COMMUNICATIONS OF THE GEOLOGICAL SURVEY OF NAMIBIA

VOLUME 17
2016

MINISTRY OF MINES AND ENERGY

MINISTRY OF MINES AND ENERGY

Director Geological Survey : Gloria Simubali

COMMUNICATIONS OF THE GEOLOGICAL SURVEY OF NAMIBIA

VOLUME 17
2016

Referees : G.I.C Schneider, H. Mocke, R. McG. Miller, M. Pickford

Manuscript handling : G.I.C. Schneider, U.M. Schreiber

Obtainable from the Geological Survey
Private Bag 13297, Windhoek, Namibia

ISSN 1026-2954

Copyright reserved
2016

COMMUNICATIONS OF THE GEOLOGICAL SURVEY OF NAMIBIA

VOLUME 17
2016

CONTENTS

PAPERS

Cover Image : The cascade tufa at Otjikondavirongo, Kaokoland, Northern Namibia, showing the basal part of the tufa cliff, the actively accreting bryophyte curtain, the algae-filled pool at its base and the cave behind the curtain. The Herero place name signifies "Place beyond Places," with the sense of "The Outback", "The Back of Beyond" or "The Middle of Nowhere".

To Titan, via Namibia

Ralph D. Lorenz[1*] and Jani Radebaugh[2]

1. Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel, MD 20723, USA
2. Department of Geological Sciences, Brigham Young University, Provo, UT 84602, USA
(** Corresponding author's e-mail: <Ralph.lorenz@jhuapl.edu> tel: +1 443 778 2903, fax: +1 443 778 8939*)

Abstract: We note the value of Namibia as an analogue location for planetary geology, and in particular for its spectacular linear dunes as morphological analogues for those found on the surface of Saturn's giant haze-shrouded moon, Titan. These dunes are linear in form, tens to hundreds of km long, spaced by 2-3 km, and up to about 150 m tall. Despite the different sand composition, different gravity and Titan's denser atmosphere, these parameters are exactly the same as those in the Namib, making it an appealing place to perform in-situ investigations to help interpret remote sensing of Titan. Roter Kamm, as a rare example of a terrestrial impact structure intruded upon by linear dunes, also has counterparts on Titan.

Key Words: Geomorphology; Planetary Science; Analogues; Dunes; Impact Crater

To cite this paper: Lorenz, R.D. & Radebaugh, J. 2016. To Titan, via Namibia. *Communications of the Geological Survey of Namibia*, **17**, 51-65.

Submitted 16th November 2013

Revised version accepted 29th November 2015

Introduction

When we were invited to submit this article, we had never been to Namibia. How dare we, then, write about Namibian geomorphology? We have never been to Saturn's giant moon, Titan, either, and yet we, and many others, have written about its landscape. This is the fundamental challenge in planetary exploration, that the landscape and the processes shaping it must be determined principally via remote sensing. But to understand what optical and, especially since we lack senses ourselves at these wavelengths, near-infrared and radar data tell us, it is essential to calibrate our interpretation with terrestrial landscapes that can serve as models or analogues for what we observe elsewhere. And this brings us to Namibia, and the Namib Sand Sea in particular.

Titan is a unique satellite in the solar system (Lorenz & Mitton, 2010; Lorenz & Sotin, 2010) in that it has a dense atmosphere, mostly of molecular nitrogen, with a surface pressure of 1.5 bar. This atmosphere endows Titan with many of the processes and phenomena more familiar on terrestrial planets than on the icy moons of the outer solar system. At Saturn's distance from the Sun (10 AU, i.e. 1.5 billion km or ten times further than the Earth is from the Sun), the surface temperature on Titan is 94 K (-179°C), as a result of the competing greenhouse effect (due principally to methane and nitrogen) which warms Titan by 22°C compared to an airless body of similar reflectivity, and the anti-greenhouse effect which lowers the temperature by about 10°C. This anti-greenhouse effect is due to sunlight absorption by the organic haze which renders Titan's atmosphere an obscuring orange-brown. This haze meant our first close views of Titan from the Voyager spacecraft in 1980 were nearly featureless. However, the Cassini spacecraft (a joint venture of NASA and the European Space Agency) has been at Saturn since 2004 and with near-infrared (Fig. 1) and radar has revealed that beneath the haze Titan has a dramatically diverse geography, shaped in large part by the interactions of the atmosphere with the surface.

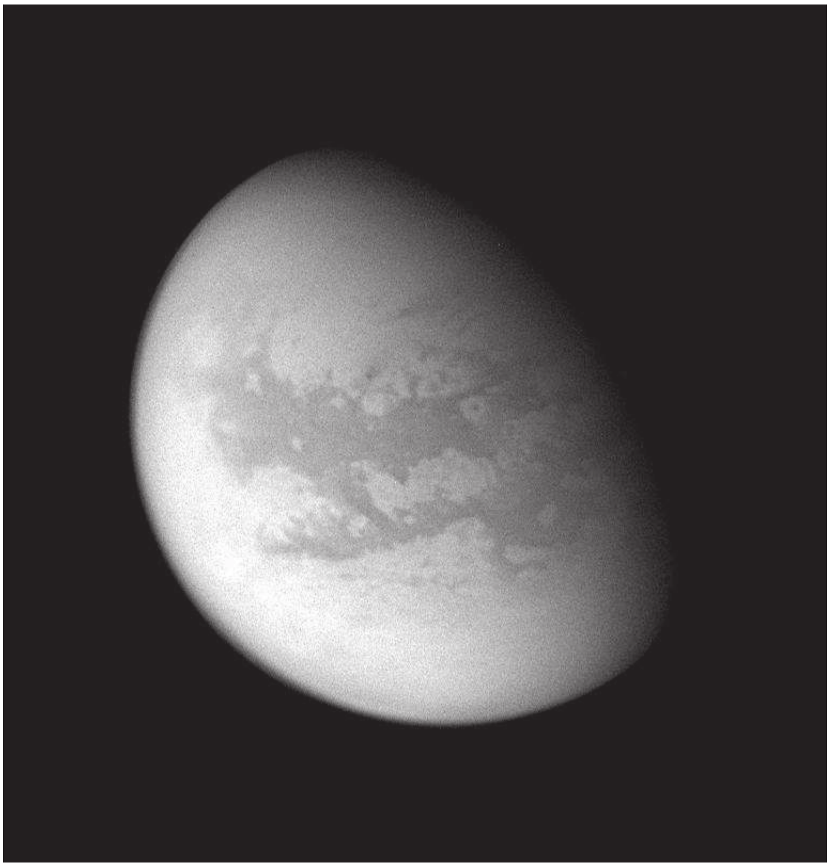

Figure 1. Titan seen by the Cassini spacecraft in the near-infrared (940 nm, the same wavelength as a typical TV remote control) showing bright and dark regions. The dark regions are sand seas. At visible wavelengths (e.g. red, 673 nm) the surface is all but invisible, owing to an optically opaque organic smog in Titan's atmosphere.

