



Contents lists available at ScienceDirect

# Aeolian Research

journal homepage: [www.elsevier.com/locate/aeolia](http://www.elsevier.com/locate/aeolia)

## Conference Report

# Summary of the Second International Planetary Dunes Workshop: Planetary Analogs – Integrating Models, Remote Sensing, and Field Data, Alamosa, Colorado, USA, May 18–21, 2010

Lori K. Fenton<sup>a,\*</sup>, Mark A. Bishop<sup>b</sup>, Mary C. Bourke<sup>b</sup>, Charles S. Bristow<sup>c</sup>, Rosalyn K. Hayward<sup>d</sup>, Briony H. Horgan<sup>e</sup>, Nicholas Lancaster<sup>f</sup>, Timothy I. Michaels<sup>g</sup>, Daniela Tirsch<sup>h</sup>, Timothy N. Titus<sup>d</sup>, Andrew Valdez<sup>i</sup>

<sup>a</sup> Carl Sagan Center at the SETI Institute, 189 N. Bernardo Avenue, Mountain View, CA 94043, USA

<sup>b</sup> Planetary Science Institute, 1700 E. Fort Lowell Road, Suite 106, Tucson, AZ 85719, USA

<sup>c</sup> School of Earth Sciences, Birkbeck College, University of London, Malet Street, London WC1E 7HX, England, UK

<sup>d</sup> United States Geological Survey, Astrogeology Science Center, 2255 N. Gemini Dr., Flagstaff, AZ 86001, USA

<sup>e</sup> Department of Astronomy, Space Sciences Building, Cornell University, Ithaca, NY 14853, USA

<sup>f</sup> Desert Research Institute, 2215 Raggio Parkway, Reno, NV 89512, USA

<sup>g</sup> Southwest Research Institute, 1050 Walnut St. Suite 300, Boulder, CO 80302, USA

<sup>h</sup> German Aerospace Center, Institute of Planetary Research, Rutherfordstrasse 2, 12489 Berlin, Germany

<sup>i</sup> Great Sand Dunes National Park and Preserve, 11500 Hwy 150, Mosca, CO 81145, USA

## ARTICLE INFO

### Article history:

Received 16 September 2010

Accepted 20 September 2010

### Keywords:

Aeolian processes  
Bedform morphology  
Bedform migration  
Meeting summary

## ABSTRACT

The Second International Planetary Dunes Workshop took place in Alamosa, Colorado, USA from May 18–21, 2010. The workshop brought together researchers from diverse backgrounds to foster discussion and collaboration regarding terrestrial and extra-terrestrial dunes and dune systems. Two and a half days were spent on five oral sessions and one poster session, a full-day field trip to Great Sand Dunes National Park, with a great deal of time purposefully left open for discussion. On the last day of the workshop, participants assembled a list of thirteen priorities for future research on planetary dune systems.

## 1. Introduction

Landforms and deposits created by the dynamic interactions between sediment and airflow (aeolian processes) occur on several planetary bodies, including Earth, Mars, Titan, and Venus. The recognition of dunes on worlds beyond Earth requires the use of terrestrial analogs and a well-established methodology for their interpretation from orbital and lander platforms. Given the similarities of dune morphology on different planetary surfaces, it is reasonable to assume that dunes are dynamically similar throughout the Solar System. Aeolian bedforms, therefore, can be indicative of surface processes and environments on unfamiliar extra-terrestrial

landscapes, provided that the fundamentals of the landforms and processes are well-understood on Earth.

Despite four decades of study of extra-terrestrial dunes, many questions regarding their composition, sediment sources, morphology, age and origins, and dynamics under present and past climatic conditions remain unanswered. Recently acquired data from orbiters and rovers, together with innovative approaches using terrestrial analogs and numerical models, are beginning to provide new insights into how these bedforms formed and what they may reveal about their environment.

Dr. Timothy N. Titus of the US Geological Survey (USGS), along with Dr. Lori Fenton (Carl Sagan Center), Dr. Nick Lancaster (Desert Research Institute), Andrew Valdez (National Park Service) and Rose Hayward (USGS) convened the Second International Planetary Dunes Workshop as a means of bringing together terrestrial and planetary researchers from diverse backgrounds with the goal of fostering collaborative interdisciplinary research. Designed for a small group (approximately 40 people), the workshop facilitated intensive discussion of the landforms and processes associated with aeolian systems on Earth, Mars, and Titan. The workshop took

\* Corresponding author. Tel.: +1 510 786 7199; fax: +1 650 962 9419.

E-mail addresses: [lfenton@carlsagancenter.org](mailto:lfenton@carlsagancenter.org) (L.K. Fenton), [bishop@psi.edu](mailto:bishop@psi.edu) (M.A. Bishop), [mbourke@psi.edu](mailto:mbourke@psi.edu) (M.C. Bourke), [c.bristow@ucl.ac.uk](mailto:c.bristow@ucl.ac.uk) (C.S. Bristow), [rhayward@usgs.gov](mailto:rhayward@usgs.gov) (R.K. Hayward), [briony@astro.cornell.edu](mailto:briony@astro.cornell.edu) (Briony H. Horgan), [nick.lancaster@dri.edu](mailto:nick.lancaster@dri.edu) (N. Lancaster), [tmich\\_ael@boulder.swri.edu](mailto:tmich_ael@boulder.swri.edu) (T.I. Michaels), [Daniela.Tirsch@dlr.de](mailto:Daniela.Tirsch@dlr.de) (D. Tirsch), [ttitus@usgs.gov](mailto:ttitus@usgs.gov) (Timothy N. Titus), [Andrew\\_valdez@nps.gov](mailto:Andrew_valdez@nps.gov) (A. Valdez).

place in Alamosa, Colorado, from May 18–21, 2010. The program and abstracts may be found online at <http://www.lpi.usra.edu/meetings/dunes2010/>.

