Using VSWIR Microimaging Spectroscopy to Explore the Mineralogical Diversity of HED Meteorites

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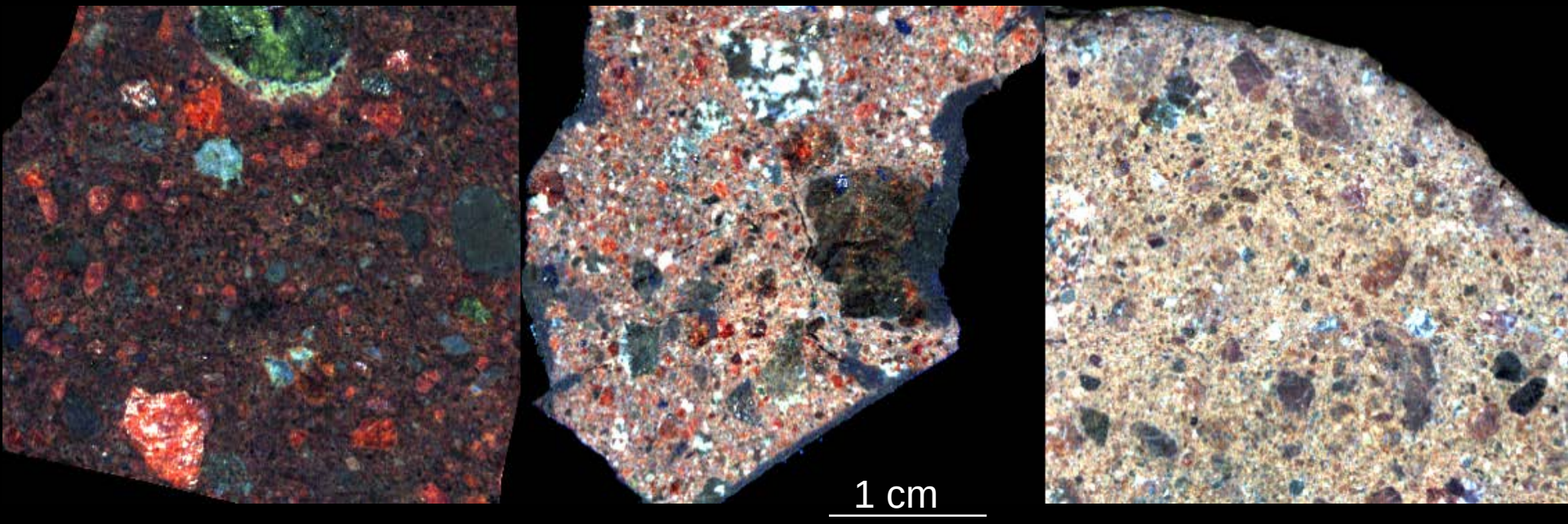

Howardites in false color: R: 2.5 µm, G: 2 µm, B: 1 µm

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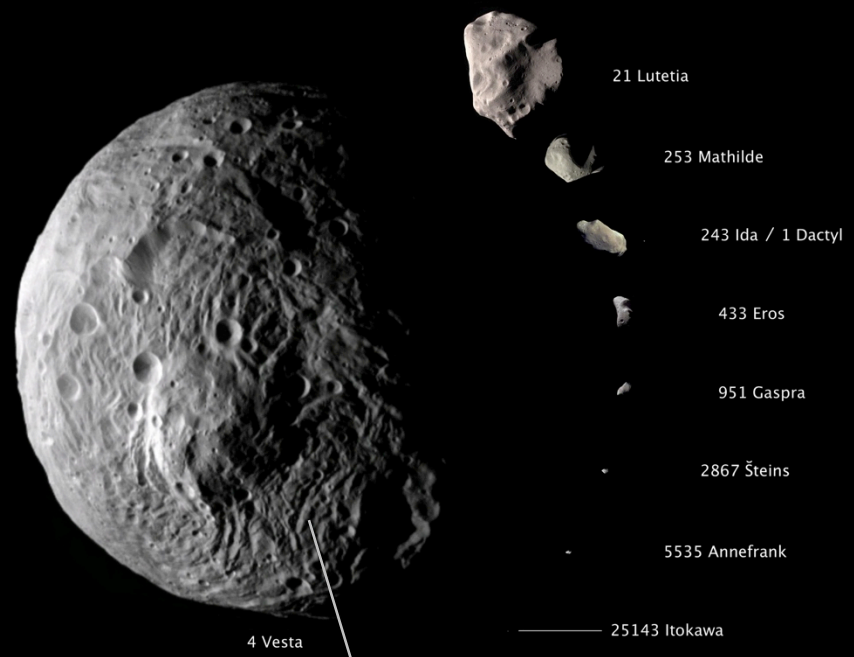
Background: The HED Meteorite Suite

- Howardite-Eucrite-Diogenite (HED) meteorites are suite of achondrites that come from the same parent body (similar Fe/Mn ratios and oxygen isotope compositions)
- **Diogenites**: Coarse grained, orthopyroxene-rich rocks (>~90% orthopyroxene)
- **Eucrites:** Basaltic rocks with low-Ca clinopyroxene and feldspar
- **Howardites**: Brecciated mixture of diogenite and eucrite material

Tatahouine diogenite

NWA 8056 Eucrite

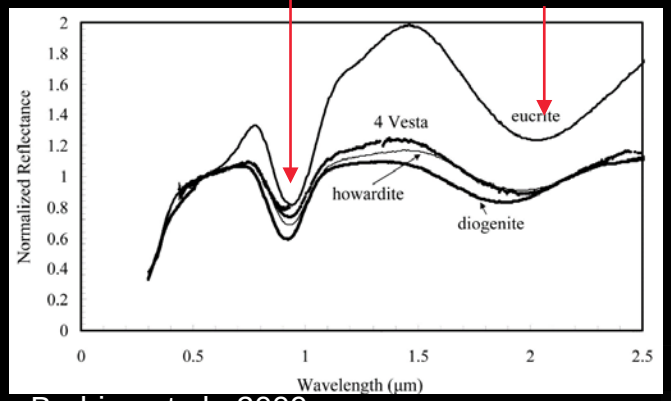
Background: Vesta and the HEDs



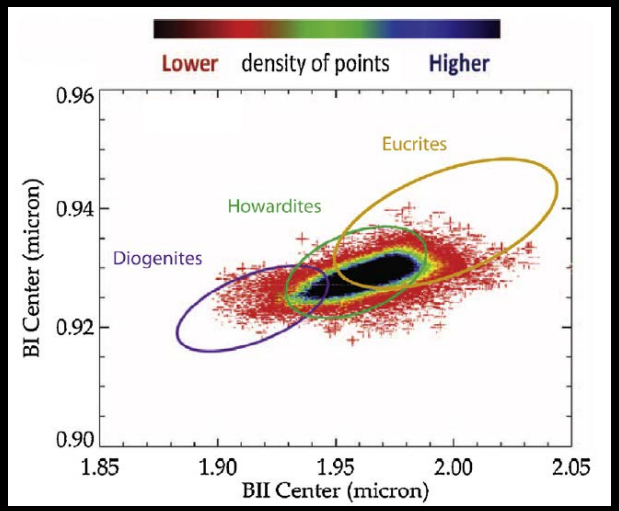
Bununu howardite

- Vesta = second largest asteroid in solar system
- Likely parent body of Howardite, Eucrite, Diogenite (HED) meteorite suite in part due to
  1. similarities in bulk spectral properties
  2. inferred age of Rehasiliva basin and meteorite delivering vestoids
  3. hydrogen in Vesta consistent with inferred abundances of xenolithtic carbonaceous chondrite materials
  4. constrained size of Vesta core consistent with geochemical models of HED parent body differentiation
- Studied by the Dawn mission from July 2011 – Sept. 2012

