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Characterisation of aeolian sediment accumulation and preservation across complex topography

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ABSTRACT

Topography fundamentally influences the distribution and morphology of aeolian landforms via the modification of surface wind flow and the creation of space for sediment deposition. This has been observed at both landform (individual topographic dune forms) and macro-landscape (sand sea) scales. Although previous studies have considered several aspects of the impact of topography on aeolian landforms, the patterns of landscape-scale aeolian sediment accumulation that emerge at the meso-scale, within topographically complex environments have received less consideration.

To address this, we present an approach that combines information on the presence of surficial sand (via remote sensing) with the morphometric feature classification method, LandSerf. Using the Cady Mountains in the Mojave Desert as a case study, we explore the relationships between sand cover and topographic indices over length scales of 10^2–10^3 m. Field observations are then used to refine our understanding of these patterns.

Aeolian deposits across the Cady Mountains are strongly controlled by the topography. Although sand cover is often continuous and highly variable in depth, four archetypal “accommodation space types” are identified from the morphometric analysis: Slopes, Plains, Valley-Fills, and Slope-Valley composite. Specific aeolian landforms within these accommodation spaces may manifest as sand ramps and climbing - falling dunes, particularly on mountain front Slopes, and as sand sheets on downwind Plains within the mountain block. In areas of high sediment supply these may also coalescence, as exemplified by the extensive and compositionally complex Slope-Valley composites in the northern Cady Mountains.

In conjunction with field observations, we argue that topography, moderated by proximity to sediment supply, strongly influences the character of the aeolian sedimentary record. However, even within the relatively complex landscape studied here, 90% of the mapped sand accumulation is associated with the four identified accommodation space types. The implication is that areas of such complex topography are amenable to analysis within the scheme outlined and that this can potentially be used to support interpretations of accompanying dune chronologies.

1. Introduction

Topography is a fundamental control on the transportation and deposition of aeolian sediment across a range of spatial scales. At the macro-scale (tens to hundreds of kilometers), topography influences the distribution of sand seas (e.g. Wilson, 1973), as well as dune fields that develop within aeolian sediment transport pathways steered by macro-scale landscape structures. Well-known examples of the latter occur in the Basin and Range landscapes of the southwest USA (Zimbelman et al., 1995; Kocurek and Lancaster, 1999; Muhs et al., 2017). Topography also controls the distribution and form of individual landforms at the micro scale (metres to tens of metres), as obstacles and vegetation induce local wind deceleration, acceleration, deflection and blocking (Howard, 1985; Hesse, 2019). Several types of topographically controlled dune form result. Sand transported onto the windward face of an obstacle can form a climbing dune (White and Tsoar, 1998; Lui et al., 1999; Dong et al., 2018) or, if the windward face of the obstacle is steeper than ~50°, an echo dune (Tsoar, 1983; Lui et al., 1999; Clemmensen et al., 1997; Qian et al., 2011). Falling dunes form on lee slopes of obstacles (Ellwein et al., 2015), while lee dunes develop downwind of gaps between obstacles (e.g. Xiao et al., 2015).

At intermediate (*meso*) scales – hundreds of metres to several kilometers – aeolian sands may coalescence against mountain fronts forming sand ramps (Lancaster and Tchakerian, 1996; Bertram, 2003; Rowell et al., 2018a). In regions of high relief and topographic complexity, wider swathes of the landscape can also be variably draped in sand (e.g. Dong et al., 2018) producing an array of individual bedforms, as well as more subtle, coalesced or composite aeolian landforms. In South Africa, for example, Telfer et al. (2014) observed that although well-defined

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sand ramps occurred against larger mountains, a less easily delineated aeolian sediment cover mantled much of the landscape, rather like a coversand (e.g. Kocurek and Nielson, 1986). In other studies, valleys have been identified as influencing both upwind and downwind wind velocity and turbulence (Bullard and Nash, 2000; Bourke et al., 2004; Garvey et al., 2005; Ellwein et al., 2011, 2015). Ellwein et al. (2015) observed that valley topography also traps aeolian sand, variously forming falling dunes, pairs of falling and climbing dunes, or in locales where sediment supply is high, coalesced “aeolian valley-fills”. Thus at the meso-scale we might anticipate that adjacent, repeated and nested aeolian deposits can develop, with sand occurrence and thicknesses varying significantly in response to topographically-induced changes in wind direction and velocity. The valley fill examples above illustrate that topography also provides the space for aeolian sand to accumulate. The term ‘accommodation space’ describes locales where aeolian sediment transport capacity is reduced and net sediment accumulation occurs. Topography frequently presents such opportunities and in this respect can be considered as a fundamental control influencing sand accumulation from micro (e.g. Ventra et al., 2017) to macro (e.g. Dong et al., 2018) scales.

At *meso* scales and over long timescales (e.g. 10^2–10^5 years) the location and availability of accommodation spaces will vary in response to changing wind regime or the effectiveness of processes opposing aeolian landform development and preservation. The latter are governed by the underlying topography, for example, overland flow (Ventra et al., 2017). Furthermore, aeolian landforms that partially or completely fill their accommodation spaces (e.g. Bateman et al., 2012; Rowell et al., 2018a) effectively become the topography and will in turn alter the operation of other processes, such as the potential to generate surface run off (Ellwein et al., 2015).

The state of an aeolian sediment accommodation space is thus conceived as emerging from the continuous interaction between wind flow, topography and the balance between sediment supply and competing erosive processes. The latter factors are sensitive to wider climate change, while erosive processes themselves are also influenced by topography. We can anticipate that the changing balance of these factors will lead to the repeated formation, reworking, destruction of aeolian landforms (Ventra et al., 2017). Thus, when using topographically-controlled dunes as palaeoenvironmental archives (e.g. Bateman et al., 2012; Rowell et al., 2018b; Paichoon, 2020; Schaetzl et al., 2018), or in more general interpretations of the aeolian geomorphic history, an understanding of the dynamic creation and preservation constraints imposed by topography is required.

This study considers how we achieve an understanding of such potentially complex scenarios, beginning with a more general question and aim: how can we characterise and understand the *meso* scale (10^2–10^3 m) patterns of aeolian sediment accumulation within landscapes of topographic complexity? To address this we sought to develop a novel approach that considers how the character of a variable and partly continuous distribution of aeolian sand can be related in a semi-quantitative manner to the underlying topography. We applied an automated morphometric feature classification method – the LandSerf GIS (Wood, 1996) – to a high relief, topographically-complex desert landscape, which we then combined with remote sensing-derived sand cover distributions. The relationship between the distribution of sand cover and topography, as represented by morphometric feature class, was established by combining these datasets, and the resulting outputs were further integrated with field observations. This approach allowed us to consider the occurrence of sand in relation to landscape form and in the context of existing classifications of meso-scale topographic dune forms.

2. Methodology

2.1. Regional setting

The Mojave Desert, California, is characterised by broad, flat basins separated by mountainous topography. It is a region in which the role of topography in shaping aeolian geomorphology is long recognised, with some basins identified as source-to-sink aeolian transport corridors flanked by topographic dunes (Evans, 1962; Smith, 1984; Lancaster and Tchakerian, 1996). The emplacement timings, morphologies (e.g. Lancaster, 1994; Tchakerian, 1991; Clarke and Rendell, 1998) and sediment sources (Kocurek and Lancaster, 1999; Ramsey et al., 1999; Pease and Tchakerian, 2003; Muhs et al., 2017) of some of these dunes have been investigated, and the importance of aeolian-fluvial-lacustrine interactions highlighted (Lancaster and Tchakerian, 2003). The Pleistocene palaeoenvironmental history of the region is also well-studied. Although the contemporary climate is semi-arid, it was markedly cooler and wetter during the Late Pleistocene, resulting in perennial flow of the Mojave River and the maintenance of several palaeo-lake systems (inter alia; Wells et al., 2003; Enzel et al., 2003).

The Cady Mountains (Fig. 1) provide our case study for a region of complex topography within a landscape associated with recent and Pleistocene aeolian activity (Smith, 1984; Zimbelman et al., 1995; Laity, 1992). Today the area experiences a semi-arid climate, with cool winters and warm summers. Mean annual precipitation is ≤150 mm yr^{-1} and annual evaporation is around 2000 mm yr^{-1} (Blaney, 1957; Enzel, 1992; Muhs et al., 2017). Precipitation is associated with cool season frontal systems (approximately 60% of rainfall) or summer convective systems (approximately 40% of rainfall (Hay, 2018)). Winds, particularly those of sufficient velocities to transport sand, are dominantly from the west, with subordinate northerly and southerly winds associated with the winter and summer (Laity, 1992; Muhs et al., 2017).

