INVESTIGATION OF THE BAGNOLD DUNES BY THE CURIOSITY ROVER: SUMMARY OF RESULTS FROM THE FIRST INVESTIGATION OF AN ACTIVE DUNE FIELD ON ANOTHER PLANET

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Introduction: At the 4th International Planetary Dunes Conference in 2015, plans were presented for the Bagnold Dune Campaign by the *Curiosity* rover in Gale Crater, Mars. This was advertised as the first investigation of an active dune field on another planetary surface. Here, at the 5th Dunes Conference, we summarize results from the campaign, which, at the time of writing this abstract, derive from 14 papers published, in press, or submitted [1-14]. The focus of the first phase was the investigation of two barchan dunes, High Dune and Namib Dune. Preliminary results from the second phase of the campaign, within linear dunes to the south, is currently ongoing and will also be presented.

Prior to arriving at Mars, it was recognized that the traverse path of the MSL *Curiosity* rover would pass through a sand dune field that had previously been shown as migrating. The first in situ study of an active dune field on another planetary surface was recognized as a unique opportunity well tied to MSL science objectives. *Curiosity* was better suited than any previous Mars mission to mount a series of investigations to address fundamental questions on Martian sand dunes, centered both on their current state and how they tie into the planet's geologic history.

Implementation: Rover Traverse and Activities: Phase I of the Bagnold Dune Campaign spanned Sols 1162 to 1253 (Nov. 13, 2015 - Feb. 14, 2016) and was partitioned into four science sub-phases: 1) Entering the dune field (Sols 1162-1180*)* the rover parked in roughly equally separated azimuths (314.2°, 193.1°, and 75.7°, respectively) to assess the local wind field and determine the ideal location to measure the strongest winds later in the campaign. 2) Activities near and at High Dune (Sols 1181-1184), including MAHLI and APXS measurements of undisturbed and disturbed sand and dune material 3) Namib Dune slip face observations (Sols 1198-1214): For 16 sols the rover was parked 15 m in front of Namib Dune, affording the opportunity to undertake long term change detection observations. REMS provided measurements showing the influence of the dune on wind recirculation [12]. 4) Coordinated Measurement Campaign at Gobabeb, Namib Dune (Sols 1221-1244): Activities included wheel scuffing into the dune to reveal internal structure; MAHLI, APXS, and ChemCam on disturbed and undisturbed sands; scooping and sieving of sand into <150 μm and 150 μm - 1 mm size fractions, with the former delivered to CheMin and both to SAM, and piles dumped on to the surface investigated with MAHLI, APXS, and ChemCam; change detection observations; and DAN in its active mode when driving off the dune to assess hydrogen in the dune interior.

Major Results

1. Dune remote sensing signatures and ground truth for orbital observations

The dunes were measured with all Mastcam filters (visible to VNIR) and ChemCam passive (UV to VNIR) spectroscopy [8]. A continuum of spectral features observed between coarse- and fine-grained dune sands suggests that mafic grains, ferric materials, and airfall dust mix in variable proportions depending on aeolian activity and grain sorting [8]. Measurements from the REMS ground temperature sensor convolved with the predicted thermal inertia from MAHLI-derived particle sizes show good agreement with THEMIS thermal inertias, providing ground truth data that can be used for other dunes on Mars [5]. Plagioclase and olivine closely match orbital TES thermal infrared measurements, but the pyroxene is lower in CheMin (which is restricted to <150 μm in size) [1]. Reflected infrared spectroscopy from CRISM matches to a 95% confidence level the CheMin measurements [1]. Mineralogy estimated from orbital CRISM observations are within 10 wt. % of that derived from CheMin [10]. Such results are proving useful in providing ground truth data for spectral unmixing calculations using the Hapke radiative transfer model [11].

2. Current dune processes, rates, and structures

REMS wind measurements confirm GCM predictions of dominant northerly daytime winds up Mt. Sharp and nightly southerly downslope winds, with a clockwise rotation between these times [12]. In the lee face of Namib Dune, blockage of northerly daytime winds results in a westerly [12] and easterly flow, the latter of which especially contributes to dune ripples seen on the lee face [7]. Based on HiRISE seasonal observations and global circulation model predictions, *Curiosity* investigated the dunes in the least windy time of the year [2]. Nevertheless, change detection images from Mastcam and RMI document grain scrambling and minor grainflow. Some of the most significant events are correlated to the highest wind speeds recorded by REMS at friction speeds of 0.3-0.4 m s^{-1}, values that are below fluid threshold on Mars [2]. As shown by [14], grain detachmant may occur under such cases when turbulent eddies harness grains that are more exposed to the wind than would be the case in a sand bed. Under these conditions, grains act as triggers that drive further saltation, resulting in a cascade of grain motion that can explain the extensive evidence for sand movement on Mars today.

