

# The dynamism of salt crust patterns on playas

**Joanna M. Nield<sup>1\*</sup>, Robert G. Bryant<sup>2</sup>, Giles F.S. Wiggs<sup>3</sup>, James King<sup>3</sup>, David S.G.**

**Thomas<sup>3,4</sup>, Frank D. Eckardt<sup>4</sup>, and Richard Washington<sup>3</sup>**

*<sup>1</sup>Geography and Environment, University of Southampton, SO171BJ, UK*

*<sup>2</sup>Department of Geography, University of Sheffield, S102TN, UK*

*<sup>3</sup>School of Geography and the Environment, University of Oxford, OX13QY, UK*

*<sup>4</sup>Department of Environmental and Geographical Science, University of Cape Town, 7701, South Africa*

\*E-mail address: J.Nield@soton.ac.uk, phone: +44 23 8059 4749

## ABSTRACT

Playas are common in arid environments and can be major sources of mineral dust that can influence global climate. These landforms typically form crusts that limit evaporation, dust-emission, modify surface erosivity and erodibility and can lead to over- or under-prediction of i) dust-emission potential and ii) water and heat fluxes in energy-balance modeling. Through terrestrial laser scanning measurements of part of the Makgadikgadi Salt Pans (a significant Southern Hemisphere dust emitter), we show that over weeks, months and a year, the shape of these surfaces changes considerably (ridge thrusting > 30 mm/week) and can switch among continuous, ridged and degraded patterns. Ridged pattern development changes the measured aerodynamic roughness of the surface (as much as 3 mm/week). The dynamic nature of these crusted surfaces must be accounted for in dust entrainment and moisture balance formulae to improve regional and global climate models.

## INTRODUCTION

Playas are common landforms in arid regions and are one of the biggest sources of mineral dust emission (Washington et al., 2003; Prospero et al., 2002). They also contribute to surface energy balances by modifying moisture and heat fluxes in the atmosphere (Bryant and Rainey, 2002). Uncertainty exists as to how much playas contribute to dust emissions (Sweeney et al., 2011) and the extent to which they influence the hydrological budget, because when the water table is shallow a protective and often heterogeneous mineral crust is typically formed (Reynolds et al., 2007). These crusts can form polygonal patterns which may be smooth and continuous, limiting subsurface exposure; or ridged and cracked, enabling unregulated exchange between surface and subsurface processes. Further, these surfaces are routinely used for satellite vicarious calibration (Biggar et al., 2003), and they can concentrate salts which can become significant mineral deposits (Mernagh, 2013).

Uncertainty in dust emission predictions (flux and location) stem from three main controls on crust patterns. (1) Crusts influence the availability of surface material which varies depending on crust moisture, type and thickness (Nickling, 1984). (2) The salt chemistry and changes in moisture may result in the formation of weak, low bulk density sediment (mineral grains plus salt crystal; fluff), thereby increasing the supply of potentially emissive material (Reynolds et al., 2009), particularly on sulfate-rich playas (Buck et al., 2011). (3) As polygon ridges grow and degrade over time they alter surface roughness and hence the erodibility of the surface and erosivity of the wind through modifications to aerodynamic roughness ( $z_o$ ), a key parameter in modeling dust-emission potential (Raupach et al., 1993; Marticorena and Bergametti, 1995).

This paper assesses surface moisture, aerodynamic roughness and crust pattern change on a large playa (Sua Pan) over weeks, months and a year. We first introduce the surface variability,

and then use Fourier Transforms to assess how surface patterns develop over time, ultimately linking surface change to atmospheric and subsurface controls through a conceptual model that identifies trajectories in crust patterning.

## **SITE LOCATION AND METHODS**

Investigations were undertaken during August 2011 and August and September 2012 at six locations on Sua Pan within a study area of 144 km<sup>2</sup> centred at 20.5754°S, 25.959°E (L5, J11, D10, G6, I4, B7). Sua Pan is part of the 3400 km<sup>2</sup> Makgadikgadi complex in Botswana. This playa experiences ephemeral flooding and its surface consists of a polygonal salt crust that is predominantly halite, thenardite and trona (Eckardt et al., 2008). The surface includes freshly formed crust with no or low topographic perturbations (**continuous**), well-formed polygon ridges (**ridged**), older broken, deflated ridges (**degraded**) or a mix of these three surfaces.