The Cady Mountains are located 50 km east of Barstow and form a mountain block approximately 25 km × 35 km, which lies on the southern and eastern margins of (palaeo) Lake Manix (Fig. 1). It has been proposed that the former lake sediments of the Manix Basin, notably those upwind of the Cady Mountains in the Manix Fan-Delta area, became available for transportation into the Cady Mountains via westerly

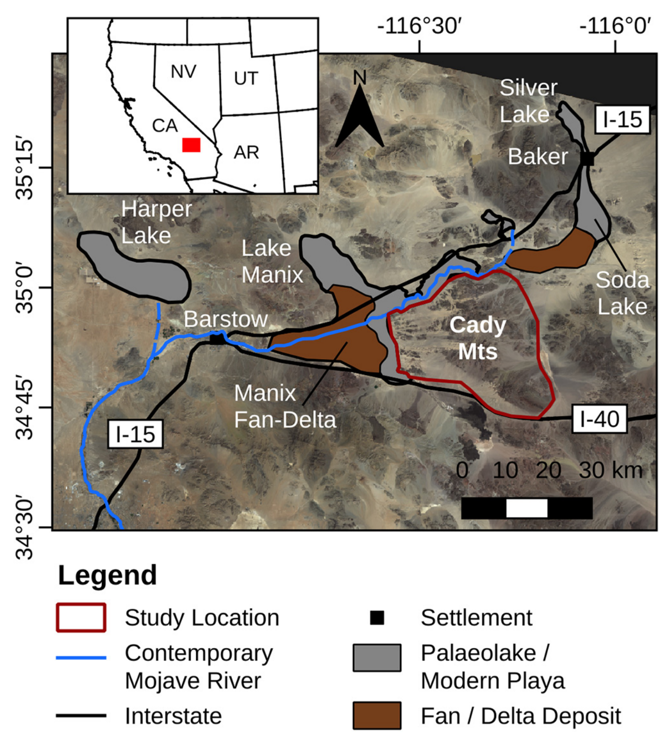

Fig. 1. Location map and satellite image for the Cady Mountains, within the southwest USA, showing the location of the Cady Mountain Block in relation to the Mojave River, palaeo-Lake Manix, Soda and Silver Lakes, which in the past formed palaeo-Lake Mojave, as well as Harper Lake Basin. Also shown is the approximate location of the Lake Manix fan delta, a putative sediment source for the Cady Mountain aeolian deposits. Landsat-8 image courtesy of the U.S. Geological Survey. Map data from OpenStreetMap contributors.

winds after Lake Manix drained ~25 ka (Meek, 1989; Reheis and Redwine, 2008; Laity, 1992; Bateman et al., 2012). Such inferences are in part based on studies of the sand ramp at Soldier Mountain, which lies in the northwest corner of the Cady Mountains (Lancaster and Tchakerian, 1996; Rendell and Sheffer, 1996; Bateman et al., 2012). The widespread occurrence of surficial sands and ventifacts (Laity, 1992) on the windward (western) side of the Cady Mountains, as well as the potential constraints on past changes in sediment availability inferred from the draining of Lake Manix, allow us use this locale as a case study to explore the patterns of aeolian sediment emplacement across a complex landscape.

2.2. Remote sensing of sand cover distribution

A cloud-free Landsat 8 image was acquired by the USGS (via http://earthexplorer.usgs.gov) on 27th September 2013 at 18:24 GMT. The spectral influence of vegetation is insignificant (Hay, 2018). A 30 m-resolution land cover classification was obtained in ERDAS Imagine 2013 using the Eolian Mapping Index (EMI) (Khiry, 2007) as a false-colour composite (for details see Hay, 2018). This classification distinguished the principal land cover types: (1) Sand Cover, (2) Stone-Covered Sands, (3) Rock Surfaces and (4) Other Land Covers (0.1% of image, principally vegetation). Capitalisation of these terms henceforth signifies reference to the classification outputs. Reference data, acquired via field survey, geotagged photographs and detailed Google Earth imagery, were used as training data (46 areas each of at least 50 pixels) for the classifier and for accuracy assessment (an Error Matrix verified with reference land cover at 267 points). To allow for the location error on the Global Navigation Satellite System (GNSS) (approximately 30 m), the reference data and land cover classification were considered to agree if the reference data at each location matched more than half of the pixels within a 3 × 3 window centred on that location. The classified image had an overall accuracy of 87%. The "Other Land Covers" class was removed from subsequent analyses as it accounted for a negligible proportion (0.1%) of the image and was mostly present as an area of high elevation vegetation. Field observations confirmed that the Sand Cover and Stone-Covered Sand classes represent accumulated sediment surfaces, and that the latter largely comprises a lag surface (pavement) of clasts overlying deposits volumetrically dominated by sands (Fig. S1). The Rock Surface class represents unmodified topography comprising largely un-weathered bedrock sometimes covered by a thin mantle of weathered material.

2.3. Mapping surface morphometry

2.3.1. Data sources and processing

The Digital Elevation Model (DEM) obtained from the USGS National Elevation Dataset (https://nationalmap.gov/elevation.html) was sub-setted and re-sampled to the same coverage, spatial reference and spatial resolution (30 m) as the Landsat 8 image. This was defined to include the Cady Mountains, but not the Mojave River, adjacent playa surfaces or areas of human influence (Fig. 1).

2.3.2. Morphometric parameter determination

LandSerf was used to classify the landscape morphometry following Wood (1996, 2009a, 2009b). Morphometric analysis of the DEM rests on comparing each pixel with those adjacent to it using a user-selected grid (e.g. the parameter slope is derived from elevation change across a three-by-three grid). The size of the grid from which morphometric parameters are obtained, termed the "window-size", can be varied with the scale of analysis required. This recognises that both morphometric parameters and features are scale-dependent and nested within the landscape (see Wood, 1996; Fisher et al., 2004; Drăguţ and Eisank, 2011).

The LandSerf feature classification is established using a bi-quadratic polynomial approximation of the surface across a specified range of window sizes and is achieved by establishing the rate of change of three orthogonal components (plan curvature, profile curvature and slope) (Wood, 1996, 2009a, 2009b). LandSerf then classifies the landscape into six morphometric classes; Passes, Peaks, Plains, Ridges, Slopes and Valleys (Fig. 2). As with the land cover classification we henceforth capitalise these terms to clarify when we are referring to LandSerf-derived morphometric classes. The Plain morphometric class is reserved for flat or undulating surfaces lacking significant hills or depressions and needs to be distinguished from the Slope class (e.g. hillslopes or piedmont features that have a non-zero slope). As very few areas have slope gradients and plan or profile curvatures of exactly zero, a threshold of 2° slope gradient is used to distinguish between Plain and Slope. A gradient threshold is also used to define how steep a surface must be to be considered part of a Pass or Peak and then a slope curvature threshold – a dimensionless ratio that defines the concavity or convexity of a part of the landscape – is used to separate these classes (Wood, 1996, 2009a). These slope and slope curvature thresholds were set at 1° and 0.1 respectively and peaks were only classified as such where they had a relative drop to surrounding topography of more than 50 m.

The morphometry parameter slope was calculated as a continuous variable across the raster dataset but is shown as a series of classes that represent areas of shallow (2–6°), intermediate (6–11°) and steep (>11°) slopes (adapted from Miliaresis, 2001; Norini et al., 2016). Aspect was treated similarly but was presented using 16 classes of equal width. We also defined valley orientation using the long-axis azimuth of the valley floor as identified by clusters of valley pixels with a spatial extent greater than 0.5 km^2 (six pixels).

3. Results

3.1. Sensitivity to the scale of analysis

LandSerf undertakes multi-scale morphometric analyses by averaging results over a range of window-sizes (Wood, 1996). However, unless one is seeking to undertake an explicit multi-scale analysis, the choice of window size range used for the final morphometric classification must be commensurate with the scale of interest. This study is primarily concerned with the influence of the meso-scale mountain topography on patterns of aeolian sediment accumulation, which we anticipate to span length scales of the order 10^2 to 10^3 m. The effect of varying the LandSerf window size was therefore analysed by considering classifications derived from a range of different maximum window sizes, ranging from 11 × 11 to 81 × 81 pixels (Table 1 and Fig. 2). Larger window sizes tend to smooth the landscape to a greater extent, with the Valley and Ridge classes increasingly reclassified as Slope as the window size increases. This is somewhat predictable given the greater spatial averaging for larger windows. However, it is the Valley class that is the most sensitive of these classes over the chosen range of window sizes (Table 1). The Plains class is very insensitive to window size. Exemplar outputs for different window size ranges are shown in Fig. 2.

a) 11 × 11 maximum window size – this classifies the landscape features with length scales of 90–330 m. This identifies much of the small-scale topography superimposed upon the major ridges, hills and mountains, but provides poor characterisation of the larger-scale features. For example, the valley marked with a dashed rectangle on Fig. 2a is classified as a combination of Ridge, Slope and Valley classes.
b) 41 × 41 maximum window size – this allows for the representation of features with length scales between 90 m and ~ 1.2 km. This window size range represents both the overall mountain block-scale topography as well as many of the significant Valleys (e.g. those highlighted by the areas delimited by the dashed rectangle and oval in Fig. 2b) and Passes at the heads of the Valleys.
c) 71 × 71 window size – this classifies landscape features with length scales of 90 m - 2.1 km. This produces a smoothed macro-scale topography, creating a 'blocky' characterisation of the landscape with much of the meso-scale topography omitted (for example, compare the area within the dashed oval in Fig. 2c with Figs. 2a and 2b).