Background: Spectral Diversity at Vesta

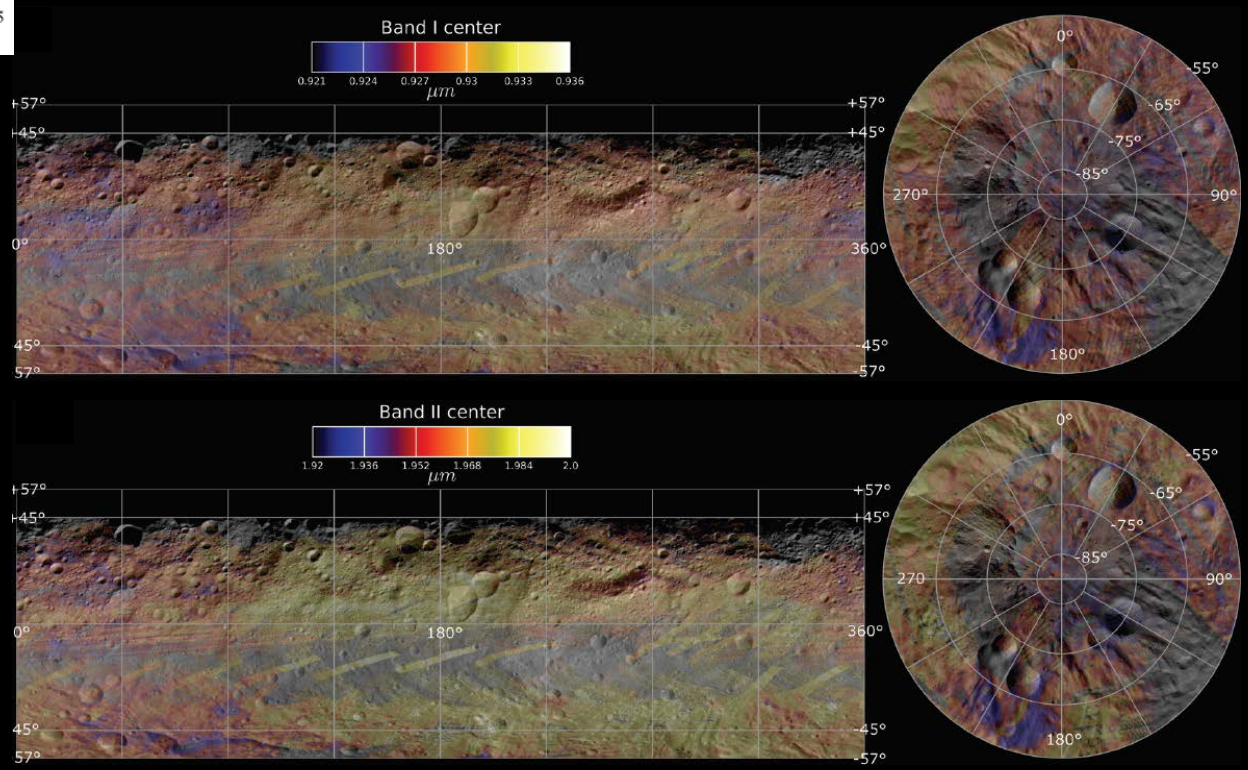


Burbine et al., 2009



DeSanctis et al., 2012

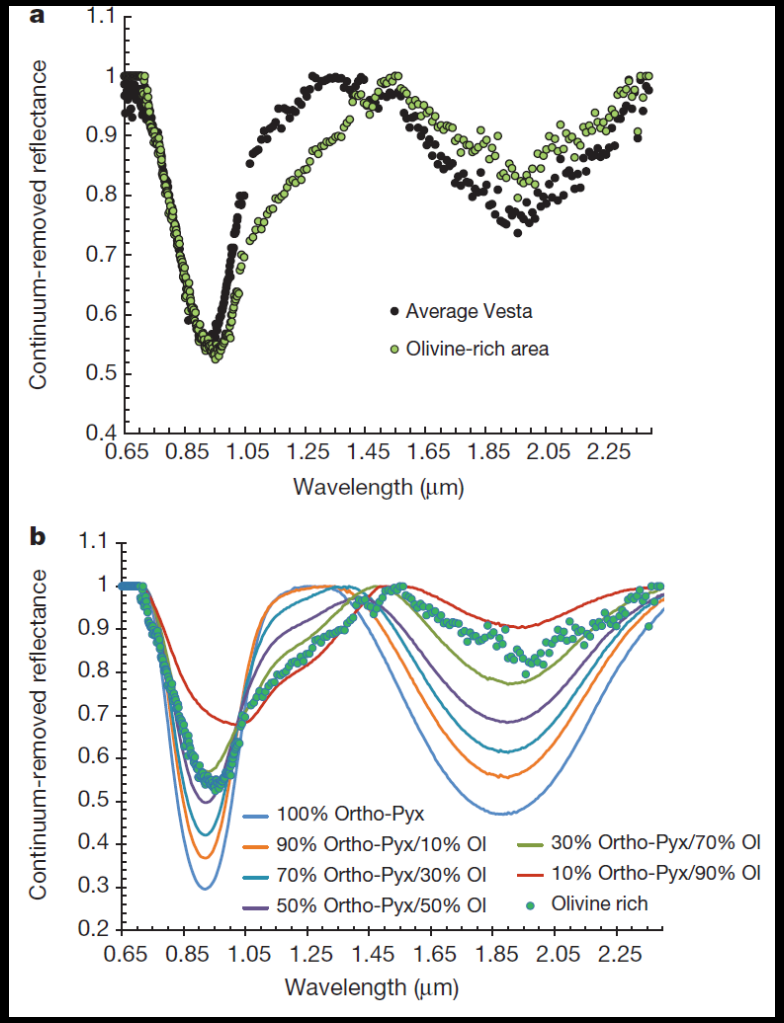
- Vesta spectra dominated by pyroxene absorptions
- Variations in band I and band II centers indicate compositional variability



