Journal of Maps, 2011, 249-259

Geomorphology of the Chihuahuan Desert based on potential dust emissions

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Abstract

The Chihuahuan Desert of central northern Mexico and southern Arizona, New Mexico and Texas, USA, is a regionally significant dust 'hot-spot' in North America. Typical of other such hot-spots, this desert consists of a mosaic of geomorphological settings, each of which has a varying propensity for dust emission. Recently, a classification system of dust emission potential based on surface geomorphic characteristics that establishes a common framework for describing the land surface has been proposed. The classification is readily applicable to different dust source regions and designed to facilitate comparison of the relative potential dust contributions and emissivity of varying geomorphological environments in such regions.

The map here (1:3,500,000) was compiled by applying the new classification to a base map of polygons from existing soil and landform maps that were produced by national government agencies. Within the study area, 11 of the 17 possible geomorphic classes were present, the most extensive being unarmoured, unincised high relief alluvial surfaces, which covered 43% of the area.

As an example of how empirical dust source point data can be used with the classification, the satellite-observed origins of dust plumes for 26 major wind erosion events from 2001 to 2009 were overlain on the map. Despite a total area of only 4%, ephemeral lakes were the source of 48% of the observed plumes. This map and the relationships derived from it provide the basis for developing equivalent maps in other dusty regions, and mark a step toward improving the representation and documentation of the strength of dust sources in numerical mineral aerosol models.

(Received 31st January 2011; Revised 22nd June 2011; Accepted 18th July 2011)

ISSN 1744-5647
doi:10.4113/jom.2011.1178

1. Introduction and Rationale

The world's major sources of aerosol emission are predominantly closed basins in semi-arid environments (Prospero et al., 2002; Washington et al., 2003). These dust source regions exhibit considerable geomorphic heterogeneity and within them, at any one time, smaller sub-basin scale dust emission 'hot-spots' can be identified. Some hot-spots are persistent and emit dust regularly (seasonally or annually), while others are sporadic or ephemeral where emission is triggered by factors such as timing of localized sediment input. To better understand the dynamics of dust hot-spots, researchers are starting to map these regions as mosaics of different geomorphic types (e.g. Wang et al., 2008; Bullard et al., 2008), each of which has a different signature of dust emission potential.

Accurate numerical modelling of dust emission and transport requires quantitative information about the relative aerosol contribution from different land surface types (e.g. Zender et al., 2003). A number of attempts have been made to determine the relative importance of different surface types for dust emissions by determining relationships between empirical dust point source data and mapped surface characteristics. However, the use of different geomorphic mapping schemes by different groups of researchers limits the extent to which the results can be compared across regions (Bullard, 2010; Bullard et al., 2009). In response to this, the QUEST (Quantifying and Understanding the Earth System) Working Group on Dust proposed a common, geomorphology-based classification scheme designed to be applicable worldwide to facilitate the comparison of dust emission from hot-spots in different regions (Table 1). Such a scheme would represent a basis for the parameterisation of dominant dust emission zones in the reduced scale global maps used in dust-cycle models. A key element of the QUEST classification is that it can be applied using data that are easily available, globally-consistent and verifiable. It is therefore based on a limited number of easily identifiable geomorphic categories that can be defined using satellite remote sensing, aerial photographs, topographic, soil and geological maps, complemented by field data. The development and justification of the classification is discussed in detail by Bullard et al. (in press). Here we map the distribution of these geomorphic categories in the Chihuahuan Desert.

The Chihuahuan Desert (Figure 1) is the third largest desert in the American continent. It lies in a relatively high-elevation basin and range region (ranging approximately 400-3100 m a.s.l.) generally south of the Colorado Plateau and between the Sierra Madre Oriental and Sierra Madre Occidental ranges and is bisected by the USA-Mexico border. This desert represents a substantial, but annually variable, source of airborne dust within the North American continent (Prospero et al., 2002). Although dust events may occur at any time of year, the strongest regional dust outbreaks are during the dry winter and spring months when strong cyclones cross over or just to the north of the region (Lee et al., 2009; Rivera Rivera et al., 2009) and emanate from unvegetated or poorly vegetated surfaces, including dry playas, scrublands and fallow agricultural fields (Rivera