This workshop follows the Planetary Dunes Workshop: A Record of Climate Change, convened in Alamogordo, New Mexico from April 29–May 2, 2008. Held in a similar format as the current workshop and including a full-day field trip to White Sands National Monument, the 2008 workshop brought planetary scientists together for the first time to discuss current research on dunes and dune systems. Much of the work presented was published in a special issue of *Geomorphology* (vol. 121, “Planetary Dune Systems”), including an introductory paper summarizing recent understanding of planetary dunes (Bourke et al., 2010). As a major outcome of this meeting, attendees agreed on ten priorities for future planetary dune research (Titus et al., 2008), a list that was updated and amended during the Second Planetary Dune Workshop.

## 2. Session and field trip summary

The workshop consisted of five oral sessions, one poster session, and a full-day field trip to Great Sand Dunes National Park. The first day began with a keynote talk from Mary Bourke, who summarized the progress in planetary dune research in the two years following the first Planetary Dune Workshop. Details of that talk will be published elsewhere. Following are summaries of each oral session; posters are discussed in the oral session for which they are most relevant.

### 2.1. Aeolian grains: sources and transport

The first session of the workshop was dedicated to studies of the sources and transport of aeolian grains on a variety of planetary surfaces. Three presentations emphasized the value of describing compositional variation using remote sensing for investigating both transport pathways and sources of grains in large aeolian systems, such as in the Gran Desierto in Sonora, Mexico (Scheidt et al., 2010), in the vast equatorial sand seas of Titan (Vixie and Barnes, 2008), and across Mars (Cornwall and Titus, 2010). Other work focused on unusual sources of aeolian grains determined through *in situ* sample collection and laboratory analysis, including a bedrock source for dune fields in eastern Colorado (Aleinikoff and Muhs, 2010) and a volcanic ash source for basaltic dune fields (with Mars-analog implications) in Hawaii (Tirsch et al., 2010) and Arizona (Hooper et al., 2010). On Mars, observations from the Mars Exploration Rovers (MER; Squyres et al., 2004) suggested that the saltation and subsequent in-air breakup of low-density sand-sized dust agglomerates may be an important process that helps maintain the atmospheric dust loading on the planet (Sullivan et al., 2010).

A major theme that emerged in discussion during this session was the concept of mineralogical maturity. On Earth, quartz-rich aeolian sediments are considered more mature than quartz-poor sediments, as the mechanical weathering involved in saltation over time tends to select for impact-resistant grains, like quartz (e.g., Pettijohn et al., 1972; Muhs, 2004). However, it is unclear how mineralogical maturity should be defined for planetary surfaces that lack abundant quartz, such as on the primarily basaltic surface of Mars. Preliminary *in situ* observations on Mars of compositional variations versus grain size by the two Mars Exploration Rovers (MERs) suggest that high olivine abundances may be an indicator of mineralogical maturity, as olivine has physical properties similar to quartz (Sullivan et al., 2008, 2010) and appears to indicate mature volcanic sand on Earth (Mangold et al., 2010). If this is the case, mineralogical maturity via aeolian transport on Mars may compete with chemical processes, as olivine may be relatively

chemically unstable on the martian surface over geological time-scales (e.g., Hurowitz et al., 2006; Bandfield and Rogers, 2008).

### 2.2. Dunes, water, and ice

The second session entitled “Dunes, Water and Ice” was dominated by papers on the martian North Polar sand seas (Putzig et al., 2010; Wood et al., 2010; Kreslavsky, 2010; Diniega et al., 2010; Horgan et al., 2010; Smith and Holt, 2010) (Note that Smith and Holt (2010) replaced Gardin et al. (2010) in the program) with one terrestrial analog talk on the dunes in the McMurdo Dry Valleys of Antarctica (Bristow et al., 2010) and a poster on the Great Kobuk Sand Dunes in Alaska (Dinwiddie et al., 2010). The papers included a range of studies that included both interpretation of remote sensing data and modelling. Critical issues surround the role of H<sub>2</sub>O and CO<sub>2</sub> ice on the surface morphology and dynamics of dunes. The source of ice in dunes is still unquantified and many potential emplacement mechanisms may be in operation: it may be derived from ice moving up through the dunes from permafrost, from ice condensed seasonally, from H<sub>2</sub>O and CO<sub>2</sub> snow, or from water vapor diffusion. Putzig et al. (2010) reported that thermal inertia of dunes in the north polar sand seas can be explained by dry basalt sand overlying ground ice, a result supported by further thermal modelling by Titus and Cushing (2010). The upward movement of water vapor from shallow ground ice into overlying dunes was supported by modelling (Wood et al., 2010). Kreslavsky (2010) noted that ice cements in dunes, either derived from water vapor from ground ice or from the martian atmosphere, would reduce dune mobility; and reported that an extensive search for impact craters in dune fields had revealed only one such crater, indicating that the dunes of Olympia Undae have some limited activity. In addition to the presence of ice cements in dunes on Mars, Horgan et al. (2010) consider other possible cements such as sulfate minerals and investigated the possible effects of ice and gypsum cements on dune morphology in the North Polar sand seas on Mars. When it comes to cold climate dunes on Earth the dunes in the McMurdo Dry Valleys of Antarctica described by Bristow et al. (2010) are probably among the best analogs for dunes on Mars. In Antarctica reversing winds constrained by the valley topography have a significant impact on dune morphology. The effects of wind reversals on dune morphology were included in the modelling studies by Diniega et al. (2010), investigating the effects of wind reversals and ice cementation on dune slope evolution. Another example of cold climate dunes are the Great Kobuk Sand Dunes in Alaska described by Dinwiddie et al. (2010) where the dunes also experience a reversing bimodal wind regime.