Methane, which is present at about 1.7% in the stratosphere, rising to ~5% near the surface, is a condensable greenhouse gas, just like water vapor on Earth. Similarly, methane forms clouds, hail and rain: the latter phenomenon carves river valleys into Titan's surface, although most such valleys appear to be presently dry. The weak sunlight that drives Titan's hydrological cycle results in methane rain being a rare occurrence : on average only a few cm per year, concentrated in high latitude summer. (Various terms such as methanological have been contrived for the cycle of evaporation, precipitation and surface flow of methane on Titan, which also involves dissolved nitrogen and ethane. They are neither elegant nor evocative. The term 'hydrological' describes the analogous process well: the fact that water is not the working fluid is unimportant, and the precedent has been set in astrophysics, where 'magnetohydrodynamics' is used to describe flows of plasma).

A given location on Titan may experience rain only once every few centuries, but as a massive downpour depositing tens of cm or even metres of rain in a few hours. In some respects, Titan is to Earth's hydrological cycle what Venus is to its greenhouse effect, with its thick carbon dioxide atmosphere - a terrestrial phenomenon taken to a dramatic extreme.

Titan has a diameter of 5,150 km, larger than the Earth's moon and greater even than the planet Mercury. Its surface gravity is 1.35 ms^{-2}, or about 1/7 that at Earth's surface. We expect the dominant 'bedrock' on Titan to be water ice, which impact abrasion experiments show to be comparable at these temperatures to 'soft' Earth rocks such as sandstone. Since the force of gravity driving river flow, mass wasting etc. is smaller too, this absolute weakness is actually less in relative terms, and the resulting geomorphology turns out to be much the same as that on Earth. In fact, Cassini data suggest that most exposed material is not actually water ice, but represents a veneer, or stratigraphically lain deposits, of carbon-bearing material produced by the photochemistry of methane in the atmosphere. Some of this material is ethane (also a liquid at Titan surface conditions), some may be soft or sticky material, and some may be hard (perhaps polycyclic aromatic hydrocarbons, PAHs).

It was initially thought that Titan's surface might be uniformly covered in this mixed mass of "goo" drizzled down from the atmosphere over billions of years, but in fact the active hydrological cycle (methane clouds and indeed wetting and subsequent drying of the surface has been observed by Cassini) and the transport of sediment by wind (easy in Titan's low gravity and thick atmosphere) has segregated materials into distinct reservoirs, notably seas presently around Titan's north pole, and vast fields of dunes near its equator.

Titan today is not the same as Titan in the remote past: there are long-term astronomically-forced climate changes - a Croll-Milankovich cycle of ~30,000 years, which may have caused Titan's seas to be more extensive at its South Pole or lower latitudes in the past. Changes in the wind patterns associated with this climate cycle may be reflected in the dune morphology, which has a memory of some tens of millennia due to the long time scale of construction or reorientation of the large dunes. Longer-term geological changes may have resulted from a changing inventory of methane moisture in the climate system as the steady photochemical depletion of methane is balanced by delivery from the interior that may be episodic on time scales of millions to hundreds-of-millions of years.

Changes in the distribution of surface liquids, at seasonal, astronomical and geological time scales, results in the precipitation of soluble materials as evaporite deposits. Whereas water on Earth yields salt and gypsum deposits, the corresponding materials on Mars or Titan (which show up as bright patches in, or rings around, lake basins) are perhaps butane or acetylene !

This highlights the fundamental theme of Titan System Science – in which familiar physical processes such as fluvial erosion, evaporite deposition and aeolian transport are occurring on Titan and result in familiar landforms, yet are conducted at rates that may be quite different from those that prevail on Earth, and with materials that are different in their chemical composition. It is the study of landforms and process, then, which brings utility to terrestrial analogues, despite the exotic chemistry.

While much more could be said about Namibian geomorphology, and its usefulness as an analogue for studying Mars or Titan, we focus in this article on the two features that attract our attention in particular: the linear dunes of the Namib Sand Sea, and the degradation and burial of an impact structure, Roter Kamm.

The Namib Desert : Type Example of Giant Linear Dunes

A dominant landform in Earth's large deserts, such as the northern Sahara, Saudi Arabia, Australia and Namibia, is the linear dune (Lancaster, 1982). This dune form, named for the morphological characteristic of the length greatly exceeding the width, is not typically found in small dune fields. Rather, these features are found in broad, uninterrupted locations such as shields, where sands can undergo transport and accumulation freely (Wilson, 1971). Linear dunes which range up to several km wide, up to 200 m in height and several hundred kilometers long (Lancaster, 1995) can contain vast volumes of sand.

The Namib Sand Sea is a type location for this dune form, possessing linear dunes of a range of sizes and morphologies across an extensive depositional basin located between the Atlantic Ocean and the eastern uplands. The sand in the system is derived from the South

African uplands via the west-flowing Orange River on the sand sea's southern margins and is then shepherded north by SSW winds and north-moving oceanic longshore drift (Lancaster, 1989). The sand sea is truncated abruptly at its north margin by the near-annual ephemeral flow of the Kuiseb River (Ward, 1987; Ward *et al*. 1983).

The relationship of varying dune morphology across the sand sea, and its relationship to the wind regime, was discussed in Breed *et al*. (1979). Although south-westerly winds dominate, slight variations in the direction of the wind about its mean direction produces stacked foresets that alternate between being left or right of the dune crest (Livingstone, 2003). These variations yield cuspate morphologies and changing slip face orientations (Fig. 2; Tsoar *et al*. 2004; Livingstone 2003; Bullard *et al*. 2011; Livingstone *et al*. 2010) and elongate the linear form, through down-axis sediment transport resulting from wind deflection in the lee of active crests (Tsoar *et al.* 2004).

