in the north of the mapping area and descending to −2450 m in the Depression region (see below) and disappearing under the Syrtis Major Volcanics to the south. This draping characteristic has also been noted by Mustard et al. (2009) at elevations as high as −500 m in their investigation −250 km north of our mapping area, and suggests that the Fractured Unit is the local expression of the Nili Fossae olivine-rich unit (e.g., Hamilton and Christensen, 2005; Mustard et al., 2009).

The thickness of the Fractured Unit is variable within the Plains region. At the contact between the Fractured Unit and the Basement Unit, the Fractured Unit is commonly ∼5–10 m thick. This thickness can range from a few meters to a few tens of meters, and may be governed in part by variable thin regolith cover or preferential erosion of the Basement Unit.

CRISM spectra of the Fractured Unit bear a broad absorption at ∼1 μm and narrower, less prominent absorptions at 1.9, 2.3, and 2.5 μm (Fig. 12). We interpret this spectrum to indicate a mixture of olivine and carbonate minerals, and possibly an additional mixture phase of smectite, consistent with the interpretations of Ehlmann et al. (2009) and Ehlmann and Mustard (2012). In NE Syrtis, the carbonate spectral signatures appear more spatially pervasive and less variable in the olivine-rich unit than observed in other locations in Nili Fossae (e.g., Ehlmann et al., 2009). This may suggest that aqueous alteration was more extensive and complete in this region than elsewhere in Nili Fossae. Possible unaltered olivine-rich outcrops lacking 1.9, 2.3, and 2.5 μm absorptions are observed in a limited number of exposures relatively free of aeolian cover, not only in dunes as previously reported (Ehlmann et al., 2010; Ehlmann and Mustard, 2012).

Several exposures of the olivine-carbonate-bearing Fractured Unit appear to bear a weak absorption at ∼2.39 μm (Fig. 12). This absorption is often approaching the level of the spectrum noise, and the approximate CRISM band minima varies between the 2.3840, 2.3906, 2.3972, and 2.4104 μm channels. While it has been suggested that talc, with an absorption at 2.386 μm (Clark et al., 2007), would be an expected mineral phase from contact metamorphism of the olivine-rich unit (Brown et al., 2010; Viviano et al., 2013), it is not clear that talc is supported by the available data, as no 1.39 μm absorptions are observed, and the 2.39 μm absorption, consistent with talc (Clark et al., 1990; Brown et al., 2010; Viviano et al., 2013), is also present in Fe/Mg-phyllosilicates. We interpret spectra bearing a broad ∼1 μm absorption, narrow 1.9, 2.3, and 2.5 absorptions, and a weak 2.39 μm absorption as a mixture of olivine and Mg-rich carbonate with lesser amounts of a phyllosilicate, possibly saponite (Fig. 12). The previous identification of serpentine in NE Syrtis (Ehlmann et al., 2010; Ehlmann and Mustard, 2012) is in an outcrop located at the southernmost extent of the Fractured Unit in our mapping area, and is not a widespread spectral component.

Regions mapped as Fractured Unit display a predominately purple color in the THEMIS DCS mosaic (Fig. 8b). This observation corroborates the enrichment in olivine observed by CRISM, as purple tones are indicative of olivine in this band combination (e.g.,
Fig. 6. Geomorphic example of the Crustal Mounds (CMD) of the Basement Unit (BAU). (a) Observed are high-standing mounds with a peak, plateau, or elevated ridge from which lineations on the slopes fan away. The CMD are embayed, and here surrounded, by the Fractured Unit (FRI). Subframe of HiRISE image ESP_016219_1980 with geometric unit contacts drawn. The arrow shows the location for the numeraror spectrum used for the CRISM ratioed reflectance spectrum (g). (b-c) Geomorphic example of the Knobby Plains (KNP) of the BAU. (b) Geomorphic map subframe depicting the KNP and the complex relationship with the Capping Unit and FRI. (c) HiRISE mosaic subframe of corresponding area to (b) with unit contacts drawn. Circular light-toned features are observed in the plains unit (arrow i) that may be indicative of megabreccia rounding or light-toned material infilling small circular depressions. The transition between the visibly discernable plains surface textures is shown (arrow ii): the lowermost is a darker-toned plain, and meters above this is a smoother, lighter-toned plain. The transition between the KNP and CMD in this scene bears strong spectral signatures for a kaolinite-group mineral (arrow iii; also showing the location for the numerator spectrum used for the CRISM ratioed reflectance spectrum in Fig. 7a). North is up in all images. (d-g) Laboratory and CRISM ratioed spectra indicative of the dominant spectra observed in the BAU. The saponite spectrum (d) is compared here with the narrow absorptions centered at 1.4, 1.9, and 2.3 μm, indicative of Fe/Mg-smectites, collected from the BAU (e). The laboratory low-Ca pyroxene spectrum (f) matches the spectrum collected from the BAU with (g) broad absorption centered at ∼2 μm and second dip in the VNIR towards broad absorption short of 1 μm. The saponite (LASK) and orthopyroxene (C2PE30) spectra are taken from the CRISM spectral library (CRISM Science Team, 2006). Vertical lines are located at 1.4, 1.91, and 2.3 μm.

Edwards et al., 2008). The Fractured Unit displays the highest thermal inertia of the mapping area at 420.29 ± 20.74 J m⁻² K⁻¹ s⁻⁰·⁵, and a modeled effective particle size of >1 mm. This value correlates well with values produced by a similar scale joint TIR-VNIR analysis by Edwards and Ehlmann (2015), where thermal inertia values of ∼400–500 J m⁻² K⁻¹ s⁻⁰·⁵ were reported from the modeling of olivine- and carbonate-bearing materials on the morenorthern Nili Fossae carbonate plains.

4.1.2.1. Large Linear Features. There are multiple linear features observed in NE Syrtis ranging from linear raised ridges (e.g., Saper and Mustard, 2013) to previously undocumented Large Linear Features (LLF) of distinct morphologic character and size. These Large Linear Features typically: (1) are 10s to 100s of meters wide and 1000s of meters long (Fig. 13a); (2) join seamlessly with edges of the Fractured Unit (Fig. 13b) and share the same olivine-carbonate-bearing VNIR spectral signature; (3) the material comprising the Large Linear Features is light-toned and blocky in a dark-toned supporting material, and raised rims commonly bound the edges of the Large Linear Features (Fig. 13c); (4) they appear to follow the trend of the local topography and are sometimes exposed as raised ridges or recessive troughs (Fig. 13d). These linear features are distinct from the raised ridges mapped in the Nili Fossae region discussed below (Saper and Mustard, 2013; Ebinger and Mustang, 2015). A select number of Large Linear Features are mapped as Capping Unit (see below) as a material consisting of rough surfaces with dark-toned boulder-shedding slopes is supported on, and conforms to, the Large Linear Feature shape (Fig. 5).