### 2.3. Field trip

Alamosa, Colorado was selected as the site of the Second International Planetary Dunes Workshop because of its proximity to Great Sand Dunes National Park. Because these dunes formed in a valley that has been subject to multiple wind directions, the Great Sand Dunes have characteristics much like many martian intracrater dune fields. These similarities make this location an important analog site for planetary aeolian studies. At the end of the first day of the workshop, National Park Service geologist Andrew Valdez gave a 30 min presentation on the Great Sand Dunes that included information about historic explanations of the origins of the dunes and the current understanding. The following day, Valdez led the field trip that included 3 stops. The first stop was at Zapata Falls, where the location at the head of an alluvial fan provided a view of the Great Sand Dunes aeolian system. From there, the mountains that source the sand and the streams that carry the sand into the San Luis Valley were viewed. The entire aeolian system includes playa lakes where sand is concentrated, then

exposed to winds, transitioning to sand sheet deposits downwind as the topography rises. Although a sand sheet is generally a zone across which sand is transported, subsidence in the San Luis Valley has created accommodation space for deposition. The aeolian system ends at the Sangre de Cristo Mountain front where the wind regime becomes complex, leading to the development of tall draas (megadunes) and sand ramps. While at stop 1, the group also visited the small waterfall, called Zapata Falls, which is located in a narrow gorge formed when a terminal moraine forced South Zapata Creek over highly fractured bedrock in a canyon side wall. Stop 2 was at the main dune field. Smithsonian Geologist James Zimbelman described his work on granule ripples, and then the field trip broke into 2 groups. One group went to a hematite cemented outcrop that showed dune, fluvial and sand sheet deposits. The other group explored the sand dunes. The last stop was at the north end of the aeolian system at the Crestone Crater, a small crater of unknown origin, located in the sand sheet north of the main dune field. A healthy discussion ensued about the origin of the crater, with possibilities including impact-, aeolian-, or permafrost-related processes. The results of previous work on the origin of the Crestone Crater were presented, and most agreed that it was unlikely to be formed by an impact. Valdez withheld that report from most of the participants to get their unbiased thoughts. The discussion included ideas for future work, including some by the Colorado School of Mines to help determine the origin of the crater. The field trip allowed the workshop participants an opportunity, and in many cases a first chance, to see a variety of aeolian features similar to those observed on Mars.

#### 2.4. Bedform Activity I and II

The degree of bedform activity on planetary bodies is a key topic of planetary aeolian science. If sand actively saltates under current climatic conditions on other worlds, then some bedforms may reflect the present-day wind circulation patterns and sediment state. If not, then bedforms must reflect a previous climate and sediment state, dating to when the dunes were built. From a lack of data coverage and image resolution, it is not yet known if dunes are active on Venus and Titan, but on Mars the subject is a topic of ongoing discussion. Until recently, the lack of observed bedform migration on Mars suggested that dunes there are largely inactive (e.g., Malin and Edgett, 2001). However, careful study of changes in dunes from orbital imagery indicates that sand does appear to saltate, eroding small dunes (Bourke et al., 2008) and possibly creating grainflows on dune slip faces (Fenton, 2006). *In situ* observations from the Mars Exploration Rovers (MERs) show clear indications of active sand saltation (Geissler et al., 2008) and ripple migration (Sullivan et al., 2008). Each of these detections occurred at different locations on Mars, indicating that martian winds are strong enough to move sand in many regions on the planet. As reported at the workshop by Silvestro et al. (2010), Chojnacki et al. (2010), and Bridges (2010), further investigations have led to new detections of saltation in the form of bedform migration and erosion. Bishop (2010) demonstrated that wind scour marks are also indicators of recent sand movement; further evidence that sand saltation may be more prevalent than previously thought. Methods of automating bedform migration detection are being tested on Earth (Scheidt and Lancaster, 2010), and they may prove useful on Mars in the future.