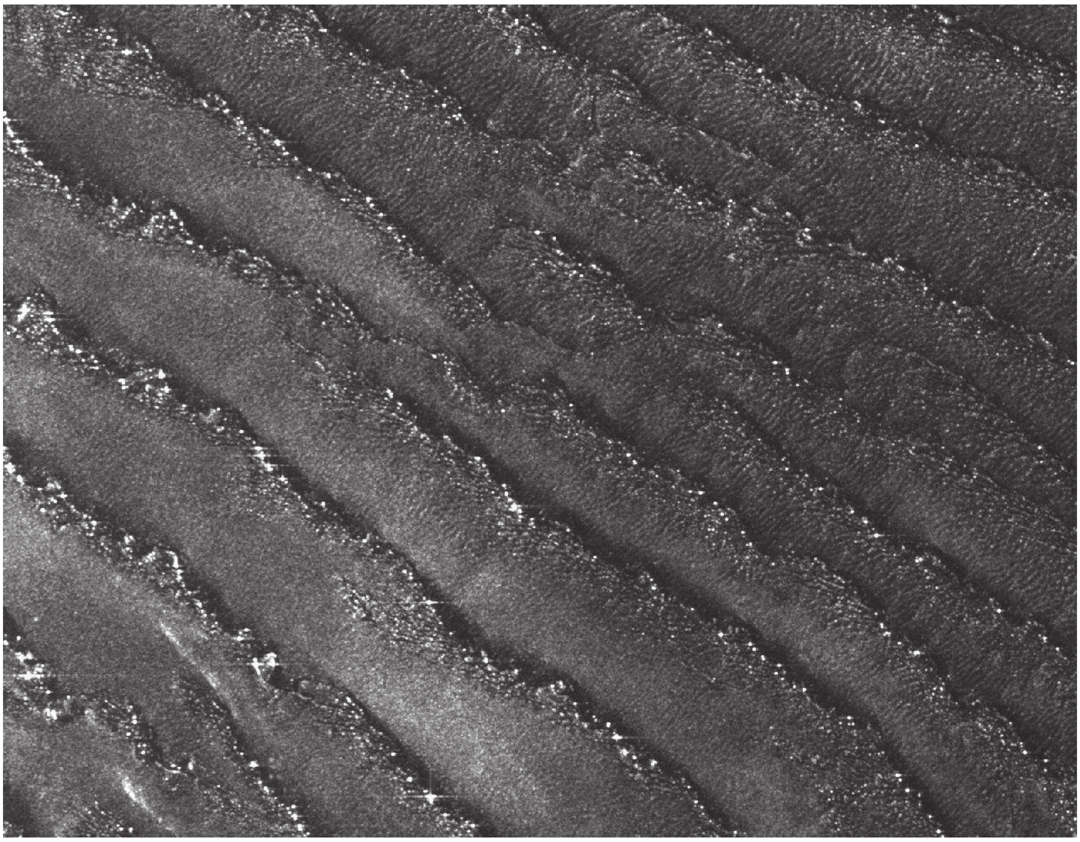

Figure 2. SIR-C/X-SAR image of the linear dunes in the Namib. Dunes are generally linear in form and are spaced ~2 km apart. This 3-cm (X-band) radar image reveals that the dune sands absorb the radar signal and are thus dark, with the exception of glints off the cuspate crest lines. Illumination from the lower left creates radar shadows on the opposite side of the ~100 m high dunes.

Linear dunes are also a dominant landform on Titan, and were discovered in Synthetic Aperture Radar (SAR) imaging by Cassini (Lorenz *et al.* 2006). These dunes cover close to 15% of the surface (Rodriguez *et al*. 2014; Le Gall *et al*. 2011; Radebaugh, 2013). The dune appearance to Cassini's 2.2 cm wavelength (Ku-band, 13.6 GHz) radar is rather similar, but at lower resolution, to images of sand dunes on Earth at 3 cm (X-band, Fig. 3). Crest line details cannot be observed in Cassini's low-resolution (~350 m) images. However, it is clear that dune sands are absorbing to the SAR signal, and thus must be fine-grained and free of any rough or reflective, solidifying coverings. Based on visual-IR images of Titan, the dune sands are carbon-bearing material from the methane photochemistry within the atmosphere (Lorenz *et al.* 2006; Barnes *et al*. 2008, 2015). Based on the observation that the dune morphologies are similar to those in the Namib and other deserts, we infer that the particles were, and probably are at present, free to move and to saltate in Titan's dense winds and lower gravity (Fig. 3, Lorenz *et al*. 2006; Radebaugh *et al*. 2008).

Figure 3. Dunes on Titan as seen by Cassini SAR at 2.2 cm wavelength. Dunes are SAR-dark and absorbing and contrast well with rough, SAR-bright substrate and surrounding regions of high topography. Image courtesy of NASA/Cassini, obtained 6/2011 at ~70°W, 0°N. Arrows indicate the presumed combination of wind directions (which must evidently vary somewhat across the scene).

The Namib Sand Sea can yield important insights into dune formation and evolution on Titan, where we have limited data. Much of the work thus far has been comparisons of dune morphologies, which has yielded important results concerning wind directions (Lorenz & Radebaugh, 2009), sand thickness variations and behavior around topographic obstacles (Radebaugh *et al*. 2010; Barnes *et al*. 2008). The Namib is characterized by especially great sand thicknesses, and even the interdunes can be sandy to significant depths (Lancaster, 1989). Large inselbergs (topographic obstacles) jut up above the towering dunes, leading to deflection of the wind and alteration of the trajectory of the linear dune forms out to several kilometers from the obstacle. This morphology can also be seen in the Belet Sand Sea on Titan, where interdunes are SAR-dark and thus sandy, and where dunes are deflected by SAR-bright, rough and elevated inselbergs (Fig. 4, Radebaugh *et al*. 2010).

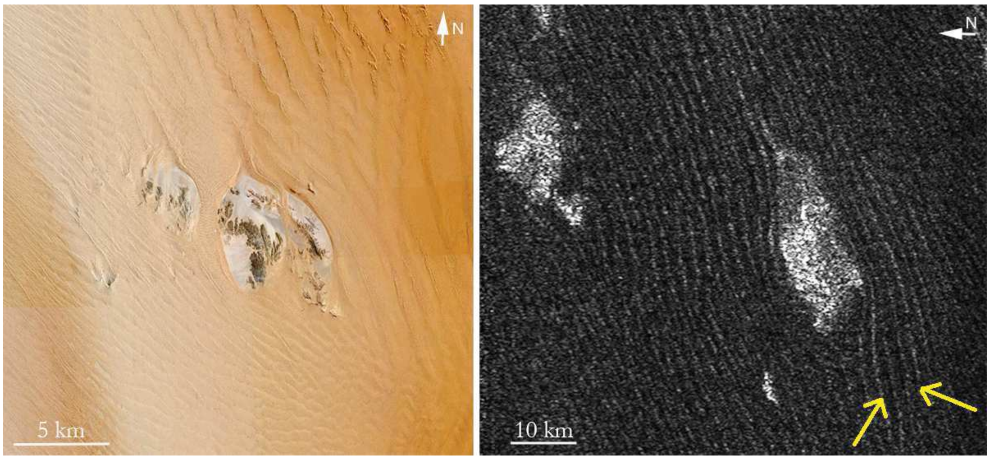

Figure 4. Dunes in Namibia (left) and on Titan (right) interact with inselbergs. The wind disruption by the obstacle has an effect on the dunes out to several dune wavelengths, and the lee-dune 'tail' towards the top in each image indicates the direction of net sand transport. The Namib image is in visible light, from Google Earth, located at 25° 23'S, 15° 16'E. The Titan image on the right is 2.2 cm Cassini SAR, from Titan's Belet Sand Sea at 6.5°S, 251°W. Arrows have been added to the Titan image to indicate the presumed wind directions whose combination leads to the linear morphology and orientation. Dunes on Titan are currently only accessible to us from a spacecraft orbiting at a rather significant distance from the body. The constraints on the images we can obtain are such that we cannot see details that may indicate whether the dunes are undergoing active development. Furthermore, the formation and elongation of linear dunes on Earth is not well understood, or may vary across regions, and thus field studies of active dune systems such as those in the Namib (Besler, 1980; Lancaster, 1989; Livingstone, 2003; Livingstone *et al.* 2010) will help us unravel linear dune histories on Titan and Earth.