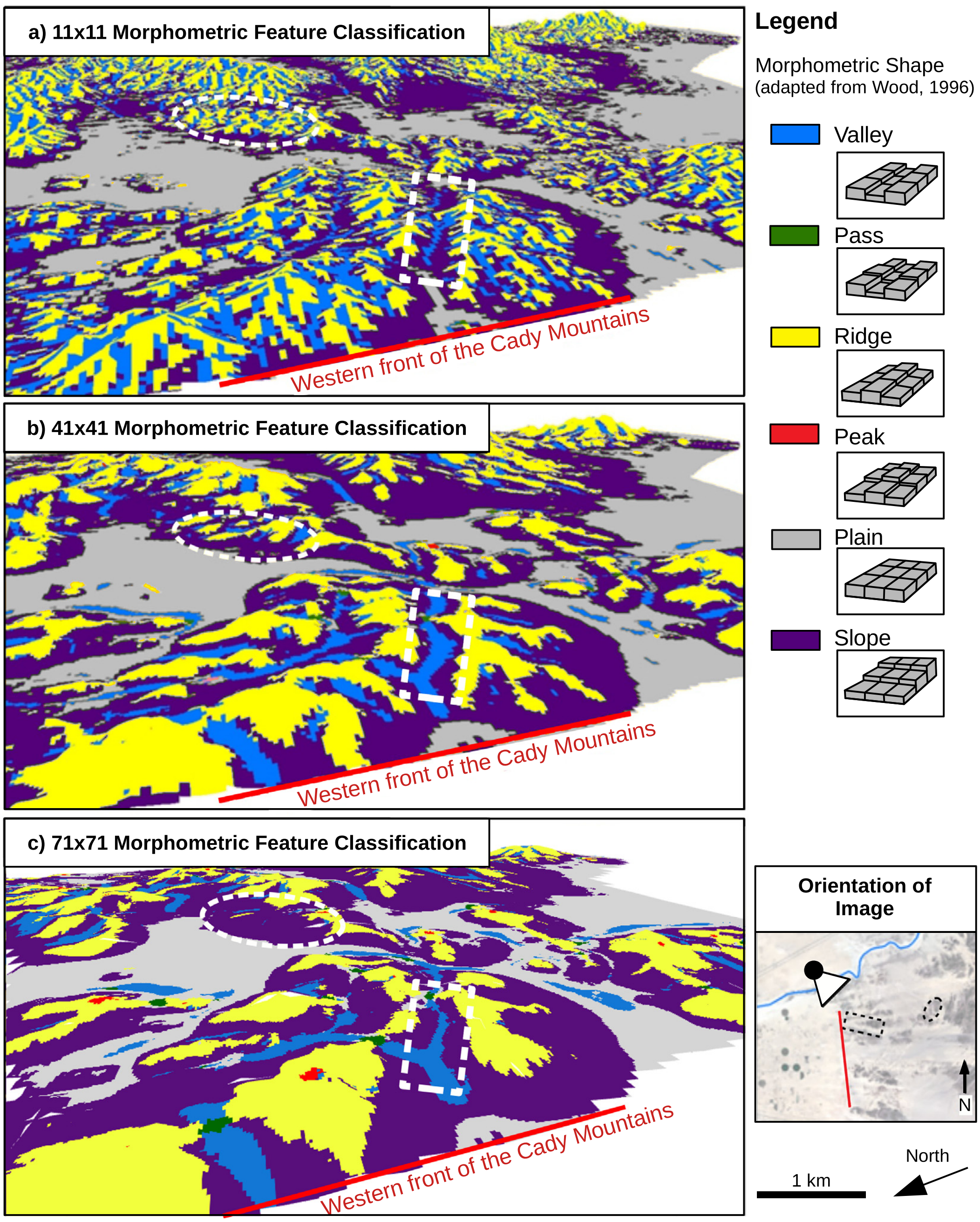

Fig. 2. Outputs of the LandSerf analyses of the Cady Mountains presented as southeast looking oblique views of the northwest Cady Mountain Block. The three panes (a-c) show morphometric classifications of the same portion of landscape using three different analysis scales (i.e. different maximum window size ranges): a) 3 × 3 to 11 × 11 pixels; b) 3 × 3 to 41 × 41 pixels; 3 × 3 to 71 × 71 pixels. Each pixel represents the most common morphometric class at the range of scales considered. The legend illustrates the six morphometric classes. The lower right-hand image shows the direction of view with an image of the wider study area, with the Mojave River in blue and the Western Flank of Cady Mountains shown in red.

The 41 × 41 maximum window size was selected for all subsequent analyses as it most appropriately maps to the largely meso-scale study focus; i.e. features with lengths up to approximately 1.2 km. Although there are to some extent predictable changes to the LandSerf output when a wider range of window sizes is utilised, at the scale of interest small changes in the window size (e.g. 37 × 37 or 45 × 45 maximum window sizes) result in less than 5% variation in individual pixel classifications and would not change the conclusions drawn.

3.2. Cady Mountain land cover, elevation and morphometry

Fig. 3a shows the mountain block topography comprises a large central peak rising to 1390 m asl. (Point A; Fig. 3a) with two smaller peak networks of lower altitude (about 1000 m asl.) to the north and south (Points B and C in Fig. 3a). The western margin of the mountain block comprises a row of smaller (about 800 m asl.) north-south trending peaks that border the former Lake Manix at 550 m asl. (Point D in Fig. 3A) hereafter referred to as the Western Flank.

Fig. 3b shows the distribution of the three land cover classes. Most of the landscape comprises Rock Surfaces, with Stone-Covered Sands covering 28%, and Sand Cover representing 12% of the landscape. The distribution of land cover classes is non-random (Tables S1 to S5). The majority of pixels in the Sand Cover and Stone-Covered Sand classes lie west of 116° 18′ W and north of 34° 50′ N. Combined, they form a broadly continuous surface that covers a large expanse of the western

Table 1
The effect of LandSerf on window size morphometric classification outputs (as percentages of the total land surface). These are the maximum sizes for a range of window sizes beginning at 3 × 3 pixels (90 × 90 m).

Maximum Window Size (pixels)	Maximum window size (metres)	Plain	Slope	Peak	Ridge	Pass	Valley
11 × 11	330 × 330	20.3	38.1	0.0	21.9	0.1	19.1
21 × 21	630 × 630	20.2	40.9	0.0	21.8	0.1	16.5
31 × 31	930 × 930	20.4	45.5	0.0	19.9	0.1	13.5
37 × 37	1110 × 1110	20.3	46.5	0.0	19.7	0.2	12.8
41 × 41	1230 × 1230	20.3	47.4	0.0	19.4	0.2	12.2
45 × 45	1350 × 1350	20.3	48.2	0.1	19.1	0.2	11.6
51 × 51	1530 × 1530	20.4	49.8	0.1	18.4	0.2	10.6
61 × 61	1830 × 1830	20.5	51.1	0.1	17.8	0.2	9.8
67 × 67	2010 × 2010	20.6	52.3	0.1	17.2	0.3	9.0
71 × 71	2130 × 2130	20.7	52.7	0.1	17.0	0.3	8.7
81 × 81	2430 × 2430	20.8	53.6	0.1	16.7	0.3	8.0
Average		20.4 ± 0.2	47.8 ± 4.9	0.1 ± 0.1	19 ± 1.8	0.2 ± 0.1	12 ± 3.4

half of the mountain block (Fig. 3b). Conversely, the eastern flank of the mountain block is less sandy. Fig. 3c shows the output of the LandSerf morphometric feature classification.

3.3. Relationships between sand cover, elevation and morphometry

The overall distribution of elevation varies between 388 m asl and 1390 m asl, with most of the landscape located between 550 m asl and 800 m asl (Fig. 4a). In terms of slope aspect (slopes here considered generically, not in terms of the morphometric classification) there is a dominance of north-facing through east-facing and southwest-facing slopes (Fig. 4b). Most of the mountain block comprises gentle slopes, with a mode of approximately 2.5° and limited areas with slope gradients <1° or >6° (Fig. 4c).

The proportion of the landscape in each morphometric feature class is shown in Fig. 4d. Slope is the most common morphometric class (47% of the landscape), with Plain and Ridge the second and third most extensive, accounting for 20% and 19% of the landscape respectively. Peaks and Passes are the least common (0.02% of the total landscape combined). The distribution of Valley orientations is shown Fig. 4b, with Valley long axes tending to be north or east facing (i.e. 52.2% combined).

In terms of land cover, Sand Cover is principally located at elevations between 550 m asl. and 1100 m asl., where it covers 10% to 40% of the landscape, reaching its highest percentage coverage by elevation (~60%) at 820 m asl (Fig. 4a). This compares with coverages between 0% and 30% above ~820 m. Stone-Covered Sand is typically found at elevations less than 800 m asl, accounting for about 40% of land cover at such elevations, dropping to around 5% cover above 800 m asl. Rock Surfaces are under-represented (15–35%) at intermediate elevations and dominant (>80%) above 1000 m asl.

Fig. 4b demonstrates that Sand Cover is preferentially associated with west- and southwest-facing slopes. This forms several contiguous west-facing areas in the western and central portions of the mountain block (Figs. 3b and 4b). Stone-Covered Sand has a broader aspect distribution, with a mode between south-west and north-west facing slopes and another mode relating to east-south-east facing slopes. Correspondingly, much of the Rock Surface class is associated with north and east-facing slopes, particularly on the eastern side of the mountain block (Fig. 3b and 4b).

Both Sand Cover and Stone-Covered Sands are preferentially associated with low angled surfaces (>80% of areas <2° slope angle; Fig. 4c). On surfaces between 2 and 6°, Sand Cover remains at 15–20% of land cover, while Stone-Covered Sand decreases to around 20%. The Rock Surface class becomes the dominant (i.e. >50%) class for surfaces steeper than 2°.

Comparing against the morphometric classification (Fig. 4d), we observe that Sand Cover is approximately equally represented across the six morphometric classes (Plains (14%), Slopes (13%), Passes (12%) and Valleys (12%) and Peaks (11%)), except for Ridges (7%). These values compare to an overall Sand Cover of ~12% for the total landscape. Stone-Covered Sand represents 28% of the total landscape, but is over-represented on Plains (58%), Passes (30%) and Slopes (25%), and under-represented for Valleys (13%), Ridges (8%) and Peaks (8%). Extensive Stone-Covered Sand Plains are present across the western half of the mountain block and along its eastern boundary (Figs. 3b and 4b). Compared with a total Rock Surface cover of 60%, Rock Surfaces are primarily represented by Ridges (84%), Peaks (80%), Valleys (74%) and on Slopes (64%) and are less represented on Plains (26%). Valleys are preferentially classified as Rock Surfaces (74%; Fig. 4d). However, Valleys associated with Sand Cover and Stone-Covered Sand are observed in the northwest of the Cady Mountains, and particularly in north-westerly orientated valleys (Fig. 3b).