A cross-cutting relationship between the Large Linear Features and the Basement Unit is observed in the Plains region. The Large Linear Features are commonly observed sharply bifurcating at angles into multiple Large Linear Features, including orthogonal intersections and triple junctions (Fig. 13a). Large Linear Features are observed in present-day troughs. These troughs are a few meters
in depth with the Large Linear Features in the topographic low at the end of smooth gradual slopes of Basement Unit material on the sides of the trough, as measured by a HiRISE DEM. Additionally, smaller raised ridges meters in width and 10s to 100s of meters in length are observed extending off the edges of Fractured Unit and Large Linear Features and tapering into the Basement Unit. Some of these ridges tapering off of the Large Linear Features were mapped by Saper and Mustard (2013), and, while they appear innately related to the Large Linear Features, for select ridges it is difficult to constrain whether the ridges are a seamless part of the Large Linear Features, or downsection ridges rising and halting at the Fractured Unit or Large Linear Feature contact.

Raised ridges or linear mounds are commonly observed along the contact of the Large Linear Features and the Basement Unit. Topographic profiles across the Large Linear Features measured from the HiRISE DEMs (Fig. 14) show the bounding ridges to be meters in height when the Large Linear Feature is present on the two plains subunits and the center remains a few meters above the level of the host unit. The bounded Large Linear Features bear a center comprised of light-toned blocky material with a darker supporting material. The light-toned bounding rims are interpreted as erosion-resistant rims of the Large Linear Feature or possible aeolian cover lapping onto the linear feature.

Fractures that follow the track of the linear feature are observed at the center of select Large Linear Features. These fractures are ~1 m wide and 10s to 100s of meters in length and have dark, shadowed crevices suggesting that they are relatively free of dust cover. Fractures of a similar scale are also observed in the mapping area in the other mapped units, including the units identified by CRISM to be olivine-rich. The dark shadows formed by these small fractures suggest they may be meters in depth.
is observed (commonly in the absence of discernable layering) across the Capping and Fractured Units. Select mesa-forming expressions of the Capping and Fractured Units have vertical expressions approaching the ~1 m resolution of the HiRISE DEMs, in particular where the contacts occur on a gradual slope. The Smooth-Sloped Mounds subunit is notable due to its significant topographic relief, with some mounds reaching 60 m in height.

An additional observed characteristic of select mesa-forming expressions of the Capping and Fractured Units is a quasi-circular nature of these two units. These Capping Unit mesas are observed with a quasi-circular rim of Fractured Unit and variably isolated from the larger expanses of the Fractured Unit (Fig. 17). The quasi-circular mesas are of a relatively uniform size, all being a few 100 m in diameter, though even much larger mesa-forming expressions of these two units, on the order of several kilometers in diameter, appear to have approximately equal perpendicular diameters (Fig. 17e).

CRISM spectra of Capping Unit surfaces are unremarkable in the spectral parameter images and spectra collected from the Capping Unit display a flat, featureless spectrum. Select slopes of Smooth-Sloped Mounds bear a broad absorption centered at ~2.2 μm indicative of high-Ca pyroxene materials in these deposits. These spectral signatures appear correlated to the mantling material and are not an inherent property of the Smooth-Sloped Mound subunit. Analyzing spectra collected of the Capping Unit or Smooth-Sloped Mounds subunit do not reveal absorptions indicative of high-Ca pyroxene, corroborating the association of the ~2.2 μm absorption with the dark-toned mantling material.

The Capping Unit displays a green-yellow color with isolated spots of purple (Fig. 9e), indicative of higher values in band 7 likely due to the main Reststrahlen features being centered towards shorter wavelengths, showing slightly more silica-rich compositions. Our observation of a Ti of 276.9 ± 18.5 J m⁻² K⁻¹ s⁻⁰.⁵ for the Capping Unit similarly correlates with the Ti range of 250–300 J m⁻² K⁻¹ s⁻⁰.⁵ reported for the low-olivine capping unit by Edwards and Ehlmann (2015). Our modeled particle size of ~375 μm for the selected Capping Unit outcrops is at the lower end of the ~300–700 μm range reported for their capping unit (Edwards and Ehlmann, 2015).

4.2. The depression southwest of the plains

To the south and west of the Plains region is a topographic depression containing variants of the geomorphic units described above (Fig. 1c). CTX DEM topography shows the Depression region’s lowest elevations lie ~500 m below the average elevation of the Plains region. From the Depression region northwards to the 6 km crater is a rise in elevation towards a Large Crustal Mound outside the mapping area to the north of this crater. The Depression region lacks extensive HiRISE coverage. The isolated HiRISE imagery in this region provides insight to the units present, but the ability to map geomorphic units characterized at HiRISE resolution is hindered.

4.2.1. Depression variations on Capping Unit and Fractured Unit

Large, rough, crater-preserving surfaces matching morphological characteristics of the Capping Unit are observed in the Depression region, but here they are commonly larger in area (few kilometers across versus few 100 m) and bearing an extensive, smooth, dark-toned cover (Fig. 18a). Similarly, in the Depression region there is a variant of the Fractured Unit termed the Dark-Toned Fractured Unit (FRU–DT) that is of matching morphology but the light-toned, polygonally-fractured surface bears a patchy but smooth, dark-toned cover. This unit is commonly identified by exposures near the contacts with neighboring units, where the surface of light-toned blocks closely packed in a darker matrix is observed.
4.2.2. Raised Linear Ridges

In addition to the Large Linear Features, linear features of smaller scale are present in NE Syrtis. These ridges are most abundant in the Depression region and are meters in width, hundreds of meters in length, and are high-standing above a relatively smooth surface (Fig. 19a). The ridges are observed in two stratigraphic positions: in linear networks stratigraphically beneath the olivine-rich Fractured Unit (mapped as Raised Linear Ridges), or in polygonal networks of short linear ridges interspersed with light-toned banded formations above the Capping Unit (mapped as Raised Boxwork Ridges, see Section 4.3).