Background: Other spectral features on Vesta

Olivine

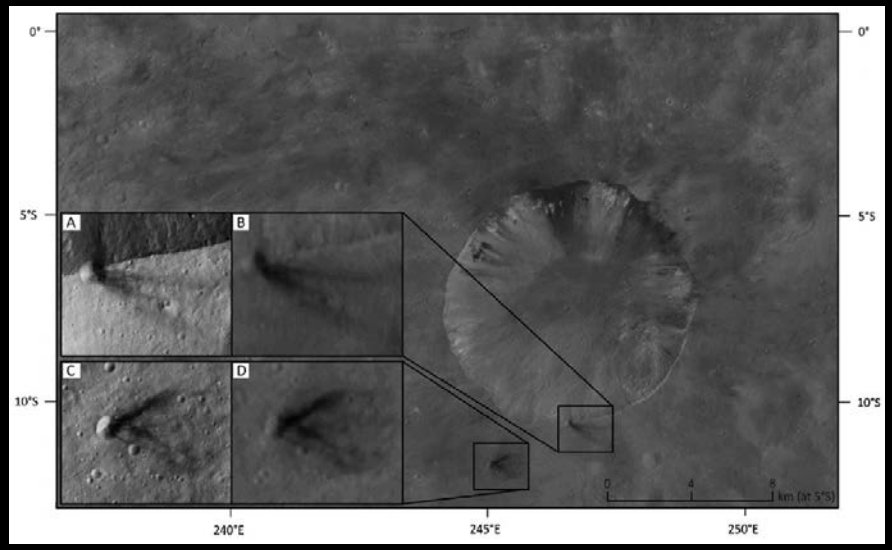
In unexpected locations



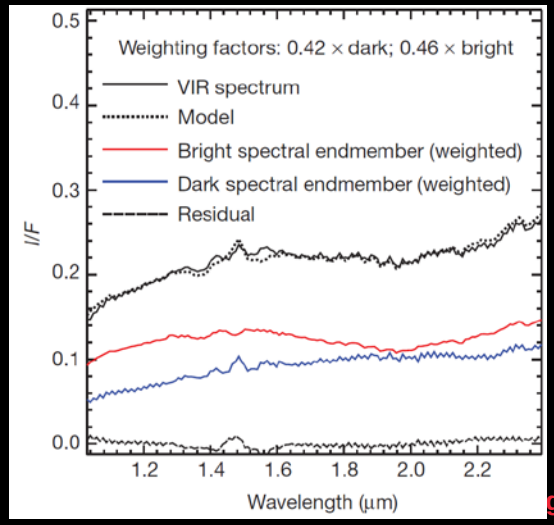
Ammannito et al., 2013

Carbonaceous material

Likely delivered by carbon-rich impactors



Jaumann et al., 2014



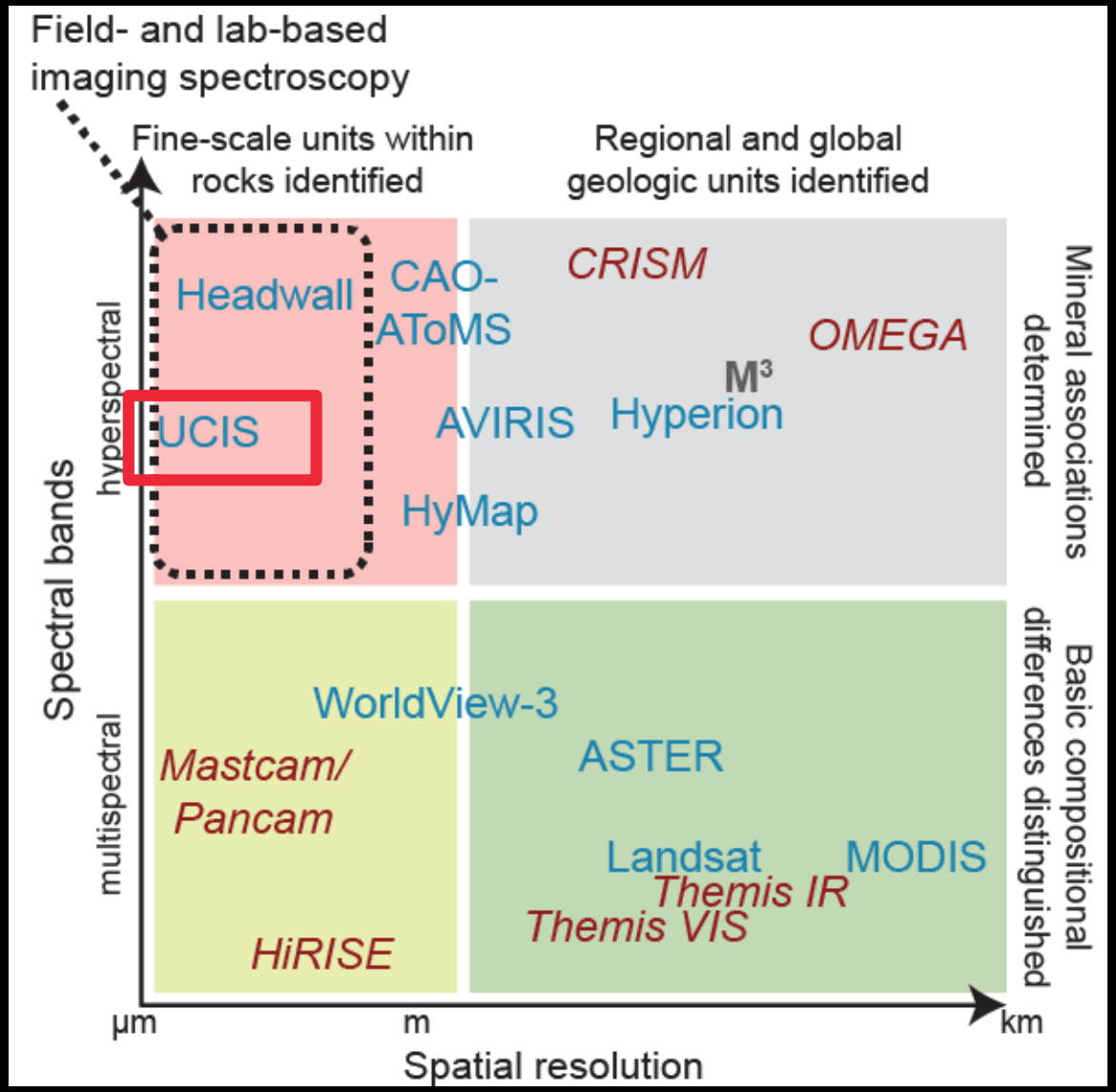
McCord et al., 2012

Key Questions

Focus of this study

- What is the spectral diversity of HED meteorites at the micrometer scale?
- How can understanding this diversity help understand how small scale heterogeneity in Vestan surface influences 70+ m/pixel spectral properties observed by Dawn?

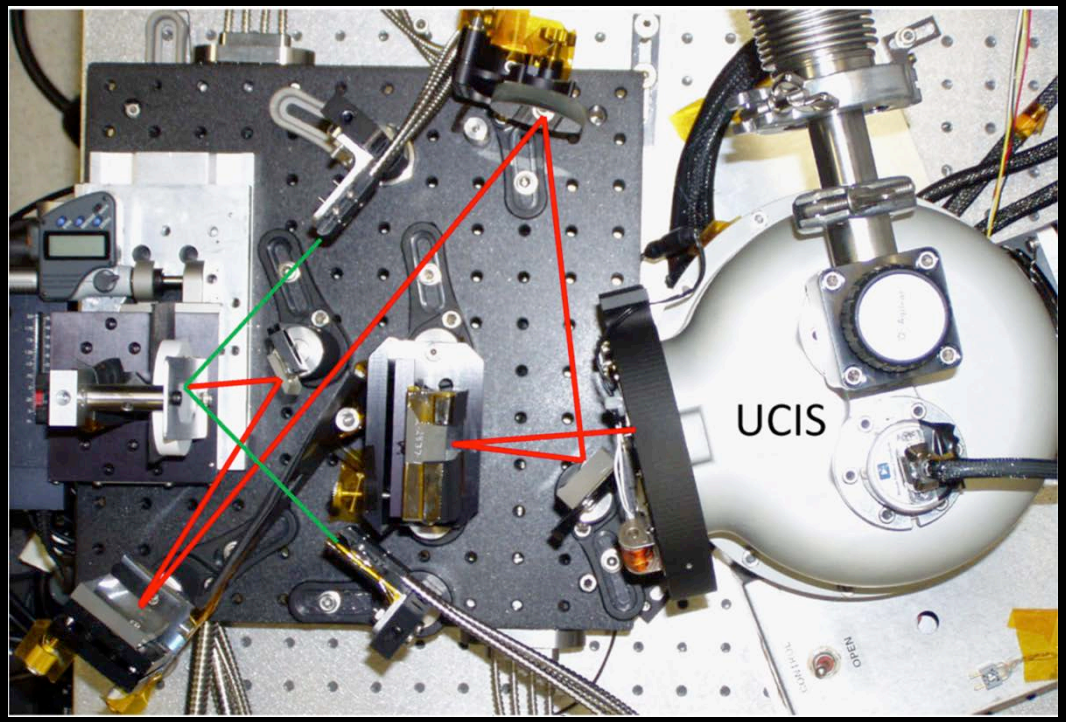
Methods: Microimaging Spectroscopy



Greenberger et al., 2015

- Hyperspectral images acquired with micrometer-scale pixels
- Rapid, non-destructive method that maintains sample context
- Has been included and proposed for future inclusion on planetary exploration missions

Methods: Ultra-compact imaging spectrometer (UCIS)



Van Gorp et al., 2014

Spectral range: 500 – 2500 nm
Spectral sampling: 10 nm
Spatial resolution in micro-mode: 80 µm/pixel

Methods: HED Samples

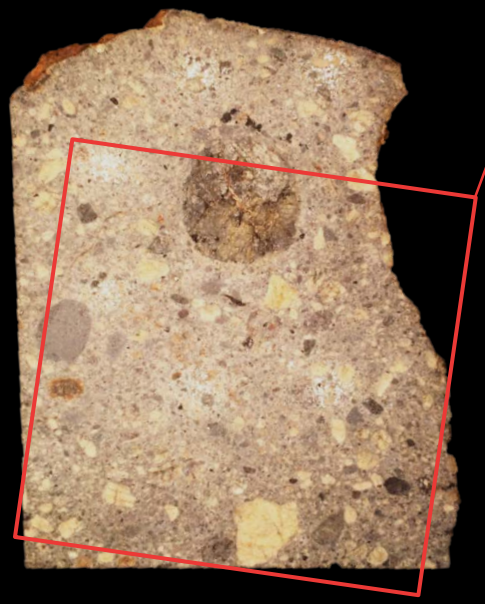
9 diogenites, 11 howardites, 8 eucrite samples

Diogenites	Howardites	Eucrites
NWA 7831	Old Homestead 001	Stannern
Los Vientos 001	NWA 7127	Sioux County a
NWA 2629	NWA 2060	Sioux County b
Aioun el Atrouss	NWA 1929	NWA 1908
NWA 6074	NWA 1769a	Juvinas
NWA 1648	NWA 1769b	Pasamonte
Bilanga	Frankfort (stony)	Hariya a
Johnstown	Kapoeta	Hariya b
Shalka	NWA 1282	
	NWA 6920	
	Muckera 002	

*Meteorite sample provided by ASU meteorite collection, Caltech mineral collection, Y. Liu, and G. Rossman

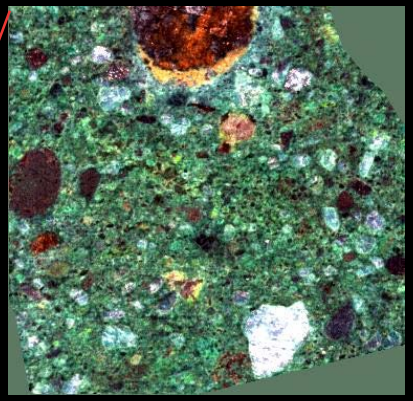
Methods: Assessing spectral diversity

Use a combination of automated and “by hand” techniques to explore spectral diversity