Determining the conditions that allow dunes to accumulate is of great importance in predicting dune activity and understanding how dunes relate to the climatic history of a region. Aeolian activity is not generally predicted by martian atmospheric models. One reason for this may be that buoyantly-driven convective wind gusts are quite strong on Mars but are not fully accounted for in the low resolution models used to estimate sand fluxes (Fenton and Michaels, 2010). Such models must be used with care when

predicting potential aeolian activity on all planetary bodies (Michaels, 2010). Using Earth analogs may help to better understand the controls on martian bedform activity (Hayward et al., 2010). For example, on Earth, the frequency, strength, and direction of wind events that produce saltation and lead to bedform activity are dependent on subtle climatic changes that influence the water table and vegetation (Redsteer et al., 2010; Bogle et al., 2010). Although liquid water and vegetation do not influence the climate on Mars, there are yet unknown processes that stabilize bedforms on Mars, leaving them to become eroded and eventually contribute to the rock record (Kerber and Head, 2010). One major step towards understanding how bedforms interact with their environment is to catalog their occurrence, a major undertaking on all planetary bodies. Automation of this process is being developed (Bandeira et al., 2010), with the promise that new planetary databases of bedforms may help further our understanding of the role dunes play in their local sedimentary history.

#### 2.5. Bedform morphology: environmental controls and patterns

The session on bedform morphology presented the results of numerical simulations, flume experiments and data collected from dunes on Mars and Titan, and Earth analogs. The session focus was on the observed variability in dune planform, morphometry and wavelength on Mars and Titan. Of note was the new data available on small-scale bedforms (ripples and transverse aeolian ridges – TARs) from the HiRISE camera (25–50 cm/pixel) (Shockey and Zimbelman, 2010). Morphometric data, such as bedform profiles can be compared with those on Earth to investigate whether TARs are megaripples or reversing dunes (Zimbelman et al., 2010). Future work utilizing the unprecedented 1 m resolution topographic data from the HiRISE stereo camera (Kirk et al., 2008) will improve comparative morphometric studies.

Several presentations showed how bedform attributes may reflect a dependence on wind (direction and velocity), atmospheric density and sufficient time for bedform evolution. All of the active major dune types on Earth were shown to be oriented to maximize the gross bedform-normal sediment transport direction (Lancaster, 2010). This strengthens confidence in the prediction of formative wind regimes using dune form on planetary surfaces. Flood-formed bedforms on Earth are analogs for similar features found on Mars (Burr et al., 2004), which are currently being mapped and studied (Rudoy and Chernomorets, 2010). Flume experiments and numerical modelling show that bi-directional wind regimes may cause many of the unusual barchan dune forms noted on the surface of Mars. The approach can be used to indicate and elucidate the variability of formative winds on planetary surfaces (Reffet and Fulchignoni, 2010). Linear dunes appear to follow streamlines, which may provide a new method of modelling dune orientation around obstacles (Lorenz, 2010). Bedform wavelength on the flanks of a martian volcano increases from 0.6 to 6 m over a 23 km range in elevation. These data suggest an inverse relationship between bedform wavelength and atmospheric density (Lorenz et al., 2010a). Morphological analysis of dunes and their surrounding environment in Moreux crater in the southern martian highlands indicate that these dunes were built under a multidirectional and changing wind regime (Cardinale and Komatsu, 2010). Pattern analysis of the wavelength and spacing of Titan's linear dunes show a uniform dune population. These data suggest that either conditions on Titan have been stable over a long time period or that evidence of past phases of dune building has been destroyed (Radebaugh et al., 2010). Unlike Mars, the sensor data available for Titan is thought to be too low to detect the elemental bedform length, estimated to be 1.5 m. Titan's dunes are therefore truly mega-dunes formed by the growth of elementary bedforms, while

their maximum size is limited by the 3 km depth of the boundary layer (Lorenz et al., 2010b).

### 3. Future research approaches

A significant portion of the workshop was dedicated to discussion, with the intent of fostering communication and encouraging collaboration. The main outcome of this discussion was general agreement on areas of research most needed to further understanding of planetary dune systems. On the final day of the workshop, participants compiled the following list to guide future planetary aeolian research:

1. Process-oriented research that includes all planetary bodies is valuable. Interdisciplinary research and collaborations are encouraged to advance the understanding of aeolian processes and forms across all planetary bodies. The workshop was organized to encourage discussion of processes that are common to multiple bodies as opposed to planet-specific discussions. This approach proved to be highly successful and highlighted the need for research interactions based on common processes.
2. Dune fields do not form in isolation; rather, they interact with topography and other processes, e.g. fluvial or lacustrine sand sources. To better understand dunes and dune fields, aeolian studies may need to include the effects from other surface modification processes.

Winds and surface-atmosphere interactions:

3. There is an increased need to compare remotely-sensed and *in situ* wind indicators (e.g. dune morphologies or convection patterns using clouds) to high resolution wind models (e.g. the Mars Regional Atmospheric Modeling system, or MRAMS). An example of this type of study was a result of the first planetary dune workshop, Hayward et al. (2009).
4. Modeling studies that determine the link between dune form, wind direction and sediment supply have shown great promise in applications to Mars and Titan and should continue.
5. All future landers and rover spacecraft should be equipped with wind instrumentation, specifically an anemometer.