The structures of Martian dunes exhibit similarities and differences with their terrestrial counterparts, the elucidation of which points to important aspects of environmental control on dune formation. The close-up imaging by *Curiosity*, including the use of stereo images to derive high resolution topography, has provided important new information. Impact ripples and grainflow and grainfall deposits are similar on the two planets, with angle-of-repose slopes measured between 29 and 33 degrees. However, larger-scale ripples are fairly common on Martian dunes but rare on Earth [7]. Their commonality on the planet may be due to the higher kinematic viscosity in the Martian atmosphere such that fluid drag processes, akin to those in water, contribute to large ripple formation [9]. Where they can be preserved on the lee slopes of dunes, they should produce a sandstone stratigraphy that is unique to Mars [7].

4. Grain sizes, sorting, shapes, and colors

MAHLI and RMI images, including those in size-segregated piles, show that sand size varies from 40 µm to 600 µm , with most sand grains less than 250 µm [4,6]. The sand is generally well rounded, with some angular light-toned grains, perhaps representing local Murray bedrock or calcium sulfate-rich vein fragments. Despite the size range, the grains are the most well sorted so far measured on Mars [6]. Colors are variable, although generally consistent with mafic compositions of pyroxene, plagioclase, olivine, and opaque phases. Colors include opaque gray of various shades, translucent yellow, opaque reddish, opaque white/light, translucent green, and translucent colorless grains [6].

5. Chemistry, Mineralogy, and Volatile Contents of Dune Sands

Elemental results come from APXS and ChemCam, mineralogy from the <150 µm size fraction from CheMin, volatiles upon release from both the <150 µm and 150 µm - 1 mm size fractions from SAM, and hydrogen from ChemCam, SAM, and DAN. Distinct from other Martian fines, the Bagnold sands have lower sulfur, chlorine, and hydrogen contents and elevated silica. The sands also have elevated pyroxene and olivine, especially as estimated for the coarser 150 µm - 1 mm size fraction in which Fe and Mn are elevated [1,6,13]. Reconciling the bulk elemental composition measured by APXS and ChemCam versus the mineralogy from CheMin indicates that a missing x-ray amorphous phase with 42% minimal abundance also exists. The <150 µm fraction has a greater proportions of plagioclase and the amorphous phase compared to the 150 µm - 1 mm fraction. Within the amorphous phase, the amount of silica is 20% greater, perhaps resulting from some sands being derived from local Murray mudstones.

The low S and Cl from ChemCam and APXS are consistent with the smaller sulfur dioxide release measured by SAM [4,13]. Given that the amorphous component at Rocknest (an indurated sand shadow investigated early in the mission) was volatile-rich and CheMin shows that the proportion of minerals to amorphous materials is the same for the two aeolian deposits, the Bagnold amorphous component indicates either 1) a lower degree of chemical alternation, 2 grains containing it were somehow physically sorted out, or 3) a greater retention of volatiles for soils that have a higher specific surface area compared to the dunes. The latter is consistent with ChemCam and APXS analyses of the <150 µm material that shows a stronger H, S, and Cl signal compared to the coarser piles [4,13]. This may be why CheMin, which is limited to <150 µm, indicates a similar amount of a volatile-rich amorphous component, whereas ChemCam, DAN, and SAM show a lower bulk H measurement [4].

Discussion and Implications

The results of the Bagnold Dune campaign have broad implications. In the modern environment, we now have a better understanding of aeolian transport rates, the mechanisms for wind moving sand, and unique structures that form under Martian conditions. The sand characteristics and compositions are consistent with a derivation from a basaltic source, including possible local contributions. A clear geochemical difference is apparent from fresh sands to indurated bedforms to sandstones. These physical and chemistry data should influence our interpretation of the Martian stratigraphic record.

Ongoing Studies: At this writing, MSL is investigating longitudinal dunes to the south. This is during a high wind season, in which more activity is apparent. Initial results will be reported at this and future conferences.

References

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