Our reconnaissance research trip to the northern Namib Sand Sea in August, 2013, included aerial overflight and ground-based morphological studies of dunes. While the view of the Namib from space might allow one to think that the sand sea's northern margin is set by slightly elevated topography, the closer aerial view makes it clear that it is occasional fluvial transport that truncates the dunes. As a result we suspect that similar ephemeral rivers cause the abrupt edge of the sand seas on Titan (Barnes *et al.* 2015).

In addition to our visual observations, we made Global Positioning System (GPS) and Ground Penetrating Radar (GPR) studies on a previously unstudied dune south of the Gobabeb Research Station. The aerial observations revealed highly variable morphologies of linear dunes across the sand sea, in particular in the heights of dunes, the morphology of crest lines, and amount of sand in the interdunes (Fig. 5). Illumination angle strongly affected dune sand colours, although sands were generally redder in the east compared with the west as a result of differences in sand maturity. Dunes were largest near Sossusvlei (Fig. 5b, c). Secondary forms could be seen across large regions, each with their own form and spacing (Fig. 5d), while the simultaneous presence of large linear dunes and smaller, near-orthogonal linear dunes (an arrangement referred to variously as 'raked dunes' and 'lace dunes') might be thought to be puzzling, recent work with computational and water-tank models (du Pont *et al.* 2014) can reproduce this morphology, with the smaller forms being referred to as 'fingering' dunes (Lucas *et al*. 2014). The discovery of Titan's dunes has stimulated much recent work on linear dunes overall (Lorenz & Zimbelman, 2014) and may in turn yield new interpretations of terrestrial sand seas like the Namib.

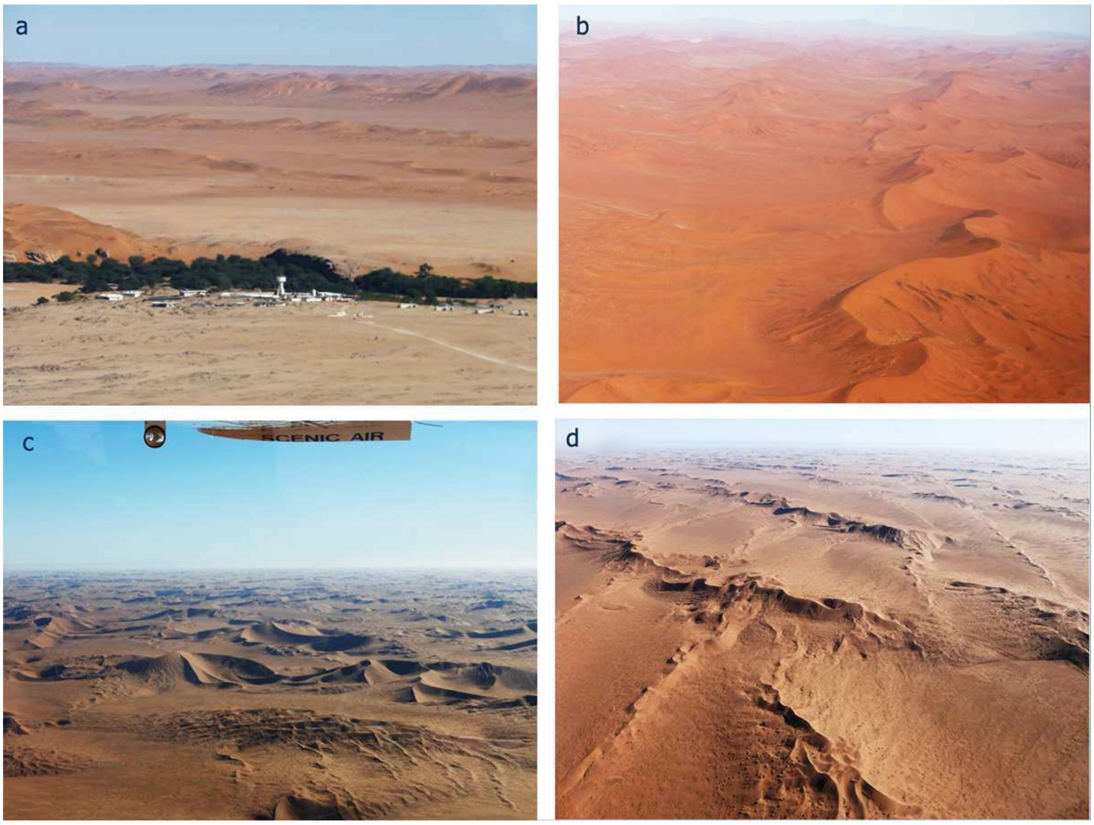

Figure 5. Dunes in the Namib Sand Sea obtained during an aerial overflight with Scenic Air in August, 2013. 5a) The Gobabeb Desert Research Station viewed from the north, with linear dunes and calcrete interdune areas with variable amounts of sand in the background. 5b) Dunes north of Sossusvlei viewed from the north. Crest lines are especially crenulate and undulatory here, as in 5c, due to the more significant influence of the strong but short-lived katabatic east winds. 5c) Dunes northwest of Sossusvlei. These regions also have sandy interdunes; main dune peaks in the middle distance are star dunes. 5d) Dunes west of Sossusvlei. Large, straight linear dunes are overprinted by smaller near-orthogonal linear dunes, the pattern being referred to as lace dunes by Besler (1980) but now recognizable as the 'fingering mode' of linear dune growth (du Pont *et al.* 2014). Photos by J. Radebaugh.

Field observations of the S. Gobabeb dune revealed that it is comprised of a gently-sloping plinth covered in vegetation that may act to stabilize this portion of the dune. In contrast, the crest line has active slip faces and is vegetation-free (Fig. 6). A GPS trace of the summit as of August 2013 reveals movement of the crest line from a position west of where it was in 2010. The amount of movement is similar to that found by Livingstone (2003) at a nearby dune, as is the observation that the plinth did not move over that time, because the plinth/interdune boundary did not change (Fig. 6 inset). Preliminary analysis of the GPR data also reveals a stable plinth and a complex, mobile summit region. Further studies using GPS and GPR, perhaps in a grid survey and at neighboring dunes, will produce a stronger story for the current state and history of the northern Namib linear dunes. Through image analysis and model studies, we will determine how these studies can yield information about dune formation and evolution on Titan.

Figure 6. Dune study area 13 km south of the Gobabeb Research station. Note the gently sloping, vegetation-covered plinth and the mobile crest, with active slip face. Student Clay Chandler for scale. Inset shows a Google Earth image of the study area, with 100 m scale bar. The crest line has shifted tens of m to the east over three years. Photo by J. Radebaugh and inset courtesy of Google Earth.