Composition and age:

6. The concept of ‘mineralogical maturity’ is important in terrestrial dune research. It is likely to be significant on Mars as well. Research should be done to determine what ‘mineralogical maturity’ would be for the mafic minerals on Mars. This concept should be expanded to other planetary bodies as compositional data become available.
7. Absolute dating methods (e.g. luminescence dating) can be used to help determine ages and time scales of evolution of aeolian bedforms. Methods should be developed, if possible, for application to planetary dunes.
8. Higher resolution images have made it possible to identify aeolianites in stratigraphic outcrops on Mars. Determining the location, age and nature of the aeolianite record will help extend our understanding of the nature and timing and geomorphological importance of major phases of aeolian activity on Mars.

Aeolian feature and change detection:

9. Higher resolution images have made it possible to detect changes in aeolian form during current missions (e.g., disappearing dunes and moving ripples). The development of automated methods of change detection may assist in this labor-intensive task.

10. In order to facilitate the development and testing of automated feature and change detection software, researchers should compile and make publically available databases of aeolian features that will provide ‘ground truth.’ Hayward et al. (2007) is an example of such a database; however, this database only contains dune fields of moderate to large size in the equatorial region of Mars. More detailed databases are required.

Interactions with volatiles:

11. Determine the composition of dune volatiles and the nature of volatile emplacement.
12. More physical experimental work (e.g. aggregate transportation, physical weathering in periglacial climates) is needed.

Field work and planetary analogs:

13. There is a need for additional studies of relevant dune analogs. Field work can be expensive, but must be funded if progress in understanding aeolian processes is to continue. Some relevant analogs are:
  - a. Climate analogs: Antarctic (cold and hyper-arid).
  - b. Mineralogical analogs: Hawaii, Iceland (also cold, but humid) plus other sites outlined in Edgett and Lancaster (1993).
  - c. Morphodynamic analogs: especially active hyper-arid deserts (e.g., Namib and Atacama Deserts).

### 4. Conclusion

The Second International Planetary Dunes Workshop further demonstrated the significant inter- and multi-disciplinary perspectives involved, and required, of aeolian research. The diversity of disciplines exemplifies the future research directions required for the comparative understanding of terrestrial and extra-terrestrial dunes and dune systems, as well as the amount of data, information, and knowledge that is being generated from remote sensing and GIS, geophysical, sedimentological and mineralogical field studies, and laboratory and computer modeling. Because of the success of the first two Planetary Dune Workshops, there are already plans for convening a third such workshop in the near future.

### References

- Aleinkoff, J.N., D.R. Muhs, 2010. Isotopic Evidence for South Platte River and Bedrock Sources for Eastern Colorado Dune Fields. Second International Planetary Dunes Workshop: Planetary Analogs – Integrating Models, Remote Sensing, and Field Data. Alamosa, Colorado, abst. #2006.
- Bandeira, L., Marques, J.S., Saraiva, J., Pina, P., 2010. Martian dune fields detection by automated approaches. Second International Planetary Dunes Workshop: Planetary Analogs – Integrating Models, Remote Sensing, and Field Data. Alamosa, Colorado, abst. #2021.
- Bandfield, J.L., Rogers, A.D., 2008. Olivine dissolution by acidic fluids in Argyre Planitia, Mars: Evidence for a widespread process? *Geology* 36 (7), 579–582.
- Bishop, M.A., 2010. Obstacle marks: Evidence of variable wind erosion and sediment transport, Hellespontus, Mars. Second International Planetary Dunes Workshop: Planetary Analogs – Integrating Models, Remote Sensing, and Field Data. Alamosa, Colorado, abst. #2020.
- Bogle, R.C., Vogel, J.M., Velasco, M., Redsteer, M.H., 2010. Sand dune migration on the Navajo Nation, Southwestern United States. Second International Planetary Dunes Workshop: Planetary Analogs – Integrating Models, Remote Sensing, and Field Data. Alamosa, Colorado, abst. #2012.
- Bourke, M.C., Edgett, K.S., Canton, B.A., 2008. Recent aeolian dune change on Mars. *Geomorphology* 94, 247–255.
- Bourke, M.C., Lancaster, N., Fenton, L.K., Parteli, E.J.R., Zimelman, J.R., Radebaugh, R., 2010. Extraterrestrial dunes: An introduction to the special issue on planetary dune systems. *Geomorphology* 121, 1–14. doi:10.1016/j.geomorph.2010.04.007.
- Bridges, N.T., 2010. Martian bedform changes and textures as seen by HiRISE. Second International Planetary Dunes Workshop: Planetary Analogs – Integrating Models, Remote Sensing, and Field Data. Alamosa, Colorado, abst. #2040.

