

## GROUND TRUTH MINERALOGY VS. ORBITAL OBSERVATIONS AT THE BAGNOLD DUNE FIELD.

C. N. Achilles<sup>1</sup> and R. T. Downs<sup>1</sup> D. W. Ming<sup>2</sup>, E. B. Rampe<sup>2</sup>, R. V. Morris<sup>2</sup>, A. H. Treiman<sup>3</sup>, S. M. Morrison<sup>1</sup>, D. F. Blake<sup>4</sup>, D. T. Vaniman<sup>5</sup>, R. C. Ewing<sup>6</sup>, S. J. Chipera<sup>7</sup> A. S. Yen<sup>8</sup>, T. F. Bristow<sup>4</sup>, B. L. Ehlmann<sup>8,9</sup>, M. G. A. Lapotre<sup>9</sup>, R. Gellert<sup>10</sup>, and R. M. Hazen<sup>11</sup>, <sup>1</sup>University of Arizona (cheriea@email.arizona.edu), <sup>2</sup>NASA Johnson Space Center, <sup>3</sup>Lunar and Planetary Institute, <sup>4</sup>NASA Ames Research Center, <sup>5</sup>Planetary Science Institute, <sup>6</sup>Texas A&M University, <sup>7</sup>Chesapeake Energy, <sup>8</sup>JPL/Caltech, <sup>9</sup>California Institute of Technology, <sup>10</sup>University of Guelph, <sup>11</sup>Carnegie Institution

**Introduction:** The Mars Science Laboratory (MSL) rover, Curiosity, is analyzing rock and sediments in Gale crater to provide in situ sedimentological, geochemical, and mineralogical assessments of the crater's geologic history. Curiosity's recent traverse through an active, basaltic eolian deposit, informally named the Bagnold Dunes, provided the opportunity for a multi-instrument investigation of the dune field.

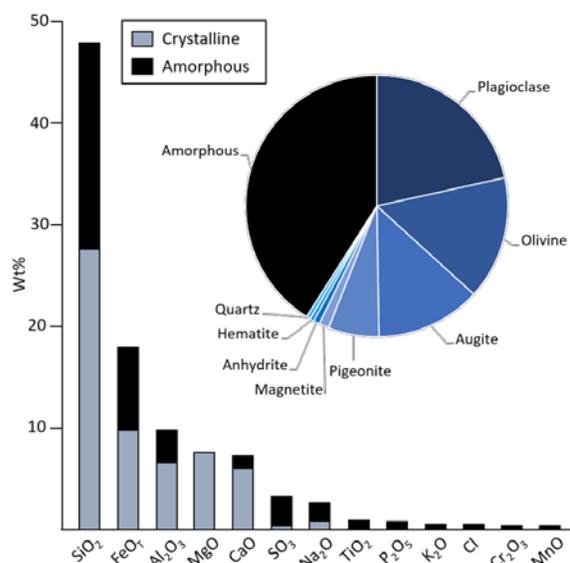
Prior to Curiosity's arrival at the Bagnold Dune Field, orbital observations characterized the geomorphology and predicted the mineralogy of the dunes. HiRISE (High Resolution Imaging Science Experiment) images showed that the dune field to be comprised of barchan, crescentic, and linear dunes with active ripple and dune migration [1-3]. Spectral mapping indicated strong high-calcium pyroxene and olivine signatures, the latter consistent with a predicted composition of Fo55(5) [4-7]. Furthermore, an enhanced spectral signature of olivine in the barchan dunes and high-Ca pyroxene in the linear dunes implies that there is spatial mineralogical sorting within the dune field [7-8]. Curiosity's traverse through the Bagnold Dune Field presents a rare opportunity to provide mineralogical ground truth for orbital observations.

**Bagnold Dune Campaign:** To meet the Bagnold Dune Campaign objectives, a strategic in situ sampling plan was conducted at the Gobabeb site, a location chosen for its strong olivine signature and high rates of sediment transport [2,8]. In the Bagnold sampling campaign, observations were designed to characterize the grain size distribution, chemical composition, mineralogy, and volatile chemistry of the Gobabeb scooped sediment samples.