Roter Kamm - Dune-Crater Interaction

A casual examination of our own moon through even a small telescope will indicate the dramatic dominance of craters as a planetary landform. Yet Earth has relatively few craters, due in part to plate tectonics, but largely as a result of erosion and in some cases, burial.

Titan, for rather similar reasons, has rather few craters : with about 40% of the surface mapped at resolutions of 1-2 km or better, only about 80 likely craters are known, and many of these are highly degraded (Wood *et al.* 2010; Neish *et al*. 2010). Unlike the airless Moon which is pockmarked down to very small scales (or indeed Saturn's other icy moons), Titan has almost no craters smaller than about 20 km, due to the screening effect of its thick atmosphere which causes impactors to break up high above the surface. This process has a significant Namib connection too - the Gibeon meteorites resulted from a similar breakup whereby the impactor underwent fragmentation in the atmosphere without excavating a crater.

Evaluation of the impact crater population on Titan suggests that the surface overall has a crater retention age of 500-2000 million years, and thus that crater obliteration processes have successfully competed against the generation of craters over time. Exactly what these processes are is a subject of active research - some craters are only partly exposed, suggesting a complex history of modification. Examination of their depth:diameter relationships (Neish *et al*. 2013) suggests that Titan craters are shallow overall, most likely as a result of infilling, and an intriguing correlation of crater density with elevation exists, suggesting that craters in lowlands (perhaps, wetlands?) are less effectively preserved (Neish & Lorenz, 2014).

In some examples (Fig. 7, 8) it is clear that at least part of the crater modification process may involve aeolian burial, in that distinct dunes are present. This interaction of dunes with craters is known in only a small number of terrestrial craters - Arounga in Chad, Wolfe Creek in Australia, and best of all, Roter Kamm in Namibia.

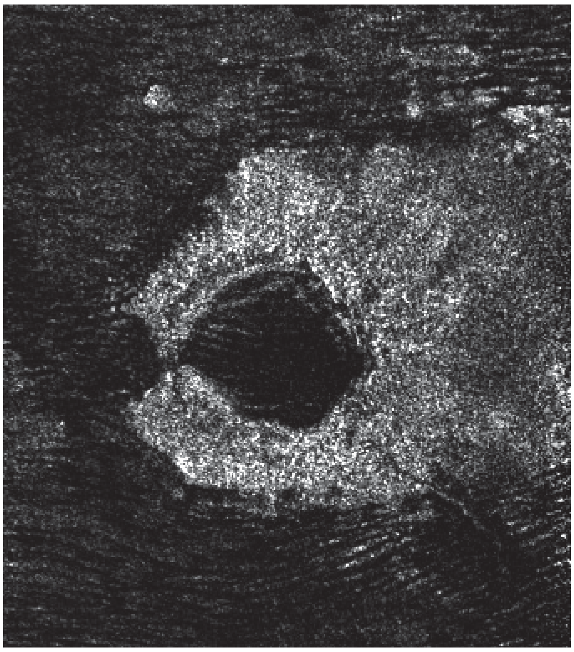

Figure 7. An unnamed impact crater on Titan, about 40 km in diameter. The bright rim and ejecta blanket is narrower on the western side from which the dominant sand transport appears to flow. Has the sand broken through the rim by itself, or was there a breach left after an azimuthally-non-uniform crater excavation (many Titan craters are somewhat polygonal rather than perfectly circular), or did fluvial erosion carve a gap in the crater wall?

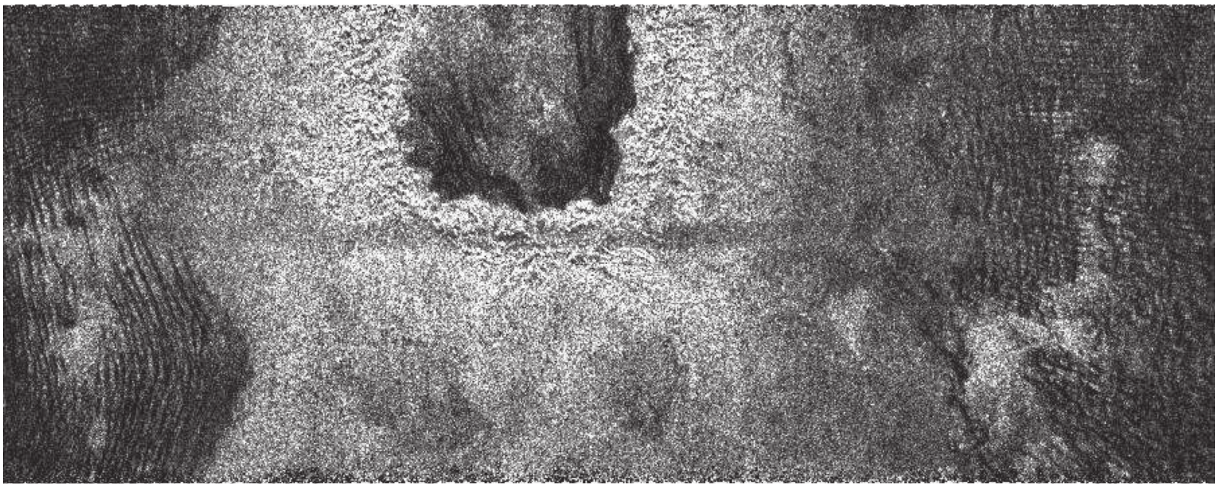

Figure 8. The crater Selk (north is to the right) amid abundant dunes, some of which can be seen in the crater floor. The elevated rim and ejecta appears to modify the orientation and morphology of the dunes outside the crater. The floor of the crater is about 60 km across.

Roter Kamm is a 2.5 km diameter structure (Fig. 9) in the Sperrgebiet in southern Namibia, estimated to be ~4 million years old, and has a dramatic appearance, having a rather shallow (~150 m) depth for its size (Miller, 2010). Its structure (and that of Wolfe Creek and Arounga) was imaged by space borne radar (Fig. 10) on the SIR-C mission (McHone *et al.* 2002). The dark sands set a strong contrast with the rim, where granitic gneiss bedrock is exposed and its rough texture gives strong backscatter at a range of wavelengths. Terrestrial radar images are often strongly affected by vegetation, and a prominent effect around Roter Kamm is the bright appearance of *Euphorbia* bushes which have a typical branch spacing comparable with the radar wavelength leading to anomalously strong returns.

Roter Kamm was studied as a Mars analogue (where aeolian infilling of craters also occurs, essentially without fluvial action) by Grant *et al*. (1997) who used a Ground Penetrating Radar (GPR) to examine the bedding structure of some of the sediment infill. Radar penetration at Roter Kamm is in fact generally weaker than in much of the sand sea, in that fog and dew results in higher soil moisture content and thus higher radio attenuation: it is this moisture that sustains the vegetation and thus the wildlife around the site. Other geophysical studies (gravity and magnetic) have been reported by Brandt *et al*. (1998).