The surface elevations of the crust were measured using a Leica Scanstation TLS and converted to 100 m<sup>2</sup> DEMs of 1 cm grid resolution following the methods of Nield et al. (2013). Registration errors between monthly and weekly scans were less than 2 mm. Locations between years were registered using a DGPS survey. Ridge height, width and spacing were calculated by linearly de-trending 1-cm-spaced transects and identifying positive height deviations (Nield et al., 2013). Two dimensional Fourier Transforms, following the method of Perron et al. (2008), were used to calculate radial frequencies and corresponding ridge-spacings which were normalized using the flat surface spectra (L5, 2011). Water-table depth was measured using a dipwell in 2 m wells. Relative surface moisture was calculated at each site using the mean intensity of the TLS return signal collected within a 2 m<sup>2</sup> area at a distance of 12.5 m, normalized by the wettest site (L5, 2011), following the methods of Nield et al. (2014). High values indicate drier surfaces.

Detection of surface moisture on the entire playa between 2000 and 2012 was based on Normalized Difference Water Index (NDWI) data extracted from MODIS MOD/MYD09A1 8-day data (500 m resolution) (Gao, 1996; Leon and Cohen, 2012). NDWI threshold values were validated using field observations of surface condition (i.e., flooded, moist and dry) from various basin locations along with high resolution remote sensing data (e.g., ASTER, Landsat). Processed data were consolidated to provide long-term and annual surface flood frequency data (F<sub>f</sub>: Fig. 1A-C), and for the 2010–2012 hydrological years, 8-day NDWI data were extracted for each study site (Fig. 1D).

Values of  $z_0$  were calculated using two weeks of easterly wind speeds measured at 0.25 m, 0.47 m, 0.89 m and 1.68 m with Vector Instruments cup anemometers (A-100R), averaged over one minute intervals following standard law-of-the-wall profile methods. Measurements below  $3 \text{ ms}^{-1}$  or with  $R^2$  values below 0.98 were discarded (Bauer et al., 1992).

## **SURFACE MOISTURE OBSERVATIONS**

Surface water varied annually as a function of elevation, with topographically lower sites in the east (L5 and J11) experiencing submergence more frequently over a ten year period than sites on the central (G6, I4) and western (D10, B7) areas (Fig. 1A). In the 2010–11 wet season prior to field measurements (Fig. 1B), only the western sites (D10, B7) remained relatively dry (Fig. 1D), while during the 2011–12 wet season (Fig. 1C) only the center (G6, I4) experienced prolonged flooding (Fig. 1D). TLS moisture measurements (Table 1) indicated drying (higher values) on surfaces that did not experience prolonged flooding in 2011–12 (L5, B7, J11, D10), and a slight increase (lower values; 1 - 3%) in surface moisture at flooded sites (G6, I4).

## **RIDGED PATTERN DEVELOPMENT**

The combination of a high water table and flooding in 2011 ‘reset’ the surface and enabled a flat, continuous crust to develop on the north-eastern of the playa (L5). After the wet season 2011–12 when no significant flooding occurred (Fig. 1D), the surface dried enough to initiate ridge formation (Fig. 2A). During nine days at the start of August 2012 (3–12; Table 1), ridge crests were thrust up by as much as 30 mm (Fig. 2E). While the mean surface change was 0.44 mm/day (Fig. 2H), most growth was near the ridge peaks and the inter-ridge areas remained at the same elevation, as indicated by the asymmetric growth distribution with a peak at zero and tail extending to 2 mm/day. This initial growth period slowed down in the latter part of August and early September (mean rate of 0.23 mm/day between the 12 August and 14 September; Fig. 2G). By late September (17–26), the growth distribution became more symmetrical (Fig. 2I), ridges had reached their maximum stability and heights began to reduce (–0.05 mm/day). Fourier transform spectra capture this pattern of ridge growth and decline and indicate increased persistence of ridge spacing in the 200–300 mm region throughout August and early September, and a slight decline in mid to late September (Fig. 2D).

