Geomorphology xxx (2012) xxx–xxx

Contents lists available at SciVerse ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Decadal-scale evolution of a small dune field: Keeler Dunes, California 1944–2010

Nicholas Lancaster [a,*], Grace McCarley-Holder [b]

[a] Desert Research Institute, Reno, NV 89512, USA
[b] Great Basin Unified Air Pollution Control District, Bishop, CA 93514, USA

ARTICLE INFO

Article history:
Received 15 May 2012
Received in revised form 16 October 2012
Accepted 16 October 2012
Available online xxxx

Keywords:
Aeolian processes
Sand dunes
Dune morphometry
Historical changes
Aerial photographs
Satellite images

ABSTRACT

Aerial photographs and satellite images have been used to document the evolution of a small (<1 km^2) dunefield over the past 60–70 years. Over this period, the dunefield has undergone significant changes, including development of well defined linear and crescentic dunes from an initial small area of partially vegetated dunes, resulting in an increase in the area of the dunes by a factor of 3 since 1944. The dune field continues to expand toward the southeast but its upwind margins are now experiencing significant erosion because the sand supply is now cut off by dust control measures in the source area and transport pathway. This study provides some information on the timescales of dune development in a high-energy aeolian environment, which formerly experienced an abundant supply of sand, with rapid development of crescentic dunes over a period of 20 years. The complexity of dunefield development is also highlighted, even on decadal timescales, and the important role of episodic sediment supply in forming new generations of dunes. Periods of rapid dunefield change involving lagged input of additional sand from external sources appear to be linked to episodes of high flows in the Owens River, which is the main sediment source for the Keeler Dunes.

1. Introduction

Understanding how dune systems respond to internal and external forcing factors and changes in boundary conditions is important to evaluating their significance as a paleo-environmental proxy, as well as a part of fundamental understanding of how dune patterns emerge and change.

Conceptual models for the evolution of dune systems in relation to changes in boundary conditions have been articulated by Kocurek and colleagues (see Kocurek and Lancaster, 1999; Ewing and Kocurek, 2010). Examples of dunefield evolution in relation to such models have mostly focused on millennial timescales, in which the dune system response to Quaternary climatic and sea level changes that affect sediment supply, availability and mobility has been documented (e.g. Lancaster et al., 2002; Beveridge et al., 2006; Kocurek et al., 2007; Derickson et al., 2008). Recent assessments of luminescence-dated records have however questioned the paleo-climatic significance of periods of aeolian accumulation (Stone and Thomas, 2008; Thomas and Wiggs, 2008; Telfer et al., 2010), indicating the need to examine modern and historical analogs for dune system evolution and response to changes in boundary conditions. There are, however, few studies on these timescales and most lack detailed information on the associated boundary conditions. They include the response of dune systems to historical droughts and recent warming on the Great Plains of the USA and Canada (Muhs and Holliday, 1995; Wolfe et al., 2001); to drought periods in Colorado (Marîn et al., 2005); to a change in wind power in China (Mason et al., 2008); and to rainfall events at White Sands, New Mexico (Rachal and Dugas, 2009).

In this paper, aerial photographs and satellite images have been used to document the evolution of a small (<1 km^2) dunefield since the 1940s. Changes observed include the expansion of the area of the dunefield, as well as changes in the morphology of the dunes that comprise it. Relationships between the observed changes and changes in boundary conditions are then discussed, especially in relation to sediment supply and mobility.

2. The Keeler Dunefield

The Keeler Dunefield is located in the Owens Valley of east-central California northeast of Owens (dry) Lake (Figs. 1 and 2). The dunefield currently occupies an area of approximately 0.68 km^2, with a further 4 km^2 consisting of thin to discontinuous sand sheets. The dunes and sand sheets overlie Late Pleistocene and Holocene distal alluvial fan deposits, as well as lacustrine deposits and shoreline features associated with Late Holocene transgressions of Owens Lake to elevations of 1103 m asl.

The dunefield currently is composed of two parts: (1) the northern dunes, which includes sand sheets on the far northwestern or trailing margin of the dunefield; together with three linear dune ridges up 3 m high and up to 500 m long; as well as sand sheets and nebkhas adjacent to these dune ridges; and (2) the southern

* Corresponding author.
E-mail address: nick@dri.edu (N. Lancaster).

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http://dx.doi.org/10.1016/j.geomorph.2012.10.017

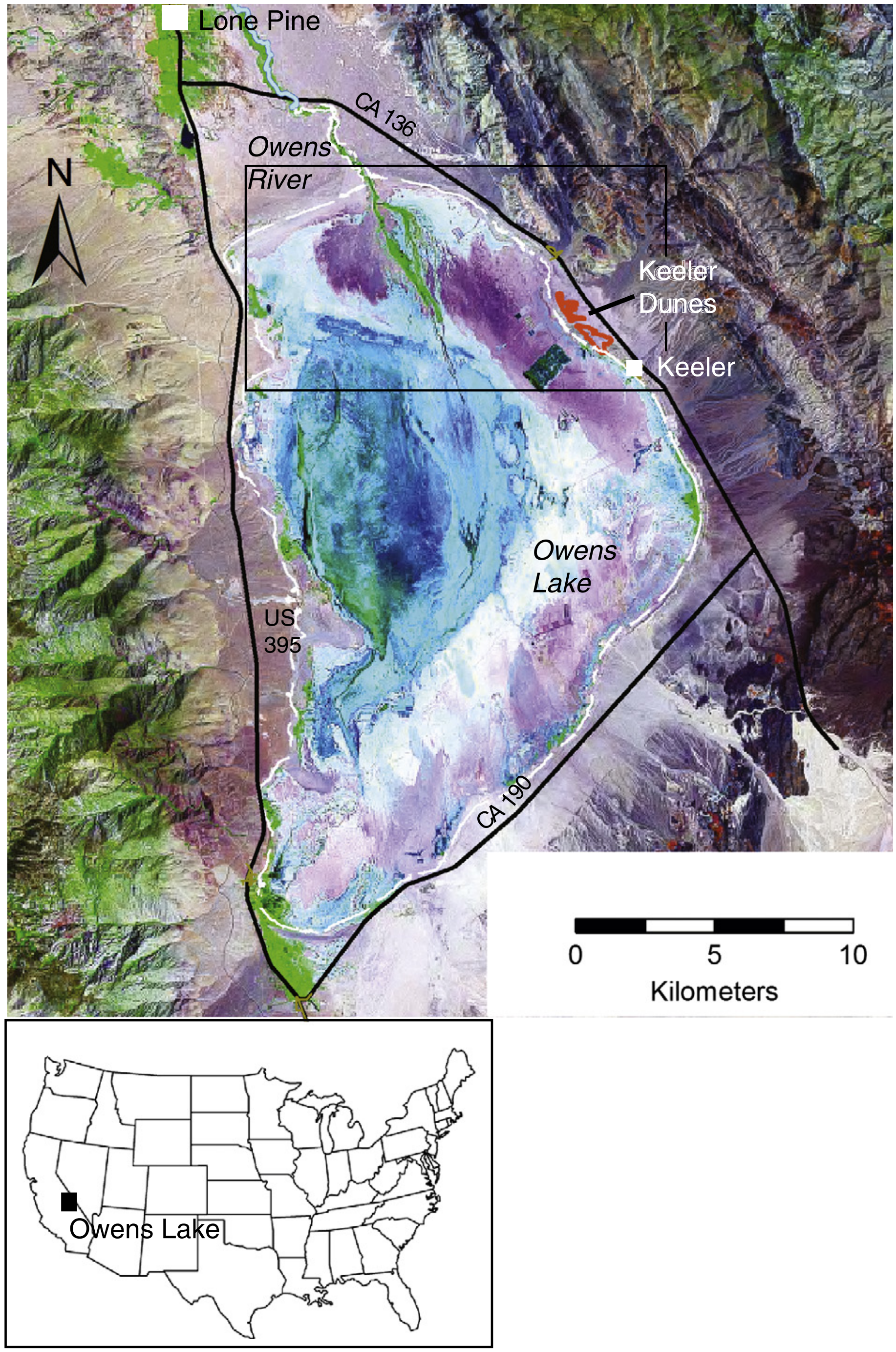

Fig. 1. Location map for Keeler Dunes. Box indicates area of Fig. 2.
Base image is Mr Sid (N-11-35_2000) downloaded from http://zulu.ssc.nasa.gov/mrsid/.

dunes, which comprise as many as 15 crescentic dune ridges up to 5 m in height, which are migrating toward the southeast. The current volume of sand involved in the dune field is estimated at 527,000 m^3 based on analyses of LiDAR digital elevation model data (HydroBioARS, 2011).