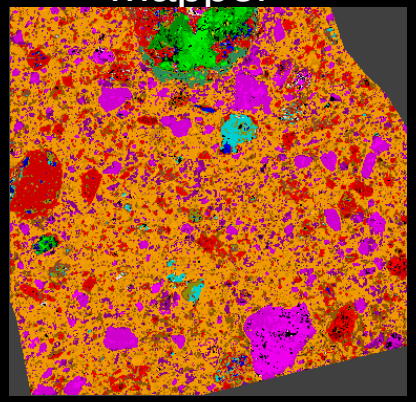
NWA 6920
iPhone photo for context

False-color



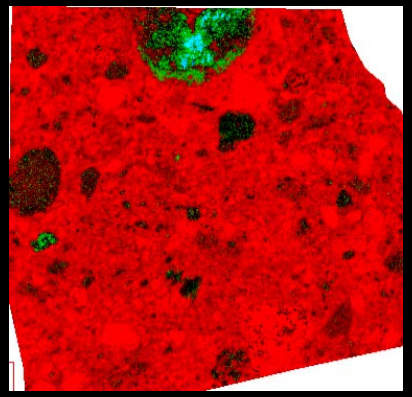
Channels:
R = 1 µm; G = 1.5 µm;
B= 2.3 µm

Spectral angle mapper



Each color represents class of spectra with similar properties;
Iterative process using automated suggestions + hand checking using built-in ENVI algorithms

Band depth mapping

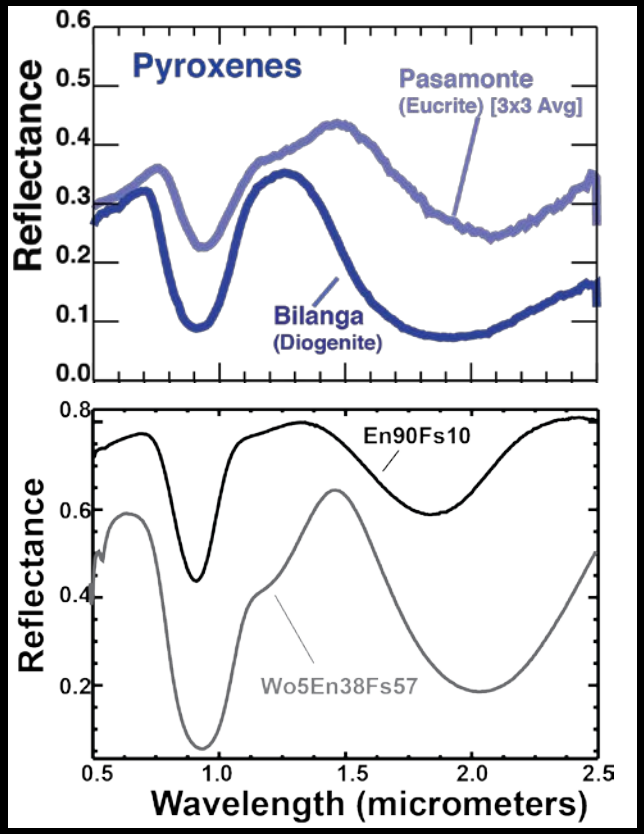


Red = Low Calcium Pyroxene
G = Olivine

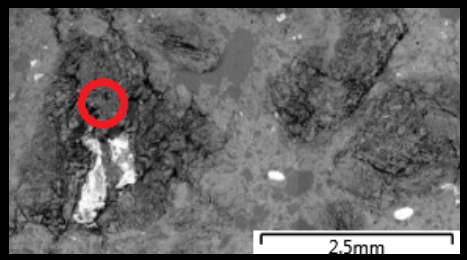
Spectral classes: 1. Pyroxene

Characterized by deep absorptions at 1 and 2 micrometers

Most prevalent spectral class



Class representative spectra



~En60Fs40

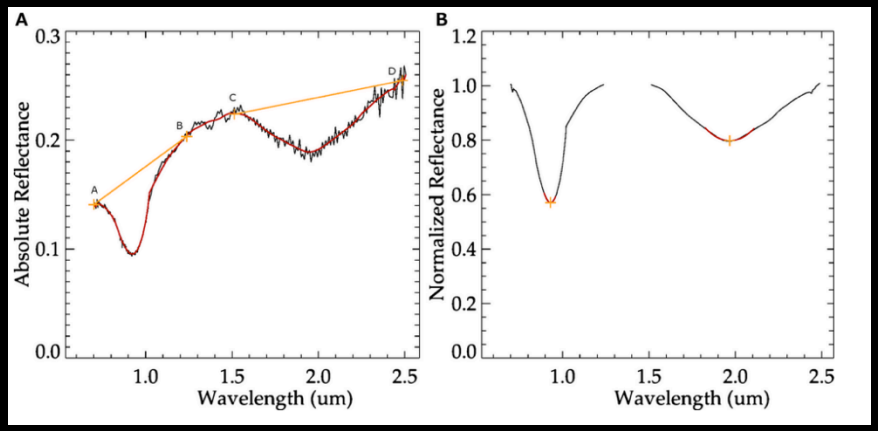
O	3.00
Si	0.94
Mg	0.69
Ca	0.05
Fe	0.38

SEM backscattered electron image spectrum from red circle

Well characterized lab spectra
Klima et al., 2007;
Klima et al., 2011

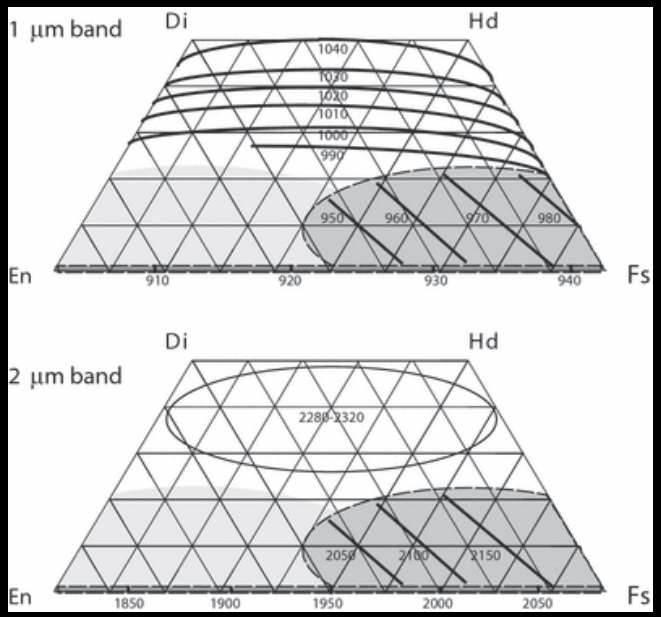
Pixels in this class comprise 96.1% of the diogenite samples, 95.3% of howardite samples, and 97.9% of the eucrite samples. This is inconsistent with HED modal mineralogy - eucrites typically up to 50% feldspar (Li & Milliken, 2015)). Sub-pixel mixing likely still occurring at this scale.

Pyroxene band positions and composition

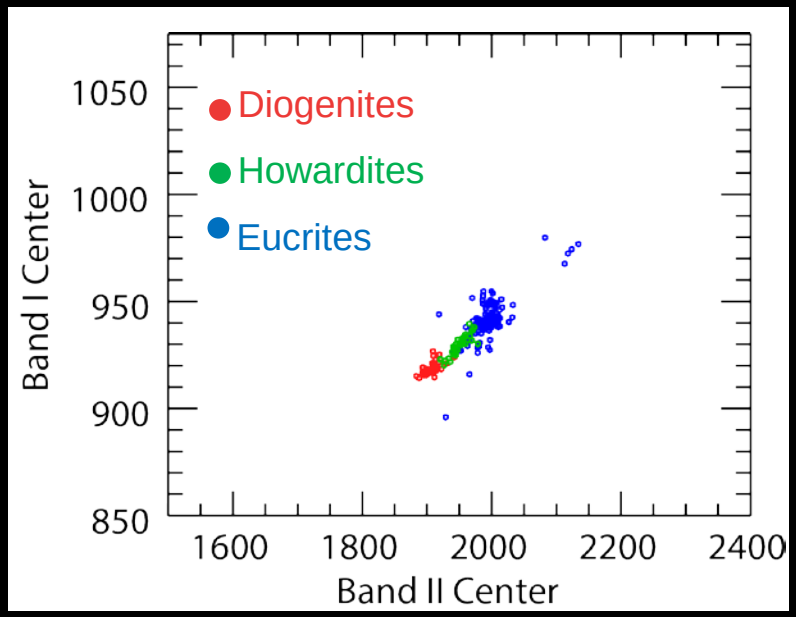


Ammannito et al., 2013

- Assign Band I and Band II centers fitting spectrum with linear continuum, continuum removal (CR), and fit CR band witih 6th order polynomial
- Position of Band I and Band II driven by cations in M1 and M2 pyroxene sites
- Average band positions of HEDs vary

