Geomorphology 276 (2017) 222–243

Contents lists available at ScienceDirect

Geomorphology

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

A complex origin for the Kelso Dunes, Mojave National Preserve, California, USA: A case study using a simple geochemical method with global applications

Daniel R. Muhs [a,*], Nicholas Lancaster [b], Gary L. Skipp [a]

[a] U.S. Geological Survey, MS 980, Box 25046, Federal Center, Denver, CO 80225, USA
[b] Desert Research Institute, Division of Earth & Ecosystem Sciences, 2215 Raggio Parkway, Reno, NV 89512, USA

ARTICLE INFO

Article history:
Received 19 March 2016
Received in revised form 2 October 2016
Accepted 4 October 2016
Available online 6 October 2016

Keywords:
Kelso Dunes
Mojave Desert
Mineralogy
Geochemistry
Provenance

ABSTRACT

The Kelso Dune field in southern California is intriguing because although it is of limited areal extent (~100 km^2), it has a wide variety of dune forms and contains many active dunes (~40 km^2), which is unusual in the Mojave Desert. Studies over the past eight decades have concluded that the dunes are derived primarily from a single source, Mojave River alluvium, under a dominant, westerly-to-northwesterly wind regime. The majority of these studies did not, however, present data to support the Mojave River as the only source. We conducted mineralogical and geochemical studies of most of the 14 geomorphically defined dune groups of the Kelso Dune field as well as potential sand sources, alluvial sediments from the surrounding mountain ranges. Results indicate that sands in the nine western dune groups have K/Rb and K/Ba (primarily from K-feldspar) compositions that are indistinguishable from Mojave River alluvium (westerly/northwesterly winds) and Budweiser Wash alluvium (southwesterly winds), permitting an interpretation of two sources. In contrast, sands from the five eastern dune groups have K/Rb and K/Ba values that indicate significant inputs from alluvial fan deposits of the Providence Mountains. This requires either rare winds from the east or southeast or, more likely, aeolian reworking of distal Providence Mountain fan sediments by winds from the west, at a rate greater than input from the Mojave River or other western sources. The results indicate that even a small dune field can have a complex origin, either from seasonally varying winds or complex alluvial-fan-dune interaction. Application of K/Rb and K/Ba in K-feldspar as a provenance indicator could be used in many of the world's ergs or sand seas, where dune origins are still not well understood or are controversial. Four examples are given from Africa and the Middle East where such an approach could yield useful new information about dune sand provenance.

1. Introduction

Dune fields occupy large areas of the world's arid and semiarid regions, mostly (though not entirely) in the subtropical deserts and in rain-shadowed mid-latitude zones (Wilson, 1973; Cooke et al., 1993; Lancaster, 1995; Livingstone and Warren, 1996; Goudie, 2002; Pye and Tsoar, 2009; Warren, 2013; Lorenz and Zimbelman, 2014). Although there have been many studies of desert dune fields, much of the focus has been on genesis of dune forms, sedimentary structures found in aeolian sand, and chronology of dune deposition as an indicator of paleoclimate. In general, there has been much less work done on understanding dune sediment provenance, with many studies simply assuming an underlying or nearby rock or sediment as the primary source or ignoring the issue of provenance altogether. Nevertheless, dune field evolution cannot really be fully understood without identifying the source sediment or sediments. Further, 'aeolian system sediment state' (as defined by Kocurek and Lancaster, 1999) cannot be assessed without provenance information. Aeolian system sediment state includes evaluation of whether a dune field is transport-limited, sediment-supply-limited or sediment-availability-limited. The latter two conditions can only be assessed if the source of sand supply is known.