The modern environment of Owens Lake has developed as a result of the diversion of the primary inflow of the Owens River first by in-valley agriculture (starting in 1878) and then to the Los Angeles via the Los Angeles Aqueduct since 1913, so that the lake was lowered from its historic level of 1096 m asl in 1872 to a largely dry playa in the 1920s (Lee, 1915; Gill, 1996). Until control measures were implemented from 2000 onwards, the bed of Owens Lake was the largest source of wind-blown dust in the USA (Gill, 1996), primarily generated by the saltation of sand across the exposed lake bed (Gillette et al., 1997).

Sand moving winds in the area are from two primary directional sectors, NW and NNW and SSE and S. Average sand drift potential was calculated from wind data at the A-Tower location (4 km northwest of the Keeler Dunefield — see Fig. 2) for the period 1990–2011 using the approach of Fryberger (1979), modified to account for the use of wind speeds measured in meters per second (Bullard, 1997). The wind regime (Fig. 3) is characterized by this method as

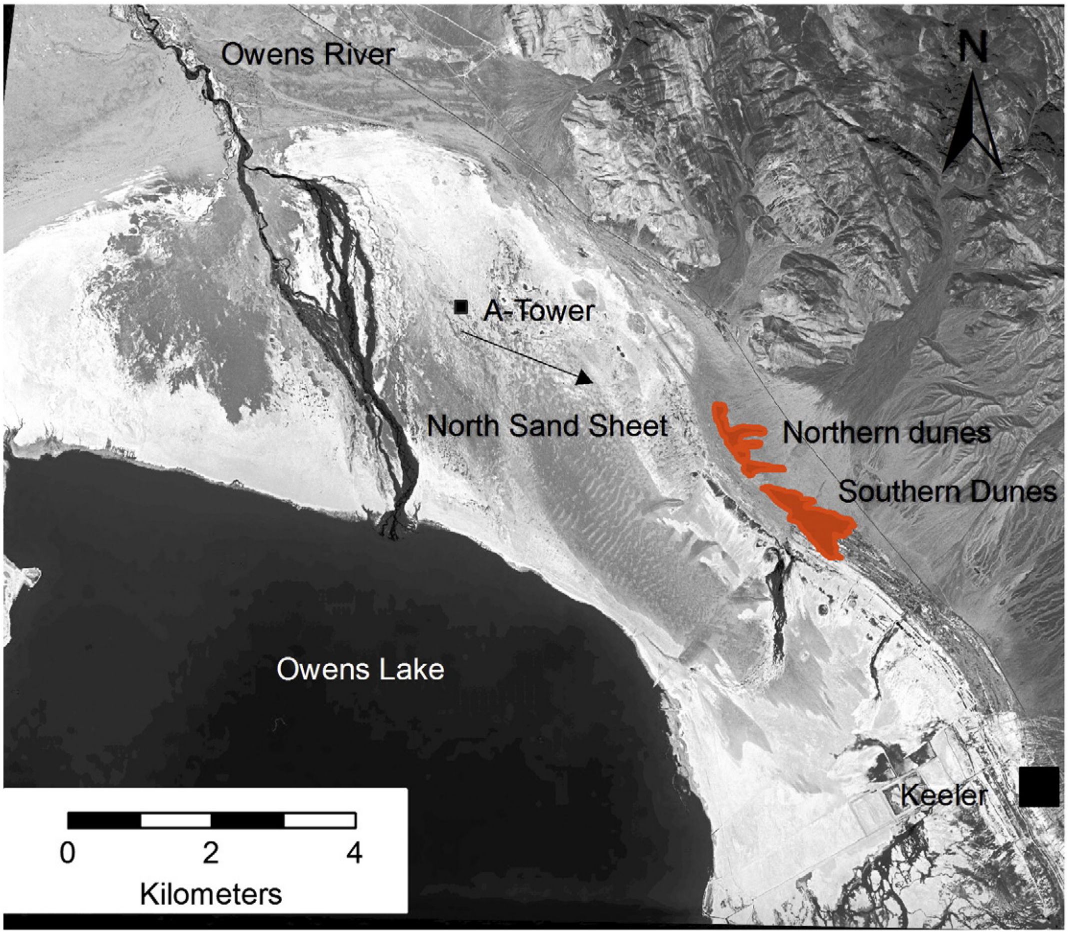

Fig. 2. Geomorphic context for Keeler Dunes: Base image is 1970 Corona image. Arrow indicates resultant potential sand transport direction (RDP). Note high water level in Owens Lake after 1969 flood. Dune extent (orange) shown from 2010. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

high-energy, with a total sand drift potential (DP) of 80.6 Velocity Units (VU). Winds from the NW–NNW sector account for 56% of the annual potential sand transport (DP); while winds from the SSE–S sector account for 31% of annual DP. The resultant or vector sum sand transport direction is toward 105°, with a resultant drift potential (RDP) magnitude of 25 VU; the DP/RDP ratio is 0.31.

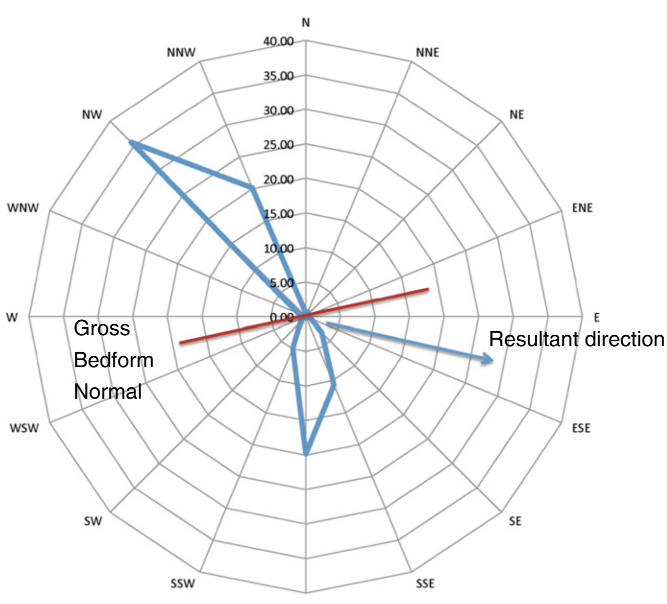

Fig. 3. Sand rose for Keeler Dunes area; data from A-Tower. Units are in drift potential calculated using Fryberger method for metric units (Bullard, 1997).

3. Methods

The primary methodology used in this study was the comparison of dune positions and extents on aerial photographs and satellite images acquired at different dates spanning the period from 1944 to 2010. High-resolution scanned versions of the aerial photographs were used wherever possible until the advent of high spatial resolution digital satellite images in the late 1990s. The aerial photographs were rectified and georeferenced to common geographic points before incorporation in a geographic information system (ARC-GIS). Dune and sand sheet extents and major dune ridges were then digitized from the images, and their dimensions measured using ARC-GIS. Table 1 gives the dates of the aerial photographs and satellite images used. The varying quality and resolution of the aerial photographs used made precise identification and delineation of the dune areas difficult in some instances. The measurements documented below represent the best estimate given the uncertainties involved in the tracing of the dune areas.