#### **SPATIAL AND TEMPORAL VARIABILITY OF CRUST PATTERNS**

In a similar way to the northeast crust at L5, high levels of surface moisture toward the southeast (J11; Fig. 3A) in 2010–11 (Fig. 1D) ‘reset’ the surface and formed a continuous crust prior to our measurements. The small moisture inputs and a diminished peak in surface water between August 2011 and August 2012 (Fig. 1D) were not enough to ‘reset’ this surface between our measurement periods but instead assisted in the development of a fast-forming, distinctive, and widely spaced ridged pattern in 2012 (similar to D10).

In the drier southwest section of the playa (D10), a well-defined ridged pattern continued to grow between August 2011 and August 2012. This growth extended the dominance of larger

spaced (600 mm) ridges (Fig. 3B) because it did not experience any substantial flooding during the wet seasons in 2010–11 or 2011–12 (Fig. 1D). The mixed pattern on the western side of the study area (B7; Fig. 3E) followed a similar temporal trend in ridge development, but it had fewer ridges initially because it experienced more extensive flooding in 2010–11 (Fig. 1D) and had a shallower water table (0.835 m and 1.815 m for B7 and D10 respectively; Table 1).

The smooth, degraded surfaces in the central areas of the playa (G6 and I4; Figure 3C, D) indicated strong smaller ridge spacing (between 100 and 300 mm) initially. This topography became muted after the substantial flooding around G6 (Fig. 1D) during the 2011–12 wet season, or transitioned through a mixed phase to a well-developed ridged pattern where standing water was not consistently present as at site I4 (Fig. 3D). The surface at G6 did not form typical polygonal ridges during 2012, but instead there was a general swelling in elevation of the entire surface. This swelling was evident to a lesser extent at the drier surface (I4) and appears to be related to the thickness of the degraded crust which limits capillary action and subsurface moisture exchange (Veran-Tissoires et al., 2012; Nickling and Ecclestone, 1981). Existing vehicle tracks on the surface (I4; Fig. 3D) followed the crust development trajectory of degraded to mixed to ridged, and highlight the importance of small-scale topography in crust pattern development. During the wet season in 2011–12 it is likely that these topographically depressed areas preferentially ponded water, initializing earlier ridge development in 2012. The forcing by moisture inverted the crust pattern resulting in vehicle tracks becoming topographically positive after the wet season (Fig. 3D).

#### **TEMPORAL VARIABILITY OF $z_o$**

In general,  $z_o$  values (Table 1) across the study site relate to ridge dimensions and were greater on surfaces with larger element heights (Nield et al., 2013). Temporally  $z_o$  values

increased as the surfaces transitioned from flatter to ridged patterns. The higher resolution measurement sequence undertaken at L5 (Table 1) demonstrates the rapidity at which the formation of a ridged pattern can induce an order of magnitude change in  $z_o$ , increasing from 0.46 mm to 4.25 mm in 9 days (from 3 to 12 August 2012). This change in  $z_o$  occurred as a result of a growth in the mean ridge height from 8.1 mm to 13.8 mm over the same period.