CTX DEM topography shows that the exposures of Raised Linear Ridges (RLR) are commonly topographically higher than the Dark-Toned Fractured Unit in elevation, but visual analysis suggests that they are stratigraphically lower (Fig. 19b). The topographical relationship appears to follow broader trends, where at higher elevations the overlying material may have been eroded away, exposing the stratigraphically lower Raised Linear Ridges. The greatest vertical relief appears to be correlated with smooth mounds a few 100 m across that form within the confines of the Raised Linear Ridges. Conversely, the Dark-Toned Fractured Unit and Capping Unit may not have been emplaced in a manner that allowed these units to fully drape the entire region and cover all of the local topographic highs. Regardless, the Raised Linear Ridges present erosional windows through the olivine-rich unit and into the Basement Unit. Small mounds of capping material akin to remnants of
the Capping Unit or Fractured Unit are observed in select locations where the ridges intersect.

The Raised Linear Ridges appear to vertically cross-cut the host unit and terminate at the upsection Fractured Unit, an observation similarly reported for the breccia dikes studied by Head and Mustard (2006). The raised ridges of Saper and Mustard (2013) closely correspond with the regions we mapped as Raised Linear Ridges, but this previous study also included the bounding ridges along the Large Linear Features, ridges tapering downstream of Fractured Unit, and the Raised Boxwork Ridges (see below).

The basement layer from which the Raised Linear Ridges cross-cut bears absorptions in CRISM images at ~1.4, 1.9, and 2.3 μm interpreted to be a Fe/Mg-smectite-bearing basement (Fig. 19c). The ~1.4 μm band is relatively broad in comparison to single-phase laboratory spectra and centered at ~1.41 μm. Broad absorptions suggest a mixture of phyllosilicates or variance in cation by substitution in the Mg/Fe solid solution of smectites (Ehlmann et al., 2009). Small doublets are observed at 2.298 and 2.318 μm for the ~2.3 μm band, or one single band is observed with a band minima at 2.305 or 2.318 μm, suggesting a degree of heterogeneity or variation in the phyllosilicate composition, corroborating the broad ~1.4 μm band. A minima at ~2.39 μm is variably present in this unit (similar to the ~2.39 μm minima of the Fractured Unit discussed above), but its magnitude is on the order of instrument and data-processing artifacts and the low signal-to-noise ratio suggests using it in mineral identification is questionable (Fig. 19c). A broad absorption (or set of absorptions) at ~1.4 μm and a narrow ~2.39 μm absorption may be indicative of the mineral saponite (Fig. 19c). We categorized the Raised Linear Ridges as a subunit of the Basement Unit as they appear stratigraphically below the Fractured Unit, and due to the observed VNIR mineralogy matching the Basement Unit.

4.2.3. Megabreccia

Exposures of megabreccia are observed throughout the mapping area but are most common in the Depression region. One particularly interesting exposure is observed at a boundary between Capping Unit and Dark-Toned Fractured Unit (Fig. 20). This megabreccia exposure consists of blocks meters to 10s of meters in size and of multiple tonalities that are dispersed amongst a dark-toned supporting material. The blocks bear rounded edges, but are variably fractured. This outcrop appears to have a horizontal progression in block size; trending towards the northwest, the breccia blocks become larger and more spread out in the dark supporting material. These breccia blocks, some 10s of meters in size, appear to have an internal fabric, suggesting layering or banding prior to disruption and amalgamation into breccia (Fig. 20a). Here, angular blocks are observed in close proximity with heavily rounded fragments, and one angular fragment appears to have a fault with a visible offset of ~10 m (Fig. 20a). The megabreccia in this region bear a relatively smooth surface as is evidenced by meter-sized boulders casting shadows on the surface (Fig. 20). The megabreccia appears to be stratigraphically equal with the olivine-carbonate-bearing Dark-Toned Fractured Unit, and is contacted on most edges with this material (Fig. 20b), though the exact stratigraphic position of the megabreccia is difficult to constrain from orbit. If this breccia is stratigraphically equal, then it is of a different provenance than the distributed megabreccia observed in the Basement Unit in the Plains region, and may have been emplaced contemporaneously with the Fractured Unit. While this megabreccia was mapped as part of the Dark-Toned Fractured Unit, other interpretations based on the imagery could include cross-cutting, underlying, or embaying relationships with the Fractured Unit. The megabreccia were not mapped as distinct geomorphic units as they are not of comparable spatial extent to the other mapped units.

4.2.4. Undifferentiated Terrain

The Undifferentiated Terrain (UNT) incorporates regions lacking sufficient high-resolution image coverage for the mapping of the geomorphic units characterized at HiRISE resolution. CTX imagery was used to map unit contacts where they were identifiable at CTX resolution, but the fidelity required to map these units is
absent, and as a result the Undifferentiated Terrain contains multiple geomorphic units. Further hindering high-resolution mapping in this region is the seemingly greater spatial heterogeneity of the geomorphic units. The general surface observed in the CTX images is composed of a lighter toned knobby terrain with small knobs and ridges in close proximity, and amongst isolated exposures of other mapped units, such as crater-preserving surfaces or light-toned fractured blocks with contacts obfuscated at this resolution (Fig. 21a). Where possible, comparing the appearance of Plains region units in overlapping HiRISE and CTX images was used to extend mapping into the regions without HiRISE coverage. The olivine-rich units identified in CRISM OLINDEX2 parameter images were also used to confirm Fractured Unit exposures and extend mapping in this region where HiRISE image data was not available (Salvatore et al., 2010). The Undifferentiated Terrain provides a unit representative of the overall geology of NE Syrtis as it incorporates diversity of units exposed in the region. It bears a motched Basement Unit expressed as a knobby slopes and dissected crust, dispersed light-toned, polygonally-fractured surfaces (likely Fractured Unit), crater-preserving surfaces, and smooth cover. The surface flow features present in the Depression region, described by Skok and Mustard (2014), are contained within this unit.