4. Results

4.1. Description of changes in the dunefield

The Keeler Dunefield has undergone significant changes over the period of available image data, as illustrated in Fig. 4 and in the

Please cite this article as: Lancaster, N., McCarley-Holder, G., Decadal-scale evolution of a small dune field: Keeler Dunes, California 1944–2010, Geomorphology (2012), http://dx.doi.org/10.1016/j.geomorph.2012.10.017

Table 1
Aerial photographs and satellite images used in this study.

Year	Agency/source	Date
1944	LADWP	13-Oct-44
1947	USGS	1-Aug-47
1954	Army Map Service	3-Jul-54
1968	LADWP	19-Jul-68
1970	Corona	17-Mar-70
1975	BLM	3-Dec-75
1982	USGS-HAP	24-May-82
1986	NHAP84	30-Aug-86
1993	NAPP	23-Sep-93
1998	NAPP	23-Aug-98
2000	GBUAPCD	9-Sep-00
2002	Spencer Gross	16-May-02
2002	NAPP	8-Jun-02
2004	Spencer Gross	7-Mar-04
2006	Ikonos	1-Jun-06
2008	Ikonos	26-Apr-08
2010	GeoEye	3-May-10

supplemental animation (video clip). From 1944 or earlier until the late 1950s or early 1960s, the dunefield was small (~0.28 km^2) and confined to an area in the far northwest of the study area (Fig. 4A). Dune ridges, where identifiable, were short and small in number (4–5). Dunefield and dune morphology was influenced by vegetation (primarily *Sarcobatus vermiculatus*), which acted to anchor these small dune ridges. Dunefield location appeared to be strongly influenced by the prominent erosional shoreline scarp developed at around 1103 m asl by a late Holocene highstand of Owens Lake (Bacon and Lancaster, 2012). This feature acted as a topographic control on sand transport, as well as the location of a zone of phreatophytic vegetation, that served to anchor this and subsequent dune deposition. A continuous sand sheet existed between the dunefield and the Owens River delta to the northwest.

In the late 1950s or early 1960s the dunefield began to grow in size, and well-defined linear ridges started to extend from the core dunefield towards the east (Fig. 4B). Three of these ridges have persisted to the present day, largely maintaining their morphology, but in recent years they have been much reduced in height and sand volume.

From 1968 to 1982, these linear dune ridges were well developed, and increased in number to six major ridges in 1975 (Fig. 4C). The dunefield area expanded dramatically to the east and southeast, reaching a size twice that of the 1940–1950s dunefield, at 0.63 km^2.

During the period from 1986 to 1993 (Fig. 4D) the dunefield continued to increase rapidly in area, expanding toward the southeast, so that it covered an area of 0.84 km^2 in 1993. From 1982 onwards, crescentic dune ridges could be identified in the southern part of the dunefield, as the volume of sand in the previously existing sand sheets in this area increased and a series of W–E oriented crescentic dune ridges formed and propagated to the southeast.

In the period from 1993 through 2010 dunefield development was characterized by erosion of the northwest margin, as evidenced by exposure of underlying alluvial deposits, but continued expansion and southeasterly migration of the southern crescentic dune area (Fig. 5). As a result, the dunefield area remained fairly constant, at around 0.77 km^2 but became divided into two separate parts. Erosion became especially prominent following the construction of the shallow flood irrigation areas on the sand sheets on the northern part of the lake bed in 2000 (Fig. 4E), resulting in widespread thinning of sand on the trailing (upwind) margin of the Keeler Dunefield and exposure of alluvial fan gravels and flood silt deposits. By 2010 (Fig. 4F), the original small partially vegetated dunefield on the northwest margin had largely disappeared and the remnant sand sheets were rapidly eroding.

4.2. Temporal trends in dunefield morphometry

Over the period of record, the area of the Keeler Dunefield has increased by a factor of 2.5–3 times. Fig. 5 shows the rapid increase in dunefield area in the 1950s and 1960s, and the significant, but less rapid, increase between the mid-1980s and the 1990s. There has been little change in area in the past decade. The change in area is quite well described by a second-order polynomial, showing the slowing of growth in the last 20 years (Fig. 6). The dunefield length (defined as the total distance from the upwind margin of the northern sand sheets to the most southerly dune) has increased linearly over time from around 1300 m in 1944–1954 to 2600 m today. Within the dunefield, the total number of dune ridges (linear and crescentic) has increased exponentially with time and also with dunefield area (Fig. 7A). The total length of the ridges has likewise increased over time in a similar fashion (Fig. 7B). The number of the crescentic dune ridges (Fig. 7C) appears to have stabilized or declined in the last decade, which suggests that the dune pattern may be reaching an equilibrium state. Development of the present pattern of crescentic ridges appears to have taken place over a period of two decades, with the number of ridges increasing from 5 in 1982 to 17 in 2002, and then stabilizing at 14–16 thereafter, largely by lateral linking of adjacent dunes (Fig. 7C).

4.3. Rates of dune and dunefield change

The availability of images at relatively closely spaced time intervals provides an opportunity to constrain rates of change in the Keeler Dunefield. The 2010 estimated spread-out or equivalent sand thickness (EST) (Wasson and Hyde, 1983) derived from LiDAR DEM data is 0.77 m (HydroBioARS, 2011). Assuming that a similar relationship between sand volume and dunefield area has existed in the past, there has been an increase in sand volume over time (Fig. 8), from around 215,000 m^3 in the 1940s–1950s to approximately 474,000 m^3 in the period 1968–1993; and to 600,000 m^3 in 1993–2010. Although the relationship is well-described by a linear model, it is more appropriately described by a step-function, with rapid growth from 1954 to 1968; and again from 1986 to 1993. Assuming sand input is equally distributed along the 1.4 km length of the northern part of the dunefield, the rapid growth in the period 1954–1968 implies an annual sand supply of 18 m^3/m/yr. Likewise, an input of sand of 24 m^3/m/yr is implied for the period 1986–1993. These estimates are similar to sand transport rates measured using Sensits and sand traps by the Great Basin Unified Air Pollution Control District (GBUAPCD) for the sand sheet in the northern part of the dunes (26 m^3/m/yr).

The southern margin of the dunefield has propagated to the southeast over the past 40 years, initially as a sand sheet and after 1982 as crescentic dunes. Comparison of the position of the southern margin on aerial photographs over this period indicates a long-term (1982–2010) vector of dune movement of 12–13 m/yr towards the ESE or SE (108–122°). Year to year variability is evident (Fig. 9), with generally high rates of movement in 1970–1975 (25 m/yr); between 1982 and 1993 (16 m/yr); and from 2006 to 2010 (18 m/yr). This variability appears to relate to: (1) periods of rapid change in the dunefield resulting from sand input and formation of new dune areas (e.g. 1970–1975; 1982–1986); and (2) year-to-year changes in winds and sand flux. Monitoring by GBUAPCD shows increased rates of sand flux in the area in 2007 and 2008. Over the same time interval, linear ridges in the northern part of the dunefield have extended to the east. The rate of extension has slowed exponentially over the years, from 21 m/yr in the period 1970–1975 to 1.4 m/yr from 2006 to 2010.