## **FEEDBACKS, CONROLS AND DRIVERS OF SALT CRUST PATTERNING**

Using high resolution TLS sequences (days and mms) we build upon the conceptual postulations of Krinsley (1970), where polygonal ridge thrusting is driven by efflorescence. We find that ridge development (Fig. 4A; L5, J11 trajectories) is a complex process likely controlled by flooding and interactions among subsurface, surface and atmospheric moisture exchange (Groeneveld et al., 2010). Positive feedback accelerates ridge development because higher, exposed ridges increase evaporation, salt phase change and thrusting. Over time negative feedback diminishes ridge growth (Fig. 4B; G6 trajectory) because ridges may collapse, either through structural weaknesses or mechanical and chemical breakdown by wind and (or) rain. Under extreme external events such as flooding from river flow, rainfall or upwelling, the surface may be ‘reset’ at any stage of the formation-degradation cycle (Fig. 4C; I4 trajectory). Continuous crusts in our conceptual model will have low evaporation and dust-emission rates, ridged crusts will have high evaporation rates but low dust-emission rates and degraded crusts will have high dust-emission rates but lower evaporation rates than other crust types. Water-table depth, salt chemistry and antecedent conditions are important controls on the extent to which a surface may progress through different pattern phases. For example, concentrations of thenardite and a high water table may increase the development of ridges and ‘fluffy’ dust emitting sediment or interlocking halite crystals may decrease the available of dust sediment (Buck et al.,

2011). Chemical salt segregation within ridged and flat surfaces may also influence dust emissivity. The resulting surface patterns modify  $z_o$  (Table 1) and therefore have important implications for dust emission and evaporation rates because  $z_o$  is a component of both dust entrainment thresholds and turbulent heat fluxes (Deol et al., 2012; Bryant, 2013). For example the increase in  $z_o$  over 9 days in August could result in an increase in shear velocity threshold by as much as 350% using the Marticorena and Bergametti (1995) scheme which could lead to an over prediction in dust emission modelling.

## CONCLUSIONS

This work shows that detailed time-series data on surface microtopography and ground/surface water status are required to fully characterize crust pattern formation/degradation. Our data suggest the following:

1. Ridge heights increase over time due to positive feedbacks between atmospheric and subsurface processes, unless external controls ‘reset’ the surface.
2. Over time, ridge growth rates decrease due to negative feedbacks limiting atmospheric and subsurface interactions.
3. On young crusts ridge initiation and growth can occur quickly ( $> 30$  mm/week), changing the erosion potential by increasing  $z_o$ .
4. Sediment supply and availability increases as the surface dries out, becomes cracked and exposes freshly made low density, fluffy sediment.

This paper gives the first indication of salt-crust-pattern variability, both temporally and spatially for a major dust ‘hot spot’ (Gillette, 1997) and one of the largest palaeolakes in the Southern Hemisphere. Ultimately, we show that it is important to include parameterization of salt-crust-pattern dynamics (at the level of detail that we provide here) within climate models to



better account for changes in water balance, dust entrainment, sediment availability and salt accumulation in the geological record.

## ACKNOWLEDGMENTS

This study was funded by NERC (NE/H021841/1), World University Network and a University of Southampton SIRDF grant. Data processing used IRIDIS Southampton Computing Facility. We thank the Botswana Ministry of Environment, Wildlife and Tourism for access to the site (permit EWT 8/36/4 XIV) and WG Nickling and reviewers for their comments.

## REFERENCES CITED

- Bauer, B.O., Sherman, D.J., and Wolcott, J.F., 1992, Sources of Uncertainty in Shear-Stress and Roughness Length Estimates Derived from Velocity Profiles: *The Professional Geographer*, v. 44, p. 453–464, doi:10.1111/j.0033-0124.1992.00453.x.
- Biggar, S.F., Thome, K.J., and Wisniewski, W., 2003, Vicarious radiometric calibration of EO-1 sensors by reference to high-reflectance ground targets: *IEEE Transactions on Geoscience and Remote Sensing*, v. 41, p. 1174–1179, doi:10.1109/TGRS.2003.813211.
- Bryant, R.G., 2013, Recent advances in our understanding of dust source emission processes: *Progress in Physical Geography*, v. 37, p. 397–421, doi:10.1177/0309133313479391.
- Bryant, R.G., and Rainey, M.P., 2002, Investigation of flood inundation on playas within the Zone of Chotts, using a time-series of AVHRR: *Remote Sensing of Environment*, v. 82, p. 360–375, doi:10.1016/S0034-4257(02)00053-6.
- Buck, B.J., King, J., and Etyemezian, V., 2011, Effects of Salt Mineralogy on Dust Emissions, Salton Sea, California: *Soil Science Society of America Journal*, v. 75, p. 1971–1985, doi:10.2136/sssaj2011.0049.

