

**Hungaria Asteroid Region Telescopic Spectral Survey (HARTSS):
Establishing Asteroid-Meteorite Connections Between Hungaria Asteroids and Meteorites
of the Acapulcoite-Lodranite Clan**

**A Dissertation Presented for the
Doctor of Philosophy
Degree
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**Michael Peter Lucas
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DEDICATION

To Mom and Dad, Margaret Ann and Paul Lucas, thank you for everything, and because I love you this is for you.

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ABSTRACT

Hungaria region asteroids are survivors of giant planet migration that destabilized a now extinct inner-portion of the primordial asteroid belt. In this scenario, the Hungaria region represents a “purgatory” for the closest, preserved samples of material from which the terrestrial planets accreted. Deciphering the surface composition of these samples may provide constraints on the nature of the primordial building blocks of the terrestrial planets. We carried out a two-phased ground-based observational campaign—Hungaria Asteroid Region Telescopic Spectral Survey (HARTSS)—to record their visible and near-infrared reflectance spectra. We analyzed these spectra to characterize the taxonomy, surface mineralogy, and potential meteorite analogs of Hungaria background and family asteroids. In HARTSS I we found that ~80% of the background population are stony S-types that exhibit spectral and mineralogical diversity. Two main asteroid-meteorite connections exist between background S-types and stony meteorites: unmelted L-/LL-ordinary chondrites, and partially-melted primitive achondrites. To strengthen connections between S-types and partially-melted meteorites, we measured the spectral and cosmochemical properties of 10 acapulcoite-lodranites. We found a well-defined relationship between the ~2 μm band center and ferrosilite (Fs) content of orthopyroxene. Because Fs in orthopyroxene and fayalite (Fa) content in olivine are well-correlated in these meteorites, the derived Fs content can be used to estimate Fa of the co-existing olivine. These relationships help to determine whether S-types are nebular (ordinary chondrites), or have experienced partial melting (primitive achondrites). In HARTSS II, we focus on family members and hypothesize that the Hungaria family is compositionally homogeneous. Surviving fragments of an asteroid collisional family typically exhibit similar taxonomies, albedos, and spectral properties. Measurements of these properties for Hungaria family members are consistent with this scenario. Spectral observations of 92 Hungarias acquired during HARTSS uncover a compositionally heterogeneous background population and a spectrally homogeneous collisional family, implying that the parent body was homogeneous. This parent body was likely consistent in composition with enstatite achondrites (aubrites) and therefore formed under reduced, igneous conditions. If aubrites are truly representative of igneous mantle material, then the Hungaria parent body was itself a collisional fragment that originated on a differentiated, heterogeneous parent body early in Solar System history.

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INTRODUCTION

Most meteorites originate from asteroidal parent bodies (see Burbine et al., 2002). Unfortunately, these samples provide little geologic context because in most cases the parent body and the source region are unknown. However, several conclusive links have been made between meteorites and their parent bodies in the past few decades. Cosmochemical and petrologic evidence indicates that the Moon and Mars are the parent bodies of several achondrite meteorite groups. Ground-based spectral observations have linked 4 Vesta and its collisional family of asteroids (Vestoids) with the howardite-eucrite-diogenite (HED) meteorites (McCord et al., 1970; Gaffey et al., 1997). This link has since been reinforced with compositional data of Vesta's surface acquired during the Dawn spacecraft mission (McSween et al., 2013; Russell et al., 2015). The Vesta-HED link appears to be the only definitive correlation between a meteorite group and a *distinct* asteroid parent body. In the near future, only several bodies will be visited for asteroid sample return. In the meantime, it remains challenging to establish robust asteroid-meteorite connection from the ground. Reasonable hypotheses can be formed and promising steps taken by comparing visible (VIS) and near-infrared (NIR) asteroid spectral data, acquired with ground-based telescopes, to spectral and cosmochemical data of meteorites, obtained in the laboratory. It is therefore tasked to the astronomer and the petrologist to identify the parent bodies and source regions of meteorites.

Main Belt asteroids larger than $D \gtrsim 20$ km exhibit a broad compositional gradient (Gradie and Tedesco, 1982; Bus, 1999; DeMeo and Carry, 2014). C-complex objects, which represent the primitive carbonaceous chondrite meteorites, are most abundant in the outer-belt, while S-complex asteroids, which represent nebular (chondritic) or igneous (achondritic) stony-meteorites, dominate the inner-belt (Gradie and Tedesco, 1982; Mothé-Diniz et al. 2003; DeMeo and Carry, 2014). Extending this trend inward, the degree of igneous differentiation experienced by asteroids *interior* to the Main Belt and in the terrestrial planet region is also of interest. The terrestrial planets likely accreted from nearby planetary embryos and planetesimals, not from material in the Main Belt (Raymond et al., 2009). But, evidence for this process has been lost as planetesimals in the inner portion of the protoplanetary disk (PPD) where the terrestrial planets formed were either accreted by planetary embryos or scattered out of the inner PPD early in solar system history (Weidenschilling et al., 1997; Bottke et al., 2006; Kleine et al., 2009). The present Hungaria asteroids are high-inclination survivors of giant planet migration that destabilized a now extinct inner portion of the primordial asteroid belt ("E-belt"; see Bottke et al., 2012) and left in its wake the current resonance structure of the Main Belt (Morbidelli et al., 2010; Minton and Malhotra, 2011). This primordial asteroid belt may have extended inward as far as 1.7 AU, much nearer to the terrestrial planets than the current Main Belt. Therefore, the Hungaria region represents a "purgatory" for preserved, *in situ* samples of the asteroidal material from which the terrestrial planets accreted. Deciphering the surface mineralogy and establishing asteroid-meteorite connections for Hungaria asteroids may provide fundamental constraints on the composition(s) of the primordial building blocks of the terrestrial planets.

To decipher the surface mineralogy and establish asteroid-meteorite connections for Hungaria region asteroids we have carried out a ground-based observational campaign entitled Hungaria Asteroid Region Telescopic Spectral Survey (HARTSS) to record reflectance spectra of these preserved samples from the inner-most primordial asteroid belt. These VIS+NIR reflectance spectra provide detailed taxonomic and compositional inferences of their surfaces. Chapter I of this dissertation represents phase one of HARTSS where we targeted Hungaria

background (i.e., non-family) asteroids to assess the compositional diversity of asteroids in the Hungaria region. To strengthen potential asteroid-meteorite connections revealed during HARTSS I between background S-type asteroids and partially melted meteorites, we turn to the laboratory for spectral and cosmochemical analyses of primitive achondrites. Chapter II of this dissertation describes our examination of 10 acapulcoite-lodranite clan meteorites. Through these analyses we have established new correlations between spectral parameters and mafic mineral compositions for partially melted asteroids. In Chapter III of this dissertation, we carry out HARTSS phase two, where we turn our attention to Hungaria family members and hypothesize that this collisional family is compositionally homogeneous. We test this hypothesis through the taxonomic classification, albedo estimates, and spectral properties of Hungaria family asteroids.

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CHAPTER I

Hungaria Asteroid Region Telescopic Spectral Survey (HARTSS) I: Stony Asteroids Abundant in the Hungaria Background Population

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Abstract

The Hungaria asteroids remain as survivors of late giant planet migration that destabilized a now extinct inner portion of the primordial asteroid belt and left in its wake the current resonance structure of the Main Belt. In this scenario, the Hungaria region represents a “purgatory” for the closest, preserved samples of the asteroidal material from which the terrestrial planets accreted. Deciphering the surface composition of these unique samples may provide constraints on the nature of the primordial building blocks of the terrestrial planets. We have undertaken an observational campaign entitled the Hungaria Asteroid Region Telescopic Spectral Survey (HARTSS) to record near-infrared (NIR) reflectance spectra in order to characterize their taxonomy, surface mineralogy, and potential meteorite analogs. The overall objective of HARTSS is to evaluate the compositional diversity of asteroids located throughout the Hungaria region. This region harbors a collisional family of Xe-type asteroids, which are situated among a background (i.e., non-family) of predominantly S-complex asteroids. In order to assess the compositional diversity of the Hungaria region, we have targeted background objects during Phase I of HARTSS. Collisional family members likely reflect the composition of one original homogeneous parent body, so we have largely avoided them in this phase. We have employed NIR instruments at two ground-based telescope facilities: the NASA Infrared Telescope Facility (IRTF), and the Telescopio Nazionale Galileo (TNG). Our data set includes the NIR spectra of 42 Hungaria asteroids (36 background; 6 family). We find that stony S-complex asteroids dominate the Hungaria background population (29/36 objects; ~80%). C-complex asteroids are uncommon (2/42; ~5%) within the Hungaria region. Background S-complex objects exhibit considerable spectral diversity as band parameter measurements of diagnostic absorption features near 1- and 2- μm indicate that several different S-subtypes are represented therein, which translates to a variety of surface compositions. We identify the Gaffey S-subtype (Gaffey et al. [1993]. *Icarus* 106, 573–602) and potential meteorite analogs for 24 of these S-complex background asteroids. Additionally, we estimate the olivine and orthopyroxene mineralogy for 18 of these objects using spectral band parameter analysis established from laboratory-based studies of ordinary chondrite meteorites. Nine of the asteroids have band parameters that are not consistent with ordinary chondrites. We compared these to the band parameters measured from laboratory VIS+NIR spectra of six primitive achondrite (acapulcoite-lodranite) meteorites. These comparisons suggest that two main meteorite groups are represented

among the Hungaria background asteroids: unmelted, nebular L- (and possibly LL-ordinary chondrites), and partially- melted primitive achondrites of the acapulcoite-lodranite meteorite clan. Our results suggest a source region for L chondrite like material from within the Hungarias, with delivery to Earth via leakage from the inner boundary of the Hungaria region. H chondrite like mineralogies appear to be absent from the Hungaria background asteroids. We therefore conclude that the Hungaria region is not a source for H chondrite meteorites. Seven Hungaria background asteroids have spectral band parameters consistent with partially-melted primitive achondrites, but the probable source region of the acapulcoite-lodranite parent body remains inconclusive. If the proposed connection with the Hungaria family to fully-melted enstatite achondrite meteorites (i.e., aubrites) is accurate (Gaffey et al. [1992]. *Icarus* 100, 95–109; Kelley and Gaffey [2002]. *Meteorit. Planet. Sci.* 37, 1815–1827), then asteroids in the Hungaria region exhibit a full range of petrologic evolution: from nebular, unmelted ordinary chondrites, through partially-melted primitive achondrites, to fully-melted igneous aubrite meteorites.

1. Introduction

The Hungaria asteroids are unique among the minor planets. These “neighbors” of the terrestrial planets reside interior to the Main Belt of asteroids by at least 0.1 AU, are highly-inclined to the ecliptic, and may have occupied their current location since early in Solar System history (Warner et al., 2009; Milani et al., 2010; Bottke et al., 2012). Mars-crossing and near-Earth asteroids (NEAs) can wander even closer to the terrestrial planets, but those objects are dynamically short-lived (~ 10 Myr) escapees from the Main Belt (Morbidelli et al., 2002; Binzel et al., 2004a). In contrast, the Hungaria region is a quasi-stable orbital space bound by mean-motion and secular resonances (Carvano et al., 2001; Warner et al., 2009; Milani et al., 2010; McEachern et al., 2010) (Figure I-1). Hence, asteroids entering this region have dynamic half-lives from ~ 100 million years (Myr) (Migliorini et al., 1998; McEachern et al., 2010) to about one billion years (Gyr) (Milani et al., 2010). It is therefore likely that many asteroids in the Hungaria region have resided there since the giant planets completed their migration to their current orbits (Warner et al., 2009; Bottke et al., 2012). Nevertheless, there is some leakage from the inner-edge of the Hungaria region, which helps to replenish the short-lived Mars-crossing population (Migliorini et al., 1998; Michel et al., 2000; Milani et al., 2010; Ćuk et al., 2014) and vice-versa (McEachern et al., 2010), thereby providing a pathway for meteoroids to reach the Earth from the Hungaria region (Gaffey et al., 1992; Ćuk et al., 2014).

The Hungaria region contains $\sim 14,000$ known, small ($D < 11$ km) asteroids (JPL Horizons¹) that populate orbital space roughly defined by; $1.78 < a < 2.0$ AU, $e < 0.18$, and $16^\circ < i < 34^\circ$ (Warner et al., 2009). This region is inhabited by the Hungaria collisional family (PDS² ID 003) of mainly Xe-type asteroids, which comprises a significant fraction of the total population in the region (Carvano et al., 2001; Assandri and Gil-Hutton, 2008; Warner et al., 2009; DeMeo and Carry, 2013). Collisional families originate from the disruption of a common parent body (Zappalà et al., 2002; Cellino et al., 2009; Nesvorný et al., 2015), and share tightly-clustered proper orbital elements (Hirayama, 1918; Zappalà et al., 1990; Zappalà et al., 1994; Zappalà et al., 1995). The collision that fragmented the Hungaria parent body occurred approximately 275 Myr (Milani et al., 2010) to 500 Myr (Warner et al., 2009) ago, forming the Hungaria family

¹ JPL Horizons, accessed March 3rd, 2016: http://ssd.jpl.nasa.gov/sbdb_query.cgi

² Planetary Data System Small Bodies Orbital Data: <http://sbn.psi.edu/pds/archive/orbital.html>

with family namesake 434 Hungaria the presumed largest existing fragment. This family is situated among a background (i.e., non-family members) of predominantly S-complex asteroids (Carvano et al., 2001; Warner et al., 2009).

Color and spectral observations of asteroids have revealed a broad compositional gradient among the larger asteroids ($D > \sim 20$ km) in the Main Belt (Gradie and Tedesco, 1982; Bus, 1999; DeMeo and Carry, 2013; DeMeo and Carry, 2014). C-complex objects, believed to represent the primitive carbonaceous chondrite meteorites, are most abundant in the outer-belt, while S-complex asteroids, believed to represent nebular (chondritic) or igneous (achondritic) stony-meteorites, dominate the inner-belt (Gradie and Tedesco, 1982; Mothé-Diniz et al. 2003; DeMeo and Carry, 2013; DeMeo and Carry, 2014). Extending this trend further, the degree of igneous differentiation experienced by asteroids *interior* to the Main Belt and in the terrestrial planet region is also of interest. The feeding zones for the accretion of terrestrial planets can be relatively narrow, incorporating very little material from beyond 2 AU in some planetary accretion models (Raymond et al., 2009). Therefore the terrestrial planets most likely accreted from nearby planetary embryos and planetesimals, not from material in the Main Belt. However, the evidence for this process has been lost as planetesimals in the inner portion of the protoplanetary disk (PPD) where the terrestrial planets formed were either accreted by planetary embryos or scattered out of the inner PPD early in solar system history (Weidenschilling et al., 1997; Bottke et al., 2006a; Kleine et al., 2009). Bottke et al. (2012) has suggested that the present Hungaria asteroids remain as high-inclination survivors of late giant planet migration that destabilized a now extinct inner portion of the primordial asteroid belt (“E-belt”) and left in its wake the current resonance structure of the Main Belt (Morbidelli et al., 2010; Minton and Malhotra, 2011). This E-belt may have extended inward as far as 1.7 AU, much nearer to the terrestrial planets than the current Main Belt. Therefore, we argue that the Hungaria region represents a “purgatory” for preserved, *in situ* samples of the asteroidal material from which the terrestrial planets accreted. Deciphering the surface mineralogy and establishing asteroid-meteorite connections for Hungaria asteroids may then provide fundamental constraints on the composition(s) of the primordial building blocks of the terrestrial planets.

The spectral and chemical properties of terrestrial and extraterrestrial minerals analyzed in the laboratory, compared with ground-based telescopic near-infrared (NIR) spectral observations, can constrain asteroid surface mineralogy and provide evidence for the establishment of asteroid-meteorite connections. This is practicable because NIR spectra of S-complex and several end-member asteroid types (DeMeo et al., 2009) that are rich in the mafic silicate minerals olivine and pyroxene carry strong 1- and/or 2- μm absorption band features (Band I and II, respectively). Cloutis et al. (1986) used laboratory spectra of natural terrestrial olivine and orthopyroxene mixtures to demonstrate that band parameters (i.e., band center, depth, area, and ratio of band areas) of the 1- and 2- μm bands can be used as a gauge of olivine and orthopyroxene modal abundance and chemistry. In particular, Cloutis et al. (1986) found that the Band Area Ratio (BAR - Band II area divided by Band I area) is a sensitive indicator of the olivine to orthopyroxene abundance and that BAR exhibits sufficient insensitivity to mineral chemistry and grain size that reasonable estimates of modal abundances can be formed. Cloutis et al. (1986) also showed that Band I center is responsive to both mineral abundance and chemistry so that the Band I center position can be used to determine the molar Fe^{2+} contents of olivine and orthopyroxene mineral phases. Utilizing these relationships, telescopic spectra can be analyzed to infer asteroid surface mineralogy and potential meteorite analogs.

From the broad compositional gradient observed in the Main Belt, it is argued that bodies of a given size located in the inner portion of the primordial asteroid belt experienced higher peak temperatures than similar sized bodies in the outer belt (McSween et al., 2002). Therefore, we hypothesize that planetesimals in the inner-most part of the primordial asteroid belt underwent partial- to full-melting and differentiation. The dynamical scenario suggested by the E-belt model implies that the present Hungaria asteroids sample material that originated in the inner-most portion of the primordial asteroid belt. Consequently, the Hungaria region should retain at least some of the petrologically-evolved material that formed there. Primitive achondrite meteorites of the acapulcoite-lodranite clan demonstrate that partially-melted asteroids exist and therefore provide a basis for spectral comparison. We test this hypothesis by analyzing NIR spectra of 42 Hungaria asteroids (36 background; 6 family) and by performing detailed spectral band parameter analyses for 24 S-complex background asteroids and for spectra of six primitive achondrite meteorites obtained from the Keck/NASA Reflectance Experiment Laboratory (RELAB) database. The spectra reported herein represent initial results from a larger NIR observational campaign of Hungaria asteroids entitled Hungaria Asteroid Region Telescopic Spectral Survey (HARTSS). The overall objective of HARTSS is to record the NIR reflectance spectra of Hungaria asteroids with absolute magnitude (H_v) <16 to evaluate their surface mineralogy and compositional diversity through taxonomic classification and spectral band parameter measurements.

2. HARTSS Observations and Data Reduction

HARTSS is an on-going observational campaign that commenced in 2009 September. As of 2013 November, we had obtained telescopic near-infrared (NIR) reflectance spectra of 42 Hungaria region asteroids (36 background; 6 family). We have employed NIR instruments at two separate facilities: the SpeX spectrograph (Rayner et al., 2003) on NASA's 3.0 m Infrared Telescope Facility (IRTF) at Mauna Kea, Hawai'i, and the Near-Infrared Camera and Spectrometer (NICS) on the 3.6 m Telescopio Nazionale Galileo (TNG) at El Roque de Los Muchachos Observatory, San Miguel de La Palma, Canary Islands, Spain (Oliva 2000; Baffa et al., 2001). Observational circumstances are provided in Table I-1. Stars with solar-like spectral type, B-V color, and V-K color were selected as solar analog standards (Table I-1). Data regarding these standard stars were obtained from the SIMBAD database³ (and references therein).

2.1. IRTF SpeX Near-Infrared Spectra

HARTSS includes 22 Hungaria asteroids observed with IRTF SpeX (0.7-2.5 μm) over eight different nights spanning 2009 September to 2013 November (Table I-1). The spectra were recorded using SpeX in the low-resolution prism mode without the dichroic and using a 0.8" x 15" slit, in which the entire wavelength range is dispersed in a single order with an average resolving power over the whole spectral range of $R \sim 75$. The telescope was nodded in a standard ABBA sequence, with the target dithered 7.5" along the slit. The slit was kept aligned with the parallactic angle ($\pm 10^\circ$) to minimize the effects of differential refraction across the wavelength range. On-chip integration times (t_{int}) were held to a maximum of 120 s due to variability of

³ <http://simbad.u-strasbg.fr/simbad/>

atmospheric emission (mainly OH⁺ line emission). Distinct local solar standard stars were observed for each target asteroid. Care was taken to closely match local solar standard and asteroid observations both temporally and spatially. Accordingly, local solar standards were located within $\sim 3^\circ$ of the target and asteroid observations were bracketed close in time (~ 25 min) by local solar standard observations (Emery et al., 2011). Typically, at least eight local solar standard integrations were collected for each ABBA asteroid sequence.

Reduction of the spectral data was performed using the custom IDL (Interactive Data Language) routine Spextool (Cushing et al., 2004). This routine enables the extraction and calibration of SpeX data, including subtraction of dithered A-B pairs to remove background sky emission, division by a master flat-field to remove pixel-to-pixel variations across the chip, and extraction from two-dimensional spectral images to one-dimensional spectra (see Emery and Brown, 2003). A calibration box attached to SpeX contains an integrating sphere that is illuminated for flat-field frames and an Ar lamp for wavelength calibration (Rayner et al., 2003). Reflectance values for each asteroid were calculated by dividing the asteroid spectrum by the corresponding local solar standard spectrum. The spectrum is corrected for atmospheric telluric absorptions and the solar spectrum during this process. Multiple integrations of the divided asteroid spectra were then summed within Spextool to increase the signal-to-noise (S/N) ratio. This process typically yielded an S/N ratio >100 for the majority of the final asteroid spectra.

We supplement our dataset with 15 additional NIR spectra also obtained with IRTF SpeX from the following sources (see Table I-1): data from the MIT-UH-IRTF Joint Campaign for NEO Reconnaissance⁴ (Binzel et al., 2006) (asteroids 2074, 2449, 3635, 3873, 5577, 5641, and 6249); data from Lindsay et al., 2015 (asteroids 2577, 3309, 4674, and 5905); data from Clark et al., 2004 (asteroids 434, 1103, and 2048); and data from Binzel et al., 2004b (asteroid 4142).

2.2. TNG NICS Near-Infrared Spectra

HARTSS includes five Hungaria asteroids observed with NICS (0.8-2.4 μm) at TNG on the night of 2013 October 31 (Table I-1). The NIR spectra were recorded using the high-throughput NICS in low-resolution mode utilizing an Amici prism disperser (Oliva, 2000; Baffa et al., 2001). All spectroscopic modes use the Large-Field camera, which has a plate scale of 0.25"/pixel. We used the 1.5" width slit, corresponding to a spectral resolving power of $R=34$, quasi-constant along the spectra. The slit was kept aligned with the parallactic angle ($\pm 10^\circ$) to minimize the effects of differential refraction across the wavelength range. Several images through the Js filter were acquired to identify the asteroid in the field-of-view and to orient the slit. The acquisition of data consisted of 90 s integrations in two different positions in the slit by nodding the telescope by 10" (i.e., positions A and B). Multiple ABBA sequences were acquired to increase the S/N. The total integration time varied depending on the visual magnitude of the target (Table I-1) and on weather conditions.

Sky conditions were poor during the night of 2013 October 31, showing wide fluctuations in seeing, wind, and cloud coverage conditions. These conditions result in the variable quality of both asteroid and solar analog standard spectra without direct correlation to brightness or airmass. Furthermore, due to sky transparency fluctuations, telluric corrections near strong atmospheric absorptions (1.32-1.46; 1.77-1.95 μm) can be poor for these objects (see Appendix I-B). Spectroscopic data reduction utilized standard Image Reduction and Analysis Facility (IRAF) tasks (see Licandro et al., 2001; Pinilla-Alonso et al., 2016). These tasks include flat-

⁴ <http://smass.mit.edu/minus.html>

field corrections, sky background removal, and extraction of 1-dimensional spectra. Wavelength calibrations were performed on consecutive AB pairs using a look-up table based on the theoretical dispersion predicted by ray-tracing and adjusted to best-fit the observed spectra of calibration sources and telluric absorptions. To obtain relative reflectance and to correct for telluric absorptions, each AB asteroid pair was divided by the spectra of several G-stars (Landolt, 1992) that have proved to be suitable solar analog standards (de León et al., 2010). Subpixel offsetting was applied during solar analog standard star division to correct for errors in wavelength calibrations due to instrumental flexures. Individual relative reflectances obtained for each asteroid respective to the different solar analog standards were averaged to derive final relative reflectances.

3. Results

3.1. Combined Visible and Near-Infrared Spectra

We combined available published visible (VIS) spectral data ($\sim 0.4\text{-}0.9\ \mu\text{m}$) with our NIR spectral data in order to provide more robust taxonomic classifications and mineralogical interpretations for our surveyed Hungaria asteroids. Overall, we supplemented 21 of 42 Hungaria asteroids in our NIR dataset with VIS spectral data from several sources (see Appendix I-B). A scaling factor was used to fit the NIR reflectance data to the normalized VIS reflectances in the wavelength region between $0.70\text{-}0.80\ \mu\text{m}$, and NIR reflectance errors are also multiplied by the same scaling factor. The final VIS+NIR spectra are normalized to unity at $0.55\ \mu\text{m}$, while final NIR spectra are normalized at $1.25\ \mu\text{m}$. We present all 42 NIR and VIS+NIR Hungaria asteroid spectra (36 background; 6 family) in Figure I-9.

3.2. Taxonomic Classification

The taxonomic classifications of our asteroid reflectance spectra were determined using the taxonomic system of Bus-DeMeo (DeMeo et al., 2009). This taxonomy builds upon the earlier visible-wavelength Bus taxonomy (Bus, 1999; Bus and Binzel, 2002) by extending the wavelength coverage of asteroid reflectance spectra into the NIR. The Bus-DeMeo taxonomic system is constructed through principal component analysis based on spectral shape (albedo is not considered) and separates asteroid reflectance spectra into 25 different spectral types within four main complexes: S-complex (S, Sa, Sq, Sr, and Sv), C-complex (B, C, Cb, Cg, Cgh, and Ch), X-complex (X, Xc, Xe, Xk, and Xn), and End Members (D, K, L, T, A, O, Q, R, and V). We identified the taxonomic type of each of our 42 Hungarias using MIT's Bus-DeMeo Taxonomy Classification Tool⁵; the results are presented in Table I-2. For our VIS+NIR spectra the Bus-DeMeo principal component analysis arrives at a unique taxonomic classification for most spectra (15 of 21). For the 21 spectra with NIR-only data the Bus-DeMeo classification is non-unique, and we report the spectral types with the two lowest absolute residuals (Table I-2). S-complex asteroids display widely varying spectral slopes, and the Bus-DeMeo classification notates high-slope (at an arbitrary cut-off of 0.25) objects with a "w" moniker.

Figure I-2 shows the Bus-DeMeo taxonomic complexes (S-, X-, and C-complex) for our sample of 42 Hungaria asteroids. We plotted H_v versus the proper semi-major axis of ~ 3800

⁵ <http://smass.mit.edu/busdemeoclass.html>

Hungarias ($H_v \leq 18.0$) that are defined as members of the family population (Knežević et al., 2002; Bottke and Nesvorný, *personal comm.*). We then plotted all remaining numbered asteroids with $H_v \leq 18.0$ (~2300) in the Hungaria region⁶ to show the background population. The thermal forces of the Yarkovsky/YORP effect spread the fragments of a collisional family primarily in semi-major axis (see Bottke et al., 2002a; Bottke et al., 2006b; Nesvorný et al., 2015). We have delineated the Hungaria family “Yarkovsky curves” (Figure I-2), which create a size-dependent V-shaped envelope around the center of the family, as in Warner et al. (2009). The taxonomic distribution within the Hungaria region shown in Figure I-2 indicates a spectrally diverse Hungaria background population prevalent in S-complex asteroids (29 of 36 objects; ~80%). The taxonomic distribution among Hungaria family members shows that three of five smaller fragments observed during HARTSS are consistent with the Xe-type taxonomy of the largest collisional fragment 434 Hungaria (Table I-2). C-complex asteroids are uncommon (2 of 42 objects; ~5%) within the Hungaria region (Figure I-2). It is important to recognize that asteroid taxonomic classifications represent spectral groups, which are not necessarily equivalent to asteroid surface compositions (Gaffey, 2010). To establish more robust compositional inferences, asteroid reflectance spectra can be analyzed for spectral band parameters to derive mineralogical information and to identify potential meteorite analogs for S-complex objects (§ 4. below).

4. Spectral Analysis

Initial calibrations useful for the correlation of asteroid surface mineralogy were developed by obtaining laboratory spectra of natural terrestrial olivine and pyroxene mixtures (Adams, 1974; Cloutis et al., 1986; King and Ridley, 1987). More recent studies have utilized the chemical and spectral analyses of stony-meteorite samples to develop mineralogic calibrations (Burbine et al., 2009; Dunn et al., 2010a; Dunn et al., 2010b; Sanchez et al., 2014). These calibrations are useful for estimating the mineral chemistry and modal abundance of mafic silicate minerals on asteroid surfaces through band parameter analyses of their reflectance spectra. Accordingly, we analyzed the band parameters of NIR and VIS+NIR spectra from a subset ($n = 24$) of the S-complex asteroids in our study for clues to their surface mineralogy, and to establish asteroid-meteorite connections between Hungaria background asteroids and analogous meteorite groups. Spectra from five S-complex asteroids in our sample: 5175 Ables, 6310 Jankonke, 7173 Sepkoski, 7187 Isobe, and 9873 1992 GH (see Figure I-9), are too noisy, or have insufficient Band I or Band II depths for useful mineralogical analysis and are not considered further.

4.1. Band Parameter Analysis

We measured spectral band parameters (Band I and II centers, depths, areas, and BARs) with a new freely-available IDL-based algorithm, the Spectral Analysis Routine for Asteroids or SARA⁷ (Lindsay et al., 2015). This routine divides the absorption bands by a straight-line continuum by fitting 5th order polynomials to absorption band shoulders and fitting the linear continuum tangentially to the shoulders. Band centers and depths are measured three times using

⁶ JPL Horizons, accessed March 3rd, 2016: http://ssd.jpl.nasa.gov/sbdb_query.cgi

⁷ SARA is freely available via GitHub: <https://github.com/SeanSLindsay/SARA.git>.

3rd through 5th order polynomial fits to the lower one-half of Band I and to the entirety of Band II. The averages of the three polynomial fits are adopted as the final values. BAR is calculated as (Band II area)/(Band I area). Errors are computed using a Monte-Carlo method, which produces 20,000 synthetic data measurements for each polynomial order, yielding 3 x 20,000 measurements to derive band centers and depths. The final 1 σ center and depth errors are defined as the average of the three error measurements. For a detailed treatment regarding SARA see Lindsay et al. (2015). The band parameter results for the 24 S-complex Hungaria background asteroids are presented in Table I-3. For comparison of the asteroid band parameter data to potential meteorite analogs for which no mineralogic calibrations have been determined, we used SARA to measure the band parameters from VIS+NIR spectra of six primitive achondrite (acapulcoite and lodranite) meteorites (Table I-4; see § 4.2.2). These meteorite spectra were obtained from the RELAB spectral database⁸.

4.1.1. Band Parameter Temperature Corrections

Hungaria asteroid equilibrium surface temperatures vary with albedo and distance from the Sun, but are generally about 200 K (see Table I-3). The surface temperature of an asteroid will affect Band I and Band II positions and widths because band centers move to shorter wavelengths as the temperature of the surface decreases (Singer and Roush, 1985; Roush and Singer, 1987; Lucey and Keil, 1998; Hinrichs et al., 1999; Schade and Wäsch, 1999; Moroz et al., 2000; Hinrichs and Lucey, 2002; Sanchez et al., 2012). Laboratory spectra of possible meteorite analogs are typically measured at room temperature (~300 K), so band parameters measured from telescopic spectra of Hungaria asteroids are not directly comparable to laboratory generated spectral data. As a result, temperature corrections to our asteroid band parameters are necessary before comparisons are made to laboratory-derived measurements or calibrations. The equilibrium surface temperature (T_{eq}) in Kelvin of an asteroid can be estimated in the fast-rotator approximation from the following equation:

$$T_{eq} = [L_{\odot}(1 - A)/16\pi\eta\epsilon\sigma r^2]^{1/4} \quad (1)$$

where $L_{\odot}$ is the Solar luminosity (3.828×10^{26} W), A is the bolometric Bond albedo of the asteroid, η is the beaming factor (assumed to be unity), ϵ is the infrared emissivity of the asteroid (assumed to be 0.9), σ is the Stefan-Boltzmann constant, and r is the heliocentric distance of the asteroid at the time of observation. We use the fast-rotator approximation as a reasonable estimate of the average daytime temperature on the surfaces, even though we expect the actual temperature distribution to be quite different from this approximation. For our sample of Hungaria asteroids, we compute Bond albedos by multiplying visible geometric albedos from IRAS (Tedesco et al., 2002) by a phase integral of 0.39. If an IRAS albedo does not exist for an asteroid, we use the average visible geometric albedo from DeMeo and Carry (2013; see their Table I-4) that is representative of the taxonomic classification of the asteroid. Sanchez et al. (2012) found that temperature effects for Band I center are negligible; the Band II absorption feature is most affected by temperature variations. Accordingly, we correct our Band II centers and BARs with the following linear corrections derived for these effects with respect to room temperature Sanchez et al. (2012):

⁸ http://www.planetary.brown.edu/relabdocs/relab_disclaimer.htm

$$\Delta BIIC (\mu m) = 0.06 - 0.0002 \times T (K) \quad (2)$$

$$\Delta BAR = 0.00075 \times T (K) - 0.23 \quad (3)$$

These corrections are added to the measured Band II centers and BARs for each asteroid in order for these data to be compared to laboratory-derived spectral data. The calculated equilibrium temperatures and temperature corrected values for Band II center and BAR ($BIIC_{tcorr}$ and BAR_{tcorr}) for each S-complex asteroid is listed in Table I-3.

4.2. Asteroid S-subtypes and Asteroid-Meteorite Connections

Because spectral band parameter analysis includes division of the absorption bands by a straight-line continuum, band parameters such as Band centers and BARs are insensitive to continuum slope variations and effectively “see through” space weathering processes (Cloutis et al., 1986; Gaffey et al., 2002; Gaffey, 2010). Gaffey et al. (1993) characterized the spectral band parameters of S-complex asteroids, separating the complex into seven subtypes, S(I-VII), that provide approximate mineralogic interpretations and possible meteorite analogs within Band I center versus BAR space. These seven subtypes exhibit a range of compositions: from nearly pure olivine [S(I)], olivine (ol) + orthopyroxene (opx) mixtures [S(II)-S(VI)], nearly pure pyroxene/pyroxene-feldspar-metal mixtures [S(VII)], to basaltic achondrite compositions [BA]. The Band I centers and BARs for our 24 Hungaria background S-complex asteroids are shown in Figure I-3a. The majority of the asteroids cluster near the ol+opx mixing line of Cloutis et al. (1986), suggesting that our sample of S-complex asteroids are composed of an essentially continuous suite of mixtures of olivine and orthopyroxene. The addition of Ca-rich pyroxene phases (clinopyroxene - cpx) to these assemblages will produce shifts in Band I (and Band II) to longer wavelengths with an increasing amount of Ca^{2+} (Adams, 1974). This shift displaces the asteroid Band I center above the ol+opx mixing line (Gaffey et al., 1993).

The same 24 objects are plotted in Figure I-3b, which illustrates generalized spectral zones for five potential meteorite analogs for S-complex asteroids on a modified version (Burbine et al., 2001; Dunn et al., 2013) of the S-subtype plot. Mineralogic calibrations using stony-meteorite samples have been developed to correlate asteroid spectral band parameters to the following zones: the BA zone using howardite, eucrite, and diogenite (HED) meteorites (Burbine et al., 2009), the S(IV) zone using *H*, *L*, and *LL* ordinary chondrite (hereafter OC) meteorites (Dunn et al., 2010a; Dunn et al., 2010b), and the S(I) zone using mono-mineralic olivine (R-chondrite, brachinite, pallasite) meteorites (Reddy et al., 2011; Sanchez et al., 2014). These mineralogic calibrations have been successful at discriminating mineral chemistry and modal abundance differences within these meteorite groups. Nine Hungaria background asteroids plot within in the S(IV) or “OC boot” zone in Figures I-3a and I-3b. Two of these asteroids, 1453 Fennia and 4142 Dersu-Uzala, have such similar Band I centers and BARs (see Table I-3) that their symbols are superimposed. Additionally, nine other asteroids plot just outside the boundaries of the S(IV) zone: five sub-S(IV) boundary, three near the S(III)/S(IV) boundary, and one supra-S(IV) boundary object. A total of seven asteroids, the five sub-S(IV) asteroids plus two objects that clearly fall within the S(VI) zone of Figure I-3a, plot within the acapulcoite-lodranite spectral analog zone (Figure I-3b). Two asteroids plot within the S(VII) zone, which is proposed to be analogous with the achondrite mesosiderite group and/or the primitive achondrite lodranite group (Gaffey et al., 1993). It is evident from Figure I-3b that two main meteorite groups appear to be represented among the Hungaria background asteroids:

unmelted, nebular *L* and/or *LL* OCs and partially-melted primitive achondrites of the acapulcoite-lodranite meteorite clan. The Bus-DeMeo taxonomy, S-subtype, and potential meteorite analog for these 24 S-complex Hungaria background asteroids are provided in Table I-5. None of the S-complex asteroids plot within the S(I) and only two S(VII) asteroids plot within error bars of the BA region (Figure I-3a). Therefore, we concentrate on mineralogic interpretations and potential meteorite analogs for the S(IV) OC zone (§ 4.2.1.) and the acapulcoite-lodranite zone (§ 4.2.2.).

4.2.1. Ordinary Chondrite S(IV) “OC Boot” Mineralogic Interpretations

The S(IV) spectral zone defined by Gaffey et al. (1993) is associated with OC meteorites. The OC meteorite class is divided into three groups *H*, *L*, and *LL* based on the bulk iron contents: *H* chondrites have high total iron contents, *L* chondrites have low total iron contents, and *LL* chondrites have low total iron as well as low metallic iron relative to total iron (Krot et al., 2007). The OCs increase in oxidation state from *H* to *L* to *LL*. Thereby, as their metallic iron content decreases, the FeO contents of their olivines and pyroxenes increase. The *H* chondrites have the lowest fayalite (Fa = mol% iron in olivine) and ferrosilite (Fs = mol% iron in pyroxene) contents and *LL* chondrites have the highest Fa and Fs contents. Dunn et al. (2010a and 2010b) derived calibration equations for determining the olivine and pyroxene mineralogies of the *H*, *L*, and *LL* groups of the OC class via spectral and cosmochemical analysis of 48 OC meteorites. Through the use of these calibrations ~80% of asteroids that plot within the S(IV) zone should be correctly classified as potential *H*, *L*, or *LL* parent bodies (Dunn et al., 2010a). The equations relate Band I centers (BIC) to Fa (Eq. 4) and Fs (Eq. 5), and BAR to the olivine/(olivine+pyroxene) ratio [hereafter ol/(ol+px)] (Eq. 6). Mineralogical results for 18 S-complex asteroids [9 S(IV), 3 S(III)/S(IV), and 6 supra- or sub-S(IV)] using these equations are shown in Table I-5.

$$Fa = -1284.9 \times (BIC)^2 + 2656.5 \times (BIC) - 1342.3 \quad (4)$$

$$Fs = -879.1 \times (BIC)^2 + 1824.9 \times (BIC) - 921.7 \quad (5)$$

$$ol/(ol+px) = -0.242 \times BAR + 0.728 \quad (6)$$

The spectra of nine Hungaria background asteroids that plot in, or within error bars of, the S(IV) zone are shown in Figure I-4. We compare our mineralogic results for these S(IV) asteroids with the Dunn et al. (2010a) equations for Fa content versus ol/(ol+px) that define three boxed regions for the *H*, *L*, and *LL* OC groups (Figure I-5). A plot of Fs content versus ol/(ol+px) yield similar OC group meteorite analog results as Figure I-5 and is not shown. The uncertainties inherent in the calibration equations (crossbar in Figure I-5), ± 1.3 mol% Fa and ± 0.03 ol/(ol+px), are larger than the propagated errors from the band parameter analysis, except for 3873 Roddy, which has an error of ± 0.04 for ol/(ol+px). The mineralogical results given by the calibration equations narrow down the probable meteorite analog for these nine Hungaria background asteroids (red squares) as *L* and/or *LL* chondrite meteorites (Table I-5 and Figure I-5). However, it is unclear whether five sub-S(IV) asteroids (blue diamonds), which plot near the bottom border of the S(IV) zone and the top of the acapulcoite-lodranite spectral zone (Figure I-3b), are analogous to *H* chondrites or possibly to primitive achondrites of the acapulcoite-

lodranite meteorite clan. We explore the possible asteroid-meteorite connection with primitive achondrites for these five asteroids in Section 4.2.2 below. The implications of asteroid-meteorite connections with OCs in regard to possible parent body sources within the Hungaria region are discussed in Section 5.1.1.

4.2.2. Primitive Achondrite Meteorite Spectral Band Parameters

Primitive achondrites of the acapulcoite-lodranite meteorite clan represents rocks that are solid residues remaining from low-degrees (~1-20%) of partial melting of chondritic material (McCoy et al., 1996; McCoy et al., 1997b; McCoy et al., 2000). Acapulcoites show very low-degrees of partial melting (~1-5%) and have been heated to ~950-1050°C, warm enough to induce some FeNi-FeS cotectic melting (Mittlefehldt et al., 1996; McCoy et al., 1996; McCoy et al., 1997b). Lodranites show higher-degrees of partial melting than acapulcoites, as they have been heated to ~1050-1200°C, hot enough to produce basaltic partial melts (Mittlefehldt et al., 1996; McCoy et al., 1997a; McCoy et al., 2000). The acapulcoite-lodranite clan is thought to originate from a single, lithologically-diverse, partially-differentiated parent body (Mittlefehldt et al., 1996; McCoy et al., 1997b, McCoy et al., 2000). Acapulcoites and lodranites are uncommon meteorites (Krot et al., 2007) with the type specimen for each group (Acapulco and Lodran, respectively) being the only known recovered falls among the clan⁹. This clan provides evidence that partially-melted material exists among the asteroids. These meteorites therefore provide a basis for spectral comparison with S-complex asteroids in the search for partially-differentiated asteroids.

To examine mineralogic interpretations and potential asteroid-meteorite connections with Hungaria background S-complex asteroids that are not associated with the OC S(IV) spectral zone, we obtained the VIS+NIR spectra of six primitive achondrites (3 acapulcoites, 2 lodranites, and 1 transitional acapulcoite-lodranite) from the RELAB database (Figure I-6a). To empirically compare meteorite spectra to asteroid surfaces, which are blanketed in regolith, we selected ground particulate (<125 µm fraction) primitive achondrite spectra from the database. We measured the band parameters of these spectra using the same SARA algorithm (see § 4.1) used for the S-complex asteroids. The results are listed in Table I-4. The Band I versus BAR values for the primitive achondrites plotted in Figure I-6b show that four of the six meteorites plot within the acapulcoite-lodranite spectral zone. The boundaries of the acapulcoite-lodranite spectral zone shown in Figure I-6b are based on the band parameter analysis of a small number of primitive achondrite meteorites (Burbine et al., 2001), and consequently should only be considered generalized boundaries.

The two recovered falls, Acapulco and Lodran, exhibit minimal terrestrial weathering compared to acapulcoite-lodranite meteorite finds. These two samples therefore offer suitable representatives of the generalized acapulcoite-lodranite spectral zone (Figures I-3b and I-6b). Both samples plot within the acapulcoite-lodranite spectral zone near the top boundary, although there is some overlap with the bottom boundary of the OC spectral zone. Regarding the meteorite finds, one acapulcoite (ALH 81187) has a much lower BAR than the other meteorite samples and plots outside of any potential meteorite analog spectral zone. This is possibly due to the effects of terrestrial weathering as this sample shows moderate to severe weathering (Antarctic Weathering Category of B/C)¹⁰. The presence of iron hydroxides due to terrestrial weathering may

⁹ Meteoritical Bulletin Database: <http://www.lpi.usra.edu/meteor/metbull.php>

¹⁰ Curation | Antarctic Meteorites: <http://curator.jsc.nasa.gov/antmet/index.cfm>

partially affect spectral band parameter results (Lucas et al., 2016). Acapulcoite ALH 81261 plots just above the acapulcoite-lodranite spectral zone, in the OC spectral zone. Although both ALH 81187 and ALH 81261 plot outside of the acapulcoite-lodranite analog spectral zone, Band I centers show a narrow range of values between 0.920- and 0.930- μm for all six meteorites. The average Band I center of (0.924 μm ; see blue-dashed line in Figure I-6a) for the six primitive achondrites is consistent with the seven Hungaria background S-complex asteroids (Figure I-7) that cluster in the acapulcoite-lodranite spectral zone (Figure I-3b). Furthermore, mineralogy derived from the Dunn et al. (2010a) equations [Fa, Fs, and ol/(ol+px)] for five sub-S(IV) asteroids (1750 Eckert, 3225 Hoag, 3635 Kruetz, 5806 Archieroy, and 26471 2000 AS152) are similar (Table I-5) and plot just within or below the bottom boundary of the *H* chondrite spectrally-derived region (Figure I-5). None of these five asteroids lie within the *H* chondrite XRD-derived region obtained from the analysis of OC meteorites. Because these five asteroids plot near a region of the acapulcoite-lodranite spectral zone that overlaps with the OC spectral zone (Figure I-3b), their mineralogies warrant further consideration. For asteroids that plot in the immediate vicinity of the OC spectral zone, the Dunn et al. (2010a) equations may offer reasonable estimates of their mineralogies (Dunn et al., 2013). Nonetheless, the mineralogic estimates for sub-S(IV) asteroids (Table I-5 and Figure I-5) using these equations should be considered with caution. Two S(VI) asteroids (2131 Mayall and 19164 1991 AU1) and two S(VII) asteroids (1019 Strackea and 17408 McAdams), were not analyzed using the Dunn et al. (2010a) equations. Gaffey et al. (1993) suggested possible meteorite analogs of lodranites, winonaites, and IAB irons for the S(VI) subtypes, all of which are partially-melted primitive achondrite meteorites. In agreement with this interpretation, we suggest that primitive achondrites are the most probable meteorite analog for the two S(VI) asteroids and the five sub-S(IV) asteroids mentioned above (Lucas and Emery, 2014). The implications of asteroid-meteorite connections with primitive achondrites in regard to possible parent body sources within the Hungaria region are discussed in Section 5.1.2.

4.2.3. Hungaria Family Member Asteroid-Meteorite Connections

Spectral homogeneity of the collisional fragments that comprise asteroid families is regularly observed, as family members are typically found to have similar albedos and taxonomies (Cellino et al., 2002). Fittingly, published VIS+NIR spectra of family namesake and largest collisional fragment 434 Hungaria (Gaffey et al., 1992; Kelley and Gaffey, 2002; Clark et al., 2004) and VIS spectra of several Hungaria family members (Fornasier et al., 2008) have shown that they are spectrally consistent with taxonomic E-type asteroids (Tholen taxonomy; Tholen, 1989).

Tholen taxonomic E-types are defined by high albedo (avg. $\rho_v=0.536$, DeMeo and Carry, 2013) and relatively flat spectra, with low to medium reddish slopes. In the Bus-DeMeo system (DeMeo et al., 2009), albedo is not included in the taxonomic classification scheme. This system uses principal component analysis (PCA) to define taxonomic classes, and the majority of the relatively flat spectra of X-complex asteroids (which include E-, M-, and P-types defined in previous taxonomies) are defined by visible-wavelength features. For the Bus-DeMeo Xe-type, these features include slight to moderate slopes ($0.2 < \text{Slope} < 0.38$) and a weak absorption at $\sim 0.49 \mu\text{m}$. Therefore, NIR-only data generate non-unique taxonomic classifications in PCA space (DeMeo et al., 2009). Hence, for our Hungaria family members we report the spectral types of the two lowest residuals (Table I-2). In these cases, visual inspection or quantitative

comparison of PCA residuals of the asteroid spectrum to the mean spectrum for each class may help determine the most likely spectral type (DeMeo et al., 2009).

Weak absorption features, centered at $\sim 0.9\ \mu\text{m}$ due to iron-poor orthopyroxene (Fs_{2-4}) and at $\sim 0.5\ \mu\text{m}$ for the sulfide mineral oldhamite (Ca,MgS), are cautiously attributed to these two minerals in some E-type asteroids (Gaffey et al., 1992; Fornasier et al., 2008). Gaffey and Kelley (2004) and Clark et al. (2004) have identified three distinct mineralogies within known E-type asteroids, we use the classification scheme of Clark et al. (2004), who categorized them in reference to three eponymous asteroids: Nysa-like, Angelina-like, and Hungaria-like. Rivkin et al. (1995) found evidence for a $3\ \mu\text{m}$ absorption band indicating the presence of hydrated minerals (i.e., mineral containing either OH^- or H_2O) on the surface of 44 Nysa and possibly for 64 Angelina. The presence of hydrated minerals is inconsistent with the igneous nature of enstatite achondrite meteorites (i.e., aubrites), which have experienced temperatures $\geq 1580\ ^\circ\text{C}$ (Keil, 1989), causing further ambiguity regarding the mineralogy of E-type asteroids. Clark et al. (2004) conclude that aubrites, which are commonly associated with E-types, are not derived from Nysa-like (0.9- and $1.8\text{-}\mu\text{m}$ absorption bands) and Angelina-like (0.5- and $0.9\text{-}\mu\text{m}$ absorption bands) E-types, but are spectrally consistent with the Hungaria-like E-types ($0.9\ \mu\text{m}$ absorption band only). Correspondingly, other workers have proposed that E-types in the Hungaria region are related to the aubrite meteorite group (Gaffey et al., 1992; Kelley and Gaffey, 2002; Čuk et al., 2014).

NIR spectra have been published of only two Hungaria *family* members, 434 Hungaria and 1103 Sequoia (Clark et al., 2004). Figure I-8 shows the spectra of four additional Hungaria family members (VIS+NIR - 6447 Terrycole; NIR - 7087 Lewotsky, 7173 Sepkoski, and 55854 1996 VS1) observed during this first phase of HARTSS compared with 1103 Sequoia and with the largest collisional fragment 434 Hungaria (Clark et al., 2004). Family members 6447 Terrycole, 7087 Lewotsky, and 1103 Sequoia have Xe-type taxonomies, although 1103 Sequoia could also be an Xc-type (Table I-2). C-complex asteroids appear to be uncommon among the Hungaria region asteroids with only two objects ($\sim 5\%$) uncovered during HARTSS - family member 55854 1996 VS1 has a taxonomic type of Cgh, and background object 6618 1936 SO is a blue-sloped B-type asteroid (Table I-2). Spectra of family members 7087 Lewotsky and 55854 VS1 include NIR-only data, and the Bus-DeMeo classification is non-unique. Without VIS spectral data, whether these two asteroids are spectrally and perhaps compositionally similar with 434 Hungaria is inconclusive. Family member 7173 Sepkoski has a Q- or Sq-type taxonomy (Table I-2 and Figure I-8), and displays significant 1- and $2\text{-}\mu\text{m}$ absorption features, inconsistent with the flat spectra of the other five family members. This result could possibly provide evidence for a heterogeneous Hungaria parent body, or alternatively, 7173 Sepkoski is an interloper and incorrectly included within the membership of the family. We use caution regarding the interpretation of the spectrum of 7173 Sepkoski here, especially considering the NIR data were acquired during poor seeing conditions (see § 2.2) and the spectrum is without VIS data.

5. Discussion

The spectral observations and analysis presented herein, reveal significant compositional diversity among Hungaria region asteroids. Among Hungaria background asteroids, our results show evidence for two main potential meteorite analogs: unmelted, nebular *L* chondrites (and

possibly *LL* chondrites), and partially-melted primitive achondrites of the acapulcoite-lodranite meteorite clan. Among the Hungaria collisional family, we find that three of the five smaller Hungaria family members analyzed are spectrally consistent with the largest collisional fragment 434 Hungaria. This asteroid is considered to be related to fully-melted aubrite meteorites (Gaffey et al., 1992; Kelley and Gaffey, 2002; Čuk et al., 2014). These meteorite groups have experienced a considerable range of peak temperatures, which leads to fundamental petrogenetic differences for their respective parent bodies. *L* chondrites represent nebular materials that have experienced thermal metamorphism, with peak metamorphic temperatures between 700 and 800 °C (Wlotzka, 2005). Acapulcoites have been heated to ~950-1050 °C, warm enough to produce metal and sulfide partial melts (McCoy et al., 1997b). Lodranites show higher-degrees of partial melting than acapulcoites, with peak temperatures ~1050-1200 °C, hot enough to produce basaltic partial melts (McCoy et al., 1997a; McCoy et al., 2000). Aubrite meteorites may represent pyroxene-rich mantle material from a differentiated asteroid (Gaffey et al., 1992) and have experienced temperatures ≥ 1580 °C (Keil, 1989), high enough to fully melt enstatite. If these asteroid-meteorite connections are truly representative of the material stored in the Hungaria region, then asteroids in the Hungaria region exhibit a full range of petrologic evolution. These results imply that asteroids with very dissimilar petrologic histories coexist in the same region of orbital space.

This compositional diversity is inconsistent with the classic model (Gradie and Tedesco, 1982) in which a well-ordered temperature and compositional gradient spanned radially across the Main Belt of asteroids. In that scenario, asteroid parent bodies that formed in the same region of the PPD should share similar compositional characteristics. However, a more recent paradigm has emerged in which giant planet migration functioned as an efficient mixer, interspersing different asteroid types throughout the Main Belt (Tsiganis et al., 2005; Gomes et al., 2005; Walsh et al., 2012), especially asteroids of smaller size (DeMeo and Carry, 2013; DeMeo and Carry, 2014). We then consider a scenario in which the inner portion of the primordial asteroid belt (E-belt) underwent compositional mixing during giant planet migration, which depleted the E-belt between $a \sim 1.7$ and ~ 2.0 AU (Bottke et al., 2012), but in the process preserved a fraction of this ancient material in the Hungaria region. This E-belt scenario implies that the present Hungaria asteroids sample material that originated in the inner-most portion of in the primordial asteroid belt closest to the terrestrial planet region. These surviving samples represent only 0.1-0.4% of the initial E-belt population (Bottke et al., 2012) and only $\sim 0.02\%$ of the mass of the current inner belt (DeMeo and Carry, 2013). However sparse this material may be, these samples can reveal much about the composition of the planetesimals in the inner PPD from which the terrestrial planets accreted.

5.1. Meteorite Parent Body Sources Within the Hungaria Region

To further strengthen connections between Hungaria region asteroids and analog meteorites, spectral analysis is coupled with the following lines of evidence to provide a more coherent picture of source regions and potential parent bodies for specific meteorite groups: 1) the spectral and compositional uniqueness of potential parent bodies, 2) dynamical considerations for the delivery of asteroidal material to Earth via mean-motion and secular resonance “escape hatches”, and 3) clustering of meteorite cosmic-ray exposure (CRE) ages (Cloutis et al., 2014). Taken together, these multiple considerations provide evidence to decipher the origin of the meteoritic material that originates in the Hungaria region and to verify the

composition of primordial asteroids stored there. We discuss each of these considerations below for asteroid-meteorite connections uncovered during HARTSS: *H*, *L*, and *LL* OC mineralogies (§ 5.1.1.), primitive achondrites (§ 5.1.2.), and the enstatite achondrites (aubrites) (§ 5.1.3.).

5.1.1. Ordinary Chondrite Parent Body Sources Within the Hungaria Background

Among the nine Hungaria background S-complex objects that plot within the S(IV) zone (Figure I-3a; spectra shown in Figure I-4), we find that the majority plot within the mineralogic boundaries of the *L* chondrites. Asteroids 2047 Smetana, 3309 Brorfelde, 3873 Roddy, and 5905 Johnson plot within the *L* chondrite spectrally-derived box (Figure I-5). A similar inspection of the *LL* chondrite spectrally-derived box shows that 4674 Pauling and 5577 Priestley have *LL* chondrite mineralogies (Figure I-5). In addition, four more asteroids that plot near the S(IV) zone [three S(III)/S(IV) and one supra-S(IV); blue diamonds in Figure I-5] likely have *L*- or *LL*-mineralogies. 5641 McCleese plots on the *L* chondrite boundary and we include this object as an *L* chondrite object, but 1509 Esclangona lies outside of both of the *L* and *LL* chondrite regions (Figure I-5). However, in an independent spectral analysis of 1509 Esclangona (from a separate NIR spectral observation), Lindsay et al. (2015) found this asteroid to be an S(IV) subtype with an *L* chondrite mineralogy. We therefore include 1509 Esclangona in our tally of *L* chondrite objects. 2074 Shoemaker and the supra-S(IV) object 9069 Hovland are clearly within the spectrally-derived box of the *LL* chondrites (Figure I-5). Asteroids 1453 Fennia, 4142 Dersu-Uzala, and 7086 Bopp have mineralogies that cannot be distinguished between *L* and *LL* chondrites. All five sub-S(IV) objects lie below the *H* chondrite XRD-measured region (Figure I-5), with asteroids 3635 Kruetz and 26471 2000 AS152 completely outside of the *H* chondrite spectrally-derived box (Figure I-5). Overall, out of 18 Hungaria background S-complex asteroids with potential OC analogs shown in Figure I-5, we find the following abundances: ~17% *H* chondrite mineralogies (including three sub-S(IV) objects at the bottom of the *H* chondrite box), ~33% *L* chondrite mineralogies, ~22% *LL* chondrite mineralogies, and ~28% have mineralogies that cannot be distinguished between *H*, *L*, or *LL* chondrites.

Several large NIR spectral datasets of NEAs (Vernazza et al., 2008; de León et al., 2010; Dunn et al., 2013; Thomas et al., 2014) have provided a good portrait of the distribution of OC mineralogies in near-Earth space. Comparing this distribution to potential parent-body source regions is a useful test of the delivery of asteroids to near-Earth space. The OC abundances in the Hungaria region from HARTSS listed above differ from results obtained from these NEA surveys, which have a breakdown of ~15-27% *H* chondrites, ~10% *L* chondrites, and ~42-63% *LL* chondrites (Vernazza et al., 2008; Dunn et al., 2013; Thomas et al., 2014). The surplus of *LL* chondrite mineralogies among NEAs is puzzling as the meteoritic material that arrives to Earth should reflect the population of objects in near-Earth space, but fall percentages for *H*, *L*, and *LL* chondrites are 34.1%, 38.0%, and 7.9% of *total* meteorite falls, respectively (Burbine et al., 2002). These abundances correspond to *H*, *L*, and *LL* chondrites as ~43%, 47%, and 10% of *OC falls*.