5. Discussion

The Keeler Dunefield has undergone significant changes since 1944. These include an increase in the area of the dunes by a factor

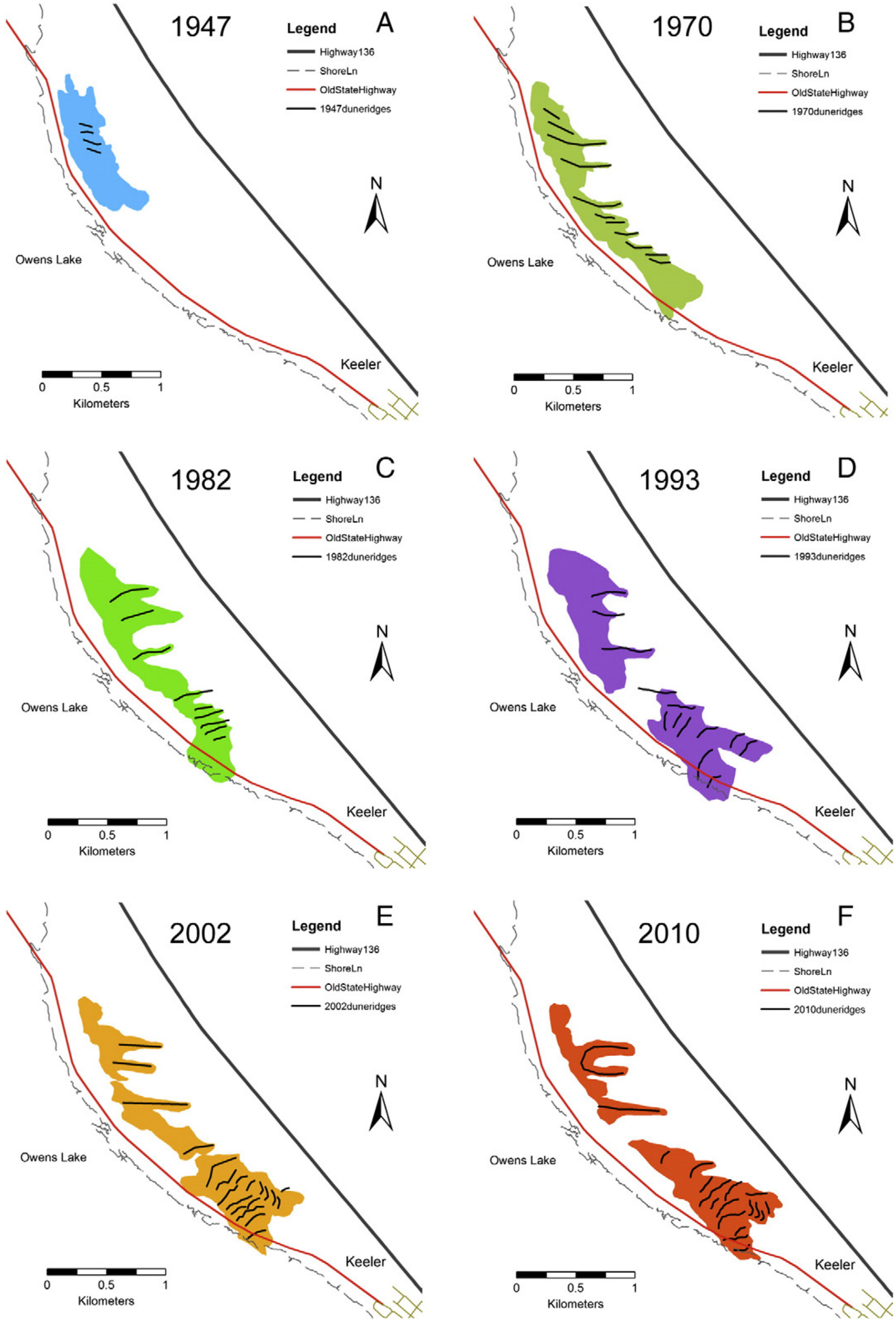

Fig. 4. The Keeler Dunefield in (A) 1947; (B) 1970; (C) 1982; (D) 1993; (E) 2002; and (F) 2010.

of 3 since 1944 and development of well-defined linear and crescentic dunes from an initial small area of partially vegetated dunes. The dune field continues to expand toward the southeast, but its upwind margins are now experiencing significant erosion.

These changes can be related to temporal variations in the boundary conditions that control the sand supply, the availability of this sand for transport, and the mobility of this sand. Trends in the extent and morphology of the Keeler Dunefield from the mid-1950s to the 1990s can further be evaluated in terms of the sediment state model (Kocurek and Lancaster, 1999), which relates dunefield dynamics to changes in boundary conditions.

5.1. Temporal trends in boundary conditions

5.1.1. Sand supply

The bulk mineralogy of Keeler dune sands and sediments of the Owens River are identical, as determined by XRD analysis, indicating that the source of this sand was the fluvial–deltaic sands of the Owens

Fig. 5. (A) Erosion and exposure of flood silt deposits on the trailing margin of the dunefield. Sand underlying silt cap was deposited about 1970, based on OSL dating (http://gbuapcd.org/keelerdunes/originanddevelopment/attachments/E-Chronology%20and%20Stratigraphy/Lancaster%20and%20Bacon%202012%20-Late%20Holocene%20stratigraphy%20and%20chronology_preliminaryfinaldraft20120831nl.pdf). Subsequent erosion of sand total 1 m; and (B) leading edge of dunefield, showing advancing crescentic dunes burying phreatophytic vegetation.

River delta, now exposed by drying of the lake (Lancaster, 2012). Aeolian sand supply from fluvial sources is typically episodic (Griffiths et al., 2002; Miller et al., 2010) and often correlates with major flood events. Major periods of high flows in the lower Owens River occurred in 1938–1939, 1969–1970, and at a much lower level in 1982 (Fig. 10). These events probably contributed significant amounts of sand-size sediment to the delta area, in addition to water to the lake. These flows have also created a distributary system graded to the new base level. Significantly, the sand transport pathway to the dunes begins in the area of one of the major distributaries of the Owens River delta (Fig. 2). This area appears on many images to regularly receive water (and sediment) from the Owens River in periods of high flows.

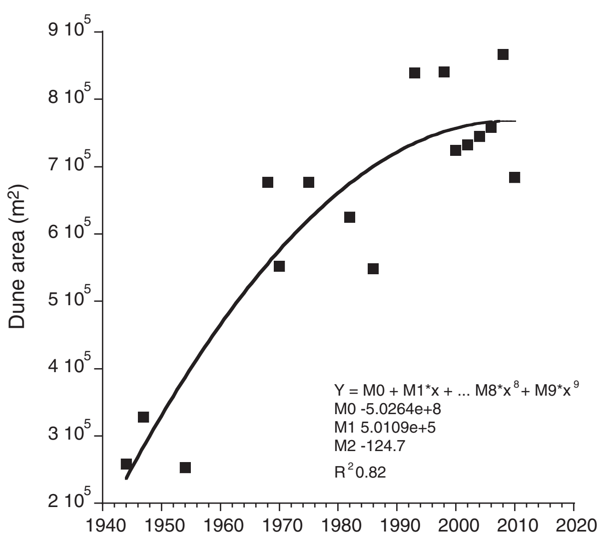

Fig. 6. Change in area of Keeler Dunefield 1944–2010.

The fluvial–deltaic sands were redistributed by NW winds, which created extensive sand sheets covering the northeast sector of Owens Lake (see Fig. 2). NW winds have a fetch of 4–5 km across these sand sheets, so that prior to the construction of dust control measures in the area, the sand supply to the dunes was limited only by the transport capacity of the wind, counteracted by surface moisture and salt crusting that could restrict sediment availability.

5.1.2. Sediment availability

Groundwater levels in the sand sheet area in the northern part of the Owens Lake bed were measured during the period 1992–2001 by GBUAPCD and range between 0.81 and 1. 09 m below the surface with little significant change from year to year (GBUAPCD, 2009), indicating that sediment availability was not reduced as a result of high groundwater tables in this area. Sediment availability could also be restricted by surface moisture as a result of rainfall and vegetation growth on the sand sheets adjacent to the delta. The rainfall record for Independence (35 km northwest of Owens Lake) (Fig. 11) shows a very wet year in 1969 (which was also a year of high flow in the Owens River). Periods of above-average rainfall occurred in the 1960s, 1976–1986 and in the late 1990s.