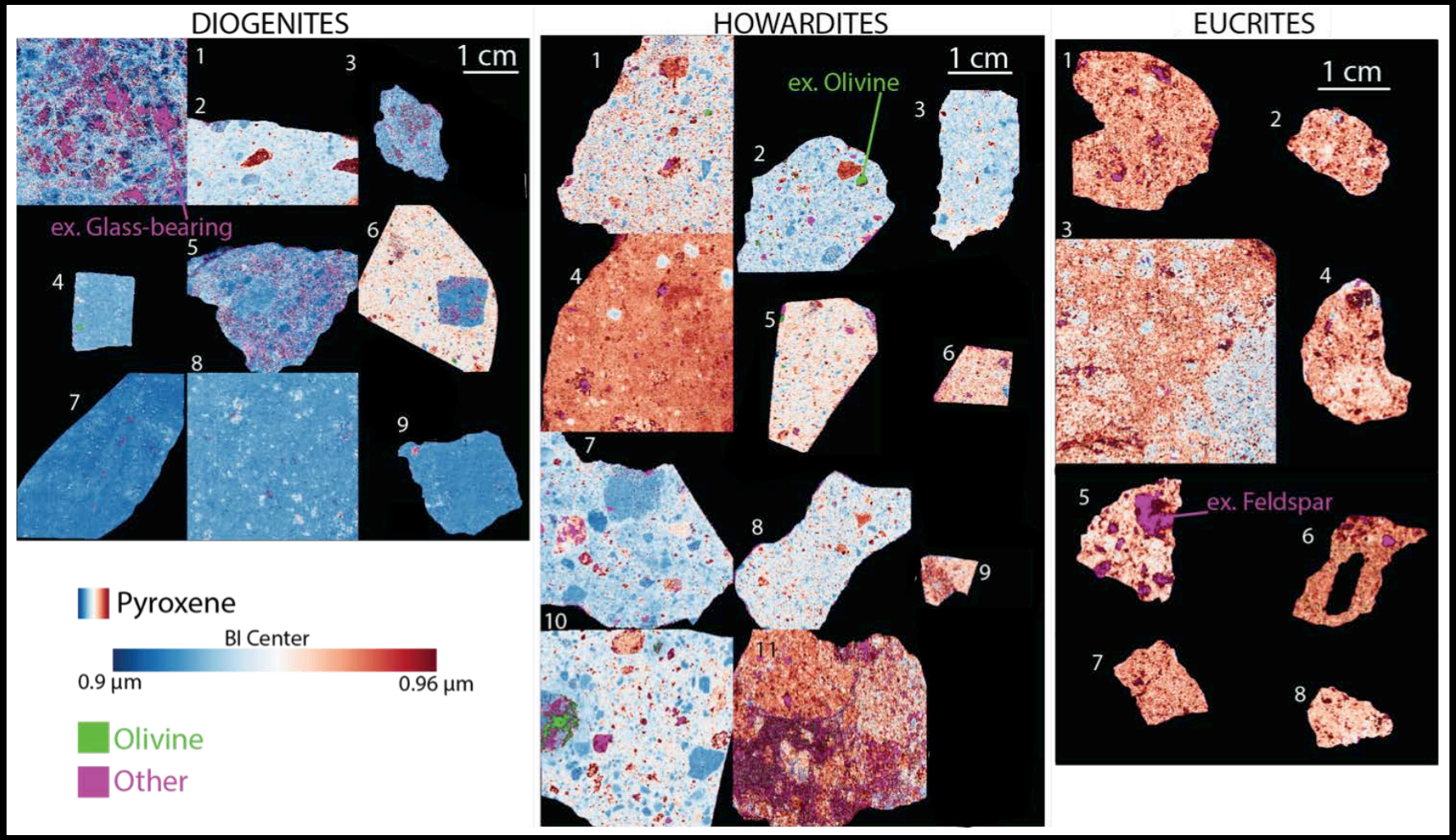


Klima et al., 2011



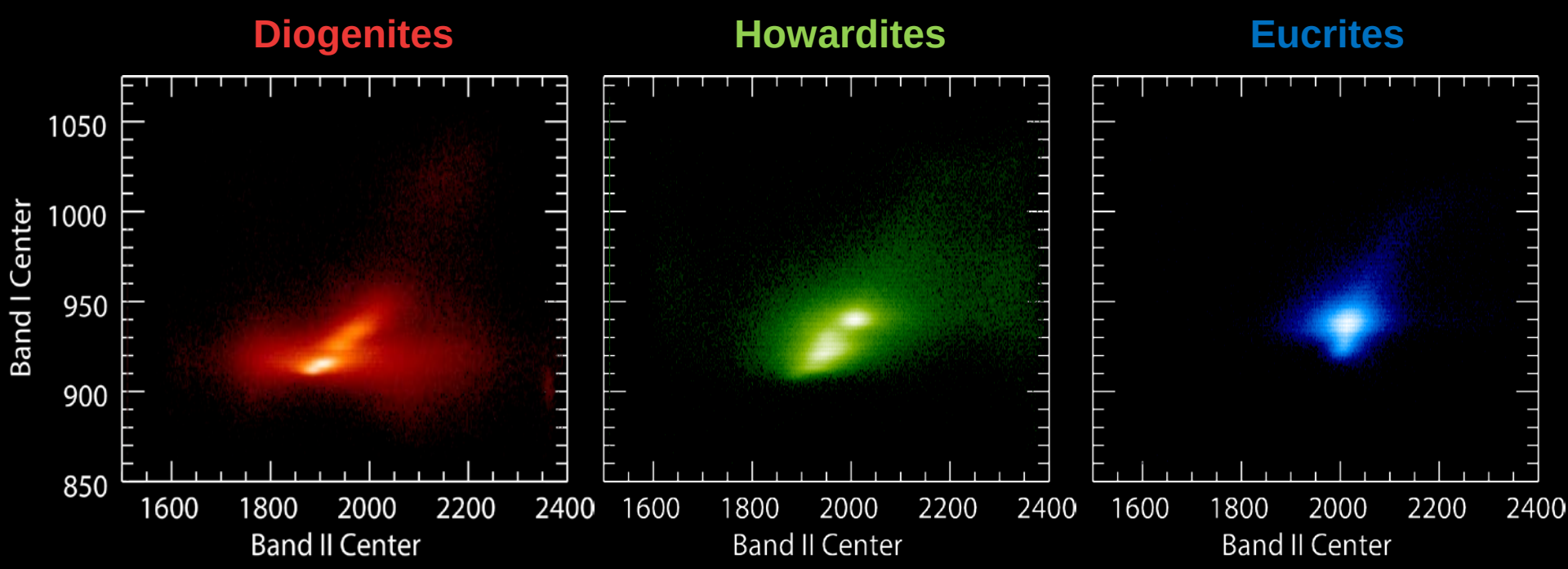
RELAB Meteorite Powders

Pyroxene Diversity



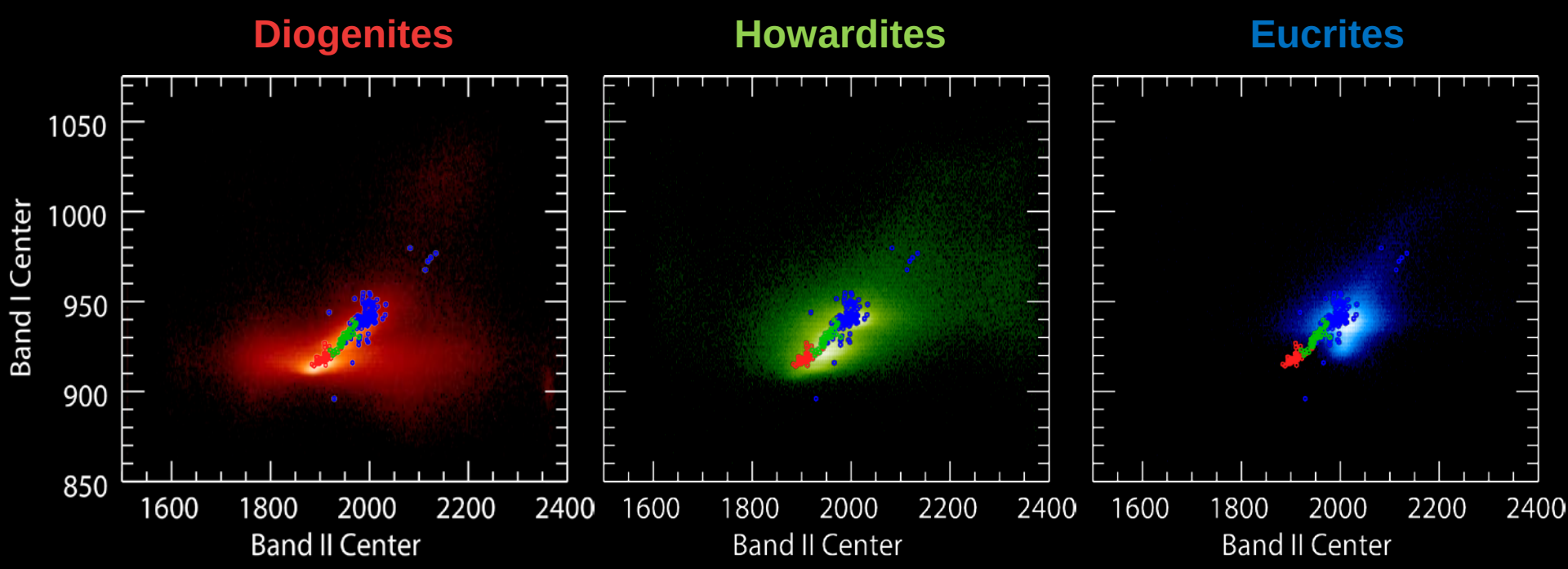
Sample IDs: Diogenites -- (1) Northwest Africa 7831 (2) Los Vientos 001 (3) Northwest Africa 2629 (4) Aioun el Atrouss (5) Northwest Africa 6074 (6) Northwest Africa 1648 (7) Bilanga (8) Johnstown (9) Shalka. Howardites – (1) Old Homestead 001 (2) Northwest Africa 7127 (3) Northwest Africa 2060 (4) Northwest Africa 1929 (5) Northwest Africa 1769 (6) Northwest Africa 1769 (7) Frankfort (8) Kapoeta (9) Northwest Africa 1282 (10) Northwest Africa 6920 (11) Muckera 