Overall, we observe that the distribution of Sand Cover with the Cady Mountains is related to the landscape morphometry and aspect. Sand Cover and Stone-Covered sand are primarily associated with the Plain, Slope and Pass morphometric classes, as well as NW aligned Valleys. They are less associated with Ridges and Peaks and non-NW aligned Valleys. The two sand-containing land cover classes are not randomly distributed (Tables S1-S5), and are preferentially clustered on west-facing, low-angled surfaces (Fig. 4c) across low to intermediate elevations (500–800 m asl; Fig. 4a) and are disproportionately associated (Chi-squared $p \leq 0.01$ in all cases; Tables S1-S5) with Plains, Slopes and Passes (Fig. 4d and Table S4).

3.4. Field observations

This section elaborates on how the analyses of land cover and morphometry relate to field observations and the character of previously described topographic dune classes.

3.4.1. Slope Class

A previously studied exemplar of sand accumulation within the Slope class is the Soldier Mountain site (Fig. 5), on the Western Flank of the Cady Mountain Block (Lancaster and Tchakerian, 1996). Here the Slope class forms a piedmont between the Ridge (Rock Surface) to the east and a sandy plain (including the Lake Manix fan delta area – not part of the morphometric analysis; Fig. 2) to the west. In detail, the LandSerf output shows the Slope and associated Sand Cover lie within an embayment closely defined by the plan-form geometry of a Rock Surface Ridge (Fig. 5). On the Slope, Sand Cover and Stone-Covered Sand form the surface materials of area approximately 0.5 km^2, with an east-west gradient of 5–7° and a vertical range of ~130 m (Fig. 5). Observed in the field, the Stone-Covered Sand forms a weakly developed desert pavement (Bateman et al., 2012). The transition between the Sand Cover or Stone-Covered Sand Slope and the Rock Surface Ridge is marked by incisions, notably on the southern margin, which can be traced to incisions within the Ridge (Figs. 5 and S2).

The internal composition of the Slope is clarified by a quarry to the north of the site. This reveals a mixed sand, gravel and boulder composition, estimated to comprise approximately 16% fluvial, debris-flow and non-aeolian sediments (Lancaster and Tchakerian, 1996; Fig. S2). Thus, in this case the Slope is formed predominantly of the aeolian sediment and compositionally is akin to a sand ramp (Lancaster and Tchakerian, 1996; Bateman et al., 2012). While this site lies on the Western Flank of the mountain front, several comparable features lacking exposed sedimentary sections can be identified within the Mountain Block itself (Figs. S6 and S7).

3.4.2. Plains Class

Extensive Sand cover associated with the Plain class is exemplified by an area about 8 km east of the Western Flank (Fig. 6). This

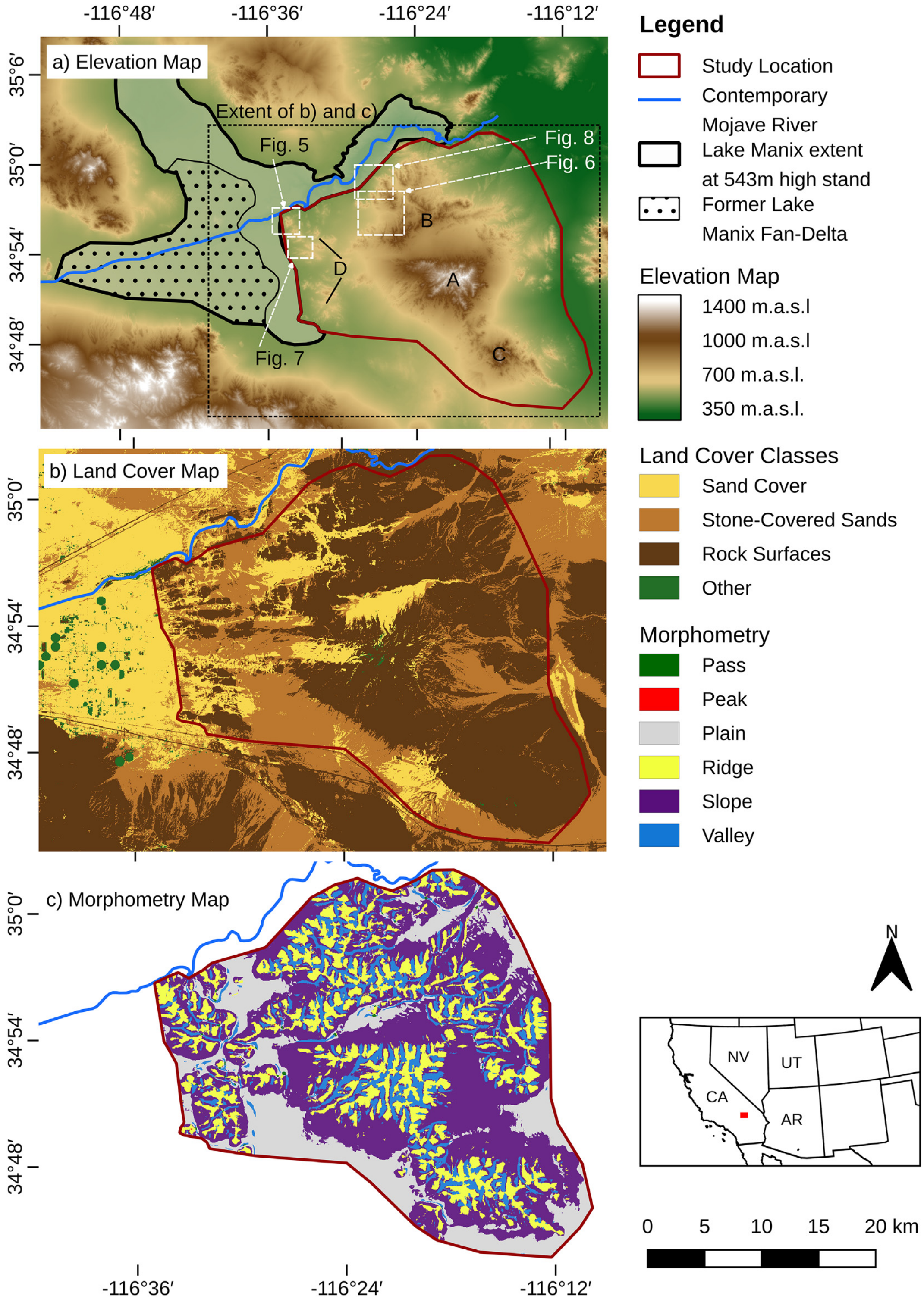

Fig. 3. (a) Elevation (b) Land cover and (c) LandSerf morphometry maps (maximum window size 41 × 41 pixels) for the Cady Mountains. Elevation Data (The National Map) courtesy of the U.S. Geological Survey. Map data from OpenStreetMap contributors.

comprises a broad, flat (<2°) Sand Plain (10 km^2). Along its northerly and southerly borders, the Plain class transitions to Slope and then, with increasing altitude, to Ridge, with the surface cover commensurately grading from Sand Cover, to Stone-Covered Sand to Rock Surface (Fig. 6). The contemporary surface of the Sand Cover on the Plain undulates over scales of <2 m but is devoid of bedforms. At least 2.5 m of structureless sand with occasional stone lines has accumulated (Hay, 2018), while the exposed roots seen for much of the shrubby (Creosote Bush) vegetation attests to recent deflation (Fig. S3).

In contrast to Soldier Mountain, the transition from Sand Cover to the surrounding (Rock Surface) landscape is gradual. In fact, the limits of the feature (in terms of morphometry) are arbitrary as the transition from Plain to Slope is defined by the 2° threshold (Fig. 6). The limits of the Plain morphometric class are not obviously morphometrically defined, but as at Soldier Mountain, they are accompanied by a transition in