Roter Kamm will serve as an important analogue as we attempt to decode what we are seeing at Titan. In addition to the radar remote sensing of Roter Kamm, high-resolution visible and near-infrared images are available (Fig. 11), and GPS transects yield high resolution, high precision topography data to support the field geological interpretation.

Two questions are of specific interest in interpreting Titan data. First, how have the moving aeolian sands interacted with the ejecta blanket around the crater? As at Titan, the regional dune form is linear, and dunes within the craters appear rather similar to those outside. However, it is clear that at Roter Kamm, the most prominent dunes at the crater are small lee dunes anchored to the rim topography, and the bed form character is quite different inside and outside. It seems likely that the difference in scale is important – Roter Kamm is itself only as large as the linear dunes that can be resolved at Titan. New computational capabilities are emerging in modeling aeolian features at this scale (Jackson *et al.* 2015) and we propose that Roter Kamm will be a particularly interesting locale to study with such techniques.

Another question is whether fluvial processes have filled the crater and/or have formed breaches in the crater wall and ejecta blanket. Mapping by Miller (2010) discounts significant fluvial action and since the Pliocene this area experiences only gentle winter rains, with summer storms occurring only considerably further north. It is possible that the breaches in the crater wall and the ejecta blanket irregularity result from jointing in the target rock (which famously leads to the somewhat square appearance of Meteor Crater in Arizona, and perhaps accounts for the polygonal appearance of several Titan craters.)

Figure 9. The 2.5 km diameter Roter Kamm impact structure, viewed from the east by a small camera suspended from a kite at an altitude of about 150 m above the ground during our field visit in August, 2013. Note the lee dunes on the left, and the sharp slip face on the nearside rim which tails off into a dune at center right (Photo R. Lorenz).

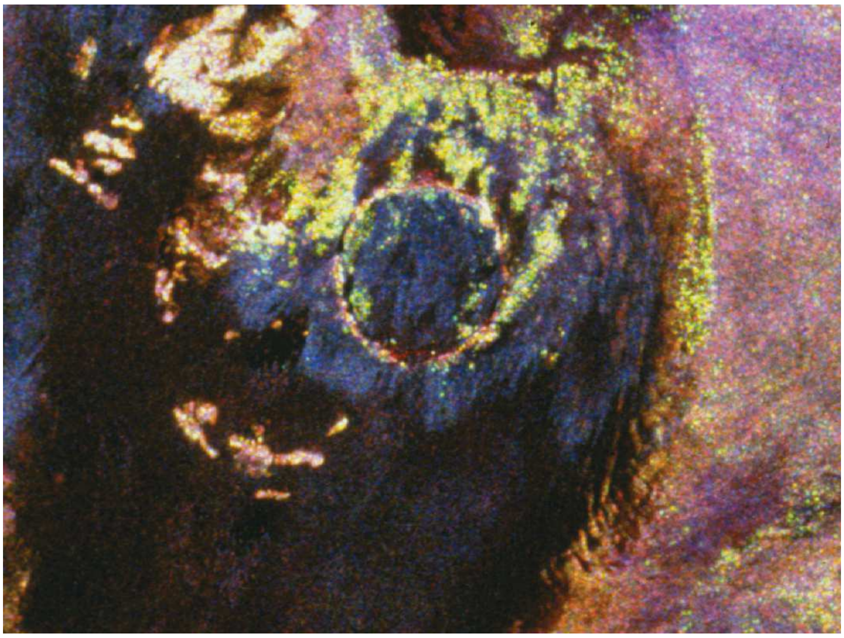

Figure 10. A colour composite image of Roter Kamm from the Shuttle Imaging Radar (SIR-C): red is L-band, HH channel; green represents the L-band, HV (horizontally transmitted and vertically received) and blue represents the C-band, HV channel. The different colours represent different scattering mechanisms and roughness scales - in this case predominantly due to vegetation (Image credit : NASA/JPL).

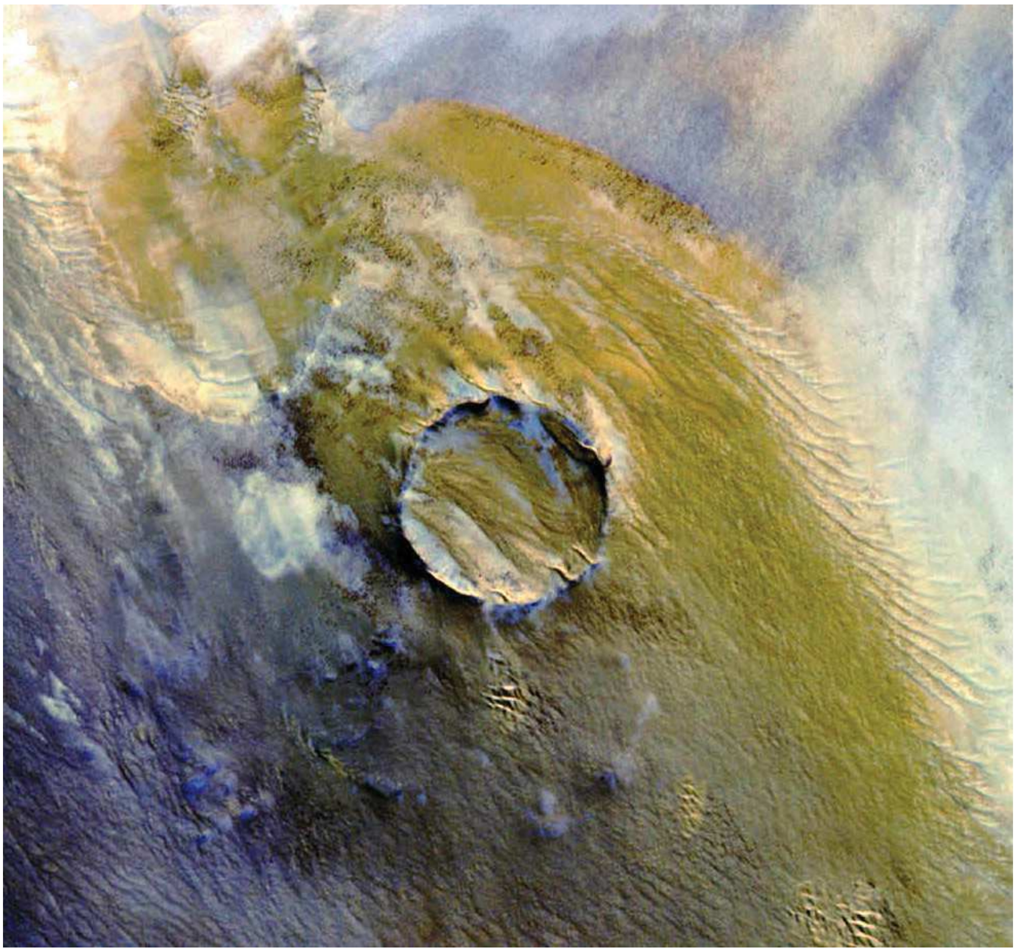

Figure 11. An ASTER near-infrared composite image of Roter Kamm that shows particularly well the crater and the dune arrangement within and surrounding it. Comparable views of Titan craters may be possible during future missions to Titan with orbiters or aircraft with near-infrared cameras, but are beyond Cassini's capabilities. (Image credit - http://www.jspacesystems.or.jp/ersdac/ASTERimage/ASTERimage_library_E.html).