4.2.5. The valley

Cutting east-west across the mapping area is a valley bearing a narrow channel that ends in an ill-defined fan-shaped structure south of Jezero crater. This valley is the main morphologic feature dividing the Plains region from the Depression region (Fig. 1c). For the final ~17 km of the channel prior to the fan, the channel is a few 100s of meters wide and filled with light-toned aeolian cover forming dunes perpendicular to the channel. Westward up the valley, the channel widens in sections along its length with large dune fields present at these locations. While features along the track of the valley bear some degree of sculpting towards streamlined features, the geomorphic units in the vicinity of the valley appear to largely preserve their primary depositional shape and extent. The western terminus of this valley opens onto large expanses of Capping Unit and Dark-Toned Fractured Unit at elevations 100 to 200 m lower than the highest elevated lengths of the valley.

4.3. The contact with the Syrtis Major Volcanics

The border region between NE Syrtis and the Syrtis Major Volcanics has been studied (Ehlmann and Mustard, 2012; Quinn and Ehlmann, 2014a, 2014b). Our geomorphic mapping incorporates the Syrtis Major Volcanics, providing additional observations and descriptions. Summaries of these units, the Syrtis Major Volcanics unit (SMV), the Feature-bearing Slope Unit (FSU), and the Raised Boxwork Ridges (RBR) are provided in Table 2.

Large contiguous regions in the west and south were mapped as the Syrtis Major Volcanics (SMV) unit where an elevated, flat, and relatively smooth surface preserving craters was observed. The Syrtis Major Volcanics are high-standing in the mapping area with elevations greater than or equal to that of the Plains region. A scarp face is observed with a sharp elevation drop of ~500 m towards the Depression region. The thickness of the Syrtis Major Volcanics, when exposed at this scarp face, is measured via a HiRISE DEM to be ~10 m. The steep slopes off of the Syrtis Major Volcanics are largely smooth, but variable exposures of light-toned layers are observed on the slopes, and at the base knobs are observed high-standing above a smooth cover. The slopes are mapped separately as Feature-bearing Slope Unit (FSU) due to these morphological (and spectral, see below) characteristics. Multiple amphitheater-headed canyons are observed along this scarp wall with subtle fluvial channels that follow the topographic gradient across the volcanic surface and terminate at the amphitheater heads (Fig. 21a). The flow features continue from the amphitheater
heads downwards into the Depression region and onto the valley (cf. Fig. 21a, Lamb et al., 2014, and Skok and Mustard, 2014).

Strong but isolated high-Ca pyroxene detections, validated in ratioed spectra, are observed in CRISM images covering the Syrtis Major Volcanics, and ratioed spectra collected from these regions bear a broad absorption centered on ~2.2 μm, interpreted to be high-Ca pyroxene. We observe spectral signatures indicative of olivine-carbonate-bearing materials associated with mounds and knobs at the base of the Feature-bearing Slope Unit and appear to rise above the smooth slope cover. This suggests that the smooth slope of the Feature-bearing Slope Unit extends past the lower contact of this unit and obscures the downslope Capping Unit and Fractured Unit at the base. Light-toned, layered outcrops of the Feature-bearing Slope Unit exhibit absorptions at 1.4 and 1.9 μm and an inflection at 2.4 μm (Fig. 21d). Variably present is a weak absorption with a minima at 2.26 μm (Fig. 21g), and this absorption is furthermore variably paired with a weaker absorption at 2.21 μm that is on the order of the spectral noise. These absorption bands are consistent with laboratory spectra of polyhydrated sulfates and the mineral jarosite, but the variability of the 2.21 μm absorption may suggest some degree of mixing or cation variance between jarosite and natrojarosite, which does not have a prominent absorption at this position (Fig. 21f). These observations confirm the previous identification and interpretation by Ehmann and Mustard (2012) in NE Syrtis, and the spatial variability of the sulfate mineral phases.

Observed stratigraphically below the Syrtis Major Volcanics and within the Feature-bearing Slope Unit are raised ridges meters in width and 10s to 100s of meters in length that frequently intersect at orthogonal angles forming a boxwork texture. Saper and Mustard (2013) previously mapped these ridges, and combined these Raised Boxwork Ridges (RBR) and our Raised Linear Ridges together. Here, we separate the two as they have distinct morphological characteristics and stratigraphic positions. The ridges are high-standing above a smooth basement and interspersed with light-toned outcrops. The Raised Boxwork Ridges are inferred to be in a subsurface stratigraphic layer beneath the capping Syrtis Major Volcanics and are exposed subsequent to erosion of the Syrtis Major capping material (Quinn and Ehmann, 2014b; Ebinger and Mustard, 2015).

The Syrtis Major Volcanics unit displays comparatively low thermal inertia values. The analyzed locations have a measured thermal inertia of 238.98 ± 11.15 J m⁻² K⁻¹ s⁻0.5 resulting in a modeled particle size of ~200 μm. These values correlate with a
regolith at the surface corroborated by the etched retained craters and influence from the dark-toned cover. A dichotomy is observed in the thermal inertia values of the Feature-bearing Slope Unit, which have a split distinction between higher- and lower-TI areas. The low TI areas produce a measured value of $207.43 \pm 11.39 \text{ J m}^{-2} \text{K}^{-1} \text{ s}^{-0.5}$ and a modeled effective particle size of ~100 mm. These lower values correlate to large areas of the thick, dark-toned cover. The high TI areas produce a measured value of $304.64 \pm 30.11 \text{ J m}^{-2} \text{K}^{-1} \text{ s}^{-0.5}$ and a modeled effective particle size of ~560 mm. The higher values correlate to local high-standing features, including high-standing exposures of olivine-carbonate-bearing materials as identified using CRISM. The THEMIS DCS mosaic similarly displays this TIR dichotomy as an overall equal distribution of colors with minor enhancements of yellow and is observed for large portions of the Feature-bearing Slope Unit (Fig. 8f). This unit also displays strong isolated concentrations of purple (Fig. 8g), correlating to mounds high-standing above the smooth cover. These data corroborate the interpretation of the high-standing mounds being exposures of the olivine-carbonate-bearing Fractured Unit.

5. Discussion

5.1. Regional and local stratigraphy

Our coordinated regional geomorphic mapping and VNIR and TIR mineralogical analyses allow NE Syrtis to be placed in conjunction with other orbital analyses throughout Nili Fossae. Mapping by Goudge et al. (2015) of Jezero crater and its associated watershed to the north of our mapping area provides an excellent opportunity to place the stratigraphy of NE Syrtis in a larger context. The largest spatial overlap between our mapping effort and that of Goudge et al. (2015) occurs with their mapped Altered basement (Bal). In our analysis, we subdivided this Altered basement region into three units, Basement Unit, Fractured Unit, and Capping Unit. This observation reflects the fact that our mapping was performed at higher spatial resolution utilizing significant coverage of HiRISE images, allowing for more extensive morphological subdivision. Our mapping scale was 1:1000 versus 1:100,000 for the Jezero crater paleolake system.