- Bristow, C.S., Augustinus, P., Jol, H.M., Wallis, I.C., Rhodes, E., 2010. Topographic steering and dune morphology in a polar desert, Analogues for Mars from the McMurdo Dry Valleys of Antarctica. Second International Planetary Dunes Workshop: Planetary Analogs – Integrating Models, Remote Sensing, and Field Data. Alamosa, Colorado, abstr. #20.
- Burr, D.M., Carling, P.A., Beyer, R.A., Lancaster, N., 2004. Flood-formed dunes in Athabasca Valles, Mars: morphology, modeling, and implications. *Icarus* 171 (1), 68–83.
- Cardinale, M., Komatsu, G., 2010. Aeolian events in the Moreux Crater: Analysis of diverse dune fields, Second International Planetary Dunes Workshop: Planetary Analogs – Integrating Models, Remote Sensing, and Field Data. Alamosa, Colorado, abstr. #2017.
- Chojnacki, M., Burr, D.M., Moersch, J.E., 2010. Evidence of bed form deflation, modification and transport at Endeavour crater, Meridiani Planum, Mars, from orbital observations. Second International Planetary Dunes Workshop: Planetary Analogs – Integrating Models, Remote Sensing, and Field Data. Alamosa, Colorado, abstr. #2028.
- Cornwall, C., Titus, T.N., 2010. Compositional analysis of 21 martian equatorial dune fields and possible sand sources. Second International Planetary Dunes Workshop: Planetary Analogs – Integrating Models, Remote Sensing, and Field Data. Alamosa, Colorado, abstr. #2016.
- Diniega, S., Byrne, S., Glasner, K., 2010. Connecting aeolian and nival processes with martian polar dune morphology. Second International Planetary Dunes Workshop: Planetary Analogs – Integrating Models, Remote Sensing, and Field Data. Alamosa, Colorado, abstr. #2005.
- Dinwiddie, C.L., McGinnis, R.N., Stillman, D.E., Hooper, D.M., Michaels, T.I., Bjella, K.L., Grimm, R.E., Necsoui, M., 2010. Sand, wind, and ice: Mars analog aeolian studies at the Great Kobuk Sand Dunes, Alaska. Second International Planetary Dunes Workshop: Planetary Analogs – Integrating Models, Remote Sensing, and Field Data. Alamosa, Colorado, abstr. #2029.
- Edgett, K.S., Lancaster, N., 1993. Volcaniclastic aeolian dunes: terrestrial examples and application to martian sands. *J. Arid Environ.* 25, 271–297.
- Fenton, L.K., 2006. Dune migration and slip face advancement in the Rabe Crater dune field, Mars. *Geophys. Res. Lett.* 33, L20201. doi:10.1029/2006GL027133.
- Fenton, L.K., Michaels, T.I., 2010. Modeling aeolian potential on Mars with the MRAMS LES. Second International Planetary Dunes Workshop: Planetary Analogs – Integrating Models, Remote Sensing, and Field Data. Alamosa, Colorado, abstr. #2026.
- Gardin, E., Bourke, M.C., Allemand, P., Quantin, C., 2010. Bright footprints suggest possible dune migration on Mars. Second International Planetary Dunes Workshop: Planetary Analogs – Integrating Models, Remote Sensing, and Field Data. Alamosa, Colorado, abstr. #2032.
- Geissler, P.E., Johnson, J.R., Sullivan, R., Herkenhoff, K., Mittlefehldt, D., Ferguson, R., Ming, D., Morris, R., Squyre, S., Soderblom, L., Golombek, M., 2008. First in situ investigation of a dark wind streak on Mars. *J. Geophys. Res.* 113, E12531. doi:10.1029/2008JE003102.
- Hayward, R.K., Mullins, K.F., Fenton, L.K., Hare, T.M., Titus, T.M., Bourke, M.C., Colaprete, A., Christensen, P.R., 2007. Mars Global Digital Dune Database and initial science results. *J. Geophys. Res.* 112, E11007. doi:10.1029/2007JE002943.
- Hayward, R.K., Titus, T.N., Michaels, T.I., Fenton, L.K., 2009. Aeolian dunes as ground truth for atmospheric modeling on Mars. *J. Geophys. Res.* 114, E11012. doi:10.1029/2009JE003428.
- Hayward, R.K., Zimbelman, J.R., Fenton, L.K., Titus, T.N., Cushing, G.E., 2010. Mars analog: Grand Falls dune field, Arizona. Modeling aeolian potential on Mars with the MRAMS LES. Second International Planetary Dunes Workshop: Planetary Analogs – Integrating Models, Remote Sensing, and Field Data. Alamosa, Colorado, abstr. #2004.
- Hooper, D.M., McGinnis, R.N., Necsoui, M., Dinwiddie, C.L., Basu, D., 2010. Volcaniclastic aeolian deposits at Sunset Crater Volcano, Arizona: Applications for martian analogs. Second International Planetary Dunes Workshop: Planetary Analogs – Integrating Models, Remote Sensing, and Field Data. Alamosa, Colorado, abstr. #2011.
- Horgan, B., Bell, J.F.III., Bourke, M.C., 2010. Ice and sulfate induration in the martian north polar sand sea. Second International Planetary Dunes Workshop: Planetary Analogs – Integrating Models, Remote Sensing, and Field Data. Alamosa, Colorado, abstr. #2023.
- Hurowitz, J.A., McLennan, S.M., Tosca, N.J., Arvidson, R.E., Michalski, J.R., Ming, D.W., Schroder, C., Squyres, S.W., 2006. In situ and experimental evidence for acidic weathering of rocks and soils on Mars. *J. Geophys. Res.* 112, E02519. doi:10.1029/2005JE002515.
- Kerber, L., Head, J.W., 2010. A progression of induration in Medusae Fossae Formation dunes. Second International Planetary Dunes Workshop: Planetary Analogs – Integrating Models, Remote Sensing, and Field Data. Alamosa, Colorado, abstr. #2027.
- Kirk, R.L., Howington-Kraus, E., Rosiek, M.R., Anderson, J.A., Archinal, B.A., Becker, K.J., Cook, D.A., Galuszka, D.M., Geissler, P.E., Hare, T.M., Holmberg, I.M., Keszthelyi, L.P., Redding, B.L., Delamere, W.A., Gallagher, D., Chapel, J.D., Eliason, E.M., King, R. and McEwen, A.S., 2008. Ultrahigh resolution topographic mapping of Mars with MRO HiRISE stereo images: Meter-scale slopes of candidate Phoenix landing sites. *J. Geophys. Res. (Planets)*, 113(E12), E00A24. doi:10.1029/2007JE003000.
- Kreslavsky, M.A., 2010. Characteristic time scales of dune-related processes in polar regions of Mars. Second International Planetary Dunes Workshop: Planetary Analogs – Integrating Models, Remote Sensing, and Field Data. Alamosa, Colorado, abstr. #2033.