002. Eucrites – (1) Stannern (2) Sioux County (3) Northwest Africa 1908 (4) Sioux County (5) Juvinas (6) Pasamonte (7) Haraiya (8) Haraiya.

Quantifying pyroxene diversity



Density plots of HED samples

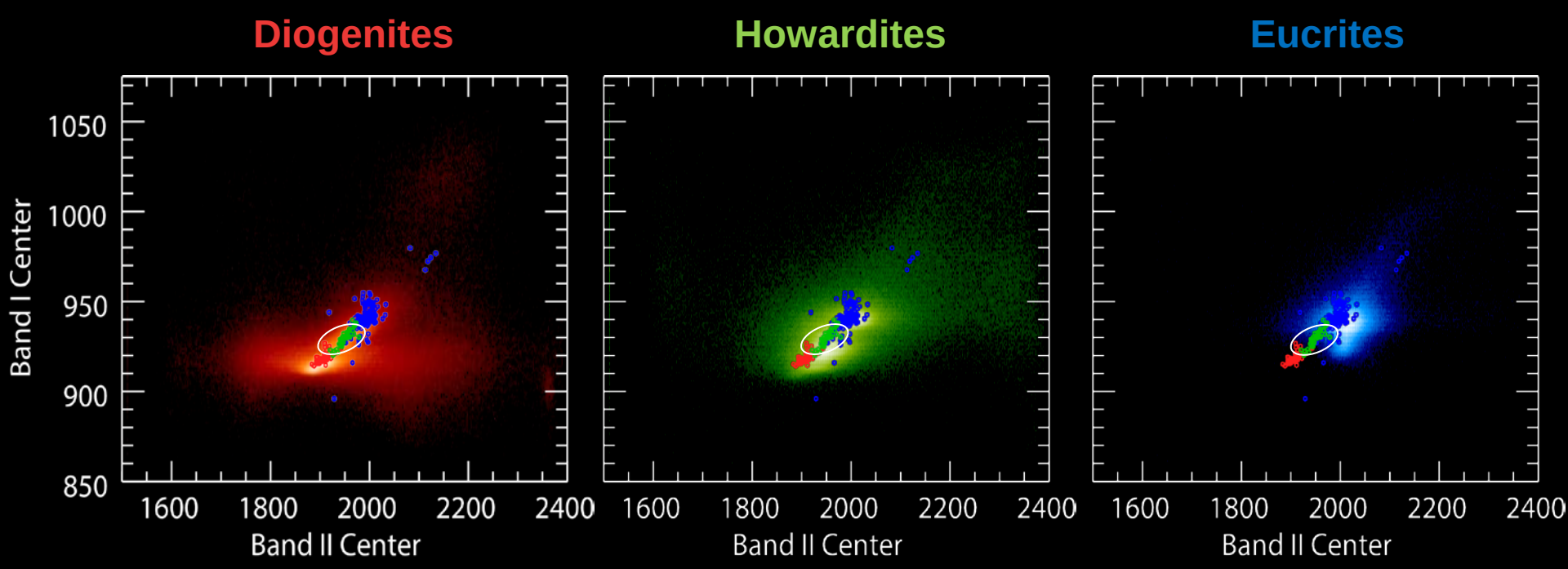
Quantifying pyroxene diversity



HED powders
from RELAB

- Diogenites
- Howardites
- Eucrites

Quantifying pyroxene diversity



HED powders from RELAB

- Diogenites
- Howardites
- Eucrites

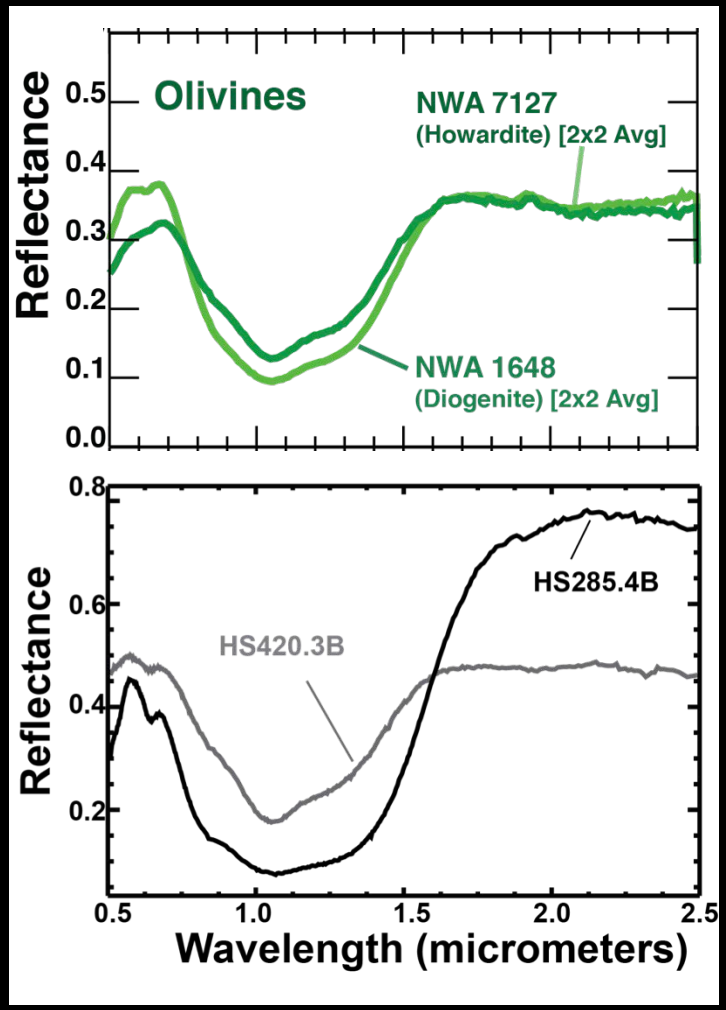
Range of Dawn data

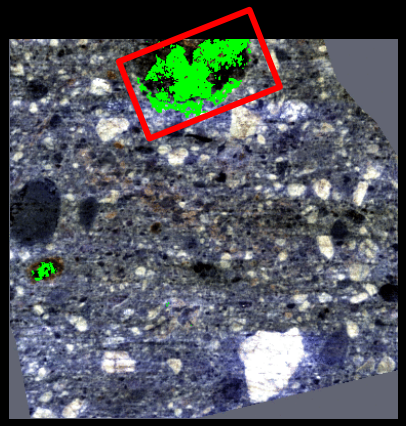
Spectral classes: 2. Olivine

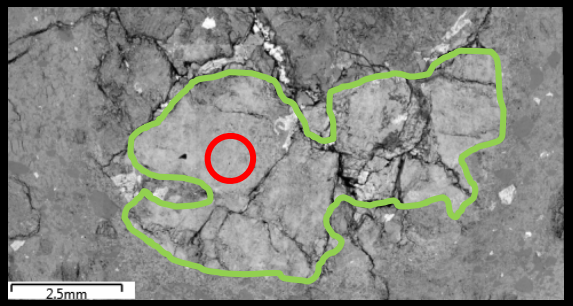
Olivine is rare but easily distinguishable in spectral data