Main geomorphology class	Geomorphology sub-division	Code	Importance for dust emission	Area (km²)	Area (%)	% of dust plumes
Lakes	Wet	1a	Low	243	<0.1	0
	Ephemeral	1b	High-Med	8905	2.8	29.5
	Dry – consolidated	1c	Low	-	-	-
	Dry – non consolidated	1d	High-Med	3564	1.1	18.4
High Relief alluvial systems	Armoured, incised	2a	Low	-	-	-
	Armoured, unincised	2b	Low	-	-	-
	Unarmoured, incised	2c	Medium	32	<0.1	0
	Unarmoured, unincised	2d	Med-High	138728	43.0	20.7
Low Relief alluvial systems	Armoured – incised	3a	Low	-	-	-
	Armoured - unincised	3b	Medium	-	-	-
	Unarmoured – incised	3c	Low	436	0.1	0
	Unarmoured– unincised	3d	Medium	64683	20.1	12.0
	Stony surfaces	4	Low	141	<0.1	0.5
Aeolian systems	Sand Sheet	5a	Low-Med	7178	2.2	1.8
	Aeolian sand dunes	5b	Low-High	9450	2.9	13.8
	Loess	6	Low-Med	-	-	-
	Low emission surfaces	7	Low	89090	27.6	3.2

Table 1. The QUEST group (Bullard et al., 2009) classification of dust source geomorphology (first four columns), and the classification as applied to the Chihuahuan Desert (right hand three columns). Percentage of dust sources per geomorphic class using the source point data in Figure 2 is shown in the grey column.

Rivera et al., 2010). El Paso, Texas / Ciudad Juarez, Chihuahua, the largest metropolitan area within the desert, experiences approximately 15 dusty days per year (with visibility <10 km) (Novlan et al., 2007). Dust from the Chihuahuan Desert can be transported considerable distances across the North American continent (Doggett et al., 2002).

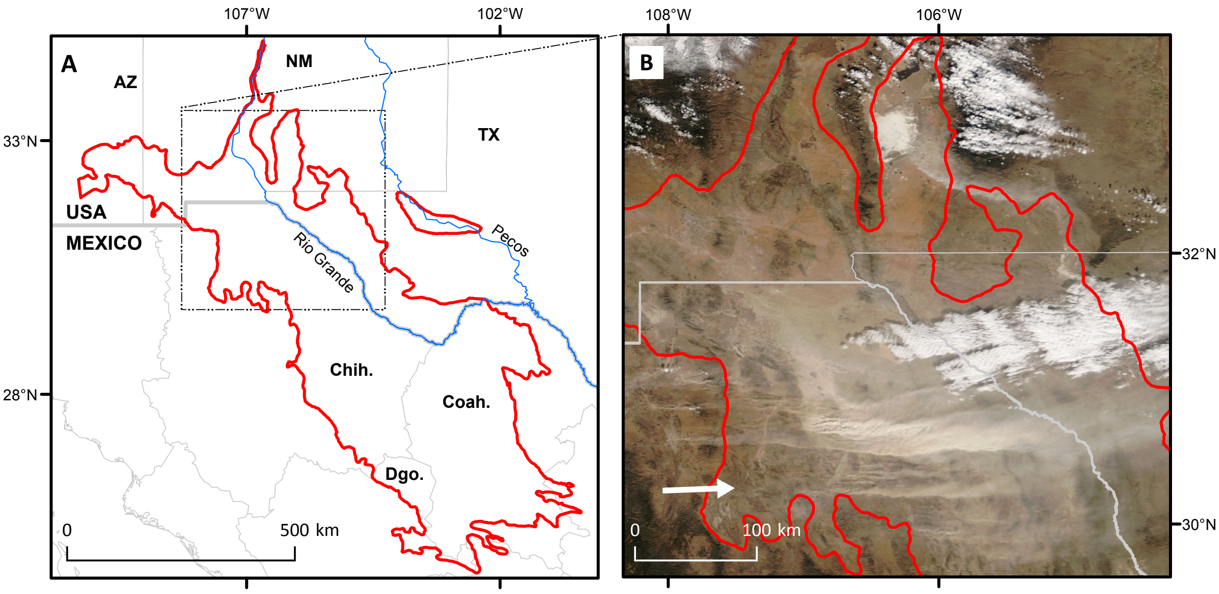

Figure 1. (a) Extent of the Chihuahuan Desert (red line) within Mexico and USA as defined by Schmidt (1979) b) 'True colour' MODIS scene of a blowing dust event (morning of 27/11/2005) from the northern Chihuahuan Desert. Arrow indicates general wind direction.