- 206 Deol, P., Heitman, J., Amoozegar, A., Ren, T., and Horton, R., 2012, Quantifying nonisothermal  
207 subsurface soil water evaporation: *Water Resources Research*, v. 48,  
208 doi:10.1029/2012WR012516.
- 209 Eckardt, F.D., Bryant, R.G., McCulloch, G., Spiro, B., and Wood, W.W., 2008, The  
210 hydrochemistry of a semi-arid pan basin case study: Sua Pan, Makgadikgadi, Botswana:  
211 *Applied Geochemistry*, v. 23, p. 1563–1580, doi:10.1016/j.apgeochem.2007.12.033.
- 212 Gao, B.C., 1996, NDWI - A normalized difference water index for remote sensing of vegetation  
213 liquid water from space: *Remote Sensing of Environment*, v. 58, p. 257–266,  
214 doi:10.1016/S0034-4257(96)00067-3.
- 215 Gillette, D.A., 1997, Physical mechanisms explaining the existence of ‘hot spots’ of dust  
216 emitting source regions, *in* Hoyningen-Huene, W., and Tetzlaff, G., eds., *Sediment and*  
217 *aerosol*: Leipzig, Germany, Alfred-Wegener-Stiftung, p. 27–31.
- 218 Groeneveld, D.P., Huntington, J.L., and Barz, D.D., 2010, Floating brine crusts, reduction of  
219 evaporation and possible replacement of fresh water to control dust from Owens Lake bed,  
220 California: *Journal of Hydrology (Amsterdam)*, v. 392, p. 211–218,  
221 doi:10.1016/j.jhydrol.2010.08.010.
- 222 Krinsley, D.B., 1970, A Geomorphological and Paleoclimatological Study of the Playas of Iran.  
223 Part 1.: Reston, Virginia, Geological Survey, Final Scientific Report CP 70-800.
- 224 Leon, J.X., and Cohen, T.J., 2012, An improved bathymetric model for the modern and palaeo  
225 Lake Eyre: *Geomorphology*, v. 173–174, p. 69–79, doi:10.1016/j.geomorph.2012.05.029.
- 226 Marticorena, B., and Bergametti, G., 1995, Modeling the atmospheric dust cycle: 1. Design of a  
227 soil-derived dust emission scheme: *Journal of Geophysical Research. Planets*, v. 100,  
228 p. 16415–16430, doi:10.1029/95JD00690.

- 229 Mernagh, T.P., 2013, A review of Australian salt lakes and assessment of their potential for  
230 strategic resources: Canberra, Geoscience Australia, 243pp.
- 231 Nickling, W.G., and Ecclestone, M., 1981, The effects of soluble salts on the threshold shear  
232 velocity of fine sand: *Sedimentology*, v. 28, p. 505–510, doi:10.1111/j.1365-  
233 3091.1981.tb01698.x.
- 234 Nickling, W.G., 1984, The stabilizing role of bonding agents on the entrainment of sediment by  
235 wind: *Sedimentology*, v. 31, p. 111–117, doi:10.1111/j.1365-3091.1984.tb00726.x.
- 236 Nield, J.M., King, J., Wiggs, G.F.S., Leyland, J., Bryant, R.G., Chiverrell, R.C., Darby, S.E.,  
237 Eckardt, F.D., Thomas, D.S.G., Vircavs, L.H., and Washington, R., 2013, Estimating  
238 aerodynamic roughness over complex surface terrain: *Journal of Geophysical Research, D,*  
239 *Atmospheres*, v. 118, p. 12948–12961, doi:10.1002/2013JD020632.
- 240 Nield, J.M., King, J., and Jacobs, B., 2014, Detecting surface moisture in aeolian environments  
241 using terrestrial laser scanning: *Aeolian Research*, v. 12, p. 9–17,  
242 doi:10.1016/j.aeolia.2013.10.006.
- 243 Perron, J.T., Kirchner, J.W., and Dietrich, W.E., 2008, Spectral signatures of characteristic  
244 spatial scales and nonfractal structure in landscapes: *Journal of Geophysical Research-Earth*  
245 *Surface*, v. 113, p. F04003, doi:10.1029/2007JF000866.
- 246 Prospero, J.M., Ginoux, P., Torres, O., Nicholson, S.E., and Gill, T.E., 2002, Environmental  
247 characterization of global sources of atmospheric soil dust identified with the Nimbus 7  
248 Total Ozone Mapping Spectrometer (TOMS) absorbing aerosol product: *Reviews of*  
249 *Geophysics*, v. 40, doi:10.1029/2000RG000095.