Other Potential Areas of Enquiry

The Namib presents the most spectacular and accessible example of linear dunes on Earth and in this respect alone deserves attention from planetary geomorphologists. But there is of course much else to see and learn, which we only touch upon here before closing. In so far as the surfaces of Mars and Titan have extensive aeolian deposits, the other bed forms seen in the Namib such as barchan dunes and granule ripples deserve study as analogues. Only recently (Bridges *et al.* 2012) has remote sensing data of Mars become of adequate time span and resolution to detect and measure the migration of barchan dunes, which can be compared with those observed in the Namib (Slattery, 1990). Fluvial, volcanic and intrusive processes are well-represented in Namibia (Schneider, 2008), and may tell us about those processes elsewhere (Fig. 12).

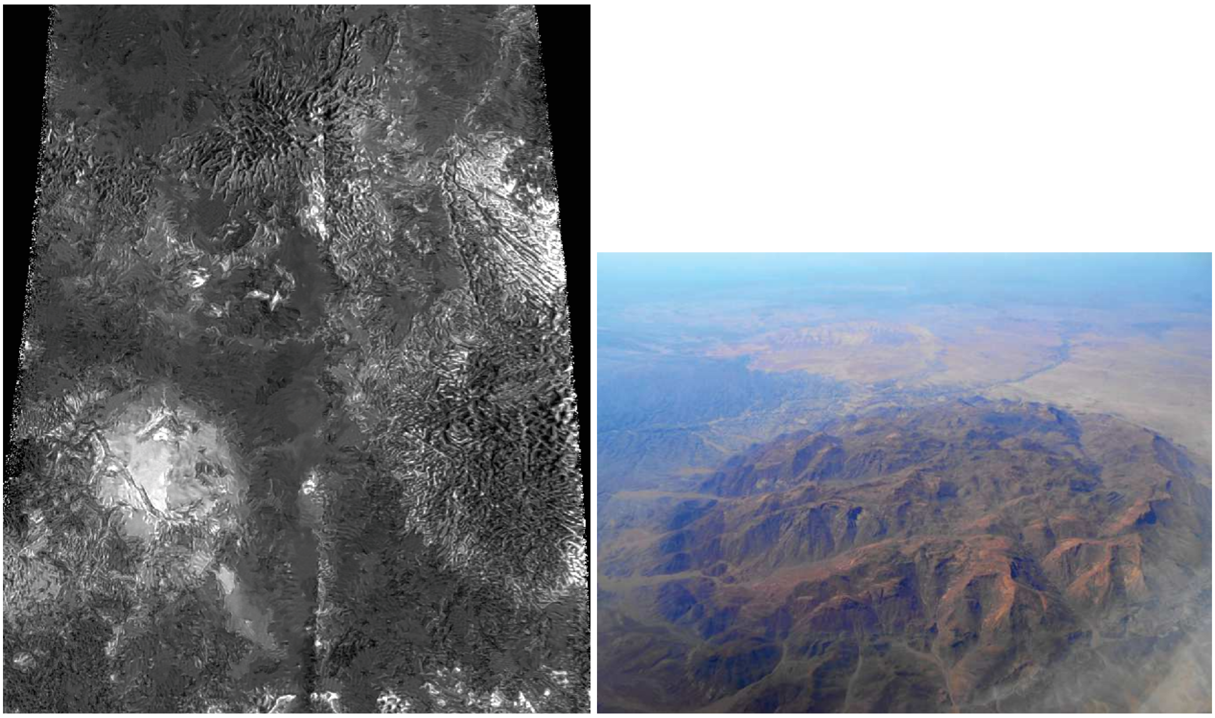

Figure 12. A region in Titan's high northern latitudes (left frame) where three elevated but dissected structures are present. It is conjectured that these may be of volcanic or perhaps intrusive origin. Image is 200 km across. It is tempting to compare these with the Brandberg structure in Namibia (right frame), seen during our flight to southern Africa (photo R. Lorenz).

Conclusions

Analogy is a powerful tool for interpreting remote sensing data of other planetary environments, and Namibia is especially gifted in having spectacular and beautiful landforms that are similar to those found on Mars and especially Titan, where the working materials and environment are very different from Earth. Namibian geology thus helps us to understand other worlds. Yet the analogies work both ways - exploring planets often makes us think anew about our own planet and the processes that shape it.

Acknowledgements

RL acknowledges the support of the Cassini project, via NASA grant "Cassini Radar Science Support" NNX13AH14G. We are grateful to Dr. Gabi Schneider of the Geological Survey of Namibia for soliciting this article and facilitating our visit to Roter Kamm, and especially to Dr. Roy Miller who guided us around this structure which he knows so well. Dr. Miller reviewed this paper and provided a number of improvements as did Dr Martin Pickford (Paris). We thank Dr Theo Wassenaar and others at the Gobabeb Research and Training Center who assisted our visit there, and Vernon Swanepoel of Frantic Naturalist Tours for logistics. Drs. Mary Bourke and Charlie Bristow gave us useful advice in planning. Tom Farr provided useful advice and remote sensing data, and Jason Barnes and Alex Hayes accompanied us in the field in what we hope is only our first visit to Namibia.

References

Barnes, J.W. Brown, R.H. Soderblom, L. Sotin, C. Le Mouelic, S. Rodriguez, S. Jaumann, R. Beyer, R.A. Clark, R. & Nicholson, P. 2008. Spectroscopy, morphometry, and photoclinometry of Titan's dune fields from Cassini/VIMS. *Icarus*, **195**, 400-414.

Barnes, J. Lorenz, R. Radebaugh, J. Hayes, A. Arnold, K. & Chandler, C. 2015. Production and Global Transport of Titan's Sand Particles. *Planetary Science*, **4**, 1-19.

Besler, H. 1980. Die Dünen-Namib: Entstehung und Dynamik eines Ergs. *Stuttgarter geographische Studien,* **96**, 208 pp.

Brandt, D. Reimold, W.U. Franzsen, A J. Koeberl, C. & Wendorff, L. 1998. Geophysical profile of the Roter Kamm impact crater, Namibia. *Meteoritics and Planetary Science*, **33**, 447-453.

Breed, C.S. Fryberger, S.G. Andrews, S. McCauley, C. Lennartz, F. Gebel, D. & Horstman, K. 1979. Regional studies of sand seas using Landsat (ERTS) imagery. *In*: A Study of Global Sand Seas *USGS Special Publication*, **1052**, pp. 305-397. US Printing Office, Washington.