2. Methods

The areal definition for the Chihuahuan desert used in this study is that of Schmidt (1979), a climatic-based definition yielding an area of 322,450 km^2. The north and north-eastern portion lies within the USA and the remainder is within Mexico. There are no detailed geomorphology-based maps of the desert that cross this political border. Due to resource constraints it was not possible to map the geomorphology of the area in detail using ground surveys, so a base map was produced using existing government data from both nations. Given there is a close relationship between geomorphic characteristics and soils data for the categories, the base map was created based on soil type and consisted of mapped polygons. For the Mexican portion, soils data at 1:1,000,000 were obtained from the Sistema de Topoformas dataset, provided by the Instituto Nacional de Estadística y Geografía (INEGI, 2001). This base layer consisted of 671 polygons inside the defined area with a positional accuracy of c.250 m. For the USA portion, the base layer data was the state-by-state US General Soil Map at 1:250,000 produced by the US Department of Agriculture's Natural Resource Conservation Service (USDA-NRCS, 2006). After edge-matching common polygons across Arizona, New Mexico and Texas, there were 605 base polygons for the USA portion with a positional accuracy that varied from 250 m to 1 km (USDA-NRCS, 2011). Since the base polygons were subsequently classified as one of the 17 geomorphic classes, the different scales of the base data between Mexico and the USA did not create detrimental biases in the output map. Both datasets used came in ESRI ArcGIS compatible form and the smallest polygon on the base map has an area of 1 km^2. Where map units terminated at the international boundary, care was taken to keep the geomorphic attribution consistent.

After establishing the initial base map of landscape units, a range of different data sources was used to assign a geomorphic category from the classification (Table 1). These sources included georegistered surface geology and soils maps (plus the descriptive layers associated with the original base polygon datasets), satellite imagery, information in published literature (e.g. Hawley et al., 1969; Langford, 2000; Castiglia and Fawcett, 2006; Hall et al., 2010), expert knowledge and dedicated verification field sorties. Digital Elevation Models and simple contour maps were used to differentiate high and low relief terrain. As well as using Google Earth, the primary satellite imagery source was the mosaic of the NASA GeoCover project for circa 2000. The latter has worldwide coverage created from Landsat ETM+ (at 14.25 m spatial resolution) (Tucker et al., 2004).

Where the geomorphological variability of the landscape was more complex than indicated in the primary dataset, for example two or more different geomorphic types within a single polygon, base layer polygons were sub-divided. This was most common in playa areas, since multiple different dry lake geomorphic classifications can exist in close proximity to one another. Once each polygon in the base map was categorized by geomorphology, adjacent polygons with the same geomorphic characteristics were merged with the result that the smallest polygon increased in size to 2 km^2.

3. Geomorphic Categories in the Chihuahuan Desert

Of the 17 geomorphic types identified by Bullard et al. (2009), 11 were present in the Chihuahuan Desert (Table 1).

The majority of Chihuahuan Desert lakes have a hydrological regime in which inundation is only occasional so these were mapped as ephemeral lakes (1b). Dry, non-consolidated lakes (1d) usually comprised the outer parts of tectonically uplifted portions of relic Quaternary lakes not known to have been supplied with loose sediments during the historical flood record. These ephemeral and dry lakes are distributed throughout the desert (Castiglia and Fawcett, 2006; Scuderi et al., 2010). Perennial water bodies were classified as 1a.

No specific criteria were used to distinguish high and low relief alluvial landscape units, rather, the two were distinguished based on variations in relative relief. Bajada surfaces were classified as high relief alluvial systems (2d) as they are transitional between the steeper exposed rock/bare mountainsides and flat depositional plains, and are characterised by surface wash processes. Channels are typically not well-developed on the bajadas so they were considered unincised, and the predominance of sand-sized sediment classifies them as unarmoured. This surface geomorphology occurs in extensive areas throughout the far northwest and central areas of the desert whereas the rest of the region has larger expanses of low relief alluvial deposits with poorly developed channels and no armouring (3d). This latter area includes the wide floodplains of perennial rivers (such as the middle to northern Rio Grande / Rio Bravo del Norte section) and ephemeral rivers (e.g. Rio Del Carmen). Parts of the Rio Grande further downstream are incised (3c). Stony desert surfaces (4) are of very limited extent within the Chihuauhan Desert.