The mismatch between the *LL* chondrite abundances within the Hungaria background and the NEA population is not surprising, however, as the major source region for *LL* chondrite NEAs is associated with the Flora asteroid family (Vernazza et al., 2008), with delivery via the ν_6 secular resonance located at the innermost edge of the Main Belt (Figure I-1). Furthermore, de León et al. (2010) found that only 8% of NEAs are sourced from the Hungaria region. Therefore there is no reason to expect similar abundances among the Hungaria region as found within inner

Main Belt sources. Although we find different OC abundances from those found in the NEA spectral surveys, it is clear that there is nothing unique about the spectral signatures of OC-like Hungaria background S-complex asteroids obtained during HARTTS. Similar *H*-, *L*-, and *LL*-like spectra and mineralogies are common to the NEA population as discussed above. Similar spectra and mineralogies are common in the Main Belt as well, as all three OC groups have proposed parent body source regions located there as discussed below.

We find a prevalence of *L* chondrite mineralogies among OC-like background S-complex objects (~33%) in the Hungaria region. This abundance could be as high as ~50% with the addition of three objects that cannot be distinguished between *L* or *LL* chondrite mineralogies (Figure I-5). Does this abundance reveal the presence of an *L* chondrite parent body among the Hungaria background? We consider dynamical arguments and CRE ages of recent *L* chondrites to explore this question. Nesvorný et al. (2009) argue that both abundant “fossil” shocked *L* chondrites of mid-Ordovician age (467 ± 2 Ma) and recent shocked *L* chondrites are related to the Gefion collisional family of asteroids. The collisional breakup of the Gefion parent body at ~470 Ma (^{39}Ar - ^{40}Ar shock age - Korochantseva et al., 2007) quickly delivered an intense bombardment of meteoroids to the Earth via the Jovian 5:2 mean-motion resonance at $a = 2.83$ AU, as evidenced by the mid-Ordovician age of the limestone strata containing the “fossil” *L* chondrites and their extremely short cosmic ray exposure (CRE) ages (0.05-1.5 Myr – Heck et al., 2004). Nesvorný et al. (2009) model a dynamical mechanism that delivers recent shocked *L* chondrites to the Earth through a slower route by drifting inward to the Jovian 3:1 mean-motion resonance at $a = 2.5$ AU. The CRE ages obtained in this model agree with the median CRE age of 20 Myr for recent *L* chondrites (Marti and Graf, 1992; Eugster et al., 2006), which have the longest median CRE age of the OC groups (*H*, *L*, and *LL* median CRE ages of 7 Myr, 20 Myr, and 15 Myr, respectively). In a NIR spectral survey of asteroids located near the Jovian 3:1 mean-motion resonance, Fieber-Beyer and Gaffey (2014; 2015) found three objects just beyond the 3:1 resonance that have *L* chondrite mineralogies and propose a small *L* chondrite genetic family located in the vicinity.

The presence of *L* chondrite mineralogies in our sample of Hungaria background asteroids suggests an independent source region for *L* chondrite material, or alternatively a dynamical mechanism to emplace this material in the Hungaria region from elsewhere. Two secular resonances with Saturn (ν_6 and ν_{16}) and the Jovian 4:1 mean-motion resonance are situated between the Hungaria region and the Jovian 3:1 mean-motion resonance at 2.5 AU (Figure I-1). Hungarias are located interior to these strong resonances. Consequently, the delivery route of meteoroids from the Hungaria region to the Earth is different than those with origins in the Main Belt. Aubrite meteorites, which are thought to originate from the Hungaria family (Gaffey et al., 1992; Kelley and Gaffey, 2002; Čuk et al., 2014), provide a test of this hypothesis. Aubrites have CRE ages ranging from 13-117 Myr, with a median of 50 Myr (Lorenzetti et al., 2003). These ages are significantly longer than those of other stony meteorites that arrive via Main Belt resonances and are therefore consistent with a delivery mechanism distinct from the Main Belt. Čuk et al. (2014) modeled the delivery time of meteoroids to Earth by way of leakage from the inner boundary of the Hungaria region (~1.7 AU) and found a good match with the range of CRE ages of aubrite meteorites. The CRE ages of *L* chondrites show peaks at ~20-30 Myr and at ~40 Myr (Marti and Graf, 1992), which overlap several aubrites with shorter CRE ages. If Hungaria family fragments can be delivered to Earth in this manner, then fragments of a potential *L* chondrite parent body among the Hungaria background may experience a similar delivery route.

Interestingly, the Hungaria background may harbor a second ancient collisional family comprised of S-types at slightly higher inclinations (Williams, 1992 – Family ID# 191; Milani et al., 2010). However, this putative genetic family is thinly spread out, and therefore has not been confirmed. Perhaps the prevalence of *L* chondrite mineralogies within our sample of Hungaria background S-complex objects reflects surviving collisional fragments of this cryptic family. The acquisition of additional NIR spectra of Hungaria background asteroids may be able to strengthen this possible connection.

We find ~22% *LL* chondrite mineralogies among our OC-like background S-complex objects. This abundance could be as high as ~40% with the addition of three objects that cannot be distinguished between *L* or *LL* chondrite mineralogies (Figure I-5). Several studies regarding the source regions of the NEA population (de León et al., 2010; Thomas and Binzel, 2010; Dunn et al., 2013) and a study regarding the mineralogy of multiple asteroid systems (Lindsay et al., 2015) have corroborated the results of Vernazza et al. (2008), who proposed an asteroid-meteorite connection between the Flora collisional family and the *LL* chondrites. The Flora family is located near the ν_6 secular resonance with Saturn in the inner Main Belt (Figure I-1), an efficient escape hatch for leakage of kilometer-size asteroids out of the inner Main Belt (Nesvorný et al., 2002). If *LL* chondrite asteroids are firmly linked to the Flora family and delivered to near-Earth space via the ν_6 secular resonance, why are *LL* chondrite mineralogies found among our sample of Hungaria background asteroids? Warner et al. (2009) found that the Hungaria region is susceptible to bombardment from Flora asteroids at their perihelia, providing a possible source of *LL* chondrite mineralogies in the Hungaria region. Furthermore, McEachern et al. (2010) proposed a scenario in which some transient Mar-crossing asteroids can be fed into stable orbits in the Hungaria region. They suggest that 5-10% of the Hungaria background population is adopted in this manner with S-complex asteroids being the most likely “adoptees.” Perhaps one or both of these mechanisms has supplied asteroids with *LL* chondrite mineralogies into the Hungaria region. However, the shorter median CRE age of ~15 Myr for *LL* chondrites is consistent with a Main Belt source region such as the ν_6 secular resonance as opposed to the longer delivery times proposed by Čuk et al. (2014) for the Hungaria region.

We find three questionable *H* chondrite mineralogies out of five sub-S(IV) asteroids (Figure I-5). This gives an abundance of potential *H* chondrite mineralogies out of the OC-like background S-complex objects of ~17%. Considering our comparison of spectral band parameters between the acapulcoite-lodranite meteorites discussed in § 4.2.2, we suggest that primitive achondrites are the best meteorite analog for these five sub-S(IV) asteroids. If this interpretation is correct, then just as significant as the potential meteorite analogs that are present among our sample of Hungaria background asteroids are the potential meteorite analogs that are absent. An inspection of (Figures I-3a and I-3b) reveals an obvious gap between asteroids in the upper portion of the OC boot and the five sub-S(IV) asteroids that plot just below it. Similarly, Figure I-5 shows a noticeable gap between Hungaria background objects with *L* and *LL* chondrite compositions and the five sub-S(IV) objects that plot just within or outside of the *H* chondrite composition. We interpret this gap in OC-like compositions as an indication that the Hungaria region is not a significant source region for *H* chondrite meteorites. The apparent absence of *H* chondrite material in the Hungaria region is consistent with the probable association of the Main Belt asteroid 6 Hebe situated near the Jovian 3:1 mean-motion resonance with *H* chondrite meteorites (Gaffey and Gilbert, 1998). Supporting this association, Thomas and Binzel (2010) found an enhanced preference for a 3:1 mean-motion resonance “express” delivery source for *H* chondrites, consistent with the dynamical model of Bottke et al. (2002b) for the

orbital distribution of near-Earth objects and with the relatively short median CRE ages of 7 Myr for *H* chondrites.

5.1.2. Primitive Achondrite Parent Body Sources Within the Hungaria Background

We find that the most probable meteorite analog for two S(VI) asteroids and five sub-S(IV) asteroids (Figure I-3a) are primitive achondrites of the acapulcoite-lodranite clan. This yields an abundance of ~20% (7/36) Hungaria background asteroids that may be associated with primitive achondrite meteorites. This abundance is higher than the ~6% (4/72) primitive achondrite like mineralogies found among NEAs by Dunn et al. (2013). There are few studies regarding the potential source regions for primitive achondrite meteorites. However, using the dynamical model of Bottke et al. (2002b), Dunn et al. (2013) found a probable source region at the Jovian 3:1 mean-motion resonance for one of the primitive achondrite like mineralogies in their sample of NEAs. Eugster and Lorenzetti (2005) found short CRE ages with a narrow range of values (~4-7 Myr) for ten meteorites from the acapulcoite-lodranite clan. These delivery times to Earth are approximately consistent with the short CRE ages found for *H* chondrites (see above) and indicate an “express” delivery source region such as the 3:1 mean-motion resonance similar to *H* chondrites as opposed to the longer delivery times proposed by Čuk et al. (2014) for the Hungaria region.

If the acapulcoite-lodranite clan has such consistently short CRE ages, why are primitive achondrite like mineralogies found among our sample of Hungaria background asteroids? McCoy et al. (1997b) concludes that a partially-differentiated acapulcoite-lodranite parent body would have a heterogeneous surface composition, and therefore the fragments of this parent body could produce all of the subtypes of S-complex asteroids. This argument could provide an explanation for the diversity of Hungaria background S-complex asteroids found during HARTSS. However, the short CRE ages are not consistent with a parent body source for primitive achondrites within the Hungaria region. Although seven asteroids within the Hungaria background have primitive achondrite like spectral features, the probable parent body source region for primitive achondrite meteorites remains inconclusive. The acquisition of additional Hungaria background asteroid spectra in conjunction with the band parameter analysis of a larger suite of primitive achondrite meteorites may provide additional evidence to resolve this issue.

5.1.3. Enstatite Achondrite Parent Body Sources Within the Hungaria Region

The largest member of the Hungaria family, 434 Hungaria, is classified as an E-type in the Tholen taxonomy (albedo ~0.47) and a Xe-type in the Bus-DeMeo taxonomy. Clark et al. (2004) note that 434 Hungaria has a strong absorption at 0.9 μm , a relatively shallow spectral slope, and a convex spectral shape. They also note that whereas all Tholen E-types (even those outside of the Hungaria region) seem to share these general characteristics, they differ in details, including whether or not a weak 1.8 μm feature is present. Other members of the Bus-DeMeo X-complex, including some other Xe-types, exhibit an even broader range of spectra. Assuming that the Hungaria family progenitor was compositionally homogeneous, we would expect all of the family members to have spectra that are very similar to 434 Hungaria’s spectrum. An inspection of Figure I-8 shows that 1103 Sequoia displays a 0.9 μm feature, like 434 Hungaria, but Clark et al. (2004) also note a weak 1.8 μm feature as well, which is not present in their spectrum of 434 Hungaria. Their mixing model results suggest that Sequoia’s spectrum is

consistent with aubrite meteorites plus olivine and orthopyroxene. Three Hungaria family members observed during HARTSS (6447 Terrycole, 55854 1996 VS1, and 7087 Lewotsky) exhibit no evidence of 0.5-, 0.9-, and 1.8- μm absorption bands found in other E-type asteroids, although the VIS+NIR spectrum of 6447 Terrycole is considerably noisy at these wavelengths and weak absorption features could be obscured. As discussed in § 4.2.3, Q-type 7173 Sepkoski is a possible interloper to the Hungaria family.

Bus-DeMeo X-complex objects are not restricted to the Hungaria collisional family; we found seven additional X-complex asteroids among Hungaria background objects (Table I-2 and Figure I-2). Four asteroids: 3169 Ostro, 3940 Larion, 4736 Johnwood, and 6249 Jennifer have Xe-type taxonomies (second residual for 3169, 3940, and 6249), whereas 2048 Dwornik, 2449 Kenos, and 9068 1993 OD classify as Xn-type taxonomies. The Xn-type is a class of neutral spectra with a narrow, Nysa-like absorption feature at 0.9 μm that has been added to the X-complex in the latest version of the Bus-DeMeo taxonomy¹¹. Whether these background objects are spectrally, and perhaps compositionally, related to the family is uncertain as all seven background X-complex objects have non-unique taxonomic classifications (Table I-2). If these X-complex objects truly are related to Xe-types, finding them among the background is not unusual as there is no *a priori* reason to expect that the parent body of the Hungaria collisional family to be the only asteroid with a Xe-type composition located in the Hungaria region.

Additional VIS+NIR spectra are needed to search Hungaria family Xe-types for the diagnostic 0.9 μm absorption feature, and the absence of the 1.8 μm feature, to corroborate that Hungaria family members truly have “Hungaria-like” spectra. Furthermore, additional albedo measurements will help verify the inferred Xe-type taxonomy of Hungaria family members, as Xe-types have the highest albedo among any other asteroid taxonomic type (DeMeo and Carry, 2013). Finally, detection of 3 μm absorptions indicating the presence of hydrated minerals on the surface of known Hungaria family members would provide evidence counter to the inferred aubrite mineralogy for the Hungaria family members. Until further spectra of Hungaria family members are acquired via HARTSS, no prediction in regard to the spectral and compositional homogeneity of the Hungaria family and their connection to the aubrite meteorite group is ventured.

6. Summary

Previous studies regarding compositional interpretations of Hungaria region asteroids were mostly limited to colorimetric and VIS spectral data. NIR spectral data expands upon mineralogic interpretations and potential asteroid-meteorite connections through the analysis of 1- and 2- μm absorption bands due to Fe^{2+} electronic transitions in mafic minerals olivine and pyroxene, which are abundant in many types of stony meteorites. Our spectral data set acquired during HARTSS for these “neighbors” to the terrestrial planet region offers a unique view of their surface mineralogy and potential meteorite analogs, which provide constraints on the composition of the asteroidal material from which the terrestrial planets accreted. Based on our comparison of HARTSS Phase I spectral data to laboratory based meteorite calibrations for OCs and spectral data of primitive achondrite meteorites, we arrive at several conclusions, which are summarized below.

¹¹ http://smass.mit.edu/_documents/v4flowchartmods.pdf

The taxonomic distribution within the Hungaria region indicates that stony S-complex asteroids are prevalent among Hungaria background asteroids (29 of 36 objects: ~80%). These background S-complex objects exhibit considerable spectral diversity as spectral band parameter measurements reveal that several different S-subtypes are represented therein, which translates to a variety of surface compositions. The taxonomic distribution among Hungaria family members shows that three of five smaller fragments observed during HARTSS are consistent with the Xe-type taxonomy of the largest collisional fragment 434 Hungaria. C-complex asteroids are uncommon (2 of 42 objects; ~5%) within the Hungaria region.

We find two main asteroid-meteorite connections among the Hungaria background asteroids, unmelted, nebular *L* ordinary chondrites (and possibly *LL* chondrites), and partially-melted primitive achondrites of the acapulcoite-lodranite meteorite clan. Laboratory spectra of six primitive achondrite meteorites are spectrally consistent with seven Hungaria background asteroids (1750, 2131, 3225, 3635, 5806, 19164, and 26471). We suggest that primitive achondrites are the most probable meteorite analog for these objects. Four fragments of the Hungaria family are spectrally consistent with the largest collisional fragment 434 Hungaria, except 7173 Sepkoski, which has a Q-type spectrum. This result could possibly provide evidence for a heterogeneous Hungaria parent body, or alternatively, 7173 Sepkoski is an interloper and incorrectly included within the membership of the family.

We suggest a source region for *L* chondrite like material from within the Hungaria region with delivery to Earth via leakage from the inner boundary of the Hungaria region. *H* chondrite like mineralogies appear to be absent from the Hungaria background asteroids. We conclude that the Hungaria region is not a source region for *H* chondrite meteorites. Although seven asteroids within the Hungaria background have spectral band parameters consistent with partially-melted primitive achondrites, the probable source region for the acapulcoite-lodranite parent body remains inconclusive. If the proposed connection with the Hungaria family to the aubrite meteorite group is accurate, then asteroids in the Hungaria region exhibit a full range of petrologic evolution: from nebular, unmelted ordinary chondrites, through partially-melted primitive achondrites, to fully-melted igneous aubrite meteorites.

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Appendix I-A

Table I-1. Observing circumstances for NIR spectroscopy.

Object	Date (UT)	Time ^e (UT)	Airmass	Mag. (V)	r^e (AU)	g^e (°)	t_{int} (min)	Solar analog
434 Hungaria ^c	2001	-	-	13.4	-	-	-	Landolt
1019 Strackea	2012 Aug 29	11:16	1.327	14.4	1.869	9.9	24	SAO 191948
1103 Sequoia ^c	2003 Aug 16	-	-	14.1	1.757	19.5	-	L112-1333
1453 Fennia	2012 Sep 18	11:35	1.018	15.2	1.916	18.1	16	SAO 92718
1509 Esclangona	2009 Sep 28	09:19	1.173	15.3	1.927	22.4	24	SAO 36472
1727 Mette	2013 Jan 22	10:25	1.052	13.8	1.686	10.9	16	SAO 115174
1750 Eckert	2013 Jan 22	10:59	1.081	15.3	1.953	10.7	16	SAO 135872
2047 Smetana	2012 Nov 09	09:35	1.002	15.4	1.869	5.6	20	SAO 75191
2048 Dwornik ^c	2003 Aug 16	-	-	15.6	1.896	15.4	-	L112-1333
2074 Shoemaker ^a	2003 Sep 30	10:51	1.008	15.1	1.680	15.5	44	16 CygB
2131 Mayall	2013 Jan 22	11:35	1.186	15.7	2.084	18.2	16	SAO 155741
2449 Kenos ^a	2010 Sep 07	05:28	1.033	16.5	1.627	33.9	24	L110-361
2577 Litva ^b	2012 Apr 10	11:40	1.06	15.8	1.97	18.8	64	HD 165479
3169 Ostro	2013 Oct 31	03:29	1.223	15.7	1.818	30.3	21	L115-271
3225 Hoag	2013 Oct 02	06:27	1.386	14.4	1.798	7.5	16	SAO 128385
3309 Brorfelde ^b	2010 Nov 13	11:45	1.11	15.4	1.91	8.1	32	HD 247554
3635 Kruetz ^a	2005 Nov 12	12:59	1.042	16.0	1.717	14.0	48	Hyades 64
3873 Roddy ^a	2004 Oct 16	06:40	1.403	17.1	2.132	27.8	30	16 CygB
3940 Larion	2013 Oct 02	05:06	1.175	15.8	2.089	20.4	24	SAO 126740
4142 Dersu-Uzala ^d	2002 Apr 15	09:57	1.030	15.2	1.810	22.1	57	Hyades 64
4674 Pauling ^b	2010 Sep 13	09:20	1.02	16.0	1.92	17.3	32	HD 215274
4736 Johnwood	2013 Jan 22	09:51	1.050	15.1	1.781	12.3	16	SAO 59815
5175 Ables	2013 Oct 31	01:43	1.049	15.8	2.020	14.2	24	L98-978
5577 Priestley ^a	2011 Aug 22	12:47	1.955	16.4	1.766	24.8	32	L110-361
5641 McCleese ^a	2005 Apr 11	14:27	1.028	15.8	1.591	31.1	40	L105-56
5806 Archieroy	2012 Sep 18	10:59	1.077	15.6	1.903	19.3	16	SAO 73226
5905 Johnson ^b	2011 Jul 06	12:50	1.43	17.1	1.78	33.4	64	HD 224908
6249 Jennifer ^a	2010 Sep 06	05:37	1.027	16.4	1.801	33.9	32	L110-361
6310 Jankonke	2012 Nov 09	12:58	1.176	15.4	1.874	13.7	16	SAO 131080
6447 Terrycole	2012 Nov 09	12:14	1.034	15.1	1.801	8.9	16	HD 285295
6618 (1936 SO)	2013 Oct 02	05:59	1.294	15.3	1.855	14.5	16	SAO 90982
7086 Bopp	2012 Sep 18	10:26	1.100	15.2	1.762	18.7	16	SAO 90243
7087 Lewotsky	2013 Oct 31	00:59	1.033	15.9	1.936	5.6	24	L115-271
7173 Sepkoski	2013 Oct 31	05:23	1.368	16.0	1.945	12.0	24	L98-978
7187 Isobe	2012 Aug 29	08:34	1.083	15.0	1.858	8.9	32	SAO 127201
9068 (1993 OD)	2013 Nov 24	13:35	1.413	14.9	1.563	26.4	16	SAO 13707
9069 Hovland	2012 Nov 09	11:33	1.088	15.4	1.690	9.4	16	SAO 75787
9873 (1992 GH)	2013 Oct 31	00:31	1.130	15.4	1.734	19.7	12	L98-978
17408 McAdams	2013 Nov 24	14:15	1.309	15.9	1.682	22.3	12	SAO 132749
19164 (1991 AU1)	2012 Aug 29	09:59	1.152	14.9	1.929	1.4	32	SAO 165008
26471(2000 AS152)	2012 Nov 09	13:39	1.093	15.4	1.905	18.9	16	SAO 58093
55854 (1996 VS1)	2012 Nov 09	10:20	1.035	15.6	1.833	5.7	32	SAO 110550

^a Data from MIT-UH-IRTF Joint Campaign for NEO Reconnaissance

^b Data from Lindsay et al., 2015

^c Data from Clark et al., 2004. Observing circumstances from Table I-2 of Clark et al., 2004.

^d Data from Binzel et al., 2004b

^e Time, r , and g given for beginning of observation

Table I-2. Hungaria asteroid orbital and physical properties and Bus-DeMeo (BDM) taxonomy.

Object	a (AU)	i (°)	H	p_v^a	Population	BDM Taxonomy ^b
434 Hungaria	1.944	22.510	11.2	0.428	family	Xe, K
1019 Strackea	1.912	26.981	12.6	0.224	background	Sw
1103 Sequoia	1.934	17.900	12.2	0.480	family	Xc, Xe
1453 Fennia	1.897	23.674	12.5	0.249	background	Q, Sq
1509 Esclangona	1.866	22.323	12.6	0.233	background	Sw ^c
1727 Mette	1.854	22.897	12.5	0.258	background	Sw
1750 Eckert	1.926	19.087	13.2	0.258	background	Srw ^c
2047 Smetana	1.872	25.278	13.9	0.258	background	Q, Sq
2048 Dwornik	1.953	23.754	13.5	0.536	background	Xn, L
2074 Shoemaker	1.800	30.075	13.8	0.258	background	Sw
2131 Mayall	1.887	33.995	12.7	0.239	background	Sw
2449 Kenos	1.909	24.985	14.3	0.460	background	Xn, L
2577 Litva	1.904	22.909	13.2	0.258	background	Sw
3169 Ostro	1.892	24.904	12.7	0.183	background	L, Xe ^d
3225 Hoag	1.880	25.062	13.2	0.258	background	S ^c
3309 Brorfelde	1.818	21.134	13.6	0.258	background	Sw
3635 Krueztz	1.794	19.222	14.6	0.258	background	Srw
3873 Roddy	1.892	23.353	12.8	0.258	background	S
3940 Larion	1.988	22.838	12.7	0.183	background	L, Xe ^c
4142 Dersu-Uzala	1.912	26.493	13.0	0.258	background	Srw
4674 Pauling	1.859	19.439	13.8	0.258	background	Sw
4736 Johnwood	1.958	21.966	13.4	0.536	background	Xe, Xc
5175 Ables	1.967	16.844	13.3	0.258	background	Q, Sq ^d
5577 Priestley	1.844	22.271	14.2	0.258	background	Q, Sq
5641 McCleese	1.820	22.203	14.0	0.455	background	Sw
5806 Archieroy	1.963	20.819	12.9	0.258	background	Sq, Q
5905 Johnson	1.910	27.524	14.0	0.258	background	Q, Sq
6249 Jennifer	1.914	28.106	13.0	0.536	background	Xc, Xe
6310 Jankonke	1.913	23.593	14.0	0.258	background	Sw ^c
6447 Terrycole	1.952	19.770	14.5	0.536	family	Xe, Xc ^c
6618 (1936 SO)	1.875	23.831	13.3	0.071	background	B, L
7086 Bopp	1.909	25.616	13.8	0.258	background	Q, Sq
7087 Lewotsky	1.956	19.542	14.1	0.536	family	Xe, Xc ^d
7173 Sepkoski	1.956	19.582	13.9	0.258	family	Q, Sq ^d
7187 Isobe	1.938	21.789	13.9	0.258	background	Sq, K
9068 (1993 OD)	1.820	20.297	13.6	0.536	background	Xn, L
9069 Hovland	1.913	19.571	14.2	0.258	background	Q, Sq
9873 (1992 GH)	1.862	19.232	13.6	0.258	background	Sq, S ^d
17408 McAdams	1.883	25.685	14.2	0.258	background	Sr, S
19164 (1991 AU1)	1.856	22.321	14.0	0.258	background	S, Sq
26471(2000 AS152)	1.918	19.693	13.2	0.258	background	Sq, S
55854 (1996 VS1)	1.930	23.293	14.2	0.083	family	Cgh, Ch

Orbital elements (a , i) at epoch 2457200.5 (2015-Jun-27.0) TDB, reference JPL (heliocentric ecliptic J2000), from <http://ssd.jpl.nasa.gov/sbdb.cgi>, referenced October 26th, 2015

^a Visible geometric albedos from IRAS where available. Values in *italics* are average albedos for taxonomic types taken from DeMeo and Carry, 2013.

^b For asteroids with non-unique Bus-DeMeo taxonomic classifications, the two lowest average residual solutions are listed

^c reflectance values extrapolated from 0.49 μm to 0.45 μm to derive Bus-DeMeo taxonomic classification

^d reflectance values extrapolated from 2.40 μm to 2.45 μm to derive Bus-DeMeo taxonomic classification

Table I-3. Band parameter analysis for 24 S-type Hungaria asteroids.

Object	Temp. (K)	BIC	BIC error	BI area ($\times 10^{-2}$)	BI area error ($\times 10^{-2}$)	BIIC	BIIC _{tcorr}	BIIC error	BIH area ($\times 10^{-2}$)	BIH area error ($\times 10^{-2}$)	BAR	BAR _{tcorr}	BAR error
1019 Strackea	204	0.920	0.005	2.22	0.13	1.906	1.925	0.062	4.11	0.36	1.86	1.78	0.20
1453 Fennia	201	0.969	0.001	3.91	0.02	1.921	1.941	0.005	1.97	0.04	0.50	0.43	0.01
1509 Esclangona	201	0.961	0.004	3.91	0.07	2.027	2.047	0.114	1.49	0.24	0.38	0.30	0.06
1727 Mette	214	1.024	0.002	5.79	0.04	2.082	2.099	0.022	1.00	0.05	0.17	0.10	0.01
1750 Eckert	199	0.924	0.003	3.50	0.06	1.898	1.918	0.008	4.10	0.12	1.17	1.09	0.04
2047 Smetana	204	0.952	0.004	3.52	0.03	1.932	1.951	0.010	2.44	0.07	0.69	0.61	0.02
2074 Shoemaker	215	0.970	0.001	7.91	0.10	1.930	1.947	0.004	3.10	0.05	0.39	0.32	0.01
2131 Mayall	193	0.917	0.002	1.65	0.03	1.916	1.937	0.015	2.14	0.10	1.29	1.21	0.07
2577 Litva	198	1.044	0.001	6.56	0.03	2.043	2.063	0.005	3.97	0.05	0.60	0.52	0.01
3225 Hoag	208	0.922	0.003	2.01	0.03	2.006	2.024	0.039	2.23	0.13	1.11	1.04	0.07
3309 Brorfelde	202	0.955	0.003	3.99	0.04	1.890	1.910	0.005	3.75	0.09	0.94	0.86	0.03
3635 Kruetz	212	0.920	0.002	5.39	0.05	1.928	1.946	0.008	4.53	0.10	0.84	0.77	0.02
3873 Roddy	191	0.958	0.010	5.31	0.43	1.988	2.010	0.143	4.97	0.74	0.94	0.85	0.16
4142 Dersu-Uzala	207	0.968	0.004	8.60	0.10	1.931	1.949	0.006	4.30	0.10	0.50	0.42	0.01
4674 Pauling	201	1.007	0.003	3.41	0.03	1.922	1.942	0.015	1.47	0.07	0.43	0.35	0.02
5577 Priestley	209	0.988	0.010	3.07	0.16	1.898	1.917	0.033	1.49	0.27	0.49	0.41	0.09
5641 McCleese	216	0.953	0.002	7.25	0.11	1.922	1.938	0.003	3.13	0.04	0.43	0.36	0.01
5806 Archieroy	202	0.925	0.001	3.24	0.03	1.926	1.945	0.007	3.05	0.07	0.94	0.86	0.02
5905 Johnson	208	0.964	0.005	4.02	0.06	1.926	1.944	0.006	2.73	0.10	0.68	0.61	0.03
7086 Bopp	210	0.981	0.002	5.88	0.03	1.942	1.960	0.011	2.79	0.09	0.47	0.40	0.02
9069 Hovland	214	1.017	0.002	7.10	0.03	2.066	2.083	0.017	2.83	0.08	0.40	0.33	0.01
17408 McAdams	215	0.917	0.005	1.79	0.04	1.879	1.896	0.011	3.64	0.20	2.04	1.97	0.12
19164 1991 AU1	200	0.917	0.003	2.23	0.08	1.916	1.936	0.070	3.13	0.21	1.40	1.32	0.11
26471 2000 AS152	202	0.917	0.002	2.61	0.04	1.898	1.917	0.006	2.95	0.09	1.13	1.05	0.04

BIC = Band I center; BIIC = Band II center; BAR = Band Area Ratio; *tcorr* = temperature corrected value

Table I-4. Band parameter analysis for primitive achondrite meteorite samples (ground particulate <125 µm fraction).

Meteorite	Group	RELAB ID	BIC	BIC error	BI area (x10⁻²)	BI area error (x10⁻²)	BIIC	BIIC error	BII area (x10⁻²)	BII area error (x10⁻²)	BAR	BAR error
ALH 81261	Acapulcoite	TB-TJM-039	0.930	0.002	13.38	0.04	1.870	0.002	8.66	0.03	0.647	0.003
ALH 81187	Acapulcoite	TB-TJM-040	0.930	0.004	5.32	0.05	1.833	0.008	0.97	0.07	0.182	0.013
Lodran	Lodranite	TB-TJM-041	0.920	0.002	13.95	0.05	1.880	0.001	12.10	0.03	0.868	0.004
EET 84302	Acap/Lod	TB-TJM-042	0.920	0.001	10.80	0.06	1.850	0.004	11.44	0.07	1.06	0.009
Acapulco	Acapulcoite	TB-TJM-043	0.923	0.002	13.25	0.04	1.863	0.002	11.32	0.05	0.854	0.005
GRA 95209	Lodranite	TB-TJM-044	0.920	0.002	10.09	0.04	1.857	0.001	7.77	0.03	0.770	0.005

BIC = Band I center; BIIC = Band II center; BAR = Band Area Ratio

Table I-5. Hungaria background asteroid S-subtype, mineralogy, and potential meteorite analog.

Object	BDM	S-sub	Fa (mol%)	Fs (mol%)	ol/(ol+px)	Meteorite analog
1019 Strackea	Sw	S(VII)	-	-	-	mesosiderite?/lodranite? ^a
1453 Fennia	Q, Sq	S(IV)	25.3	21.1	0.62	<i>L</i> or <i>LL</i> chondrite
1509 Esclangona	Sw	S(III)/S(IV)	24.0	20.2	0.66	ureilite?/ <i>L-LL</i> chondrite?
1727 Mette	Sw	-	-	-	-	olivine-rich?
1750 Eckert	Srw	sub-S(IV)	15.4	14.0	0.47	<i>H</i> chondrite?/acap-lod?
2047 Smetana	Q, Sq	S(IV)	22.1	18.8	0.58	<i>L</i> chondrite
2074 Shoemaker	Sw	S(III)/S(IV)	25.6	21.3	0.65	ureilite?/ <i>LL</i> chondrite?
2131 Mayall	Sw	S(VI)	-	-	-	acap-lod?/winonaite? ^a
2577 Litva	Sw	S(II)	-	-	-	cpx-rich ureilite?/brachinite? ^a
3225 Hoag	S	sub-S(IV)	14.6	13.5	0.48	<i>H</i> chondrite?/acap-lod?
3309 Brorfelde	Sw	S(IV)	22.8	19.3	0.52	<i>L</i> chondrite
3635 Kruetz	Srw	sub-S(IV)	14.1	13.1	0.54	<i>H</i> chondrite?/acap-lod?
3873 Roddy	S	S(IV)	23.5	19.8	0.52	<i>L</i> chondrite
4142 Dersu-Uzala	Srw	S(IV)	25.3	21.1	0.63	<i>L</i> or <i>LL</i> chondrite
4674 Pauling	Sw	S(IV)	29.8	24.5	0.65	<i>LL</i> chondrite
5577 Priestley	Q, Sq	S(IV)	28.1	23.2	0.63	<i>L</i> or <i>LL</i> chondrite
5641 McCleese	Sw	S(III)/S(IV)	22.5	19.1	0.64	ureilite?/ <i>L</i> chondrite?
5806 Archieroy	Sq, Q	sub-S(IV)	15.6	14.1	0.52	<i>H</i> chondrite?/acap-lod?
5905 Johnson	Q, Sq	S(IV)	24.5	20.6	0.58	<i>L</i> chondrite
7086 Bopp	Q, Sq	S(IV)	27.2	22.5	0.63	<i>L</i> or <i>LL</i> chondrite
9069 Hovland	Q, Sq	supra-S(IV)	30.4	25.0	0.65	<i>LL</i> chondrite
17408 McAdams	Sr, S	S(VII)	-	-	-	mesosiderite?/lodranite? ^a
19164 1991 AU1	S, Sq	S(VI)	-	-	-	acap-lod?/winonaite? ^a
26471 2000 AS152	Sq, S	sub-S(IV)	13.3	12.5	0.47	acapulcoite-lodranite?

^a possible meteorite analog for S-subtypes from Table VI of Gaffey et al. (1993)

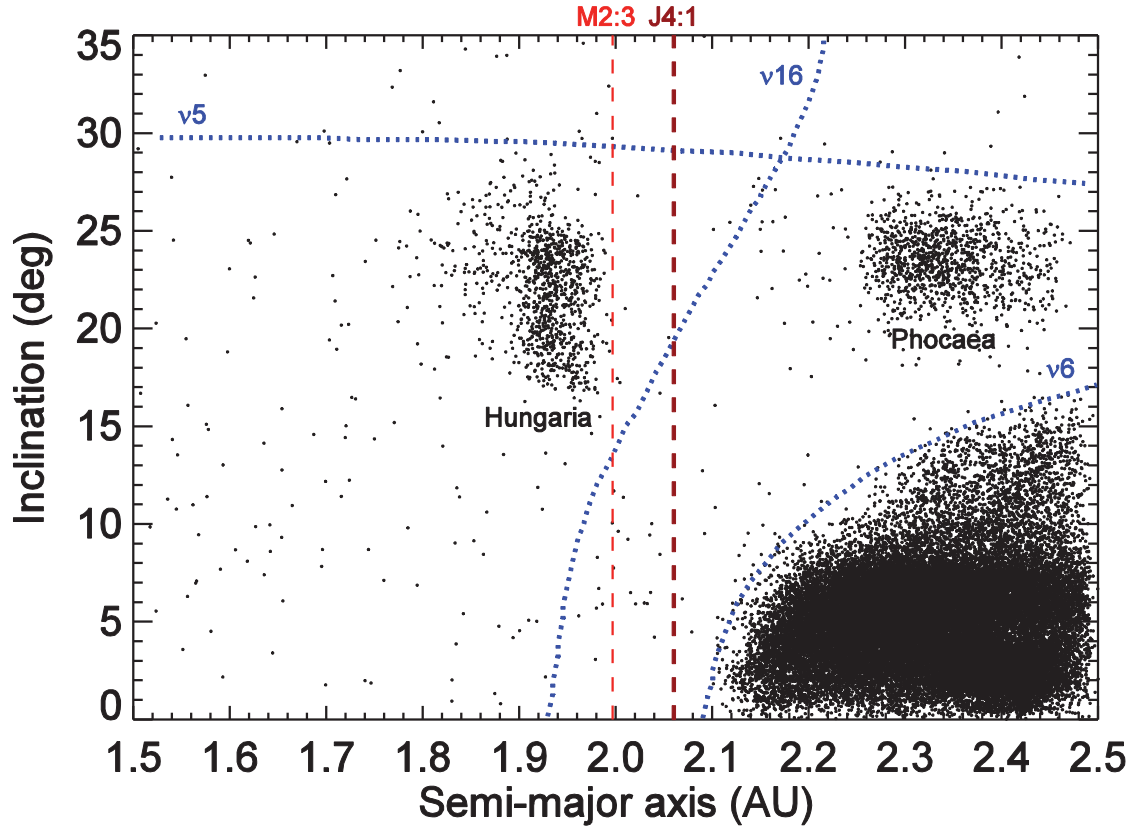


Figure I-1. The inner portion of the Main Belt of asteroids shown in osculating i versus a space indicating the location of the Hungaria dynamical region. Major perihelion secular resonances with Saturn are indicated by blue dotted lines. The Jupiter 4:1 mean-motion resonance is indicated by the brown thick-dashed line. The red thin-dashed line indicates the exterior Mars 2:3 mean-motion resonance, which appears to bound the outer edge of the Hungaria region. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article).

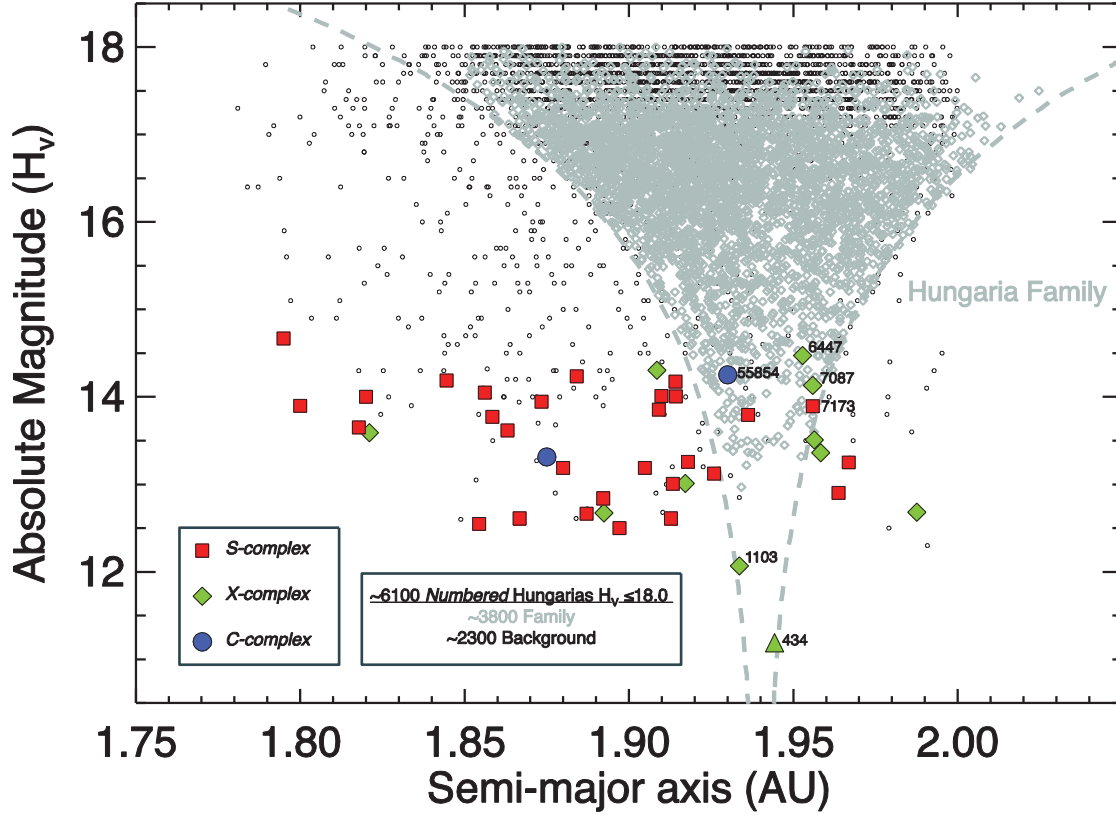


Figure I-2. Numbered Hungaria region asteroids (~ 6100) with absolute magnitude (H_v) ≤ 18.0 in H_v versus a space. Largest collisional fragment and family namesake 434 Hungaria (green triangle) and family members (small gray diamonds) are thought to be spectrally homogeneous. Hungaria family Yarkovsky curves (gray-dashed curved lines) are delineated as in Warner et al. (2009). Hungaria background asteroids (i.e., non-family) are indicated by small black circles. Family members plotted with proper a , background asteroids plotted with osculating a . Large symbols show the taxonomic classification of our sample of 42 Hungaria asteroids. Large symbols with asteroid numbers indicate the six Hungaria family members from our sample. S-complex (red squares) asteroids are prevalent ($\sim 80\%$) among the Hungaria background population. X-complex (large green diamonds) asteroids are spectrally consistent with 434 Hungaria and its collisional fragments represented by family members. C-complex (large blue circles) asteroids are uncommon among our sample ($\sim 5\%$). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article).

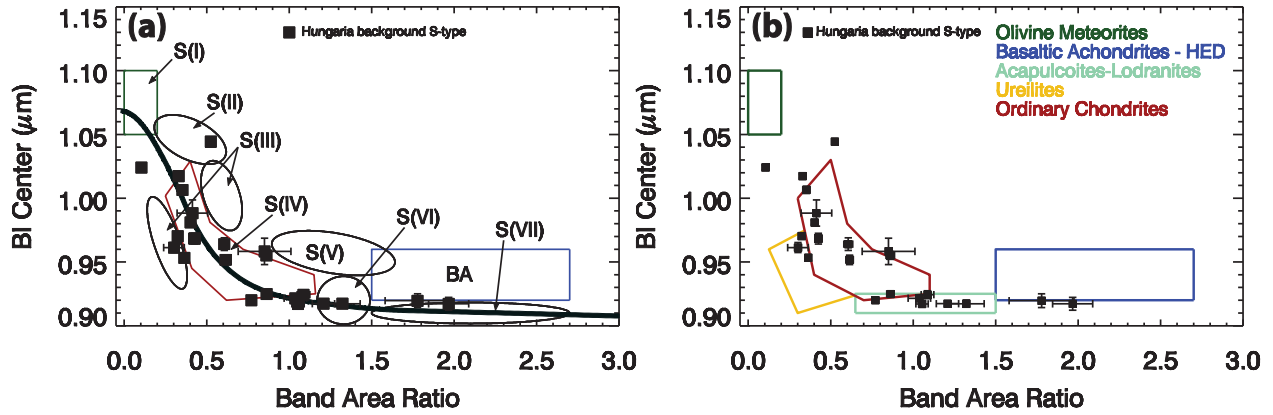


Figure I-3. Band I center versus BAR for 24 Hungaria background S-complex asteroids (solid squares). **(a)** Band I center versus BAR shown relative to the S(I)-S(VII) and basaltic achondrite (BA) zones of Gaffey et al. (1993), the thick black curve indicates the location of the olivine-orthopyroxene mixing line (Cloutis et al., 1986). **(b)** Band I center versus BAR shown relative to spectral zones analogous to potential meteorite groups. The olivine, ordinary chondrite, and basaltic achondrite zones are from Gaffey et al. (1993); the primitive achondrite zone is from Burbine et al. (2001), the ureilite zone is from Cloutis et al. (2010). For both (a) and (b) the symbols for two objects (1453 Fennia and 4142 Dersu-Uzala) plot on top of each other in the ordinary chondrite zone at Band I center ~ 0.97 and BAR ~ 0.43 . For both (a) and (b) the 1σ errors for Band I center and BAR from Table I-3 are plotted for each object (for some objects the error is smaller than the symbol size).

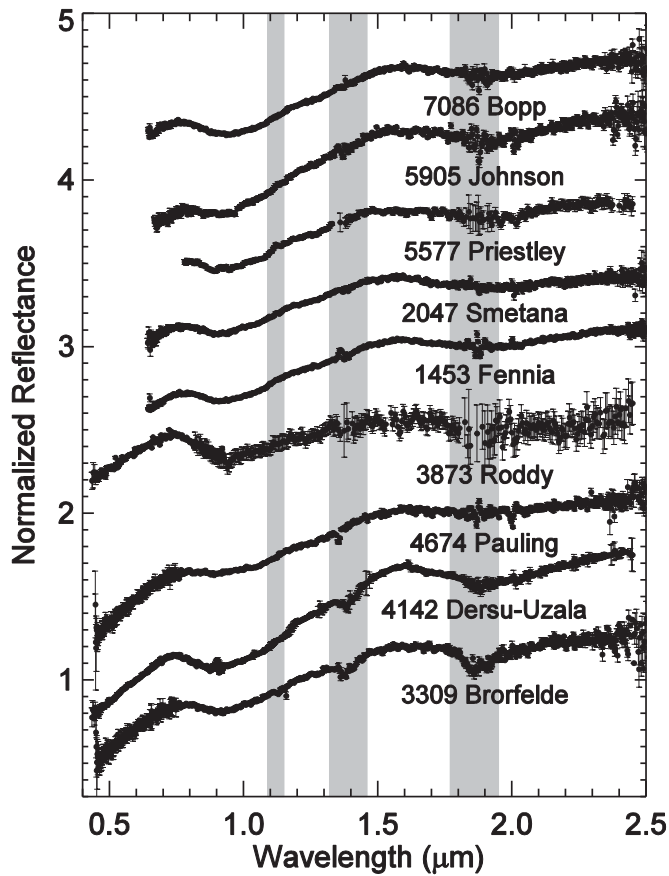


Figure I-4. Spectra of nine Hungaria background asteroids that plot within the Gaffey S(IV) subtype region zone of Figure 3a, VIS+NIR spectra for the lower four asteroids, NIR-only data for the upper five asteroids. All spectra are normalized to unity at 1.20 μm and are offset for clarity. Most spectra show noise at $\sim 1.4 \mu\text{m}$ and $1.9 \mu\text{m}$ (gray regions) due to incompletely corrected telluric bands. Note the shallow 2 μm feature for all spectra.

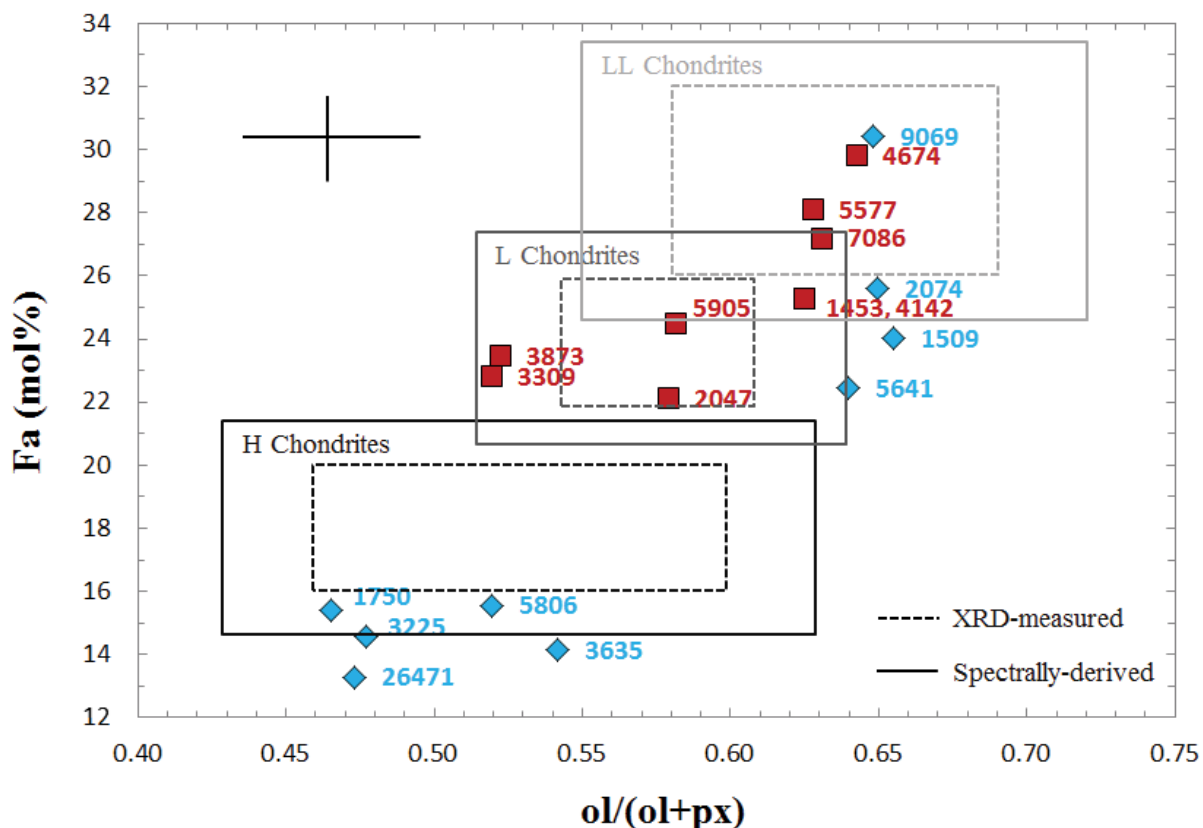


Figure I-5. The mol% Fa in olivine versus ol/(ol+px) ratio for 18 Hungaria background S-complex asteroids. The S(IV) subtypes are indicated by red squares, the S(III)/S(IV), and supra- and sub-S(IV) subtypes that plot near the boundary but not within the S(IV) “OC boot” (see Figures I-3a and I-3b) are indicated by blue diamonds. The dashed boxes show the ranges of ol/(ol+px) measured via X-ray diffraction by Dunn et al. (2010b) and the range of Fa contents in *H*, *L*, and *LL* ordinary chondrites (Brearley and Jones, 1998). The solid boxes are larger and include the errors in the calibration equations for the spectrally derived values (± 0.03 for ol/(ol+px) and 1.3 mol% for Fa; represented by the crossbar). Error for ol/(ol+px) for 3873 Roddy is ± 0.04 . (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article).

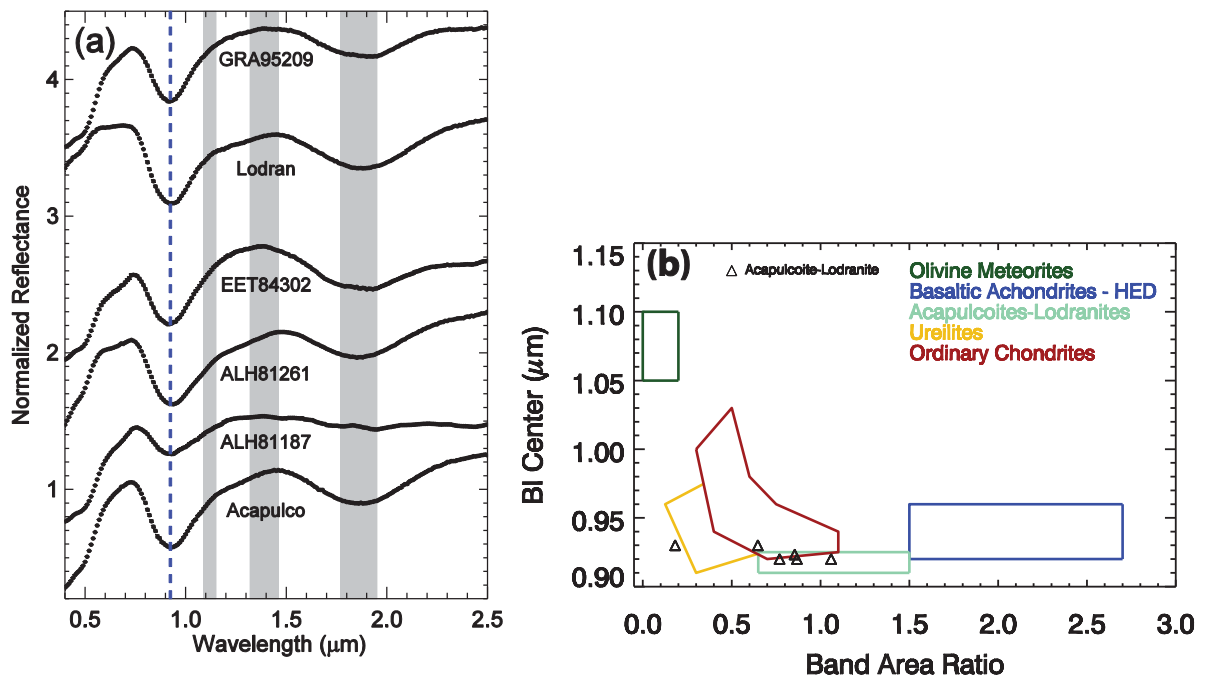


Figure I-6. Primitive achondrite meteorite spectra obtained from the RELAB database. **(a)** VIS+NIR spectra of six primitive achondrite meteorites, Acapulco, ALH 81187, and ALH 81261 are acapulcoites, EET 84302 is a transitional acapulcoite-lodranite, and Lodran and GRA 95209 are lodranites. Blue-dashed line indicates the average Band I center of $0.924 \mu\text{m}$ for these six meteorites. Spectra are normalized to unity at $1.20 \mu\text{m}$ and are offset for clarity. See Table I-4 for band parameter values. **(b)** Band I center versus BAR for the six primitive achondrites (open triangles) from (a). Spectral zones that are analogous to potential meteorite groups are the same as Figure I-3b. The 1σ errors for Band I center and BAR from Table I-3 are on the order of the symbol size.

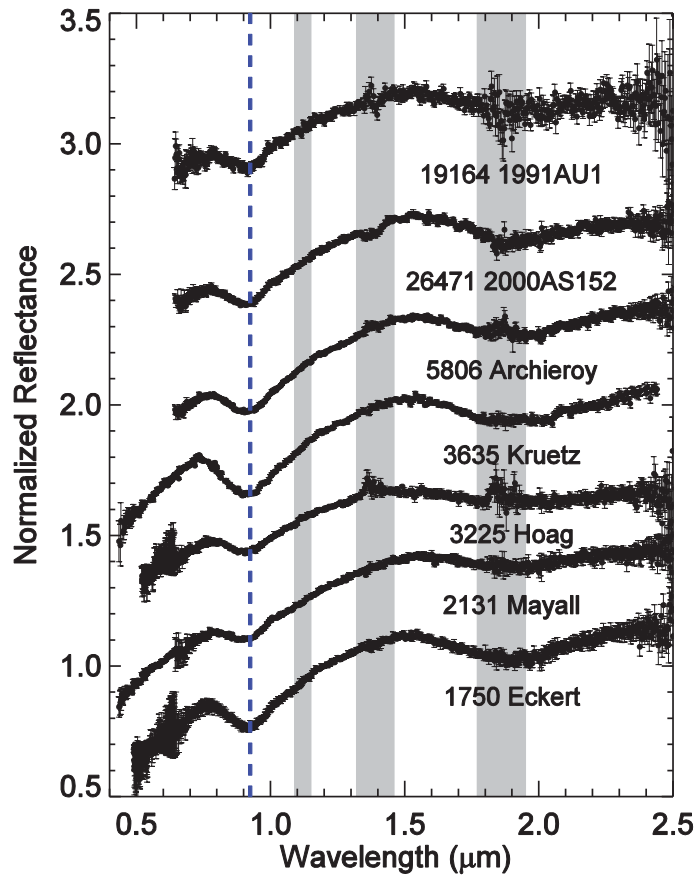


Figure I-7. Spectra of seven Hungaria background asteroids that plot in the Gaffey S(VI) or below the S(IV) subtype region [sub-S(IV) in Table I-5] of Figure I-3a, and in the spectral zone analogous to acapulcoites-lodranites from Figure I-3b, VIS+NIR spectra for the lower four asteroids, NIR-only data for the upper three asteroids. All spectra are normalized to unity at 1.20 μm and are offset for clarity. Blue-dashed line indicates the average Band I center of 0.924 μm for the six primitive achondrite meteorites from Figure I-6a. Most spectra show noise at $\sim 1.4 \mu\text{m}$ and $1.9 \mu\text{m}$ (gray regions) due to incompletely corrected telluric bands.