Characterized by deep absorption near 1 micrometer

Variability in this class due to Mg/Fe content + degree of mixing with pyroxene







SEM backscattered electron image spectrum from red circle

Well characterized lab spectra; USGS spectral library

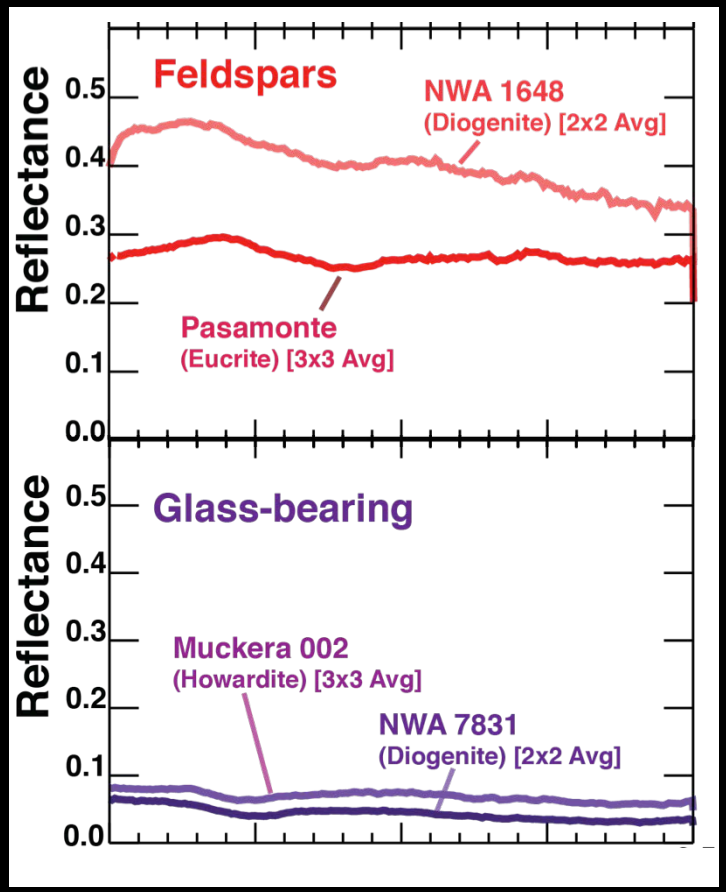
~Fo50

O	4.00
Mg	1.10
Si	0.98
Fe	0.94

Spectral classes: 3. Feldspar & 4. Dark material

Feldspar are important component in howardites and eucrites but are usually spectrally masked by pyroxene

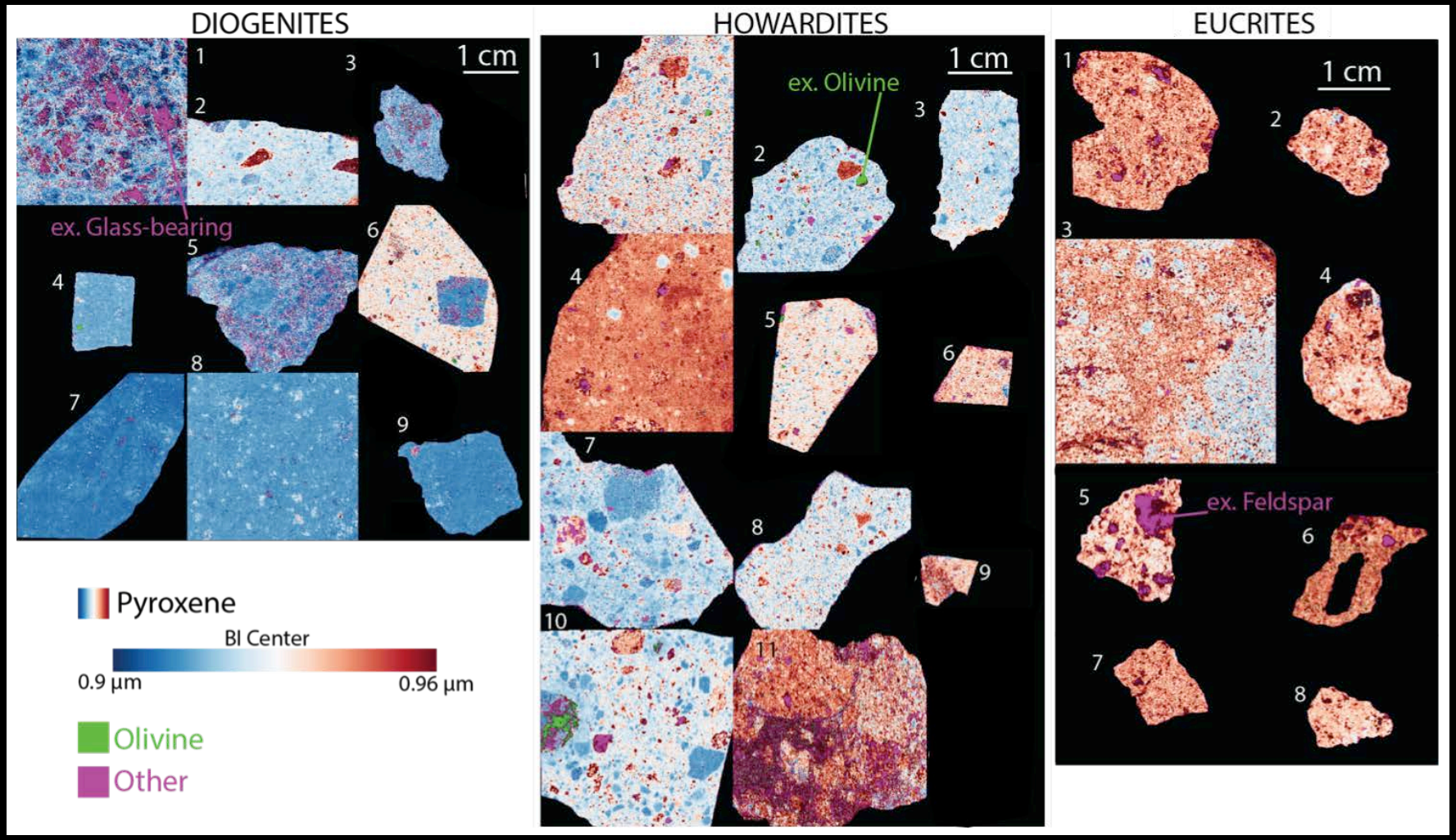
Dark materials represents glasses, impact melt, carbonaceous material, other opaque phases, space weathering products?



Some feldspars have minor absorptions near 1.3 micrometers due to iron substitutions

Pixels in the feldspar class comprise only a small proportion of the meteorites samples. This is inconsistent with HED modal mineralogy - eucrites typically contain up to 50% feldspar (Li & Milliken, 2015)). Sub-pixel mixing likely still occurring at this scale.