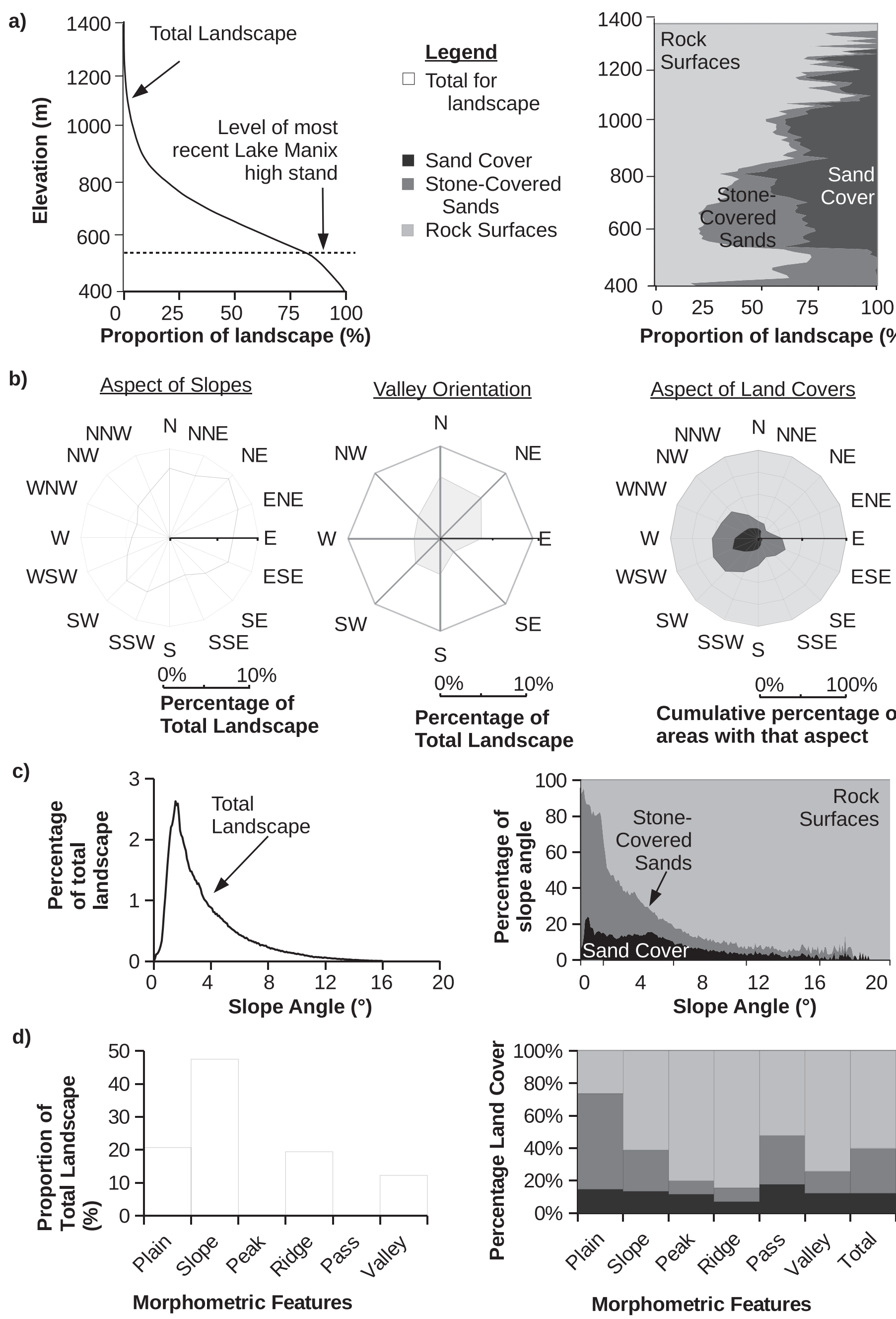

Fig. 4. Summary statistics of elevation, aspect, slope angle and morphometric classes. The four rows represent (a) Elevation - showing the hypsometric curve (left) for the Cady Mountains, noting the level of the most recent Lake Manix high stand and the distribution of land cover with elevation (right) within the Cady Mountains; (b) Aspect - presenting slope aspects (for all slopes >2°(left)), Valley orientations (centre) and the percentage land cover for differing slope angles (right); (c) Slope angle - presenting the distribution of slope angles (left) and the relationship between slope angle and land cover class - that is, proportion of land cover class at any given slope angle (right); (d) Morphometry - presenting the six morphometric classes in terms of total land area (left) and in terms of land cover (right). Percentages are stacked to sum to 100%.

surface materials. The transition from Sand Cover to Stone-Covered Sands on the southern and western boundaries (Fig. 6) implies contribution of clasts from a Rock Surface sediment source. Additional examples of Sand Cover associated with the Plains class are seen to the south of the example described here, and in the central Cady Mountains (Fig. 3).

3.4.3. Valley Class

An example of Valley morphometric class lies along the Western Flank of the Cady Mountains, immediately south of Soldier Mountain (Fig. 7). This represents the relatively unusual situation of significant Sand Cover within the Valley class, linked to the Pass morphometric class. The Valley has a long-axis azimuth of ~275°, is about 2 km long and 1 km wide and narrows towards two Passes at its uppermost points. The elevation ranges from 550 m asl to 700 m asl with the uppermost 50 m of the Valley associated with a Rock Surface. The Valley has a concave low-angle long axis profile (3–5°). The Valley is about 2 km^2, of which 1.8 km^2 is either Sand Cover or Stone-Covered Sands. The Sand is incised along the centreline of the valley (Fig. 7), exposing >3 m of well-sorted medium-grained structure-less sands (largely without clasts cf. Soldier Mountain). The Valley Sand Cover is bordered on three sides by Rock Surface, although the true extent is dependent on where the western border is inferred. The highest

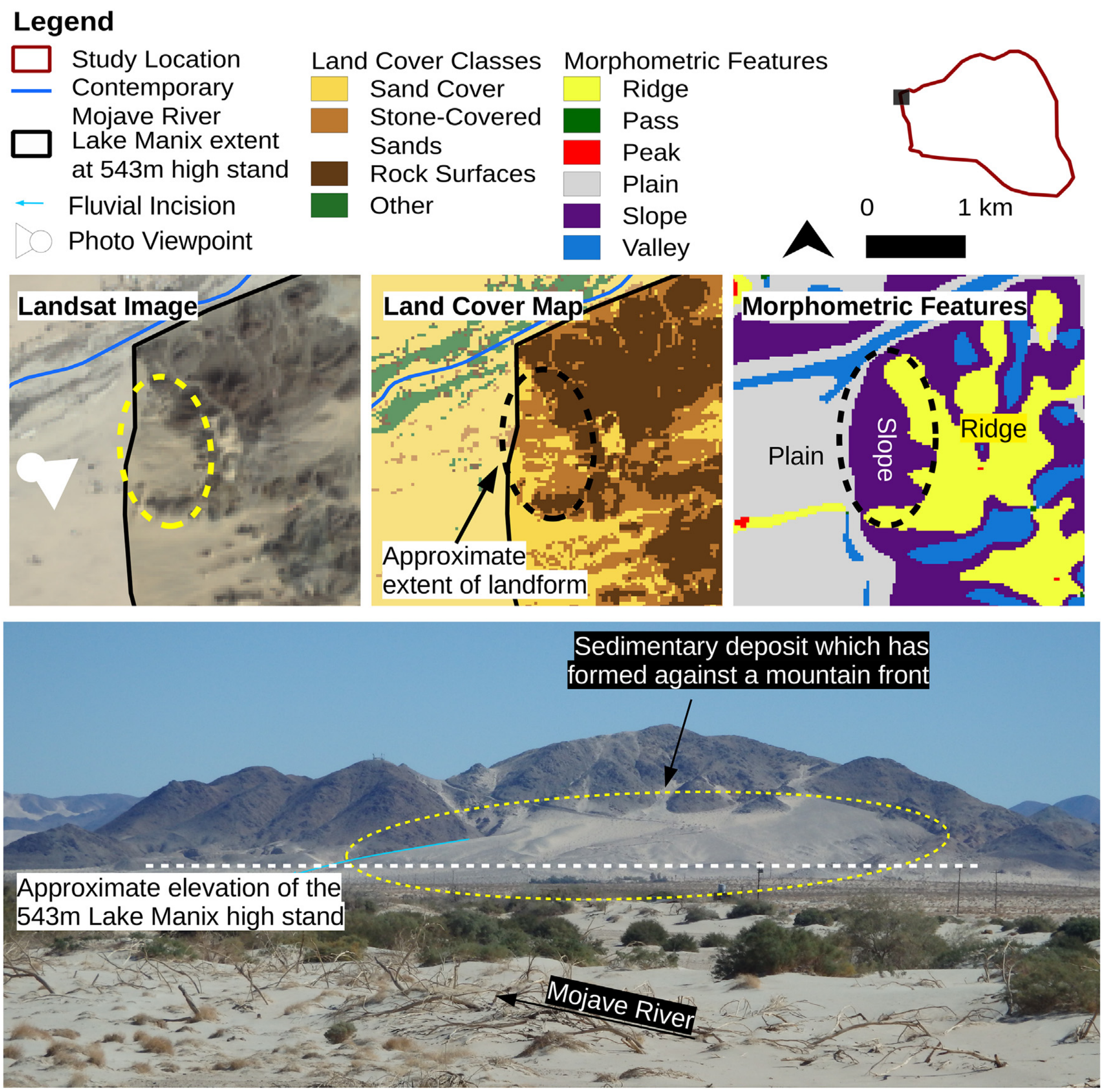

Fig. 5. Land cover, morphometric feature class output and a ground-based image of Soldier Mountain. This locale represents an archetype of the Slope accommodation space type, characterised by an embayed Rock Surface Ridge (land cover and feature class respectively). The deposit itself is relatively un-dissected and is characterised by a mixture of Sand Cover and Stone-Covered Sand. The elevation range from the Lake Manix high stand to the upper limit of sand occurrence is ~130 m. Landsat-8 image courtesy of the U.S. Geological Survey. See also Fig. S2.

points of the Valley adjacent to the Passes are largely devoid of sand, although the cover is varied and the transitions abrupt in places (Fig. S4). The Pass is associated with significant quantities of W-E orientated ventifacted stones, implying transport without accumulation (Laity, 1992; Fig. 7).

3.4.4. Composite

Field observations also identified more complex situations that illustrate the challenges of this analysis approach. In these cases, we observed the close juxtaposition of the Slope and Valley morphometric classes, exemplified on the northern margins of the Cady Mountains, where we identify the Slope-Valley composite as a locale associated with significant Sand Cover (Fig. 8). Here the Sand Cover associated Valley class emerges from the mountain block, and is partially incised into a near continuous Sand and Stone-Covered Sand Slope. The Slope comprises a low-angle concave Stone Covered Sand and Sand Cover surface (3 km^2) extending from the mountain front, decreasing in gradient from about 5° near the mountain front to around 2° at the Mojave River. The Slope unit is bounded on its southern and eastern sides by the Rock Surface Ridges of the mountain block, with Sand extending into five N-S orientated valleys. The break of slope between the Slope unit and Rock Surface Ridges tends to be associated with Sand Cover. The Slope is incised by several channels, which reveal at least 15 m of sands (Fig. S5) interbedded with gravel and sandy-gravel. The Sand Cover and Stone-Covered sand surfaces extend up the Valleys, occasionally reaching a Pass. Sedimentary exposure indicates that they vary substantially in their volumetric sand and gravel contents (Fig. 8 and Fig. S5).