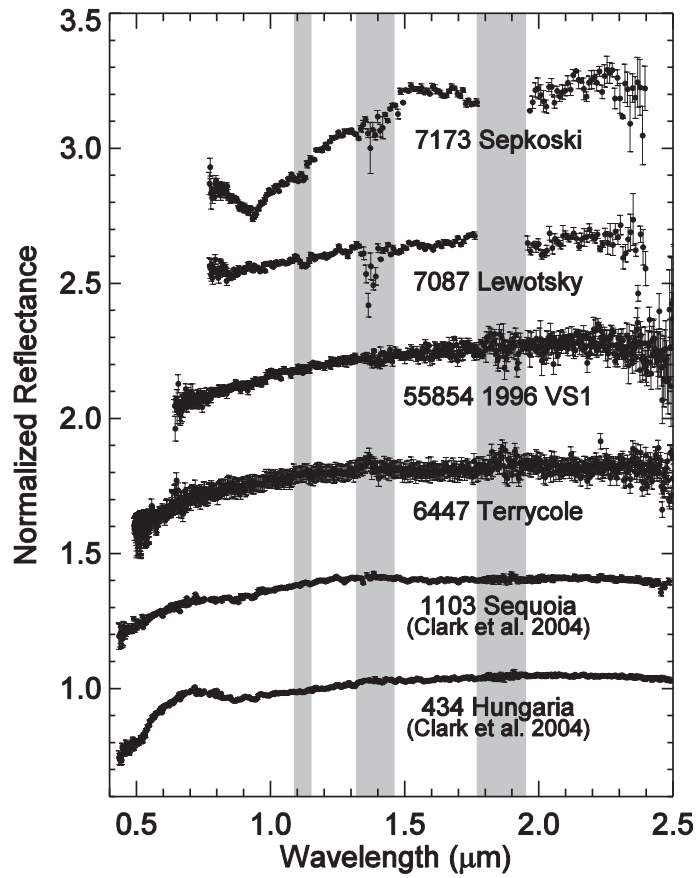
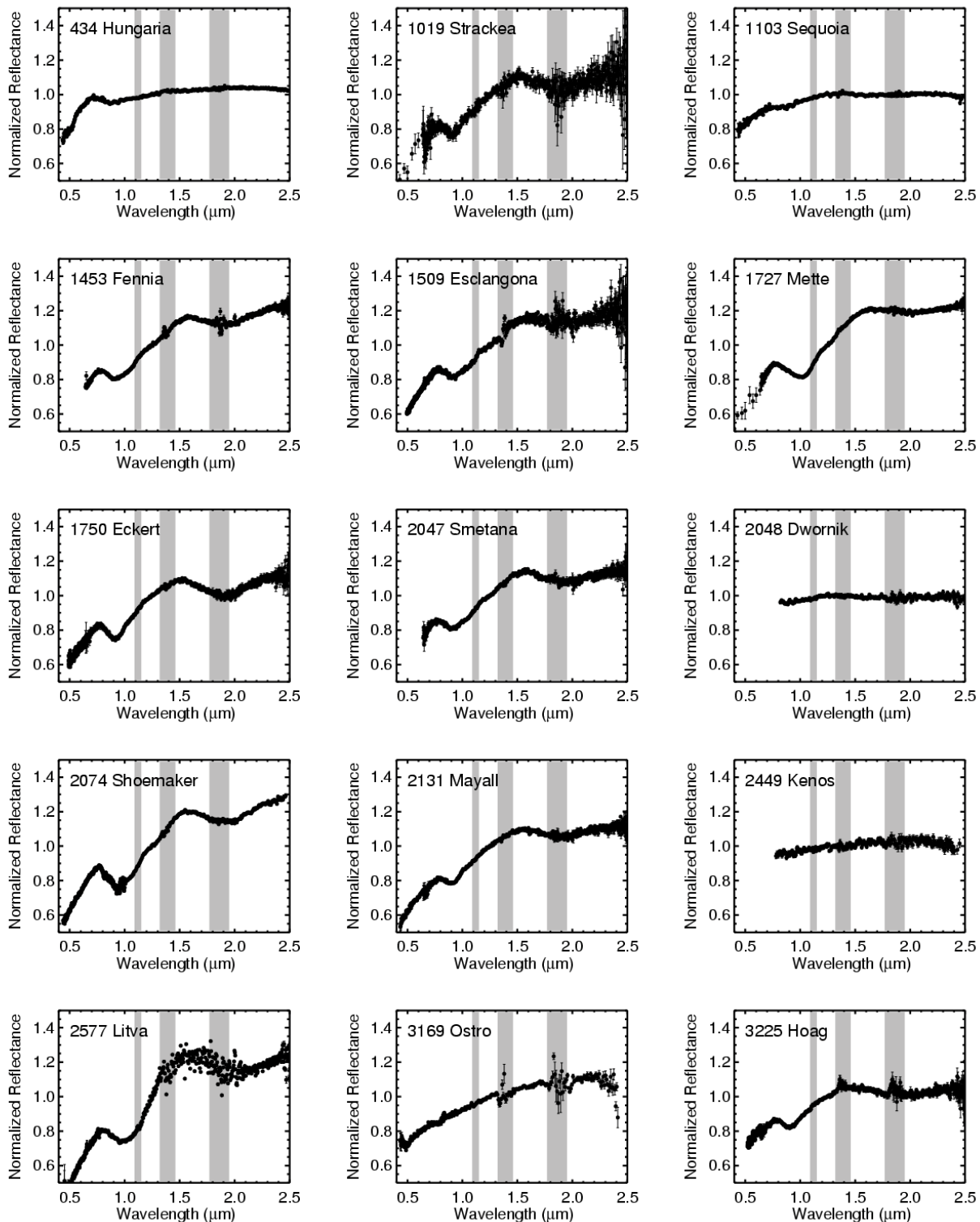


Figure I-8. Spectra for six Hungaria family member asteroids, VIS+NIR spectra for the lower three asteroids, NIR-only data for the upper three asteroids. All spectra are normalized to unity at 1.20 μm and are offset for clarity. Most spectra show noise at $\sim 1.4 \mu\text{m}$ and $1.9 \mu\text{m}$ (gray regions) due to incompletely corrected telluric bands. Reflectance data between $\sim 1.75\text{--}1.95 \mu\text{m}$ for 7087 Lewotsky and 7173 Sepkoski are not shown for clarity.

Appendix I-B

This Appendix contains plots of the final reduced VIS+NIR spectra of 42 Hungaria asteroids presented in this paper (Figure I-9). The NIR spectral data are supplemented with VIS spectra for 21 asteroids from the following sources: the 24-Color Asteroid Survey (Chapman et al., 1993) for asteroids 1019 and 1727; the Small Main-Belt Asteroid Spectroscopic Survey (SMASS) database (Xu et al., 1995) for asteroid 2074; the SMASS Phase II database (Bus and Binzel, 2002) for asteroids 434, 1103, 2131, 3169, 3635, 3873, 4142, 5641, and 6249; the Small Solar System Objects Spectroscopic Survey (S³OS²) dataset (Lazzaro et al., 2004) for asteroids 1509, 1750, 3225, 3940, 6310, and 6447. Visible spectra (0.45-0.85 μm) for asteroids 2577, 3309, and 4674 were acquired with the Southern Astrophysical Research (SOAR) telescope using the Goodman High Throughput Spectrometer (Clemens et al., 2004) and were provided by Lindsay et al. (2015). All spectra have been normalized to unity at the isophotal wavelength of *J*-band at 1.25 μm (MKO-NIR filter system; Tokunaga and Vacca, 2007). The gray bars on each plot denote wavelengths of strong absorption by water vapor in Earth's atmosphere. These absorptions can be difficult to correct for spectra obtained during nights of poor or variable weather, and residual bands can be noticed in several of the spectra.

Figure I-9. The NIR and VIS+NIR spectra of 42 Hungaria asteroids presented in this study. In this appendix, all spectra are normalized to unity at 1.25 μm .



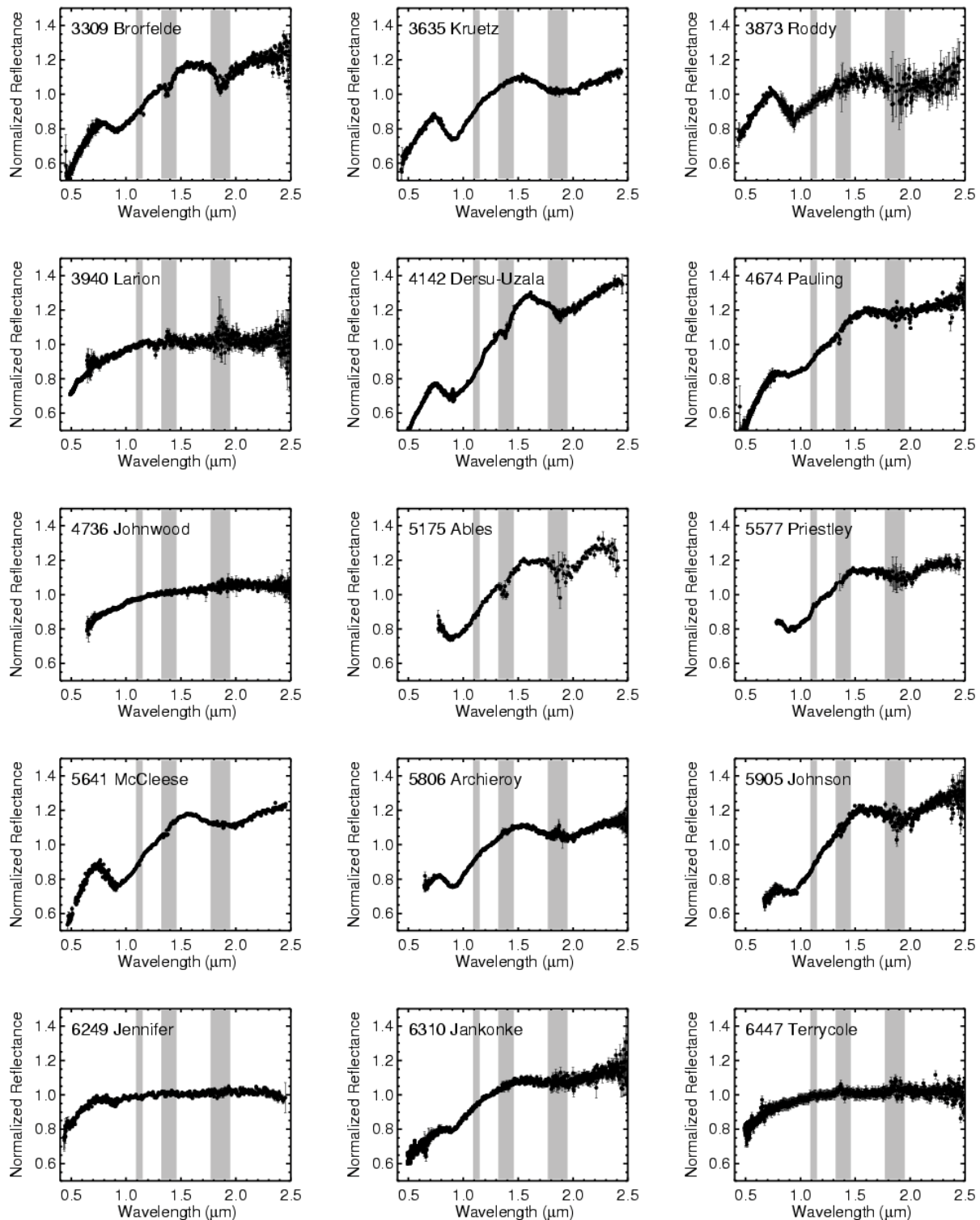


Figure I-9. (continued)

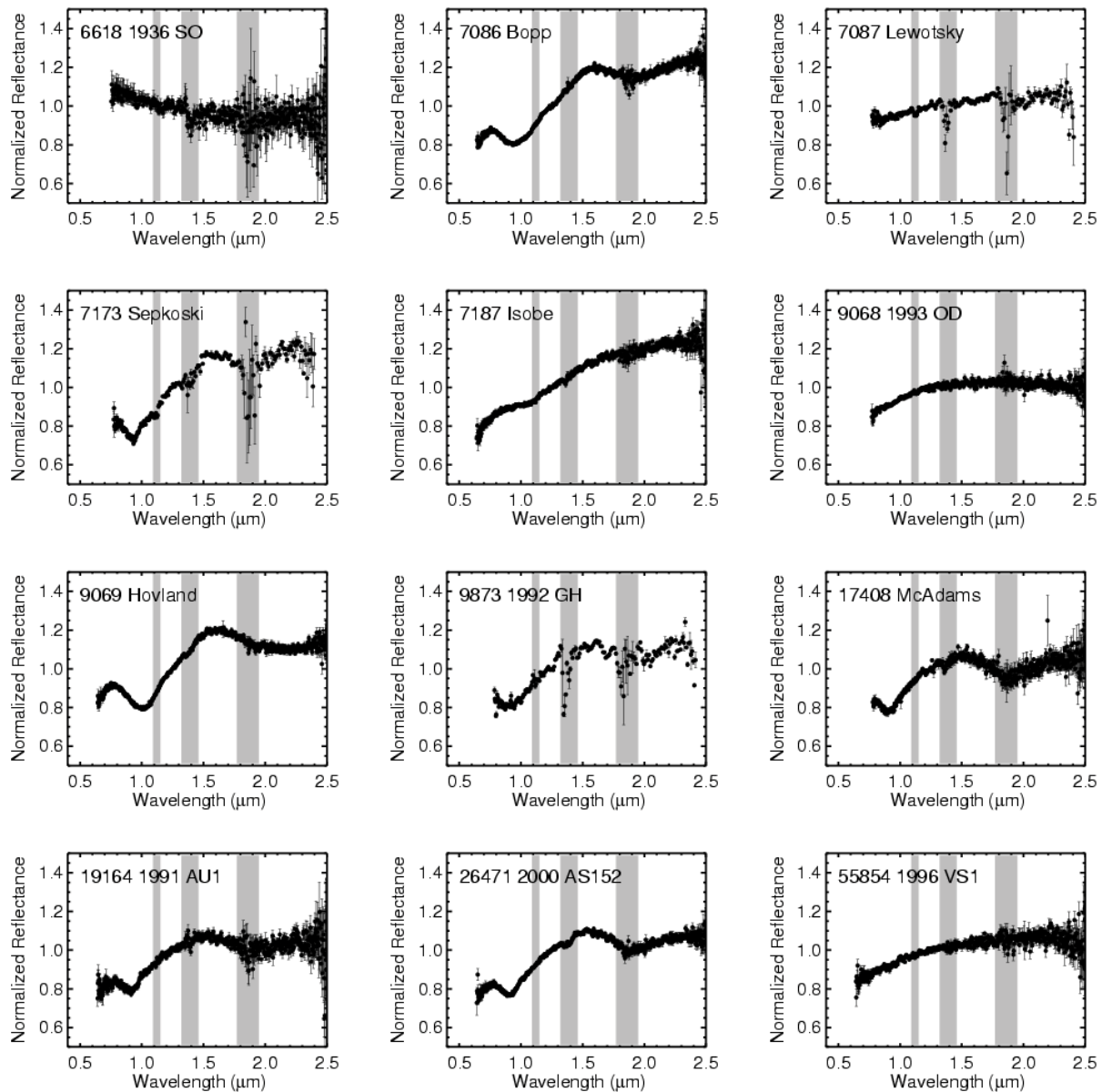


Figure I-9. (continued)

CHAPTER II

Spectral Properties and Mineral Compositions of Acapulcoite-Lodranite Clan Meteorites: Establishing S-type Asteroid-Meteorite Connections

This chapter is a reformatted version of a manuscript in preparation to be submitted to the journal *Meteoritics & Planetary Science* by Michael P. Lucas, Joshua P. Emery, Takahiro Hiroi, and Hap Y. McSween. Michael P. Lucas collected the data, performed the analyses, and drafted this manuscript, tables, and figures. Joshua P. Emery, Takahiro Hiroi, and Hap Y. McSween provided advice on the science and edited the manuscript, tables, and figures.

Abstract

In lieu of asteroid sample return missions, measurements of the VIS+NIR spectral properties of both meteorites and asteroids afford the best possibility of linking meteorite groups with their parent asteroid(s). The spectra of stony asteroids and their meteorite fragments reveal distinguishing absorption features controlled mainly by the Fe^{2+} content and the modal abundances of olivine and pyroxene. Meteorites can be measured in the laboratory to develop relationships between spectra and mineralogy. These relationships are useful for estimating the olivine and pyroxene mineralogy of stony (S-complex) asteroid surfaces through the band parameter analysis of their telescopic VIS+NIR spectra. Using a suite of 10 samples of the acapulcoite-lodranite clan, we have developed new correlations between spectral parameters and mafic mineral compositions for partially melted objects. We applied a novel method for the neutralization and removal of terrestrial weathering products using an ethanolamine thioglycolate (EATG) solution to acquire high-quality reflectance spectra of the meteorites. A well-defined relationship exists between Band II center and ferrosilite (Fs) content of orthopyroxene. Because Fs in orthopyroxene and fayalite (Fa) content in olivine are well-correlated in these meteorites, the derived Fs content can be used to estimate Fa of the co-existing olivine. We derive new equations for determining the mafic silicate compositions of partially-melted S-complex asteroid parent bodies. Stony meteorite spectra have been previously used to delineate meteorite analog spectral zones in Band I versus band area ratio (BAR) parameter space for the establishment of asteroid-meteorite connections with S-complex asteroids. However, the spectral parameters of the partially melted acapulcoite-lodranite clan overlap with those of nebular H chondrites in this parameter space. We find that Band I versus Band II center parameter space reveals a clear distinction between the acapulcoite-lodranite clan and the H chondrites. This distinction enables the correct choice of mineralogic equations between those valid for ordinary chondrite-like mineralogies and those derived here for acapulcoite-lodranites. Comparison of S-complex asteroids and stony meteorite groups using these mineralogic equations provide evidence to decipher whether S-complex asteroids are nebular (ordinary chondrites), or have experienced some degree of igneous processing (primitive achondrites).

1. Introduction

Significant progress has been made during the last several decades in linking stony (S-complex) asteroids to their olivine- and/or pyroxene-rich stony meteorite counterparts. Initial work to formulate correlations between the spectral parameters of mafic silicate assemblages and their mineralogical properties utilized laboratory visible (VIS) plus near-infrared (NIR) reflectance spectra of natural terrestrial olivine and pyroxene mixtures (Adams, 1974; Cloutis et al., 1986; King and Ridley, 1987). More recent studies make use of mineralogical and spectral

properties of actual meteorite samples to develop equations useful for estimating the olivine and pyroxene mineralogy of asteroid surfaces from the band parameter analysis of their VIS+NIR spectra. In particular, these studies have demonstrated that Fe^{2+} compositions of olivine Fa (mol% fayalite; Fe_2SiO_4), and pyroxene Fs (mol% ferrosilite; FeSiO_3), and modal mineral abundances of these minerals can be extracted from the reflectance spectra of some S-complex asteroids. Mineralogic equations based on stony meteorites for the estimation of S-complex asteroid surface mineralogy have been published for ordinary chondrites (H, L, LL) (Burbine et al., 2003; Dunn et al., 2010a), howardite, eucrite, diogenite (HED) meteorites (Burbine et al., 2007a; Burbine et al., 2009; Moskovitz et al., 2010), and olivine-dominated (R chondrite, brachinite, pallasite) meteorites (Reddy et al., 2011; Sanchez et al., 2014). Considering these rocks in petrologic terms, these equations help to correlate S-complex asteroids to meteorite types that possess diverse petrologic histories: unmelted nebular material represented by chondrites; and magmatic (totally melted) achondrites represented by HED meteorites. The petrologic histories of rare olivine-dominated asteroids are not as evident. They may represent: magmatic olivine meteorites (e.g., pallasites; Sunshine et al., 2007), nebular material (e.g., R chondrites; Sanchez et al., 2014), partially-melted primitive achondrites of the brachinite group (Sunshine et al., 2007; Sanchez et al., 2014), or a combination of the above. In the near future, only several bodies will be visited for asteroid sample return. In the meantime, spectral and mineralogical studies of meteorites in the laboratory make it possible to derive S-complex asteroid surface mineralogies using solely ground-based observations.

Gaffey et al. (1993) categorized the spectral parameters of S-complex asteroids into seven mineralogical subtypes that generally cluster near the olivine-orthopyroxene mixing line of Cloutis et al. (1986): olivine-dominated objects [S(I)], olivine-pyroxene mixtures representing ordinary chondrites and primitive achondrites [S(II) to S(VI)], to nearly pure pyroxene or pyroxene-feldspar-metal mixtures [S(VII)] (Figure II-1). These classifications are possible because S-complex asteroids reflect near-infrared photons that carry strong 1 μm (Band I) and/or 2 μm (Band II) absorptions caused by the presence of Fe^{2+} in olivine and pyroxene (Burns, 1993). Band I center is sensitive to the iron content of olivine and pyroxene and their modal abundances, and the ratio of the two band areas (BAR; Band II area/Band I area) is sensitive to their modal abundances (Cloutis et al., 1986). The Gaffey et al. (1993) subtypes are defined by these spectral properties into mineralogical spectral zones. These authors propose potential meteorite analogs for each of the seven subtypes plus a basaltic achondrite (BA) zone. The BA zone is associated with howardite-eucrite-diogenite (HED) meteorites that are generally accepted as originating from 4 Vesta and its collisional family of asteroids (Vestoids) (McCord et al., 1970; Gaffey et al., 1997; McSween et al., 2013; Russell et al., 2015). The nebular ordinary chondrite (OC) class of meteorites is associated with the S(IV) mineralogical zone (“OC boot”) (Gaffey et al., 1993; Gaffey et al., 2002). Significant progress has been made in extracting detailed mineralogic interpretations for S-complex asteroids that possess spectral properties connected with the S(IV) zone. Burbine et al. (2003) derived an equation for determining the olivine and pyroxene modal abundances of OCs from analysis of BAR. This correlation was modified by Dunn et al. (2010a and 2010b) who added equations for determining the compositions of olivine (Fa) and pyroxene (Fs) in OCs from analysis of Band I centers. These equations have demonstrated success at discriminating between the H, L, and LL groups of the OC class. Despite these improvements in forming asteroid-meteorite links for nebular (OCs) and igneous (BA) material, associations between S-complex asteroids and partially-melted primitive achondrite meteorites have not been established. Primitive achondrites possess silicate

mineralogies composed predominantly of olivine and pyroxene and have been associated with some S-complex asteroids (Hiroi et al., 1993; Gaffey et al., 1993; McCoy et al., 2000; Burbine et al., 2001; Dunn et al., 2013; Lucas and Emery, 2014). Yet, because there have not been many laboratory spectral measurements of primitive achondrites meteorites, the association remains fairly vague.

Primitive achondrites include several groups of stony meteorites that have mineral and bulk compositions that are similar to chondrites in many aspects, but have achondritic textures formed as residues from low-degrees of partial melting (Prinz et al., 1983). These groups include the ureilites, acapulcoites, lodranites, brachinites, and winonaites, along with two groups of silicate-bearing iron meteorites (IAB and IIICD) that may have formed on the same parent body as the winonaites (Krot et al., 2007). Primitive achondrites of the acapulcoite-lodranite clan (hereafter ALC) have been described by McCoy et al. (2000), McCoy et al. (1997b), and Mittlefehldt et al. (1996). Acapulcoites are essentially chondritic in composition, but have experienced very low-degrees of partial melting (<1 to ~5%). These meteorites have been heated to ~950-1050°C, warm enough to induce FeNi-FeS cotectic melting (McCoy et al., 1997b). They exhibit granular, recrystallized textures, and are fine-grained with grain interstices typically filled with FeNi metal, indicative of this heating. Lodranites have larger grain-sizes and show higher-degrees of partial melting (~5 to 20%) than the acapulcoites, enough for melt pockets to grow substantially to form interconnected channels, conducive for melt segregation. These meteorites experienced temperatures of ~1050-1200°C, hot enough to produce basaltic partial melts (McCoy et al., 1997a). Accordingly, they display equigranular textures with numerous 120° triple-junctions that are indicative of extensive heating (McCoy et al., 2000). Oxygen isotope (McCoy et al., 1996; Clayton et al., 1992) and cosmic ray exposure age (CRE) data (Eugster and Lorenzetti, 2005; Patzer et al., 2003) of acapulcoites and lodranites overlap and point to a single parent body for the clan (Mittlefehldt et al., 1996; McCoy et al., 1997a). These meteorites are posited to represent samples from a lithologically-diverse, partially-differentiated asteroid (Mittlefehldt et al., 1996; McCoy et al., 1997b; McCoy et al., 2000).

Several models have been developed to explain the petrologic and chemical properties of these partially-melted rocks. The ALC display properties of a continuous range of range of whole-rock partial melting (<1 to ~20%) that could be evidence for parent-body scale igneous properties on the acapulcoite-lodranite parent body (ALPB). Yet, petrologic and geochemical evidence are consistent with the petrogenesis of these rocks from heterogeneous precursor materials and more localized igneous processes (Mittlefehldt et al., 1996; McCoy et al., 2000). Most models invoke a heterogeneous ALPB to explain the petrologic characteristics of the ALC. Mittlefehldt et al. (1996) argues that igneous heating on the ALPB was heterogeneous in both space and time, and that melting on a parent-body scale (e.g., resembling Vesta and the HEDs) probably did not occur. McCoy et al. (1997a) conclude that acapulcoites and lodranites represent the residues from different degrees of partial melting of common, yet isotopically and chemically heterogeneous chondritic precursor materials. Lodranites experienced temperatures high enough to segregate basaltic partial melts (plagioclase-pyroxene). The lack of preservation of these partial melts or their crystallized products (basalts) may suggest that they were removed from the asteroid parent body early in Solar System history. McCoy et al. (1997b) evoked a pyroclastic volcanism model operating on the ALPB to explain the missing basalts that would be complementary to the residual lodranites. However, removal by the gradual or catastrophic comminution of an ALPB basaltic crust cannot be ruled out. Eugster and Lorenzetti (2005) proposed a two-layer “onion shell” model that suggests acapulcoites formed from an earlier- and

faster-cooling outer layer, while lodranites formed within a slower- and later-cooling inner layer of the ALPB. Rubin (2007) posited that the petrogenesis of the ALC clan involved shock melting of a CR-like carbonaceous chondrite precursor, with subsequent post-shock annealing taking place beneath an insulating regolith to explain the low shock-stage rocks of the clan.

Trace element (Floss, 2000a) and bulk-rock (Patzner et al., 2004) cosmochemical analyses show an entire range of different metamorphic degrees, from primitive acapulcoites that have textures similar to chondrites (some with relict chondrules) and near chondritic compositions, to lodranites that have experienced the highest temperatures and segregation of silicate melts. These analyses show that the petrologic diversity of the ALC is more complex than simple division into each meteorite group. Consequently, Patzner et al. (2004) subdivided the ALC into five petrologic types based on increasing temperature and migration of sulfide melts, features that help to explain their varying degrees of petrologic evolution: 1) primitive acapulcoites, 2) typical acapulcoites, 3) transitional acapulcoites, 4) enriched acapulcoites, and 5) lodranites. Small-scale melt migration processes within these rocks would have contributed to the mineralogical heterogeneity of the ALPB (Patzner et al., 2004).

Multiple studies have demonstrated that the ALPB should be spectrally related to some asteroid subtype of the S-complex (Gaffey et al., 1993; Hiroi et al., 1993; McCoy et al., 1997b; McCoy et al., 2000; Burbine et al., 2001). Before the Near Earth Asteroid Rendezvous spacecraft (NEAR Shoemaker) studied the surface composition of the near-Earth asteroid (NEA) 433 Eros (Cheng, 2002), there was some speculation that 433 Eros may have experienced some degree of melting and have a composition analogous to primitive achondrites (McCoy et al., 2000; Burbine et al., 2001). However, mission results indicated homogeneous spectral properties across its surface consistent with an ordinary chondrite composition (McCoy et al., 2001; Cheng, 2002). One clue regarding the search for the source of the ALPB is that ALC meteorites possess short CRE ages (~4-7 Myr) and display a tight cluster of values (Eugster et al., 2006). These values indicate an “express” delivery source region for the clan. Dunn et al. (2013) found a probable source region at the Jovian 3:1 mean-motion resonance for one primitive achondrite-like NEA. Interestingly, H chondrites are thought to be sourced from the 3:1 mean-motion resonance (Gaffey and Gilbert, 1998; Thomas and Binzel, 2010), and this group also has short CRE ages (median ~7 Myr) (Marti and Graf, 1992) that overlap that of acapulcoite-lodranites (Eugster and Lorenzetti, 2005). Despite the similarities in CRE ages between the ALC and H chondrites, the source region(s) for the ALPB remains unclear.

Acapulcoite-lodranite clan meteorites are most likely samples from a distinct partially differentiated asteroid. Although a parent body candidate has not been identified, the spectral properties of some S-complex asteroid types have olivine+pyroxene mineralogies consistent with the clan. The chemical and mineralogic properties of ALC meteorites are well known. However, the difficulty in the identification of plausible parent asteroids for the ALC is in part due to the lack of high-quality reflectance spectra of these uncommon meteorites. To address this shortcoming, we acquired high-quality VIS+NIR reflectance spectra of 10 ALC meteorites after the neutralization and removal of terrestrial weathering products (Figure II-2). We performed detailed spectral band parameter measurements of these spectra. In order to derive more robust relationships between the spectral parameters and mineral compositions of acapulcoites-lodranites, we also measured the mineral compositions of their silicate phases using electron probe microanalysis (EPMA). The chemical and spectral analyses of acapulcoite-lodranite meteorites presented here provide additional measurements to help identify asteroids that have mineralogies consistent with the ALC. Our comparison of the spectral and compositional

features of these samples yield spectral calibrations to provide more accurate mineralogic interpretations for S-complex asteroid spectra, which may make it possible to spectrally distinguish other partially differentiated asteroids.

2. Acapulcoite-Lodranite Samples

A suite of 10 meteorites of the acapulcoite-lodranite clan were obtained for this study. The samples were then prepared for major element mineral chemistry analysis and for the acquisition of VIS+NIR reflectance spectra. Many meteorites of the ALC have been well-characterized geochemically; however, there is a lack of data regarding VIS+NIR reflectance spectra for these partially-melted rocks. All of the samples analyzed in this study are classified as meteorite “finds”; the eponymous meteorites of the ALC, Acapulco and Lodran respectively, are the only known “falls” among the clan¹². Our sample suite includes four acapulcoites, five lodranites, and one transitional acapulcoite-lodranite. Transitional meteorite LEW 86220 is an acapulcoite in composition and grain-size, but also contains a discrete coarse-grained gabbroic lithology (McCoy et al., 1997b; Floss, 2000b).

Four Antarctic samples were provided by the NASA Meteorite Working Group (MWG)¹³ of the Johnson Space Center (JSC) which houses the extensive U.S. Antarctic Meteorite collection (Table II-1). We acquired six meteorite samples commercially, five found in Northwest Africa (NWA), and one sample found in Dhofar, Oman (Table II-1). For the Antarctic samples, we obtained both bulk chip specimens (~500 mg) and polished thin-sections. For the six commercial samples, we obtained bulk unpolished slabs (~1-2 g) in order to have enough material for powdering and polished thick sections preparation (Table II-1). Sample characteristics are listed in Table II-1.

2.1 Petrographic Sample Preparation

Polished thin- or thick-sections were prepared for petrographic and major element mineral chemistry analyses for the 10 acapulcoite-lodranite samples. The Antarctic specimens were prepared at JSC as polished thin sections of ~30 μm thickness mounted on one-inch acrylic disks. The commercially-acquired specimens were cut into thick sections using a low-speed petrographic saw with cutting oil as a lubricant in order to avoid oxidation of the specimens. One surface of each thick section was chosen as the analytical surface, and the section was cast in acrylic for electron probe microanalysis. The analytical surfaces of each specimen was first ground using aluminum oxide sanding disks to 400 grit (~22 μm) size, then polished to a final surface of ~1 μm using diamond polishing paste of three progressively smaller particle sizes. Water was not used in any part of the process. Rather, oil and reagent alcohol were used for the cutting, grinding and polishing stages.

2.2 Reflectance Spectroscopy Sample Preparation

We prepared meteorite powders (<125 μm) from the bulk chips or unpolished slabs of each sample for use in the acquisition of VIS+NIR reflectance spectra. Sample preparation

¹² Meteoritical Bulletin Database; <https://www.lpi.usra.edu/meteor/>, accessed June 4th, 2017

¹³ <https://curator.jsc.nasa.gov/antmet/mwg.cfm>

techniques were consistent for all specimens and we thoroughly cleaned all instruments with isopropanol (99.9% assay) after each specimen to prevent cross-contamination. These meteorites contain from <1 to 29 vol% metal. Although band parameters used to derive mafic silicate mineralogy are largely insensitive to metal contents <80 wt% (Cloutis et al., 2009; Cloutis et al., 2015), metal content can alter the slope of reflectance spectra and suppress absorption bands (Cloutis et al., 2015). We therefore removed the metallic fraction of each acapulcoite-lodranite sample during our powdering procedure, in order to acquire reliable spectra of the silicate fraction.

The meteorites were coarsely crushed (~250-500 μm) and placed in a glass culture dish with isopropanol. The metal fraction of each meteorite was isolated from the silicate fraction by passing a strong magnet underneath the culture dish. The metal fraction was then removed from the culture dish with tweezers, leaving behind the silicate fraction and weathered material. This method was performed serially (3-5x) to remove a maximum amount of metal from each sample. After drying, masses of the separated metal and silicate fractions were measured. We typically recovered 90-95% of the initial mass of each bulk specimen used for powdering.

In order to compare the reflectance spectra of meteorites to asteroids, we powdered the remaining silicate fractions in an agate mortar and pestle and dry sieved the powder to <125 μm (Burbine et al., 2003). Asteroid surfaces are generally blanketed in regolith, therefore meteorite powders of <125 μm provide a suitable analogue in the laboratory. For a detailed treatment regarding meteorite sampling and preparation see the Appendix in Jarosewich et al. (1990).

2.3 Ethanolamine Thioglycolate (EATG) Treatment

The spectral signatures of meteorite “finds” are affected by terrestrial weathering during the long intervals spent in Antarctic ice or on the desert floor (Hiroi et al., 1993). For meteorites that contain considerable amounts of metallic FeNi; weathering is typically expressed through the oxidation of metal into iron hydroxides (e.g., limonite). All 10 acapulcoite-lodranite samples suffer from variable amounts of terrestrial alteration (Table II-1).

We used a method of neutralization and removal of these weathering products using an ethanolamine thioglycolate (EATG) solution (Cornish and Doyle, 1984) that, to our knowledge, has not been previously applied to reflectance spectroscopy of meteorite powders. The EATG leaching method has been used to remove iron hydroxide alteration products from weathered meteorites for oxygen isotope studies (Martins et al., 2007; Greenwood et al., 2012). This method is preferred to conventional leaching using dilute HCl, as treatment in acid can partially remove feldspathic silicates (Greenwood et al., 2012). Experience by one of us (T. Hiroi) has shown that treatment with dilute HCl can also result in a residual H₂O absorption band near 2 μm that is difficult to remove for particulate samples.

We applied the EATG leaching method to the powders (<125 μm) of all samples and acquired their VIS+NIR reflectance spectra both before and after treatment. The effectiveness of this method in removing iron hydroxide alteration from meteorite powders can be observed qualitatively from photographs of the powder specimens (Figure II-3). Individual samples were placed in glass scintillation vials and leached in a solution of 15% EATG in isopropanol (99.9% assay) for a minimum of four hours. The thioglycolate anion will react with Fe³⁺ in solution to form a violet-colored ferrothioglycolate complex (Cornish and Doyle, 1984). The intensity of this colored-complex serves as a handy gauge of the degree of weathering for each specimen. The more weathered samples were given a second treatment in 5% EATG solution for a

minimum of two hours. The samples were washed several times with isopropanol and then dried for spectral analysis.

To investigate possible effects that the EATG leaching method may have on spectral band parameters we applied the same EATG method on sample powders ($<125\text{ }\mu\text{m}$) of natural olivine and pyroxene control samples. We measured the spectral band parameters for these controls both before and after treatment with EATG. Band parameter results for these control samples are discussed in Section 4.3.1. Additionally, to compare our EATG “cleaned” meteorite spectra with spectra of “fresh” acapulcoite-lodranite falls, we have included in our analysis the reflectance spectra of the Acapulco and Lodran meteorites from the RELAB spectral database¹⁴.

3. Analytical Methods

3.1 Petrography

Petrographic analysis of 4 polished thin sections and 6 polished thick sections (mounted on 1 inch acrylic rounds) was performed using a polarizing light microscope. After noting petrographic descriptions, we prepared high-resolution photomosaic images of each sample section. For the thin sections we created 3 photomosaics, one each in plane-polarized (PPL), cross-polarized (XPL), and reflected light (RL). For the thick sections we created only RL photomosaics. We used low-power (25x) under a planachromat objective with a Nikon DS-Fi1 camera to record high-resolution photomicrographs. These images were then stitched together in software (NIS Elements 2.30) to construct the photomosaics. Relevant mineralogic and petrologic properties from our analysis as well as from the literature are described below for acapulcoites (§ 4.1.1) and for lodranites (§ 4.1.2).

3.2. Electron Probe Microanalysis (EPMA)

We measured major elements in silicate and spinel phases with electron probe microanalysis (EPMA), using the Cameca SX100 electron microprobe at the University of Tennessee. Quantitative analyses were carried out via wavelength dispersive spectrometry (WDS), using a 15 kV accelerating voltage, beam currents of 10-30 nA, and a spot size of 1 μm . Standards, which include both natural (olivine, diopside, hematite, spessartine, spinel, and rutile) and synthetic (Cr and Ni metal) reference materials, were measured regularly during analytical sessions to ensure data quality. Background and peak counting times for the major elements were typically 20-30 s, and ZAF corrections were applied using the Cameca PAP procedure. Mineral phases varied from sample to sample, but when present, the following mineral phases were analyzed using WDS mode: olivine (Ol), orthopyroxene (Opx), clinopyroxene (Cpx), plagioclase (Pl), spinel (Spl), and apatite (Ap). We typically did not analyze iron-nickel (FeNi) metal or iron sulfides (FeS, or troilite). For each meteorite, we analyzed the cores of multiple grains (typically $n = 10\text{-}12$) of major mineral phases and at least three spots per grain for minor mineral phases. To check for mineral zoning, we analyzed transects (typically 10-20 spots) across representative grains for all major mineral phases in each meteorite sample. Detection limits for silicates and spinels were: $<0.03\text{ wt\%}$ for SiO_2 , MgO , TiO_2 , Al_2O_3 , CaO , and Na_2O ; $<0.04\text{ wt\%}$ for K_2O and Cr_2O_3 ; $<0.05\text{ wt\%}$ for FeO , MnO , and P_2O_5 ; and $<0.06\text{ wt\%}$ for NiO . Electron backscatter (BSE)

¹⁴ <http://www.planetary.brown.edu/relabdata/>

images were obtained of representative phases for each meteorite specimen. Our EPMA results for major element mineral compositions of acapulcoite-lodranite meteorites are presented in Tables II-2 through II-5.

3.3. VIS+NIR Bi-directional Reflectance Spectroscopy

We measured reflectance spectra of the powdered silicate fraction of each meteorite using the bi-directional spectrometer (0.32-2.55 μm) at Brown University's Keck/NASA Reflectance Experiment Laboratory (RELAB). For a detailed discussion of the capabilities of the instruments at RELAB see Pieters and Hiroi (2004). The spectra were collected under standard operating parameters, which include a viewing geometry of 30° incidence- and 0° emergence-angle and a spectral resolution of 0.01 μm . We collected reflectance spectra for all meteorite powders both before and after removal of alteration products due to terrestrial weathering (see § 3.3.2 below). Reflectance spectra of ALC meteorites used in this study are shown in Figure II-2. The RELAB IDs of 10 spectra from our sample suite are listed in Table II-1. The RELAB IDs of spectra of the namesake “falls” of the acapulcoite and lodranite groups are: Acapulco (TB-TJM-043), and Lodran (TB-TJM-041).

3.4 Spectral Band Parameter Measurements

We measured the band parameters of the strong 1- and 2- μm absorption bands (Band I and II, respectively) for 8 meteorite spectra from our sample suite, and also the meteorites Acapulco and Lodran. We used an Interactive Data Language (IDL) based code, the Spectral Analysis Routine for Asteroids or SARA¹⁵ (Lindsay et al., 2015) to measure Band I and II centers, depths, areas, band area ratios, and their uncertainties. The band area ratio (BAR) is defined as the ratio of (Band II area)/(Band I area). The SARA algorithm computes linear continua across the broad Band I and II absorptions by fitting 5th order polynomials to the absorption band shoulders and then fitting linear continua tangentially to the shoulders, and then divides the spectral segments by their respective continuum. We used a red-edge (i.e., the termination wavelength of Band II) of 2.44 μm as the SpeX spectrograph loses sensitivity longward of 2.45 μm (Lindsay et al., 2016). Band centers and depths are measured three times using 3rd through 5th order polynomial fits to the lower one-half of Band I and to the entirety of Band II. Final band center values are taken as the average of the three polynomial fits. Errors are calculated using a Monte-Carlo method, which creates 20,000 synthetic data reflectance data points for each polynomial order, thereby generating 3 x 20,000 measurements to obtain band center and depth errors. The final 1 σ center and depth errors are defined as the average of the three error measurements. For a detailed description of SARA see Lindsay et al. (2015). Band parameter results for untreated acapulcoite-lodranite meteorites are presented in Table II-6 and band results for EATG treated meteorites are listed in Table II-7.

4. Results

Petrographic descriptions and mineral compositions for some (6 of 10) of the ALC samples have been published by other workers (see references in § 4.1.1 and § 4.1.2). Here, we

¹⁵ SARA is freely available via GitHub: <https://github.com/SeanSLindsay/SARA.git>.

report in Section 4.1 brief petrographic descriptions for all 10 meteorites. We have analyzed all samples for major element mineral chemistry (see § 4.2) and for spectral band parameters (see § 4.3) to enhance the interpretive power of these acapulcoite-lodranite meteorite analyses for associations with potential asteroid spectral analogs. Of the 10 meteorites from our sample suite, we only found a VIS+NIR reflectance spectra for one acapulcoite-lodranite (MAC 88177) in the literature (Hiroi et al., 1993). We report the results of our VIS+NIR spectral analysis in Section 4.3.

4.1 Petrography

4.1.1 Acapulcoite Petrographic Descriptions

MET 01212,14

Acapulcoite MET 01212 (Russell et al., 2004) has a typical grain-size of ~0.15 mm (McCoy et al., 1996). It is an equigranular rock composed of subhedral olivine, orthopyroxene, plagioclase, clinopyroxene, FeNi metal, and troilite, with minor chlorapatite, spinel, and chromite. Olivine makes up roughly 40 vol% of the rock, with roughly 20 vol% orthopyroxene, 20 vol% plagioclase, 10 vol% clinopyroxene, and 10 vol% FeNi metal constituting the other major phases. This rock displays several characteristics of partial melting: its distinctive recrystallization texture, grain boundaries with prominent 120° triple-junctions, and migration of FeNi melt within silicate grain interstices (Figure II-4a) are indicative of low degrees (~1%) of partial melting (McCoy et al., 1997b). A XPL photomosaic of our thin section of MET 012012 is illustrated in Figure II-5a. MET 01212 is very likely paired with MET 01195, 01198, 01232, and 01244⁵. The paired meteorite MET 01195 has been described in detail by Rubin (2007).

Dhofar 125

Acapulcoite Dhofar 125 (Grossman and Zipfel, 2001) is very fine-grained (~0.1 mm), with average grain sizes below the lower limit of 0.15 mm typical for acapulcoites (McCoy et al., 1996). The rock has an equigranular texture with very apparent FeNi metal veining throughout the section (Figure II-4b). The meteorite is moderately weathered (W1) as most FeNi metal is at least partially replaced by iron hydroxides. Modal abundances for Dhofar 125 were found by (Greshake et al., 2001) as follows: olivine (27.5 vol%), low-Ca pyroxene (35.6 vol%), plagioclase (14.0 vol%), troilite (7.7 vol%), augite (6.5 vol%), FeNi metal (5.3 vol%), chlorapatite (0.7 vol%), chromite (0.5 vol%), and weathering products (~2 vol%). Greshake et al. (2001) calculated a two-pyroxene equilibrium temperature of 1120 °C. Accordingly, this acapulcoite displays evidence for low degrees of partial melting (~2-3%); in the form of its equigranular, recrystallized texture and abundant 120° triple junctions. Additionally, most grain interstices are filled with FeNi metal, and the rock exhibits several FeNi metal veins up to ~5 mm in length where metal segregation has started to take place. Dhofar 125 was described by Greshake et al. (2001) and Patzer et al. (2004).

NWA 725

NWA 725 (pseudonym Tissemoumine) is classified as an acapulcoite (Grossman and Zipfel, 2001). This meteorite is also very fine-grained (~0.1 mm) for an acapulcoite (Figure II-4c). This is consistent with the fine-grained nature of winonaites, which have typical grain sizes of ~0.05 to ~0.2 mm (Benedix et al., 1998). This rock has a granular texture with anhedral to subhedral silicate grains. This meteorite is primitive in composition and preserves relict chondrules (Patzner et al., 2004; Rubin, 2006; Greenwood et al., 2012); several large (~2 mm) relict chondrules are visible in our unpolished slab specimen of NWA 725 (Figure II-6). Acapulcoites that include relict chondrules have a greater abundance of opaque phases (30-40 wt%) than typical of acapulcoites (13-20 wt%) (Rubin, 2006). This high abundance of opaque phases is observed in NWA 725, as anhedral FeNi metal blebs are abundant throughout the section, with some as large as ~1 mm. Patzner et al. (2004) estimated modal abundances for these phases as follows: olivine (29.0 vol%), Opx (11.0 vol%), plagioclase (11.0 vol%), clinopyroxene (9.0 vol%), troilite (8.7 vol%), FeNi metal (29.0 vol%), whitlockite (1.0 vol%), and chromite (<1 vol%). As in other acapulcoites, most grain interstices are filled with FeNi metal and the metal veins cross-cut silicate grains in this rock. However, veins are restricted to very thin (~1 μ m) channels of only ~1-2 mm in length, suggesting there has been little metal melt migration. Other evidence for partial melting includes recrystallized texture and abundant 120° triple junctions in some regions of the section. NWA 725 (Tissemoumine) has been described by in detail by Patzner et al. (2004), Rubin (2006), and Greenwood et al. (2012).

NWA 2871

Acapulcoite NWA 2871 is paired with NWA 2656 (Connolly et al., 2006). This specimen has silicate grain-sizes ranging from ~0.25–0.5 mm, larger than typical (0.15-0.23 mm) for acapulcoites (McCoy et al., 1996). The meteorite has a granular texture that has recrystallized into subhedral grains with 120° triple-junctions in some regions of the section. Major mineral phases include: olivine, orthopyroxene, clinopyroxene, plagioclase, FeNi metal, and troilite, with minor phases of spinel and schreibersite. Modal mineral abundances were not estimated for this specimen. This acapulcoite displays several features that indicate that it has experienced partial melting: a recrystallized texture with 120° triple-junctions, grain interstices filled with FeNi metal, and extensive cross-cutting of silicate grains by metal veins (Figure II-4d). FeNi metal has pooled in some areas of the section into anhedral metal grains, with some of these grains interconnected with vein channels up to ~5mm in length. This texture suggests that FeNi metal has undergone melt migration, further indicating low-degrees (~2-3%) of partial melting (McCoy et al. 1997b).

LEW 86220

LEW 86220 is transitional between the acapulcoites and lodranites (Grossman, 1994). Two lithologic textures are present within this specimen: a fine-grained region (~0.15 mm) which is similar in mineralogy and texture to acapulcoites, and a coarser-grained (0.5-2.0 mm) gabbroic-like region that contains plagioclase, clinopyroxene, FeNi metal, and troilite (Figure II-5b). No distinct boundary is observed between the two lithologies. McCoy et al. (1997b; 2000) and Floss (2000b) conclude that this gabbroic lithology represents a basaltic partial melt

segregated from a residual lodranite, which then intruded an acapulcoite layer of the ALPB. Another unusual meteorite thought to originate on the ALPB, the transitional acapulcoite-lodranite FRO 93001, is described as possessing a similar gabbroic lithology of that which intruded LEW 86220 (Folco et al., 2006).

The acapulcoite-like region of our specimen contains subhedral to euhedral grains with rough modal abundances of: olivine (~20 vol%), plagioclase (~20 vol%), orthopyroxene (~10 vol%), clinopyroxene (~10 vol%), and FeNi metal (~40 vol%), with minor troilite. The gabbroic-like lithology contains: plagioclase (~60 vol%), clinopyroxene (~20 vol%), FeNi metal (~20 vol%), troilite, and minor orthopyroxene. The meteorite displays many features typical of acapulcoites that indicate that it has experienced partial melting. The acapulcoite-like region shows an equigranular, recrystallized texture, with abundant 120° triple-junctions, metallic veins that cross-cut the silicates, ubiquitous metal in the grain interstices, and large (~1-3 mm), anhedral metal grains where FeNi melts have pooled. The gabbroic-like region displays a large-grained, granular, igneous texture, and its mineral assemblage is consistent with a segregated basaltic melt. Detailed descriptions of LEW 86220 can be found in McCoy et al. (1997b; 2000), Floss (2000b), Patzer et al. (2004), and Rubin (2007).

4.1.2 Lodranite Petrographic Descriptions

LAR 06605,8

Lodranite LAR 06605 (Weisberg et al., 2010) has a granular texture with abundant 120° triple-junctions. The rock is coarse-grained with subhedral to euhedral silicates with a typical grain-size of ~0.5 mm, somewhat typical for lodranites (0.54-0.70 mm) (McCoy et al., 1996). Olivine and orthopyroxene are in roughly equal proportions within the rock (~40 vol%), with the next most abundant phases of clinopyroxene and FeNi metal making up about 10 vol% each. Plagioclase and troilite are minor phases in the meteorite. Lodranites display evidence for higher-degrees of partial melting than acapulcoites. LAR 06605's crystalline texture with abundant 120° triple-junctions, large grain-size, minor plagioclase (plagioclase makes up ~10-20 vol% in our acapulcoites), and anhedral FeNi grains (~0.5-1.5 mm) where migrated metal has pooled, are evident of partial melting processes. LAR 06605 has experienced higher-degrees of partial melting (~5%) than acapulcoites and may have included some silicate partial melting (McCoy et al., 1997b).

MAC 88177,53

Lodranite MAC 88177 (Grossman, 1994) has an equigranular texture with abundant 120° triple junctions. The silicates in this rock are euhedral to subhedral and are dominated by olivine and orthopyroxene. The rock is coarse-grained with a typical grain-size of ~0.5 mm, and it shows evidence of being highly shocked (shock-stage S5). Shock effects include mosaic extinction in the olivine and pyroxene, several fine-grained metal-troilite assemblages that show characteristics of shock heating and quenching, and minor veining (Rubin, 2007). The opaque phases are generally discrete FeNi metal (1.1 vol%) and troilite grains (3.1 vol%) of ~1 mm grain-size and make up a small proportion of this meteorite, with chromite (0.7 vol%) as a minor phase (Rubin, 2007). Clinopyroxene is an interstitial phase and contains exsolution lamellae of orthopyroxene and inclusions of metal and troilite (Figure II-7a). Prinz et al. (1991) estimated

modal abundances and found: olivine (51.3 vol%), orthopyroxene (38.4 vol%), clinopyroxene (7.4 vol%), and troilite (1.9 vol%), with FeNi metal, chromite, and feldspathic glass as minor phases. Herrin et al. (2006) calculated a two-pyroxene closure temperature of 1200 °C (McCoy et al., 1997a calculated 1140 °C), consistent with the high-degree of partial melting (>10%) estimated by McCoy et al. (1997b) for this rock. MAC 88177 is depleted in plagioclase and troilite relative to chondrites and acapulcoites, indicating that basaltic partial melts have been largely removed from this residual lodranite. Further detailed petrographic information regarding MAC 88177 can be found in (Prinz et al., 1991; Mittlefehldt et al., 1996; McCoy et al., 1997a; Floss, 2000a; and Rubin, 2007), and for detailed geochemical data see (Rubin et al., 2002; and Floss, 2000a).

NWA 5488

Lodranite NWA 5488 (Weisberg et al., 2009) is paired with NWA 4478 and 4933. This specimen is composed of large subhedral to euhedral olivine grains of up to ~5 mm across with a finer-grained lithology of interstitial (typically ~0.5-1 mm) olivine, clinopyroxene, and orthopyroxene. The interstitial lithology also contains troilite and FeNi metal, with minor chromite. Plagioclase is absent in the section, and the abundance of metal (plus iron hydroxide weathering products) is roughly 5 vol%. Modal mineral abundances of silicates were not estimated for this specimen. Olivine grains contain numerous blebs of FeNi metal and/or troilite and are typically cross cut by metallic veins. Clinopyroxene contains exsolution lamellae of orthopyroxene and discontinuous veinlets of metal and troilite (Figure II-7b). NWA 5488's polycrystalline texture, large grain-size, absence of plagioclase, and low abundance of metal and troilite indicates a degree of partial melting high enough to have segregated basaltic partial melt.

NWA 7312

Lodranite NWA 7312 (Ruzicka et al., 2015a) has a crystalline, equigranular texture with abundant 120° triple-junctions. The rock is coarse-grained, with euhedral to subhedral olivine and orthopyroxene grains ranging in size from ~1- to ~3-mm, somewhat large for lodranites. Olivine and orthopyroxene make up almost all of the rock, with minor FeNi metal in the interstices of some grain boundaries. Clinopyroxene and plagioclase are absent. Modal mineral abundances were not estimated for this specimen. Some orthopyroxene grains contain bleb-like inclusions of olivine (Figure II-7c). Shock stage and weathering grade are considered low for this meteorite (Ruzicka et al., 2015a). NWA 7312 clearly has experienced temperatures high enough to segregate basaltic partial melt. The presence of a crystalline texture with abundant 120° triple-junctions, coarse grain-size, absence of plagioclase and clinopyroxene, and almost complete migration of FeNi metal and sulfides out of the rock indicate that NWA 7312 is a basalt-depleted residue of a high-degree (>10%) of partial melting (McCoy et al., 1997b).

NWA 7674

Lodranite NWA 7674 (Ruzicka et al., 2015b) has a coarse-grained, granular texture with typical silicate grain-sizes in the range ~0.3- to 0.8-mm. Constituent mineral phases are olivine, orthopyroxene, clinopyroxene, FeNi metal, and troilite, with minor plagioclase, chlorapatite, and chromite. Modal mineral abundances were not estimated for this specimen. Some olivine grains

contain bleb-like inclusions of clinopyroxene and vice versa (Figure II-7d). One side of the section displays abundant anhedral FeNi metal and troilite grains from ~1-3 mm across where metal/sulfides have pooled, and multiple, weathered FeNi metal and troilite veins connecting some of the grains. These features are evidence for the segregation of metal on the meteorite's parent body. Shock stage and weathering grade are considered low for this meteorite (Ruzicka et al., 2015b). Olivine grains contain numerous blebs of FeNi metal and/or troilite and are typically cross cut by metallic veins and the metal is ubiquitous in the grain interstices. NWA 7476's granular, grain-size, minor plagioclase, and metal and troilite that has pooled are evident of partial melting processes. NWA 7476 has experienced higher-degrees of partial melting (~5%) than acapulcoites and may have experienced some silicate partial melting (McCoy et al., 1997b).

4.2 Mineral Compositions

4.2.1 Olivine

Olivine core compositions are listed in Table II-2. Olivine fayalite composition [$Fa = \text{molar Fe}/(\text{molar Mg} + \text{Fe}) \times 100$] ranges from $Fa_{3.4}$ (NWA 7312) to $Fa_{14.0}$ (MAC 88177). Olivines within the lodranite group are generally more iron-rich than the acapulcoites. Olivine grains from several lodranites exhibit reverse zoning (FeO decreases from core to rim). No zoning of olivine is observed in acapulcoites.

4.2.2 Pyroxenes

Low-Ca pyroxene core compositions are given in Table II-3, and high-Ca pyroxene core compositions are listed in Table II-4. Low-Ca pyroxene ferrosilite compositions [$Fs = \text{molar Fe}/(\text{molar Mg} + \text{Fe} + \text{Ca}) \times 100$] show a broader range of Fs ($Fs_{3.3}$ to $Fs_{12.8}$), than for high-Ca pyroxene ($Fs_{3.4}$ to $Fs_{6.5}$). Similar to the olivine compositions, pyroxenes in lodranites are more iron-rich than those in acapulcoites. Orthopyroxenes in the lodranites have a higher average CaO and Al_2O_3 content than within the acapulcoites. The lodranites exhibit reverse CaO zoning (CaO decreases from core to rim) in orthopyroxene. Exsolution lamellae of orthopyroxene in clinopyroxene (see Figure II-7a) and vice versa are observed in some lodranites, but were not observed in the acapulcoites. High-Ca pyroxene is more abundant volumetrically within acapulcoites, and is less abundant or even absent (NWA 7312) in the lodranites. We analyzed high-Ca pyroxenes in both the acapulcoite-like and gabbroic lithologies of transitional acapulcoite-lodranite LEW 86220 and their chemistries are remarkably similar (Table II-4). High-Ca pyroxenes in both meteorite groups contain significant amounts of Cr_2O_3 (1.10 to 1.73 wt%) and therefore are considered to be chromium diopsides (McCoy et al., 1997a). Figure II-8 shows the Fs of orthopyroxenes versus the Fa of olivines for ALC meteorites. Orthopyroxene (i.e., low-Ca pyroxene) Fs values are well correlated with Fa of co-existing olivine. The mafic silicates of ALC meteorites span a wide range of oxidation states and plot between those of highly reduced enstatite (E) chondrites and H chondrites. Lodranites are generally more iron-rich than acapulcoites and the two groups cluster in separate Fs versus Fa fields, although there is some overlap between the groups (Figure II-8). NWA 7312 has a significantly lower iron content compared to the rest of the clan and plots in the E chondrite field.

4.2.3 Plagioclase

We identified plagioclase in all of our acapulcoites and only as a minor phase in two lodranites (LAR 06605 and NWA 7674). Plagioclase compositions are listed in Table II-5. Plagioclase is oligoclase in composition and has relatively homogeneous K₂O contents. Plagioclase chemistries range from An_{12.6} to An_{20.0} [An = molar Ca/(molar Ca+Na+K) x 100] for all meteorites except lodranite NWA 7674. The high-Ca value (An_{36.8}) for this lodranite was measured from a single plagioclase grain enclosed within an olivine grain. McCoy et al. (1997a) found that lodranites with high Fa content in olivine (~Fa_{7.5-13}) tend to have very low plagioclase modal abundances, and those lodranites with lower Fa content in olivine (~Fa_{<7.5}) tend to have higher plagioclase abundances (6.0 - 10.3 vol%). All lodranites from this study have high iron contents in olivine (>Fa_{10.5}). Plagioclase was absent in three lodranites and a minor phase in two others, so our results support this trend. Lodranite NWA 7312 does not follow this trend however, as plagioclase is absent even though it has a very forsteritic olivine composition (Fa_{3.4}). Plagioclase is absent in MAC 88177, although we found a ~40 µm diameter SiO₂-rich feldspathic glass melt inclusion within an olivine grain, consistent with melt inclusions reported by Prinz et al. (1991) in the same meteorite.

4.3 Acapulcoite-Lodranite Spectral Results

The acapulcoite and lodranite spectra collected during this study reveal distinguishing absorption features controlled mainly by the Fe²⁺ content and the modal abundances of the mafic silicate minerals olivine and pyroxene. Olivine exhibits a broad absorption band centered at ~1 µm, and ortho- and clino-pyroxene typically display two strong absorptions centered at ~0.9 µm and ~2.0 µm. Cloutis et al. (1986) showed that olivine+orthopyroxene mixtures exhibit well-defined behavior in Band center versus Band Area Ratio (BAR) parameter space. Band I and Band II center positions can be used as a gauge of iron content, and BAR is a useful indicator of the relative modal abundance of these minerals.

The analysis of our acapulcoite-lodranite spectra (Figure II-2) is therefore focused on olivine and orthopyroxene. These minerals are the dominant silicate phases in these meteorites, and they are present in quantities abundant enough to exhibit strong 1 and 2 µm spectral absorptions. The results of our band parameter analysis for untreated (i.e., before removal of terrestrial alteration) sample spectra are given in Table II-6, and the band parameter results of our sample spectra after removal of alteration via EATG treatment are listed in Table II-7. We also analyzed the spectral band parameters of the only recovered “falls” among the ALC, Acapulco and Lodran, for spectral comparison to our EATG treated acapulcoite-lodranite meteorite finds (Table II-7). These falls show minimal effects of terrestrial alteration and therefore provide suitable characteristic spectra of “fresh” acapulcoite-lodranite meteorites.