- Lancaster, N., 2010. Assessing Dune-forming Winds on Planetary Surfaces: Application of the Gross Bedform Normal Concept. Second International Planetary Dunes Workshop: Planetary Analogs – Integrating Models, Remote Sensing, and Field Data. Alamosa, Colorado, abstr. #2030.
- Lorenz, R.D., 2010. Dunes as streamlines: modelling topographic diversion and blocking of linear dunes with potential flow theory. Second International Planetary Dunes Workshop: Planetary Analogs – Integrating Models, Remote Sensing, and Field Data. Alamosa, Colorado, abstr. #2019.
- Lorenz, R.D., Bridges, N.T. and Rosenthal, A.A., 2010a. Elevation Dependence of Bedform Wavelength on Tharsis Montes, Mars. Second International Planetary Dunes Workshop: Planetary Analogs – Integrating Models, Remote Sensing, and Field Data. Alamosa, Colorado, abstr. #2015.
- Lorenz, R.D., Radebaugh, J., Claudin, P., Andreotti, B. and Tokano, T., 2010b. Huygens Boundary Layer Data Explain the ~3 km Spacing of Titan's Dunes. Second International Planetary Dunes Workshop: Planetary Analogs – Integrating Models, Remote Sensing, and Field Data. Alamosa, Colorado, abstr. #2014.
- Malin, M.C., Edgett, K.E., 2001. Mars Global Surveyor Mars Orbiter Camera: Interplanetary cruise through primary mission. *J. Geophys. Res.* 106(E10), 23,429–23,570. doi:10.1029/2000JE001455.
- Mangold, N., Baratoux, D., Arnalds, O., Bardinetzef, J.-M., Platevoët, B., Grégoire, M., Pinet, P., 2010. Segregation of olivine grains in volcanic sands in Iceland – Implications for Mars. Second International Planetary Dunes Workshop: Planetary Analogs – Integrating Models, Remote Sensing, and Field Data. Alamosa, Colorado, abstr. #2008.
- Michaels, T.I., 2010. Obtaining relevant atmospheric context for dune studies. Second International Planetary Dunes Workshop: Planetary Analogs – Integrating Models, Remote Sensing, and Field Data. Alamosa, Colorado, abstr. #2041.
- Muhs, D.R., 2004. Mineralogical maturity in dunefields of North America, Africa and Australia. *Geomorphology* 59, 247–269.
- Pettijohn, F.J., Potter, P.E., Siever, R., 1972. *Sand and Sandstone*. Springer-Verlag, New York.
- Putzig, N.E., Mellon, M.T., Herkenhoff, K.E., Phillips, R.J., Davis, B.J., Ewer, K.J., 2010. Thermal anomaly in Martian North Polar Erg likely due to near-surface ice. Second International Planetary Dunes Workshop: Planetary Analogs – Integrating Models, Remote Sensing, and Field Data. Alamosa, Colorado, abstr. #2037.
- Radebaugh, J., Savage, C.J., Lorenz, R.D., Lancaster, N., Wall, S.D., Stofan, E.R., Lunine, J.I., Kirk, R.L., Le Gall, A. and Farr, T.G., 2010. Dunes on Titan: Wind Directions, Behavior, and Evolution from Statistical and Morphological Studies. Second International Planetary Dunes Workshop: Planetary Analogs – Integrating Models, Remote Sensing, and Field Data. Alamosa, Colorado, abstr. #2.
- Redsteer, M.H., Bogle, R., Vogel, J., 2010. Active dune fields of the Navajo Nation, southwestern United States. Second International Planetary Dunes Workshop: Planetary Analogs – Integrating Models, Remote Sensing, and Field Data. Alamosa, Colorado, abstr. #2039.
- Reffet, E. and Fulchignoni, M., 2010. Planetary Dunes Analogs Using Laboratory Experiments and Numerical Simulations. Second International Planetary Dunes Workshop: Planetary Analogs – Integrating Models, Remote Sensing, and Field Data. Alamosa, Colorado, abstr. #2025.
- Rudoy, A.N., Chernomorets, S.S., 2010. Giant current ripple marks: Remote sensing of new locations on the Earth. Second International Planetary Dunes Workshop: Planetary Analogs – Integrating Models, Remote Sensing, and Field Data. Alamosa, Colorado, abstr. #2009.
- Scheidt, S.P., Lancaster, N., 2010. Sensitivity of automatic determination of sand transport direction and rate to dune morphology in the Namib Sand Sea. Second International Planetary Dunes Workshop: Planetary Analogs – Integrating Models, Remote Sensing, and Field Data. Alamosa, Colorado, abstr. #2025.
- Scheidt, S.P., Lancaster, N., Ramsey, M.S., 2010. Sand Composition of the Gran Desierto: A Terrestrial Analogue for Thermal Infrared Imaging and Spectroscopy Techniques. Second International Planetary Dunes Workshop: Planetary Analogs – Integrating Models, Remote Sensing, and Field Data. Alamosa, Colorado, abstr. #2010.
- Shockey, K.M. and Zimbelman, J.R., 2010. Transverse Aeolian Ridges as seen in HiRISE Images. Second International Planetary Dunes Workshop: Planetary Analogs – Integrating Models, Remote Sensing, and Field Data. Alamosa, Colorado, abstr. #2018.
- Silvestro, S., Fenton, L.K., Vaz, D.A., Ori, G.G., 2010. Ripple migration on active dunes in Nili Patera (Mars). Second International Planetary Dunes Workshop: Planetary Analogs – Integrating Models, Remote Sensing, and Field Data. Alamosa, Colorado, abstr. #2025.
- Smith, I.B., Holt, J.W., 2010. Onset and migration of spiral troughs on Mars revealed by orbital radar. *Nature* 465 (7297), 450–453.
- Squyres, S.W., Arvison, R.E., Bell, J.F., Brückner, J., Cabrol, N.A., Calvin, W., Carr, M.H., Christensen, P.R., Clark, B.C., Crumpler, L., Des Marais, D.J., d'Uston, C., Economou, T., Farmer, J., Farrand, W., Folkner, W., Golombek, M., Gorevan, S., Grant, J.A., Greeley, R., Grotzinger, J., Haskin, L., Herkenhoff, K.E., Hviid, S., Johnson, J., Klingelhöfer, G., Knoll, A., Landis, G., Lemmon, M., Li, R., Madsen, M.B., Malin, M.C., McLennan, S.M., McSwen, H.Y., Ming, D.W., Moersch, J., Morris, R.V., Parker, T., Rice, J.W., Richter, L., Rieder, R., Sims, M., Smith, M., Smith, P., Soderblom, L.A., Sullivan, R., Wänke, H., Wdowiak, T., Wolff, M., Yen, A., 2004. The Spirit rover's Athena science investigation at Gusev crater, Mars. *Science* 305 (5685), 794–800.