Spatial distribution of pyroxene, olivines, feldspar+ glass



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Conclusions

- Initial results show microimaging spectroscopy will be a powerful tool for characterizing precious meteorite samples
- HED meteorite samples have at least four major spectral classes of materials: pyroxene, olivine, feldspar, and glassy materials. There is variability within each class due to differences in mineral chemistry, grain size, orientiation, and subpixel mixing.
- We are able to observe a much greater spectral diversity at micrometer scale than previously seen by spacecraft or in powdered samples
  - phases that are hard to observe/not seen in bulk spectra (olivine, feldspar)
  - more diversity within spectral classes
- Future work will use knowledge of small scale spectral variability to gain insight into large scale Dawn data + evolution of Vesta

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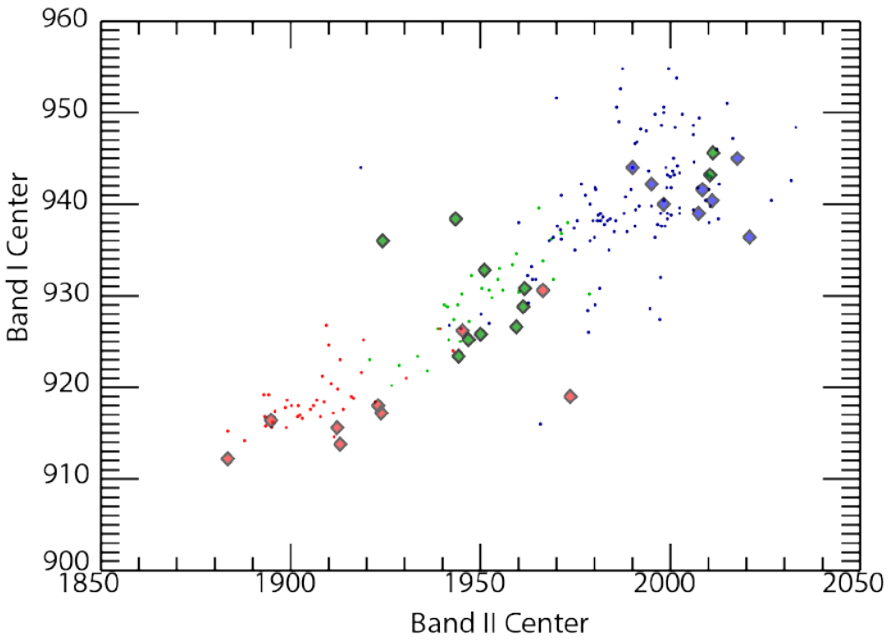
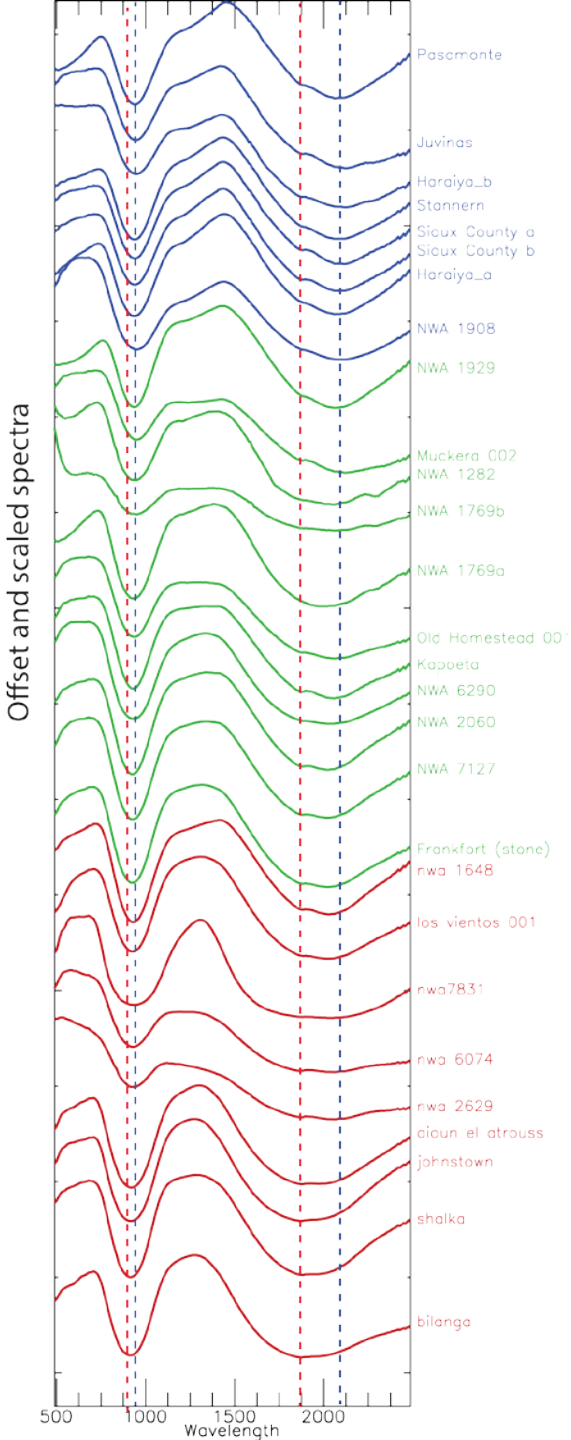
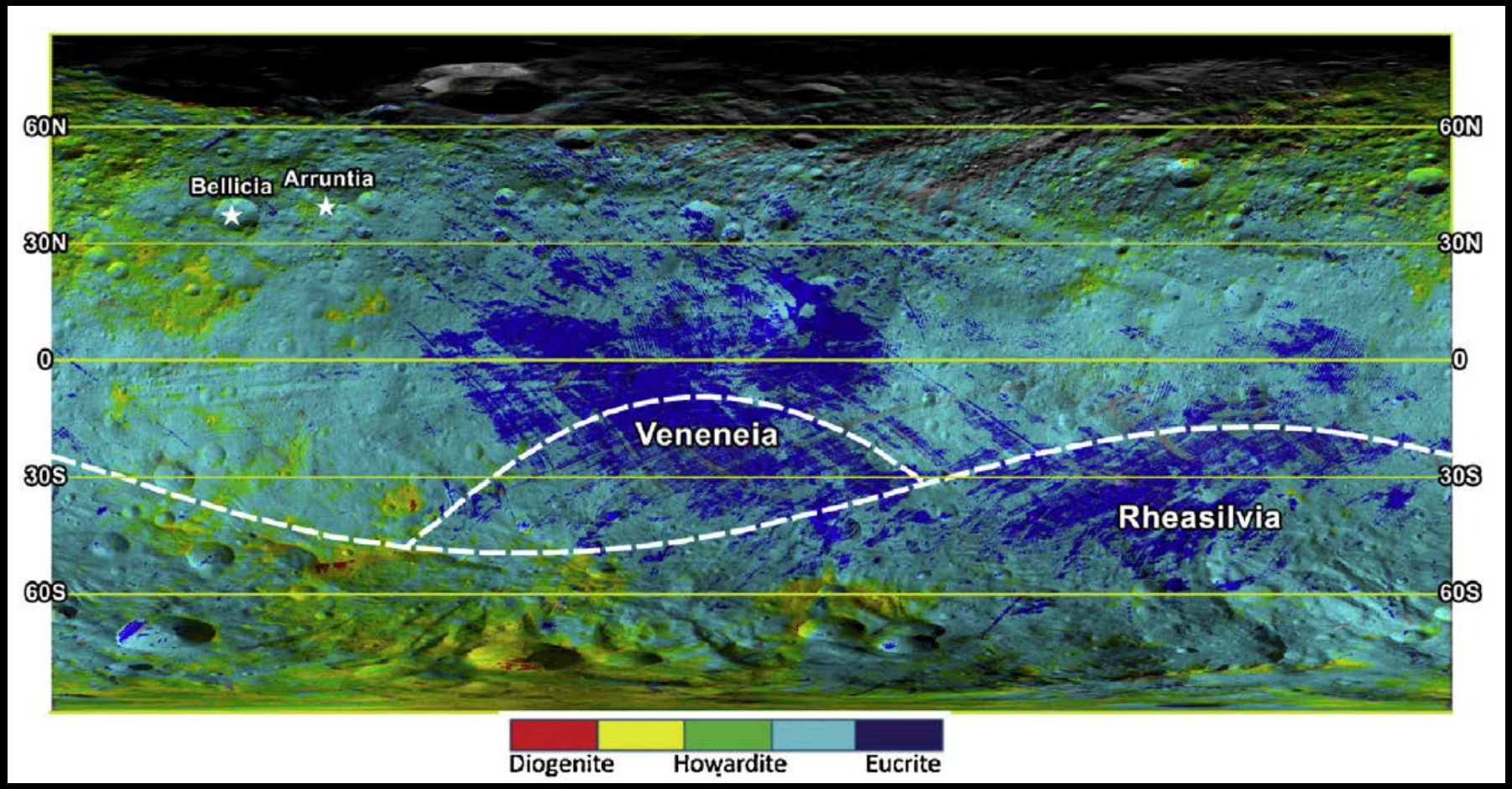
Average spectral from UCIS samples compared with RELAB HED powdered spectra





Background: Vesta and the HEDs



Amminato et al., 2013; McCoy et al., 2015