3.5. Synthesis

From these observations, and by combining the morphometry of landform surfaces and their immediate topographic geometry, three zones of preferential sand accumulation within this topographically complex environment are proposed. Henceforth, we refer to these as *accommodation space types* (Fig. 9). The Plain accommodation space type is defined by a flat (or near-flat) Sand Cover surface without significant adjacent topography. These occur *within* the mountain block in several locations (Fig. 3); 2) The Slope accommodation space type represents Sand and Stone-Covered sand that has accumulated *onto* (and partly forms) a

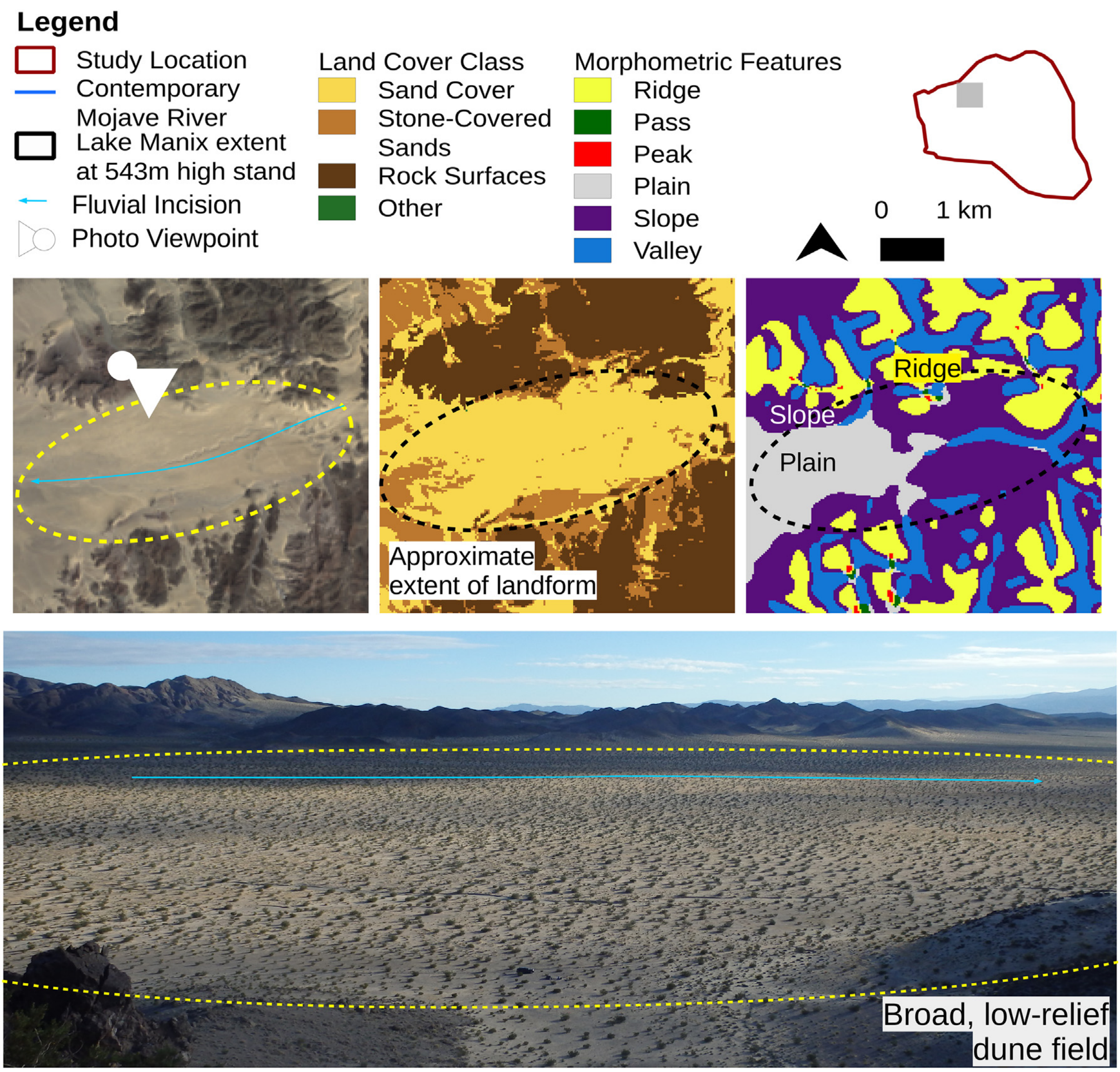

Fig. 6. Land cover, morphometric feature class output and a ground-based image for an exemplar of the Plains morphometric class. Here at least 2.5 m of Sand Cover has accumulated upon a broad and open Plain. The landscape is un-dissected and lacks aeolian bedforms. Note that the transition from Plain to Slope in the morphometric classification is arbitrarily defined (2°) (see text). See also Fig. S3. Landsat-8 image courtesy of the U.S. Geological Survey.

Slope and is associated particularly, but not uniquely, with the northern and western Cady Mountain margins ("the Mountain Front"). Soldier Mountain falls within this class; 3) Landscapes within the Valley accommodation space type are bounded by the mountain block topography (Rock Surface). These largely occur at the margins of the mountain block, where Valleys (e.g. the Western Flank) alternate with the Slope (class (Figs. 2 and 3). A fourth composite accommodation space type is represented by the Slope-Valley composites that typify the northern Cady Mountain margins. In total, these three individual and one composite accommodation space types account for ~90% of the mapped sandy landscape (i.e. 90% of the mapped Sand and Stoney Sand cover). It should be noted that in the field sand cover also clearly varies at the micro scale, from near continuous to patchier cover, with very variable depth. This detail (e.g. Fig. S4), which occurs over scales 10^1 m, is not captured at the scale of the LandSerf analysis.

4. Discussion

Our goal was to develop a framework to consider how complex topography influences aeolian sand deposition and aeolian landform development and preservation. The combination of land cover classification, morphometric classification and field observations demonstrates that although aeolian sediment forms a broadly continuous cover across the western (windward) portion of the Cady Mountains, in relation to topography, the majority of sand-covered locales (i.e. Sand Cover and Stone-Covered Sand) are associated with three "accommodation space types" and one composite form. These account for ~90% of Sand and Stone-Covered Sand occurrence and are depicted in Fig. 9, with the likely aeolian sediment inputs and outputs (i.e. overland flow degradation) routes indicated. The next question is how such classes relate to existing aeolian landform types or classifications.

4.1. Sand ramps, climbing dunes and falling dunes

Landforms accumulating in the Slope accommodation space type are in some cases morphologically and compositionally comparable to sand ramps, as exemplified by Soldier Mountain (Lancaster and Tchakerian, 1996; Bateman et al., 2012). Its mixed composition results from the accumulation of aeolian, fluvial and sediment gravity deposits over time (Tchakerian, 1989; Bertram, 2003; Lancaster and Tchakerian, 2003; see Rowell et al., 2018a). The latter contribution relies on a proximal Rock Surface Slope. The surface land cover also reflects this mixed composition, although free dunes can be formed on these surfaces (Bateman et al., 2012; Dong et al., 2018). Within the Cady Mountains, four

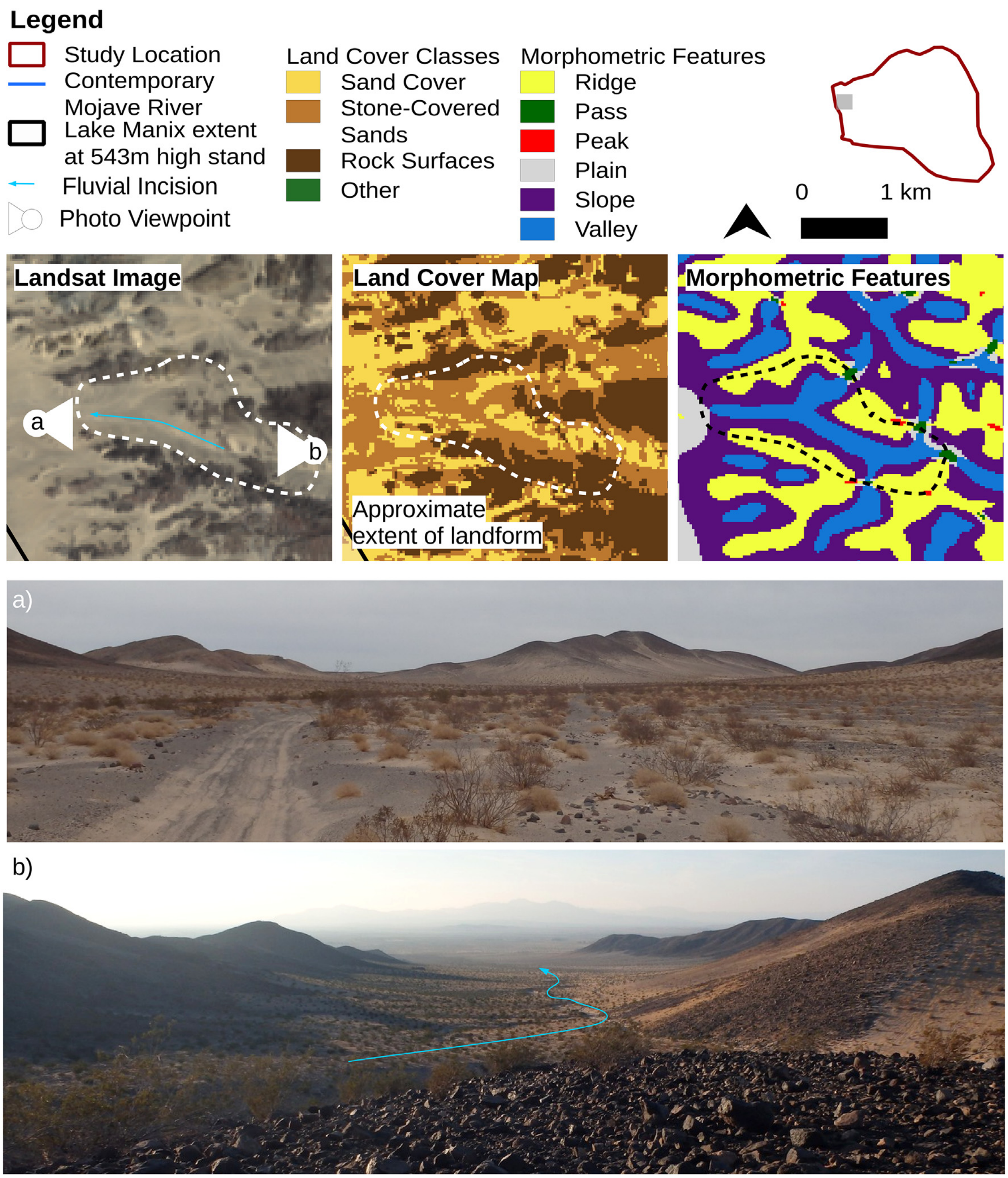

Fig. 7. Land cover, morphometric feature class output and a ground-based images of an exemplar of the Valley morphometric class. a) is a view up Valley (to the east) and b) down Valley to the west with blue line showing the approximate route of a modern channel. a) shows the Stone Covered Sand of the lower valley. In b) note the Rock Surface at the top of Valley where the clasts show evidence of E-W orientated ventifaction. An exposure through the Sand Cover is located in the middle left of b), revealing >3 m of structureless sands. See also Fig. S4. Landsat-8 image courtesy of the U.S. Geological Survey.