5.1.3. Sediment mobility (sand drift potential)

As noted above, this area is characterized by a high-energy wind regime, with winds from two main directional sectors: NW–NW

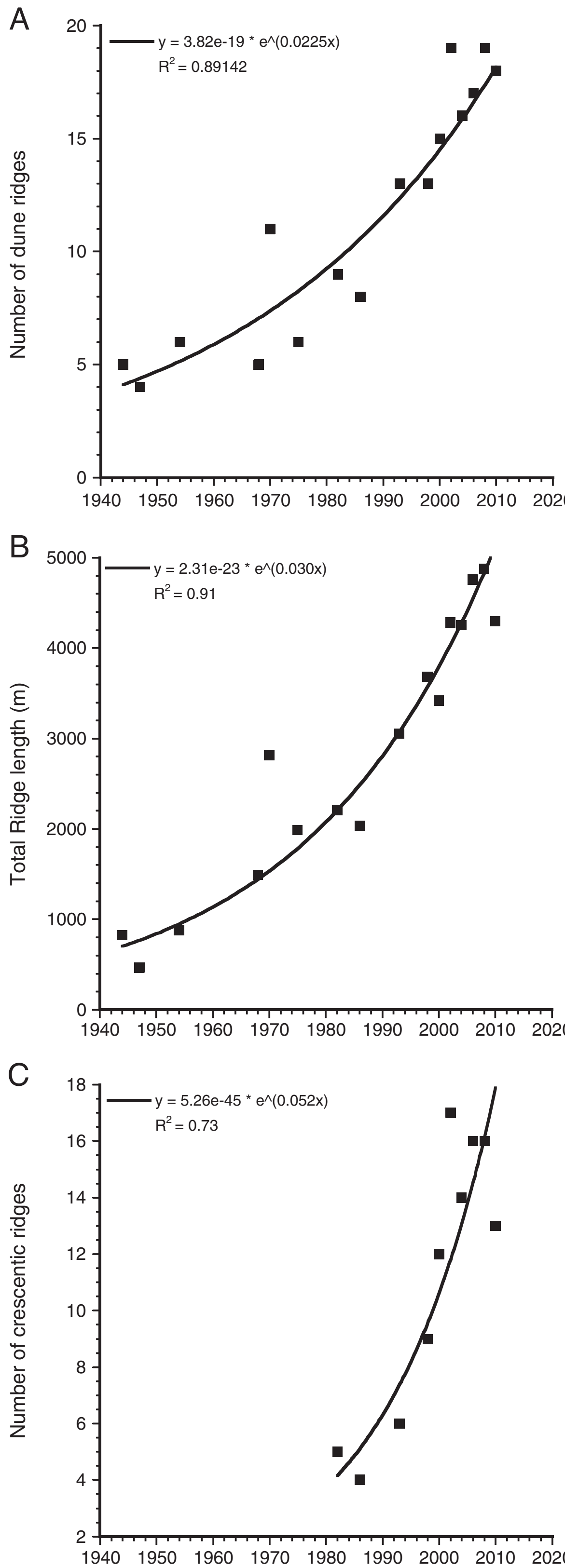

Fig. 7. Change in (A) total number of dune ridges for the period 1944–2010; (B) total length of dune ridges; and (C) number of crescentic dune ridges.

and SE–S. Wind records for the area of Keeler Dunes begin in 1991, when the A-tower site was established. The wind record for Bishop Airport (http://www.wrcc.dri.edu/cgi-bin/rawMAIN.pl?caKBIH) covers the period 1948 to present and can be used to provide an indication of

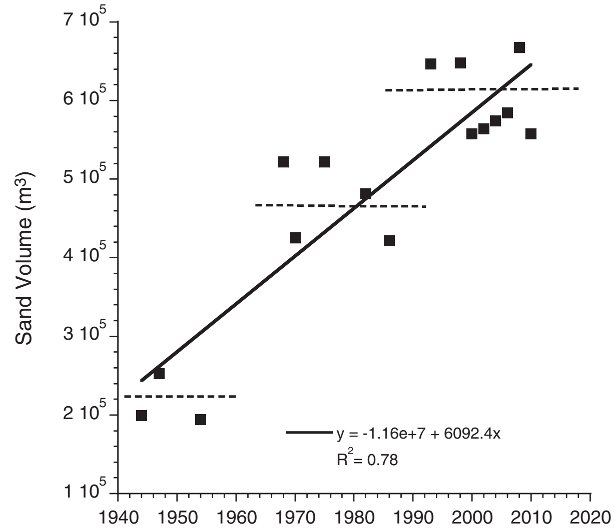

Fig. 8. Change in estimated sand volume over time. Note rapid changes in the late 1950s and late 1980s. Dotted line shows mean sand volume at three main time periods of dunefield development.

changes in sediment mobility. Although wind strength is lower than that at Owens Lake, the wind regime appears to be very similar, with strong topographic control of the two main directional sectors (N and S). The relative proportions of these sectors at Bishop and Owens Lake vary in a closely similar way (Fig. 12) indicating that the Bishop record can be used as a proxy for temporal changes in winds over the period of record prior to 1991. Drift potential at Bishop, calculated using the Fryberger method for metric units, varies from a low of 5.7 VU in 1963 to a maximum of 105.8 VU in 1965, and with considerable variability from year to year (Fig. 13). As noted by Jewell and Nicoll (2011), there are some consistent trends in DP, which are of regional significance. Generally, the period 1948–1963 is characterized by low drift potential (mean 22 VU); drift potential in the period from 1964 to 1980 is much higher (mean 51 VU); from 1981 to 1993 is moderate (mean 34 VU); while from 1994 to 2010 drift potential decreased to a mean value of 26 VU.

In addition to changes in total and resultant drift potential, there are significant changes in the proportion of total drift potential from the two main sectors at Bishop, which parallel those from the A-tower after 1991 (Fig. 14). In the period 1948–1966, northerly

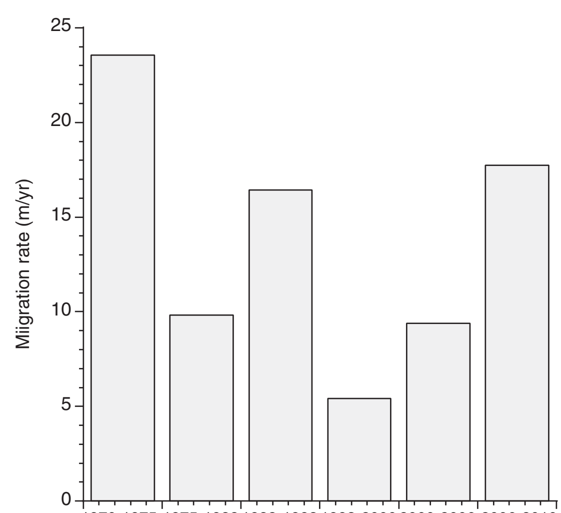

Fig. 9. Changes in rate of migration of southern margin of Keeler Dunes (1970–2010).

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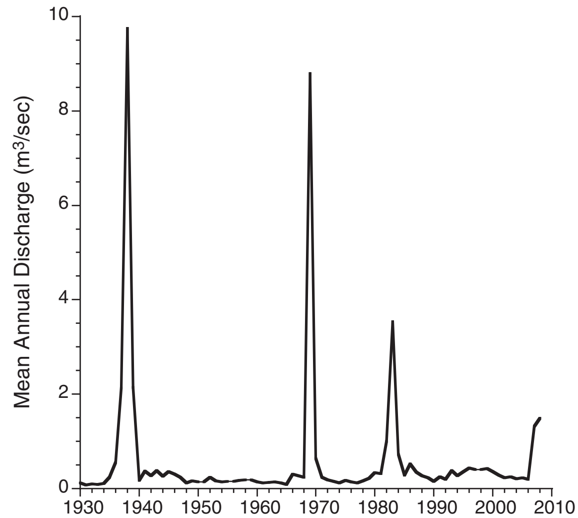

Fig. 10. Discharge of the Owens River at Keeler Bridge (5 km north of Owens Lake). Data from Los Angeles Department of Water and Power.

winds gave rise to an average of 57% of the drift potential, compared to 26% from southerly directions. From 1967 to 1980, the two sectors were evenly balanced (45% northerly, 37% southerly). From 1981 onwards, DP from the northerly sector increased again to 51% (1981–1990), 48% (1991–2000), and 50% (2001–2010), with great variability from year to year. DP from southerly directions remained similar at 37–38% throughout this later period.