It is fair to ask why an understanding of dune sand provenance is important. Assessment of whether a dune field could grow larger in the future requires understanding whether there are supplies of sand available for growth. Dune field growth in turn has important implications for ecosystems that are hosted by the dune field itself, if it is stabilized, or for impacts on ecosystems that are downwind of a dune field, if it is active now and could expand in that direction with enhanced supplies of sediment. Paleoclimatic interpretations of dune fields are dependent on assessment of sand provenance. Very commonly, geomorphologists interpret evidence of past activity of a dune field as an indicator of an arid paleoclimate and evidence of past stability of a dune field as an indicator of a more humid paleoclimate. This need not be the case, however, if past periods of activity are in fact linked to

* Corresponding author.
E-mail address: dmuhs@usgs.gov (D.R. Muhs).

http://dx.doi.org/10.1016/j.geomorph.2016.10.002
0169-555X/Published by Elsevier B.V.

enhanced sediment supply and past periods of stability are linked to diminished sediment supply. Aeolian sediments are unusual among geologic records of climate change in that they are direct indicators of atmospheric circulation. Aeolian sediments that lack geomorphic indicators of paleowind can still be used for inferring paleoclimate if sand provenance can be determined. Further, if a stratigraphic section composed of alternating beds of aeolian sand exists, changes in paleowind direction can be determined if provenance of each aeolian sand unit can be ascertained.

The Kelso Dunes are situated in the Mojave Desert region of southern California, one of a number of modest-sized dune fields in the southwestern USA and northwestern Mexico (Fig. 1). Unlike many of the other Mojave Desert dunes, however, parts of the Kelso Dunes are unvegetated and active. Because of their unusual nature, both from a geomorphological viewpoint and as the home for a number of desert plants and animals, the Kelso Dunes and surrounding areas are now protected as part of Mojave National Preserve (Fig. 2). The dunes host a number of rare and sensitive desert plants (Thorne et al., 1981; Pavlik, 1989; André, 2014), as well seven species of endemic insects and a lizard that, while not strictly endemic, is rare outside of Mojave National Preserve (Schoenherr, 1992, p. 470).

Speculation about the origin of the Kelso Dunes is found in a surprisingly large number of studies that span more than eight decades. In his pioneering exploratory study of the Mojave Desert, Thompson (1929) thought that the Kelso Dunes probably originated from sediments of the Mojave River (Fig. 3), although he presented no direct evidence to support this hypothesis. More than three decades passed before there were any detailed studies of the dunes, but in a now-classic paper Sharp (1966) provided mineralogical and particle size data for Kelso Dunes and proposed that, in agreement with Thompson (1929), the Mojave River was likely the main source for the dunes. In a follow-up study some years later, Sharp (1978) reiterated the importance of the Mojave River as a source. Nevertheless, in his earlier study Sharp (1966) also noted, on the basis of particle size data, that 'local' sources could be important. Norris and Webb (1976) agreed with the early studies, citing the Mojave River as the main source, but also suggested that Soda Lake could be an important source. Yeend et al. (1984) reported mineralogical data for the Kelso Dunes, but departed from earlier studies in proposing that in addition to the Mojave River, Kelso Wash could have been an important source for the dunes, as well as sediments derived from the Granite Mountains and Providence Mountains. Paisley et al. (1991) returned to the concept of the Mojave River as the primary source. Lancaster (1993, 1994) conducted detailed mapping of the different geomorphic units within the Kelso Dunes and, in agreement with Yeend et al. (1984) hypothesized that the Mojave River, Soda Lake, Kelso Wash, the Granite Mountains, and the Providence Mountains could all have been contributors to the dunes. Three papers on the luminescence geochronology of the dunes proposed the Mojave River and Soda and Silver Lakes as sources (Edwards, 1993; Clarke, 1994), or a combination of these three sources and the Granite Mountains (Wintle et al., 1994), although no mineralogical or geomorphic data were presented to test these hypotheses. Ramsey et al. (1999) presented both traditional mineralogical data and thermal infrared remote sensing data to propose that the dunes could have had a complex origin, with contributions from the Mojave River, Kelso Wash, the Providence Mountains, and the Granite Mountains. Lancaster and Tchakerian (2003) agreed with the multiple-source concept articulated by Ramsey et al. (1999). Further, Sweeney et al. (2013) reported evidence that fans and dry washes of the Providence Mountains are an important source of aeolian sand that is a part of soil Av horizons in the region. Nevertheless, Warren (2013) and Lorenz and Zimbelman (2014) returned to the simpler model of the Mojave River as the primary source of the Kelso Dunes.