exemplars are identified. Two, Soldier Mountain and the East Ramp, are well defined features, whose lateral extents are well (Soldier Mountain; Fig. 5) and somewhat (East Ramp; Fig. S6) defined by surrounding Rock Surfaces and the Ridge morphometric class. Two are less defined by a surrounding Rock Surface, and grade laterally to low-angle sand covered Plains (Middle Cady and Cady Peak; Figs. S7 and S8). Except for Solider Mountain these examples occur *within* the Cady Mountain block, demonstrating that aeolian sediment accumulation on Slopes, and the creation of sand ramp-like forms, is not exclusive to the mountain front piedmont zone, which given the prevailing wind direction (W to NW), is assumed to be proximal to the primary sediment source (Section 1.2). The restricted exposure of sediment at these interior sites (Hay, 2018) provides limited insight into the relative contribution of aeolian sand versus slope material and limits our ability to differentiate between climbing dunes and sand ramps (e.g. Rowell et al., 2018a).

4.2. Sand sheets

Sand sheets (Kocurek and Nielson, 1986; Warren, 2013) accumulate within the Plain accommodation space type and in all cases are found *within* the wider mountain block. Each merges gradually with adjacent Slopes and their boundaries are poorly defined. Of the three accommodation space types, these have the highest proportion of surficial sand cover (14.8% Sand Cover and about 59% Stone Covered sand). Where observed this was generally un-bedded with continuous vegetation cover. These characteristics are typical of sand sheets, although some coarse-

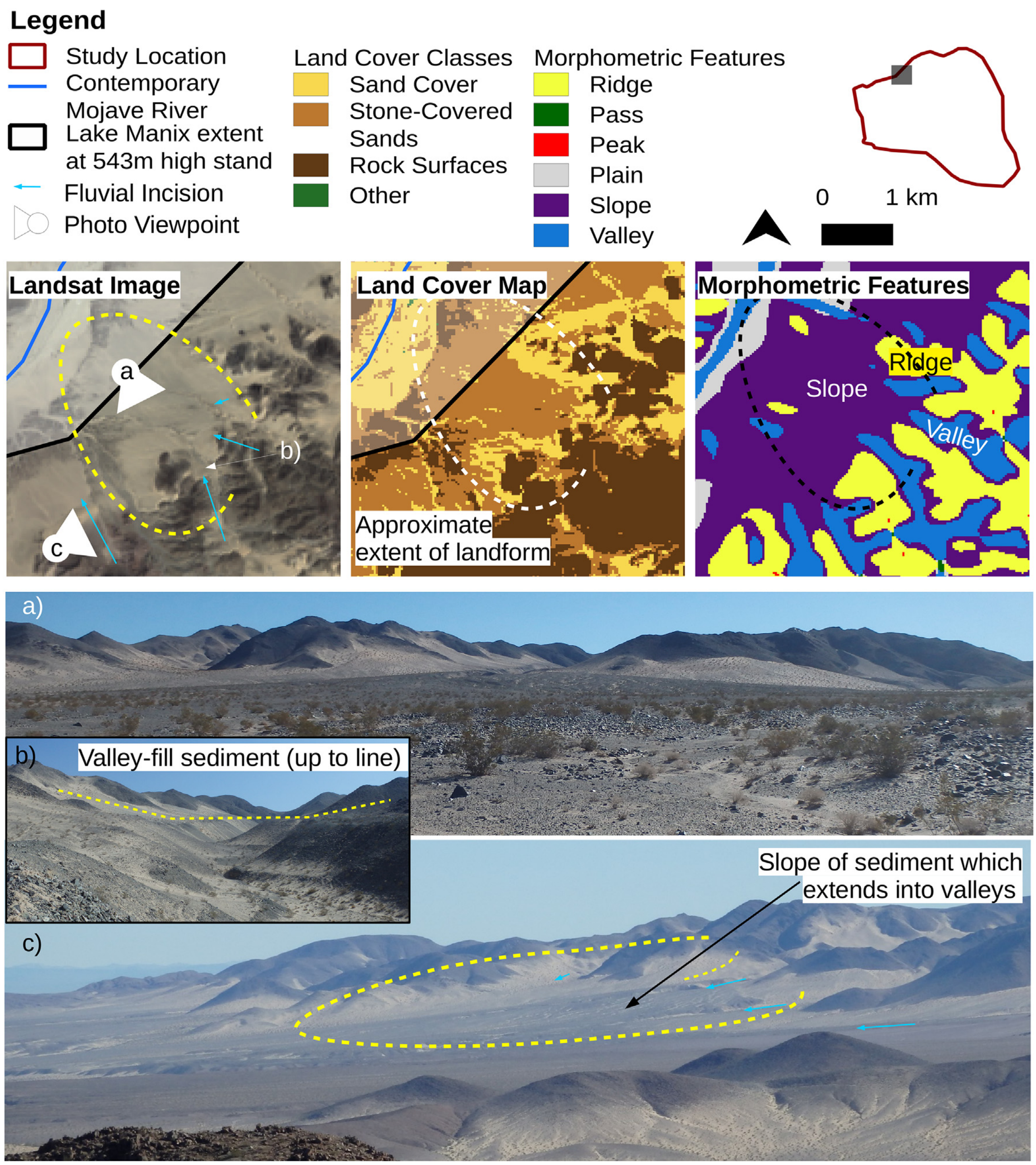

Fig. 8. Land cover, morphometric feature class output and a ground-based image of an exemplar of the "Slope-Valley composite" class. The Slope is dominated by Stone Covered Sand, which at the (limited) available exposures, is seemingly typical of the overall sediment body itself (Fig. S5). Sand and Stone Covered Sand cover also extend into the Valleys. Landsat-8 image courtesy of the U.S. Geological Survey.

grained material is incorporated as stone lines or isolated clasts (Hay, 2018). Plains are located within the mountain block interior and away from piedmonts. Given the prevailing wind direction and the probable sediment sources, their formation *within* the mountain block implies transfer of sand across Slope (mountain front) or through Valley accommodation space types. Their extensive nature and ill-defined margins reflect a gradual transition, over hundreds of metres, to steeper Slopes and a more mixed sediment composition (Fig. 7). This, and to some extent, a definition based on gradual land cover change and arbitrary slope thresholds, i.e. Slope vs. Plain morphometric classes, results in gradual rather than sharp transitions between areas of Sand Cover and Rock Surfaces.

4.3. Valley-fill

Landforms within the Valley accommodation space type are morphologically similar to Valley-Fill sediments (Ellwein et al., 2015). The composition of sediments within the Cady Mountain valley-fills, vary from relatively stone rich (see Hay, 2018) to pure sand (Fig. S4). In contrast to some descriptions of aeolian sediment trapping by valleys (Bourke et al., 2004; Ellwein et al., 2015), the Cady examples have their long axes aligned parallel to or oblique to the prevailing sand transport direction. The ventifaction seen in the Rock surfaces at their upper boundaries (Passes) shows that they act both as conduits and as stores of sandy sediment.

4.4. Composite

The composite form represents the connection of the Slope and Valley accommodation spaces. These are most clearly expressed on the northern Cady Mountains, proximal to the Mojave River, and it is noteworthy that similar forms are not identified on the Western Flank of the Cady Mountains, where the bedrock topography (i.e. alternating

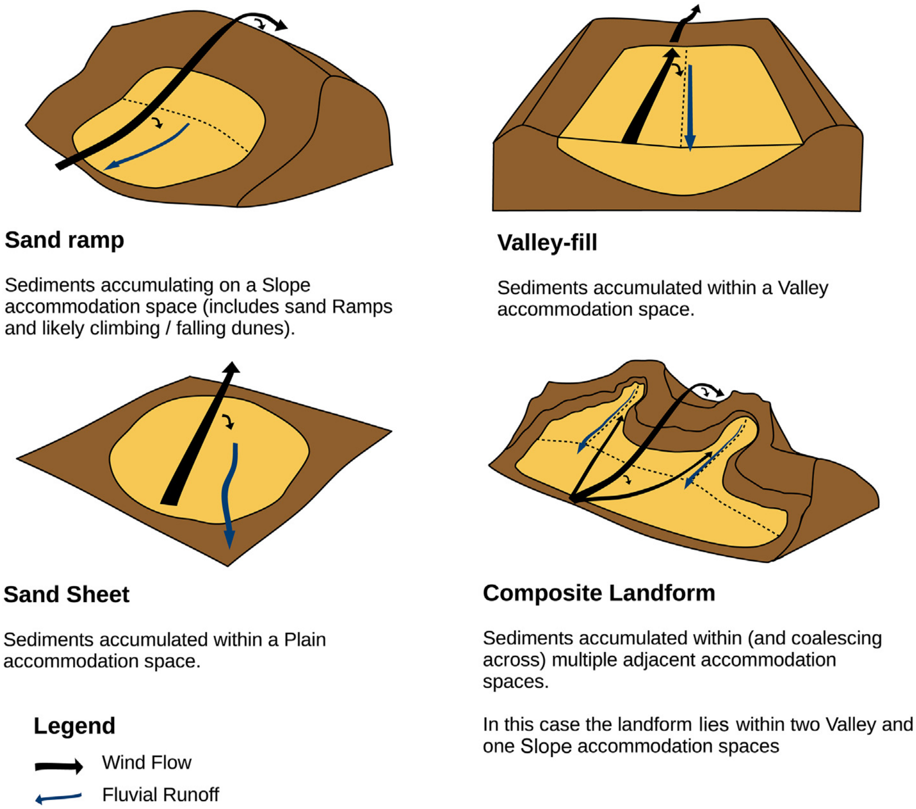

Fig. 9. Characteristic meso-scale (lengths 10^2–10^3 m) accommodation space types and landforms within the Cady Mountains. The composite class manifests as a Slope-Valley composite form. This is largely associated with the northern flank of the Cady Mountains (see also Fig. 8 and Fig. S5).