Altered basement (and the Rigid and Dusty massive subunits) of Goudge et al. (2015) morphologically corresponds with the Basement Unit (particularly the Raised Linear Ridges subunit). These units display small, light-toned knobs, variable topography, and no obvious structure in select locations, matching observations of the dissected exposures of the Crustal Mounds, Knobby Plains, and Smooth Plains subunits. The Altered basement units and the Basement Unit share a CRISM-inferred mineralogy of Fe/Mg-smectite. These units also share many morphological similarities with the Undifferentiated Terrain. Additionally, the valley cutting east-west through NE Syrtis (Section 4.2.5) matches the spatial size and mor-
phology of a valley mapped in the watershed as Valley network floor.

Morphological and mineralogical similarity is observed for the Mottled terrain (MT, and subunits) and the Light-toned floor unit (LTF) of Gouge et al. (2015) with our Fractured Unit. The Mottled terrain displays a similar, though less degraded, hummocky, corrugated surface as the Fractured Unit. The Light-toned floor unit displays light-toned blocky materials, as does our Fractured Unit. CRISM spectra collected of the Mottled terrain and Light-toned floor unit show absorptions indicative of a mixture of olivine and Mg-rich carbonate (Gouge et al., 2015), matching the mineralogy observed for the Fractured Unit. The Jezero crater watershed does not appear to have preserved the Capping Unit to the same extent as in NE Syrtis, though perhaps the Capping Unit was not emplaced this far northward or was emplaced in a patchy distribution. The Thin dark capping unit (Teu) mapped on the rim of Jezero morphologically matches our Capping Unit.

Recent mapping by Quinn and Ehlmann (2014a, 2014b) of the NE Syrtis sulfate unit shows that this unit, mapped here as the Feature-bearing Slope Unit, is laterally contiguous beneath the Syrtis Major Volcanics and continues ∼55 km south of our mapping area.

Paired morphology observations and TIR analysis allows NE Syrtis to be compared with similar mapping results in Nili Fossae and the Isidis basin. As discussed above, our Fractured Unit and Capping Unit share thermophysical properties and morphology with the olivine/carbonate-bearing materials and low-olivine capping unit of Edwards and Ehlmann (2015), respectively. Combining high-resolution morphological and spectral investigations of others (Ehlmann and Mustard, 2012; Edwards and Ehlmann, 2015; Gouge et al., 2015) with our work suggests that these capping units may have been laterally contiguous, or that materials with these properties and compositions are common throughout this region. If these units were emplaced via similar or the same processes, then the units mapped in NE Syrtis would have been contiguous throughout the Jezero watershed and continue further more towards the north-northeast.

The observations of olivine-rich bedrock mapped by Hamilton and Christensen (2005) in Nili Fossae do not extend southward to include NE Syrtis, but the thermal inertias of ∼455 J m⁻² K⁻¹ s⁻⁰.⁵ reported for the strongest olivine signatures are similar for our measurements of the Fractured Unit. Global maps of olivine by Ody et al. (2012) using OMEGA data show that NE Syrtis resides at the southernmost edge of the large Nili Fossae olivine-rich terrain. These two observations along with the similarities of the olivine-rich materials described by Gouge et al. (2015) and Edwards and Ehlmann (2015) confirm that the NE Syrtis olivine-rich Fractured Unit is part of this regional unit, though perhaps the most degraded.

These observations show that the geology and stratigraphy of NE Syrtis, while exceptionally exposed and bearing diverse alteration products, is associated with the geology of the larger Nili Fossae region as observed throughout are units bearing comparable compositional and morphological characteristics in analogous stratigraphic succession. Our geomorphic and spectral analyses confirm that NE Syrtis exhibits considerable geomorphic and mineralogic diversity within a relatively small geographic area that is representative of the geologic processes occurring throughout the broader Nili Fossae region during the Noachian and Hesperian. The overall stratigraphy matches that of the regional Nili Fossae group of Mangold et al. (2007); a stratigraphy of basement phyllosilicates overlain by an olivine-rich unit and capped by the Syrtis Major lavas with a trend of decreasing alteration upsection. NE Syrtis adds to this lithostratigraphic sequence by exposing the diverse environmental history of this region as observed through the

Fig. 15. Mesa-forming expressions of the basal Fractured Unit (FRU) and the upper Capping Unit (CAU). (a) These units are mapped throughout the study area with the FRU more spatially extensive than the CAU. Geomorphic map overlain on a subframe of HiRISE image ESP_016443_1980. (b) Subframe of HiRISE image ESP_016443_1980, with corresponding area to (a), depicting the local context. The crater-preserving CAU is observed as well as the separation into small mesas. The location of (c) is indicated by the white rectangle. The approximate vantage point for Fig. 16a is shown with the white ‘*’ symbol. (c) The layered nature of the CAU. Here, the top crater-preserving layer of the CAU is clearly distinguished from the lower light-toned, fractured, and blocky layer. The lowermost outer rim, beneath the light-toned, fractured CAU layer, is the olivine-carbonate-bearing FRU. North is up in all images.
presence of alteration minerals not present in this fidelity or proximity elsewhere in Nili Fossae.

5.2. Geological history of Northeast Syrtis Major

We constructed a detailed geological history of NE Syrtis on the basis of our high-resolution geomorphic mapping and integration with previous mapping efforts and spectral characterizations. The history began with the pre-Noachian formation of the primitive martian crust and the large basin-forming impacts with the exception of Isidis. Primitive crustal materials may be observed in the region, perhaps identifiable through mafic signatures such as low-Ca pyroxene (Mustard et al., 2005), and large megabrecia blocks displaying layering, hint at active geological processes prior to the basin-forming impacts affecting NE Syrtis.