Raupach, M.R., Gillette, D.A., and Leys, J.F., 1993, The Effect of Roughness Elements on Wind  
Erosion Threshold: Journal of Geophysical Research, D, Atmospheres, v. 98, p. 3023–3029,  
doi:10.1029/92JD01922.

Reynolds, R.L., Bogle, R., Vogel, J., Goldstein, H., and Yount, J., 2009, Dust emission at  
Franklin Lake Playa, Mojave Desert (USA): Response to meteorological and hydrologic  
changes 2005–2008.

Reynolds, R.L., Yount, J.C., Reheis, M., Goldstein, H., Chavez, P., Fulton, R., Whitney, J.,  
Fuller, C., and Forester, R.M., 2007, Dust emission from wet and dry playas in the Mojave  
desert, USA: Earth Surface Processes and Landforms, v. 32, p. 1811–1827,  
doi:10.1002/esp.1515.

Sweeney M, McDonald E, and Etyemezian V., 2011, Quantifying dust emissions from desert  
landforms, eastern Mojave Desert, USA: Geomorphology v. 135, p. 21–34,  
doi:10.1016/j.geomorph.2011.07.022.

Veran-Tissoires, S., Marcoux, M., and Prat, M., 2012, Discrete Salt Crystallization at the Surface  
of a Porous Medium: Physical Review Letters, v. 108,  
doi:10.1103/PhysRevLett.108.054502.

Washington, R., Todd, M., Middleton, N.J., and Goudie, A.S., 2003, Dust-storm source areas  
determined by the total ozone monitoring spectrometer and surface observations: Annals of  
the Association of American Geographers, v. 93, p. 297–313, doi:10.1111/1467-  
8306.9302003.

Figure 1. Surface moisture trends [F<sub>j</sub>] assessed by MODIS over A) 10 years between 2002 and  
2012 (scale is fraction of time between 0 and 20% of time that the playa was inundated), B) year  
prior to ground measurements (September 2010–2011), and C) year between ground

273 measurements (September 2011–2012) using the same scale. D) Temporal sequence of surface  
274 moisture within 0.25 km<sup>2</sup> area surrounding each site. S1 and S2 indicate study periods.  
275 Figure 2. A-C) Examples of planform surfaces at L5 depicting ridge development. Colors  
276 indicate surface elevation above (red) and below (blue) mean height of 3/8/12 surface. D)  
277 Relative amplitude of 2D Fourier Transform wavelengths for each surface measurement. E-F)  
278 Surface change over 9 days. G-I) Frequency of elevation change, mean and standard deviations  
279 indicated by  $\mu$  and  $\sigma$  respectively in mm/day.  
280 Figure 3. Examples of surfaces in 2011 and subsequent patterns in 2012. Colors indicate surface  
281 elevation above (red) and below (blue) mean height for each year in August. Relative amplitude  
282 of 2D Fourier Transform wavelengths for each pattern indicated in right column, normalized to  
283 the spectra from the flat surface at site L5 in 2011.  
284 Figure 4. Conceptual diagram linking salt crust pattern change to feedbacks and extreme events.  
285 Axes indicate A) Positive feedback controlled by subsurface, surface and atmospheric processes,  
286 which over time leads to ridge development. B) Negative feedback controlled by atmospheric  
287 processes which over time, together with wind and/or rain leads to crust degradation. C) Extreme  
288 flooding events controlled by subsurface and atmospheric processes ‘reset’ the crust. Dashed  
289 lines indicate the trajectories of each surface between August 2011 and September 2012.