Two lodranites, NWA 5488 and NWA 7312, contain significant amounts of opx±cpx (see § 4.1.2), but well-defined absorption bands are absent in the 2 µm region (Figure II-2b). NWA 5488 is spectrally flat longward of a subtle ~1 µm absorption feature, and the spectrum of NWA 7312 displays a gradual reddening in reflectance longward of the 1 µm region. Spectra of materials containing pyroxene can exhibit a 1 µm band while also displaying little or no indication of a 2 µm absorption band (Cloutis et al., 2010). This effect has been observed in shock-blackened ordinary chondrites (Britt and Pieters, 1994) and has been predicted from theoretical modeling (Moroz and Arnold, 1999). Shock darkening is caused by the dispersion of

micron-scale FeNi metal and troilite (Britt and Pieters, 1994) and may be a process affecting these meteorites. Without the presence of a $\sim 2\ \mu\text{m}$ absorption, we cannot derive Band II centers and BARs for these samples, so NWA 5488 and NWA 7312 are not included in our spectral band parameter analysis.

Iron oxides/hydroxides (e.g., limonite) from terrestrial weathering typically exhibit an absorption edge near $0.55\text{--}0.6\ \mu\text{m}$, absorption bands centered near 0.5 and $0.9\ \mu\text{m}$, and weaker absorptions associated with OH^- may also be present in the 1.4 and $1.9\ \mu\text{m}$ regions (Hiroi et al., 1993; Cloutis et al., 2010). The presence of iron oxides/hydroxides can mask the characteristic spectral properties associated with the Fe^{2+} content and modal abundances of olivine and pyroxene.

To compare the spectra of our weathered acapulcoite-lodranite powders with “cleaned” powder spectra, we plotted the Band I centers versus BAR for the nine samples before and after treatment with EATG (Figure II-9). From an inspection of Figure II-9 and a comparison of Band I and BAR values for untreated samples (Tables II-6) and EATG treated samples (Table II-7), it is apparent that terrestrial weathering has a minimal effect on band center positions. Measured Band I centers are identical or show minimal differences between the untreated meteorite spectra and the EATG treated spectra. Band II centers also show minimal differences, typically within $0.017\ \mu\text{m}$ between untreated and treated samples. However, it is clear that BAR is significantly affected by the presence alteration products. The untreated, weathered samples have lower measured BAR values than samples treated with EATG (Table II-6 and II-7; Figure II-9). EATG treated samples show deeper bands and therefore an increase in band area, with Band I exhibiting a smaller overall increase in area due to the contribution of a $\sim 0.9\ \mu\text{m}$ band from limonite in the untreated samples.

Although we demonstrate that BAR values increase with removal of terrestrial alteration products, some of our EATG treated spectra still exhibit some noticeable effects of weathering (Figure II-2). This is visible as a sharp absorption edge near $0.6\ \mu\text{m}$ for several meteorites (e.g., see LEW 86220 in Figure II-2c). Also, an inflection of the steep red-slope near $0.5\ \mu\text{m}$ for many of the spectra (e.g., see Dhofar 125 in Figure II-2a) is most likely due to unremoved terrestrial alteration. Despite the presence of these residual spectral features due to weathering products, EATG treated spectra are unmistakably shifted to higher BAR values.

Gaffey et al. (1993) used Band I center versus BAR to characterize the olivine and pyroxene mineralogy and possible meteorite analogs of stony asteroids of the S-complex, separating the S-complex into seven subtypes [S(I) through S(VII)]. Later workers analyzed the spectral properties of meteorite samples to delineate spectral zones in Band I versus BAR parameter space for the establishment of asteroid-meteorite connections with stony S-complex asteroids. Figure II-10 shows Band I versus BAR of our EATG treated acapulcoite-lodranite samples and the meteorite falls Acapulco and Lodran (see Table II-7) relative to generalized spectral zones for five meteorite groups on a modified version (Burbine et al., 2001; Dunn et al., 2013) of the S-subtype plot.

The acapulcoite-lodranite meteorites we measured have Band I centers between 0.913 and $0.940\ \mu\text{m}$ and BARs between 0.46 and 0.99 , and most of the samples cluster near the “fresh” falls of the clan, Acapulco and Lodran, in band parameter space. The samples display a restricted range of BAR values compared to the generalized primitive achondrite spectral zone of Burbine et al. (2001), and plot below the ordinary chondrite “boot” spectral region or overlap with this region. The lodranite samples (except for Lodran) display more overlap with the ordinary chondrite spectral zone than do the acapulcoite samples (Figure II-10). High levels of shock can

cause BAR to decrease, while producing no significant shift in Band I center (King, 1986; Cloutis et al., 2010). This is a plausible explanation for the low BAR value (0.529 ± 0.002) for lodranite MAC 88177 relative to other samples as this meteorite is classified as shock-stage S5 (Rubin, 2007). Acapulcoite NWA 2871 has the lowest BAR value (0.464 ± 0.004) of all the samples and plots within the ureilite spectral zone (Cloutis et al., 2010). This low BAR value may be due to incomplete weathering removal; this meteorite is one of the most weathered of our samples (weathering grade - W3). Excluding these two meteorites, acapulcoite-lodranite spectra share similar band parameters, and there is some overlap with the bottom boundary of the ordinary chondrite spectral zone. The bottom portion of the ordinary chondrite boot is associated with the H chondrite group (see Figure II-9) of ordinary chondrites (Dunn et al., 2010a). It may therefore be challenging to discriminate between acapulcoite-lodranite and H chondrite meteorite analogs when comparing asteroid spectral band parameters.

4.3.1 EATG Treated Olivine and Orthopyroxene Control Results

We have shown that the presence of terrestrial weathering products reduces measured BAR values for acapulcoite-lodranite meteorites (Figure II-9). In order to demonstrate that measured band centers of the mafic silicates found within our samples are not affected by the EATG leaching procedure, we applied the EATG method to powders ($<125 \mu\text{m}$) of natural mineral specimens that we used as control samples. The formation of a faint violet-colored ferriothoglycolate complex during the leaching procedure verified that the control samples contained a minor amount of oxidized material.

We acquired the VIS+NIR reflectance spectra of the following natural mineral specimens both before and after treatment with EATG: San Carlos olivine (Fa_{10}), an orthopyroxene (enstatite) sample from Tanzania (Fs_9), and a 50/50 wt% mixture of the two minerals. Untreated versus EATG treated sample spectra are over plotted (reflectances not offset) for each of the three controls in Figure II-11. The EATG treated samples show a slight increase in band depth for both Band I and Band II. This small increase may be the result of the removal of a small amount of weathering products during the leaching procedure. The band centers are essentially unaffected by the EATG treatment.

To quantify these observations, we measured the band parameters of both untreated and treated control samples using the same methods (see § 3.4) used for the acapulcoite-lodranite meteorites. The results are provided in Table II-8. We plotted the Band I center versus BAR for the Tanzania enstatite and the 50/50 wt% Ol+En mixture samples before and after treatment with EATG as with the meteorite samples (Figure II-9). The EATG treated sample of Tanzania enstatite shows a slightly increased BAR, consistent with the results of the meteorites. The BARs of the untreated and EATG treated sample of the 50/50 wt% Ol+En mixture are virtually the same. Similar to the results observed for the meteorite samples, measured Band I centers for EATG treated control samples are identical to the untreated values. Measured Band II centers for EATG treated controls only show small variation ($\leq 0.01 \mu\text{m}$) from untreated values. We conclude that band center positions of olivine and orthopyroxene are unaffected by the application of the EATG weathering removal method.

4.4 Olivine and Orthopyroxene Compositions/Spectral Band Correlations

Examination of the FeO contents of the equilibrated olivine (Fa) and orthopyroxene (Fs) from this study show that the data cluster into separate fields for acapulcoites and lodranites (Figure II-8). Furthermore, the Fa and Fs for acapulcoites and lodranites are close to their equilibrium relationships and appear to form a linear trend spanning the two groups. The relationship between the measured Fa and Fs for 10 acapulcoite-lodranite meteorites for which we have spectral data (Table II-7) is shown in Figure II-12 (axes inverted from Figure II-8). This relationship demonstrates that the Fa of olivine and the Fs of orthopyroxene in acapulcoite-lodranite are well correlated and form a linear trend. We can use this relationship to estimate the FeO content for one of mafic silicates if the other is known. The Fa of olivine can be calculated if the Fs of orthopyroxene is known using the linear equation:

$$Fa = 1.100 \times Fs - 1.270. \quad (1)$$

This linear relationship has an R^2 of 0.86. Dunn et al. (2010a) showed that the Fa content of olivine and Fs content of orthopyroxene in ordinary chondrites (H, L, and LL) correlate well with Band I center, with correlation coefficient (R^2) values of 0.92 and 0.91 respectively. We found that the correlation between mafic silicate FeO contents and Band I center for our acapulcoite-lodranite meteorites is poorly constrained, with R^2 values of 0.17 for Fa, and a very low correlation of 0.08 for Fs. The mafic silicate FeO compositions of ordinary chondrites are mainly inherited by the redox state of the solar nebula. (Brearley and Jones, 1998). The oxidation states of mafic silicates in acapulcoite-lodranite meteorites are lower than those of H chondrites, the most reduced group of the ordinary chondrites (Figure II-8). Partial melting of chondritic material produces residues that become increasingly magnesium-rich (FeO poor) with increased partial melting. Perhaps different processes controlling the mafic silicate compositions within ALC meteorites are the reason for the poor correlation with Fa and Fs with Band I center for these meteorites.

We found a correlation between the Fs content of orthopyroxene within acapulcoite-lodranite meteorites and Band II center. The relationship between measured Fs and Band II center is shown in Figure II-13. This relationship demonstrates that a correlation exists between the FeO content of orthopyroxene and Band II center in these meteorites and is described by a linear fit:

$$Fs = 107.6 \times (BIIC) - 189.5, \quad (2)$$

with Fs here being a spectrally-derived value. This linear relationship has a R^2 of 0.72. The correlation between Fs and Band II center allows for the estimation of the mol% Fs (spectrally-derived) of orthopyroxene for S-complex asteroid spectra that are analogous to acapulcoite-lodranite meteorites. Because there appears to be a well-established correlation between Fa and Fs in acapulcoite-lodranite meteorites (Figure II-12), the Fa content of olivine from S-complex asteroid spectra that are analogous to acapulcoite-lodranite meteorites can be estimated from Equation 1. Figure II-14a shows that spectrally-derived Fs values from Equation 2 are correlated with EPMA measured Fs, with moderate positive offsets for one acapulcoite and the transitional acapulcoite-lodranite LEW 86220, and slight negative offsets for several acapulcoites and lodranites. Figure II-14b shows that derived Fa values using Equation 1 are well correlated with

EPMA measured Fa, with only slight offsets, except for a large positive offset for LEW 86220. Because the FeO contents of the acapulcoite group plot in a distinct field from that of the lodranite group (Figure II-8), the calculation of Fa and Fs values from the band parameter analysis of S-complex asteroid spectra may allow to the discrimination between plausible acapulcoite-like and lodranite-like asteroid parent bodies.

5. Discussion

Examination of the spectral properties and mineral compositions of ALC meteorites presented here reveal characteristics that enable the characterization of partially-differentiated parent bodies from other S-complex asteroids through the analysis of their spectra. Mafic mineral chemistries for the ALC occupy distinct fields in FeO parameter space, and are also unlike the nebular chondritic meteorite analog groups related to S-complex asteroids (Figure II-8). FeO chemistries are well correlated and form a linear trend in Fa versus Fs that spans the two meteorite groups of the clan (Figure II-12). Spectral properties for the two groups cluster in Band I center versus BAR parameter space, and Band II centers can be used to calculate the Fs composition of orthopyroxene in these meteorites (Figure II-13). Yet, the spectral parameters for the ALC overlap with those of H chondrites on a plot of generalized spectral zones for various stony meteorite groups (Figures II-9 and II-10), blurring the ability to spectrally distinguish between potential nebular ordinary chondrite parent bodies and partially-differentiated parent bodies using established Band I center versus BAR S-complex meteorite analog spectral zones. This overlap is addressed using spectral properties that are more useful for pyroxene-dominated mineralogies, namely Band I center versus Band II center, which reveals a clear distinction between the ALC and the H chondrites.

The characteristics of acapulcoites and lodranites meteorites presented here prompt interesting questions as to the nature of the ALPB, and the spectral and mineralogic properties of the parent bodies of partially-differentiated asteroids. We discuss several considerations below regarding these questions including: the unexpectedly high FeO contents of mafic silicates of the lodranite group relative to the acapulcoite group (§ 5.1), clues from the spectral properties of pyroxene-dominated mineralogies that help to distinguish between potential H chondrite and acapulcoite-lodranite parent bodies (§ 5.2), and spectral trends regarding potential meteorite parent bodies that are residues of partial melting versus the spectral trends of their complementary segregated liquids (§ 5.3). Taken together, these considerations provide evidence to decipher the petrologic histories of some S-type asteroids, specifically whether they are nebular (ordinary chondrites), or have experienced some degree of igneous processing (primitive achondrites).

5.1. Puzzling Mafic Silicate FeO Contents of the Acapulcoite-Lodranite Clan

Primitive achondrite meteorites have mineral and bulk compositions that are similar to chondrites in many aspects, but have experienced varying degrees of partial melting. The partial melting of chondritic material will produce silicate partial melts that are enriched in plagioclase and pyroxene (basalts) that are distinctly more ferroan than the solid residue. Therefore, progressive partial melting will result in residual mafic silicate minerals that become increasingly magnesian. The ALC is thought to originate from a single asteroidal parent body (ALPB).

Acapulcoites have experienced very low-degrees of partial melting and therefore have not lost silicate melts, whereas many lodranites have experienced higher-degrees of melting (up to ~20%) with temperatures hot enough to have segregated basaltic liquids. If both of these groups originated on a single parent body from the same chondritic precursor material, then lodranites should have mafic silicates that are more magnesian than acapulcoites. However, most lodranites from this study contain mafic silicates that are more ferroan than those within the acapulcoites (Table II-2 and 3; Figure II-8), the converse of what is predicted from partial melting. This unexpected result leads to the conclusion that the same chondritic precursor material could not have produced both the acapulcoite and lodranite meteorite groups. If originating on the same parent body, these precursor materials must have been heterogeneous in composition and were not homogenized by metamorphic or igneous processes (Mittlefehldt et al., 1996).

5.2 Distinguishing H chondrite and Acapulcoite-Lodranite Clan Parent Asteroids

Our equations to determine the mafic silicate compositions of S-complex asteroid spectra may enable the interpretation of the petrologic histories of some S-complex asteroids, specifically whether they are related to nebular, ordinary chondrite material, or if they have experienced partial melting, and are related to the ALC. However, one difficulty in discriminating between these two distinct petrologic histories is that the spectral parameters in Band I versus BAR parameter space for our 10 acapulcoite-lodranite meteorites overlap with those of the H chondrites (see Figures II-9 and II-10). Dunn et al. (2010a) showed that the different groups (H, L, and LL) of the ordinary chondrite class can be separated in Band I center versus BAR parameter space, with H chondrites occupying the lower portion of the OC “boot” meteorite spectral zone. Consequently, the overlap of these spectral parameters would lead to uncertainty for the interpretation of detailed mineralogies for some S-complex asteroid spectra. Specifically, there would be ambiguity whether to estimate the FeO composition of mafic silicates with our Equations 1 and 2, which are valid for acapulcoite-lodranite-like parent asteroids, or to derive mineral compositions with the equations of Dunn et al. (2010a) that are valid to estimate the mineralogy of ordinary chondrite-like parent asteroids. To investigate this overlap beyond that of simply plotting spectral parameters relative to generalized meteorite spectral zones, we plotted the Band I centers and BARs of our acapulcoite-lodranite samples versus those of 18 H chondrites analyzed in Dunn et al. (2010a) (Figure II-15). For their mineralogic calibration study of 48 ordinary chondrites, Dunn et al. (2010a) used a red edge of 2.5 μm for Band II to derive BAR values. The choice of the red edge for Band II in the analysis of NIR spectra can lead to differences in Band II area, which will affect calculated BARs (Lindsay et al., 2106). In order to directly compare asteroid spectra acquired with the SpeX spectrograph to our acapulcoite-lodranite meteorite spectral parameters, we analyzed our acapulcoite-lodranite spectra with a red edge of 2.44 μm . Therefore, to directly compare the BARs of our acapulcoite-lodranites to the H chondrites analyzed in Dunn et al. (2010a), we adjusted our BAR values to a red edge of 2.5 μm using the equation of Lindsay et al. (2016) with a slope coefficient for ordinary chondrites:

$$BAR_{adj} = BAR_0 - 1.265(\lambda_0 - \lambda_{RE}), \quad (3)$$

where BAR_{adj} is the adjusted BAR value, BAR_0 is the BAR measured at the red edge of λ_0 (in this case 2.44 μm), and λ_{RE} is the red edge wavelength being adjusted to (in this case 2.5 μm). BAR_{adj}

values are listed in Table II-7. Figure II-15 shows that ALC meteorites cluster near the olivine+orthopyroxene mixing line of Cloutis et al. (1986), while H chondrites plot above the mixing line. Band I center values for ALC meteorites are on average lower than for H chondrites (average Band I centers of 0.926 and 0.939 μm , respectively). However, there is considerable overlap of BAR values between the groups. It is apparent from Figure II-15 that Band I center versus BAR is not a useful discriminator between the ALC and H chondrites.

Relationships between spectral absorption band centers and pyroxene compositions Fs and Wo (mol% wollastonite; CaSiO_3) were first examined with natural pyroxenes by Adams (1974) and revisited by Cloutis and Gaffey (1991a). These relationships were then further studied using synthetic pyroxene samples by Klima et al. (2007; 2011). Equations derived from these spectral relationships have been applied to estimate the pyroxene compositions of olivine+pyroxene assemblages from S-complex asteroid spectra (Gaffey et al., 2002). However, these mineralogic equations have been shown to overestimate (by 8-20 mol%) measured Fs compositions when applied to the spectra of ordinary chondrite-like mineral assemblages (McCoy et al., 2007), therefore limiting the usefulness of these equations. More recently, absorption band centers have been used to estimate the pyroxene compositions of HED meteorites (Burbine et al., 2007a; 2009), and band centers have shown to be successful at separating the howardite, eucrite, and diogenites groups in plots of Band I center versus Band II center parameter space (Burbine et al., 2009; Moskovitz et al., 2010; Beck et al., 2011; McSween et al., 2013).

To investigate if absorption band centers are effective in discriminating between acapulcoite-lodranite and H chondrites meteorites, we plotted Band I center versus Band II center for our acapulcoite-lodranite meteorites against the band centers of the same H chondrites (Dunn et al., 2010a) shown in Figure II-16. The ALC and the H chondrite group plot in distinct fields in this parameter space, which enable the discrimination of potential asteroidal parent bodies between these groups from band parameter analysis of S-complex asteroid spectra. Comparison of S-complex asteroid spectral parameters to these fields allow for the appropriate choice of equations for the estimation of olivine and orthopyroxene FeO content. For example, if the meteorite analog spectral zone of an S-complex asteroid spectrum is ambiguous between the ALC and the H chondrites in Band I center versus BAR parameter space (Figure II-15), an examination of Band I versus Band II center parameter space should reveal the distinction. If band centers plot in the field defined by our acapulcoite-lodranite meteorites in Figure II-16, then Fs can be calculated from Band II center using Equation 2, and then the relationship between Fa and Fs defined in Equation 1 can be used to estimate Fa. If band centers plot in the region defined by H chondrite meteorites in Figure II-16, then Fa and Fs can be calculated from the Band I center using equations valid for ordinary chondrites described in Dunn et al. (2010a). The mineralogical distinction between ALC meteorites and H chondrites can be revealed through spectral parameters, which enable the characterization of partially-melted parent bodies from nebular, unmelted ordinary chondrite parent bodies.

5.3 Spectral Trends for Meteorite Partial Melting Residues versus Complementary Liquids

The spectral and mineralogical parameters of acapulcoite-lodranite meteorites presented here will enable the identification of potential partially melted asteroid parent bodies that are related to the ALC. Yet, there are several other primitive achondrite meteorite groups that are residues of partial melting processes. These include the brachinites, ureilites, and the winonaites.

Excluding the brachinite group, whose olivine-dominated mineralogy would possess spectral parameters that would plot in the olivine meteorite spectral zone (see Figure II-10), residues of partial melting possess moderate to low BAR values (<1.5) and Band I centers that are slightly lower than ordinary chondrites (e.g., new generalized acapulcoite-lodranite spectral zone in Figure II-15), or overlap with that of the ordinary chondrites (e.g., ureilite spectral zone in Figure II-10). The ureilites are thought to be residues from the partial melting/smelting of carbonaceous chondrite-like precursor material (Warren and Kallemeyn, 1992; Singletary and Grove, 2006). Ureilites have experienced at least 15% partial melting (Warren and Kallemeyn, 1992; Krot et al., 2007), generally higher than that of ALC meteorites. Ureilites have low BAR values (<0.6) and Band I centers that overlap with that of ordinary chondrites. Cloutis et al. (2010) analyzed the VIS+NIR spectral properties of 18 ureilites and found that the majority of samples plot to the left the OC boot in Band I center versus BAR parameter space (see Figure II-10). However, many of the ureilite specimens from that study are weathered finds, and increasing weathering products drives the spectral parameters in the direction of the generalized ureilite spectral zone. Regardless, BAR values can vary widely in primitive achondrite meteorites due to several complex processes that can be hard to constrain. These processes include: terrestrial weathering, shock darkening (see § 4.3), and for ureilite meteorites the presence of opaque phases (e.g., graphite) (Cloutis et al., 2010).

The winonaites are a small group (~30 meteorites¹) of primitive achondrites that exhibit chondritic mineralogies and bulk compositions. They have oxygen isotopic compositions similar to IAB iron meteorites and are petrographically similar to angular silicate inclusions within these meteorites, suggesting the formation of both groups on a common parent body (Benedix et al., 1998). VIS+NIR reflectance spectra of winonaites are lacking. However, to investigate the spectral properties of winonaites in relation to other primitive achondrites, we acquired the reflectance spectra of two winonaites, NWA 1463 (Benedix et al., 2003) and NWA 4024. The VIS+NIR spectra of NWA 1463 was obtained from the RELAB database and NWA 4024 was obtained commercially by our group and prepared for reflectance spectroscopy at RELAB using the same techniques as the ALC meteorites presented herein. Winonaite spectral band parameters are listed in Table II-9. Figure II-17 shows the Gaffey et al. (1993) S-complex asteroid subtypes in relation to the 10 ALC meteorites of our sample suite and the two winonaites. These authors categorized the spectral parameters of S-complex asteroids into 7 mineralogical subtypes [plus the basaltic achondrite (BA) region] in Band I versus BAR parameter space and proposed possible meteorites analogs for each subtype. They predict that the winonaites (and IAB irons) could be related to the S(IV) (i.e., OC boot), S(VI), or S(VII) S-subtypes, and that the lodranites are possible meteorite analogs for the S(IV to VII) subtype. The two winonaites have low Band I centers and BARs consistent with our acapulcoite-lodranites and the ureilites of Cloutis et al. (2010). The spectral analyses of our EATG “cleaned” ALC meteorites have constrained the Band I versus BAR parameter space for these partial-melt residues. From our data it is clear that the majority of the ALC meteorites cluster in a restricted range of BAR (~0.6 to 1.05) (Table II-7; Figures II-15 and II-17) and Band I centers between 0.91 and 0.94 μm (Table II-7; Figure II-16). The winonaites have similar Band I centers (0.92 μm) to the ALC meteorites and even lower BARs (<0.4). It is apparent from our data and the ureilite spectra of Cloutis et al. (2010) that primitive achondrite meteorite groups are not associated with the S(VI) and S(VII) asteroid S-subtypes. Then this begs the question – if not primitive achondrites, what meteorite analogs are associated with S(VI) and S(VII) S-subtypes?

The S(VI) subtype should be composed of a pyroxene-bearing mixture of ol±opx and the S(VII) subtype should be dominated by orthopyroxene. Both of these spectral regions straddle the ol+opx mixing line of Cloutis et al. (1986). Are there meteorites that represent these S(VI) and S(VII) subtypes? The S(VII) meteorite analog spectral zone plots below the basaltic achondrite (BA) spectral region in Band I center versus BAR parameter space (Figure II-17), and Gaffey et al. (1993) suggests mesosiderites as a meteorite analog for the S(VII) objects.

Mesosiderites are stony-iron meteorites, and are thought to be a mixture of material from the pyroxene-rich crust and the metallic core of a differentiated parent body. They are composed of sub-equal proportions of silicates and FeNi metal, with the silicate fraction typically composed of magnesian-rich orthopyroxene and Ca-rich plagioclase (Burbine et al., 2007b). These silicates closely resemble basaltic clasts and appear similar to the basaltic achondrites of the HEDs, which consist of a suite of basaltic and gabbroic rocks generally accepted to originate from 4 Vesta (McCord et al., 1970; McSween et al., 2013; Russell et al., 2015). In contrast to the HEDs, mesosiderite silicates also include a significant component (typically <10 vol%) of olivine as individual mineral fragments and dunitic clasts (Wadhwa et al., 2003; Burbine et al., 2007b).

To test whether mesosiderites are suitable meteorite analog of the S(VI) and/or the S(VII) subtype regions, we measured the band parameters of three mesosiderites obtained from the RELAB database first described in Burbine et al. (2007b). The band parameters are listed in Table II-9 and we show them in relation to the ALC and winonaite group meteorites in Figure II-17. All three mesosiderites have measured Band I centers of 0.930 μm , and Estherville and Lamont have high BAR values consistent with pyroxene-dominated lithologies. Estherville's spectral parameters plot in the basaltic achondrite spectral zone slightly above the S(VII) spectral region, and Lamont's possess such a distinctive Band II absorption feature that it has an extremely high BAR of 3.03. Vaca Muerta has subdued absorption features compared to the other mesosiderites, and has a lower BAR value, and plots in the S(VI) spectral region. Based on the evidence from the ALC, winonaite, and mesosiderite spectra shown in Figure II-17, we find that primitive achondrites are not associated with the pyroxene-rich S(VI) and S(VII) spectral regions.

Including the ALC meteorites and the winonaite measured here, in addition to the ureilite data of Cloutis et al. (2010), the spectral properties of residues of partial melting are better understood. Armed with this understanding, interesting questions arise. What becomes of the complementary silicate liquids that are generated during partial melting? What spectral properties do these segregated basaltic liquids possess? Are meteorite analogs that are related to these basaltic liquids found among the world's meteorite collections? The temperatures experienced by the acapulcoite group are too low to have segregated silicate liquids, however, the lodranite group temperatures hot enough for the removal of basaltic partial melts. Besides the basaltic achondrites represented by the HED meteorites, basaltic meteorites from asteroid parent bodies are rare. One other magmatic achondrite of basaltic nature is the angrite group (Krot et al., 2007).

The uncommon nature of asteroidal basaltic material is what makes the "gabbroic-like" lithology of the transitional acapulcoite-lodranite LEW 86220 so unique. This lithology is composed mainly of granular, coarse-grained clinopyroxene and plagioclase, consistent with a segregated basaltic melt (Figure II-5b). The gabbroic-like lithology of LEW 86220 lithology is thought to represent a basaltic partial melt from a residual lodranite, which then intruded an acapulcoite-like region of the ALPB (McCoy et al., 1997b). Silicate trace element distributions

measured in the gabbroic-like lithology (Floss, 2000b) of LEW 86220 are consistent with this suggestion. However, other examples of basaltic liquids complementary to primitive achondrites are unknown among the world's meteorite collections. To investigate the spectral properties of these unaccounted for basaltic liquids, we measured the spectral band parameters of two clinopyroxene (Cpx) samples obtained from the RELAB database that have similar Cpx compositions as that found within the “gabbroic-like” lithology of LEW 86220.

Cloutis and Gaffey (1991b) found that the absorption band due to plagioclase near 1.2 μm is only clearly resolvable when plagioclase abundance is >75%, and that the wavelength position of the band center is unaffected. Accurate modal abundances are not available for the gabbroic-like lithology of LEW 86220 due to the small area of the specimen; however, the plagioclase abundance is estimated at ~60 vol% (Figure II-5b). Therefore, spectral parameters measured from the two Cpx equivalents should approximate the that of the gabbroic-like lithology. The composition of Cpx from the gabbroic-like lithology of LEW 86220 is $[\text{Wo}_{44.2} \text{En}_{51.8} \text{Fs}_{4.0}]$ (Table II-4). We measured the spectral band parameters of a natural clinopyroxene, PYX018 $[\text{Wo}_{48} \text{En}_{48} \text{Fs}_4]$ from (Cloutis and Gaffey, 1991a), and a synthetic clinopyroxene, CPX077 $[\text{Wo}_{45} \text{En}_{52} \text{Fs}_3]$ from (Klima et al., 2011). The band parameters (Band I center and BAR) of PYX018 is associated with the S(II) region of Gaffey et al. (1993), consistent with their suggestion of Cpx-rich meteorite assemblages (Figure II-17). These authors propose Cpx-bearing ureilites or Cpx-bearing brachinites as possible meteorite analogs for the S(II) subtype. CPX077 has a lower Band I center and BAR than PYX018 and plots above the S(IV) OC boot region. These results indicate that clinopyroxene samples of similar composition to the gabbroic-like lithology of LEW 86220 have spectral parameters that are very different from that of known basaltic achondrites of the HED group. Perhaps Cpx-rich gabbroic parent bodies that represent the segregated liquids from primitive achondrite-like parent bodies are found among S(II) subtype asteroids. Investigation of the spectral parameters of particulate samples of natural gabbroic assemblages would add useful data to help identify potential asteroid parent bodies related to these cryptic segregated basaltic liquids.

6. Summary

Spectral and mineralogical studies of meteorites afford the best possibility of linking meteorite groups with their parent asteroid(s) using solely ground-based asteroid spectral observations. Using spectral properties, relationships between the mineralogy of stony meteorites and S-complex asteroid surface mineralogy have been well established for nebular ordinary chondrites and for igneous basaltic achondrites. Here, we have analyzed the spectral parameters and mafic silicate compositions of a suite of acapulcoite-lodranite clan meteorites to establish asteroid-meteorite connections between these partial melt residues and their S-complex parent asteroids. Previously, the identification of potential S-complex parent asteroids for the acapulcoite-lodranite clan was difficult in part due to the lack of high-quality reflectance spectra of these relatively rare and usually weathered meteorites. To address this need, we applied a method for the neutralization and removal of terrestrial weathering products. We show that the presence of terrestrial weathering products in meteorite powders mainly reduces measured BAR values and that the band center positions of olivine and orthopyroxene are unaffected by the application of the EATG weathering removal method.

FeO mineral compositions of orthopyroxene (Fs) and co-existing olivine (Fa) are well correlated in acapulcoite-lodranites and form a linear trend in Fa versus Fs parameter space that spans the two meteorite groups of the clan. Lodranites are generally more iron-rich than acapulcoites and the two groups cluster in separate Fs versus Fa fields, requiring that the chondritic source materials of the two groups were different if they come from the same parent asteroid. Correlations between mineral chemistry and spectral parameters in our suite of 10 acapulcoite-lodranite clan meteorites indicate that a well-defined relationship exists between Band II center and Fs content of orthopyroxene, thus the derived Fs content can be used to estimate the Fa content of the co-existing olivine. These correlations can be used to calculate mineral compositions from the spectra of S-complex parent bodies that are related to acapulcoite-lodranite meteorites. The spectral properties of acapulcoite-lodranite clan meteorites cluster in Band I center versus BAR parameter space near the previously defined primitive achondrite spectral zone. However, acapulcoite-lodranite spectral parameters overlap with those of H chondrites in this parameter space, blurring the ability to distinguish between nebular ordinary chondrite parent bodies and parent bodies that may have experienced partial melting. Nevertheless, we find that a plot of Band I versus Band II center parameter space reveals a clear distinction between the acapulcoite-lodranite clan and the H chondrites. Our spectral and mineralogic study of acapulcoite-lodranite clan meteorites has established relationships between the mineralogy of these meteorites and the surface mineralogy of their asteroid parent bodies. These data will enable more robust asteroid-meteorite connections for the identification of partially-differentiated S-complex parent bodies.

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Appendix II

Table II-1. The sample suite of acapulcoite-lodranite meteorites analyzed in this study.

Meteorite Name^a	Meteorite Group	Weather Grade^b	Original Mass (g)	Bulk Sample Mass	Sample Type^c	RELAB ID	Sample Source^d
Acapulcoite							
MET 01212,14	Acapulcoite	B/C	31.37	0.522	PM,CP	MT-JPE-301-A	MWG
Dhofar 125	Acapulcoite	W1/2	2697	0.916	UPS	MT-JPE-304-A	TMM
NWA 725	Acapulcoite	-	3820	2.435	UPS	MT-JPE-305-A	TMM
NWA 2871	Acapulcoite	W3	3467	1.498	UPS	MT-JPE-306-A	TMM
Lodranite							
LAR 06605,8	Lodranite	B	34.61	0.488	PM,CP	MT-JPE-300-A	MWG
MAC 88177,53	Lodranite	B/C	35.27	0.393	PM,CP	MT-JPE-302-A	MWG
NWA 5488	Lodranite	-	110	1.588	UPS	MT-JPE-308-A	MFM
NWA 7312	Lodranite	low	778	2.145	UPS	MT-JPE-309-A	MFM
NWA 7674	Lodranite	low	225	2.266	UPS	MT-JPE-310-A	MFM
Transitional							
LEW 86220	Acap/Lod	-	25.04	0.436	PM,CP	MT-JPE-314-A	MWG

^a MET=Meteorite Hills; NWA=Northwest Africa; LAR=Larkman Nunatak; MAC=MacAlpine Hills; MIL=Miller Range; LEW=Lewis Cliff

^b Letter (A-D) weathering grade for Antarctic hand specimens; numerical (W) weathering grade for polished sections from Meteoritical Bulletin

^c UPS=unpolished slice; PM=polished thin section; CP=chip

^d MWG=Meteorite Working Group; TMM=The Meteorite Market; MFM=Michael Farmer Meteorites

Table II-2. Average major element compositions (wt% oxides above; atoms per formula unit below) for representative olivine grains (basis of 4 oxygens).

Sample Name	MET 01212	Dhofar 125	NWA 725	NWA 2871	LEW 86220	LAR 06605	MAC 88177	NWA 5488	NWA 7312	NWA 7674
# Grains	<i>n</i> =10	<i>n</i> =10	<i>n</i> =10	<i>n</i> =10	<i>n</i> =1 [3] ^c	<i>n</i> =12	<i>n</i> =11	<i>n</i> =10 [3] ^c	<i>n</i> =11	<i>n</i> =11
SiO₂	40.8 (2) ^a	40.4 (2)	40.7 (3)	40.4 (3)	40.9 (2)	40.2 (2)	39.6 (3)	39.9 (3)	41.7 (1)	40.5 (2)
TiO₂	n.d. ^b	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Al₂O₃	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.04 (1)	n.d.
Cr₂O₃	0.03 (1)	0.08 (3)	0.04 (6)	n.d.	n.d.	n.d.	n.d.	0.06 (1)	0.25 (1)	n.d.
FeO	8.63 (8)	8.50 (17)	6.23 (17)	8.57 (8)	7.42 (4)	11.6 (3)	13.5 (2)	10.4 (1)	3.36 (23)	10.3 (2)
MnO	0.47 (2)	0.49 (2)	0.48 (1)	0.50 (2)	0.48 (3)	0.49 (1)	0.48 (1)	0.44 (1)	0.22 (1)	0.52 (2)
MgO	50.3 (2)	50.4 (3)	51.9 (4)	50.4 (2)	51.2 (1)	47.8 (4)	46.3 (4)	48.4 (3)	54.0 (2)	49.1 (3)
CaO	n.d.	0.06 (1)	n.d.	n.d.	n.d.	n.d.	n.d.	0.04 (1)	0.14 (1)	n.d.
P₂O₅	n.d.	n.d.	n.d.	n.d.	0.05 (1)	n.d.	n.d.	n.d.	n.d.	n.d.
Σ	100.3 (2)	99.9 (5)	99.4 (4)	100.0 (4)	100.2 (2)	100.1 (4)	99.9 (5)	99.3 (6)	99.8 (3)	100.5 (3)
<i>Molar Fe/Mn; Fo = 100 x Mg/(Mg+Fe); Fa = 100 x Fe/(Mg+Fe)</i>										
Fe/Mn	18.3	17.4	12.9	17.0	15.0	23.8	27.9	23.8	15.7	19.4
Fo	91.2	91.3	93.7	91.3	92.5	88.0	86.0	89.2	96.6	89.5
Fa	8.8	8.7	6.3	8.7	7.5	12.0	14.0	10.8	3.4	10.5
<i>Atoms per formula unit</i>										
Si	0.993	0.988	0.990	0.987	0.992	0.993	0.990	0.990	0.996	0.992
Ti	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Al	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.001	n.d.
Cr	0.001	0.002	0.001	n.d.	n.d.	n.d.	n.d.	0.001	0.005	n.d.
Fe	0.176	0.174	0.127	0.175	0.150	0.240	0.282	0.217	0.067	0.211
Mn	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.009	0.004	0.011
Mg	1.825	1.836	1.882	1.838	1.851	1.761	1.725	1.791	1.924	1.791
Ca	n.d.	0.002	n.d.	n.d.	n.d.	n.d.	n.d.	0.001	0.004	n.d.
P	n.d.	n.d.	n.d.	n.d.	0.001	n.d.	n.d.	n.d.	n.d.	n.d.
Σ	3.005	3.012	3.010	3.010	3.004	3.004	3.007	3.009	3.001	3.005

^a Units in () represent one standard deviation of replicate analyses in terms of least units cited^b n.d. = not detected; <0.03 wt% for SiO₂, MgO, TiO₂, Al₂O₃, CaO, and Na₂O; <0.04 wt% for K₂O and Cr₂O₃; <0.05 wt% for FeO, MnO, and P₂O₅^c numbers within [] represent number of spots analyzed per grain

Table II-3. Average major element compositions (wt% oxides above; atoms/formula unit below) for low-Ca pyroxene grains (basis of 6 oxygens).

Sample	MET 01212	Dhofar 125	NWA 725	NWA 2871	LEW 86220 ^c	LAR 06605	MAC 88177	NWA 5488	NWA 7312	NWA 7674
# Grains	n=10	n=9	n=10	n=11	n=10	n=10	n=11	n=10 [3] ^d	n=8	n=10
SiO ₂	57.4 (2) ^a	57.4 (2)	57.1 (6)	56.8 (2)	57.7 (2)	56.7 (2)	56.4 (2)	57.4 (4)	57.9 (1)	56.5 (2)
TiO ₂	0.22 (2)	0.21 (1)	0.16 (2)	0.19 (1)	0.23 (2)	0.19 (2)	0.14 (1)	0.07 (3)	0.15 (1)	0.13 (1)
Al ₂ O ₃	0.35 (2)	0.36 (2)	0.22 (4)	0.45 (1)	0.32 (2)	0.44 (3)	0.59 (5)	0.41 (15)	1.31 (2)	0.67 (2)
Cr ₂ O ₃	0.34 (3)	0.45 (2)	0.26 (4)	0.59 (5)	0.26 (3)	0.56 (7)	0.53 (4)	0.37 (19)	0.38 (1)	0.95 (2)
FeO	5.97 (7)	5.49 (11)	5.52 (33)	6.33 (5)	6.03 (15)	7.93 (7)	8.61 (19)	6.97 (23)	2.27 (6)	7.37 (7)
MnO	0.54 (1)	0.55 (2)	0.55 (1)	0.56 (1)	0.50 (1)	0.54 (1)	0.51 (1)	0.47 (1)	0.22 (2)	0.54 (1)
MgO	34.4 (2)	34.8 (2)	35.0 (4)	33.5 (2)	35.0 (3)	32.2 (3)	31.7 (3)	34.0 (4)	36.6 (1)	32.1 (1)
CaO	1.07 (13)	1.08 (13)	0.82 (8)	1.68 (10)	0.79 (12)	1.77 (24)	1.73 (24)	0.95 (31)	0.98 (2)	2.13 (2)
Na ₂ O	n.d. ^b	0.04 (1)	n.d.	0.05 (1)	n.d.	0.06 (2)	0.05 (1)	n.d.	n.d.	0.08 (1)
K ₂ O	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Σ	100.3 (2)	100.3 (3)	99.6 (6)	100.1 (3)	100.9 (3)	100.3 (3)	100.2 (3)	100.6 (5)	99.8 (2)	100.4 (2)
<i>Molar Fe/Mn; pyroxene mineral end members</i>										
Fe/Mn	10.7	9.8	9.9	11.1	11.6	14.6	16.7	14.5	10.6	13.4
Wo	2.0	2.0	1.5	3.2	1.5	3.3	3.3	1.8	1.8	4.0
En	89.3	90.0	90.5	87.6	89.9	84.9	83.9	88.1	94.9	85.0
Fs	8.7	8.0	8.0	9.3	8.7	11.7	12.8	10.1	3.3	11.0
<i>Atoms per formula unit</i>										
Si	1.979	1.974	1.977	1.970	1.976	1.976	1.972	1.980	1.968	1.967
Ti	0.006	0.005	0.004	0.005	0.006	0.005	0.004	0.002	0.004	0.004
Al	0.014	0.015	0.009	0.018	0.013	0.018	0.024	0.017	0.052	0.027
Cr	0.010	0.012	0.007	0.016	0.007	0.015	0.015	0.010	0.010	0.026
Fe	0.172	0.158	0.160	0.184	0.173	0.231	0.252	0.201	0.065	0.215
Mn	0.016	0.016	0.016	0.017	0.015	0.016	0.015	0.014	0.006	0.016
Mg	1.768	1.785	1.806	1.733	1.788	1.672	1.655	1.746	1.856	1.666
Ca	0.040	0.040	0.030	0.062	0.029	0.066	0.065	0.035	0.036	0.079
Na	n.d.	0.003	n.d.	0.003	n.d.	0.004	0.004	n.d.	n.d.	0.006
K	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Σ	4.005	4.008	4.009	4.008	4.007	4.003	4.006	4.005	3.997	4.006

^a Units in () represent one standard deviation of replicate analyses in terms of least units cited^b n.d. = not detected; <0.03 wt% for SiO₂, MgO, TiO₂, Al₂O₃, CaO, and Na₂O; <0.04 wt% for K₂O and Cr₂O₃; <0.05 wt% for FeO, MnO, and P₂O₅^c Acapulcoite-like lithology of LEW 86220^d numbers within [] represent number of spots analyzed per grain

Table II-4. Average major element compositions (wt% oxides above; atoms/formula unit below) for high-Ca pyroxene grains (basis of 6 oxygens).

Sample	MET 01212	Dhofar 125	NWA 725	NWA 2871	LEW 86220 ^c	LEW 86220 ^d	LAR 06605	MAC 88177	NWA 5488	NWA 7674
# Grains	<i>n</i> =10	<i>n</i> =10	<i>n</i> =10	<i>n</i> =10	<i>n</i> =9	<i>n</i> =2 [3] ^e	<i>n</i> =1	<i>n</i> =4	<i>n</i> =10 [3] ^e	<i>n</i> =6
SiO ₂	54.1 (2) ^a	54.0 (2)	53.8 (2)	54.0 (2)	54.1 (3)	54.2 (2)	54.0	53.5 (6)	54.1 (4)	53.7 (1)
TiO ₂	0.58 (4)	0.62 (5)	0.56 (3)	0.45 (2)	0.73 (20)	0.72 (6)	0.37	0.30 (2)	0.11 (3)	0.33 (2)
Al ₂ O ₃	0.87 (11)	0.89 (10)	0.67 (2)	1.00 (15)	0.76 (10)	0.68 (12)	1.12	1.33 (6)	0.79 (25)	1.34 (3)
Cr ₂ O ₃	1.44 (13)	1.51 (16)	1.24 (3)	1.56 (11)	1.28 (7)	1.27 (5)	1.73	1.40 (12)	1.10 (21)	1.51 (4)
FeO	2.33 (22)	2.24 (15)	2.13 (13)	2.67 (21)	2.46 (7)	2.49 (19)	3.11	3.99 (59)	2.67 (41)	3.56 (21)
MnO	0.30 (3)	0.32 (2)	0.27 (1)	0.32 (2)	0.29 (2)	0.32 (4)	0.30	0.33 (1)	0.26 (3)	0.35 (2)
MgO	18.2 (5)	18.4 (2)	17.9 (1)	18.6 (5)	18.1 (3)	18.2 (4)	17.3	17.8 (7)	18.1 (4)	18.9 (4)
CaO	21.3 (7)	21.0 (6)	22.0 (3)	20.5 (9)	21.6 (2)	21.6 (5)	21.1	20.4 (9)	22.3 (5)	19.6 (5)
Na ₂ O	0.74 (4)	0.77 (5)	0.68 (2)	0.72 (3)	0.72 (3)	0.74 (4)	0.86	0.63 (4)	0.47 (3)	0.52 (4)
K ₂ O	n.d. ^b	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Σ	99.8 (4)	99.7 (2)	99.2 (2)	99.7 (2)	100.1 (4)	100.1 (2)	99.9	99.6 (5)	99.9 (5)	99.8 (3)
<i>Molar Fe/Mn; pyroxene mineral end members</i>										
Fe/Mn	7.6	6.8	7.7	8.1	8.4	7.8	10.6	11.9	10.2	10.0
Wo	44.0	43.4	45.4	42.3	44.4	44.2	44.3	42.3	45.0	40.2
En	52.2	53.0	51.2	53.4	51.7	51.8	50.6	51.2	50.8	54.1
Fs	3.8	3.6	3.4	4.3	3.9	4.0	5.1	6.5	4.2	5.7
<i>Atoms per formula unit</i>										
Si	1.966	1.963	1.967	1.962	1.964	1.965	1.968	1.956	1.970	1.952
Ti	0.016	0.017	0.015	0.012	0.020	0.020	0.010	0.008	0.003	0.009
Al	0.037	0.038	0.029	0.043	0.032	0.029	0.048	0.057	0.034	0.057
Cr	0.041	0.043	0.036	0.045	0.037	0.037	0.050	0.041	0.032	0.043
Fe	0.071	0.068	0.065	0.081	0.075	0.076	0.095	0.122	0.081	0.108
Mn	0.009	0.010	0.008	0.010	0.009	0.010	0.009	0.010	0.008	0.011
Mg	0.984	0.996	0.976	1.006	0.979	0.983	0.940	0.970	0.980	1.026
Ca	0.829	0.816	0.864	0.797	0.841	0.838	0.824	0.801	0.869	0.763
Na	0.052	0.054	0.049	0.051	0.051	0.052	0.060	0.045	0.033	0.037
K	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Σ	4.005	4.005	4.009	4.007	4.008	4.010	4.004	4.010	4.010	4.006

^a Units in () represent one standard deviation of replicate analyses in terms of least units cited^b n.d. = not detected; <0.03 wt% for SiO₂, MgO, TiO₂, Al₂O₃, CaO, and Na₂O; <0.04 wt% for K₂O and Cr₂O₃; <0.05 wt% for FeO, MnO, and P₂O₅^c Acapulcoite-like lithology of LEW 86220; ^d Gabbroic-like lithology of LEW 86220^e numbers within [] represent number of spots analyzed per grain

Table II-5. Average major element compositions (wt% oxides above; atoms/formula unit below) for representative plagioclase grains (basis of 8 oxygens).

Sample	MET 01212	Dhofar 125	NWA 725	NWA 2871	LEW 86220 ^c	LEW 86220 ^d	LAR 06605	NWA 7674
# Grains	n=10	n=10	n=2 [3] ^e	n=10	n=10	n=2 [3] ^e	n=2	n=1
SiO ₂	63.8 (2) ^a	64.2 (4)	64.6 (6)	62.8 (6)	64.3 (4)	65.0 (11)	65.0 (5)	58.4
Al ₂ O ₃	21.6 (2)	22.2 (2)	21.4 (3)	22.9 (5)	21.4 (3)	20.9 (9)	21.7 (9)	25.1
FeO	0.14 (6)	0.41 (8)	0.62 (33)	0.22 (6)	0.26 (22)	0.16 (19)	0.38 (1)	0.39
MgO	n.d. ^b	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
CaO	3.55 (11)	3.29 (3)	2.69 (4)	4.17 (46)	3.06 (20)	2.7 (9)	2.90 (11)	7.77
Na ₂ O	9.18 (10)	9.47 (25)	9.37 (19)	8.92 (22)	9.52 (14)	9.7 (4)	8.5 (14)	7.21
K ₂ O	0.59 (4)	0.37 (5)	1.03 (19)	0.50 (7)	0.63 (8)	0.78 (26)	0.59 (4)	0.25
Σ	98.9 (2)	100.0 (4)	99.7 (5)	99.5 (3)	99.2 (3)	99.2 (6)	99.1 (1)	99.2
<i>Feldspar mineral end members</i>								
Or	3.4	2.1	5.9	2.8	3.6	4.4	3.7	1.4
Ab	79.6	82.1	81.2	77.2	81.9	83.0	81.0	61.8
An	17.0	15.8	12.9	20.0	14.5	12.6	15.3	36.8
<i>Atoms per formula unit</i>								
Si	2.851	2.837	2.867	2.796	2.864	2.891	2.883	2.640
Al	1.138	1.159	1.121	1.202	1.124	1.095	1.134	1.337
Fe	0.005	0.015	0.023	0.008	0.010	0.006	0.014	0.015
Mg	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Ca	0.170	0.156	0.128	0.199	0.146	0.128	0.138	0.376
Na	0.796	0.812	0.807	0.770	0.822	0.838	0.730	0.631
K	0.034	0.021	0.059	0.028	0.036	0.044	0.034	0.014
Σ	4.994	5.000	5.005	5.003	5.002	5.002	4.933	5.013

^a Units in () represent one standard deviation of replicate analyses in terms of least units cited

^b n.d. = not detected; <0.03 wt% for SiO₂, MgO, Al₂O₃, CaO, Na₂O; <0.04 wt% for K₂O₃; <0.05 wt% for FeO

^c Acapulcoite-like lithology of LEW 86220

^d Gabbroic-like lithology of LEW 86220

^e numbers within [] represent number of spots analyzed per grain

Table II-6. Band parameter analysis for acapulcoite-lodranite meteorite samples (ground particulate <125 μm fraction; untreated with EATG).

Meteorite	Group	RELAB ID	BIC	BIC error	BI area ($\times 10^{-2}$)	BI area error ($\times 10^{-2}$)	BIIC	BIIC error	BII area ($\times 10^{-2}$)	BII area error ($\times 10^{-2}$)	BAR	BAR error
MET 01212	Acapulcoite	MT-JPE-301-A	0.923	0.002	7.67	0.02	1.843	0.001	4.73	0.02	0.617	0.002
Dhofar 125	Acapulcoite	MT-JPE-304-A	0.920	0.001	3.88	0.02	1.840	0.002	2.14	0.02	0.552	0.005
NWA 725	Acapulcoite	MT-JPE-305-A	0.913	0.001	3.09	0.01	1.820	0.003	1.65	0.02	0.533	0.007
NWA 2871	Acapulcoite	MT-JPE-306-A	0.930	0.001	7.18	0.02	1.830	0.003	2.27	0.03	0.316	0.005
LAR 06605	Lodranite	MT-JPE-300-A	0.923	0.001	12.37	0.02	1.853	0.001	7.70	0.04	0.623	0.004
MAC 88177	Lodranite	MT-JPE-302-A	0.940	0.001	13.04	0.02	1.863	0.002	5.64	0.02	0.432	0.002
NWA 7674	Lodranite	MT-JPE-310-A	0.930	0.001	6.83	0.02	1.853	0.001	3.88	0.02	0.569	0.004
LEW 86220	Acap/Lod	MT-JPE-314-A	0.940	0.001	5.93	0.02	1.843	0.003	1.66	0.02	0.280	0.003

BIC = Band I center; BIIC = Band II center; BAR = Band Area Ratio

Table II-7. Band parameter analysis for acapulcoite-lodranite meteorite samples (ground particulate <125 μm fraction; EATG treated except for falls Acapulco and Lodran). BAR_0 is the band area ratio measured with a red edge of 2.44 μm , BAR_{adj} is the BAR adjusted to 2.50 μm .

Meteorite	Group	RELAB ID	BIC	BIC error	BI area ($\times 10^{-2}$)	BI area error ($\times 10^{-2}$)	BIIC	BIIC error	BII area ($\times 10^{-2}$)	BII area error ($\times 10^{-2}$)	BAR_0	BAR_0 error	BAR_{adj}
Acapulco (<i>fall</i>)	Acapulcoite	TB-TJM-043	0.923	0.003	13.25	0.04	1.863	0.002	11.32	0.05	0.854	0.005	0.930
MET 01212	Acapulcoite	MT-JPE-301-T	0.920	0.001	11.14	0.03	1.847	0.001	9.03	0.03	0.811	0.004	0.887
Dhofar 125	Acapulcoite	MT-JPE-304-T	0.923	0.004	5.54	0.02	1.850	0.004	3.82	0.03	0.690	0.005	0.766
NWA 725	Acapulcoite	MT-JPE-305-T	0.913	0.001	3.87	0.02	1.827	0.002	3.52	0.03	0.910	0.008	0.986
NWA 2871	Acapulcoite	MT-JPE-306-T	0.930	0.001	8.01	0.03	1.840	0.003	3.72	0.03	0.464	0.004	0.540
Lodran (<i>fall</i>)	Lodranite	TB-TJM-041	0.920	0.002	13.95	0.05	1.880	0.001	12.10	0.03	0.868	0.004	0.944
LAR 06605	Lodranite	MT-JPE-300-T	0.927	0.001	17.11	0.03	1.870	0.001	13.21	0.04	0.772	0.002	0.848
MAC 88177	Lodranite	MT-JPE-302-T	0.940	0.001	18.13	0.03	1.873	0.001	9.59	0.03	0.529	0.002	0.605
NWA 7674	Lodranite	MT-JPE-310-T	0.930	0.001	9.42	0.03	1.853	0.003	7.06	0.04	0.749	0.004	0.825
LEW 86220	Acap/Lod	MT-JPE-314-T	0.937	0.003	6.77	0.03	1.860	0.004	4.81	0.04	0.710	0.007	0.786

BIC = Band I center; BIIC = Band II center; BAR = Band Area Ratio

Table II-8. Band parameter analysis for three EATG leaching method mineral control samples (ground particulate <125 µm fraction; RELAB ID suffix “A” for untreated samples, “T” for EATG treated samples).

Control Sample	Description	RELAB ID	BIC	BIC error	BI area (x10 ⁻²)	BI area error (x10 ⁻²)	BIIC	BIIC error	BII area (x10 ⁻²)	BII area error (x10 ⁻²)	BAR	BAR error
San Carlos Olivine	untreated	OL-JPE-020-A	1.06	0.001	30.6	0.04	-	-	-	-	-	-
	EATG											
San Carlos Olivine	treated	OL-JPE-020-T	1.06	0.003	33.8	0.06	-	-	-	-	-	-
Tanzania Enstatite	untreated	PX-JPE-020-A	0.910	0.001	16.2	0.04	1.830	0.003	32.5	0.06	2.01	0.01
	EATG											
Tanzania Enstatite	treated	PX-JPE-020-T	0.910	0.001	18.5	0.04	1.820	0.002	38.4	0.06	2.08	0.01
Ol+En 50/50 mixture (wt%)	untreated	MX-JPE-019-A	0.910	0.001	17.9	0.04	1.840	0.001	14.8	0.05	0.825	0.003
	EATG											
Ol+En 50/50 mixture (wt%)	treated	MX-JPE-019-T	0.910	0.001	21.6	0.04	1.843	0.001	17.1	0.05	0.793	0.003

BIC = Band I center; BIIC = Band II center; BAR = Band Area Ratio

Table II-9. Band parameter analysis for S-complex meteorite analog comparisons. Clinopyroxene samples selected to approximate the pyroxene composition (Wo, En, and Fs) of Cpx from the “gabbroic-like” lithology of LEW 86220. Band parameters analyzed with a red edge of 2.50 µm.