Dune fields of course can be derived from either a single source or multiple sources, and sources can also change over time. A complex origin for a desert dune field, with multiple or changing sources, can be

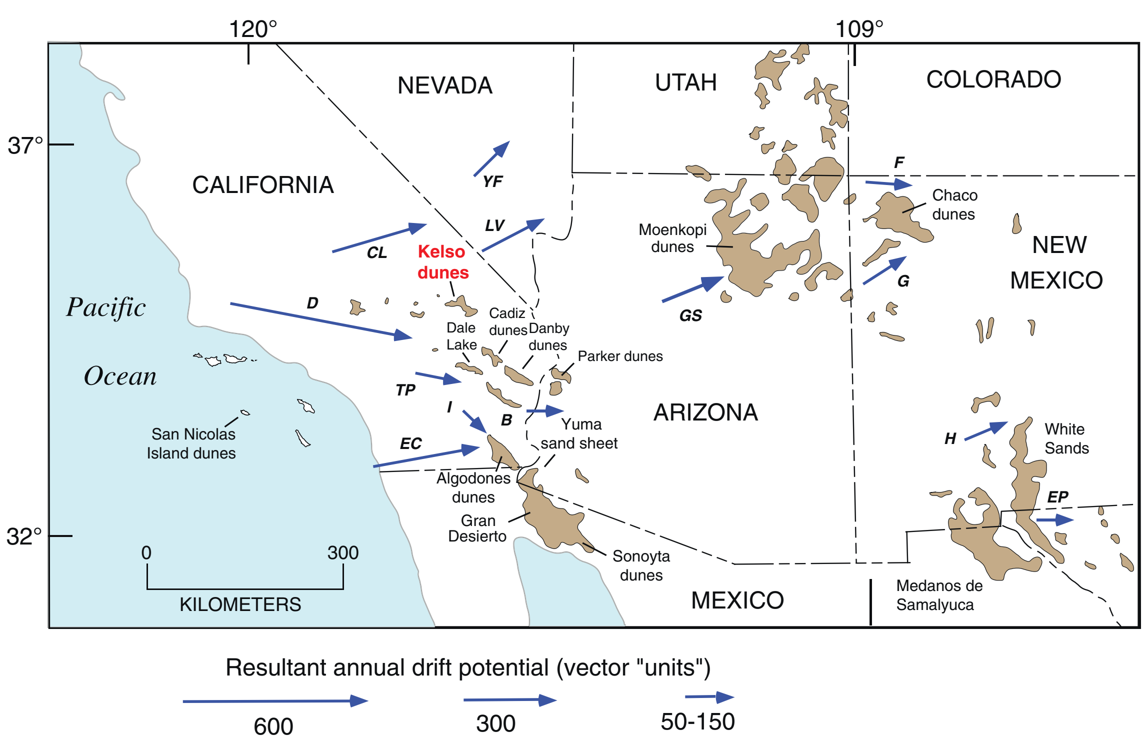

Fig. 1. Map showing the distribution of aeolian sand (brown shades – online version) in arid and semiarid regions of the southwestern United States and northern Mexico and modern sand transport directions (resultant drift directions and resultant drift potential, calculated using methods of Fryberger and Dean (1979)). Aeolian sand distribution is from compilation in Muhs and Zárate (2001) and references therein; see also Soller and Reheis (2004). Abbreviations for wind direction localities, which approximate the station locations: D, Daggett; Cl, China Lake; TP, Twenty-nine Palms; EC, El Centro; I, Indio; B, Blythe; YF, Yucca Flat; LV, Las Vegas; GS, Gold Spring; F, Farmington; G, Gallup; H, Holloman Air Force Base; EP, El Paso. Resultant annual drift potentials calculated by the authors except for Gold Spring, which is from Helm and Breed (1999) and Holloman Air Force Base, which is from Fryberger and Dean (1979).