5.2. Dune morphology, vegetation cover and wind regime

The Keeler Dunefield is characterized by two distinct areas of dunes (dune generations), with a different morphology (linear vs. crescentic); yet they are separated spatially by only a few hundred meters. The linear dunes appear to have developed in the 1960s directly from the partially vegetated core of the 1940s dunefield, as a result of interactions between NW winds and perennial vegetation, in a manner similar to that proposed by Tsoar (1989). Their subsequent morphology is however more similar to unvegetated linear dunes, or seifs. The trend of these linear dunes is approximately 100°, closely parallel to the resultant sand transport direction

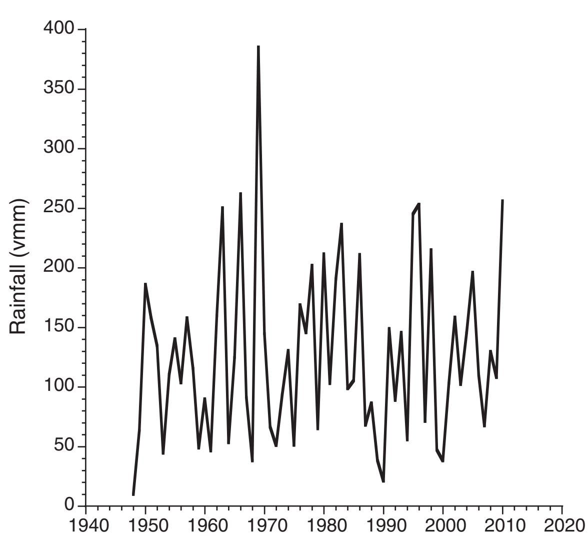

Fig. 11. Annual total rainfall at Independence, CA. Data from Western Regional Climate Center www.wrcc.dri.edu.

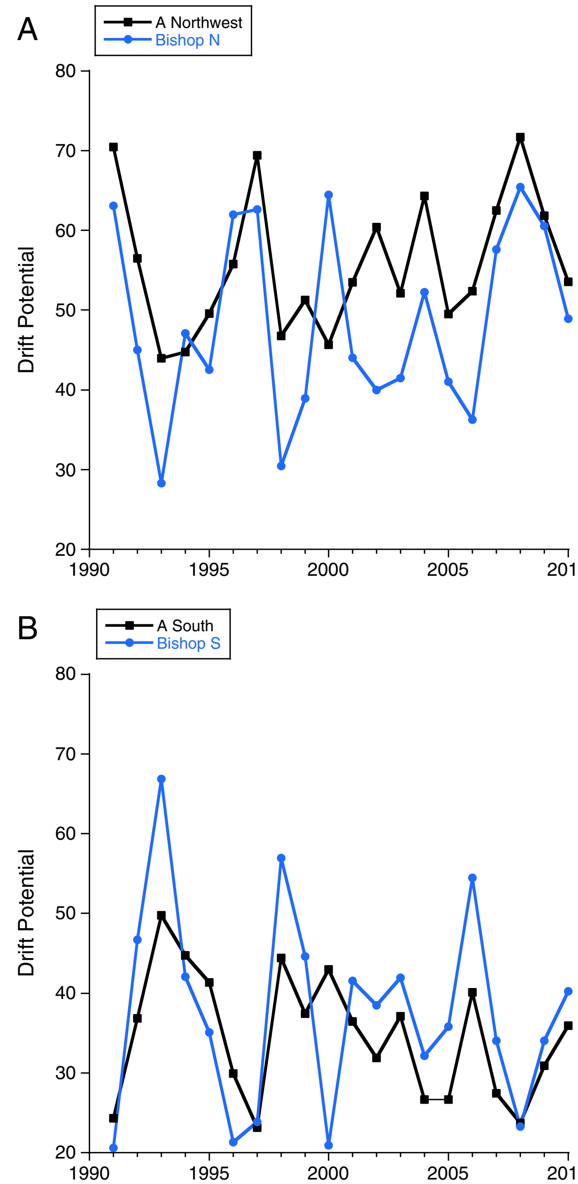

Fig. 12. Comparison of drift potential from (A) north and northwest and (B) southerly sectors at Bishop Airport and A-Tower locations for 1991–2010.

(105°). By contrast, the crescentic ridges in the southern dunes are aligned at approximately 45°, or transverse to the dominant NW winds, and slightly oblique to the gross bedform normal trend (065°).

The development of linear dunes in the late 1960s and the 1970s and then crescentic dunes in the 1980–1990s may be related to changes in wind regime. As noted above, the period from 1964 to 1980 was characterized by an increase in wind energy and drift potential, accompanied after 1967 by a sand-moving wind regime in which the two sectors each contributed similar proportions (~35–45%) of the total drift potential. The RDP/DP ratio in this period averaged 0.13, compared to 0.33 in the preceding period. In the 1980s and 1990s, crescentic dunes developed and were then maintained in subsequent years by a wind regime in which approximately 51% of drift potential was from the northwesterly sector, with an RDP/DP ratio of 0.31 and resultant transport towards the ESE.

The dunefield has evolved by expanding towards the southeast in a direction approximately parallel to the dominant sand transport direction. The expansion of the dunefield area has occurred largely by the formation of crescentic dune ridges in the southern part of the dunefield and their subsequent propagation to the southeast in the

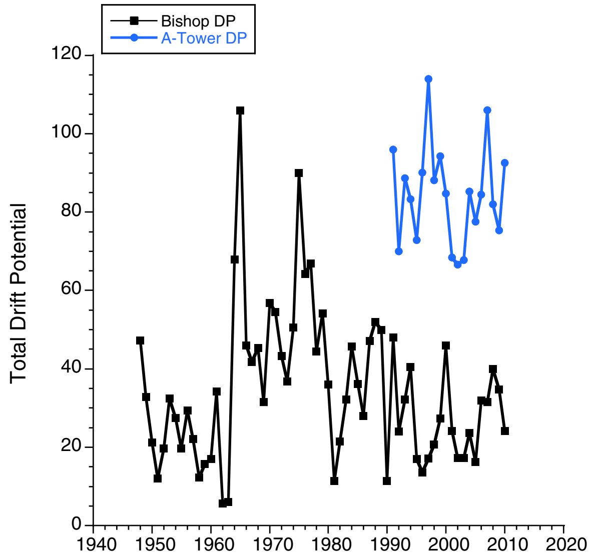

Fig. 13. Annual drift potential for the period of record at Bishop Airport and A-Tower.

southern part of the dunefield, while the linear ridges in the northern area remained largely unchanged in morphology and position but with some extension to the east. The persistence of the linear dunes may be explained by their conservative nature in which change can occur only at defects in the pattern or at terminations such as the tip of such dunes (Werner and Kocurek, 1997).

5.3. Decadal-scale dunefield dynamics

Changes in the extent and morphology of the Keeler Dunefield from the mid-1950s to the 1990s can be evaluated in terms of the sediment state model (Kocurek and Lancaster, 1999), which relates dunefield dynamics to changes in boundary conditions, especially sand supply, the availability of this sand for transport, and the mobility of this sand.

The significant expansion of dunefield area, sand volume, and number of dune ridges that occurred between 1954 and 1968, and again between 1986 and 1993, separated by periods of apparently little change implies addition of sand from outside the dunefield, which formed two new generations of dunes. In the late 1950s and 1960s, it appears that most of the additional sand was incorporated in the northern part of the dunefield, forming the three linear ridges that still exist today. From the late 1960s to the 1990s, sand input largely bypassed the northern part of the dunefield and was directed towards forming the southern dunes.