During the Noachian, the crust was aqueously altered, perhaps by subsurface hydrothermal circulation (Ehlmann et al., 2011) or top-down pedogenic weathering, producing Fe/Mg-smectites as the dominant hydrated silicate mineral. Additional phyllosilicate formation hypotheses, including formation during the last stages of a magma ocean (Cannon et al., 2016) or via magmatic precipitation (Meunier et al., 2012), would be applicable here. The Isidis basin formed in the Middle-to-Late Noachian at 3.96 Ga (Werner, 2005), resetting the surface morphology with extensive ejecta deposits and excavated material in the mapping area. Megabrecia observed in the Basinment Unit may be due to this impact and/or the pre-impact substrate. The overall topography of the region was likely a result of the cratering process and the subsequent crustal readjustment of the basin as evidenced by the formation of the Nili Fossae and the potential provenance of the large crustal mounds as part of a basin ring structure (Wichman and Schultz, 1989; Mustard et al., 2007).

Contemporaneous or following the basin formation was a period of heavy cratering. Craters ranging from 100s of meters to a few kilometers in size were formed, and their influence may be observed in the present by the quasi-circular mesa-forming expressions of the Capping and Fractured Units suggestive of pooling into the topographic lows of pre-existing small cavities. The nearby Jezero crater formed subsequent to Isidis and would have covered the Plains region of NE Syrtis with a continuous ejecta blanket. The dynamic topography of the mapping area likely completed major structural alterations not long after the period of heavy cratering. The Depression region and Jezero crater were formed prior to the emplacement of the olivine-rich Fractured Unit, as well as the unnamed 6 km crater that has departed from circularity, suggesting minor crustal movements or preferential erosion may have affected it.

The major stratigraphic marker of the olivine-rich Fractured Unit was emplaced subsequent to the formation of the dynamic topography of the region. The olivine-rich Fractured Unit Embays the basement unit and drapes the topography on both local and regional scales. It is observed draping small topographic lows on the scale of 100s of meters, as well as covering the regional topography from top of the southwest rim of Jezero crater, across the sloping plains, and draping the walls of the Depression region towards the Syrtis Major Volcanics. The draping of the olivine-rich Fractured Unit could additionally be explained by emplacement on an undulating crust, emplacement as an ash-fall deposit, or emplacement contemporaneous with basin formation as a sheet that adjusted with the large-scale crustal movement. The presence of megabreccia possibly within the Dark-toned Fractured Unit in the Depression region suggests that this olivine-carbonate-bearing Fractured Unit may be impact related, as suggested by Mustard et al. (2007).

The Large Linear Features were also emplaced at this point as they are observed branching off of the Fractured Unit, though
Fig. 17. The quasi-circular mesa-forming expressions of the Capping Unit (CAU) and Fractured Unit (FRU). Subframes of a HiRISE mosaic constructed from images listed in Table S2. Numerous occurrences display a quasi-circular appearance formed by both the FRU and CAU. (a–d) Quasi-circular exposures of approximately equal spatial extent. The local context of (c) can be observed in Fig. 10a. (e) Quasi-circular shapes are common at the scale of a few 100 m, but expressions on the scale of several kilometers also display approximately equal perpendicular diameters and some rounded edges. North is up in all images.

The process leading to their emplacement is difficult to deduce at an orbital scale. The bifurcation of the Large Linear Features at angles forming triple or orthogonal junctions hints that this subunit displaced the Basement Unit during emplacement of the Fractured Unit. The raised bounding ridges, and their sharp contacts, may suggest a contact metamorphism interaction occurred between the Large Linear Features and the host Basement Unit. The raised bounding ridges and lower internal material indicate that the bounding ridges are hardened and less susceptible to erosion. The Large Linear Features are also observed in present-day troughs and appear to have conformed to the shape of these troughs, which may indicate that the olivine-rich melts followed topographic gradients on the surface during emplacement and pooled in topographic lows. These observations suggest an emplacement relationship exists between fracturing of the Basement Unit and the olivine-rich material, though here multiple hypotheses can exist. The Large Linear Features may be remnants of a network of fractures that supported the mobilization of olivine-rich melts in the near-surface crust. The high-temperature fluids may have altered the host wall rock along its interface and, following subsequent erosion, this less erosion-susceptible rock became the high-standing bounding ridges. The sharp bifurcation angles seen in the Large Linear Features and the long lengths not deviating from a straight line may support this crustal-interaction hypothesis. Similarly, these observations may suggest emplacement occurred contemporaneous with a pervasive fracturing of the crust, such as during impact basin formation. Therefore, the Large Linear Features could be indicative of volcanic dykes or an impact melt sheet emplaced and mobilized upon a heavily fractured surface subsequent to the formation of the Isidis basin. These features do not exclude any of the current hypotheses for emplacement of the Fractured Unit.

Enigmatically, the presence of the olivine-rich Fractured Unit on the rim and floor of Jezero crater and its presence as quasi-circular features suggest a significant period of time elapsed between the formation of the Isidis basin and the emplacement of the Fractured Unit. Possible implications include the emplacement of the Fractured Unit subsequent to the formation of Jezero crater by a volcanic process, the olivine-rich material superposing Jezero crater being of different provenance than in NE Syrtis, or the formation of Jezero crater as a secondary crater formed by the fallback of ejecta during the formation of the Isidis basin. The formation age of the Nil Fossae is poorly constrained, although it is argued that they formed subsequent to the olivine-rich unit emplacement (Mustard et al., 2009); likely shortly after Isidis was formed (Wichman and Schultz, 1989), or in the Middle Noachian (Tanaka et al., 2005).

Subsequent to the emplacement of the Fractured Unit was the deposition of the Capping Unit. The origin of this material may have been volcanic flows into the region or an ash-fall deposit of volcanic or impact-generated debris. The layered nature of the Capping Unit suggests that either multiple deposits were emplaced or the unit was emplaced and, then during solidification, differentiated into two layers of differing physical properties. The layered nature is not always observed for the Capping Unit, but this may be the result of varying degrees of erosion and exposure. The layers may conversely represent temporally and spatially separated episodes of deposition.