Ridges and E-W Valleys) might imply they can (could have) form(ed). In terms of its morphology and expression, the northern Cady flank is akin to the "sand ramp complexes" described around a complex inselberg by Bertram (2003). The importance of sediment supply in filling of accommodation space and then allowing coalescence is emphasised. In addition, and in contrast to the largely sandy Valley accommodation spaces on the Western Flank (Fig. 7 and also Hay, 2018), the Valley-Slope composites of the northern Cady Mountains are frequently composed of mixed sands and gravels. The degree of filling and extension of Sand Cover into the north-south orientated Valleys (Fig. S5) implies that at times sediment supply has greatly exceeded the Valley catchments' capacity to evacuate sediment. Such forms are found primarily in the areas closest to Mojave River, which presumably represents an upwind sediment source. In conjunction with their apparent incision under modern conditions (Fig. S5) the stacked sequences of sand, mixed sand gravel, and gravel within the Slope unit imply a long and complex history of sediment filling and evacuation.

4.5. Implications

Although the Cady Mountain block is a topographically complex area, this analysis suggests that four broad types of accommodation space are associated with the majority of the remotely sensed Sand Cover and Stoney Sand Cover. This provides a framework with which to consider the preserved aeolian record in this region. Some accommodation spaces have clearly delimited boundaries. The Soldier Mountain sand ramp is an exemplar, with an arcuate planform determined by a Rock Surface Ridge. Similarly, many previously described sand ramps occur against isolated inselbergs (Rowell et al., 2018a). However, Soldier Mountain and to a lesser extent the Eastern Ramp (ER; Fig. S6), are largely the exception within the Cady Mountains. By contrast, Sand Cover, and by inference, aeolian sedimentation history, is represented by a semi-continuous patchwork of accommodation space types. In some locales this is the result of the coalescence of deposits that are initially associated with discrete accommodation spaces, exemplified today on the northern Cady Mountain margin. Four factors may influence this: 1) the proximity of underlying accommodation spaces (geological control); 2) subtle or gradual changes in underlying topography (e.g. the Plain to Slope transition); 3) variation in, or proximity to, a sediment supply; 4) the preservation of sediment once within spaces.

Considering temporal aspects, it is assumed that accommodation spaces fill or degrade as the balance between aeolian sand supply and erosive capacity fluctuates. Thus, an accumulation may coalesce or divide as it grows and degrades. Progressive filling of low points has been observed, in a more subtle manner, associated with debris flow levees on steep coastal slopes in the Atacama Desert (Ventra et al., 2017). Substituting space (distance from sediment source) for time, Ellwein et al. (2015) also argued that valley fill aeolian deposits develop through progressive space-filling, whereby sand accumulates within topographic lows, increasingly masking smaller-scale topography and non-aeolian deposits in the process. This potentially enhances preservation potential as the land surface becomes sandier and more permeable. Comparable processes are operating in the Valley and Plain accommodation spaces within the Cady Mountains.

Ventra et al. (2017) argued that local-scale topographic control via the generation of surface run off is critical in controlling the long-term accumulation and preservation of topographic dune forms. Presently available dating for the Soldier Mountain sand ramp demonstrates the preservation timescale for sands within the Cady Mountain Slope accommodation space type is of the order 10^4 years (note contrasting age estimates; Rendell and Sheffer, 1996; Bateman et al., 2012). However, evidence for incision of the existing deposits, particularly in the case of the Slope and Slope-Valley composite, under modern conditions is clearly identified (Figs. 5, 7 and 8).

In this sense, we can also consider the character and drivers of the Cady Mountain aeolian sedimentary records within different accommodation spaces as, for example, one might seek to infer via a programme of luminescence dating. For example, the Plains accommodation space is, in all cases, distal to the assumed sediment source. In general, sand sheets tend to be associated with several factors, including a high water-table, periodic flooding, and the presence of vegetation (Kocurek and Nielson, 1986). Despite the relatively slow accumulation of aeolian sediment on a vegetated surface that is implied, in this context, preservation potential may be higher than Slope and Valley contexts as the accommodation space is more distant from areas of concentrated surface runoff. Conversely, in lacking significant stone cover these sands – via changing vegetation cover (e.g. Forman et al., 2006; Chase and Thomas, 2007) – are potentially more sensitive to reworking due to climatic perturbations (assuming no change in upwind sediment supply). Indeed, Ellwein et al. (2011, 2015) reported distinct suites of OSL ages for topographic dunes compared to sand sheets at Black Mesa, Arizona, with the latter inferred to represent the timing of sand stabilisation with soil development.

In the Slope and Valley accommodation space types the sediment source is more (e.g. Soldier Mountain) or less (East Ramp) proximal and in the case of the former, accumulation rates were potentially high (Bateman et al., 2012, but cf. Rendell and Sheffer, 1996). However, accumulation rates and deposit thickness are challenging to compare as the Slope and Valley accommodation spaces will almost certainly include contributions of talus from Rock Surfaces (Bateman et al., 2012). More generally, any tendency for accumulation in such contexts is tempered by the preservation-limiting factor of the surrounding Rock Surfaces, which readily generate overland flow, which will also respond to climatic changes. Thus, the controls on the accumulation and erosion balance in such contexts are potentially subtle and site specific (Ventra et al., 2017). Both Soldier Mountain and the composite Slope-Valley fills on the northern Cady Mountains margin are cut by well-developed channels, which are tied to major (geologically controlled) Valley forms.

Overall, we propose that the preserved aeolian sedimentary record, driven by fluctuations in sediment supply, availability and transport capacity will be further mediated by meso-scale topographic controls. This reflects the fact that the morphometric analysis suggests a large proportion of sand cover is associated with four meso-scale topographic contexts. The identified accommodation space types may be more or less sensitive to event-based accumulation and erosion, e.g. Slopes, or to secular changes in climatic conditions, e.g. Plains, both of which will generate characteristic "residence times" for sand in different contexts. There is potential to test such inferences by combining luminescence dating chronologies, regional palaeoclimatic information and the morphometric analyses presented here, although an obvious corollary is that a limited suite of luminescence ages would be very challenging to interpret.

A challenge to the approach outlined here is the use of a DEM based on the modern land surface, which includes the accumulated sand. In almost all instances, there is a weakly constrained thickness of sediment fill and uncertainty in the volume of the accommodation space(s). Although there is an absence of sedimentary exposure in most cases, the fill exceeds 25 m at Soldier Mountain, and 15 m on the northern margins of the Cady Mountains (Fig. S5). The degree to which this is an impediment to this mapping approach is probably site dependent. In the Cady Mountains the relief of the mountain block is far greater than that of most exposed aeolian deposits, and it is likely that the large-scale shape of the underlying topography is reasonably well represented by the DEM. Quantities of aeolian sediment sufficient to alter the morphometry are focused on piedmonts. At these locales, notably the northern and western margins of the Cady Mountains, it is likely that the contemporary surface of aeolian deposits obscures the bedrock topography, leading to an increase in the proportion of landscape morphometrically classified as Slope. The interpretation of such areas therefore needs to be supported by field observation.

5. Conclusions

Based on a combination of land cover mapping and morphometric analysis, we sought to characterise the patterns of aeolian sediment accumulation across an area of complex topography. From this we show that despite a high-relief topographically complex setting, aeolian deposits are primarily associated with three morphometric classes (and hence accommodation space types); Slope, Plain and Valley and one composite (Slope-Valley) class. Together these account for ~90% of the mapped sand cover in the study area. These broadly map to or include recognised aeolian landforms, such as sand ramps, sand sheets and valley-fills. However, most accommodation spaces lack distinct boundaries and, where sediment supply is high, composite forms develop. Whether such coalescence occurs is likely to depend upon the association of different accommodation space types (controlled by the form of the underlying bedrock) and the progressive filling of the accommodation spaces, which will be time-bounded.

Overall, we show that meso-scale topography is a clear control on the character of aeolian sediment accumulation in the Cady Mountains. Topography will mediate the residence time or climatic sensitivity of the aeolian sedimentary record through its impact on: 1) sediment storage volume, 2) potential for erosion via runoff, 3) preservation moderated via vegetation vs. moderate stone coverage and 4) sediment supply (nature of, and distance to, character of intervening topography). We hypothesise that these may generate differences in the preserved aeolian chronostratigraphic records between sites. In this instance, the most obvious differences are likely to be between downwind sand sheet deposits and upwind, more strongly Rock Surface-influenced, Slope (Mountain Front) and Valley Fill contexts.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geomorph.2021.107704.

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