Sample	Group	RELAB ID	BIC	BIC error	BI area (x10 ⁻²)	BI area error (x10 ⁻²)	BIIC	BIIC error	BII area (x10 ⁻²)	BII area error (x10 ⁻²)	BAR	BAR error
NWA 1463	Winonaite	MT-GKB-009	0.920	0.002	2.26	0.03	1.810	0.007	0.831	0.04	0.368	0.018
NWA 4024	Winonaite	MT-JPE-307-T	0.920	0.004	5.01	0.02	1.797	0.003	0.894	0.03	0.179	0.005
Estherville	Mesosiderite	TB-TJM-148	0.930	0.001	10.72	0.02	1.930	0.001	24.9	0.1	2.32	0.01
Vaca Muerta	Mesosiderite	TB-TJM-149	0.930	0.004	2.73	0.02	1.943	0.003	3.79	0.03	1.39	0.01
Lamont	Mesosiderite	TB-TJM-150	0.930	0.001	13.13	0.02	1.903	0.001	39.8	0.1	3.03	0.01
PYX018	Cpx (natural)	PP-EAC-069	1.045	0.001	12.58	0.02	2.292	0.001	5.23	0.02	0.416	0.002
CPX077	Cpx (synthetic)	DL-CMP-077-A	1.018	0.001	17.22	0.04	2.295	0.005	4.78	0.04	0.278	0.002

BIC = Band I center; BIIC = Band II center; BAR = Band Area Ratio

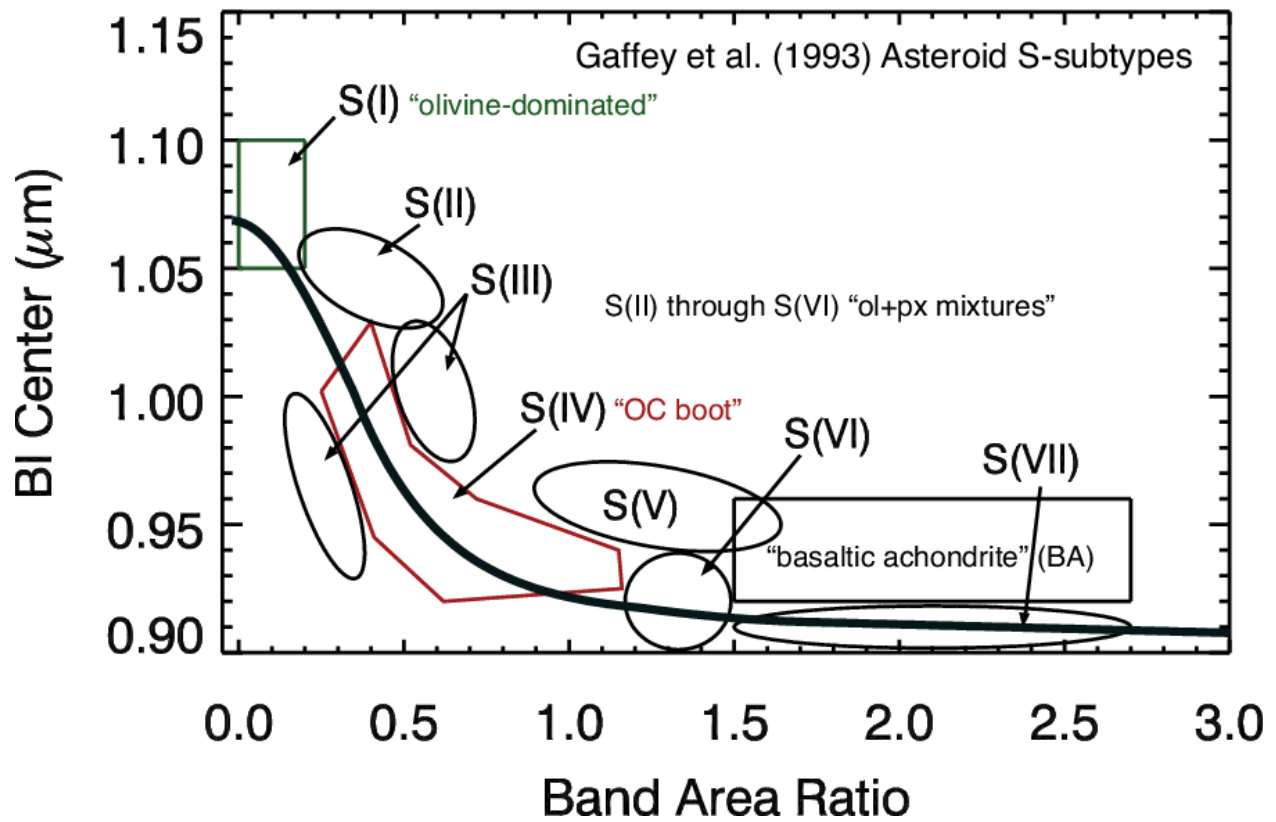


Figure II-1. Asteroid S-subtypes [S(I) through S(VII)] and the basaltic achondrite (BA) spectral regions of Gaffey et al. (1993) shown in Band I center ($\sim 1 \mu\text{m}$) versus band area ratio (BAR) parameter space, the thick black curve indicates the location of the olivine-orthopyroxene mixing line of Cloutis et al. (1986).

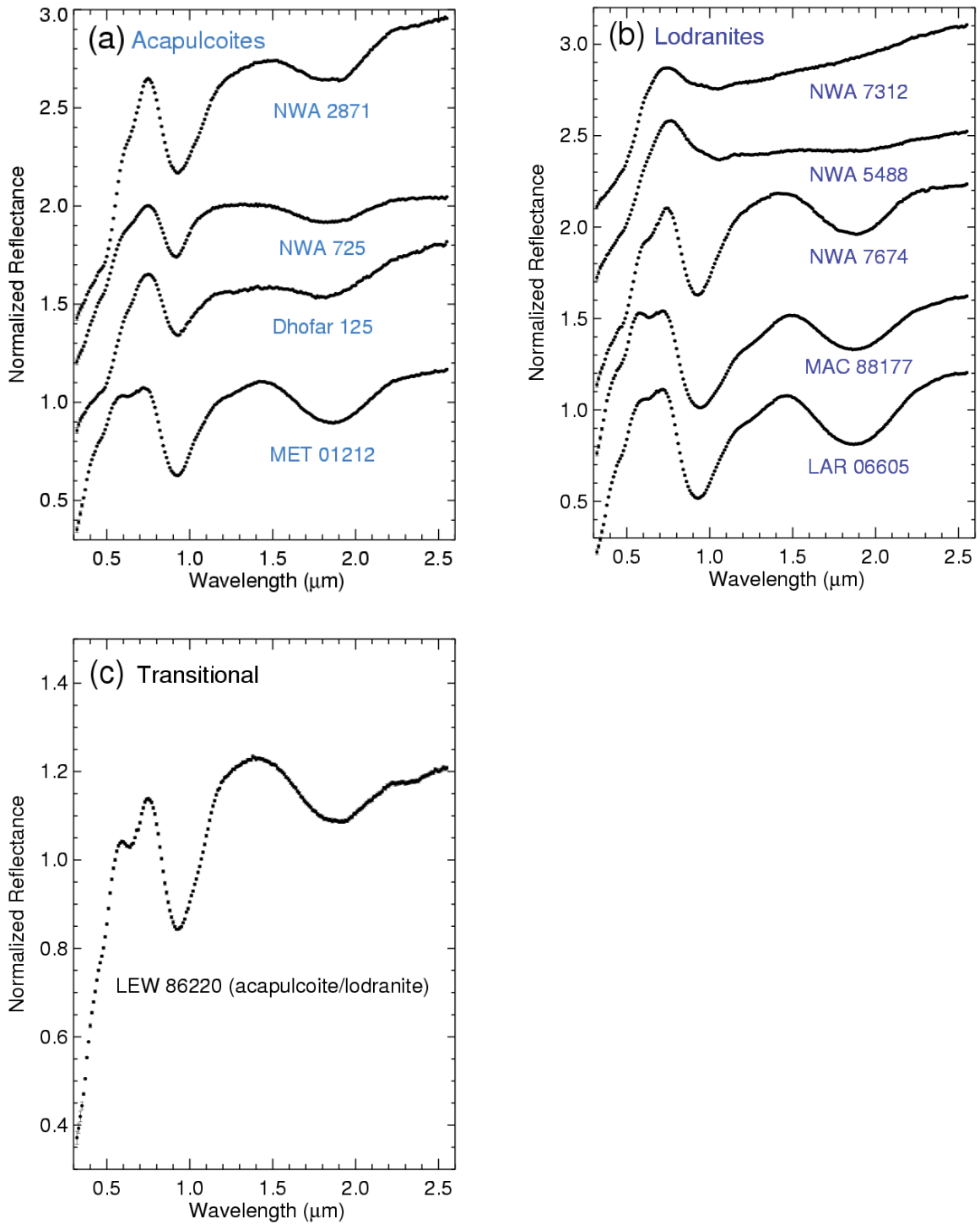


Figure II-2. Reflectance spectra (0.3-2.55 μm) of acapulcoite-lodranite meteorites used in this study after removal of terrestrial alteration via EATG method. **(a)** Acapulcoite spectra. **(b)** Lodranite spectra, the ~ 2 μm feature due to pyroxene is absent in samples NWA 5488 and NWA 7312, and therefore are not analyzed for spectral band parameters (§ 4.3). **(c)** Transitional meteorite LEW 86220 spectrum. All spectra are normalized to unity at 0.55 μm and are offset for clarity.

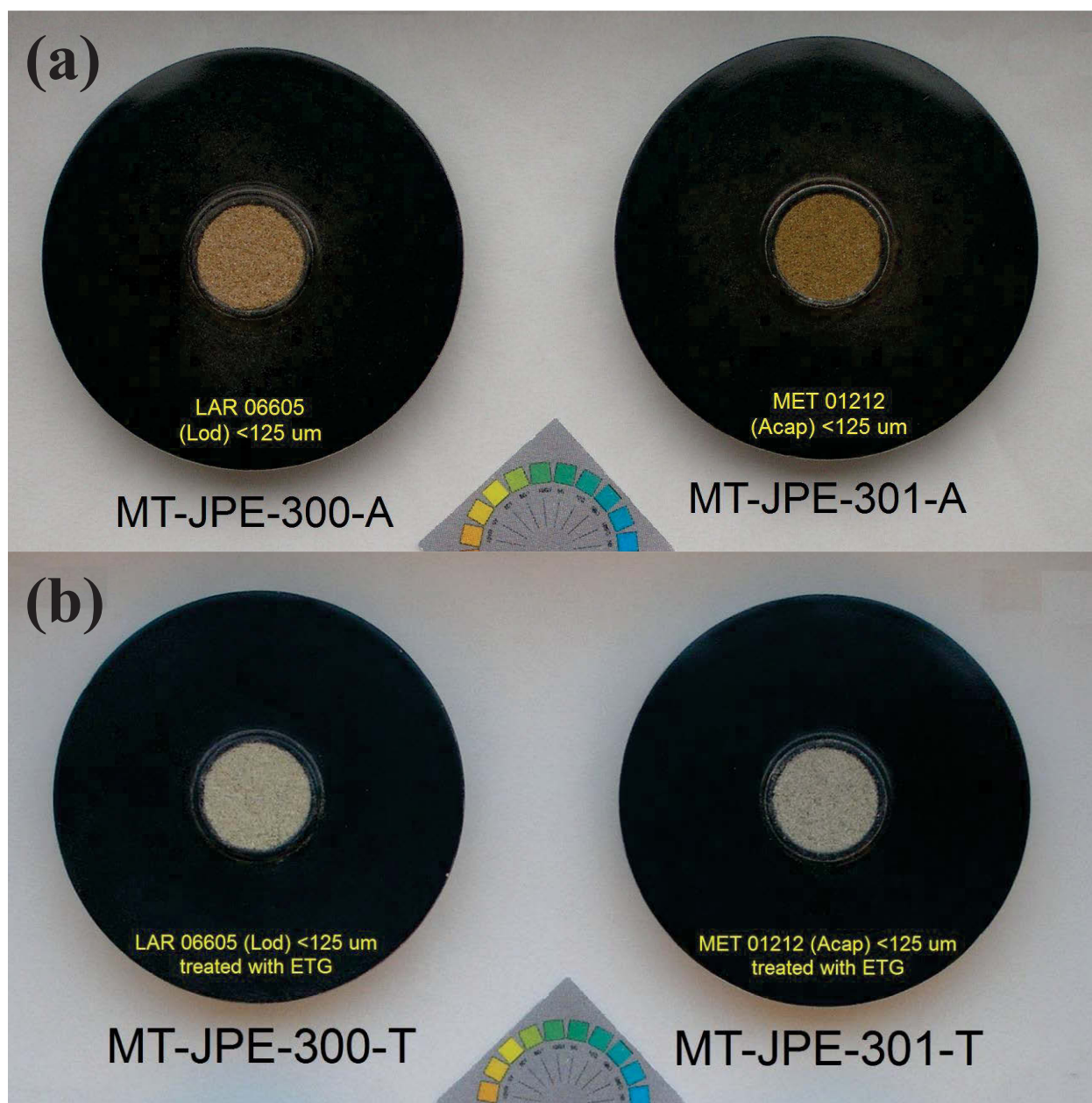


Figure II-3. Lodranite LAR 06605 (left) and acapulcoite MET 01212 (right) meteorite powders (<125 μm) shown within sample dishes before and after removal of terrestrial weathering products. RELAB IDs for each sample shown under sample dish. **(a)** Above - sample powders before treatment with EATG show significant iron hydroxide staining. **(b)** Below - the same sample powders after treatment with EATG to remove terrestrial alteration. Iron hydroxide staining is considerably reduced with EATG treatment.

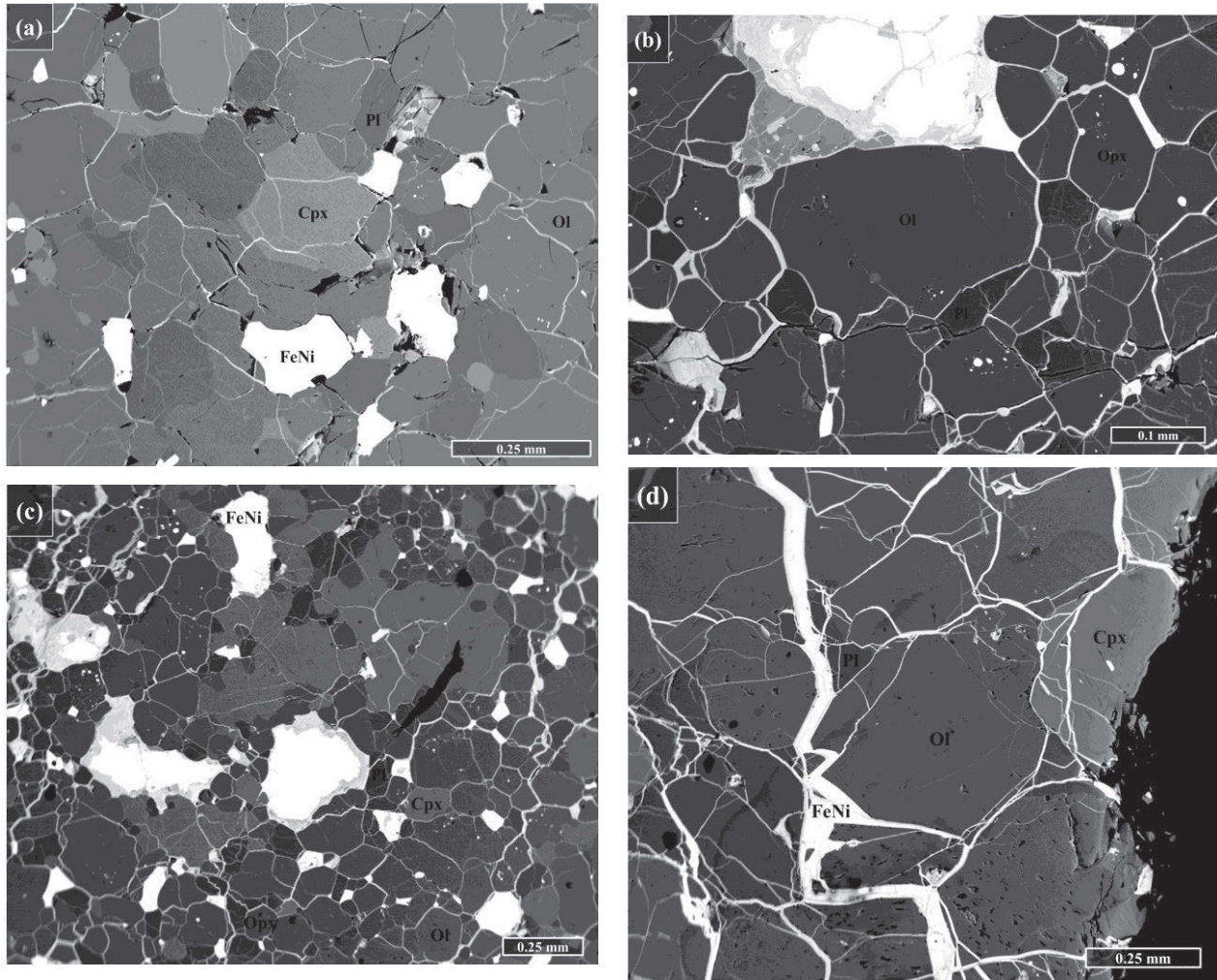


Figure II-4. Back-scattered electron (BSE) images of portions of acapulcoite polished sections: **(a)** MET 01212's granular, metal-rich texture displays well-defined metal blebs, metal within the grain interstices, and metallic veins that cross cut the silicates. **(b)** Dhofar 125's equigranular, recrystallized texture, and abundant 120° triple junctions are readily visible in this image. Most grain interstices are filled with FeNi metal. **(c)** NWA 725 is very fine-grained (~0.1 mm) for an acapulcoite. This rock has a granular texture with abundant 120° triple-junctions and metal blebs. **(d)** In NWA 2871 grain interstices are filled with metal, and metallic veins that cross-cut the silicates, FeNi metal appears to have undergone melt migration in grains interconnected with vein channels.

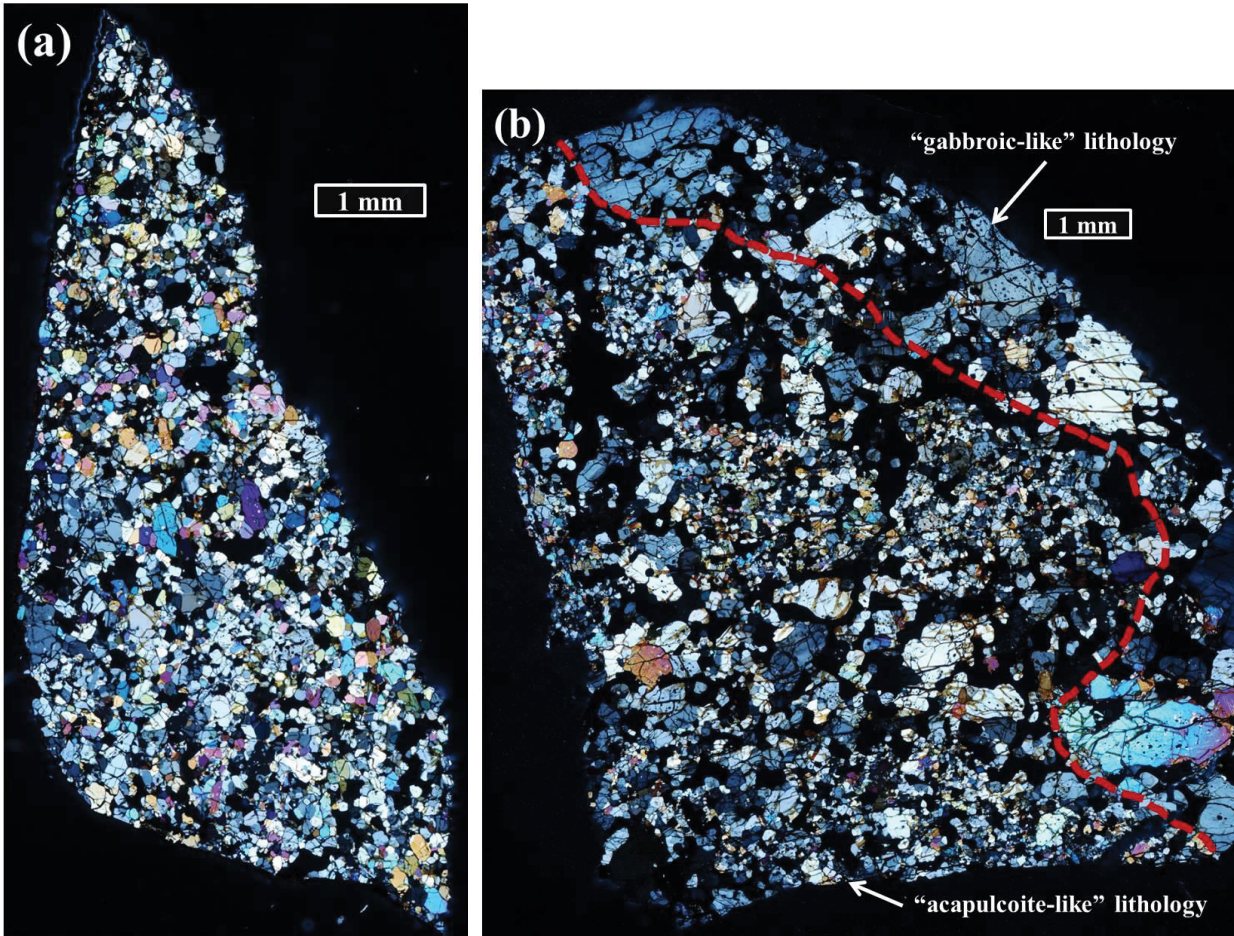


Figure II-5. (a) Crossed-polarized photomicrograph mosaic of acapulcoite MET 01212. The fine-grained recrystallized, equigranular texture and abundant 120° triple-junctions typical for acapulcoites are apparent in the thin section. Note the two different grain-sizes within this rock. **(b)** Crossed-polarized photomicrograph mosaic of transitional acapulcoite-lodranite LEW 86220. Two lithologic textures are present within this specimen, a fine-grained region (~ 0.15 mm) with an acapulcoite-like texture and mineralogy (left side of image), and a coarser-grained (0.5-2.0 mm) gabbroic-like region that is rich in plagioclase and clinopyroxene. The boundary between the two lithologies (red-dashed line) is not sharp and is difficult to demarcate.

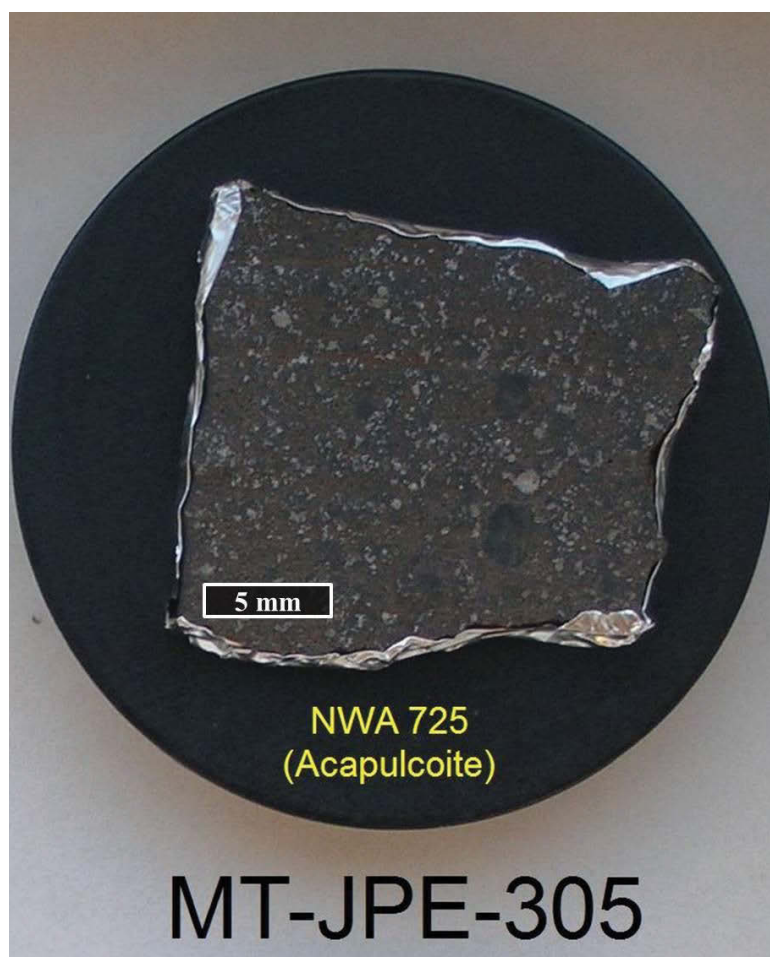


Figure II-6. Macroscopic photograph of unpolished slab specimen of NWA 725 showing several large (~2 mm) relict chondrules (dark gray roughly circular grains). Anhedral FeNi metal blebs are abundant throughout the section, with some as large as ~1 mm.

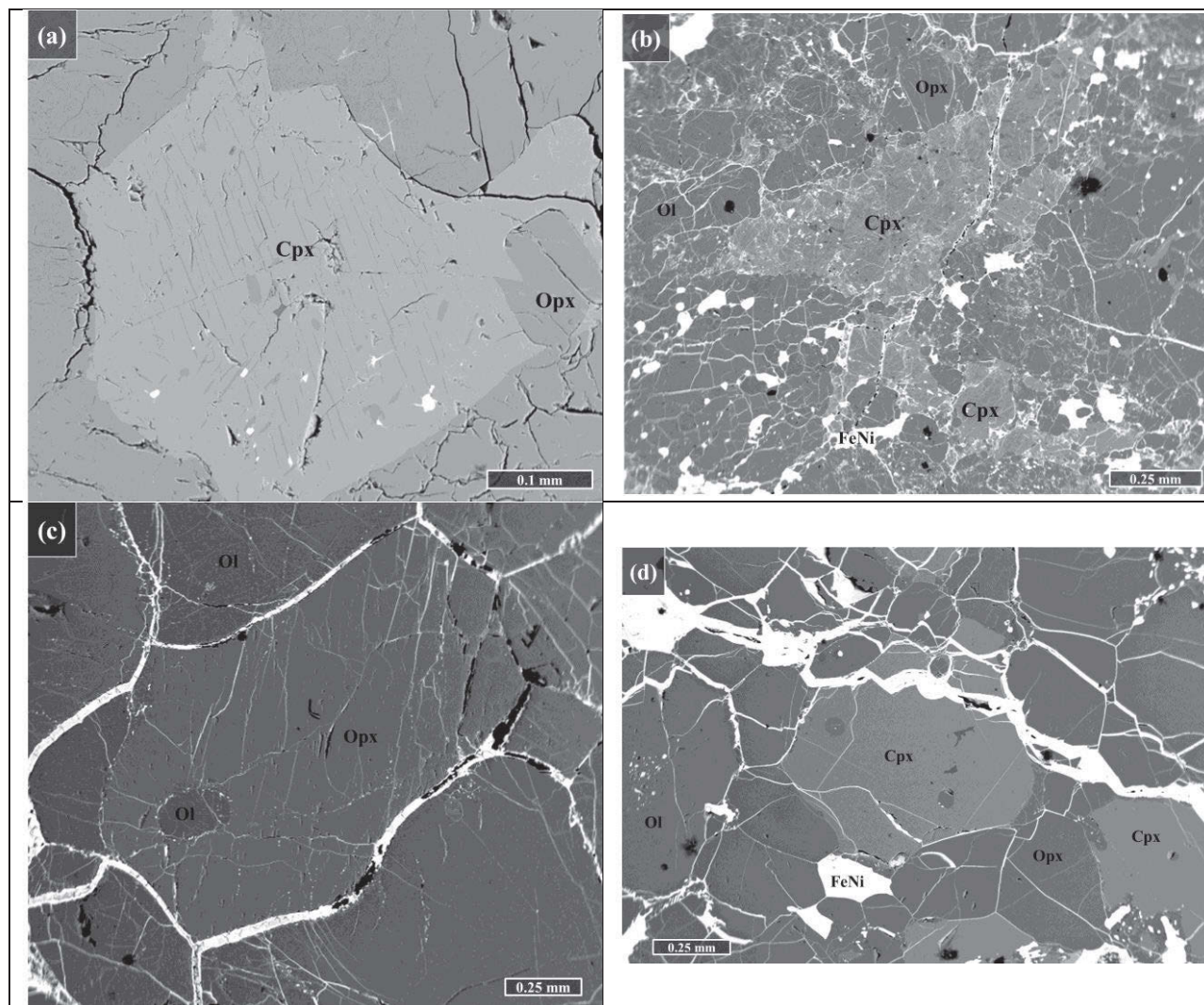


Figure II-7. Back-scattered electron (BSE) images of portions of lodranite polished sections: **(a)** MAC 88177 contains clinopyroxene as an interstitial phase that displays exsolution lamellae of orthopyroxene and inclusions of metal and troilite. **(b)** NWA 5488 has olivine grains that contain numerous blebs of FeNi metal and/or troilite and are typically cross cut by metallic veins. Clinopyroxene contains exsolution lamellae of orthopyroxene and discontinuous veinlets of metal and troilite **(c)** NWA 7312 has a crystalline texture with abundant 120° triple-junctions, coarse grain-size, olivine and orthopyroxene make up most of the mineralogy of this meteorite, plagioclase and clinopyroxene are absent, and some orthopyroxene grains contain bleb-like inclusions of olivine. **(d)** NWA 7674's olivine grains contain numerous blebs of FeNi metal and/or troilite and are typically cross cut by metallic veins, with metal ubiquitous in the grain interstices.

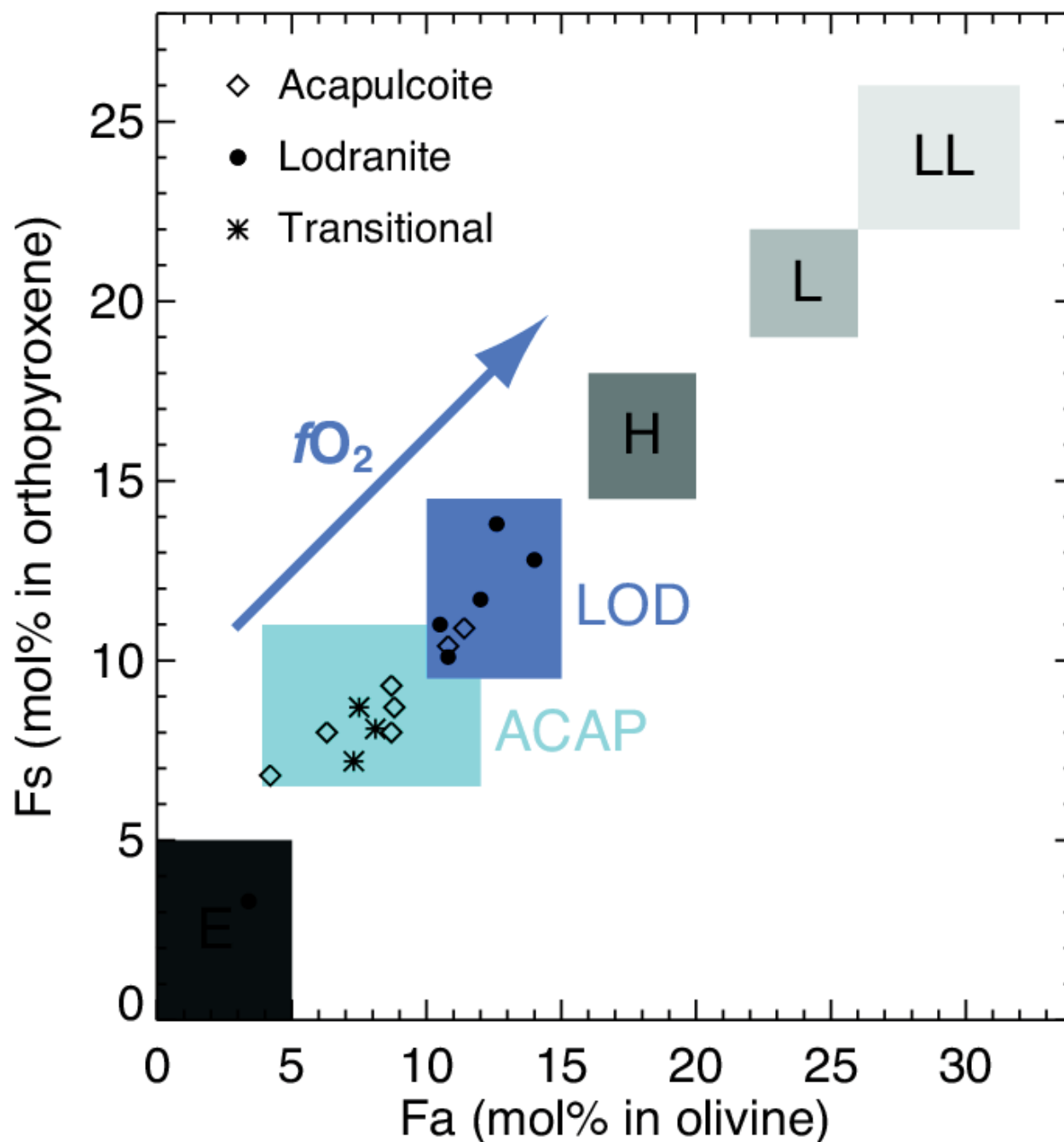


Figure II-8. Iron contents of orthopyroxenes (Fs) and olivines (Fa) for 16 ALC meteorites (ten of our sample suite plus six from the literature; see below) in relation to those of enstatite (E) chondrites and ordinary chondrites (H, L, and LL). Increasing oxygen fugacity (fO_2) trend shown with arrow. Lodranites are more iron-rich than acapulcoites and the two groups plot in separate fields with some overlap. The E chondrite field is from Hiroi et al. (1993) and the ordinary chondrite fields are from Dunn et al. (2010a). NWA 7312 is highly reduced compared to the other ALC meteorites and plots in the E chondrite field. Mineral compositions from: Acapulco (Zipel et al., 1995), Lodran (Bild and Wasson, 1976), ALH 81261 and ALH 81187 (McCoy et al., 1996), EET 84302 (Mittlefehldt et al., 1996), and GRA 95209 (McCoy et al., 2006).

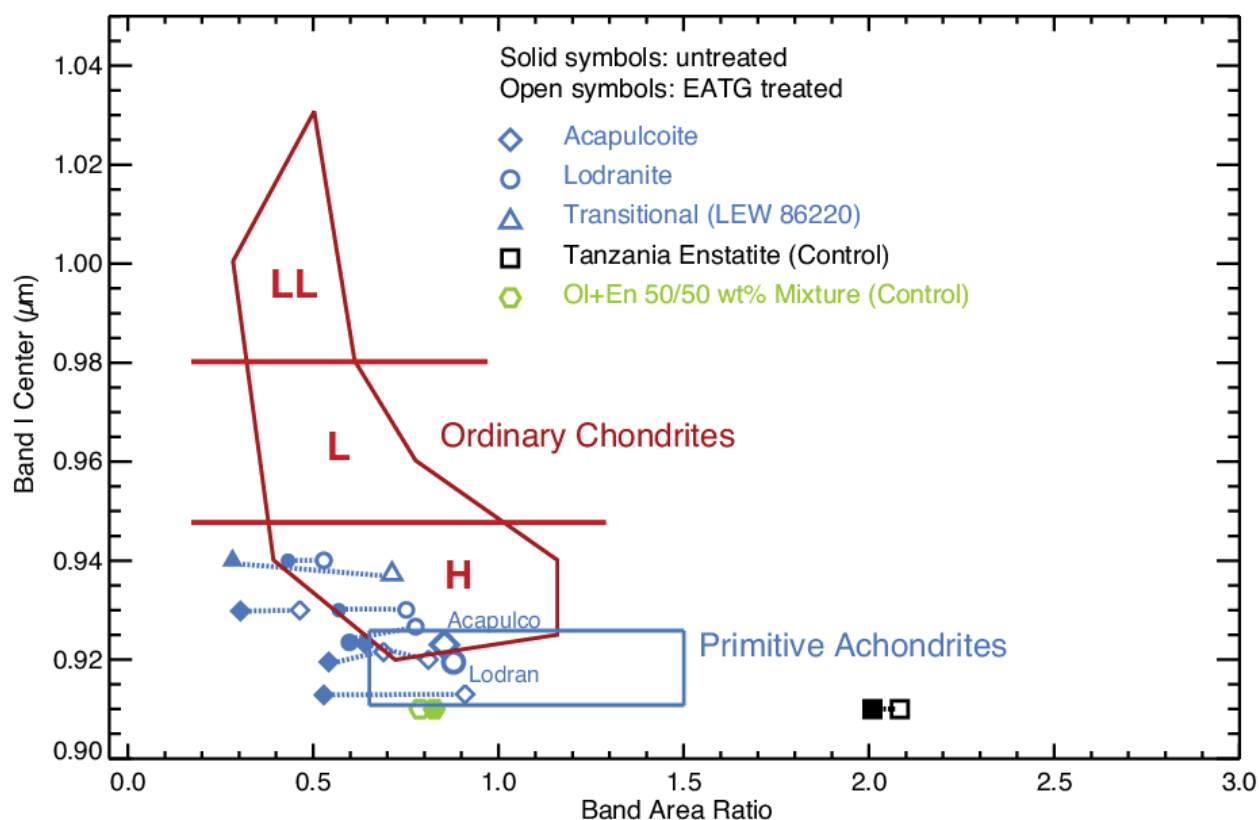


Figure II-9. Band I center versus BAR for ALC meteorites and mineral control samples. Acapulcoite (blue diamonds), lodranite (blue circles), transitional meteorite LEW 86220 (blue triangle), and Tanzania enstatite (black square), and San Carlos olivine and Tanzania enstatite 50/50 wt% mixture (green hexagon) band parameters plotted for meteorite spectra before weathering removal (solid symbols) and after weathering removal via EATG treatment (open symbols). Dashed tie lines connect the same specimen. Band I centers are identical or minimally shifted for weathered versus EATG “cleaned” spectra. Generalized spectral zones are delineated for ordinary chondrites (boundaries for H, L, and LL groups from Dunn et al., 2010a) and for primitive achondrites (Burbine et al., 2001; Dunn et al., 2013). Weathered samples have reduced BAR values compared to EATG treated samples. BARs shift toward higher values with removal of terrestrial alteration. The EATG treated samples cluster near the eponymous meteorite falls of the clan, Acapulco and Lodran (larger symbols). Errors are on the order of the symbol size.

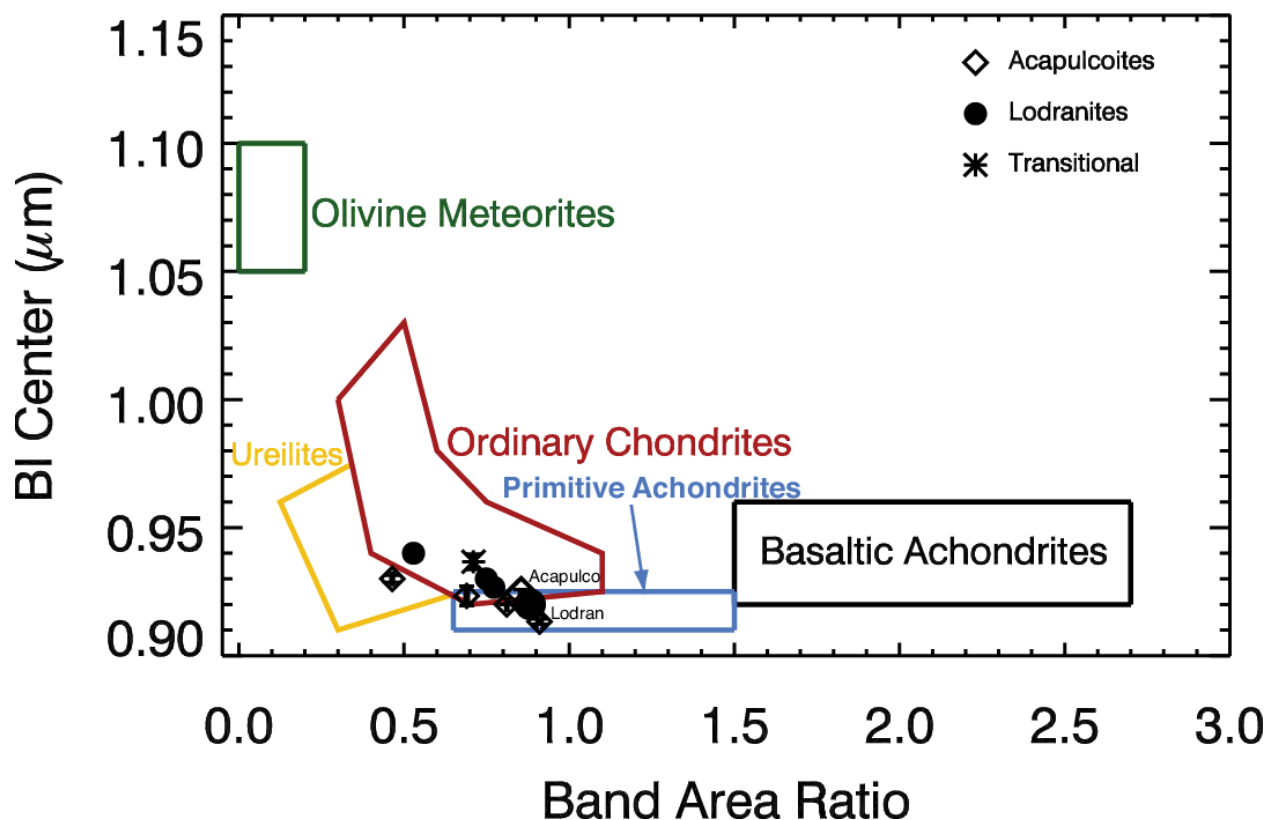


Figure II-10. Band I center versus BAR for EATG treated ALC meteorites shown relative to generalized spectral zones of various stony meteorite groups. The olivine, ordinary chondrite, and basaltic achondrite zones are from Gaffey et al. (1993), the primitive achondrite zone is from Burbine et al. (2001; Dunn et al., 2013), and the ureilite zone is from Cloutis et al. (2010). Band parameters of the only meteorite falls among the clan, Acapulco and Lodran (larger symbols) are shown for comparison. The 1σ errors for Band I center and BAR from Table II-7 are plotted for each object (error is typically smaller than the symbol size).

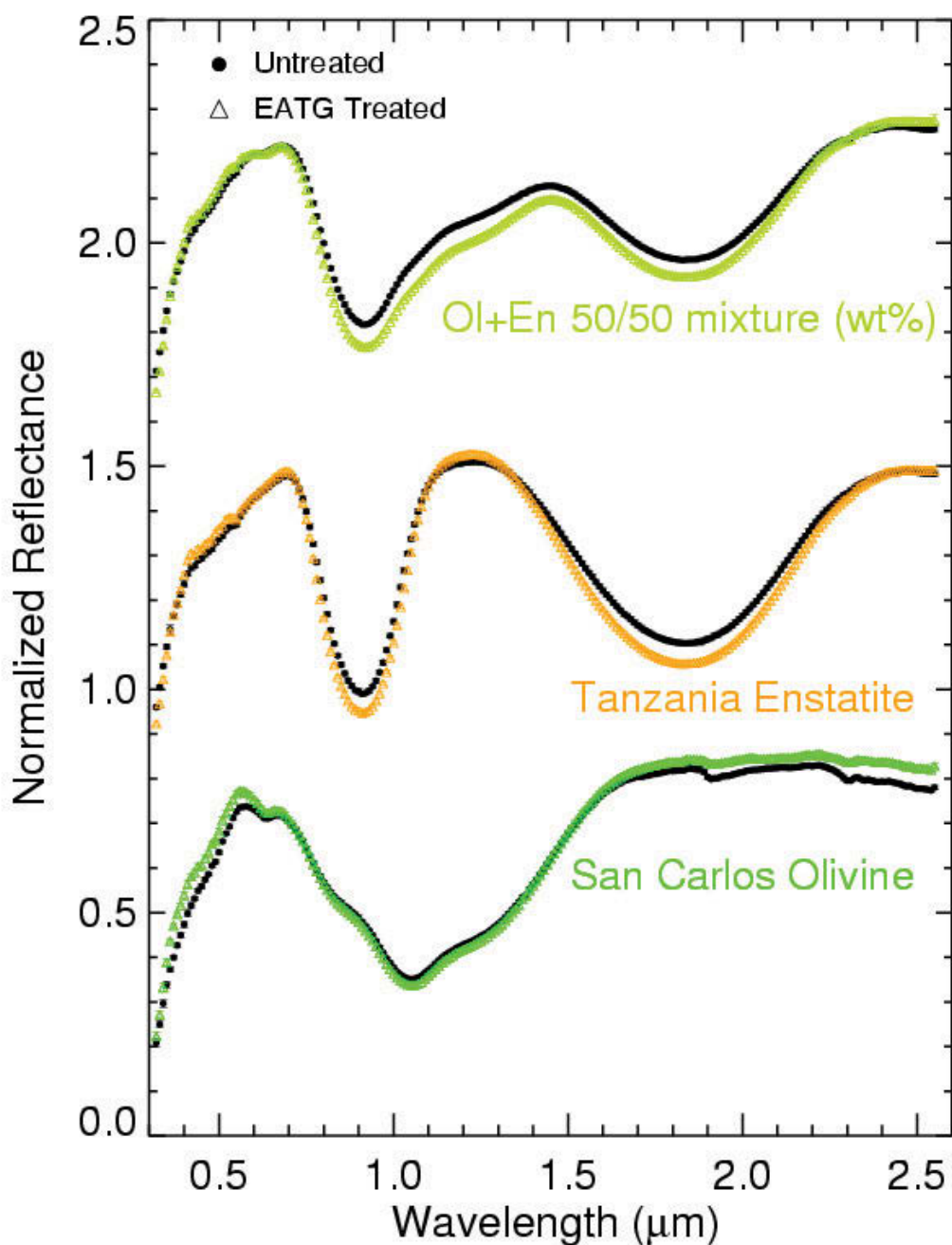


Figure II-11. VIS+NIR reflectance spectra of olivine and enstatite minerals and a 50/50 wt% mixture of these minerals used as control samples for the EATG weathering removal procedure. Untreated sample spectra reflectance values are shown as solid black circles, while EATG reflectance values are shown as open colored triangles. Reflectance values of different samples are offset for clarity, however, reflectances for the same samples (untreated and EATG treated) are not offset. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article).

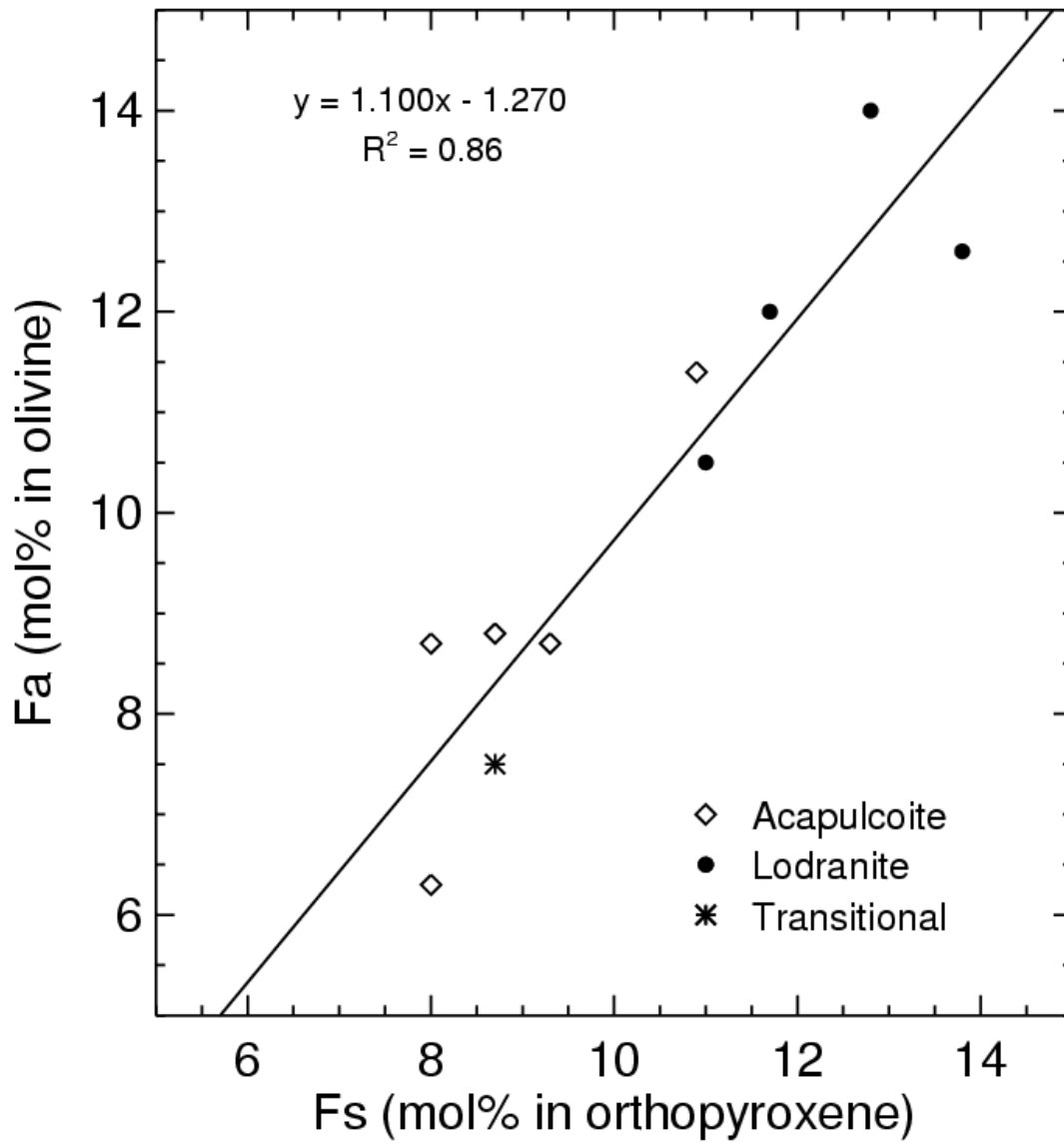


Figure II-12. Iron contents of olivines (Fa) and orthopyroxenes (Fs) for ten ALC meteorites for which we have spectral data. The relationship between measured Fa and Fs forms a linear trend with an R^2 of 0.86.

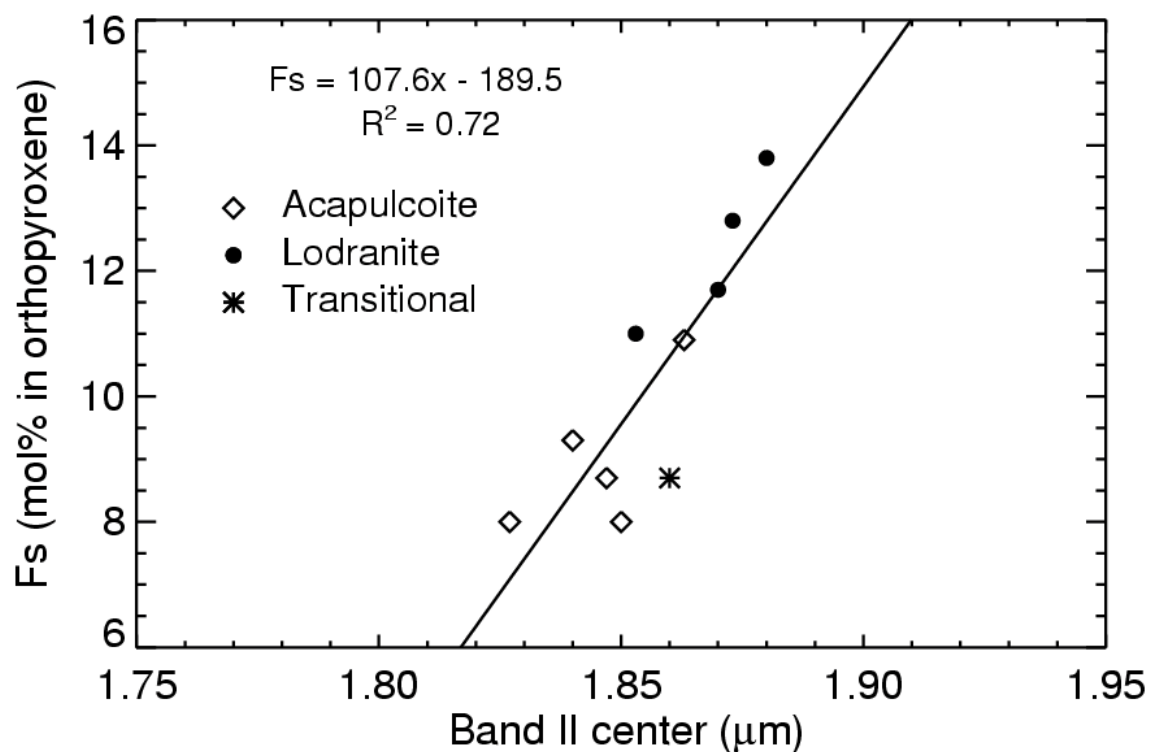


Figure II-13. Fs of orthopyroxene versus Band II center for the ten ALC meteorites from Figure II-12. This relationship demonstrates that a correlation exists between the FeO content of orthopyroxene within these meteorites and Band II center. The linear fit has a R^2 of 0.72.

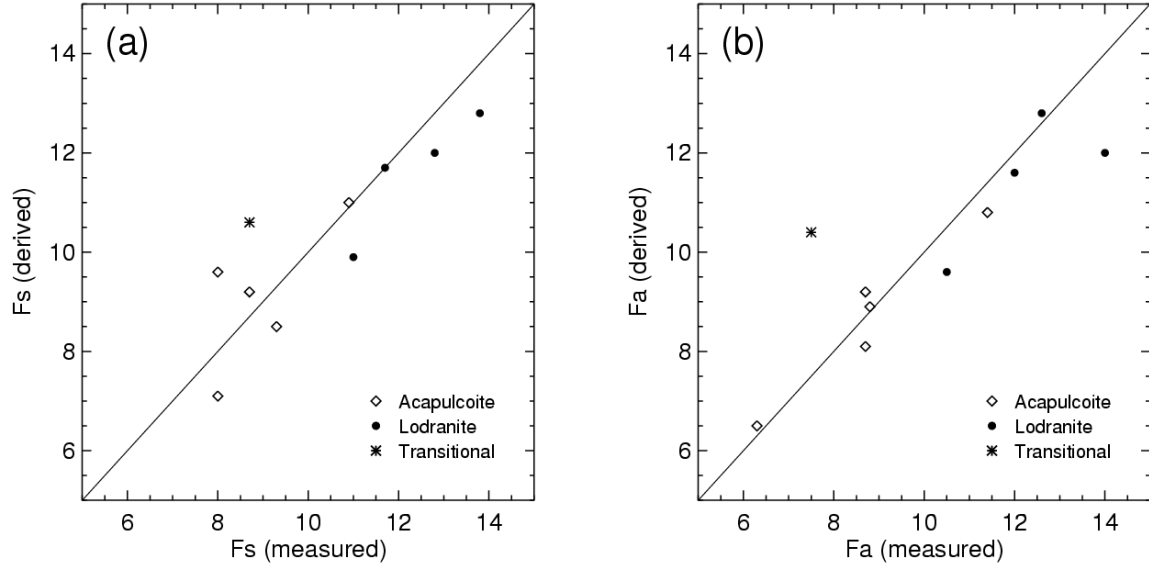


Figure II-14. Derived FeO contents versus measured FeO of mafic silicates for ten ALC meteorites from Figures II-12 and II-13. **(a)** Spectrally-derived F_s values using Band II center correlate well with EPMA measured F_s for orthopyroxene with moderate positive offsets for one acapulcoite and the transitional acapulcoite-lodranite LEW 86220, and slight negative offsets for several acapulcoites and lodranites. **(b)** Derived F_a values using Equation 1 versus EPMA measured F_a in olivine. Derived values correlate well with EPMA measured F_a , with only slight offsets, except for a large positive offset for LEW 86220.

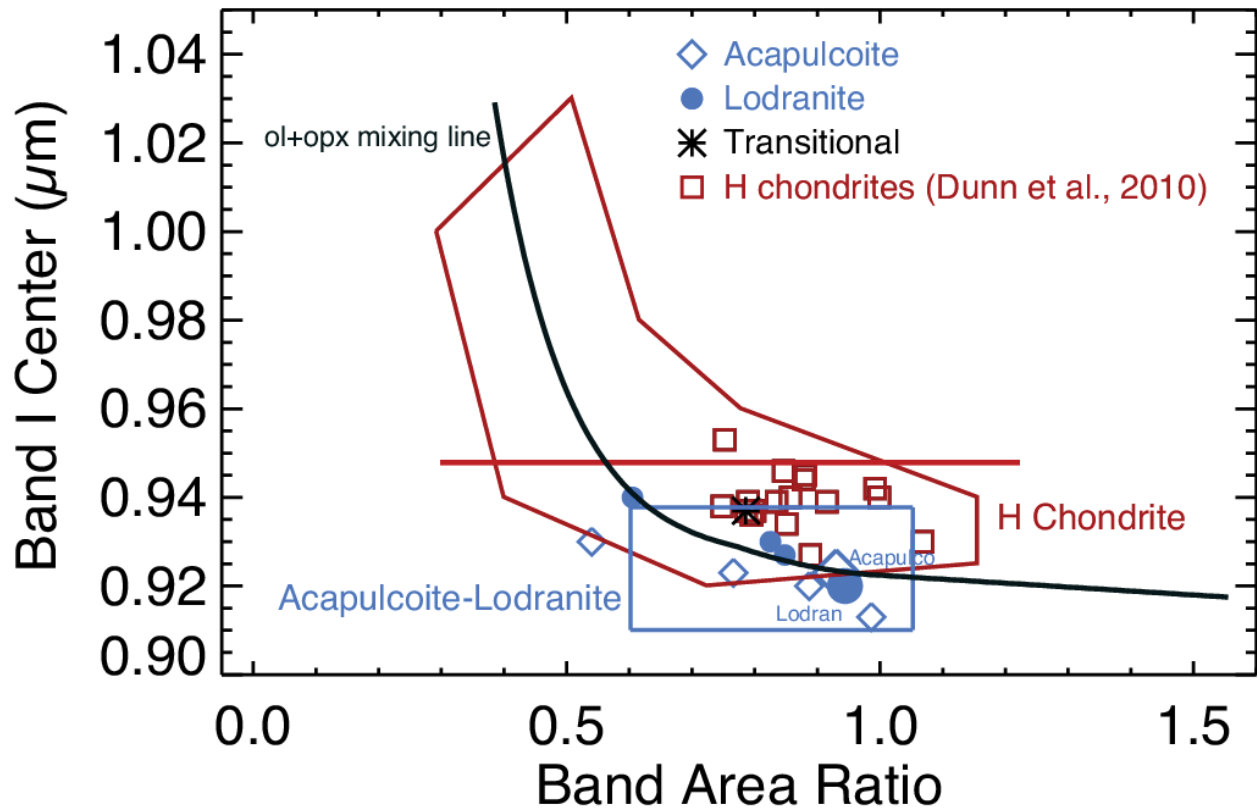


Figure II-15. Band I center versus BAR for ALC meteorites and H chondrite meteorites (data from Dunn et al., 2010a). Generalized spectral zone delineated for ordinary chondrites (boundary shown for H chondrites) shown. We delineate a new generalized spectral zone for acapulcoite-lodranite clan meteorites (blue rectangle). Larger symbols show eponymous meteorite falls of the clan, Acapulco and Lodran. BAR values for acapulcoite-lodranite meteorites are adjusted for a red-edge of 2.50 μm for direct comparison to the H chondrite values (see § 5.2). Acapulcoite-lodranite meteorites cluster near the olivine+orthopyroxene mixing line of Cloutis et al. (1986). H chondrites plot above the mixing line. Errors are on the order of the symbol size.