Bridges, N. Ayoub, F. Avouac, J.-P. Leprince, S. Lucas, A. & Mattson, S. 2012. Earth-like Sand Fluxes on Mars. *Nature*, **485**, 339-342, doi: 10.1028/nature11022.

Bullard, J.E. White, K. & Livingstone, I. 2011. Morphometric analysis of aeolian bedforms in the Namib Sand Sea using ASTER data. *Earth Surface Processes and Landforms*, **36**, 1534–1549. DOI: 10.1002/esp.2189.

du Pont, S.C. Narteau, C. & Gao, X. 2014. Two modes for dune orientation. *Geology*, **42**, 743-746.

Grant, J.A. Koeberl, C. Reimold, W.U. & Schultz, P.H. 1997. Gradation of the Roter Kamm Impact Crater, Namibia. *Journal of Geophysical Research*, **102**, 16,327-16,338.

Jackson, D.W. Bourke, M.C. & Smyth, T.A. 2015. The dune effect on sand-transporting winds on Mars. *Nature Communications*, **6**, 8796, doi:10.1038/ncomms9796.

Lancaster, N. 1982. Linear dunes. *Progress in Physical Geography*, **6**, 476-504.

Lancaster, N. 1989. *The Namib Sand Sea*. Balkema, Rotterdam, 192 pp.

Lancaster, N. 1995. *The Geomorphology of Desert Dunes*. Routledge, London and New York, 290 pp.

Le Gall, A. Janssen, M.A. Wye, L.C. Hayes, A.G. Radebaugh, J. Savage, C. Zebker, H. Lorenz, R.D. Lunine, J.I. Kirk, R.L. & Lopes, R.M.C. 2011. Cassini SAR, radiometry, scatterometry and altimetry observations of Titan's dune fields. *Icarus*, **213**, 608-624.

Livingstone, I. 2003. A twenty-one year record of surface change on a Namib linear dune. *Earth Surface Processes and Landforms*, **28**, 1025-1031.

Livingstone, I. Bristow, C. Bryant, R.G. Bullard, J. White, K. Wiggs, G.F.S. Baas, A.C.W. Bateman, M.D. & Thomas, D.S.G. 2010. The Namib Sand Sea digital database of aeolian dunes and key forcing variables. *Aeolian Research*, **2**, 93-104. doi:10.1016/j.aeolia.2010.08.001.

Lorenz, R.D. & Mitton, J. 2010. *Titan Unveiled*. Princeton University Press, Princeton, 280 pp.

Lorenz, R.D. & Sotin, C. 2010. The Moon that would be a Planet. *Scientific American*, March **2010**, 36-43.

Lorenz, R.D. & Radebaugh, J. 2009. Global Pattern of Titan's Dunes: Radar Survey from the Cassini Prime Mission. *Geophysical Research Letters*, **36**, L03202, doi:10.1029/2008GL036850.

Lorenz, R.D. & 39 colleagues, 2006. The sand seas of Titan: Cassini radar observations of longitudinal dunes. *Science*, **312** (5774), 724-727, doi: 10.1126/science.1123257.

Lorenz, R.D. & Zimbelman, J. 2014. *Dune Worlds: How Wind-Blown Sand Shapes Planetary Landscapes*. Springer, New York. 308 pp.

Lucas, A. Rodriguez, S. Narteau, C. Charnay, B. Pont, S.C. Tokano, T. & Aharonson, O. 2014. Growth mechanisms and dune orientation on Titan. *Geophysical Research Letters*, **41**, 6,093-6,100.

McHone, J.F. Greeley, R. Williams, K.K. Blumberg D.G. & Kuzmin, R.O. 2002. Space shuttle observations of terrestrial impact structures using SIR-C and X-SAR radars. *Meteoritics and Planetary Science,* **37**, 407-420.

Miller, R. McG. 2010. Roter Kamm impact crater of Namibia: New data on rim structure, target rock geochemistry, ejecta, and meteorite trajectory. *In*: Gibson, R.L. &

Reimold, W.U. (Eds) *Large Meteorite Impacts and Planetary Evolution IV: Geological Society of America Special Paper*, **465**, 1-20.

Neish, C.C. & Lorenz, R.D. 2014. Elevation distribution of Titan's craters suggests extensive wetlands. *Icarus*, **228**, 27-34.

Neish, C.D. Kirk, R.L. Lorenz, R.D. Bray, V.J. Schenk, P. Stiles, B. Turtle, E. Mitchell, K. Hayes, A. & the Cassini RADAR Team, 2013. Crater topography on Titan: Implications for landscape evolution. *Icarus*, **223**, 82-90.

Neish, C.D. Lorenz, R.D. Kirk, R.L. & Wye, L.C. 2010. Radarclinometry of the sand seas of Namibia and Saturn's Moon Titan. *Icarus*, **208**, 385-394.

Radebaugh, J. 2013. Dunes on Saturn's Moon Titan as revealed by the Cassini Mission. *Aeolian Research*, **11**, 23-41.

Radebaugh, J. & 14 colleagues, 2008. Dunes on Titan observed by Cassini radar. *Icarus*, **194**, 690-703. doi: 10.1016/j.icarus.2007.10.015.

Radebaugh, J. Lorenz, R. Farr, T. Paillou, P. Savage, C. & Spencer, C. 2010. Linear Dunes on Titan and Earth: Initial Remote Sensing Comparisons. *Geomorphology*, **121**, 122-132.

Rodriguez, S. Garcia, A. Lucas, A. Appéré, T. Le Gall, A. Reffet, E. & Turtle, E.P. 2014. Global mapping and characterization of Titan's dune fields with Cassini: correlation between RADAR and VIMS observations. *Icarus*, **230**, 168-179.

Schneider, G. 2008. *The Roadside Geology of Namibia*, 2nd Ed. Borntraeger, Berlin. 294 pp.

Slattery, M.C. 1990. Barchan migration on the Kuiseb River Delta, Namibia, *South African Geographical Journal*, **72**, 5-10.

Tsoar, H. Blumberg, D.G. & Stoler, Y. 2004. Elongation and migration of sand dunes. *Geomorphology*, **57**, 293-302.

Ward, J.D. 1987. The Cenozoic succession in the Kuiseb Valley, central Namib Desert. *Memoir of the Geological Survey of Namibia*, **9**, 1-124.

Ward, J.D. Seely, M.K. & Lancaster, N. 1983. On the antiquity of the Namib. *South African Journal of Science,* **79**, 175-183.

Wilson, I.G. 1971. Desert sandflow basins and a model for the development of ergs. *Geographical Journal*, **137**, 180-199.

Wood, C.A. Lorenz, R. Kirk, R. Lopes, R. Mitchell, K. & Stofan, E. 2010. Impact Craters on Titan. *Icarus*, **206**, 334-344.