Aeolian deposits in the Chihuahuan Desert are located mainly in the north and south central areas and are dominated by coarse-grained sand sheets (5a) and dunes (5b) with no loess deposits identified. There is an extensive area of coppice dunes in the north central desert straddling the USA-Mexico border west of El Paso, and the largest dunefield of unvegetated bedforms (400 km^2) is part of the White Sands complex. Sand sheets cover a few basins in the northeast edge of the desert in Texas and New Mexico.

Although the scale of the map captures the gross geomorphic characteristics of the region, there are areas where geomorphic surfaces vary over small distances, or where two or more units are closely coupled. For example, there are areas where sand dunes are superimposed on dry lakes such that the interdune areas expose lake bed; in other areas floodplain sediments have evidently been re-worked into aeolian features. The geomorphology in these cases is mapped according to the spatially dominant surface type.

Surfaces with low emission potential (7), such as extensive exposed mountain and escarpment rocky areas, are rarely dust sources in this region unless they are subjected to anthropogenic disturbance (e.g. mining). They are predominantly in the south of the desert.

4. Comparison with Point Sources of Dust Emission

The map can be combined with empirical dust source data to determine the relative importance of each geomorphic surface type in terms of dust emissions. To illustrate this, a dataset of dust source points identified using an established remote sensing technique (e.g. Bullard et al., 2008; Rivera Rivera et al., 2010) for 26 dust events between 2001 and 2009 was overlain on the map (Figure 2) and is summarized in Table 1. Although ephemeral and dry lakes cover only a small proportion of the region (<4%) they account for nearly half (48%) of the dust plumes. In contrast, only 21% of the dust plumes mapped are associated with the high relief alluvial systems which cover over 43% of the Chihu-