The importance of external sand supply to the Keeler Dunefield is supported by images from the 1940s to the early 1980s which show a sand sheet extending from the northeast sector of Owens Lake to the dunes and covering the area between the historic shoreline of Owens Lake and the dunefield (Fig. 2). Crossing this area is the “Old State Highway” from Keeler to Lone Pine, which is variably covered by sand following its abandonment in the early 1950s. The length of the old highway covered by sand between fixed points at each end of the dunefield area was measured on aerial photographs and satellite images using ARC-GIS, and provides an index of the sand supply to the dunes (Fig. 15). Sand cover was extensive and apparently thick in the late 1960s and 1970s, which was when the dunefield was transformed in area and morphology. The data indicate that sand supply to the dunes peaked in the 1980s and has since decreased, most rapidly following 2000 when construction of dust control measures started.

5.4. Temporal changes in boundary conditions

The availability of multiple proxies for sand supply, availability and mobility to the Keeler Dunefield permits reconstruction of the boundary conditions, and combinations thereof, that gave rise to changes in the dunefield (Fig. 16). The 1950s were characterized by a low energy wind regime and generally dry conditions. Although sand availability was high, wind energy was insufficient to move this sand to the dunefield. From 1964 until 1980, sand mobility, as measured by DP, was very high. Although rainfall was generally above average, sand supply to the dunefield was high, resulting in extensive dune construction in this period. From 1986 to 1993 sand mobility and supply were again relatively high, resulting in further dune construction in this period.

Although it is clear that sand supply from the Owens River delta is a major contributor to dune construction, the role of major flood events in providing an episodic supply of sand is less clear. The major period of linear dune construction and associated expansion of the dunefield occurred prior to the 1969 flood event, but there was significant expansion of the dunefield after the much smaller

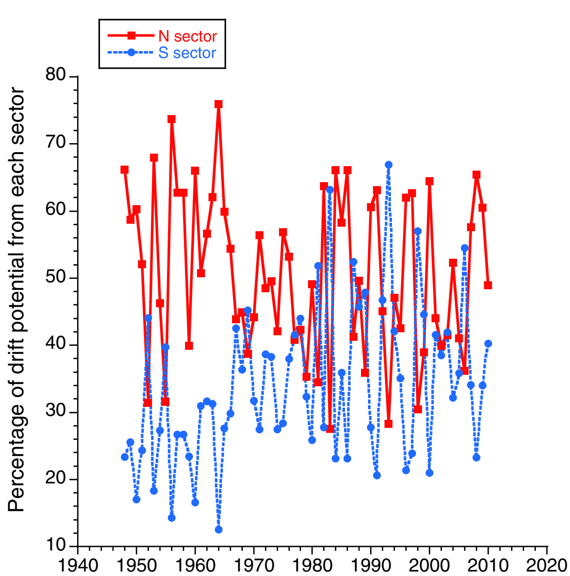

Fig. 14. Comparison of percentage of total drift potential (DP) at Bishop Airport from southerly and northerly sectors for the period 1948–2010.

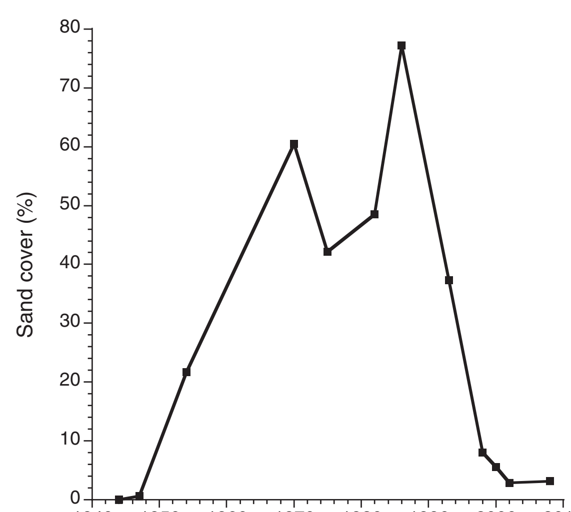

Fig. 15. Variation in sand input to Keeler Dunes over time, as estimated by proportion of sand cover on “Old State Highway” that ran from Keeler to Lone Pine. Secondary peak in cover in 1986 may relate to coverage of highway by dunes.

Please cite this article as: Lancaster, N., McCarley-Holder, G., Decadal-scale evolution of a small dune field: Keeler Dunes, California 1944–2010, Geomorphology (2012), http://dx.doi.org/10.1016/j.geomorph.2012.10.017

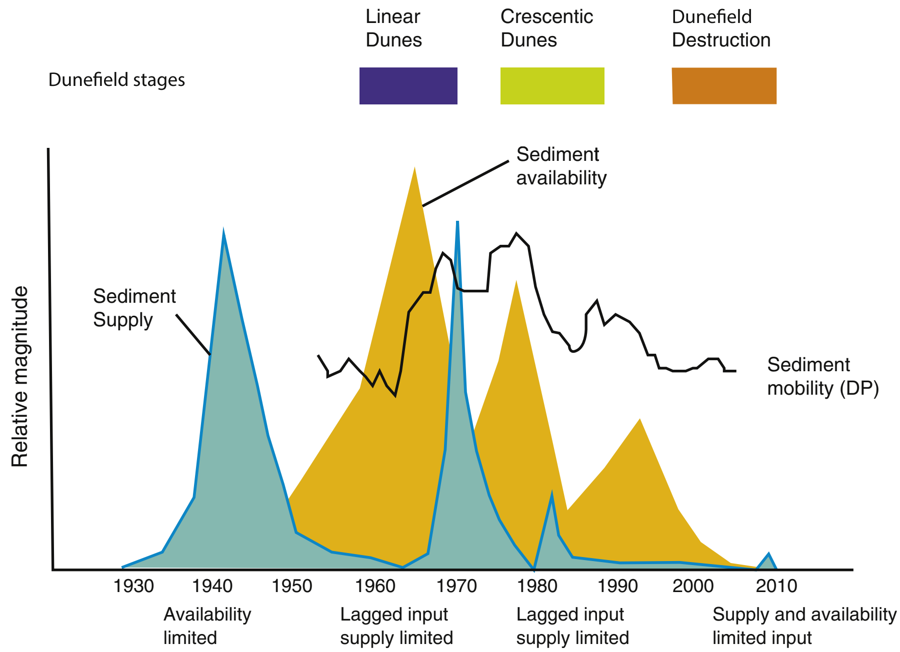

Fig. 16. Sediment state of the Keeler Dunes (sensu Kocurek and Lancaster, 1999). Sediment supply is estimated from Owens River discharge data; sediment mobility from Bishop Airport DP; sediment availability based in part on sand input to dunes. Time periods for phases of dune development are shown across the top.

1982 event, when the southern area of crescentic dunes were formed. It is hypothesized that that sand input to the Keeler Dunes lags behind the sand supply event from the Owens River by 10–20 years. The long dry interval following the major floods in the Owens River in 1939 gave rise to extensive movement of sand and dune construction only after 1954; the shorter dry interval following the 1969 event also led to dune construction, especially in the area of the southern dunes, after 1980. The effect of the much smaller 1982 flood event was not manifested for several years, and probably overlaps with the effect of the 1969 flood.

Between 1982 and 2002, the main processes were the development and southeastward migration of the southern dunes, with limited input of sand. With the construction of dust control measures starting in 2000, the dunefield has been starved of sand and is in a state of negative (supply and availability limited) sediment budget, so that erosion is occurring on the upwind margin. The continued expansion of the southern dunes towards the southeast is a result of reworking of existing sand in these dunes, augmented by redistribution of sand from the northern part of the dunefield. It does not represent any significant addition of sand from external sources.

6. Conclusions

The Keeler Dunefield has developed to its present form since the mid- to late 1950s, with rapid development in the 1970s and 1980s, when the southern dunes were formed, as a result of input of sand from external sources. Presently it receives no sand input and is in a state of negative sediment budget, with a net loss of sand, which is leading to erosion of its upwind margins. Analysis of dune morphologic changes over time indicates clearly that the southern part of the dunefield may be reaching an equilibrium with sand supply and wind conditions, which have changed significantly since the pattern was first established. This study also provides some information on the timescales of dune development in a high-energy aeolian environment, which formerly experienced an abundant supply of sand, with rapid development of crescentic dunes over a period of 20 years. This study has also highlighted the complexity of dunefield development, even on decadal timescales, and the role of episodic sediment supply in forming new generations of dunes.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.geomorph.2012.10.017.