Multiple formation mechanisms are hypothesized for the carbonate observed in conjunction with the olivine-rich Fractured Unit. The timing of its formation is both important and difficult to constrain. If the carbonate formed in the process of hydrothermal serpentinization, a carbonatization system, or a talc-carbonate system, then the carbonate would have formed in the Late Noachian near-contemporaneously with the emplacement of the Fractured Unit. These mechanisms have been invoked to explain the Nil Fossae carbonate. The water would percolate through the olivine-rich Fractured Unit, and the heat driving the reaction would be from the emplacement of the unit, the geothermal gradient, or burial diagenesis resulting from the Syrtis Major Volcanics (Ehlmann et al., 2008; Brown et al., 2010; Viviano et al., 2013). If the carbonate formed via low-temperature alteration induced by overland flow of water into the region, then it may have been contemporaneous with the formation of the valley networks, regional rises in groundwater, regional glaciation, or an Isidis ice sheet in the Hesperian or Early Amazonian (see below). If the carbonate formed from surface weathering of olivine-rich rocks in a manner akin to evaporites observed on meteorites found in Antarctica (e.g., Jull et al., 1988; Velbel et al., 1991), then the carbonate may have formed at any time throughout martian history, including in recent times at the cold and dry surface conditions. This mechanism
could activate on olivine-rich rocks exposed at the surface during transitory periods of limited surface water, or perhaps even thin films of water as was suggested for the carbonate observed by the Phoenix lander (Boynton et al., 2009).

The depositional event subsequent to the emplacement of the Capping Unit, and after a period of non-deposition as suggested by its cratered surface, was the emplacement of the sulfate-bearing Feature-bearing Slope Unit. Raised Boxwork Ridges are confined to, and mapped as a subunit of, the Feature-bearing Slope Unit. Regional mapping and structural analysis favors a sedimentary emplacement origin for this unit and filled volume-loss fractures as the origin of the ridges (Quinn and Ehlmann, 2014b). If the sulfate-bearing layers were produced in a sedimentary depositional environment, the aqueous environment producing the Feature-bearing Slope Unit may have been relatively long-lived, as it produced ~500 m of layers. Further running hypotheses for the emplacement of this unit include ash layers, volcanic flows, or sedimentary deposits that developed sulfate-bearing mineralogy via subsequent digenesis, perhaps in a manner similar to that observed at Meridiani Planum (e.g., McLennan et al., 2005). Sulfate formation in this manner could suggest that this deposit is tied to regional groundwater circulation (e.g., Andrews-Hanna and Lewis, 2011), therefore the formation timing of these sulfates may be similarly linked to global sulfate-forming phenomena.

Initiating at ~3.7 Ga (Hiesinger and Head, 2004; Ivanov et al., 2012) and subsequent to the deposition of the Feature-bearing Slope Unit, the Hesperian volcanic flows from Syrtis Major began to enter the region. If these flows extended onto the Plains region of NE Syrtis, then a significant amount of subsequent erosion has occurred as there is no morphological evidence for remnant flows on the Plains region. The one exception being the Smooth Sloped Mounds with their possible dark-toned, high-Ca pyroxene cover; for if high-Ca pyroxene was inherent to the Smooth Sloped Mounds and not the cover, then this could suggest the flows covered the Plains region. The volcanic flows from Syrtis Major likely halted not much further than their present location and the subsequent erosion developed the scarp of Feature-bearing Slope Unit. At the contact with the Nili Fossae, the Syrtis Major Volcanics may have encountered ice deposits as evidenced by the highly irregular margins of lava flows in the region (Ivanov and Head, 2003). If the valley of NE Syrtis (Section 4.2.3) was formed by overland fluvial processes, then the presence of glaciers and surface waters could explain the flow patterns from the Syrtis Major Volcanics into the Depression region and eastward out through the valley, as opposed to following the main topographic gradient south (Skok and Mustard, 2014). The valley needs to be reconciled with the observation that the geomorphic units remain relatively intact with minor sculpting towards streamlines shapes, and therefore the duration or intensity of fluvial activity may have been limited. Numerical simulations suggest that an ice sheet may have covered the entire Isidis basin and formed the thumbprint terrain on Isidis Planitia dated at 2.8 to 3.5 Ga (Souček et al., 2015). If the formation of the valley was in conjunction with the presence of an Isidis basin ice sheet, then the valley would have formed in the Late Hesperian or Early Amazonian, likely from runoff related to the ice sheet. Fluvial, alluvial, or glacial processes throughout the Hesperian and Early Amazonian may have been responsible for the erosion and removal of significant amounts of material from NE Syrtis, as suggested by the absence of continuous ejecta blankets for Jezero crater or the unnamed 6 km crater in the northwest quadrant of the mapping area, the high-standing nature and erosional scarps of the mesa-forming expressions of the Capping and Fractured Units, and the significant removal of the Capping Unit from the Fractured Unit.

It is difficult to pinpoint the time of formation of the Al-phyllosilicate clay-bearing deposits, as they appear distributed in isolated patches within the Fe/Mg-smectite-bearing Basement Unit and not as a distinct stratum. Several hypotheses exist for the formation of Al-phyllosilicates. The deposits may have formed as a result of the alteration of somewhat heterogeneous parent rocks or pedogenic-type leaching of phyllosilicate-bearing parent rocks (Ehlmann et al., 2009), long-term weathering (Gaudin et al., 2011), or deep hydrothermal alteration (Ehlmann et al., 2011). The emplacement of a hot capping rock may have allowed the Al-phyllosilicate to form from hydrothermal fluids circulating in a Fe/Mg-smectite parent rock (Ehlmann et al., 2009), and subsequent erosion exposing the Al-phyllosilicates at the surface. Our observations at the contact of the upsection Fractured Unit do not support the presence of a distinct stratum bearing Al-phyllosilicate in NE Syrtis. As we observe scattered detections of Al-phyllosilicates at the surface of the crustal basement, we favor the formation of this material via isolated leaching of the crustal rocks, perhaps