- Sullivan, R., Arvidson, R., Bell, J.F.III., Gellert, R., Golombek, M., Greeley, R., Herkenhoff, K., Johnson, J., Thompson, S., Whelley, P., Wray, J., 2008. Wind-driven particle mobility on Mars: Insights from Mars Exploration Rover observations at "El Dorado" and surroundings at Gusev Crater. *J. Geophys. Res.* 113, E06S07. doi: 10.1029/2008JE003101.
- Sullivan, R., Geissler, P., Herkenhoff, K., Landis, G., Vaughan, A., 2010. Mars Exploration Rover Observations of Sand Saltation and Sand-Sized Dust Aggregates. Second International Planetary Dunes Workshop: Planetary Analogs – Integrating Models, Remote Sensing, and Field Data. Alamosa, Colorado, abst. #2036.
- Tirsch, D., R.A. Craddock, and R. Jaumann. Spectral Analysis of Dark Dunes in Ka'u Desert (Hawai'i): Initially Altered Terrestrial Analogs to Dark Dunes on Mars, 2010. Second International Planetary Dunes Workshop: Planetary Analogs – Integrating Models, Remote Sensing, and Field Data. Alamosa, Colorado, abst. #2022.
- Titus, T.N., Cushing, G.E., 2010. Thermal inertia characterization of possible niveo-aolian formation in Olympia Undae, Mars. Second International Planetary Dunes Workshop: Planetary Analogs – Integrating Models, Remote Sensing, and Field Data. Alamosa, Colorado, abst. #2034.
- Titus, T.N., Lancaster, N., Hayward, R., Fenton, L., Bourke, M., 2008. Priorities for future research on planetary dunes. *Eos Trans. AGU* 89 (45), 447–448.
- Vixie, G. and J.W. Barnes, 2008. Sand Sources and Transport Mechanics on Titan. Second International Planetary Dunes Workshop: Planetary Analogs – Integrating Models, Remote Sensing, and Field Data. Alamosa, Colorado, abst. #2031.
- Wood, S.E., Griffiths, S.D., Bourke, M.C., 2010. Subsurface thermal effects of dune migration on Mars: Implications for ground ice stability. Second International Planetary Dunes Workshop: Planetary Analogs – Integrating Models, Remote Sensing, and Field Data. Alamosa, Colorado, abst. #2035.
- Zimbelman, J.R., Williams, S.H. and Johnston, A.K., 2010. Cross-Sectional Profiles of Ripples, Megaripples, and Dunes: A Method for Discriminating Between Formational Mechanisms. Second International Planetary Dunes Workshop: Planetary Analogs – Integrating Models, Remote Sensing, and Field Data. Alamosa, Colorado, abst. #2013.