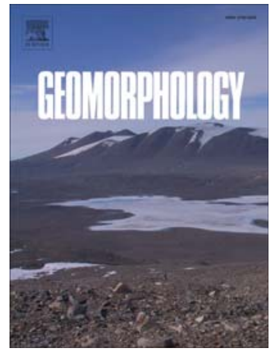

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A complex origin for the Kelso Dunes, Mojave National Preserve, California, USA: A case study using a simple geochemical method with global applications

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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 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 be 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 challenging to document, but recent studies have shown that multiple sources have contributed to dune fields in a number of arid regions. For example, in addition to Ramsey et al. (1999), cited above, for the Kelso Dunes, Scheidt et al. (2011) demonstrated that the Gran Desierto dune field in northwestern Mexico is derived in part from ancestral Colorado River sediments, but also has had contributions from local sources. Although the Negev and Sinai dunes of Israel and Egypt are derived primarily from Nile River sands, Muhs et al. (2013a) showed that sand derived from local carbonate rocks have also made contributions to the dunes.

Herein, we use simple geochemical methods for assessing the origin of Kelso Dunes using the composition (K, Ba, Rb) of one of the most common minerals found in dune fields, K-feldspar. Both feldspars and micas host K as a major element, but the major K-bearing mineral phase in most dune fields is K-feldspar, either microcline or orthoclase. Micas, the second most common K-bearing group of minerals, are rarely reported in dune fields, and it is not difficult to understand why this is the case. K-feldspar is approximately seven times as abundant as biotite in granite and it is about five times as abundant as biotite in granodiorite (Wedepohl, 1969, p. 248). These two rock types are estimated to comprise ~78% of the upper continental crust of the Earth. Thus, on the surface of the Earth, there is simply less mica available, compared to K-feldspar, for delivery to dune fields from average upper crustal rocks. Thus, bulk analyses of sediment for concentrations of K, as well as Rb and Ba (trace elements that follow K; see Heier and Adams, 1964; Lange et al., 1966), typically will reflect K-feldspar compositions. Muhs et al. (2008, 2013b) showed that K/Rb and Ba/Rb have the ability to distinguish loess deposits of different provenance in both Alaska and the North American midcontinent. Comparison of K-feldspar composition of Kelso Dunes with compositions of candidate source sediments can potentially identify the most important source or sources of aeolian sand. To our knowledge, K/Rb and K/Ba values have not been applied to deciphering provenance of sand in dune fields. Here, we apply this to the Kelso Dunes as a case study, and then suggest how the methods could be applied to other dune fields in west Africa, southwest Africa, north Africa, and the Middle East, where the sources of sand are unknown or controversial.

2. Study area

2.1. Geology of the Kelso Dunes area

The Kelso Dunes are situated in the arid Mojave Desert of southern California, a region that is part of the Basin and Range physiographic province. The Kelso Dunes occupy a structural basin surrounded by small, dominantly granitic mountain ranges (with maximum elevations ranging from ~1200 m to ~2200 m), in turn flanked by alluvial fans (Figs. 2, 3). Sediments from these fan deposits and nearby dry-wash drainages are the major candidates for sources of aeolian sand. Miller et al. (1991) provide a good summary of the bedrock geology of the mountain ranges surrounding the Kelso Dunes. To the north, the Kelso Mountains are composed of early Proterozoic granitoids and gneiss, as well as Cretaceous monzogranite. East of the dune field, the Providence Mountains are comprised of early Proterozoic gneiss, Jurassic and Cretaceous granite, monzogranite, and quartz monzonite, as well as carbonate and siliciclastic sedimentary rocks. To the south, the Granite Mountains are composed of Jurassic and Cretaceous granite, granitoids, granodiorite, monzogranite, diorite, and quartz diorite gneiss. Budweiser Wash, situated largely to the west of the Kelso Dunes, carries sediment from both the Granite Mountains, described above, as well as the Old Dad Mountains (composed of Jurassic granitoids and Tertiary rhyolite) and the Bristol Mountains (composed largely of Jurassic granitoids and metavolcanic rocks). The source of Kelso dune sand cited most frequently, as mentioned above, is the Mojave River, which heads in the San Bernardino Mountains. In the upper drainage basin of this river, the major bedrock types are Cretaceous or Jurassic granodiorite and quartz monzonite, along with some metamorphic rocks of uncertain age (Bortugno and Spittler, 1986).