The mineralogy and chemical composition of the Gobabeb sediment was characterized by the CheMin (Chemistry and Mineralogy) and APXS (Alpha Particle X-ray Spectrometer) instruments [9,10]. The CheMin X-ray Diffraction (XRD) instrument uses a microfocuss X-ray tube with a Co target, transmission geometry, and an energy-discriminating X-ray sensitive charged-coupled device (CCD) to produce two-dimensional (2D) XRD patterns. CheMin provided diffraction patterns of the sieved, <150  $\mu\text{m}$  fraction of the Gobabeb sediment. Rietveld refinements of the patterns provided mineral abundances and unit-cell parameters of major crystalline phases. FULLPAT analyses of the diffraction pattern were used to estimate the abundance of the

amorphous component and its composition was calculated from mass-balance calculations derived from APXS chemical data and CheMin-derived crystal chemistry [10-11].

**Gobabeb Mineralogy:** Gobabeb is dominated by basaltic minerals and X-ray amorphous phases. Plagioclase, olivine, and two Ca-Mg-Fe pyroxenes comprise the majority of crystalline phases; minor minerals include magnetite, quartz, hematite, and anhydrite (Fig. 1). The X-ray amorphous component is comprised mainly of  $\text{SiO}_2$  (~50 wt%),  $\text{FeO}_T$  (~20 wt%),  $\text{Al}_2\text{O}_3$  (~8 wt%), and  $\text{SO}_3$  (~7 wt%) (Fig. 1).



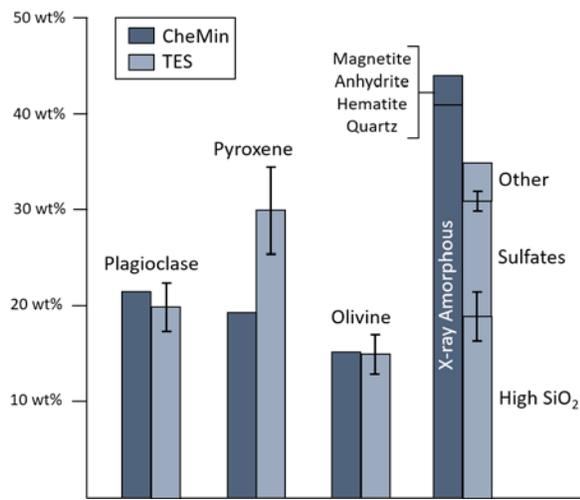
**Figure 1.** Gobabeb mineral and X-ray amorphous abundances (pie chart) and calculated compositions of the crystalline and amorphous components (bar graph). Based on CheMin and APXS data, the amorphous component is estimated at 41 wt% of the total sample.

**Orbital vs. in situ Mineralogy:** Curiosity's analysis of Gobabeb presents a unique opportunity to provide mineralogical ground truth for orbital observations. The CheMin-determined mineralogy at Gobabeb are especially valuable, because the sand dunes show little fine-grained dust cover that dominates the orbital signature of much of the martian surface. This wind-blown dust is likely reduced in the Bagnold Dune Field due to its active sediment transport [ ].

CRISM (Compact Reconnaissance Imaging Spectrometer for Mars) spectra of barchan dunes in Gale

crater, similar to the dune from which Gobabeb was sampled, show that the sands contain significant amounts of both the more abundant olivine and the less abundant high-Ca pyroxene, consistent with CheMin results which show ~26 wt% olivine and 22 wt% augite [7]. A targeted study by Lapotre et al. quantitatively estimated the abundances of olivine, plagioclase, pyroxene, magnetite, and volcanic glass at the Namib dune based on radiative transfer theory modeling of CRISM data. Their predicted 95% confidence intervals on phase abundances contain the CheMin-determined mineralogy from Gobabeb [8].