Acknowledgments

Nate Pepe (DRI) carried out geo-registration of image data and extraction of wind data from the A-tower record; discussion in the field with Steve Bacon and Scott Stine helped to clarify thoughts on dunefield origins.

References

Bacon, S., Lancaster, N., 2012. Geomorphic mapping of the Keeler Dunefield and surrounding areas. Draft Report Prepared by the Desert Research Institute for the Great Basin Unified Air Pollution Control District (August 2012. http://www.gbuapcd.org/keelerdunes/originanddevelopment/attachments/D-Geomorphic%20Mapping/Bacon%20and%20Lancaster%202012%20-%20FINAL_DRAFT_Geomorphic_Mapping_of_the_Keeler_Dunfield_and_Adjacent_Areas.pdf).

Beveridge, C., Kocurek, G., Ewing, R., Lancaster, N., Morthekai, P., Singhvi, A., Mahan, S., 2006. Development of spatially diverse and complex dune-field patterns: Gran Deserierto Dune Field, Sonora, Mexico. Sedimentology 53, 1391–1409.

Bullard, J.E., 1997. A note on the use of the "Fryberger method" for evaluating potential sand transport by wind. Journal of Sedimentary Research 67 (3), 499–501.

Derickson, D., Kocurek, G., Ewing, R.C., Bristow, C.S., 2008. Origin of a complex and spatially diverse dune-field pattern, Algodones, southeastern California. Geomorphology 99, 186–204.

Ewing, R.C., Kocurek, G., 2010. Aeolian dune-field pattern boundary conditions. Geomorphology 114 (3), 175–187.

Fryberger, S.G., 1979. Dune forms and wind regimes. In: McKee, E.D. (Ed.), A Study of Global Sand Seas: United States Geological Survey. Professional Paper, U.S.G.S. Professional Paper, pp. 137–140.

GBUAPCD, 2009. Owens Lake Shallow Hydrology Monitoring Data and Chemistry (1992–2004). (111 pp., Bishop, CA. http://www.gbuapcd.org/owenslake/hydrology/OwensLakeShallowHydrologyMonitoringDataAndChemistry1992-2004/Final%20Report%20(Compiled%20Text_Figs).pdf).

Gill, T.E., 1996. Eolian sediments generated by anthropogenic disturbance of playas: human impacts on the geomorphic system and geomorphic effects on the human system. Geomorphology 17 (1–3), 207–228.

Gillette, D.A., Fryrear, D.W., Gill, T.E., Ley, T., Cahill, T.A., Gearhart, E.A., 1997. Relation of vertical flux of particles smaller than 10 μm to total aeolian horizontal mass flux at Owens Lake. Journal of Geophysical Research 102 (D22), 26,009–26,015.

Griffiths, P.G., Webb, R.H., Lancaster, N., Kaehler, C.A., Lundstrom, S.C., 2002. Long-term sand supply to Coachella Valley fringe-toed lizard (*Uma inornata*) habitat in the northern Coachella Valley, California. Water-Resources Investigations Report, 02-4013. United States Geological Survey, Washington DC.

HydroBioARS, 2011. Sand volume estimate of Keeler Dunes. Public Workshop (Keeler, CA, January 2011. http://www.gbuapcd.org/keelerdunes/presentations/SandVolumeAssessment.pdf).

Jewell, P.W., Nicoll, K., 2011. Wind regimes and aeolian transport in the Great Basin, U.S.A. Geomorphology 129 (1–2), 1–13.

Kocurek, G., Lancaster, N., 1999. Aeolian system sediment state: theory and Mojave Desert Kelso dune field example. Sedimentology 46, 505–515.

Kocurek, G., Carr, M., Ewing, R., Havholm, K.G., Nagar, Y.C., Singhvi, A.K., 2007. White Sands Dune Field, New Mexico: age, dune dynamics, and recent accumulations. Sedimentary Geology 197, 313–331.

Lancaster, N., 2012. Keeler Dunes: mineralogical and particle size analyses to determine sand source(s). Draft Report Prepared by the Desert Research Institute for the Great Basin Unified Air Pollution Control District (February 2012. http://gbuapcd.org/keelerdunes/originanddevelopment/attachments/E-Chronology%20and%20Stratigraphy/Lancaster%202012b_Keeler%20Dunes%20sand%20sources_XRD%20and%20seive%20results.pdf).

Lancaster, N., Kocurek, G., Singhvi, A.K., Pandey, V., Deynoux, M., Ghienne, J.-P., Lo, K., 2002. Late Pleistocene and Holocene dune activity and wind regimes in the western Sahara of Mauritania. Geology 30 (11), 991–994.

Lee, C.H., 1915. Report on the hydrology of Owens Lake Basin and the natural soda industry as affected by the Los Angeles Aqueduct diversion. Report prepared by City of Los Angeles Hydraulic Engineer, October 1915.

Marîn, L., Forman, S.L., Valdez, A., Bunch, F., 2005. Twentieth century dune migration at the Great Sand Dunes National Park and Preserve, Colorado, relation to drought variability. Geomorphology 70, 163–183.

Mason, J.A., Swinehart, J.B., Lu, H., Miao, X., Cha, P., Zhou, Y., 2008. Limited change in dune mobility in response to a large decrease in wind power in semi-arid northern China since the 1970s. Geomorphology 102 (3–4), 351–363.

Miller, D.M., Schmidt, K.M., Mahan, S.A., McGeehin, J.P., Owen, L.A., Barron, J.A., Lehmkuhl, F., Lehrer, R., 2010. Holocene landscape response to seasonality of storms in the Mojave Desert. Quaternary International 215 (1–2), 45–61.

Muhs, D.R., Holliday, V.T., 1995. Active dune sand on the Great Plains in the 19th century: evidence from accounts of early explorers. Quaternary Research 43, 118–124.

Rachal, D.M., Dugas, D.P., 2009. Historical dune pattern dynamics: White Sands Dune Field, New Mexico. Physical Geography 30 (1), 64–78.

Stone, A.E.C., Thomas, D.S.G., 2008. Linear dune accumulation chronologies from the southwest Kalahari, Namibia: challenges of reconstructing late Quaternary palaeoenvironments from aeolian landforms. Quaternary Science Reviews 27 (17–18), 1667–1681.

Telfer, M.W., Bailey, R.M., Burrough, S.L., Stone, A.E.S., Thomas, D.S.G., Wiggs, G.S.F., 2010. Understanding linear dune chronologies: insights from a simple accumulation model. Geomorphology 120 (3–4), 195–208.

Thomas, D.S.G., Wiggs, G.F.S., 2008. Aeolian system responses to global change: challenges of scale, process, and temporal integration. Earth Surface Processes and Landforms 33, 1396–1418.

Tsoar, H., 1989. Linear dunes — forms and formation. Progress in Physical Geography 13 (4), 507–528.

Wasson, R.J., Hyde, R., 1983. Factors determining desert dune type. Nature 304, 337–339.

Werner, B.T., Kocurek, G., 1997. Bed-form dynamics: does the tail wag the dog? Geology 25 (9), 771–774.

Wolfe, S.A., Huntley, D.J., David, P.P., Ollerhead, J., Sauchyn, D.J., MacDonald, G.M., 2001. Late 18th century drought-induced sand dune activity, Great Sand Hills, Saskatchewan. Canadian Journal of Earth Sciences 38, 105–117.

Please cite this article as: Lancaster, N., McCarley-Holder, G., Decadal-scale evolution of a small dune field: Keeler Dunes, California 1944–2010, Geomorphology (2012), http://dx.doi.org/10.1016/j.geomorph.2012.10.017