The age of aeolian sand at Kelso Dunes has been estimated primarily on the basis of luminescence geochronology. From infrared stimulated luminescence (IRSL) methods, some parts of the Kelso Dunes appear to have formed by the late Pleistocene (~16 ka), based on data in Clarke (1994). She also reports that some aeolian sands, particularly in the eastern parts of the dune field (units I-V of Lancaster [1993, 1994]; see below), are interbedded with alluvial fan deposits from the Providence Mountains, observations confirmed by detailed mapping and stratigraphy conducted by McDonald et al. (2003). More recent studies by Sweeney et al. (2015) show that there may have been a long and complex history of alternating aeolian and fluvial sedimentation for dunes in this area, as well as in sand ramps along the margins of Kelso Dunes. Nevertheless, IRSL geochronology shows that the major landforms in Kelso Dunes formed or were reformed during the Holocene and particularly in the past ~4,000 years (Edwards, 1993; Clarke, 1994; Wintle et al., 1994). All aeolian sands sampled in the present study were taken either from active dune sand or, where stabilized, from dunes considered to be of late Holocene age.

2.2. Climatology of the Kelso Dunes area

The climate of the Kelso Dunes area is warm and arid. All data presented here are for the 1981-2010 period of record from the two weather stations closest to the Kelso Dunes, Daggett, California (N34°52'; W116°47'), ~94 km to the west and Baker, California (N35°16'; W116°04'), ~46 km to the northwest. Mean July temperatures at Daggett and Baker are 31.6°C and 30.9°C, respectively, with mean January temperatures of 9.3°C (Daggett) and 9.2°C (Baker). Mean monthly low temperatures are above freezing in all months. Aridity of the Mojave Desert is due to its position in the lee of southern California's mountains. The San Bernardino Mountains (to the south), San Gabriel Mountains (to the southwest), Tehachapi Mountains (to the northwest), and the coastal mountain ranges (to the northwest) are high enough that much, though not all, of the moisture from frontal systems derived from the north Pacific Ocean is blocked from transport to the east, leaving the Mojave Desert in a rain shadow. Thus, mean annual precipitation at Daggett is just 105.4 mm and at Baker it is 104.9 mm. Measurable precipitation, on average, is recorded in all months, but is typically highest in winter (December, January, and February) from Pacific-derived frontal systems. Rainfall in the winter months accounts for approximately 58% (Daggett) to 49% (Baker) of the mean annual precipitation. There is a smaller, secondary rainfall peak, primarily in the form of convective storms, in late summer/early fall (July, August, and September). Late summer/early fall precipitation is due to a moderate monsoonal flow of tropical moisture derived from the Pacific Ocean and Gulf of California off the coasts of Baja California and mainland Mexico. This warm-season precipitation accounts for ~22% (Daggett) to 28% (Baker) of the mean annual rainfall. During El Niño years, when warm, tropical waters of the equatorial western Pacific Ocean migrate eastward, winter precipitation in the Mojave Desert is significantly higher, whereas during La Niña years, drier winters occur (Hereford et al., 2004).

Winds in the Mojave Desert are important in understanding both dune geomorphology and potential source sediments. Of particular importance are those winds above the threshold velocity for transport of sand-sized particles. For loose, non-vegetated, medium-sized (500-250 μm) sand particles, the threshold velocity is ~5-6 m/s, when recorded with an anemometer that has a standard height of ~10 m. Resultant annual drift potentials (RDP), using the method of calculation in Fryberger and Dean (1979), show a wide range of values in the areas of dunes in the southwestern USA and northwestern Mexico, although all show dominant sand-moving winds from the northwest, west, or southwest (Fig. 1). RDP for Daggett, California is ~600 vector units, putting it in the 'high-energy wind environment' class of localities of Fryberger and Dean (1979).

Although the resultant drift direction for the area around Daggett is northwest-to-southeast (Fig. 1), there is a significant seasonal variability in wind directions in the Mojave National Preserve area. We generated wind roses for four representative months of the year (Fig. 4) for the Mojave 'Sink' area (location shown on Fig. 3). The plots show the frequency of winds above a threshold velocity of 5 m/s and therefore display only winds strong enough to entrain sand-sized particles. Common to all four seasons are frequent winds from the west and southwest. In addition, however, fall (represented by October) and winter (represented by February) frequently have winds from the northwest and north. Summer (represented by July) frequently has winds from the southeast, likely due to the monsoonal flow of air from the south.