Based on spectra collected by the Thermal Emission Spectrometer (TES), Rogers and Bandfield (2009) calculated that the Bagnold dunes contain 20(5)% feldspar, 30(9)% pyroxene, 15(4)% olivine, 19(5)% high-silica phases (including possible silica glass, opal, zeolite, and phyllosilicate), 12(2)% sulfate and 4% other phases (volume abundance) [4]. The abundances of crystalline phases determined by CheMin, adjusted to accommodate ~40 wt% amorphous phases, are consistent with the TES-estimated quantities of feldspar (20% TES, ~22% CheMin) and olivine (15% TES, ~15% CheMin), but CheMin measured lower proportions of pyroxenes (30% TES, ~19% CheMin) (Fig 2). The CheMin-derived composition of the olivine, Fo56(3), is identical within error to that calculated from TES analyses (Fo55(5)) [6].



**Figure 2.** Phase abundances of the Bagnold Dune sediments, derived from CheMin and TES measurements. CheMin uncertainties are <1 wt% and are not shown.

TES data represent a bulk surface analysis over many km<sup>2</sup>, whereas CheMin analyzes the <150 μm fraction acquired at a single sample site. To bridge this scale gap, we calculated normative mineralogies from APXS analyses of both the bulk sand and the CheMin-analyzed <150 μm fraction. The calculated mineral abundances are within error of TES and CheMin com-

parisons despite the range of grain sizes and sample scales.

The identity of specific amorphous phases cannot be unambiguously determined from CheMin diffraction data because many X-ray amorphous materials produce similar broad scattering profiles [13]. However, the chemical composition of the amorphous component along with the TES predictions can suggest the nature of its potential constituents.

TES calculations attribute 19(5)% to high-silica phases. A minimum of ~20 wt% SiO<sub>2</sub> is allocated to the amorphous component in the mass balance calculations. The SiO<sub>2</sub> component cannot be represented by basaltic glass alone, given that its composition is limited by MgO; therefore, other phase(s) must be contributing to the SiO<sub>2</sub> abundance. TES modeled high silica phases as a combination of silica glass, opal, zeolite, and phyllosilicate. CheMin diffraction data show no evidence of zeolite or phyllosilicate, but the compositional data do support silica glass (e.g., basaltic glass, maskelynite, etc.), allophane, and/or amorphous silica (e.g., opal-A, opal-CT) as strong candidates to account for the high SiO<sub>2</sub>.

The remainder of the amorphous component is comprised mainly of FeO<sub>T</sub>, Al<sub>2</sub>O<sub>3</sub>, and SO<sub>3</sub>. A majority of the amorphous FeO<sub>T</sub> can be attributed to nanophase iron oxides. Maskelynite, allophane, and/or amorphous Al-sulfates are possible Al-bearing phases. The SO<sub>3</sub> proportion is likely attributed to amorphous sulfates. Although TES attributed 12(2)% of the Bagnold spectrum to sulfates, this appears to be an overestimate for the results observed at Gobabeb. Based on APXS measurements, a maximum of ~4 wt% sulfate is present at the site, and ~1 wt% is attributed to anhydrite.

Overall, the predicted mineralogy based on orbital spectral measurements of the Bagnold Dune Field shows high fidelity to in situ CheMin mineralogical analyses at Gobabeb. This unique ground-truth comparison can be used to validate and improve upon spectral models, as well as provide information regarding possible amorphous phases which may be ambiguous or poorly constrained in surface measurements.

**References:** [1] Hobbs et al. (2010) *Icarus* 210 102-115. [2] Silvestro et al. (2013) *Geology* 41 483-486. [3] Day and Kocurek (2015) *Icarus* 280 37-71. [4] Rogers and Bandfield (2009) *Icarus* 203 437-453. [5] Milliken et al. (2010) *Geophys. Res. Lett.* 37. [6] Lane and Christensen (2013) *Geophys. Res. Lett.* 40 3517-3521. [7] Seelos et al. (2014) *Geophys. Res. Lett.* 41 4880-4887. [8] Lapotre et al. (in review) *JGR*. [9] O'Connell-Cooper et al. (submitted) *JGR*. [10] Achilles et al. (submitted) *JGR*. [11] Chipera and Bish (2013) *Adv. Mater. Phys. Chem.* 3. [13] Morris et al. *LPSC XLVI*, Abstract #2434.