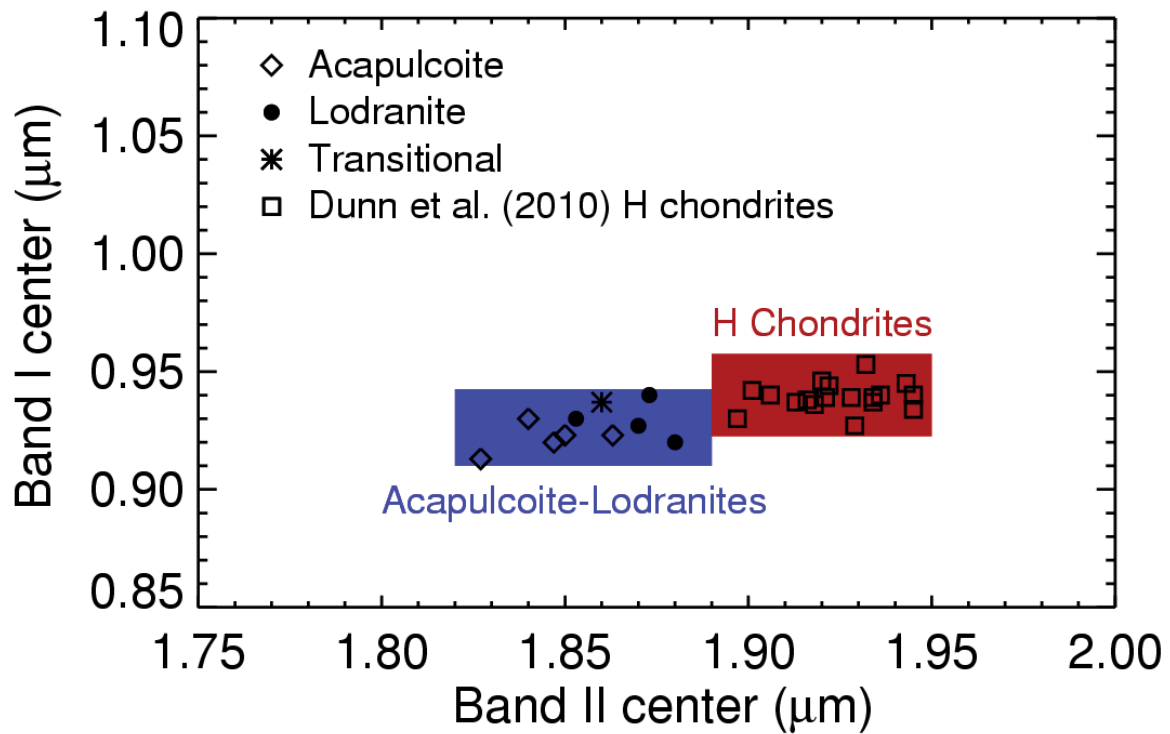


Figure II-16. Band I center versus Band II center for ALC meteorites (this study) and H chondrite meteorites (data from Dunn et al., 2010a). The ALC and the H chondrite group plot in distinct fields in this parameter space allowing for the discrimination of potential asteroidal parent bodies from the analysis of asteroid spectra. Errors are on the order of the symbol size.

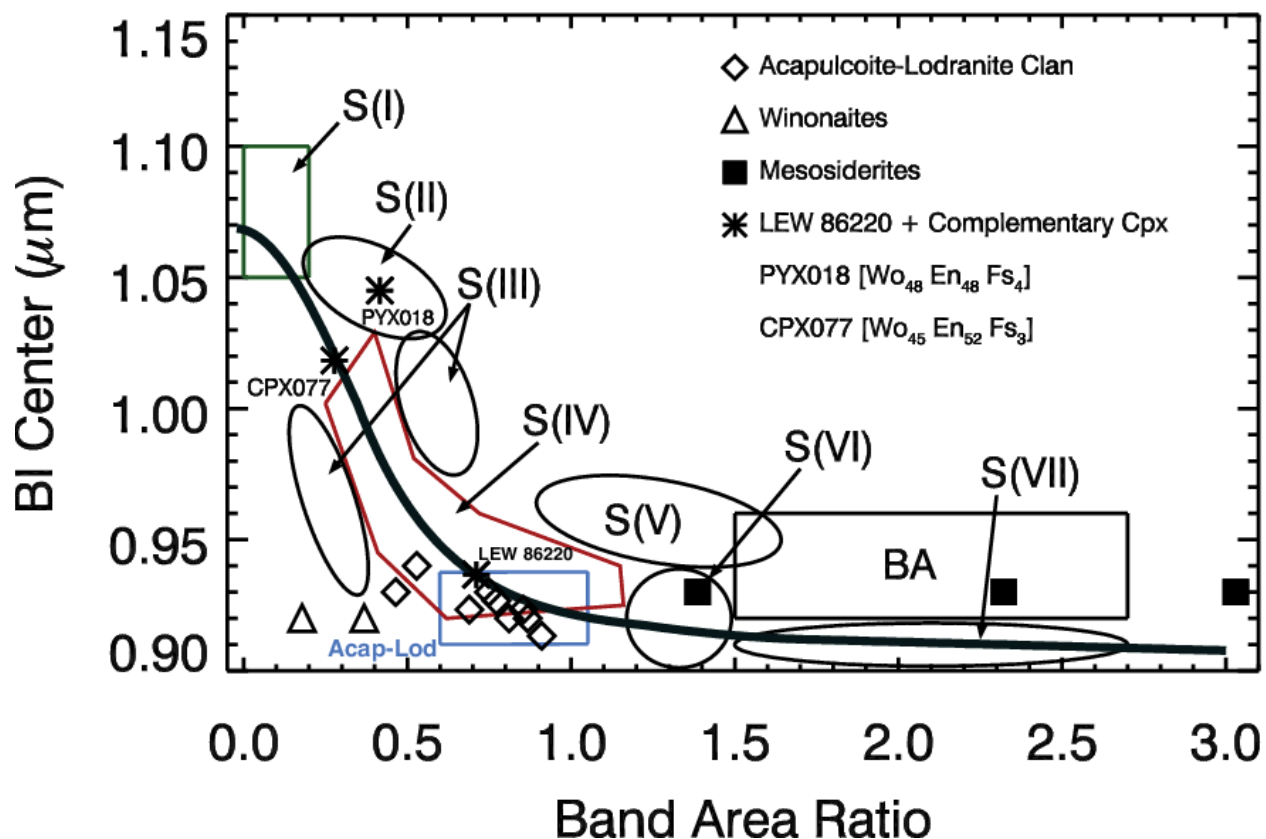


Figure II-17. Band I center versus BAR for the spectral comparison of winonaite (open triangles) and mesosiderite (solid squares) meteorite groups to our suite of ALC meteorites (open diamonds). Transitional acapulcoite-lodranite LEW 86220 spectral parameters (ground particulate <125 μm) is indicated (asterisk). Two clinopyroxene (Cpx) samples (asterisks), PYX018 (Cloutis and Gaffey, 1991a) and CPX077 (Klima et al., 2011) represent similar Cpx compositions as found within the “gabbroic-like” lithology of LEW 86220. The “gabbroic-like” lithology of LEW 86220 is thought to represent the complementary segregated liquid from a residual lodranite (McCoy et al., 1997b). Our new generalized spectral zone for the acapulcoite-lodranite clan (Acap-Lod) meteorites is indicated by a blue rectangle. Errors are on the order of the symbol size.

CHAPTER III

Hungaria Asteroid Region Telescopic Spectral Survey (HARTSS) II: Spectral Homogeneity Among Hungaria Family Asteroids

This chapter is a reformatted version of a manuscript to be submitted to the journal *Icarus* by Michael P. Lucas, Joshua P. Emery, Noemi Pinilla-Alonso, Sean S. Lindsay, Eric M. MacLennan, Richard J. Cartwright, Vishnu Reddy, Juan A. Sanchez, Cristina A. Thomas, and Vania Lorenzi. Michael P. Lucas collected the data, performed the analyses, and drafted this manuscript, tables, and figures. Joshua P. Emery provided advice on the science and helped to edit the manuscript, tables, and figures.

Abstract

Spectral observations of asteroid family members provide valuable information regarding parent body interiors, the origin and source regions of near-Earth asteroids, and the link between meteorites and their parent bodies. Asteroids of the Hungaria family constitute the closest samples to the Earth from a collisional family (~ 1.94 AU), permitting observations of smaller family fragments than accessible for Main Belt families. We have carried out a ground-based observational campaign entitled Hungaria Asteroid Region Telescopic Spectral Survey (HARTSS) to record reflectance spectra of these preserved samples from the inner-most regions of the primordial asteroid belt. During HARTSS phase one (Lucas et al. [2017]. *Icarus* 291, 268-287) we found that $\sim 80\%$ of the background population is comprised of stony S-complex asteroids that exhibit considerable spectral and mineralogical diversity. In HARTSS phase two, we turn our attention to family members and hypothesize that the Hungaria collisional family is compositionally homogeneous (or conversely heterogeneous). We test this hypothesis through taxonomic classification, albedo estimates, and near-infrared (NIR) spectral properties of Hungaria family members.

During phase two of HARTSS we acquired near-infrared (NIR) spectra of 50 new Hungarias (19 family; 31 background) with the SpeX spectrograph at NASA's Infrared Telescope Facility (IRTF) and with the NICS spectrograph at the Telescopio Nazionale Galileo (TNG). We analyzed X-type family spectra for NIR color indices ($0.85\text{-}J$; $J\text{-}K$), and a subtle ~ 0.9 μm absorption feature that may be attributed to Fe-poor orthopyroxene $\pm$ the sulfide mineral oldhamite. Surviving fragments of an asteroid collisional family typically exhibit similar taxonomies, albedos, and spectral properties. Spectral analysis of X-type Hungaria family members and independently calculated WISE albedo determinations for 428 Hungaria asteroids is consistent with this scenario. Furthermore, about one-fourth of the background population exhibit similar spectral properties and albedos to family X-types.

Spectral observations of 92 Hungaria region asteroids acquired during both phases of HARTSS uncover a compositionally heterogeneous background population and spectral homogeneity down to ~ 2 km for collisional family members. Taxonomy, albedos, and spectral properties indicate that the Hungaria family progenitor was an igneous body that formed under reduced conditions, and was likely consistent in composition with the enstatite achondrite (i.e., aubrite) meteorite group.

1. Introduction

Asteroid families are born through violent collisions between asteroids. In some instances, the impact is so energetic that it results in the catastrophic disruption of the parent

asteroid. Numerous daughter fragments, once buried beneath the surface, are ejected into space during the collisional break-up of the parent body. These collisional events then provide an opportunity to probe the interior compositions of asteroid parent bodies. Asteroid surface compositions are typically constrained through spectral observations in the visible (VIS) and near-infrared (NIR) wavelengths. However, VIS+NIR spectral observations sense the upper few tens of microns to few millimeters of the surface of an asteroid, depending on the mean free photon path at a given wavelength, and therefore provide little information regarding the structure and composition of the interior. Spectral observations of the members of an asteroid family may then open a window for the examination of asteroid interiors.

Dynamical identification and physical characterization of asteroid families add significant knowledge to theories regarding the collisional history, compositional structure, and dynamical evolution of the Main-belt (Nesvorný et al., 2015). After a disruption event, the ensuing collisional fragments spread out, principally in a , due to the thermal forces of the Yarkovsky and YORP effect (see Bottke et al., 2002a, 2006b; Vokrouhlický et al., 2006; Vokrouhlický et al., 2015). Through this process, over Myr to Gyr timescales, fragments can reach mean-motion and secular resonance “escape hatches” that can deliver them to the inner Solar System (Vokrouhlický and Farinella, 2000). Thus, the study of asteroid families also provides valuable information regarding the origin and source regions of near-Earth asteroids (NEAs) (Zappalà et al., 2002; Cellino et al., 2009) and the link between meteorites found on Earth and their asteroid parent bodies. Another reason that the study of asteroid families is important to asteroid science is that it appears that a significant fraction of all Main-belt asteroids are members of dynamically related clusters. Approximately one-third of Main-belt asteroids detected by the NEOWISE survey (Mainzer et al., 2011a) were found to be attached to the nuclei of dynamical families (Masiero et al., 2013). Asteroid families are identified dynamically, as families can persist as a cluster in proper orbital element space even Gyrs after the catastrophic disruption event. The most commonly used algorithm to detect these clusters is the Hierarchical Clustering Method (HCM; Zappalà et al., 1990, 1994, 1995). Physical characterization of asteroid families, by means of: albedo measurements, colors, estimates of size distribution functions (SDF), and spectral observations complement dynamical information for asteroid families. These physical properties furnish valuable data to help identify interlopers (i.e., asteroids that belong to the background population) (Nesvorný et al., 2015), and of significant interest for this study, provide evidence regarding the homogeneity/heterogeneity of asteroid family parent bodies.

Color and albedo information from large datasets (SDSS and WISE/NEOWISE) have shown that homogeneity of physical properties persists even down to the smallest observable family members (Ivezić et al., 2001; Parker et al., 2008; Masiero et al., 2013). Furthermore, Masiero et al. (2013) demonstrated that almost all of the 76 distinct families identified through HCM and using WISE/NEOWISE physical properties show unimodal albedo distributions. Collisional family members are typically found to have similar taxonomies and spectral properties as well (Cellino et al., 2002). It therefore seems that homogeneity is the rule among asteroid families. A simple explanation of these observations is that asteroid families are sprung from relatively homogeneous parent bodies, at least to the scale of the observable fragments (Nesvorný et al., 2015). This implies that most asteroid parent bodies were not differentiated, or alternatively, that gravitational re-accumulation of collisional fragments into rubble piles have concealed differentiated bodies through the amalgamation of compositionally distinct layers (Weiss and Elkins-Tanton, 2013).

The lack of evidence for differentiation among asteroid families has led to an intriguing search for workers interested in asteroid petrogenesis: to identify an asteroid family born from a differentiated parent body (DeMeo et al., 2016; Thomas et al., 2017). Extensive melting and differentiation of a body of chondritic composition is thought to produce an object with an iron-nickel core, a thick olivine-dominated mantle, and a thin plagioclase/pyroxene crust (Xu et al., 1995; Burbine et al., 2002a). Collisional fragments that would represent a stratigraphic cross-section of such an object are rarely found among asteroid families. The Eos family, located in the outer Main-belt, is a possible exception. Although Eos family members show considerable taxonomic and spectral diversity, it remains unclear whether these fragments sample the layers of a shattered differentiated parent body (Mothé-Diniz et al., 2008).

Approximately one-half of the whole asteroid population in the Hungaria region ($1.78 < a < 2.0$ AU, $e < 0.18$, and $16^\circ < i < 34^\circ$; Warner et al., 2009) with absolute magnitudes $H_v \leq 18$ are collisional fragments of the Hungaria family [PDS¹⁶ ID 003; Family Identification Number (FIN) 003; Nesvorný et al., 2015]. These collisional fragments are not distributed generally over the region, but are localized within Yarkovsky curves delineated for the family (Warner et al., 2009; Milani et al., 2010). The collision which shattered the parent body of the Hungaria family took place approximately 275 Myr (Milani et al., 2010) to 500 Myr ago (Warner et al., 2009). This blow left in its wake a collisional family, which researchers presently observe as high albedo, spectrally-flat, E-type (Bus-DeMeo - Xe-type) fragments. This family of E-types has been associated compositionally (Gaffey et al., 1992; Kelley and Gaffey, 2002) and dynamically (Ćuk et al., 2014) with enstatite achondrite (i.e., aubrite) meteorites. These stony meteorites may represent the igneous pyroxene-rich mantle from a differentiated asteroid (Gaffey et al., 1992), as they have experienced temperatures ≥ 1580 °C (Keil, 1989). If this scenario is accurate, spectral observations of Hungaria family members provides a unique opportunity to search for possible fragments of other igneous (achondritic) layers of a differentiated family progenitor. Hungaria family members constitute the closest samples to the Earth of an asteroid collisional family, permitting spectral observations of smaller family fragments (~2-3 km) than typically accessible for Main-belt families.

Physical properties such as color and albedo measurements provide limited information regarding the surface composition of asteroid family members. However, VIS+NIR reflectance spectra of collisional family members allow for more detailed taxonomic and compositional inferences of their surfaces. Since September 2009, we have carried out a ground-based observational campaign entitled Hungaria Asteroid Region Telescopic Spectral Survey (HARTSS) to record reflectance spectra of Hungaria asteroids. During the first phase of HARTSS (hereafter HI) we found that the majority (~80%) of the background population is comprised of stony S-complex asteroids, and that these exhibit considerable spectral diversity and mineralogies (Lucas et al., 2017). Therefore, a major objective for this second phase of HARTSS (hereafter HII) is to acquire spectra of Hungaria family members with $H_v < 16$ to determine if this collisional family is compositionally homogeneous (or conversely heterogeneous) through the determination of asteroid taxonomic classifications, albedo determinations, and NIR spectral analysis. During HII, we have acquired NIR spectra of 50 new Hungarias (19 family; 31 background). These 19 family members, with the addition of the five family members observed during HI, are a representative sample of the physical properties of an asteroid collisional family. We hypothesize that the Hungaria family parent body was compositionally homogenous; therefore smaller fragments derived from the catastrophic

¹⁶ JPL Horizons, accessed June 3rd, 2017: http://ssd.jpl.nasa.gov/sbdb_query.cgi

disruption that formed the family should be spectrally consistent with the larger fragments heretofore spectrally observed. We test this hypothesis by performing detailed spectral band and slope analyses of family members observed during HARTSS and through the calculation of new WISE/NEOWISE (Wright et al., 2010; Mainzer et al., 2011a) albedos for 428 Hungaria region asteroids.

2. Observations and Methods

HII includes 50 NIR (0.7 to 2.5 μm) spectra (31 background; 19 family) and four visible (0.42 to 0.80 μm) wavelength (VIS) spectra of Hungaria region asteroids (Table III-1). We used spectrographs at two ground-based facilities to acquire the NIR observations: SpeX (Rayner et al., 2003) on NASA’s 3.0 m Infrared Telescope Facility (IRTF) at Mauna Kea, Hawai’i, and the Near-Infrared Camera and Spectrometer (NICS) on the 3.6 m Telescopio Nazionale Galileo (TNG) at El Roque de Los Muchachos Observatory, San Miguel de La Palma, Canary Islands, Spain (Oliva 2000; Baffa et al., 2001). In addition to 46 newly observed NIR spectra, we included IRTF SpeX spectra of four Hungarias from the following sources: the MIT-UH-IRTF Joint Campaign for NEO Reconnaissance¹⁷ (Binzel et al., 2006) for asteroids 53424 and 134746, and Sanchez et al. (2014) for asteroids 4125 and 4490. We used the Goodman spectrograph (Clemens et al., 2004) on the 4.1 m Southern Astrophysical Research (SOAR) telescope to obtain VIS spectra for four Hungaria asteroids. Distinct local solar analog (hereafter LSA) stars were observed for each target asteroid (Table III-1). Care was taken to choose LSA stars that possess solar-like spectral type, B-V color, and V-K color. Data for the LSA stars were extracted from the IRTF’s Locator for Nearby AOV and G2V Stars¹⁸ online tool and/or the SIMBAD¹⁹ online database (and references therein). Throughout the two phases of HARTSS, we have acquired 92 NIR reflectance spectra and four VIS spectra of Hungaria region asteroids to date.

2.1. IRTF SpeX Near-Infrared Spectra

HII includes 38 Hungaria asteroids that we observed with the SpeX spectrograph (see SpeX Observing Manual²⁰) at IRTF over eleven nights spanning 2014 August to 2016 November (Table III-1). SpeX underwent an instrument upgrade to replace control electronics and detector arrays, which was completed in 2014. The new HgCdTe 2048x2048 Hawaii-2RG array records spectral data with a pixel scale of 0.10 arcsec (18 μm pixels). The spectra were recorded in the low-resolution prism mode using a 0.8 x 15 arcsec slit without the dichroic. With this setup, the entire wavelength range (0.7-2.52 μm) is dispersed in a single spectral order with an average resolving power over this wavelength range of $R \sim 75$. During observations, the telescope was nodded in a standard ABBA sequence, with the target dithered 7.5 arcsec along the slit between the A and B position. During observations, the slit was rotated to maintain alignment with the parallactic angle ($\pm 10^\circ$). This adjustment minimizes differential refraction across the wavelength range. Individual asteroid integration times were typically 120 s. Restricting integrations to a maximum of two minutes minimizes fluctuations due to variable atmospheric emissions (OH

¹⁷ <http://smass.mit.edu/minus.html>

¹⁸ http://irtfweb.ifa.hawaii.edu/cgi-bin/spex/find_aov.cgi

¹⁹ <http://simbad.u-strasbg.fr/simbad/>

²⁰ <http://irtfweb.ifa.hawaii.edu/~spex/>

line emission). Total asteroid integration times (t_{int}) varied between 16-72 min depending on the visual (V) magnitude of the asteroid (Table III-1) and the quality of seeing conditions at the time of observation. Individual LSA star integrations were typically between 1-10 s. LSA stars were located within $\sim 5^\circ$ spatially of the target asteroid and asteroid observations were bracketed with LSA observations within ~ 25 min temporally (Emery et al., 2011). A typical observational sequence consisted of two ABBA cycles of an asteroid target (eight individual integrations) bracketed by a minimum of one ABBA cycle of a LSA star (four individual integrations) acquired at the beginning and end of the asteroid integrations.

Reduction of the SpeX data was performed using the custom IDL (Interactive Data Language) package Spextool⁴ (Spectral Extraction Tool) developed by Cushing et al. (2004). The extraction, calibration, and summation of SpeX reflectance data was performed in the same manner as in HI (see Lucas et al., 2017). For a detailed treatment of this process see Emery and Brown (2003). The reduction of the spectral data typically yielded a signal-to-noise ratio (S/N) >50 for the majority of the final refined asteroid spectra.

2.2. TNG NICS Near-Infrared Spectra

HII includes eight Hungarias observed with the NICS spectrograph (0.8-2.3 μm) at TNG on the nights of 2014 May 12-13 and 13-14 UT (Table III-1). These spectra were recorded using NICS in the low-resolution mode. With a 1.5 arcsec slit in this mode, NICS utilizes an Amici prism to disperse the entire wavelength range into a single spectral order with an average resolving power of $R \sim 34$, quasi-constant over this range (Oliva, 2000; Baffa et al., 2001). The spectral data were recorded using the Large-Field (LF) camera with a pixel scale of 0.25 arcsec (18 μm pixels). Before spectral data could be acquired, it was first necessary to identify the asteroid in the field-of-view (FOV) and then orient the slit over the target. These tasks were accomplished by recording several images with the J_s filter and positioning the telescope accordingly. As with IRTF SpeX, the slit was rotated to stay aligned with the parallactic angle to minimize the effects of differential refraction. Individual asteroid integrations were set at 90 s and were acquired at two different positions along the slit by nodding the telescope by 10 arcsec (i.e., positions A and B). For each asteroid, we obtained several ABBA mosaics in order to increase the S/N. We varied t_{int} between 12 and 36 min based on the V magnitude of the target (Table III-1) and on variable sky conditions.

Data reduction was performed with standard Image Reduction and Analysis Facility (IRAF) tasks. In brief, these tasks include: 1) flat-field corrections, 2) subtraction of AB pairs for sky background removal, 3) extraction from two-dimensional (2D) spectra to one-dimensional (1D) spectra, and 4) wavelength calibration and the division of a solar analog star to obtain relative reflectance values and to correct for telluric absorptions using a Python routine. For a detailed treatment of these tasks regarding the reduction of TNG asteroid spectra see Pinilla-Alonso et al. (2016). Because of the low spectral resolution of the NICS Amici prism, the emission lines of Ar- and Xe-lamps cannot be resolved to establish the wavelength calibration. Therefore, wavelength calibration was performed on consecutive AB extracted pairs using a look-up table²¹ based on the theoretical dispersion predicted by ray-tracing and then adjusted to best-fit the observed spectra of calibration sources and telluric absorptions. For both TNG observing nights, distinct LSA stars were observed for each asteroid as described in § 2.1 above for IRTF observations. In addition to the LSA stars, three G-dwarf Landolt stars (Landolt, 1992)

²¹ http://www.tng.iac.es/instruments/nics/files/amici_wlcal.dat

that have proved to be suitable solar analog standards (de León et al., 2010) were observed each night. For task 4 described above, each Hungaria asteroid AB asteroid pair was divided by the following combinations of observed solar analog standards: 1) LSA star-only, 2) G-dwarf Landolt star-only, and 3) LSA divided by G-dwarf Landolt star. The resulting divided spectra were then inspected for minimized reflectance errors ($1-\sigma$) and minimal telluric absorptions. For all eight Hungaria asteroids observed over the two nights the LSA star-only division produced the final spectral reflectance values with the smallest $1-\sigma$ errors and residual telluric absorptions. The final relative reflectances derived for each asteroid are therefore based on the division of the observed LSA star-only. Additionally, to correct for possible errors in wavelength calibrations that are due to instrument flexures, subpixel offsetting was applied during solar analog divisions.

2.3. *SOAR Goodman Visible Spectra*

We acquired VIS wavelength spectra using the Goodman spectrograph (Clemens et al., 2004) on the night of 2015 May 08-09 UT. The observing run was scheduled for the entire night, although observations did not commence until $\sim 2:30$ UT due to overcast sky conditions. Consequently, we were only able to obtain VIS wavelength spectra ($0.42\text{--}0.80\ \mu\text{m}$) of four Hungaria asteroids during the second-half of the night: 5477 Holmes, 7173 Sepkoski, 9068 1993 OD, and 9873 1992 GH (Table III-1). Spectral data were recorded with a charge-coupled device (CCD) with a pixel scale of $0.15\ \text{arcsec}$ ($15\ \mu\text{m}$ pixels). We varied t_{int} between 30 and 40 min based on the V magnitude of the target asteroid. We observed distinct LSA stars for each asteroid as described in § 2.1. We used the GG-385 blocking filter, and a $1.03\ \text{arcsec}$ slit with the $400\ \text{l/mm}$ grating that yielded a resolving power $R\sim 800$.

Visible wavelength spectral reduction followed standard procedures with several modifications that are attributable to the fabrication of the Goodman instrument, one due to a problem regarding quartz flat-field calibration, and another due to an effect that produces considerable fringing longward of $\sim 0.65\ \mu\text{m}$ (see Lindsay et al. 2015). In brief, standard reduction procedures are performed using a custom IDL-based routine that includes: 1) extraction from 2D spectra to 1D spectra by summing pixels in the data range and subtracting the background value (median of column outside of data range) for each column, 2) cleaning the spectra by the rejection of anomalous pixel detections ($5-\sigma$ outliers) using an 100 pixel box iterative step method, 3) shifting the cleaned asteroid and LSA star spectra to a common reference and co-adding to produce combined asteroid and LSA star frames, 4) dividing the asteroid co-added frame by the LSA star co-added frame to calculate the final relative reflectance values for each spectrum, and 5) wavelength calibration using Hg- and Ar-lamp spectral frames.

Flat-fielding is left out of the reduction procedure because back-scattered light from the second filter wheel²² introduces a ghost-like arc feature onto quartz flat calibration frames. This feature is difficult to remove from the quartz flat image frames. However, because we placed the asteroid and LSA star at the same position on the CCD, flat-fielding is essentially performed during step 4 above through the division of the asteroid spectrum by the LSA star spectrum. The aforementioned fringing effects longward of $\sim 0.65\ \mu\text{m}$ are corrected by the application of a Fast Fourier Transform (FFT) routine prior to co-addition and wavelength calibration, which isolates the fringing frequencies. See Lindsay et al. (2015) for a detailed treatment of this routine.

²² <http://www.ctio.noao.edu/soar/content/goodman-spectrograph-overview>

2.4. Thermal Modeling and Albedo Methods

To supplement and revise the current albedo (p_v) and diameter (D) determinations for Hungaria region asteroids, we used observations from the WISE/NEOWISE (Wright et al., 2010; Mainzer et al., 2011a) survey in combination with the near-Earth Asteroid Thermal Model (NEATM) (Harris, 1998). The WISE and NEOWISE missions have detected more than 160,000 asteroids and comets, providing measurements of their albedo, diameters, and orbital properties. The NEOWISE pipeline detects and reports individual moving object detections to the Minor Planet Center²³ (MPC), where the time and sky position (RA and dec) of each observation can be retrieved. These times and location are used to parse the WISE all-sky single exposure (L1b) catalog on the Infrared Science Archive²⁴ (IRSA) maintained by the Infrared Science and Analysis Center (IPAC). We used search criteria to retrieve detections within 10 s and 10 arcsec of those reported to the MPC. According to the WISE Explanatory Supplement (Cutri et al., 2012), detector non-linearity begins at 3.6 and -0.6 magnitude and sources brighter than -3 and -4 magnitude saturate WISE channel 3 (12 μ m) and channel 4 (22 μ m), respectively. We take care to exclude any asteroid brighter than the saturation limit and set measurement errors to 0.2 magnitude in the non-linearity regime (Mainzer et al., 2011b). As suggested by Wright et al. (2010) and Cutri et al. (2012), color-corrections must be made to account for the discrepancy between the spectrum of the object and that of Vega used to calculate raw magnitudes. The model flux spectrum as calculated by NEATM (described below) is used to perform this color correction instead of the spectrum of a blackbody as done by Mainzer et al. (2011c). The fluxes are averaged, in order to determine the lightcurve-mean value of the asteroid brightness.

NEATM assumes the surface of a sphere as being in thermal equilibrium with the incoming solar radiation (S_0) in order to calculate temperatures for the sunlit portion of an atmosphereless, spherical object. The maximum temperature (at the sub-solar point), T_{ss} , is calculated from the equation:

$$\frac{S_0(1-A)}{r_{AU}^2} = \eta \epsilon \sigma T_{ss}^4, \quad (1)$$

where A is the bond albedo, r_{AU} is the heliocentric distance, η is the beaming parameter, ϵ is the emissivity, and σ is the Stephan-Boltzmann constant. Temperatures across the sunlit hemisphere fall to zero at the terminator and on the nightside, and model fluxes are calculated using the summation of blackbody flux contribution from individual surface facets across the hemisphere visible to the observer. The NEATM requires flux observations at two wavelengths (we used WISE 12 and 22 μ m thermal infrared bands) in order to properly constrain the diameter, albedo, and beaming parameter. Diameter and geometric albedo are related through:

$$D[\text{km}] = \frac{1329[\text{km}]}{\sqrt{p_v}} 10^{-\frac{H_V}{5}}. \quad (2)$$

In this study, the absolute magnitude (H_V) for each object is taken from Oszkiewicz, et al. (2011), in which the phase function is explicitly calculated, resulting in more accurate and precise

²³ <http://www.minorplanetcenter.net/iau/mpc.html>

²⁴ <http://irsa.ipac.caltech.edu/Missions/wise.html>

measurements of H_v than provided in the JPL/Horizons database. Better estimates of H_v , in turn, directly lead to more reliable albedos.

3. Results

3.1. SOAR Visible Spectra

The VIS spectra of four Hungaria asteroids that were observed with the Goodman Spectrograph at SOAR are shown in Figure III-1a. Hungaria asteroids 7173 Sepkoski, 9068 1993 OD, and 9873 1992 GH are background objects, and NIR spectra for each of these three objects were reported in HI (Lucas et al., 2017). Although 5477 Holmes is included as a member of the Hungaria dynamical family (FIN 003) as compiled by Nesvorný et al. (2015), we infer that it is an interloper and not part of the collisional family. Holmes is classified as an S-type in the visible wavelength Bus taxonomy (Bus and Binzel, 2002), whereas Hungaria family members are predominately E-types. S-types have been shown to be prevalent within the Hungaria background (Warner et al., 2009; Lucas et al., 2017). Furthermore, Holmes has a semi-major axis $a=1.917$ and absolute magnitude $H_v=14.0$, which places this asteroid outside of the Hungaria family “Yarkovsky curves” (see Figure III-2). See § 3.2 below for details regarding the combination of VIS and NIR spectral data for Hungaria asteroids observed during HARTSS.

3.2. Combined Visible and Near-Infrared Spectra

The analysis of VIS+NIR spectral data allows for more robust taxonomic classifications and mineralogical interpretations of asteroid surfaces to be made than with NIR-only spectral data. Fittingly, we have combined VIS spectral data ($\sim 0.4\text{-}0.9\ \mu\text{m}$) with NIR spectral data for our surveyed Hungaria asteroids where data exist. We have combined three of our SOAR VIS spectra (Figure III-1a) with NIR data acquired during HI for the following Hungaria background asteroids: 7173 Sepkoski, 9068 1993 OD, and 9873 1992 GH. The combined VIS+NIR spectra for these asteroids are shown in Figure III-1b. The asteroid 7173 Sepkoski was included as a family member in an earlier Hungaria family compilation (Bottke and Nesvorný, *personal comm.*) used in HI (Lucas et al., 2017). A more recent compilation of Hungaria family members (FIN 003) from Nesvorný et al. (2015) does not include 7173 Sepkoski as a family member. Sepkoski exhibits broad 1- and 2- μm absorption features (Figure III-1b) inconsistent with the featureless spectra of other family members. Furthermore, with the addition of VIS spectral data (Figure III-1a), 7173 Sepkoski is now uniquely classified as a Sw-type (see Table III-2), dissimilar from the X-complex taxonomy of other family members. As suggested in HARTSS Phase I, we conclude that 7173 Sepkoski is an interloper and not a member of the Hungaria collisional family.

We supplemented an additional 10 asteroids from our HII NIR dataset (see Appendix III-B and III-C) with VIS spectral data from the following sources: the Small Main-Belt Asteroid Spectroscopic Survey Phase II (SMASS) database (Bus and Binzel, 2002) for asteroids 1600 and 4713, and the Small Solar System Objects Spectroscopic Survey (S^3OS^2) dataset (Lazzaro et al., 2004) for asteroids 1355, 1656, 2150, 3043, 3447, 4125, 4490, and 4764. To combine the VIS and NIR datasets for each object, a numerical factor was used to scale the NIR reflectances to the normalized VIS reflectances in the wavelength region between 0.70 and 0.80 μm , while NIR

reflectance errors are also multiplied by the same factor. The final NIR and VIS+NIR spectra are then normalized to unity at 1.25 μm . We present the final reflectance spectra for 50 Hungaria asteroids from HII in the Appendices: 19 Hungaria family members in Appendix III-B (Figure III-12), and 31 Hungaria background in Appendix III-C (Figure III-13).

3.3. HARTSS Taxonomy

We identified the taxonomic type of 53 of the 54 Hungarias listed in Table III-2 using MIT's Bus-DeMeo Taxonomy Classification Tool²⁵ (DeMeo et al., 2009). The principal component analysis (PCA) performed with the online tool is most reliable for reflectance data that encompass the VIS+NIR (0.45-2.45 μm). The taxonomic types reported in Table III-2 are derived from the spectra published within this paper; we do not let any previous taxonomic classification (i.e., for VIS-only taxonomy) bias our taxonomic results. The classification tool provided a unique taxonomic type for the majority (10 of 13) of our Hungaria spectra for which we have obtained VIS+NIR data (see § 3.2 above). For most (39 of 40) of the NIR-only (i.e., no VIS data) spectra, the Bus-DeMeo classification system returned a non-unique classification. The one NIR-only Hungaria asteroid spectra that returned a unique taxonomic classification is background object 6271 Farmer, which is a steep red-sloped D-type asteroid (see § 4.2.4). For the remaining 39 spectra with NIR-only data, we report the Bus-DeMeo spectral types that exhibit the two lowest absolute residuals (Table III-2). We acquired VIS-only data for 5477 Holmes, and this asteroid is classified as S-type in the visible-wavelength Bus taxonomy (Bus, 1999; Bus and Binzel, 2002).

Figure III-2 illustrates the Bus-DeMeo taxonomic complexes (S-, X-, C-complex, and End Member) for the complete HARTSS sample of 92 Hungaria asteroids for which we have obtained NIR or VIS+NIR spectra (42 from HI; 50 from HII). We plotted H_v versus proper semi-major axis (a_p) of ~ 3000 Hungarias ($H_v \leq 18.0$) that are reported as members of the Hungaria family from Nesvorný et al. (2015). These collisional family fragments are dispersed in semi-major axis by the thermal forces of the Yarkovsky/YORP effect (see Bottke et al., 2002a; Bottke et al., 2006b; Vokrouhlický et al., 2015) amid the background asteroids that populate the Hungaria region. To reveal this background population, we subtracted the members of FIN 003 from the whole population of *numbered* asteroids with $H_v \leq 18.0$ (~ 6100) in the Hungaria region²⁶.

In Figure III-2, the Hungaria family members are indicated by the large colored symbols with thick black borders. The taxonomy of these 24 family members is remarkably similar. The majority (21 of 24) of family members are classified as X-complex objects, and the remaining three objects are classified as C-complex. For relatively flat spectra such as X- and C-complex asteroids, a unique spectral type is difficult to distinguish with NIR-only data. The additional, subtle information contained within VIS wavelength data allows for the unambiguous distinction between these two complexes in the Bus-DeMeo scheme.

The relatively featureless spectra of the Bus-DeMeo X-complex incorporate the E-, M-, and P-types defined in previous taxonomies (Tholen and Barucci, 1989). The Tholen taxonomy separates the X-complex into these three spectral types using albedo. The mineralogies of high albedo E-types have been associated with stony enstatite-rich surfaces, moderate albedo M-types with metal-rich surfaces, and low albedo P-types with organic-rich surfaces (e.g., Tholen and

²⁵ <http://smass.mit.edu/busdemeoclass.html>

²⁶ JPL Horizons, accessed January 3rd, 2017: http://ssd.jpl.nasa.gov/sbdb_query.cgi

Barucci, 1989; Britt et al., 1992). However, albedo is not included in the Bus-DeMeo system. The X-types in the Bus-DeMeo system (Xc, Xe, Xk, and Xn) are defined by subtle characteristics in the visible wavelength region and do not directly correspond with the albedo separation. The distinction between the Xc-, Xe-, Xk-, and Xn-subtypes depends on the presence or absence of three subtle absorption features: the 0.49 μm absorption feature, a shallow 0.8 to 1.0 μm absorption, and a weak to moderate absorption centered near 0.9 μm (DeMeo et al., 2009)

Sixty-eight background asteroids are included in Figure III-2 (31 from HII; 34 from HI; 3 background asteroids shown in Figure III-1b observed in both HI and HII). The large sample size of background objects with the addition of HII spectra reveals a similar taxonomic distribution among the Hungaria background as that uncovered during HI. Figure III-2 reveals a Hungaria background population dominated by S-complex asteroids, 48 of 68 objects; $\sim 71\%$, a slightly lower percentage than the $\sim 80\%$ found during HI; Lucas et al. (2017). The background contains a significant number of X-complex asteroids as well. We found that $\sim 24\%$ (16 of 68) of the background population consists of X-types. We found three “End Member” spectral types among the Hungaria background: two olivine-dominated A-types (Sanchez et al., 2014) and one D-type. Similar to the result found in HI, C-complex asteroids are uncommon (4 of 92 objects; $\sim 4\%$) throughout the Hungaria region (Figure III-2). It is important to note that all four of the C-complex objects found in the Hungaria region during HARTSS are NIR-only data and their taxonomic determinations are non-unique. These objects may yet prove to be X-type objects with the addition of VIS spectra data. See Figure III-3 for a breakdown of the taxonomic distribution of both the Hungaria background and family populations.

While the taxonomic analysis illuminates trends in the Hungaria population, it is important to understand that taxonomic classifications only represent spectral groups, which are not necessarily equivalent to asteroid surface compositions (e.g., Gaffey, 2010). Therefore, in our effort to decipher the surface compositions of Hungaria region asteroids, we perform detailed spectral analyses for Hungaria X-complex asteroids (family members and background objects) in Section 4.1 and for Hungaria S-complex background objects in Section 4.2.

3.4. Hungaria Region Albedo Dichotomy

We used WISE measurements from two thermal infrared bands (12 and 22 μm) to estimate the physical properties (D and p_v) of 428 Hungaria region asteroids. We compare these new calculations of p_v for Hungaria region asteroids with the p_v from other sources where available (NEOWISE, IRAS) for the 54 Hungarias observed during HII in Table III-2. Additionally, a text data file listing the calculated physical properties and corresponding uncertainties for all 428 Hungarias with WISE detections using the methods described above (§ 2.4) is provided in HARTSSII_WISE_physicalproperties.txt (see FILE 1).

Figure III-4 shows separate histograms of p_v for Hungaria family members and background. The histogram bins are logarithmically scaled to match the average percent error ($\sim 25\%$) of the albedo values. It is apparent from Figure III-4 that the albedo distribution of the Hungaria family differs from the albedo distribution of the background. Family members exhibit a prominent peak near $p_v \sim 0.50$, consistent with high albedos previously known for taxonomic E-type asteroids (Tholen taxonomy; Tholen and Barucci, 1989) found in the Hungaria region (see Clark et al., 2004; Fornasier et al., 2008), and consistent with the average albedo for E-types (avg. $p_v = 0.536 \pm 0.247$, DeMeo and Carry, 2013). Background asteroids display a prominent

albedo peak at $p_v \sim 0.25$, consistent with the average albedo for S-type asteroids (avg. $p_v = 0.258 \pm 0.087$, DeMeo and Carry, 2013), and also consistent with taxonomic results from HARTSS that indicate a prevalence of S-types among the background (Lucas et al., 2017; this work). However, the albedo distributions for family members and background objects are both possibly non-uniform as they exhibit hints of separate minor peaks at $p_v \sim 0.25$ and $p_v \sim 0.08$, respectively (Figure III-4). The lesser peak for the Hungaria family is aligned with the steep peak for the background objects at $p_v \sim 0.25$. This result may be an indication that the current Hungaria family (FIN 003) contains a significant proportion of S-type background interlopers, which are incorrectly included in the family list. The alternative interpretation is that the albedo bimodality is real and an indication that the Hungaria family is not compositionally homogeneous after all.

To investigate the possibility of a bimodal distribution of albedos within the Hungaria family, in Figure III-5 we show a comparison of albedo versus diameter for Hungaria family members. If the minor peak at $p_v \sim 0.25$ is indicative of a subset of lower albedo S-type family members, distinct from the predominant high albedo E-type family members, segregation of the two materials as a function of diameter could perhaps uncover evidence of a differentiated family progenitor (e.g., darker S-type crustal? material is battered to smaller bits during catastrophic disruption than the brighter E-type mantle? material or vice-versa). This scenario would be apparent as separate populations in albedo versus diameter space (Ali-Lagoa, *personal comm.*). An inspection of Figure III-5 suggests that this is not the case; the diameters of our family members are similar across a wide range of albedos.

In general, our calculated albedo distributions indicate a compositional dichotomy between Hungaria collisional family members and background objects. The albedo distributions are in close agreement with the average albedos (DeMeo and Carry, 2013) of taxonomic types characteristic of the Hungaria region, and are consistent with the taxonomic distributions revealed by HARTSS (Figure III-2 and III-3) for the Hungaria family and background objects.

4. Spectral Band and Slope Analysis

Absorption features that arise in their VIS+NIR and NIR spectra of provide important clues regarding their surface mineralogy. Although spectra of Hungaria X-type asteroids do not generally exhibit strong features, their spectra can be analyzed for subtle absorption features and for the distribution of spectral slopes to provide evidence of compositional similarities among the family (see § 4.1). S-complex asteroid reflectance spectra, on the other hand, exhibit broad 1 and 2 μm absorption features due to the presence of the crystalline silicate minerals olivine and/or pyroxene, and these features can be analyzed to derive surface mineralogy (see § 4.2). These analyses can also provide evidence regarding the petrologic history of the asteroid through the recognition of potential meteorite analogs, which then furnish real samples that can be studied in detail in the laboratory. Establishing asteroid-meteorite connections in this manner enhances compositional knowledge for objects which otherwise could only be explored through the collection of photons through the telescope.

4.1. Hungaria X-complex Asteroid Spectral Analysis

The search for weak absorption features in our sample of Hungaria family members is somewhat hindered by the lack of VIS spectral data for most objects. As discussed in Section

3.3, the identification of subtypes (X, Xc, Xe, Xk, and Xn) relies on subtle characteristics are found in the visible wavelength region. An important subtle feature in the characterization of X-subtypes is found near 0.49 μm , but 4764 Joneberhart is the only Hungaria family member in our HII sample with VIS spectral data (see Figure III-12). Unfortunately, even for this asteroid, an inspection for the $\sim 0.49 \mu\text{m}$ feature cannot be made because the shortest wavelength of the VIS spectrum for this object is 0.52 μm . This weak feature at $\sim 0.49 \mu\text{m}$ has been attributed to the sulfide mineral oldhamite (Ca,Mg)S (Gaffey et al., 1992; Burbine et al., 2002b; Fornasier et al., 2008). Oldhamite and the Fe-poor orthopyroxene discussed below have been identified in enstatite achondrite (i.e., aubrite) meteorites (Keil, 1989; Mittlefehldt et al., 1998; Keil, 2010).

Another feature that has been observed in connection with X-complex asteroids is a weak to moderate absorption centered near 0.9 μm (Clark et al., 2004; Hardersen et al., 2005). For Xe-type asteroids (E-type; Tholen taxonomy) this $\sim 0.9 \mu\text{m}$ feature has been attributed to iron-poor orthopyroxene (Gaffey et al., 1992) with an iron-content of $\sim \text{Fs}_{2.4}$ (ferrosilite; Fs = mol% iron in pyroxene). We analyzed our sample of 17 X-complex family members from HII for this weak $\sim 0.9 \mu\text{m}$ absorption band (see § 4.1.1). We also analyzed nine X-type background asteroids observed during HII for the same $\sim 0.9 \mu\text{m}$ absorption feature. To determine if the asteroids of the collisional family are compositionally homogeneous, we also included the largest known family member 434 Hungaria (Clark et al., 2004) in the analysis. Figure III-6 illustrates this weak $\sim 0.9 \mu\text{m}$ absorption feature in the spectrum of Hungaria family member 1920 Sarmiento (Xe-type), and the inset shows the feature after removal of a linear continuum. The two ambiguous C-complex asteroids found among the family, 13245 1998 MM19 and 21261 1996 FF, are not analyzed.

A search for patterns in the NIR data of X-complex asteroids can be particularly useful considering that they display subtle or no verifiable absorption features. A useful analysis in this regard is to compare the distribution of spectral slopes to determine whether spectrally featureless asteroids belong to similar or distinctly different spectral groups. We analyze the same sample of X-type Hungaria asteroids (17 family; 9 background) for near-infrared color indices (0.85 - J ; J - K) to search for patterns in the distribution of spectral slopes between these two groups (see § 4.1.2). These patterns may reveal clues to determine whether the surface compositions of Hungaria X-complex asteroids are related, and ultimately evidence for their origin.

4.1.1. X-type 0.9 micron Band Analysis

We analyzed 27 Hungaria X-type asteroid spectra to search for a weak $\sim 0.9 \mu\text{m}$ absorption band. We performed the band analysis with a custom IDL-based routine, and the calculated band centers and band depths with their errors are listed in Table III-3. First, a continuum-removed absorption feature (see Figure III-6) is calculated by fitting a linear continuum to the reflectance maxima (i.e., shoulders) that bound the 0.9 μm feature and dividing the spectrum by that continuum. The reflectance maxima are taken as the average of seven reflectance points about the chosen shoulder of the absorption feature. The wavelengths of the short and long shoulders that bound the feature are typically found at $\sim 0.8 \mu\text{m}$ and $\sim 1.05 \mu\text{m}$, respectively, and are also listed in Table III-3. Band centers are then estimated by fitting 2nd through 6th order polynomial functions to the continuum-removed feature. Band center error is taken as the standard deviation of band centers derived from the five different polynomial fits. We then compute the average reflectance at the band center (R_b) as the average of seven

reflectance points about the estimated band center. Next, the reflectance of the continuum at the band center (R_c) is calculated, and the band depth (%) is computed as $1 - (R_b/R_c) \times 100$. Reflectance uncertainties are propagated throughout the calculations to obtain the band depth errors.

Fifteen of the 18 Hungaria family X-types and five of the nine Hungaria background X-types exhibit significant $\sim 0.9 \mu\text{m}$ band depths ($>1\%$) (Table III-3). Qualitatively, none of the 27 X-types analyzed for the $\sim 0.9 \mu\text{m}$ feature display evidence of the broad $\sim 2 \mu\text{m}$ absorption characteristic of pyroxene. Background asteroid 1355 Magoeba and family member 5579 Uhlherr show very broad lows that extend from about 1.2 to 2.5 μm , but these are not consistent with pyroxene. Some of the analyzed X-types are affected by high residual noise in the 1.8 - 2.0 μm region due to poor or variable weather conditions, or low S/N in the K-band (1.95-2.5 μm) (see Figures III-12 and III-3), effectively masking the detection of a weak $\sim 2 \mu\text{m}$ feature even if present. Therefore, we did not attempt to measure 2 μm bands for our X-type Hungarias. Determining the relationship between spectral band parameters and pyroxene mineral chemistry depends primarily on ~ 1 and $\sim 2 \mu\text{m}$ band center positions (Adams, 1974; Cloutis and Gaffey, 1991; Gaffey et al., 2002). Consequently, without the presence of the $\sim 2 \mu\text{m}$ absorption band in our X-type Hungarias, pyroxene Fs compositions cannot be calculated using the equations of Gaffey et al. (2002) to determine if the surface mineralogy of these asteroids is equivalent to that of enstatite. We can, however, compare spectral band parameters of the 0.9 μm feature alone for evidence that the compositions of these objects are similar.

Figure III-7 shows the $\sim 0.9 \mu\text{m}$ band center versus band depth for the X-type Hungarias including the band center and depth of the largest family member 434 Hungaria for comparison. Most of the band centers range from 0.88 to 0.95 μm . Asteroid 5579 Uhlherr (family), however, gave a band center of 0.839 μm , and 34817 Shiominemoto (background) produced a band center of 0.826 μm , anomalously short for pyroxenes and compared to rest of the Hungaria X-types (Table III-3). The band centers and depths of Hungaria family and background X-types overlap each other considerably. Both family and background X-types cluster around $\sim 1\%$ band depth. It is unclear why the largest family member 434 Hungaria has a much greater band depth (4.40%) than the rest of the objects.

We tested the null hypothesis that Hungaria X-types are compositionally related by employing the two-sample case of the Kolmogorov-Smirnov (K-S) statistical test. The two-sample case of this statistic is calculated under the null hypothesis that the samples are drawn from the same distribution. Therefore, if Hungaria X-type family members are compositionally related to background X-types, then null hypothesis will not be rejected for empirical distributions functions (ECDF) calculated for both Hungaria family and background asteroids. We created two sets of ECDFs (x' for band center; x'' for band depth) for both family and background samples and performed the two-sample K-S test individually for each of these band parameters. The maximum difference between the two sets of ECDFs (D_{max}) for band center is 0.33, and 0.46 for band depths. The probability of the two-sample data being drawn from the same distribution (ρ_{KS}) is 50% and 14%, respectively. The results of the two-sample K-S tests for band center and band depth are listed in Table III-7. The results from these tests do not reject the null hypothesis that the X-type family members are compositionally related to the background X-types. Thus, the visual impression from Figure III-7 that the Hungaria family and background X-types are drawn from the same distribution is supported.

4.1.2. Hungaria X-type NIR Color Indices

The NIR spectral slopes of the Hungaria X-types asteroids observed during HARTSS generally show two distinct reddish slopes: a moderate reddish slope between ~ 0.7 and ~ 1.3 μm , and a shallower reddish slope between ~ 1.3 and ~ 2.5 μm (see Figure III-6). The distributions of spectral slopes between the family and background X-types appear to cluster together in color-color space. This is illustrated in Figure III-8 using NIR color indices ($0.85 - J$ and $J - K$) calculated for the same 27 Hungaria X-type asteroid spectra that we analyzed for a 0.9 μm absorption band in Section 4.1.1. The $J - K$ color index of family member 7488 Robertpaul is anomalously high due to the poor quality of the spectral data in the K -band (1.95 - 2.5 μm) for this object and is not shown in Figure III-8 for clarity. The NIR color indices of the largest family member 434 Hungaria is also included here for comparison.

The color indices shown in Figure III-8 were computed from the normalized reflectance spectra of Hungaria X-types using the equation:

$$m_{\lambda 1} - m_{\lambda 2} = 2.5 \log(R_{\lambda 2} / R_{\lambda 1}), \quad (3)$$

where $m_{\lambda 1} - m_{\lambda 2}$ is the color index for the two wavelengths, and $R_{\lambda 2} / R_{\lambda 1}$ is the corresponding reflectance ratio at those wavelengths. Solar colors have already been removed from the reflectance values via the division of a LSA star during data reduction; therefore using Eq. 3, the Sun would plot at (0,0) on Figure III-8. Uncertainties are estimated by propagation of errors in reflectance through the calculation in Eq. 3. The NIR color indices calculated by this method are listed in Table III-4 (including outlier 7488 Robertpaul).

We again utilized the two-sample case of the K-S statistic to test the null hypothesis that Hungaria family and background X-types are related. Although the main cluster of data points appears to have a positively-sloped linear trend, the trend is not aligned with either of the plotted color indices. To evaluate the null hypothesis that the Hungaria family and background are drawn from the same distribution we used the K-S statistic on three sets of ECDFs. First, we rotated axes to create one synthetic color index that measures the both color indices along a linear fit. Then, we also tested ECDFs for $0.85 - J$ and $J - K$. The synthetic color index calculated as follows is $x' = (J - K)\sin\theta + (0.85 - J)\cos\theta$, where $\theta = 27.6^\circ$. We found a maximum difference between the ECDFs ($D_{\max}$) of: 0.43 for the synthetic color index, 0.49 for $0.85 - J$, and 0.37 for $J - K$ (Table III-7). The probability of the two-sample data being drawn from the same distribution (ρ_{KS}) is 16% for the synthetic color index, 8% for $0.85 - J$, and 33% for $J - K$ (Table III-7). The results from these tests do not reject the null hypothesis that the Hungaria X-type family and background samples are related (i.e., drawn from the same parent population). Thus, the visual impression from Figure III-8 that the Hungaria family and background X-types are drawn from the same distribution is supported.

4.2. Hungaria S-complex Asteroid Band Parameter Analysis

Spectral band parameter analysis of diagnostic absorption features present in VIS and NIR spectra provide valuable clues regarding asteroid surface mineralogy. For mafic silicate minerals, these diagnostic absorptions arise due to electronic transitions that take place in the 3d orbital shell for elements of the first transitions series (i.e., Sc, Ti, V, Cr, Mn, Fe, Co, Ni, and Cu), as explained by crystal field theory (Burns, 1970). Of these metals, Fe has by far the highest

solar system elemental abundance, and it is a major constituent in the crystalline structure of the minerals olivine and pyroxene. These two mafic silicates are the most abundant minerals found on the rocky bodies of the solar system and within stony meteorites that provide us samples of those bodies. Spectra of asteroids that belong to the S-complex (DeMeo et al., 2009) expose broad, deep 1 and/or 2 μm absorption bands (Band I and II, respectively) indicating the presence of Fe^{2+} in olivine and/or pyroxene. Analysis of spectral band parameters related to these absorptions (band center, depth, area, and ratio of band areas) is commonly used as a gauge of olivine and pyroxene modal abundance and mineral chemistry (Adams, 1974; Cloutis et al., 1986; King and Ridley, 1987).

Recent studies have made use of chemical and spectral analyses of stony meteorite samples in order to directly compare their mineralogy to the asteroids from which they originate. Forming these asteroid-meteorite connections can greatly constrain the surface mineralogy for asteroids that are related to these meteorite groups. We analyzed the band parameters of VIS+NIR and NIR spectra from a subset ($n = 18$) of the S-complex Hungaria background asteroids to constrain surface mineralogy and to search for potential meteorite analogs. Spectra from five S-complex asteroids in our sample: 5627 1991 MA, 31793 1999 LB6, 53424 1999 SC3, 105445 2000 QW182, and 134746 2000 BO6 (see Figure III-13), are either lacking the VIS spectral data to adequately define the Band I shoulder near 0.7 μm , or the reflectance data are too noisy for useful mineralogical analysis and are not considered further.

4.2.1. Spectral Analysis Routine for Asteroids (SARA)

The spectral band parameters of S-complex Hungaria background asteroids were measured using the same methods as in HI (Lucas et al., 2017). Briefly, we used the IDL-based algorithm Spectral Analysis Routine for Asteroids or SARA²⁷ (Lindsay et al., 2015) to measure the band parameters (Band I and II centers, depths, areas, and band area ratio) of S-type (and two A-type) Hungaria background asteroids. This algorithm normalizes the broad Band I and II absorptions by fitting 5th order polynomials to the absorption band shoulders, fitting linear continua tangentially to the shoulders, and dividing by the continua. Band centers and depths are measured three times using 3rd through 5th order polynomial fits to the lower one-half of Band I and to the entirety of Band II. The averages of the three polynomial fits are adopted as the final band center values. For asteroids 4713 Steel, 6382 1988 EL, 9873 1992 GH, and 30856 1991 XE, the linear continuum undercut reflectance values on Band I before the continuum fit tangentially to the second shoulder. For these four objects, we fit 4th and 5th polynomial orders to the full band instead of the lower $\frac{1}{2}$ of the band. The 3rd order polynomial fit band values in these cases were consistently outliers and were discarded. The band depths are calculated as one minus a ten-point boxcar smooth of the reflectance at the band center wavelength position. Band areas are calculated as the area between continuum and the continuum divided reflectance data for the band. The Band Area Ratio (BAR) is the ratio of (Band II area)/(Band I area). Errors are calculated using a Monte-Carlo method, which generates 20,000 synthetic spectra for each polynomial order, producing 3 x 20,000 measurements to obtain band center and depth errors. The final 1 σ center and depth errors are defined as the average of the three error measurements. The measured band area is independent of the three polynomial fits, and the 1 σ band area error is taken as the standard deviation of the 20,000 measured areas (Lindsay et al., 2015).

²⁷ SARA is freely available via GitHub: <https://github.com/SeanSLindsay/SARA.git>.

For S-complex asteroid spectra collected with NICS at TNG, the longest wavelength data is at $\sim 2.30 \mu\text{m}$, too short for fitting a linear continuum to the red edge of Band II. The red edge used in SARA for this study is set at $2.44 \mu\text{m}$, as the SpeX spectrograph at IRTF loses sensitivity longward of $2.45 \mu\text{m}$. Lindsay et al. (2016) has developed equations regarding this “Red Edge Problem” for use with spectrographs where spectral sensitivity is lost beyond $2.40 \mu\text{m}$. This problem is of concern when comparing telescopic NIR spectrograph data of asteroids with shorter wavelength red edges to spectral data of meteorite analogs where NIR data can extend as far as $2.55 \mu\text{m}$ for some laboratory spectrographs. For four of our S-complex asteroids with NIR spectra collected with NICS: 1600 Vyssotsky, 1656 Suomi, 7173 Sepkoski, and 9873 1992 GH, we extrapolated the NIR reflectance data from $2.30 \mu\text{m}$ to $2.45 \mu\text{m}$ by fitting a 3rd order polynomial to Band II starting at the shoulder of the band (typically $\sim 1.6 \mu\text{m}$). We used a red edge of $2.44 \mu\text{m}$ in the SARA band parameter analysis for the Hungarias observed with NICS for consistency with fourteen other S-complex Hungarias observed with SpeX. For a comprehensive treatment regarding SARA see Lindsay et al. (2015). The band parameter results for the 18 S-complex Hungaria background asteroids are presented in Table III-5.