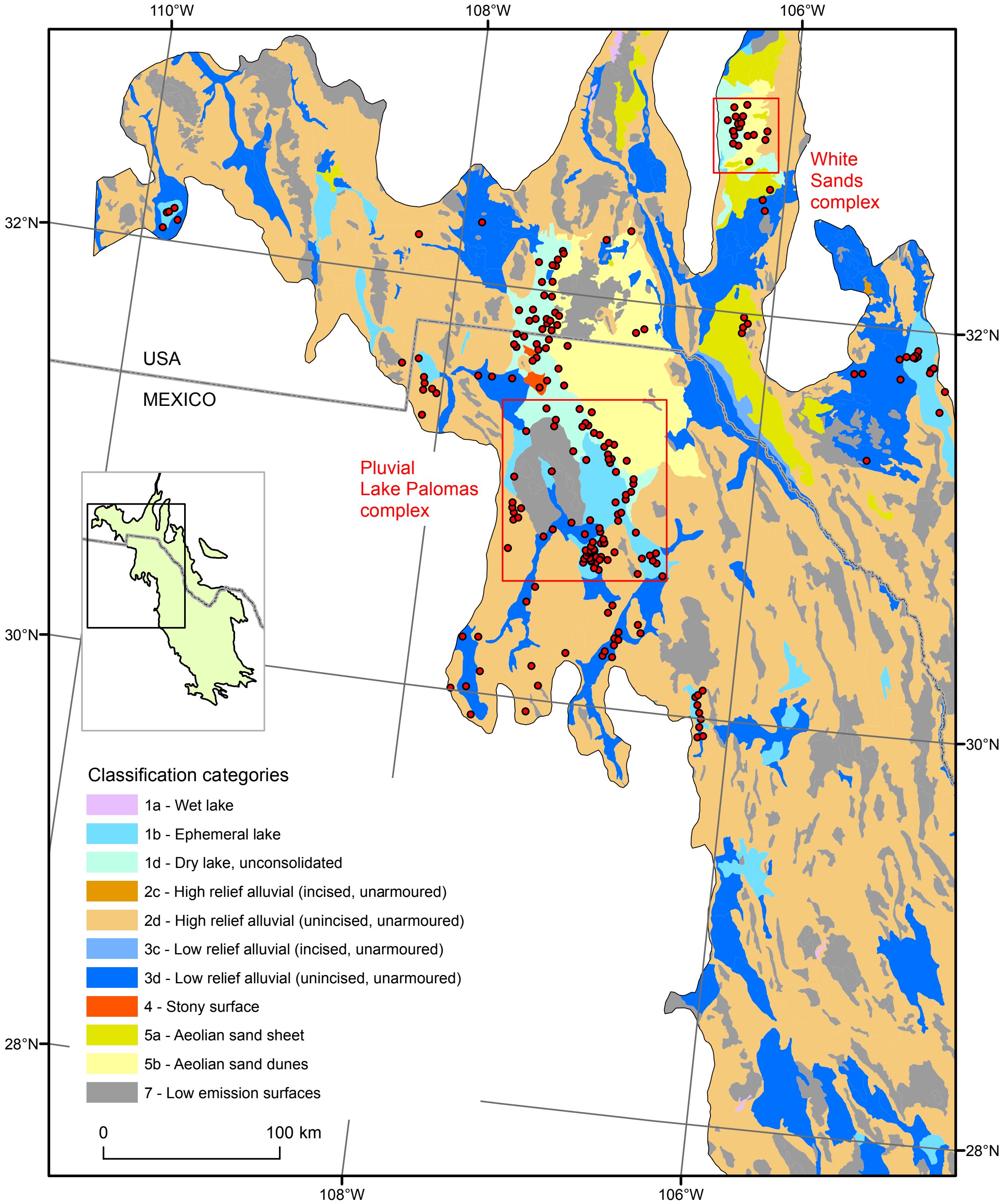

Figure 2. Detailed view of the geomorphic classification for the area containing all satellite-determined dust source points (red dots) from 26 studied dust events occurring 2001-2009. No sources were observed south of 29.5°N. Dust source data summarised in greyed column of Table 1.

ahuan Desert. The dataset used only provides an indication of dust plume frequency (not relative plume size or concentration), but the number of dust plumes per unit area suggests that intermittent or dry lakes are more important for dust emissions than is suggested by their limited spatial coverage.

5. Conclusion

We have presented a new map of the geomorphology of the Chihuahuan Desert using a classification scheme designed to improve our understanding and assist numerical modelling of dust emissions. Of the 17 possible geomorphic classes, 11 were identified and mapped, with High Relief Alluvial (unincised, unarmoured) accounting for 43% of total area, Low Emission Surfaces 28% and Low Relief Alluvial (unincised, unarmoured) 20%. Overlaying dust point sources on the map illustrates the relationship between surface types (e.g. ephemeral lakes and alluvial systems) and aeolian dust emissions.

Although this classification scheme is applicable to any dust source area of interest, its ease of application depends on factors such as quality of pre-existing datasets, familiarity with the study region and desired level of detail. The baseline for this map of the Chihuahuan Desert was derived from pre-existing high quality soil and geology polygon data. Application of the classification does not necessarily require such inputs, since surface types could be mapped from any available base maps or digitized entirely originally from satellite imagery (e.g. Ballantine et al., 2005). The main disadvantage of creating an entirely original classification map will be the time demands of digitizing all polygons.

The mapping scheme effectively, although somewhat qualitatively, reflects the key geomorphic factors controlling dust emission. Its scale, while providing less detail than typical regional geomorphic maps, is much more complex than is typically used in numerical models of dust emission (Bullard et al., in review). Application of this scheme to the Chihuahuan Desert illustrates a more sophisticated delineation of emitting and non-emitting surfaces, and thus should improve the parameterization of aerosol sources in dust-cycle models. The authors hope that this exercise will provide the basis for the development of a global series of maps of aeolian dust source areas.

Software

The base data and interpretation layers were all managed, and the final map built, using ESRI ArcGIS 9.3 and Adobe Illustrator.

Acknowledgments

Thanks to Porfirio Peinado, Joseph Mbuh and Jeff Lee. Gill and Dominguez were supported in part by grant 003661-0027-2007 from the Norman Hackerman Advanced Research Program of the Texas Higher Education Coordinating Board. Rivera and Rivera and Gill were supported in part by NOAA through the Educational Partnership Program for Minority Serving Institutions (EPP/MSI) Cooperative Agreement NA17AE1623. We are also grateful for the comments of Colin Pain, Paul Hesse and Grant McTainsh whose reviews helped improve the manuscript, and Bernhard Jenny of ETH Zurich for his detailed cartographic critique.

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