Fig. 18. The Dark-Toned Fractured Unit (FRU-DT). Subframes of a HiRISE mosaic constructed from images listed in Table S2. (a) The crater-preserving surface of the Capping Unit (CAU) is observed in the Depression region with a darker appearance than on the Plains region. The CAU transitions to a smooth, dark surface with the light-toned, fractured, and blocky appearance of the FRU-DT observed at the outer edges. The location of (b) is indicated with the white rectangle. (b) The outer reaches of the FRU-DT. Here the light-toned, fractured, and blocky component of the FRU is observed at a contact with the Basement Unit. Away from the contact and towards the center of the FRU-DT is an increasing dark-toned cover. North is up in both images.
Fig. 19. Geomorphic example of the Raised Linear Ridges (RLR). (a) Areas mapped as RLR bear ridges meters in width, hundreds of meters in length, and are high-standing above a relatively smooth basement. Subframe of HiRISE image ESP_038029_1980 overlain by a corresponding subframe of the geomorphic map (Fig. 4). North is up in the image. (b) As in (a), but without the geomorphic map. The RLR are observed stratigraphically below the Fractured Unit (FRU) and are categorized as a subunit of the Basement Unit. (c) CRISM ratioed reflectance spectrum (d) collected of the RLR through a FRU erosional window. Narrow absorptions observed centered at ~1.4, 1.9, and 2.3 μm are indicative of Fe/Mg-smectites. A weak absorption at ~2.39 μm may be present, and can be indicative of Fe/Mg-smectites or phyllosilicates, including saponite (e) or talc (f). The saponite spectrum (LASA53) taken from the CRISM spectral library (CRISM Science Team, 2006), and the talc spectrum (GDS23) is from the USGS digital spectral Library (Clark et al., 2007). Vertical lines are located at 1.41, 1.91, 2.31, and 2.39 μm.

Fig. 20. Breccia-bearing terrain in the Depression region. (a) Large megobreccia blocks 10s of meters in size are observed at a flat surface as evidenced by small boulders casting shadows (arrow i). Some blocks display an internal texture suggestive of layering or banding present prior to disruption via impact (arrow ii). One breccia block appears to have been offset ~10 m by faulting (arrow iii). (b) Smaller breccia blocks are observed in a clast-rich outcrop that sharply contacts the olivine-rich Fractured Unit (light-toned fratured outcrops surrounding the clast-rich breccia). (b) is to the southwest of (a) showing the southwest trend of breccia blocks become larger and more spread out in the dark supporting material. Subframes of HiRISE image ESP_018988_1980. North is up in both images.

influenced by heterogeneous initial composition or the result of localized surface weathering.

Due to the presence of the parallel north-south trending dunes in NE Syrtis, it is suggested that the Amazonian period witnessed the slow and continual erosion of the surface by aeolian denudation, with the Isidis basin governing the motion of local air masses. The complexity of the landscape results from the differing mechanical properties of the various units, and the multiple events of deposition, aqueous alteration, and erosion.

6. Conclusions

NE Syrtis exposes a stratigraphic sequence spanning the Noachian-Hesperian boundary, encapsulating ~250 Myr of geological history. Between the bookend stratigraphic markers of the Isidis-forming impact and the Syrtis Major lavas at 3.96 and ~3.7 Ga, respectively, exists great geomorphic heterogeneity that is unifiable under five distinct units. They are, ascending the stratigraphic column: (1) the Basement Unit, (2) the Fractured Unit, (3) the Capping Unit, (4) the Featuring-bearing Slope Unit, and (5) the Syrtis Major Volcanics unit. NE Syrtis bears a local variation on the
regional Nil Fossae group (Mangold et al., 2007) where basement phyllsolicates are overlain by an olivine-rich unit and topped by the Syrtis Major lavas, displaying a trend of decreasing alteration. NE Syrtis adds to this lithostratigraphic sequence by exposing the diverse environmental history of this region as observed through the presence of alteration minerals that are not exposed or apparent in this fidelity elsewhere in Nili Fossae.

NE Syrtis bears extensive coverage of the Nili Fossae regional olivine-rich unit that is variably altered to carbonate. Mapped as the Fractured Unit, it is identified here from the contact with the Syrtis Major Volcanics to the southwest rim of Jezero crater. The Large Linear Features of the Fractured Unit are intriguing and enigmatic landforms. Their geomorphic features suggest that the olivine-rich melts were mobilized in a highly-fractured surface or near-surface crust, with contact metamorphism being suggested by the raised bounding ridges. Megabreccia textures are observed within NE Syrtis, both stratigraphically below and within the olivine-rich Fractured Unit. In the Plains region, large and spatially distributed megabreccia appear stratigraphically older than the Fractured Unit and, in the Depression region, clast-rich breccias sharply contact the Fractured Unit and appear to be stratigraphically contemporaneous. Despite the compilation of additional orbital observations presented herein, the continuation of both a volcanic and impact melt emplacement hypotheses remains viable.

The presence of Fe/Mg-smectites, kaolin-group minerals, carbonates, and sulfates distributed amongst three of our geomorphologic units (Basement Unit, Fractured Unit, Feature-bearing Slope Unit, respectively) confirms initial work by Ehlmann and Mustard (2012) that as many as four temporally distinct aqueous environments existed in NE Syrtis. These three units span the Noachian-Hesperian and Phyllosian-Theiellian boundaries and are capped by the Syrtis Major flows, suggesting an aqueous history of at least 250 Myr and extending further into the Noachian past. Spectral signatures of a kaolin-group mineral are observed in isolated patches within the Basement Unit and not as a distinct stratigraphic unit. Their location and geomorphic characteristics argue for formation via isolated leaching or heterogeneous initial crustal composition, rather than extended weathering profiles or magma precipitation. The aqueous history of the region extends from the Late Noachian into the Hesperian and, depending on the formation mechanism for these alteration minerals, may extend to the Late Hesperian or Amazonian.

Perhaps no other location on Mars offers the diversity of geology, mineralogy, and geomorphology in such spatial proximity than NE Syrtis. The geomorphic diversity is revealed through the variety of landforms observed in the mapped geomorphic units, the fluvial valley cutting through the mapping area, the geomorphic remnants from impact and volcanic processes, and from the eons of denudation of the landforms and aeolian processes. The chronology of the region is relatively well constrained as it is bottlenecked by the impact processes that resulted from the formation of the Isidis basin to the later emplacement of the Syrtis Major Volcanics. In close spatial proximity are igneous mineralogies spanning from potential primitive crust to those from later volcanism and impact processes, in addition to alteration mineralogies alluding to multiple distinct aqueous environments. The stratigraphically-bounded alteration minerals within NE Syrtis suggests the presence of multiple, potentially habitable (Ehlmann and Mustard, 2012), environments located in this region in the martian past. Understanding the detailed formation mechanisms of these alteration minerals, the geological history of the geomorphic units, and the chronology of active processes in this ancient terrain will greatly constrain the likelihood of these environments as being conducive to life. As we turn our eyes to the next target for in situ exploration on the martian surface, no location offers better access of the gamut of geological processes active at Mars than Northeast Syrtis Major.

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Supplementary materials

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References