4.2.2. Band Parameter Temperature Corrections

The cold surface temperatures typical of Main-Belt and Hungaria asteroids will affect Band I and Band II positions and widths as band centers move to shorter wavelengths as the temperature of the surface decreases (Singer and Roush, 1985; Roush and Singer, 1987; Hinrichs et al., 1999; Schade and Wäsch, 1999; Moroz et al., 2000; Hinrichs and Lucey, 2002; Sanchez et al., 2012). Calculated equilibrium surface temperatures for Hungaria asteroids are typically around 200 K (see Table III-5). Therefore, corrections to shift the measured asteroid band parameters with respect room temperature ($\sim 300 \text{ K}$) are required. First, we estimate the equilibrium surface temperature (T_{eq}) of each Hungaria asteroid using the fast-rotator approximation:

$$T_{eq} = [L_{\odot}(1 - A)/16\pi\eta\epsilon\sigma r^2]^{1/4}, \quad (4)$$

where $L_{\odot}$ is the Solar luminosity ($3.828 \times 10^{26} \text{ W}$), A is the bolometric Bond albedo of the asteroid, η is the beaming factor (assumed to be unity), ϵ is the infrared emissivity of the asteroid (assumed to be 0.9), σ is the Stefan-Boltzmann constant, and r is the heliocentric distance of the asteroid at the time of observation. The fast-rotator approximation yields a reasonable estimate of the average daytime temperature on asteroid surfaces, although the actual temperature distribution across the dayside will vary considerably. We estimate Bond albedos for each Hungaria by multiplying its visible geometric albedo (Table III-2) by a phase integral of 0.39 (Bowell et al., 1989). For most Hungarias observed in HII, we use our new computed WISE visible geometric albedos (see § 2.4). For several Hungarias without WISE 12 and $22 \mu\text{m}$ thermal infrared detections, we used published visible geometric albedos from NEOWISE²⁸ based on flux observations at 3.4 and $4.6 \mu\text{m}$.

The Band II ($\sim 2 \mu\text{m}$) absorption feature is most affected by temperature variations, while temperature effects for Band I ($\sim 1 \mu\text{m}$) center are negligible (Sanchez et al., 2012). As a result, we correct our Band II centers and BARs back to 300 K with the following linear corrections from Sanchez et al. (2012):

²⁸ <http://adsabs.harvard.edu/abs/2012ApJ...759L...8M>

$$\Delta BIIC (\mu m) = 0.06 - 0.0002 \times T (K) \quad (5)$$

and

$$\Delta BAR = 0.00075 \times T (K) - 0.23. \quad (6)$$

The corrections from Eq. 5 and 6 are added to the measured Band II centers and BARs, respectively, for each Hungaria asteroid in order for these data to be compared to mineral and meteorite analog band parameter data from spectra acquired in the laboratory. The calculated equilibrium temperatures and temperature corrected values for Band II center and BAR ($BIIC_{tcorr}$ and BAR_{tcorr}) for each S-complex background asteroid are listed in Table III-5.

4.2.3 Hungaria S-type Mineralogy and Asteroid-Meteorite Connections

Cloutis et al. (1986) showed that Band I center is a sensitive indicator of olivine and orthopyroxene mineral composition (molar Fe^{2+} content), and that BAR is a function of the modal abundance of these two minerals while being nearly independent of mineral composition and particle size. Gaffey et al. (1993) used these spectral relationships as an approach to establish mineralogic interpretations and potential meteorite analogs for S-complex asteroids that display 1 and 2 μm absorptions. This approach separates Band I center versus BAR parameter space into eight S-subtypes, S(I) through S(VII) plus basaltic achondrites (BA). These subtypes represent a range of compositions: i) monomineralic and olivine-rich compositions [S(I)], ii) olivine (ol) + orthopyroxene (opx) mixtures [S(II)-S(VI)] (see ol+opx mixing line; Figure III-9a), iii) nearly pure pyroxene/pyroxene-feldspar-metal mixtures [S(VII)], and iv) basaltic achondrite compositions [BA]. The Band I centers and BARs for 16 S-type and two A-type Hungaria background asteroids are plotted in Figure III-9a, which denotes the regions of the Gaffey subtypes. The Gaffey S-subtype for each of the 18 asteroids is listed in Table III-6. Similar to the results found in HI (Lucas et al., 2017), most Hungaria S-complex background asteroids plot in the S(IV) ordinary chondrite (hereafter OC) “boot” of Gaffey et al. (1993), below the OC boot [sub-S(IV) in Table III-6], or in the S(VI) region. Asteroid 6382 1988 EL has a temperature corrected $BAR_{tcorr} = 1.64$, near the boundary of the S(VII) zone (Figure III-9a), which is thought to be analogous with the primitive achondrite lodranite group and/or the achondrite mesosiderite group (Gaffey et al., 1993). Asteroid 7173 Sepkoski plots near the boundary of the S(III) zone, thought to be analogous with the primitive achondrite ureilite group (Gaffey et al., 1993; Cloutis et al., 2010). Two A-type asteroids, 4125 Lew Allen and 4490 Bambery, plot in the S(I) region, at the olivine-rich end of the ol+opx mixing line (see thick gray curve in Figure III-9a).

The same 18 asteroids are plotted in Figure III-9b on an adapted version (Burbine et al., 2001; Dunn et al., 2013) of the Gaffey et al. (1993) S-subtype plot, which shows generalized spectral zones for five potential meteorite analogs for S-complex asteroids. Spectral calibrations have been developed to correlate asteroid spectral band parameters with detailed mineralogy of stony-meteorite samples for three of these meteorite analog zones: the BA zone (associated with 4 Vesta and Vesta family asteroids - Vestoids) using howardite, eucrite, and diogenite (HED) meteorites (Burbine et al., 2009), the S(IV) zone using *H*, *L*, and *LL* OC meteorites (Dunn et al., 2010a; Dunn et al., 2010b), and the S(I) zone using mono-mineralic olivine (*R*-chondrite, brachinite, pallasite) meteorites (Reddy et al., 2011; Sanchez et al., 2014).

Four Hungaria background asteroids plot within the S(IV) or OC boot zone in Figure III-9, and six additional asteroids plot just outside its boundaries: five sub-S(IV), and one (1656 Suomi) near the S(III)/S(IV) boundary (within error bars). Five sub-S(IV) asteroids (Figure III-

9a; Table III-6), plot within the acapulcoite-lodranite clan analog zone (Figure III-9b). None of our S-complex asteroids plot within the basaltic achondrite analog zone (Figure III-9), and mineralogical calibrations for the acapulcoite-lodranite clan spectral zone are currently under development (Lucas et al., 2016; 2018). We therefore concentrate our detailed mineralogic interpretations and potential meteorite analogs for the S(IV) OC zone. Interpretations of olivine mineral chemistry and asteroid-meteorite connections for two A-type asteroids, 4125 Lew Allen and 4490 Bamberg, are discussed in section 5.3. The Bus-DeMeo taxonomy, S-subtype, and potential meteorite analog for all 18 S-complex Hungaria background asteroids that were analyzed for band parameters are provided in Table III-6.

Dunn et al. (2010a and 2010b) derived equations for estimating the olivine and pyroxene mineralogies of the *H*, *L*, and *LL* clan through the spectral and cosmochemical analysis of 48 OC class meteorites. The equations relate Band I centers (BIC) to Fa (Eq. 7) and Fs (Eq. 8), and BAR to *ol/(ol+px)* (Eq. 9). With these equations ~80% of asteroids that plot within the OC boot should be correctly categorized as potential *H*, *L*, or *LL* parent bodies (Dunn et al., 2010a).

$$Fa = -1284.9 \times (BIC)^2 + 2656.5 \times (BIC) - 1342.3 \quad (7)$$

$$Fs = -879.1 \times (BIC)^2 + 1824.9 \times (BIC) - 921.7 \quad (8)$$

$$ol/(ol+px) = -0.242 \times BAR + 0.728 \quad (9)$$

We used these equations to compute mineralogy and potential meteorite analogs for 2150 Nyctimene, 6485 Wendeesther, 9554 Dumont, and 16421 Roadrunner, which clearly plot within the OC boot. These equations may also offer reasonable estimates of mineralogy for asteroids that plot outside, but in the vicinity of, the OC spectral zone. We therefore also calculated mineralogies for five sub-S(IV) asteroids and for 1656 Suomi [S(III)/S(IV) boundary], but the results for these six objects should be interpreted with caution. The mineralogical results [Fa, Fs, and *ol/(ol+px)*] for these ten S-complex asteroids using the Dunn et al. (2010a) equations are listed in Table III-6. The uncertainties inherent in the calibration equations are: Fa ± 1.3 mol%, Fs ± 1.4 mol%, and ± 0.03 *ol/(ol+px)* (Dunn et al., 2010a), and are larger than band parameter errors (Table III-5) propagated through the equations.

Figure III-10a illustrates these results graphically for olivine compositions: Fa versus *ol/(ol+px)*. Results for pyroxene compositions, Fs versus *ol/(ol+px)*, are virtually identical and are not shown. The olivine compositions, when plotted in relation to XRD- and spectrally-derived regions of *H*, *L*, and *LL* OCs (Dunn et al., 2010a) indicate that the probable meteorite analogs for the four S(IV) background asteroids (red squares) are relatively Fe-rich *L* and/or *LL* chondrite meteorites. One S(III)/S(IV) asteroid, 1656 Suomi, has error bars that overlap with the S(IV) OC boot (Figure III-9) and is most likely related to *L* chondrites. Five sub-S(IV) asteroids (blue diamonds) are relatively Fe-poor (Table III-6) compared to the *L* and/or *LL* chondrite objects and plot within or below the lower boundary of the *H* chondrite spectrally-derived region, but outside of the XRD-derived region (Figure III-10a). These sub-S(IV) asteroids plot within (or within error bars) of the acapulcoite-lodranite clan spectral zone of Figure III-9b. However, these objects overlap spectrally (Figure III-9) with the lower region of the S(IV) OC boot and mineralogically with the *H* chondrites (Figure III-10a). It remains unclear, therefore, whether sub-S(IV) Hungarias are related to *H* chondrites or to acapulcoite-lodranite clan meteorites (Table III-6).

4.2.4. *Hungaria End Member Mineralogy and Asteroid-Meteorite Connections*

During HII we uncovered three End-member taxonomic types, two rare olivine-dominated A-type asteroids (4125 Lew Allen and 4490 Bambery), and one asteroid that was classified as D-type (6271 Farmer). The spectra of 4125 Lew Allen and 4490 Bambery were collected during a study of 12 olivine-dominated asteroids (Sanchez et al., 2014) and at present are the only known Bus-DeMeo taxonomic A-type objects in the Hungaria region. The VIS+NIR spectra of both of these asteroids (Figure III-13) are included in our mineralogical analysis of Hungaria background objects. Sanchez et al. (2014) distinguished two classes of olivine-dominated asteroids: one whose spectra only exhibit the $\sim 1\ \mu\text{m}$ absorption feature, called – “monomineralic-olivine” asteroids, and another whose spectra display the $\sim 1\ \mu\text{m}$ feature plus a weak $\sim 2\ \mu\text{m}$ absorption feature, called – “olivine-rich” asteroids. The spectral properties of 4125 Lew Allen and 4490 Bambery are analogous with monomineralic-olivine asteroids, as both asteroids only exhibit the broad, deep $\sim 1\ \mu\text{m}$ absorption feature and lack a detectable $\sim 2\ \mu\text{m}$ feature due to pyroxene. We report their Band I centers and errors (Table III-5) and potential meteorite analogs (Table III-6) as analyzed in Sanchez et al. (2014). These A-types plot in the S(I) region of Figure III-9a, and in the olivine meteorite spectral zone of Figures III-9b.

5. Discussion

5.1 *Spectral Homogeneity of the Hungaria Family*

Throughout both phases of HARTSS we have observed a total of 24 Hungaria family members (19 from HII; 5 from HI). The taxonomic distribution within the family reveals that X-types comprise about 90% of family members (Figure III-3). Although X-type spectra are relatively featureless, we were still able to analyze Hungaria family members for their taxonomy, albedos, and subtle NIR spectral properties. Using these lines of evidence, we can determine whether the collisional family is compositionally homogeneous (or conversely heterogeneous). This information can then provide clues as to the composition and structure of the Hungaria family parent asteroid.

First, we consider the taxonomic distribution of the Hungaria family. All 24 family members have relatively, flat, featureless spectra (Figure III-12). The majority ($\sim 88\%$) of family members are classified as X-type objects: 21 X-types, two C-types, and one blue-sloped B-type were identified within the Hungaria family during HARTSS (Table III-3). For relatively featureless spectra such as X- and C-complex asteroids, a unique spectral type is often difficult to distinguish with NIR-only data. The additional, subtle information contained within VIS wavelength data allows for the unambiguous distinction between these two complexes in the Bus-DeMeo taxonomic scheme. Unfortunately, X-type 4764 Joneberhart is the only Hungaria family member in our HII sample including VIS spectral data. Three family members have C-complex taxonomies (Figures III-2 and 3; Table III-2): 13245 1998 MM19 is a Cb-type, 21261 1996 FF is a blue-sloped B-type, and 55854 Stoppani (1996 VS1) is a Cgh-type (Stoppani observed in HI; Lucas et al., 2017). Our spectral data for these asteroids is NIR-only so the taxonomic classification for these objects is ambiguous. Therefore it remains uncertain if these three Hungaria family members are truly carbonaceous objects. The consistent spectral shapes

(and therefore taxonomies) of the Hungaria family asteroids observed during HARTSS supports the hypothesis that the Hungaria family parent body was compositionally homogenous.

In addition to information gathered from spectral observations and the taxonomic classification of asteroid family members, albedo measurements provide fundamental physical data to help determine if the members of an asteroid family are truly related. For example, if the original parent body of an asteroid family was homogeneous in composition (i.e., did not experience differentiation), then surviving fragments of the catastrophic disruption should reflect the homogeneous composition of the progenitor, and albedos of the fragments will be similar. Conversely, if the parent body experienced differentiation and then underwent catastrophic disruption, the surviving fragments should be compositionally heterogeneous and exhibit differences in albedo. Therefore, albedo measurements of numerous members of an asteroid family can provide a first order diagnostic test of the homogeneity or heterogeneity of an asteroid family.

In order to test the above scenario, we can inspect C-type and X-type family member albedos to determine if they are consistent with the inferred surface composition for that taxonomy. C-type objects have low albedos (avg. $p_v=0.083\pm0.076$; DeMeo and Carry, 2013), while E-types (BusDeMeo Xc-type) typical of the Hungaria family have the highest albedo among any other asteroid taxonomic type (avg. $p_v=0.536\pm0.247$; DeMeo and Carry, 2013). Thus, confirmation of the taxonomic type by verifying if the asteroid has an albedo consistent with that taxonomy can sometimes be instructive. If the three C-complex Hungaria family members are truly carbonaceous, they should have low albedos consistent with this composition. Unfortunately, all these family members do not have published albedo values, nor did they have WISE detections and therefore were not included in our new calculated albedos (§ 2.4) for Hungaria region asteroids (Table III-2). We suspect that new albedo measurements and VIS spectral data for these asteroids would reveal them to be related to X-type family members. On the other hand, an inspection of albedos listed in Table III-2 demonstrates that there is no case in which an X-type family member has a low albedo consistent with carbonaceous compositions. There are three X-types (15692 1984 RA, 39791 Jameshessner, and 45874 2000 WM3) that have calculated albedos consistent with S-types (avg. $p_v=0.258 \pm 0.087$, DeMeo and Carry, 2013) (Table III-2). However, all three have relatively flat spectral shapes that are inconsistent with this albedo and the spectral shape typical of S-types. The high albedos of our Hungaria family asteroids (Table III-2) are consistent with those found previously found for E-types (Tedesco et al., 2002; Clark et al., 2004; Fornasier et al., 2008) and supports the hypothesis that the Hungaria family parent body was homogeneous.

The relatively featureless taxonomic X-complex is interpreted to be associated with a wide range of compositions. X-subtype asteroids have been associated with metallic material, with carbonaceous chondritic material (or carbon-coated), and with non-chondritic silicate compositions. Regarding the latter, the existence of crystalline silicates on the surface of an asteroid that is spectrally featureless in the NIR cannot be entirely ruled out. An asteroid with a surface mineralogy corresponding to Fe-poor (Mg-rich) olivine or pyroxene (forsterite or enstatite, respectively) would not exhibit the strong 1 and/or 2 μm absorption bands due to these minerals. The magnesium end members of these common silicates contains so little Fe^{2+} in the crystalline structure that absorption features are either very weak, or they are absent altogether. If absorptions are present but weak, analysis of these subtle absorption features can lead to correlations with specific minerals that may constrain the surface mineralogy of these otherwise “featureless” asteroids (Hardersen et al., 2005). Subtle features attributed to Fe-poor mafic

silicates have been detected in the spectra of E-type (Bus-DeMeo Xc-type) asteroids (Gaffey et al., 1992; Kelley and Gaffey, 2002; Clark et al., 2004). These features include low to medium reddish slopes ($0.2 < \text{slope} < 0.38$) and weak spectral absorptions that can appear at $\sim 0.49 \mu\text{m}$, $\sim 0.9 \mu\text{m}$, and $1.8 \mu\text{m}$.

We were able to search the spectra of 17 X-type family members observed during HII, plus the largest collisional fragment, 434 Hungaria, for subtle clues as to their composition (see § 4.1.1 and § 4.1.2). Assuming that the Hungaria family parent body was compositionally homogeneous, we would expect all family members to have spectral properties very similar to 434 Hungaria. 434 Hungaria exhibits an absorption feature at $\sim 0.94 \mu\text{m}$ (Figure III-7) and a relatively shallow spectral slope (Figure III-8), similar to the other 17 X-type family members analyzed for spectral properties in this study. Clark et al. (2004) point out that whereas all Tholen E-types (even those in the Main Belt) share these general characteristics, they differ in details, including whether or not the weak $1.8 \mu\text{m}$ feature is present. We were able to measure a subtle $\sim 0.9 \mu\text{m}$ absorption feature ($>1\%$ band depth) attributed to Fe-poor orthopyroxene (i.e., enstatite) in 15/18 Hungaria family X-types, however, none of these asteroids exhibited evidence of a $\sim 1.8 \mu\text{m}$ absorption feature (see § 4.1.1). Clark et al. (2004) showed that E-types in the Hungaria region display the $\sim 0.9 \mu\text{m}$ absorption band only and conclude that these asteroids are spectrally consistent with enstatite achondrites (i.e., aubrites). Similarly, other workers have proposed that E-types from the Hungaria region are associated with the aubrite meteorite group (Gaffey et al., 1992; Kelley and Gaffey, 2002; Čuk et al., 2014). Furthermore, the high albedos of E-type asteroids are consistent with the values found for aubrite meteorites (0.23 to 0.48 range, $n=4$; Cloutis and Gaffey, 1993), but inconsistent with lower albedos found for other enstatite-rich meteorites groups such as enstatite chondrites (0.16 to 0.26 range; Vernazza et al., 2009).

Our analyses of the spectral properties of Hungaria family members presented here implies a compositionally homogeneous parent body. Based on the inferred meteorite association with aubrites, this parent body formed under reduced conditions and experienced fully-melted igneous processes. Likewise, Gaffey et al. (1992) suggested that aubrite meteorites may represent pyroxene-rich mantle material from a differentiated asteroid. If aubrites truly are representative of igneous mantle material, then the Hungaria parent body was itself a collisional fragment that originated on a differentiated, heterogeneous parent body very early in Solar System history (Wadhwa et al., 2006).

5.2 Compositional Diversity of the Hungaria Background

Throughout both phases of HARTSS we have observed 68 total Hungaria background asteroids (31 from HII; 34 from HI; 3 during both). The taxonomic distribution within this background reveals that stony S-types make up $\sim 3/4$ of asteroids found there (Figure III-3). Yet, this fraction exhibits considerable spectral diversity (Figure III-12) and comprise a variety of surface compositions, which are primarily mixtures of olivine and pyroxene. Forty-eight S-type and two olivine-dominated A-type asteroids have been identified within the Hungaria background during HARTSS. We were able to perform band parameter analyses and determine potential meteorite analogs for 42 out of these 50 asteroids. These include 18 background asteroids from HII (Figure III-9; Table III-6) and 24 background asteroids analyzed during HI (Lucas et al., 2017). Figure III-11 shows Band I versus BAR for these 42 objects and we discuss their potential meteorite analogs below.

First, we consider ordinary chondrite meteorite analogs for these 42 Hungaria background asteroids. We were able to calculate detailed mineralogies [Fa, Fs, and $ol/(ol+px)$] for ten S-complex background Hungarias from HII that plot in or near the S(IV) “OC boot” spectral region (Figure III-9; Table III-6). Figure III-10a illustrates these results graphically for olivine compositions: Fa versus $ol/(ol+px)$. Rather than discuss just these ten OC-like asteroids from HII, we combine these with 18 S-complex background asteroids from HI that plot in or near the S(IV) OC boot (Figure III-10b). Overall, out of these 28 asteroids with potential OC meteorite analogs shown in Figure III-10b, we find the following abundances: ~25% H chondrite like mineralogies [7/10 sub-S(IV) objects], ~30% L chondrite like mineralogies, ~20% LL chondrite like mineralogies, and 25% have mineralogies that cannot be distinguished between H, L, or LL chondrites. The L chondrite like abundance could be as high as ~45%, and the LL abundance as high as ~35%, if we include four asteroids that cannot be discriminated between L or LL chondrite mineralogies (Figure III-10b). There are ten relatively Fe-poor sub-S(IV) asteroids (blue diamonds) in Figure III-10b that plot just within or below the lower boundary of the H chondrite spectrally-derived region (Figure III-10). Including the three objects below the spectrally-derived box would bring the abundance of H chondrite like mineralogies to 35%. However, none of these asteroids fall within the H chondrite XRD-derived region of Figure III-10b. All ten plot within (or within error bars) the acapulcoite-lodranite spectral zone (Figure III-11). It is unclear whether these ten Hungarias have mineralogies consistent with H chondrites or with these primitive achondrite meteorites.

Figure III-9 shows a cluster of four S-complex background Hungarias observed during HII that plot in the Gaffey S(VI) spectral region (Figure III-9a). Also, 6382 1988 EL has the highest BAR value of all 18 background S-complex objects and plots on the boundary of the Gaffey S(VII) spectral region. An inspection of Figure III-11 shows a total of nine Hungaria background S-complex asteroids with high BAR values that are not situated in or near the S(IV) OC boot. This includes six Hungarias that have higher BARs (1.2 - 1.5) than that of the acapulcoite-lodranite clan spectral zone and three Hungarias (1019 Strackea, 6382 1988 EL, and 17408 McAdams) with $BAR > 1.5$ that plot near the Gaffey S(VII) spectral region. Although these three asteroids have error bars that overlap with the basaltic achondrite (BA) zone, these asteroids have S-complex taxonomies (Sw, Sq, and Sr, respectively) and shallow Band II absorptions relative to pyroxene-rich V-types and therefore are not consistent with basaltic achondrite mineralogies.

So what potential meteorite analogs are associated with the S(VI) and S(VII) subtypes? The $ol+opx$ mixing line of Cloutis et al. (1986) bisects the Gaffey S(VI) and S(VII) spectral regions, so the mineralogies of their potential meteorite analogs should be largely composed of olivine and pyroxene. The mineralogy of the S(VI) subtype should be composed of a pyroxene-rich mixture of $ol \pm opx$ and the S(VII) subtype should be dominated by orthopyroxene. Gaffey et al. (1993) invokes primitive achondrites of the winonaite (and IAB irons) and lodranite groups as possible meteorite analogs for the S(VI) and S(VII) spectral regions. However, spectral band parameter measurements of a suite of primitive achondrites from the acapulcoite-lodranite clan meteorite show that these meteorites cluster in the sub-S(IV) region in this parameter space and typically have BAR values < 1.05 (Lucas et al., 2016; Lucas et al., 2018 *in preparation*). Based on these results it is unlikely that S(VI) subtype Hungarias (Figure III-9a) are related to primitive achondrites of the acapulcoite-lodranite clan. Until further mineralogic and spectral analyses are acquired of other primitive achondrite meteorite groups (e.g., winonaites) the probable meteorite analog for S(VI) subtype asteroid parent bodies remains uncertain.

The S(VII) meteorite analog spectral region plots below the basaltic achondrite (BA) region in Band I center versus BAR parameter space (Figure III-9a) and Gaffey et al. (1993) suggest mesosiderites as a possible meteorite analog for this S-subtype. Mesosiderites are stony-iron meteorites composed of sub-equal proportions of silicates and FeNi metal. The silicate fraction typically consists of magnesian-rich orthopyroxene and Ca-rich plagioclase (Burbine et al., 2007). The mineralogy of this silicate fraction resembles basaltic clasts and in this regard is similar to basaltic achondrites of the HED clan, which consist of a suite of basaltic and gabbroic rocks generally accepted to originate from 4 Vesta (McCord et al., 1970; McSween et al., 2013; Russell et al., 2015). However, in contrast to the HEDs, mesosiderite silicates also contain a minor component (typically <10 vol%) of olivine as individual mineral fragments and dunitic clasts, therefore it is improbable that these materials formed on the same parent body (Wadhwa et al., 2003; Burbine et al., 2007). These stony-irons are thought to be a mixture of material from the pyroxene-rich crust (or px-rich mantle?) and the metallic core of a differentiated parent body (Wadhwa et al., 2003). Mesosiderites are the most likely meteorite analog for S(VII) subtype 6382 1988 EL (Figure III-9a; Table III-6) observed during HII, and for S(VII) subtypes 1019 Strackea and 17408 McAdams observed during HI (Figure III-11).

X-complex asteroids are not just restricted to the collisional family; the Hungaria background of mostly S-types contains ~24% X-complex objects (Lucas et al., 2017; Figure III-3). Comparing spectral analyses of X-type family members with those spread among the background provides clues to whether these asteroids are compositionally related. There is no *a priori* reason to presume that the parent body that suffered the catastrophic disruption which formed the family was the only asteroid with a similar composition located in the Hungaria region. Hungaria background X-types observed during HII exhibit similar spectral properties (Figures III-7 and III-8) and albedos (Table III-2) to Hungaria family X-types. The results of two-sample K-S statistical tests (Table III-7) from analyses of these spectral properties (e.g., subtle 0.9 μm absorption feature; near-infrared color indices) for family and background X-types do not reject the null hypothesis that the X-type background objects are compositionally related to X-type family members (i.e., drawn from the same parent population). It therefore seems likely that the Hungaria family parent body was merely one enstatite-like object out of a population of asteroids with similar composition residing in the Hungaria region. The relatively recent collision that shattered the Hungaria parent body at ~275 Myr (Milani et al., 2010) to ~500 Myr (Warner et al., 2009) ago permeated the Hungaria region with X-type fragments. The pervasiveness of these family fragments can lead to overestimates of the actual relative abundance, which is ~1/4 (Table III-3), of enstatite-like material in the Hungaria region.

Here, we find similar distributions of Band I center and BAR, and therefore meteorite analogs, for Hungaria background S-complex asteroids as uncovered during HI (Figure III-11). We confirm our conclusions regarding Hungaria background S-complex asteroids as revealed in HI: the mineralogies of OC-like background objects observed during HII show similar compositions and relative abundances between the H, L, and LL OC groups (Figure III-10). A negative detection can also be a result, and as observed in HI, H chondrite like mineralogies appear to be absent in the Hungaria region (Figure III-11). Finally, the variety of surface compositions revealed through these asteroid-meteorite connections for Hungaria background asteroids exhibit the full range of petrologic evolution, unmelted, nebular L and/or LL OCs, partially-melted primitive achondrites, and fully-melted igneous aubrites (and possibly igneous mesosiderites). Perhaps these diverse stony asteroids are the shattered remnants from an ancient, internally-differentiated, parent body that was covered with a primitive chondritic crust (Elkins-

Tanton et al., 2011). Alternatively, the assortment of stony compositions found among the Hungaria background may simply reflect compositional mixing that took place in the primordial asteroid belt due to giant planet migration (Tsiganis et al., 2005; Gomes et al., 2005; Walsh et al., 2012), which occurred before the Hungarias were displaced to their current high-inclination orbits (Bottke et al., 2012).

5.3 Peculiar Hungaria Region End Members

We found two rare olivine-dominated A-type asteroids, 4125 Lew Allen and 4490 Bamberg, among the Hungaria background. These A-types only represent only 3% of the Hungaria background population (Figure III-3), a slightly higher relative proportion than the ~1% (Lucas et al., 2012) found among ~2150 asteroids observed during three major visible-wavelength taxonomic surveys. There are several possible meteorite analogues for A-type asteroids: two with origins that are magmatic – dunites and pallasites, two that are possible residues of partial melting – ureilites and brachinites, and one with a nebular origin – the R chondrites. R chondrites formed under highly-oxidizing nebular conditions, higher than that of nebular OCs. These meteorites are composed primarily of olivine (typically 65 to 78 vol%) and olivine compositions (Fa₃₈₋₄₁) in equilibrated samples (R4-R6) reflect these high oxygen fugacity (fO_2) conditions (Bischoff et al., 2011). Contrary to findings of Sunshine et al. (2007), who found that olivine-dominated asteroids are likely associated with Mg-rich igneous olivine compositions (pallasites = Fa₁₂), mineral chemistries found for monomineralic-olivine asteroids are much more fayalitic (Fa_{33.7} for Lew Allen; Fa_{43.5} for Bamberg) (Sanchez et al., 2014). Based on their olivine mineral chemistry and monomineralic nature, primitive achondrites of the brachinite group are the best meteorite analog for 4125 Lew Allen, and brachinites or nebular R chondrites are the most probable meteorite analogs for 4490 Bamberg (Table III-6).

We found one D-type asteroid, 6271 Farmer, among the Hungaria background. Our NIR spectrum (Figure III-13) of this object is featureless with a very steep reddish slope, and was found to have a D-type taxonomy using the Bus-DeMeo classification system. D-type asteroids make up a significant fraction of outer Main-belt asteroids (Gradie and Tedesco, 1982; DeMeo and Carry, 2013) and are one of the dominant spectral types among the Jupiter Trojans (e.g., Emery et al., 2011). Previously, very few D-types have been found within the inner Main-belt and among the near-Earth Object (NEO) population. However, DeMeo et al. (2014) confirmed the presence of three interloper D-types among in the inner Main-belt by collecting NIR spectra of SDSS D-type candidates. Although D-types lack detectable absorption bands, they are thought to have surfaces rich in organic compounds (Gradie and Veverka, 1980; Cruikshank and Kerridge, 1992). Our calculated albedo of 6271 Farmer is significantly higher ($p_v=0.319$) than the median albedo of $p_v=0.09$ found for other inner Main-belt D-types (DeMeo and Carry, 2013). Lacking distinguishable absorption features, it is possible that D-type 6271 Farmer is compositionally distinct from D-type asteroids that reside in the inner Main-belt or further out in the Solar System (DeMeo et al., 2014). Until more D-types are identified in the inner Main-belt and Hungaria region, compositional inferences of their surfaces and how these apparent interlopers arrived in their current locations will remain unexplained questions.

6. Summary

Previous studies regarding the homogeneous or heterogeneous nature of asteroid collisional families relied mainly on physical properties such as color and albedo information, which provide limited information regarding the surface composition of asteroid family members. Analysis of VIS+NIR spectral data of collisional family members allows for more detailed taxonomic and compositional inferences of their surfaces. In this second phase of HARTSS, we focus our spectral analyses on Hungaria family members. Hungaria family members constitute the closest samples to the Earth from a collisional family, therefore our spectral data set of 19 family asteroids acquired during HARTSS II permits analyses of smaller family fragments than accessible for Main Belt families.

We also acquired NIR spectra for 31 more Hungaria background asteroids during HARTSS II, significantly increasing the sample size of asteroids observed from the background population. In total, we have acquired NIR spectra of 92 Hungaria asteroids (24 family; 68 background) throughout both phases of HARTSS. These spectral data provide information regarding the surface compositions of these preserved samples from the inner-most regions of the primordial asteroid belt. Based on taxonomic classifications, independently calculated WISE albedo determinations for 428 Hungaria asteroids, and near-infrared (NIR) spectral properties of Hungaria family members and background asteroids, we arrive at several conclusions, which are summarized below.

We corroborate our findings as established in HARTSS I; stony S-complex asteroids dominate the Hungaria background (~71%). The spectral diversity of these S-complex asteroids represent a variety of surface compositions. The mineralogies of ordinary chondrite like background objects observed during HARTSS II show similar compositions to those uncovered during HARTSS I; they are most likely related to the L and/or LL groups. As observed in HARTSS I, H chondrite like mineralogies appear to be absent within the Hungaria region. Background asteroids that cluster in the sub-S(IV) spectral region in Band I center versus BAR band parameter space are likely related to acapulcoite-lodranite like mineralogies. Furthermore, about one-fourth of the background population exhibit similar spectral properties and albedos to family X-types, which are likely related to enstatite achondrites (i.e., aubrites). Several S-complex background asteroids plot in the S(VI) and S(VII) subtype regions and may be associated with other primitive achondrite groups and/or stony-iron mesosiderite meteorites, however their potential meteorite analogs remain uncertain.

Spectral observations of Hungaria family members provides an opportunity to open a window into the interior composition of the parent body. Surviving fragments of an asteroid collisional family typically exhibit similar taxonomies, albedos, and spectral properties. Spectral analysis of X-type Hungaria family members for a subtle ~0.9 μm absorption feature that may be attributed to Fe-poor orthopyroxene and the analysis of NIR color indices (0.85- J ; J - K) indicate spectral homogeneity among Hungaria family members. Furthermore, independently calculated WISE albedo determinations for 428 Hungaria asteroids presented herein corroborate these findings.

Spectral observations of 92 Hungaria region asteroids acquired during both phases of HARTSS uncover a compositionally heterogeneous background population of stony asteroids and spectral homogeneity down to the smallest observed family members (~2 km diameter). The variety of surface mineralogies revealed through spectral band parameter analyses for background asteroids exhibit a full range of petrologic evolution, unmelted, nebular L and/or LL

ordinary chondrites, partially-melted primitive achondrites, most likely acapulcoite-lodranite like mineralogies, and fully-melted igneous aubrites (and possibly igneous mesosiderites). Analyses of the spectral properties of family members presented herein implies a compositionally homogeneous parent body. This parent body was likely consistent in composition with aubrites and therefore formed under reduced conditions and experienced igneous processing. If aubrites truly are representative of igneous mantle material, then the Hungaria parent body was itself a collisional fragment that originated on a differentiated, heterogeneous parent body very early in Solar System history.

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Appendix III-A

Table III-1. VIS and NIR spectroscopy observational circumstances.

Object	Date (UT)	Time ^e (UT)	Airmass	Mag. (V)	<i>r</i> (AU)	<i>g</i> (°)	<i>t_{int}</i> (min)	Solar analog
1355 Magoeba	2016 Sep 08	06:02	1.006	16.2	1.878	29.5	16	HD 177082
1600 Vyssotsky ^c	2014 May 12	22:58	1.029	15.4	1.846	28.5	12	SAO 82156
1656 Suomi ^c	2014 May 13	22:00	1.107	16.1	1.831	32.7	12	BD+15 2238
1920 Sarmiento	2014 Dec 17	06:36	1.021	16.3	1.771	22.7	24	SAO 93023
2083 Smither	2016 Sep 08	08:33	1.146	16.3	1.965	24.8	16	HD 182081
2150 Nyctimene	2014 Oct 08	10:34	1.030	14.7	1.845	8.8	32	HD 13043
3043 San Diego	2014 Aug 20	12:53	1.395	15.0	1.784	11.7	20	HD 220022
3447 Burckhalter ^c	2014 May 13	23:11	1.498	15.6	1.938	30.3	12	BD+07 2313
4125 Lew Allen ^b	2003 Aug 15	-	1.00	15.0	1.703	21.2	24	BS5996
4490 Bambery ^b	2003 Feb 17	-	1.04	15.7	1.878	24.2	36	Hyades 64
4531 Asaro	2014 Dec 17	05:16	1.132	16.7	1.862	25.0	48	BD+45 411
4713 Steel	2015 Feb 22	08:33	1.119	15.7	1.971	17.9	16	SAO 42627
4764 Joneberhart	2016 Aug 11	08:31	1.318	15.4	1.841	6.5	32	HD 195204
5378 Ellyett	2014 Dec 18	13:23	1.152	16.4	1.784	29.0	32	SAO 136813
5477 Holmes ^d	2015 May 09	06:10	1.006	15.9	1.938	9.1	30	SAO 184153
5579 Uhlherr	2016 Nov 27	12:44	1.265	15.9	1.947	6.8	16	HD 26749
5627 (1991 MA) ^c	2014 May 14	03:31	1.310	16.2	1.838	16.1	24	SAO 160485
6029 Edithrand	2015 Feb 22	13:20	1.079	16.2	1.784	22.1	16	SAO 44279
6141 Durda	2016 Aug 12	10:21	1.107	16.2	1.897	11.1	16	HD 198273
6271 Farmer	2016 Sep 08	07:19	1.029	16.0	1.930	19.8	16	HD 206828
6382 (1988 EL)	2015 Feb 22	11:59	1.014	15.0	1.744	10.4	16	BD+11 2369
6485 Wendeesther	2014 Dec 17	11:47	1.108	15.7	1.784	18.4	16	HD 55316
6646 Churanta	2015 Feb 22	05:44	1.441	16.1	1.797	15.7	32	SAO 80520
6901 Roybishop	2015 Feb 22	06:58	1.058	16.1	1.895	21.9	16	SAO 115185
7173 Sepkoski ^d	2015 May 09	07:46	1.031	16.2	1.960	15.5	35	SAO 185145
7488 Robertpaul ^c	2014 May 14	00:02	1.003	17.2	1.872	26.2	30	SAO 63954
7783 (1994 JD)	2014 Dec 18	12:26	1.035	15.6	1.791	8.7	16	SAO 79030
7829 Jaroff	2016 Aug 11	09:44	1.015	16.7	2.051	12.9	32	SAO 126270
8026 Johnmckay	2015 May 11	11:22	1.250	16.8	2.026	5.2	24	SAO 158686
9068 (1993 OD) ^d	2015 May 09	09:34	1.010	17.1	2.017	27.6	40	SAO 211685
9554 Dumont	2014 Dec 17	11:13	1.024	16.0	1.820	6.7	16	SAO 59236
9873 (1992 GH) ^d	2015 May 09	03:49	1.061	16.0	1.943	16.4	38	HD 128245
13245 (1998 MM19) ^c	2014 May 13	02:14	1.109	16.8	1.877	13.6	36	HD 137973
15692 (1984 RA)	2015 Feb 22	09:55	1.005	16.5	1.925	4.5	32	SAO 98981
16421 Roadrunner	2015 Feb 22	11:27	1.261	16.2	1.817	13.5	16	SAO 155987

Table III-1. (*continued*).

Object	Date (UT)	Time^e (UT)	Airmass	Mag. (V)	<i>r</i> (AU)	<i>g</i> (°)	<i>t_{int}</i> (min)	Solar analog
16585 (1992 QR)	2016 Aug 11	13:36	1.112	16.7	1.784	22.9	64	HD 224383
16589 Hastrup	2016 Aug 11	12:56	1.375	16.5	1.834	19.6	24	HD 224693
20231 (1997 YK)	2016 Oct 21	14:04	1.061	16.6	1.784	28.2	16	HD 30854
21261 (1996 FF)	2015 May 11	10:08	1.067	16.6	2.002	9.4	32	SAO 140573
24077 (1999 TD233)	2015 May 11	09:16	1.391	16.0	1.872	2.1	24	SAO 183185
24654 Fossett	2014 Dec 17	07:20	1.029	17.0	2.034	18.3	64	SAO 110874
25318 (1999 CH12)	2015 Feb 22	09:07	1.084	16.4	1.894	1.1	24	SAO 99057
26074 Carlwirtz	2014 Dec 17	10:22	1.068	16.5	1.811	12.8	32	HD 33344
30856 (1991 XE)	2015 May 11	12:16	1.078	15.9	1.893	13.6	32	HD 146564
30935 Davasobel	2014 Dec 17	14:02	1.156	16.3	1.806	16.0	24	SAO 41869
31793 (1999 LB6) ^c	2014 May 13	04:05	1.128	16.9	1.974	17.6	36	SAO 102326
34817 Shiominemoto	2016 Sep 08	07:54	1.066	15.7	1.659	25.2	16	HD 206828
39791 Jameshesser	2015 Feb 22	07:37	1.262	16.3	1.889	4.2	24	SAO 98763
45874 (2000 WM3)	2016 Aug 11	10:53	1.063	17.3	1.879	13.9	72	SAO 126270
53424 (1999 SC3) ^a	2012 Dec 14	14:24	1.066	17.9	1.871	23.5	40	Hyades 64
53431 (1999 UQ10)	2014 Dec 17	12:22	1.357	16.9	1.934	20.4	64	SAO 14154
53433 (1999 VV10)	2014 Dec 17	08:58	1.021	16.8	1.750	15.1	48	HD 23169
105445 (2000 QW182) ^c	2014 May 13	00:27	1.159	16.8	1.874	13.9	36	SAO 139742
134746 (2000 BO6) ^a	2015 Feb 17	09:12	1.001	18.1	1.727	11.4	32	Hyades 64

^a Data from MIT-UH-IRTF Joint Campaign for NEO Reconnaissance

^b Data from Sanchez et al. (2014)

^c NIR spectra obtained with NICs at TNG

^d VIS spectra obtained with the Goodman Spectrograph at SOAR

^e Time given for beginning of observation

Table III-2. Hungaria asteroid orbital and physical properties and Bus-DeMeo (BDM) taxonomy.

Object	a (AU)	i (°)	H_v	p_v^a	p_v^b	D (km)	Population	BDM Taxonomy ^c
1355 Magoeba	1.854	22.826	12.9	0.582	0.670	4.31	background	L,Xe
1600 Vyssotsky	1.849	21.172	12.7	0.321	-	7.41	background	Sw
1656 Suomi	1.878	25.068	13.0	0.156	0.180	7.79	background	Sw
1920 Sarmiento	1.930	22.802	14.2	0.466	0.436	2.95	family	Xe,Xn
2083 Smithers	1.872	18.452	13.2	0.613	0.674	3.75	background	Xe,Xc
2150 Nyctimene	1.913	25.325	13.2	0.220	0.235	6.39	background	Sw
3043 San Diego	1.926	21.789	13.5	0.252	0.250	5.32	background	Sw
3447 Burckhalter	1.991	20.717	12.3	0.779	-	6.00	background	L,Xe
4125 Lew Allen	1.921	20.440	13.2	0.172	0.207	6.56	background	A
4490 Bamberg	1.931	26.117	13.2	0.141	-	9.32	background	A
4531 Asaro	1.862	23.978	14.5	0.988	0.453	2.49	background	Xe,Xc
4713 Steel	1.962	22.669	13.3	0.381	0.205	6.43	background	Sw
4764 Joneberhart	1.932	24.835	13.8	0.803	0.616	2.89	family	Xk,Xe
5378 Ellyett	1.934	19.114	13.7	0.499	0.731	2.85	family	Xe, Ch
5477 Holmes	1.917	22.549	14.0	0.310	0.510	2.92	family?	S (Bus)
5579 Uhlherr	1.949	23.542	14.1	1.00	1.05	1.98	family	Xn,L
5627 (1991 MA)	1.878	26.354	14.3	0.519	-	2.68	background	Q,Sq
6029 Edithrand	1.927	24.271	14.1	0.784	0.701	2.42	family	Xn,L
6141 Durda	1.818	16.454	14.2	-	0.887	2.01	background	Xn,L
6271 Farmer	1.968	23.556	13.2	0.363	0.319	5.42	background	D
6382 (1988 EL)	1.824	18.556	13.5	0.254	0.279	5.10	background	Sq,K
6485 Wendeesther	1.910	20.464	13.8	-	0.310	4.15	background	Q,Sq
6646 Churanta	1.925	17.589	14.5	1.00	0.561	2.25	family	Xn,L
6901 Roybishop	1.943	23.142	13.3	0.191	0.305	5.32	background	Q,Sq
7173 Sepkoski	1.956	19.582	13.8	0.236	0.293	4.29	background	Sw
7488 Robertpaul	1.959	24.105	14.6	-	-	2.18	family	X,C
7783 (1994 JD)	1.934	23.534	14.2	0.816	0.519	2.62	family	Xn,Xe
7829 Jaroff	1.952	17.868	14.5	0.851	0.420	2.58	family	Xn,L
8026 Johnmckay	1.925	19.935	15.0	0.815	0.371	2.14	family	Xn,L
9068 (1993 OD)	1.820	20.297	14.2	-	0.567	2.58	background	Xe
9554 Dumont	1.905	24.870	14.5	0.277	0.306	3.09	background	Q,Sq
9873 (1992 GH)	1.862	19.232	13.7	0.220	0.177	5.73	background	Sw
13245 (1998 MM19)	1.938	21.252	14.9	-	-	4.83	family	Cb,C
15692 (1984 RA)	1.926	23.219	14.9	0.780	0.279	2.63	family	Xn,L
16421 Roadrunner	1.931	22.824	14.1	0.263	0.319	3.62	background	Q,Sq
16585 (1992 QR)	1.923	22.997	14.7	1.00	0.425	2.38	family	Xn,B
16589 Hastrup	1.934	20.019	14.5	0.580	0.477	2.38	family	Xn,L
20231 (1997 YK)	1.948	17.965	14.0	-	-	2.88	family	Xn,L

Table III-2. (*continued*).

Object	a (AU)	i (°)	H_v	p_v^a	p_v^b	D (km)	Population	BDM Taxonomy^c
21261 (1996 FF)	1.943	20.629	14.6	-	-	6.00	family	B,Xn
24077 (1999 TD233)	1.961	18.750	14.7	0.309	0.453	2.30	family	Xn,L
24654 Fossett	1.894	27.344	14.3	-	0.777	2.05	background	L,Xn
25318 (1999 CH12)	1.928	21.141	15.2	0.345	0.359	1.99	background	L,S
26074 Carlwirtz	1.811	31.608	14.9	-	0.494	1.97	background	Xe,Xc
30856 (1991 XE)	1.827	26.649	14.2	0.386	0.265	3.76	background	S,Sr
30935 Davasobel	1.904	27.811	14.3	0.581	0.696	2.21	background	Xk,Cgh
31793 (1999 LB6)	1.863	23.484	14.5	0.325	-	2.93	background	Q,Sq
34817 Shiominemoto	1.879	22.226	14.0	-	0.363	3.43	background	Xn,L
39791 Jameshesser	1.946	23.612	15.0	0.890	0.254	2.66	family	Xn,L
45874 (2000 WM3)	1.957	23.159	15.4	0.638	0.242	2.24	family	Xc,Ch
53424 (1999 SC3)	1.866	23.147	15.3	-	-	2.28	background	Q,Sq
53431 (1999 UQ10)	1.837	25.372	14.3	0.547	0.317	3.29	background	S,Sr
53433 (1999 VV10)	1.844	23.082	15.4	0.340	0.262	2.15	background	Sr,S
105445 (2000 QW182)	1.803	22.891	14.9	0.361	-	2.32	background	Sq,K
134746 (2000 BO6)	1.839	19.746	16.8	-	-	1.14	background	Q.Sq

Orbital elements (a , i) at epoch 2457600.5 (2016-Jul-31.0) TDB, reference JPL (heliocentric ecliptic J2000), from

<http://ssd.jpl.nasa.gov/sbdb.cgi>, referenced January 3rd, 2017

^a Visible geometric albedos from NEOWISE: <http://adsabs.harvard.edu/abs/2012ApJ...759L...8M>; bold geometric albedo for 1656 Suomi from IRAS (Tedesco et al., 2002)

^b WISE albedos calculated in this work (see § 2.4)

^c For asteroids with non-unique BDM taxonomic classifications, the two lowest average residual solutions are listed; “w” moniker for S-complex notates high-slope (>0.25) objects

Table III-3. 0.9 μm spectral band analysis for 27 X-type Hungaria asteroids.

Object	Band shoulder (short)	Band shoulder (long)	Band center (μm)	Band center error	Band depth (%)	Band depth error
<i>Family</i>						
434 Hungaria	0.710	1.365	0.936	0.036	4.40	0.29
1920 Sarmiento	0.780	1.060	0.910	0.005	1.22	0.54
4764 Joneberhart	0.805	1.011	0.933	0.011	1.15	0.53
5378 Ellyett	0.824	1.062	0.919	0.017	0.92	0.90
5579 Uhlherr	0.800	0.975	0.839	0.007	1.30	0.32
6029 Edithrand	0.782	1.060	0.882	0.010	1.01	1.20
6646 Churanta	0.799	1.059	0.934	0.008	1.58	0.94
7488 Robertpaul	0.822	1.076	0.924	0.022	2.86	5.01
7783 1994 JD	0.814	1.038	0.934	0.009	1.01	0.71
7829 Jaroff	0.803	1.054	0.927	0.017	0.39	1.32
8026 Johnmckay	0.815	1.047	0.934	0.003	2.68	1.55
15692 1984 RA	0.850	0.984	0.909	0.033	0.01	0.68
16585 1992 QR	0.801	1.089	0.947	0.008	2.30	1.10
16589 Hastrup	0.799	1.094	0.951	0.148	1.45	1.34
20231 1997 YK	0.821	0.982	0.884	0.006	1.45	1.10
24077 1999 TD233	0.821	1.041	0.978	0.007	1.40	0.83
39791 Jameshesser	0.801	1.040	0.927	0.005	1.62	1.16
45874 2000 WM3	0.830	0.980	0.926	0.010	1.46	1.79
<i>Background</i>						
1355 Magoeba	0.790	1.049	0.883	0.017	3.27	1.61
2083 Smither	0.798	1.067	0.921	0.010	0.83	0.71
3447 Burckhalter	0.820	1.104	0.894	0.043	0.58	3.25
4531 Asaro	0.813	1.063	0.916	0.012	1.23	0.72
6141 Durda	0.805	1.046	0.916	0.015	0.95	1.10
24654 Fossett	0.825	1.093	0.963	0.012	1.36	0.84
26074 Carlwirtz	0.813	1.058	0.936	0.034	1.05	0.56
30935 Davasobel	0.815	0.998	0.947	0.022	0.92	1.56
34817 Shiominemoto	0.811	0.989	0.826	0.009	1.22	0.62

Table III-4. NIR color-indices for 27 X-type Hungaria asteroids.

Object	0.85-<i>J</i>	0.85-<i>J</i> error	0.85-<i>H</i>	0.85-<i>H</i> error	0.85-<i>K</i>	0.85-<i>K</i> error	<i>J</i> - <i>H</i>	<i>J</i> - <i>H</i> error	<i>J</i> - <i>K</i>	<i>J</i> - <i>K</i> error	<i>H</i> - <i>K</i>	<i>H</i> - <i>K</i> error
<i>Family</i>												
434 Hungaria	0.046	0.006	0.073	0.005	0.087	0.005	0.027	0.004	0.040	0.004	0.014	0.003
1920 Sarmiento	0.065	0.005	0.073	0.007	0.095	0.008	0.007	0.008	0.029	0.009	0.022	0.010
4764 Joneberhart	0.092	0.007	0.134	0.006	0.155	0.009	0.042	0.007	0.063	0.010	0.021	0.010
5378 Ellyett	0.077	0.010	0.112	0.013	0.155	0.021	0.035	0.014	0.079	0.021	0.043	0.023
5579 Uhlherr	0.107	0.010	0.080	0.010	0.105	0.011	-0.027	0.006	-0.001	0.007	0.026	0.007
6029 Edithrand	0.025	0.012	0.018	0.019	0.030	0.039	-0.008	0.021	0.005	0.040	0.012	0.043
6646 Churanta	0.013	0.009	-0.008	0.013	-0.022	0.026	-0.021	0.014	-0.036	0.027	-0.015	0.028
7488 Robertpaul	0.060	0.038	0.136	0.040	0.313	0.063	0.076	0.019	0.253	0.052	0.177	0.054
7783 1994 JD	0.066	0.007	0.084	0.009	0.105	0.013	0.018	0.009	0.039	0.012	0.022	0.014
7829 Jaroff	0.037	0.011	0.016	0.016	0.018	0.027	-0.021	0.017	-0.019	0.028	0.002	0.030
8026 Johnmckay	0.030	0.015	0.036	0.020	0.040	0.032	0.006	0.021	0.011	0.033	0.005	0.035
15692 1984 RA	0.046	0.006	0.064	0.011	0.050	0.015	0.019	0.011	0.005	0.015	-0.014	0.018
16585 1992 QR	-0.007	0.010	-0.020	0.013	0.045	0.018	-0.014	0.013	-0.038	0.018	-0.025	0.020
16589 Hastrup	0.046	0.011	0.075	0.017	0.068	0.036	0.029	0.017	0.022	0.035	0.007	0.038
20231 1997 YK	0.040	0.010	0.051	0.014	0.051	0.021	0.010	0.013	0.011	0.021	0.000	0.023
24077 1999 TD233	0.021	0.010	0.016	0.017	0.004	0.018	-0.005	0.020	-0.016	0.020	-0.011	0.025
39791 Jameshesser	0.024	0.010	0.009	0.020	-0.006	0.029	-0.015	0.021	-0.030	0.029	-0.014	0.034
45874 2000 WM3	0.036	0.019	0.077	0.032	0.113	0.051	0.041	0.033	0.078	0.051	0.037	0.058
<i>Background</i>												
1355 Magoeba	0.094	0.008	0.085	0.008	0.111	0.013	-0.009	0.008	0.017	0.012	0.026	0.013
2083 Smither	0.041	0.007	0.056	0.008	0.072	0.011	0.015	0.009	0.031	0.012	0.016	0.012
3447 Burckhalter	0.169	0.009	0.220	0.008	0.244	0.019	0.051	0.011	0.074	0.020	0.023	0.020
4531 Asaro	0.076	0.006	0.106	0.007	0.107	0.011	0.031	0.008	0.031	0.011	0.000	0.012
6141 Durda	0.026	0.008	-0.004	0.012	-0.010	0.023	-0.030	0.012	-0.035	0.023	-0.005	0.024
24654 Fossett	0.045	0.009	0.071	0.013	0.057	0.021	0.026	0.014	0.012	0.022	-0.014	0.024
26074 Carlwirtz	0.069	0.006	0.102	0.009	0.101	0.013	0.033	0.009	0.033	0.013	0.000	0.014
30935 Davasobel	0.098	0.009	0.145	0.012	0.185	0.018	0.047	0.012	0.087	0.018	0.040	0.020
34817 Shiominemoto	0.097	0.009	0.105	0.010	0.091	0.013	0.009	0.008	-0.006	0.011	-0.015	0.012

Table III-5. Band parameter analysis for 18 S-subtype Hungaria background asteroids.

Object	Temp. (K)	BIC	BIC error	BI area ($\times 10^{-2}$)	BI area error ($\times 10^{-2}$)	BIIC	BIIC _{tcorr}	BIIC error	BII area ($\times 10^{-2}$)	BII area error ($\times 10^{-2}$)	BAR	BAR _{tcorr}	BAR error
1600 Vyssotsky	203	0.918	0.005	4.70	0.16	1.972	1.991	0.177	6.25	0.80	1.33	1.25	0.18
1656 Suomi	207	0.951	0.011	5.06	0.25	1.925	1.944	0.240	1.69	0.94	0.33	0.26	0.18
2150 Nyctimene	205	0.998	0.004	6.03	0.12	2.118	2.137	0.138	2.81	0.36	0.46	0.39	0.06
3043 San Diego	208	0.916	0.004	2.85	0.07	1.905	1.924	0.006	4.21	0.08	1.48	1.40	0.05
4125 Lew Allen ^a	203	1.065	0.005	-	-	-	-	-	-	-	-	-	-
4490 Bambery ^a	206	1.070	0.005	-	-	-	-	-	-	-	-	-	-
4713 Steel	199	0.920	0.002	1.72	0.04	1.920	1.940	0.012	2.48	0.12	1.44	1.36	0.08
6382 1988 EL	210	0.917	0.002	1.95	0.04	1.918	1.936	0.008	3.34	0.10	1.71	1.64	0.06
6485 Wendeesther	207	0.967	0.002	4.44	0.02	1.952	1.971	0.009	2.32	0.15	0.52	0.45	0.03
6901 Roybishop	201	0.923	0.005	2.62	0.06	1.920	1.940	0.024	2.85	0.14	1.09	1.01	0.06
7173 Sepkoski	199	0.946	0.002	7.96	0.17	1.842	1.862	0.245	2.28	1.15	0.28	0.20	0.14
9554 Dumont	205	0.958	0.002	3.44	0.03	1.924	1.943	0.011	2.04	0.11	0.59	0.52	0.03
9873 1992 GH	213	0.924	0.004	4.88	0.25	1.853	1.870	0.240	3.45	0.88	0.71	0.64	0.18
16421 Roadrunner	205	0.986	0.008	5.14	0.24	1.980	1.999	0.086	3.01	0.74	0.58	0.51	0.14
25318 1999 CH12	200	0.918	0.002	2.62	0.03	1.951	1.971	0.076	1.55	0.33	0.59	0.51	0.13
30856 1991 XE	202	0.921	0.002	3.32	0.05	1.887	1.906	0.014	2.26	0.19	0.68	0.60	0.06
53431 1999 UQ10	199	0.917	0.002	3.14	0.04	2.006	2.026	0.038	4.72	0.23	1.50	1.42	0.08
53433 1999 VV10	210	0.922	0.001	5.20	0.05	1.884	1.901	0.010	4.15	0.18	0.80	0.73	0.04

BIC = Band I center; BIIC = Band II center; BAR = Band Area Ratio; *tcorr* = temperature corrected value^a Temperature corrected Band I center values and errors from Sanchez et al. (2014)

Table III-6. Hungaria background asteroid S-subtype, mineralogy, and potential meteorite analogs.

Object	BDM	S-sub	Fa (mol%)	Fs (mol%)	ol/(ol+px)	Meteorite analog
1600 Vyssotsky	Sw	S(VI)	-	-	-	acap-lod?/winonaite? ^a
1656 Suomi	Sw	S(III)/S(IV)	21.9	18.6	0.66	ureilite? ^a /L chondrite?
2150 Nyctimene	Sw	S(IV)	29.1	23.9	0.63	LL chondrite
3043 San Diego	Sw	S(VI)	-	-	-	acap-lod?/winonaite? ^a
4125 Lew Allen ^b	A	S(I)	33.7	-	-	brachinite?
4490 Bambery ^b	A	S(I)	43.5	-	-	brachinite?/R chondrite?
4713 Steel	Sw	S(VI)	-	-	-	acap-lod?/winonaite? ^a
6382 1988 EL	Sq,K	S(VII)	-	-	-	mesosiderite ^a ?/lodranite? ^a
6485 Wendeesther	Q,Sq	S(IV)	25.1	21.0	0.62	L chondrite/ LL chondrite
6901 Roybishop	Q,Sq	sub-S(IV)	15.0	13.7	0.48	acap-lod?/H chondrite?
7173 Sepkoski	Sw	S(III)	-	-	-	ureilite? ^a /L chondrite?
9554 Dumont	Q,Sq	S(IV)	23.5	19.8	0.60	L chondrite
9873 1992 GH	Sw	sub-S(IV)	15.4	14.0	0.57	acap-lod?/H chondrite?
16421 Roadrunner	Q,Sq	S(IV)	27.8	23.0	0.60	LL chondrite
25318 1999 CH12	L,S	sub-S(IV)	13.6	12.8	0.60	acap-lod?/H chondrite?
30856 1991 XE	S,Sr	sub-S(IV)	14.5	13.4	0.58	acap-lod?/H chondrite?
53431 1999 UQ10	S,Sr	S(VI)	-	-	-	acap-lod?/winonaite? ^a
53433 1999 VV10	Sr,S	sub-S(IV)	14.6	13.5	0.55	acap-lod?/H chondrite?

^a possible meteorite analog for S-subtypes from Table VI of Gaffey et al. (1993)^bTemperature corrected Fa (mol%) values and meteorite analogs from Sanchez et al. (2014)**Table III-7.** Two sample Kolmogorov-Smirnov (K-S) test results.

Parameter	$c(\alpha)$	D_α	D_{max}	ρ_{KS}
X-type 0.9 micron Band Analysis				
0.9 μ m band center	1.36	0.58	0.33	50%
0.9 μ m band depth	1.36	0.58	0.46	14%
X-type NIR Color Indices				
synthetic color index	1.36	0.56	0.43	16%
0.85 - J	1.36	0.56	0.49	8%
J - K	1.36	0.56	0.37	33%

 $c(\alpha)$ - critical value for $\alpha = 0.05$ D_α - null hypothesis is rejected if D_{max} is $>D_\alpha$ ρ_{KS} - probability of the two sample data being drawn from the same distribution

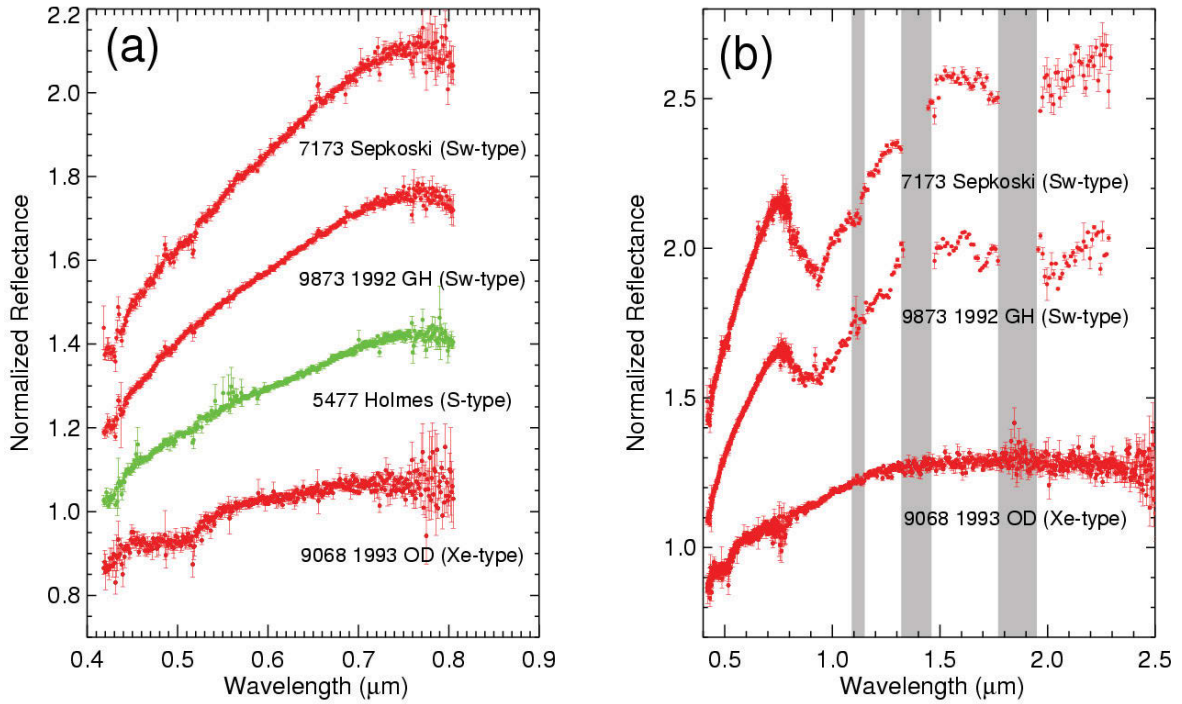


Figure III-1. (a) VIS spectra of four Hungaria asteroids observed with the Goodman spectrograph at SOAR. Spectra are normalized to unity at $0.55 \mu\text{m}$ and are offset for clarity. All four spectra show larger reflectance errors longward of $\sim 0.76 \mu\text{m}$ and shortward of $\sim 0.44 \mu\text{m}$. Green indicates Hungaria family and red indicates Hungaria background, this color scheme will be used throughout this paper to distinguish these two populations. The one family member shown (5477 Holmes) is an S-type typical of the Hungaria background and is most likely an interloper that is incorrectly included as a family member of FIN 003 (Nesvorný et al., 2015). **(b)** VIS+NIR spectra of three Hungaria background asteroids. SOAR VIS data for the asteroids as shown in Figure III-1a, NIR data from HI (Lucas et al., 2017). Spectra are normalized to unity at $0.55 \mu\text{m}$ and are offset for clarity. Spectra for 9873 1992 GH and 7173 Sepkoski are affected by significant noise due to incompletely corrected telluric bands (gray regions), therefore reflectance data between ~ 1.32 - 1.46 and ~ 1.77 - $1.95 \mu\text{m}$ are not shown for clarity. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article).

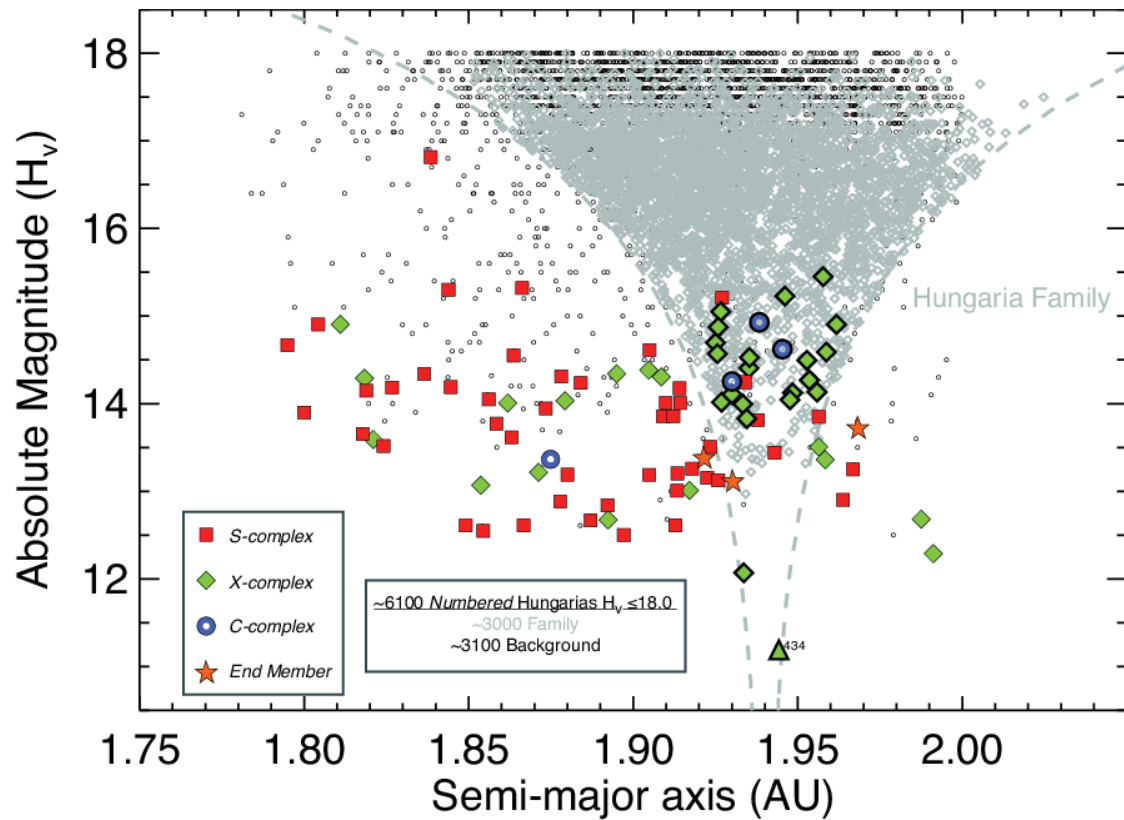


Figure III-2. H_V versus a for numbered (~ 6100) Hungaria family (small gray diamonds) and background asteroids (small black circles). Hungaria family Yarkovsky curves (dashed curved lines) are delineated as in Warner et al. (2009). Family members are plotted in proper a , whereas background asteroids are plotted in osculating a . Large symbols show the taxonomic complex of 92 Hungarias with NIR and VIS+NIR spectral data from HARTSS Phase I & II. Twenty-four Hungaria family members observed during HARTSS are indicated by large symbols with thick black borders. Five S-complex asteroids (red squares) within the cone are most likely interlopers. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article).

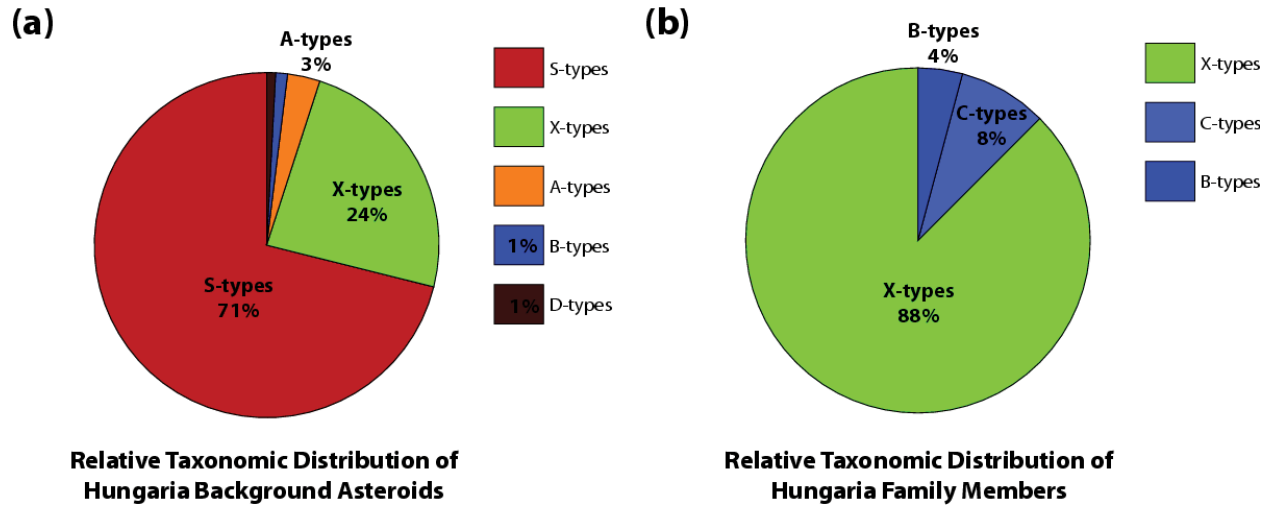


Figure III-3. Bus-DeMeo relative taxonomic distributions for **(a)** Hungaria background asteroids ($n = 68$), and **(b)** Hungaria family members ($n = 24$).

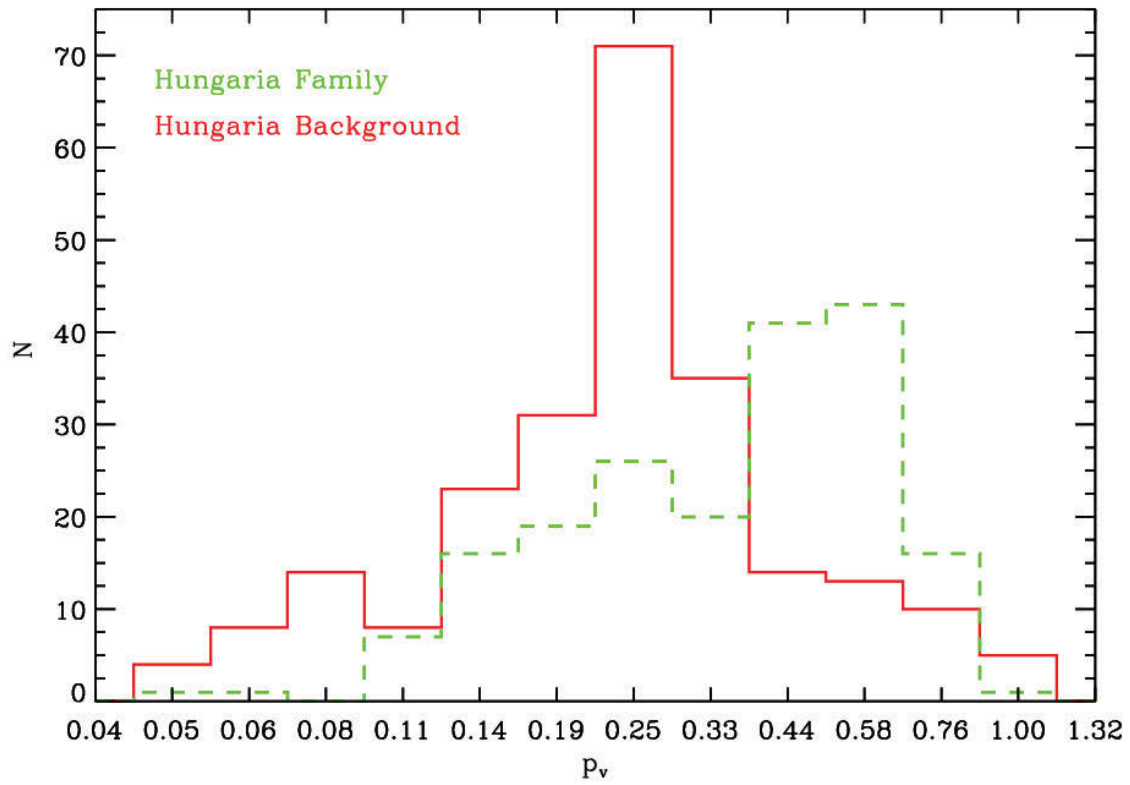


Figure III-4. Calculated WISE albedos (using 12- and 22-um bands) for 428 Hungaria region asteroids. Logarithmic bin sizes were chosen in order to match the average percent error of the albedo values ($\sim 25\%$). Gaussian distributions of albedos for family members (dashed green line) and background objects (red solid line) indicate a compositional dichotomy between background objects and collisional family members. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article).

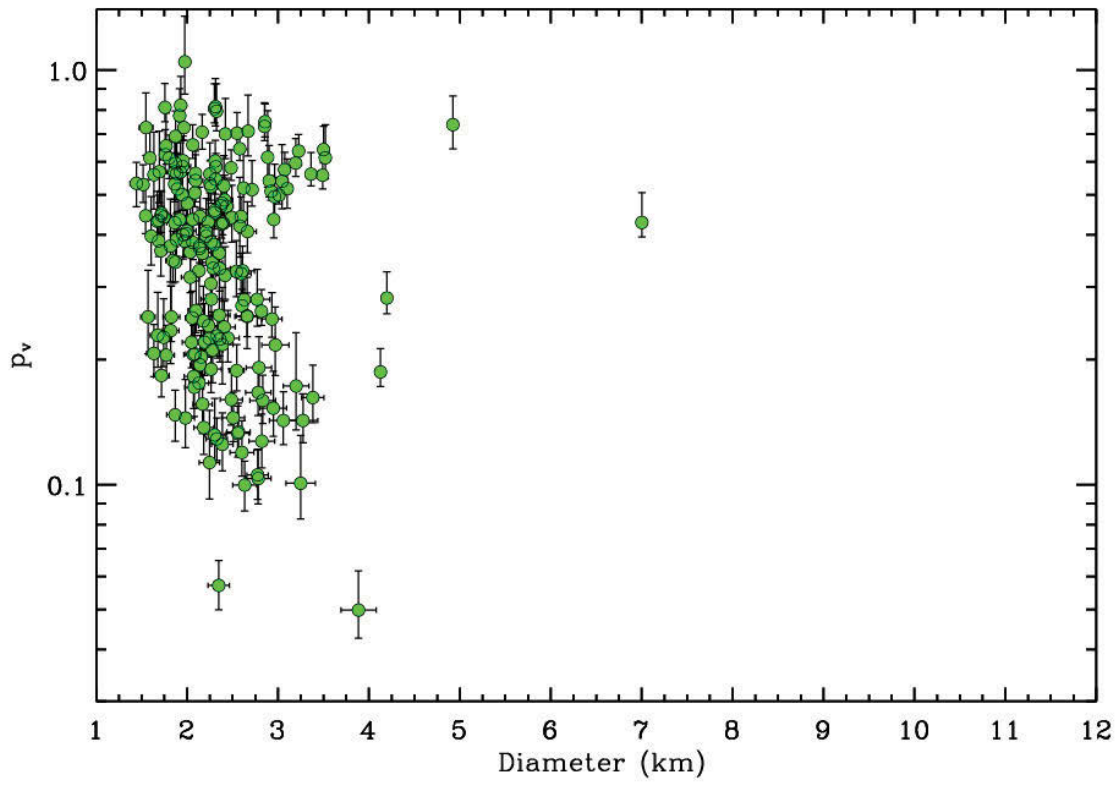


Figure III-5. Logarithmic p_v versus D for 192 Hungaria family members that are a subset of the Hungarias with calculated WISE albedos and diameters (see § 3.4). Hungaria family member albedos do not appear to be segregated as a function of diameter.

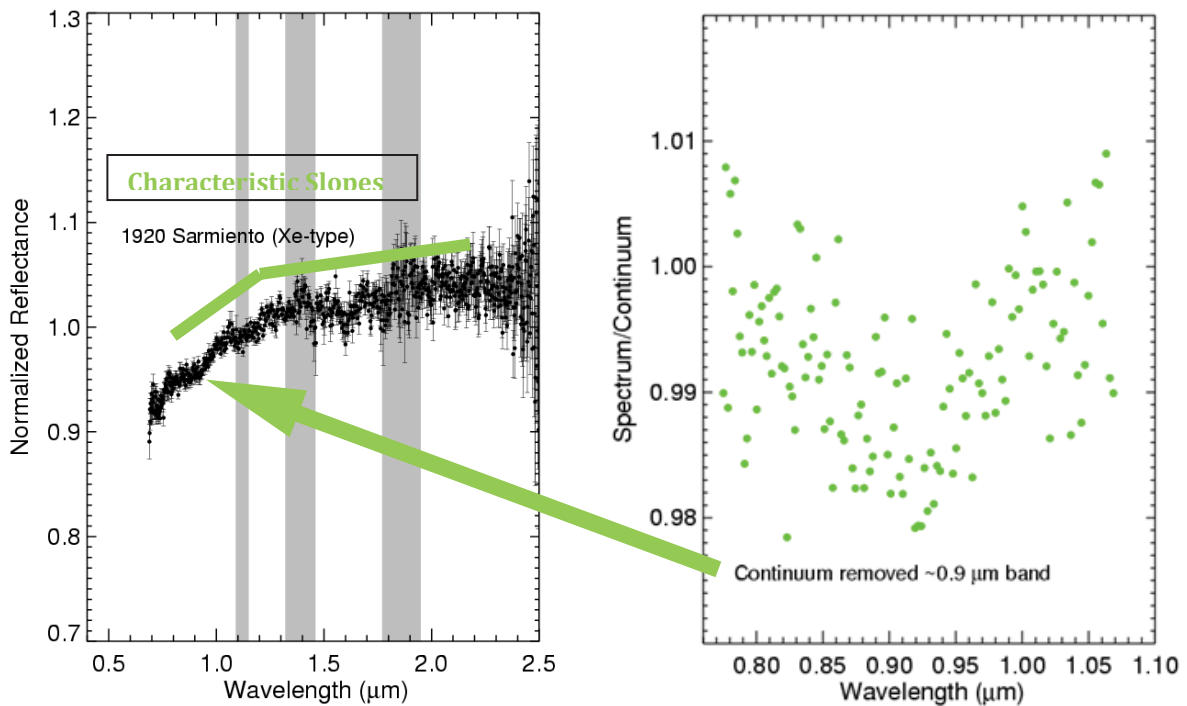


Figure III-6. Spectrum of Hungaria family member 1920 Sarmiento, the spectrum is normalized to unity at 1.20 μm . The vertical gray bars on each plot denote wavelengths of strong absorption by water vapor in Earth's atmosphere. Solid green lines indicate two distinct slopes characteristic of Hungaria X-type asteroids, steeper slope denoted by 0.825- J , shallower slope denoted by J - K , see § 4.1.2 for color-color analyses of Hungaria X-types (**inset**) Green arrow indicates the weak $\sim 0.9 \mu\text{m}$ absorption feature found in many Hungaria family and background X-type asteroids. Inset plot shows the continuum removed $\sim 0.9 \mu\text{m}$ feature of 1920 Sarmiento in preparation for spectral band analysis.

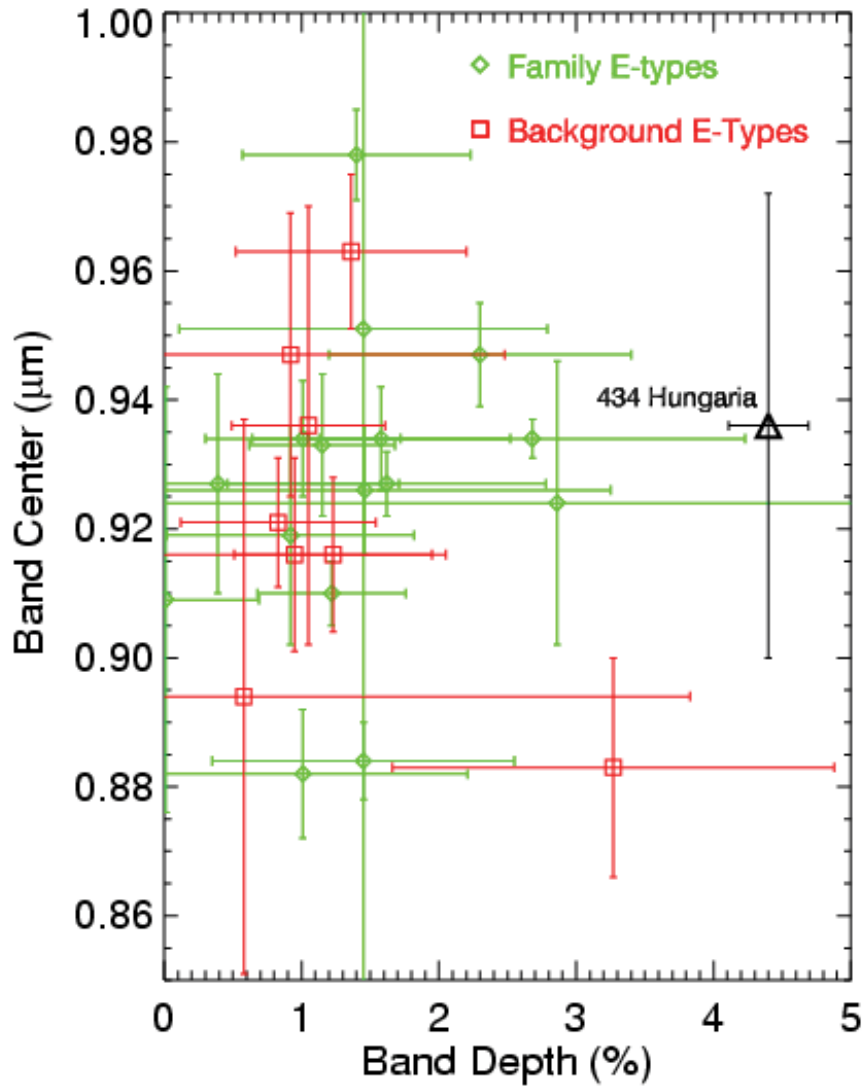


Figure III-7. Band center ($\sim 0.9 \mu\text{m}$) versus band depth for X-complex Hungaria asteroids. X-complex family members (green diamonds) show similar band centers and depths to X-complex Hungaria background asteroids (red squares). Family namesake and largest collisional fragment 434 Hungaria (black triangle) shown for comparison. Two asteroids (5579 Uhlherr and 34817 Shiominemoto) have anomalously short band centers for pyroxenes and are not shown (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article).

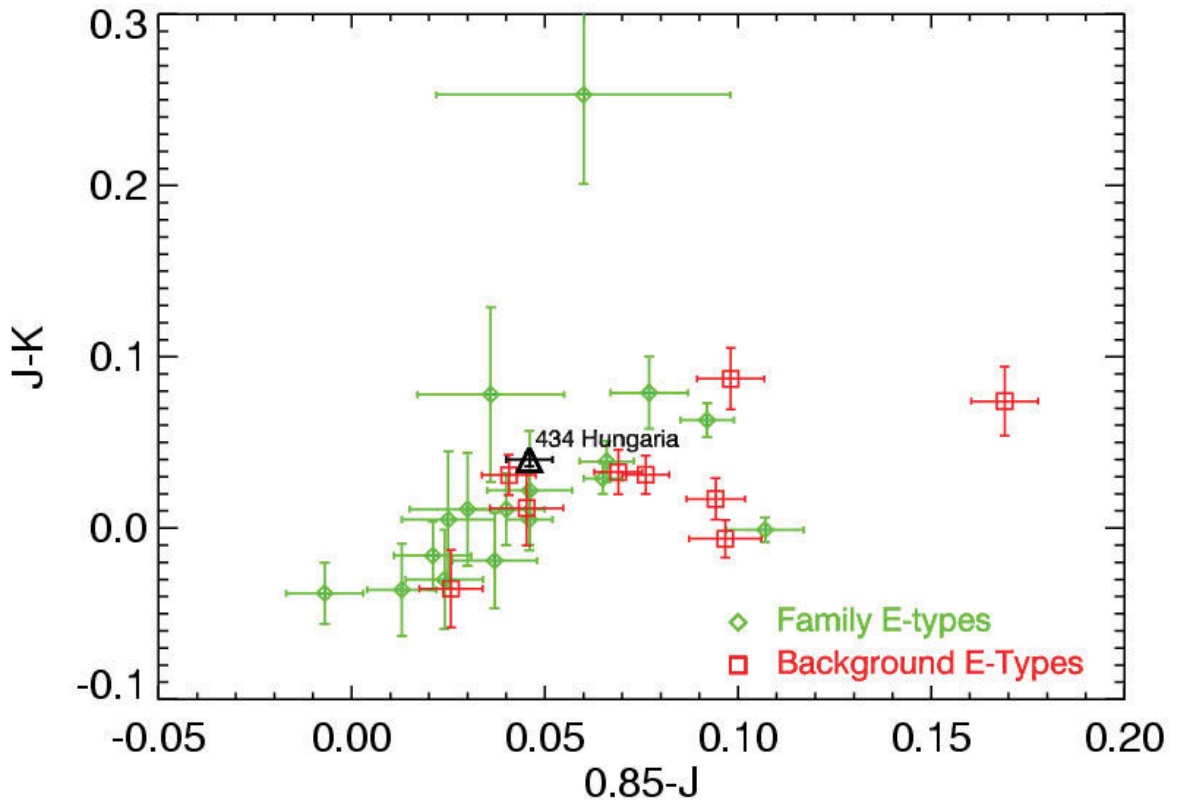


Figure III-8. Color indices calculated from NIR spectra of 26 Hungaria X-type asteroids. Green diamonds represent 16 family members, while red squares indicate 9 background objects. Family member 7488 Robertpaul has an anomalously high $J-K$ color index due to poor quality spectrum and is not shown for clarity. Largest family member 434 Hungaria (black triangle) shown for comparison. Color-color distribution between background and family reveal overlap in NIR color space indicating similar spectral properties between the two groups (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article).

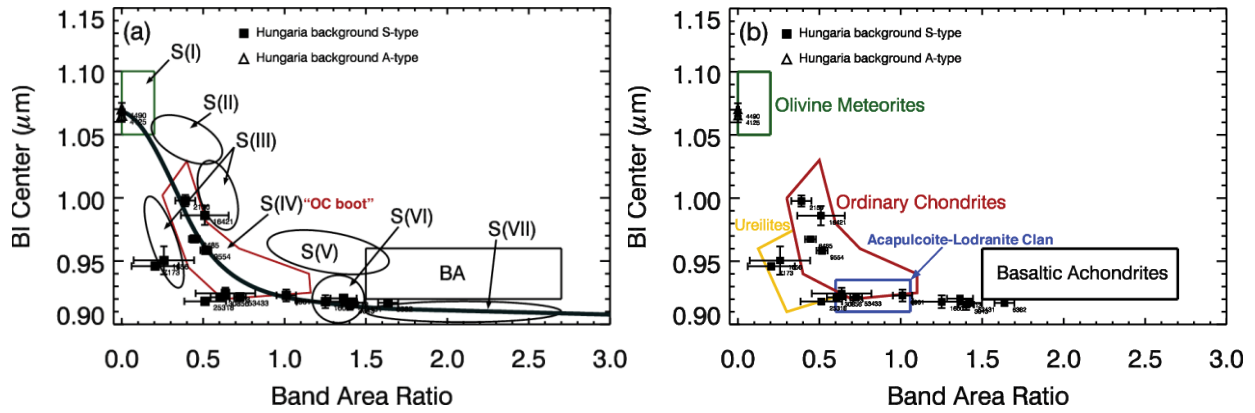


Figure III-9. Band I center versus BAR for 16 Hungaria background S-type (solid squares) and two A-type asteroids (open triangles). The asteroid number is plotted to the bottom right of each symbol. **(a)** Eighteen Hungarias shown relative to the S(I)-S(VII) and basaltic achondrite (BA) zones of Gaffey et al. (1993), the thick gray curve indicates the olivine-orthopyroxene mixing line (Cloutis et al., 1986). **(b)** The same 18 Hungarias shown relative to spectral zones analogous to potential meteorite groups. The olivine, ordinary chondrite, and basaltic achondrite zones are from Gaffey et al. (1993); the acapulcoite-lodranite clan zone is from Lucas et al. (2018), the ureilite zone is from Cloutis et al. (2010). For both (a) and (b) the 1σ errors for Band I center and BAR from Table III-5 are plotted for each object (for some objects the error is smaller than the symbol size).

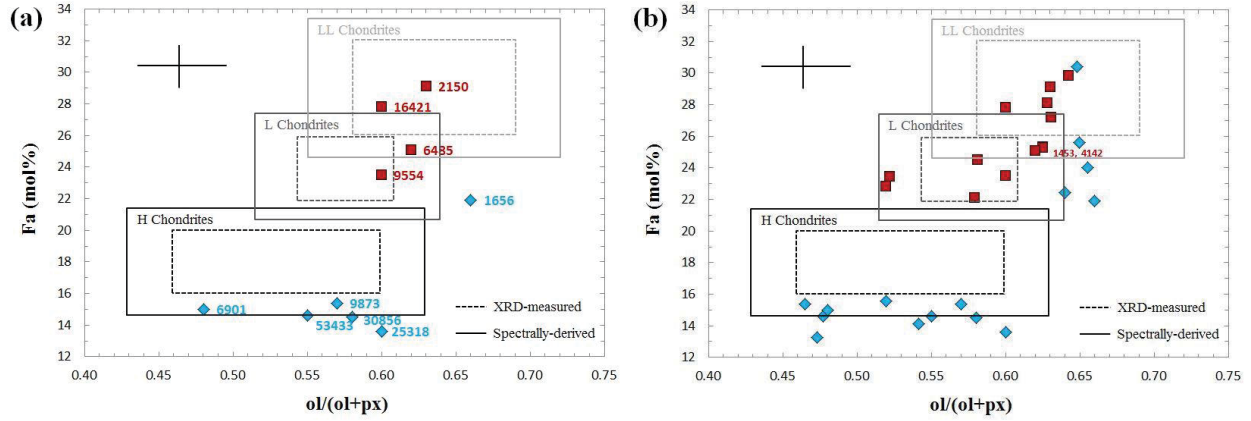


Figure III-10. Olivine chemistry (Fa) versus $ol/(ol+px)$ ratio for OC-like Hungaria background S-complex asteroids. S(IV) subtypes are indicated by red squares, sub-S(IV) and S(III)/S(IV) Hungarias, which plot near the boundaries of the OC boot (see Figures III-9a and III-9b), are indicated by blue diamonds. The dashed boxes show the ranges of $ol/(ol+px)$ measured via X-ray diffraction by Dunn et al. (2010b) and the range of Fa contents in H, L, and LL ordinary chondrites (Brearley and Jones, 1998). The spectrally-derived solid boxes are larger and include the errors in the calibration equations (± 0.03 for $ol/(ol+px)$ and $Fa \pm 1.3$ mol%; see crossbar). **(a)** Ten OC-like Hungarias from HII with asteroid numbers indicated. **(b)** Twenty-eight OC-like Hungarias (10 from Figure III-10a; 18 from HI), the symbols for two Hungarias (1453 Fennia and 4142 Dersu-Uzala) plot on top of each other and are indicated by their asteroid number. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article).

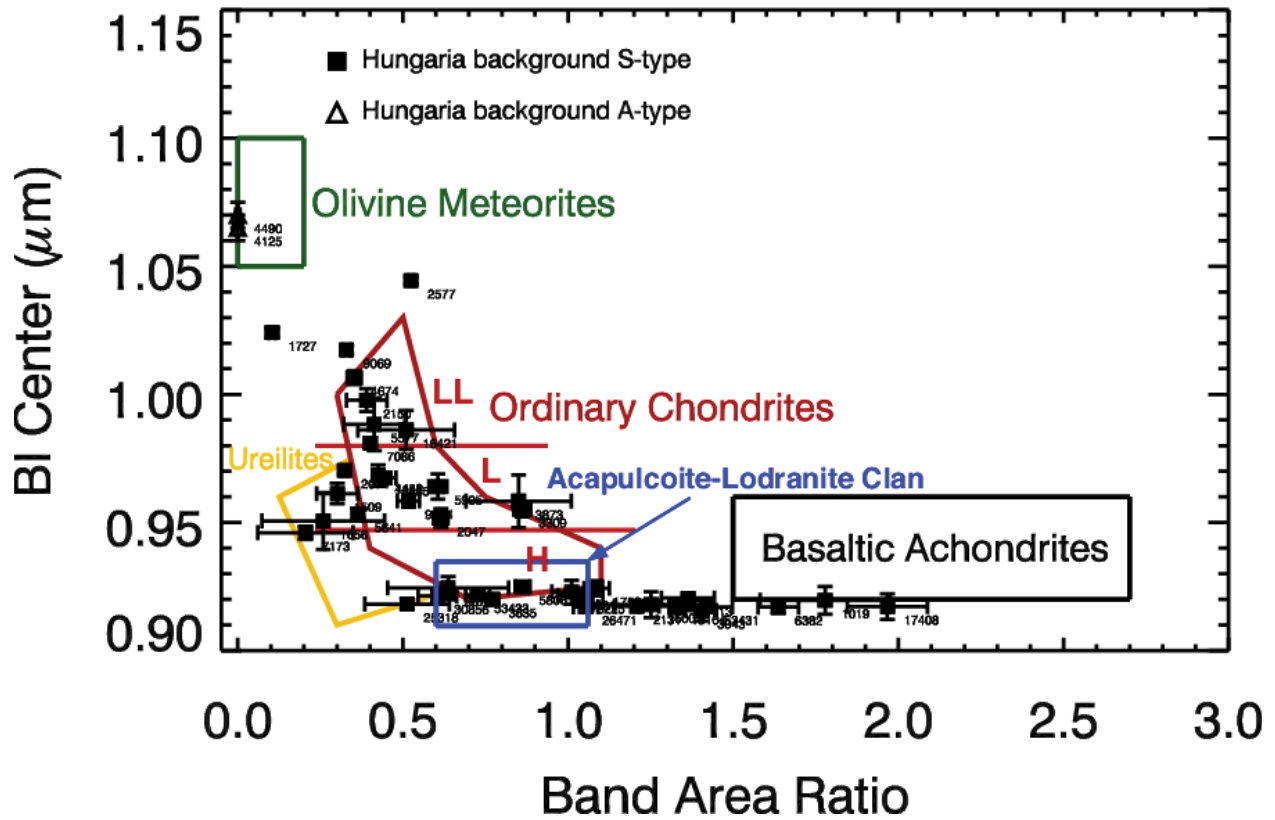
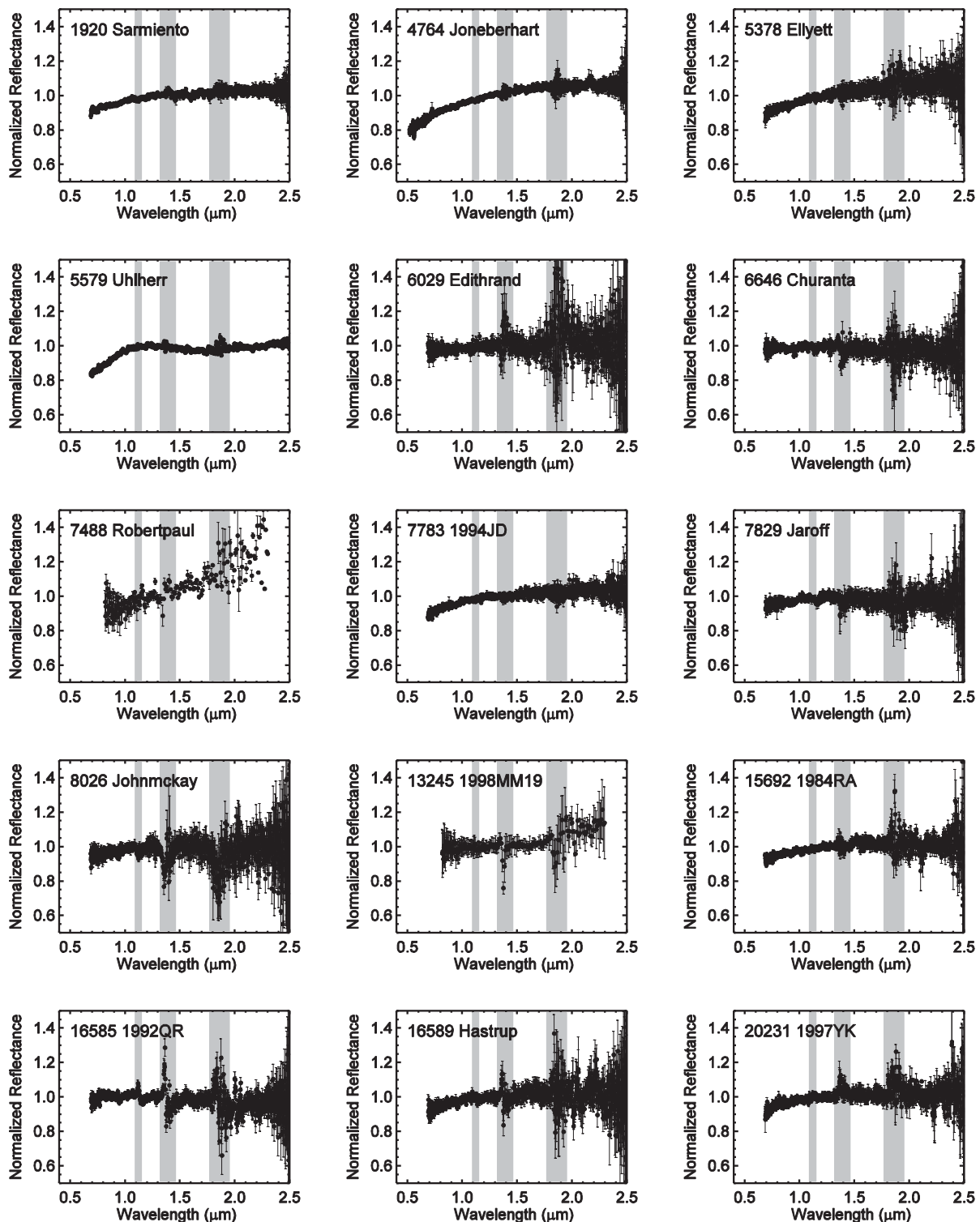


Figure III-11. Band I center versus BAR for 42 Hungaria background S-complex asteroids, 24 from HI (Lucas et al., 2017) and 18 from HII as shown in Figure III-9. Meteorite spectral analog zones are the same as in Figure III-9b. Boundaries for ordinary chondrite for H, L, and LL groups are from Dunn et al. (2010a). The absence of *H* chondrite-like mineralogies among Hungaria S-types is clearly evident. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article).

Appendix III-B. Hungaria Family NIR Spectral Plots

Appendix III-B contains plots of the final reduced NIR and VIS+NIR spectra (4764 Joneberhart only) of 19 Hungaria family asteroids presented in this paper (Figure III-12). All spectra have been normalized to unity at the isophotal wavelength of *J*-band at 1.25 μm (MKO-NIR filter system; Tokunaga and Vacca, 2007). The vertical gray bars on each plot denote wavelengths of strong absorption by water vapor in Earth's atmosphere. These absorptions can be difficult to correct for spectral observations obtained during nights of poor or variable weather conditions, and residual noise can be noticed in several of the spectra in these regions.

Figure III-12. NIR spectra of 19 Hungaria family asteroids presented in this study.



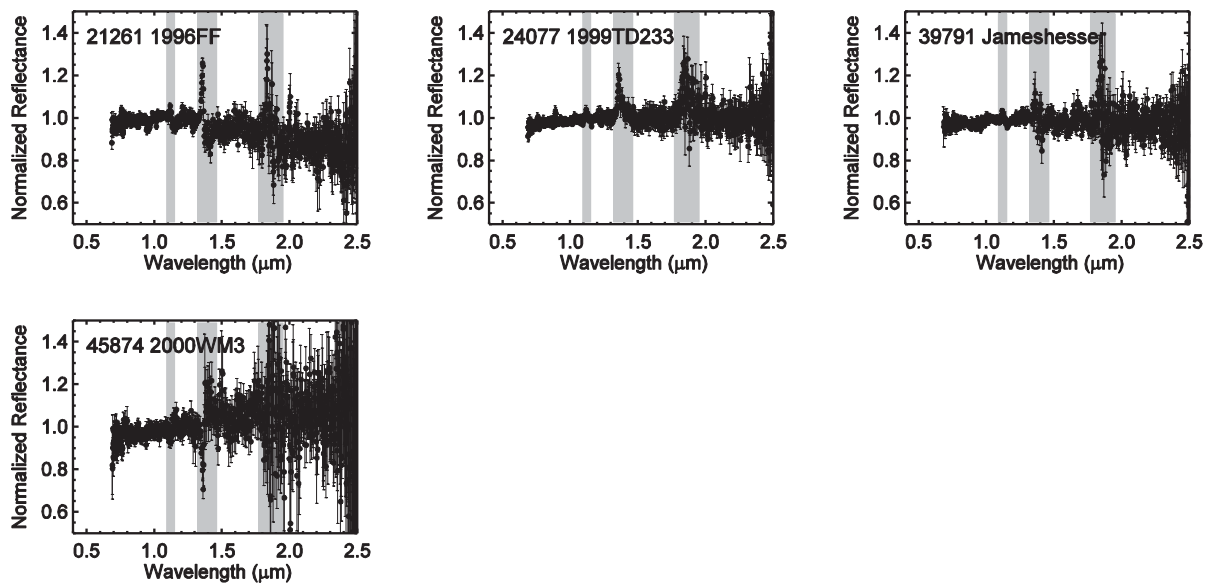
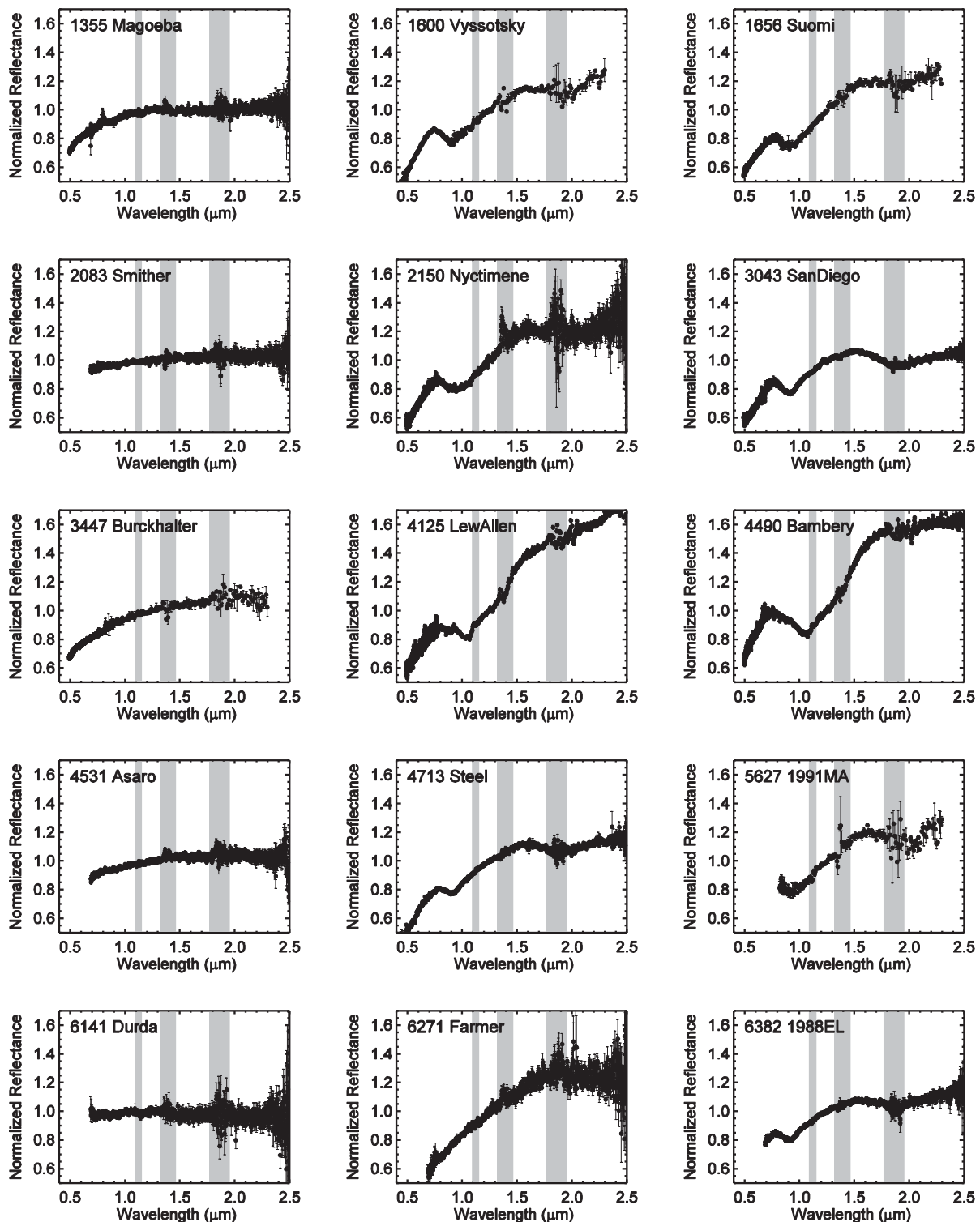


Figure III-12. (*continued*)

Appendix III-C. Hungaria Background NIR Spectral Plots

Appendix III-C contains plots of the final reduced NIR and VIS+NIR spectra of 31 Hungaria background asteroids presented in this paper (Figure III-13). See § 3.2 for list of asteroids that include combined VIS+NIR spectral data and for the reference to the VIS data source. Spectral normalization and gray bars for each plot are the same as in Appendix III-B.

Figure III-13. NIR spectra of 31 Hungaria background asteroids presented in this study.



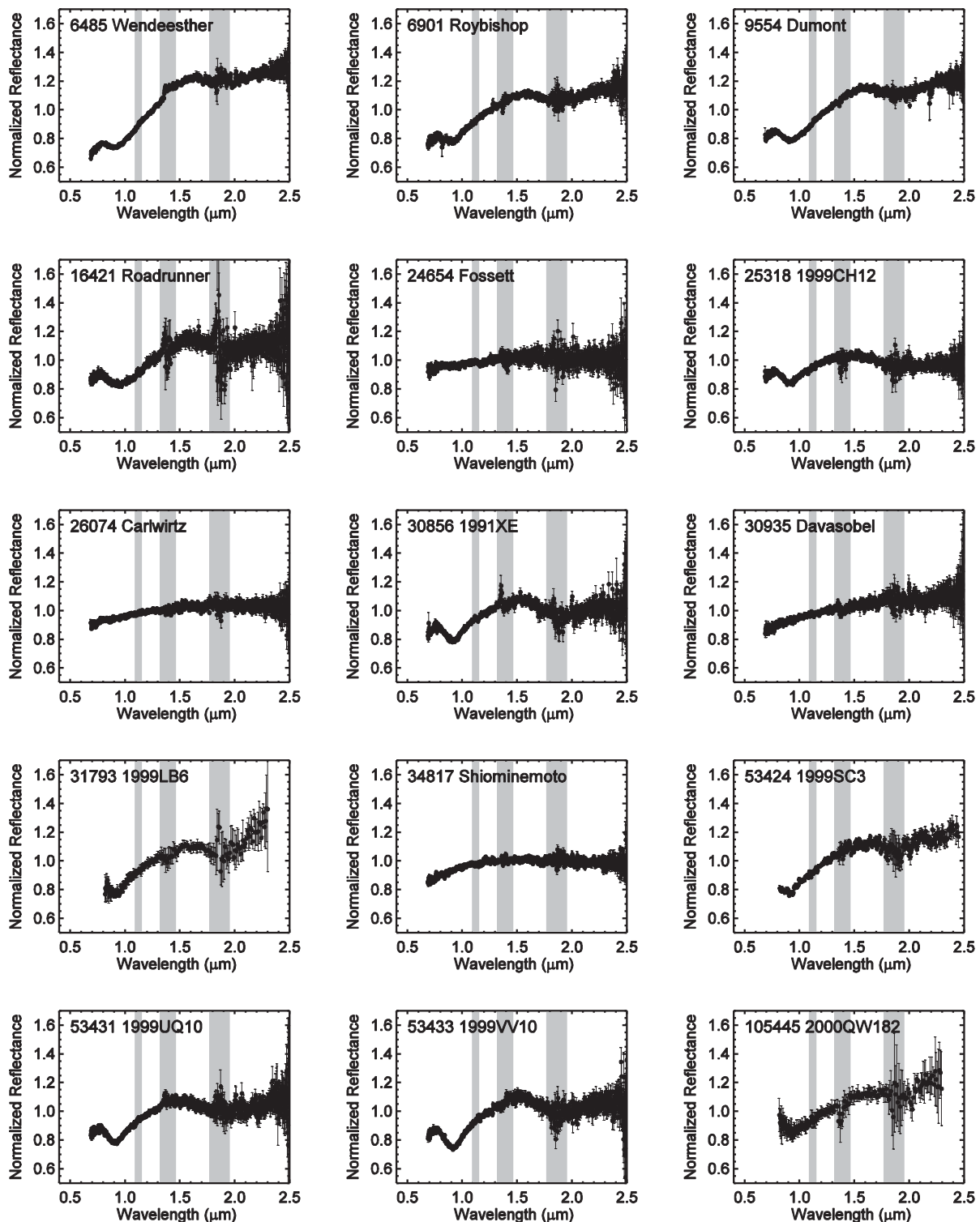


Figure III-13. (continued)

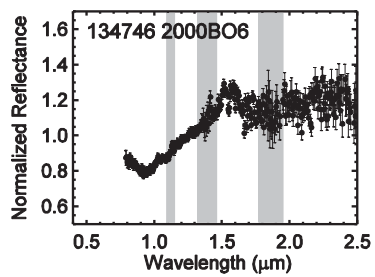


Figure III-13. (*continued*)

CONCLUSION

The research undertaken during the completion of this dissertation has led to new understanding of the surface compositions of primordial Hungaria region asteroids through the acquisition of ground-based telescopic VIS+NIR spectra and the spectral and cosmochemical analyses of partially melted acapulcoite-lodranite clan meteorites. Establishing these asteroid-meteorite connections enhances our understanding of igneous processes and asteroid differentiation in the early Solar System. Yet, this new research spawns many unanswered questions, which hopefully will inspire new research to be performed regarding asteroid-meteorite connections and the asteroid petrogenesis. Through the spectral observations of 92 Hungaria regions asteroids and the analyses of 10 acapulcoite-lodranite meteorites, we arrive at several conclusions for each dissertation chapter, which are summarized below.

Results from Chapter I show that the taxonomic distribution in the Hungaria background population is dominated by stony S-complex asteroids (~80%). These background S-complex objects exhibit considerable spectral diversity as their spectral properties reveal several different S-subtypes, which translates to a variety of surface compositions. We find two main asteroid-meteorite connections among the Hungaria background asteroids, unmelted, nebular *L* ordinary chondrites (and possibly *LL* chondrites), and partially-melted acapulcoite-lodranite like mineralogies. *H* chondrite like mineralogies appear to be absent from the Hungaria background. We suggest a source region for *L* chondrite like material from within the Hungaria region with delivery to Earth via leakage from the inner boundary of this region. The source region for the acapulcoite-lodranite parent body remains inconclusive.

Results from Chapter II show that FeO mineral compositions of orthopyroxene (Fs) and co-existing olivine (Fa) are well correlated in acapulcoite-lodranite meteorites and form a linear trend in Fa versus Fs parameter space that spans the two meteorite groups. Lodranites are generally more iron-rich than acapulcoites and the two groups cluster in separate Fs versus Fa fields, requiring that the chondritic source materials of the two groups were different if they come from the same parent asteroid. Correlations between mineral chemistry and spectral parameters in our suite of 10 acapulcoite-lodranite clan meteorites indicate that a well-defined relationship exists between Band II center and Fs content of orthopyroxene, thus the derived Fs content can be used to estimate the Fa content of the co-existing olivine. Our spectral and mineralogic study of acapulcoite-lodranite clan meteorites has established relationships between the mineralogy of these meteorites and the surface mineralogy of their asteroid parent bodies. These data will enable more robust asteroid-meteorite connections for the identification of partially-differentiated S-complex parent bodies.

Results from Chapter III reinforce the finding from HARTSS I of a compositionally heterogeneous Hungaria background population of stony asteroids and reveal a spectrally homogeneous Hungaria collisional family. The variety of surface mineralogies uncovered for background asteroids exhibit a full range of petrologic evolution, unmelted, nebular *L* and/or *LL* ordinary chondrites, partially-melted primitive achondrites, likely acapulcoite-lodranite like, and fully-melted igneous aubrites. Analysis of the spectral properties of Hungaria family members implies a compositionally homogeneous parent body. This parent body was likely consistent in composition with aubrites and therefore formed under reduced conditions and experienced igneous processing. If aubrites are truly representative of igneous mantle material, then the Hungaria parent body was itself a collisional fragment that originated on a differentiated, heterogeneous parent body very early in Solar System history.

VITA

Michael Peter Lucas was born in Leesburg, Virginia, the second son of Paul and Margaret Lucas. A native son of the Commonwealth of Virginia, he was raised in his beloved hometown of Annandale, Virginia. Michael attended St. Michael's Catholic School in Annandale through the eighth grade, where he received an excellent education in many subjects, especially grammar. Despite very little coursework in science at catholic school, Michael realized as a very young child that he would become a scientist. Michael had a delightfully happy childhood and was always outdoors, playing sports, riding his bicycle, or exploring creek beds and nearby woods. Michael excelled in athletics, playing on football and baseball teams every year during his childhood.

Michael attended Thomas Jefferson High School in Alexandria, VA, where he joined the astronomy club and competed in the 400 m and the 4x400 m relay for the track team. Michael was accepted into George Mason University out of high school but decided to attend part-time as he started a full-time job one week after graduating high school as a lab assistant for a biomedical laboratory. During young adulthood, Michael worked slowly towards a bachelor's degree at several institutions, then got married and started a family at 26 years of age. Returning to his education five years after the birth of his son, Anthony, he gained scientific knowledge through coursework in astronomy and geology, and decided to complete a bachelor's in geology after taking his first geology course at Florida Gulf Coast University while working there as founding staff member of that institution. Continuing to take coursework one or two classes at a time, Michael completed his B.A. in Geology at the University of South Florida in 2003.

Michael's stimulating life became even more interesting in the summer of 2006 when he discovered that he was seriously ill with stage-four blood cancer, and was immediately immersed in a two year fog of treatment and renewal. He survived this illness as he had done in his twenties, and Michael's life flourished after his rebirth. His perception of life was changed forever as he was humbled by this experience and strove to become a more compassionate and generous human being. Before returning to his dear University of South Florida for graduate studies, Michael enjoyed a successful laboratory career, first at the lab bench, then as a manager in various private, academic, and governmental laboratory settings.

Michael completed his M.S. in Geology at the University of South Florida in 2011 and directly afterward moved to Knoxville, TN to pursue a Ph.D. in planetary science in Department of Earth & Planetary Sciences at the University of Tennessee. He has held numerous fellowships throughout his academic career, including a *Space Grant Fellowship* and a *Richard H. Davis Endowed Fellowship in Geology* during his master's work. At the University of Tennessee, he has held an *Oscar R. Ashley Fellowship* and was a *NASA Earth and Space Science Fellow*. Michael owns too many telescopes, enjoys playing guitar/bass in rock bands, digests as much civil war history as he can make time for, takes long backpacking trips in the woods of the Appalachian Trail, and is grateful that he is still agile enough to play centerfield for his softball team. Michael believes strongly in public service and stays active in cancer patient advocacy and outreach.