3. Methods

In the Kelso Dunes, aeolian sands from most of the major geomorphic units (Fig. 5) defined by Lancaster (1993, 1994) were collected for mineralogical and geochemical analyses. For source sediments, we collected samples from the following drainages: (1) Mojave River wash, from Afton to ~1 km east of Crucero (n=36); (2) Budweiser Wash, along an ~8 km reach between the Granite Mountains and the Bristol Mountains (n=10); (3) fan deposits of the Granite Mountains, collected along a ~16 km transect to the north of the mountains, from just west of Cottonwood Wash to Budweiser Wash (n=27); (4) Providence Mountain fan deposits, collected to the west of the mountain front, on a 4.4 km transect along the Vulcan Mine Road and a 5.4 km transect along the pipeline access road to the south of the Vulcan Mine Road (n=25); and (5) Kelso Wash, sampled from eight separate small washes, along a 1.8 km transect northwest of the town of Kelso (n=15). As discussed above, a number of investigators have hypothesized that sediments in the basins of Silver Lake and Soda Lake playas could have been sources of sand for the Kelso Dunes. Our examination of these areas, however, indicates very little sand-sized material is available for aeolian transport, except along the margins of the playas. Moreover, as pointed out by Wells et al. (2003) and Enzel et al. (2003), the vast majority of sediment reaching these basins, including the minor sand-sized component, is ultimately derived from the Mojave River, which we sampled separately.

Aeolian sands from each of the major geomorphic units were analyzed as bulk samples, with no pretreatments other than pulverization. Alluvial samples from the potential source sediments were pretreated to yield a particle size distribution similar to that of aeolian sand. After disaggregation and removal of coarse gravel, the samples were placed in de-ionized water, a Na-pyrophosphate dispersant was added, particles in suspension were stirred, and then allowed to sit overnight. After this treatment, the samples were stirred again by ultrasonication and then wet-sieved to remove fine gravel and coarse sand (>500 μm). Silt and clay were removed by sieving with either a 53 μm or 63 μm sieve; no materials finer than 53 μm are present in any of the samples. Thus, the final sediment separates contained grains ranging from medium sand to very fine sand, similar to the size range of well-sorted dune sands at Kelso Dunes (see data in Lancaster, 1993, 1994).

Mineralogy was determined by X-ray diffractometry (XRD) on pulverized, randomly packed powder mounts. Percentages of quartz, K-feldspar, plagioclase, and calcite in Kelso dune sands and samples from other dune fields were estimated using a method developed by Dr. Amir Sandler of the Geological Survey of Israel (written communication, 9 August 2012), wherein the following factors are applied to XRD peak heights at two-theta, summed, and calculated as percentages: quartz, 26.6°, x 1.0; K-feldspar, 27.4°, x 3.0; plagioclase, 27.8°, x 3.5; and calcite, 29.4°, x 1.1. Crouvi et al. (2009), Enzel et al. (2010) and Muhs et al. (2013a) have used this method previously and results show good agreement with major element geochemistry. Abundances of K, Ca, Ti, Rb, Sr, Y, Zr, Nb, Ba, La, and Ce were determined by energy-dispersive X-ray fluorescence (ED XRF), following the methods in Muhs et al. (1995). USGS rock standard GSP-1 was included with each sample batch and resulting concentrations for this standard agree well with published values for most elements (see Muhs et al., 1995, their Table 2). For this rock standard, ED XRF element concentrations agree with published values within 5% (K), 0.4% (Rb), and 0.8% (Ba). Precision for these elements (±1 sigma) is 0.9% (K), 1.2% (Rb), and 0.8% (Ba). We note that there could be minor differences in element abundances determined by ED XRF compared to wavelength-dispersive X-ray fluorescence (WD XRF). In particular, concentrations of K by ED XRF may be biased high by ~5%, based on routine runs of USGS rock standards (e.g., a sample with a K_2O concentration of 3.5% by ED XRF might yield a concentration of 3.3% by WD XRF). Thus, we caution readers that element concentrations determined by WD XRF in the literature may be only approximately comparable to data presented here. Mineralogical interpretations of all geochemical data presented here are based on first principles of geochemistry and element substitution in minerals (Mason and Moore, 1982).

4. Results

4.1. Geomorphology of Kelso Dunes

Lancaster (1993, 1994) showed that despite the small area occupied by the Kelso Dunes, there is a diverse geomorphology, and he identified 14 distinct landform units. These landform units can be distinguished on Landsat ETM+ imagery (Fig. 5), but we also examined larger-scale stereoscopic aerial photography (black-and-white and color aerial photographs from the U.S. Geological Survey's NAPP (National Aerial Photography Program; images acquired in 1989, 1994, and 1995) and oblique aerial photography to assess the geomorphology of the dune field (Figs. 6, 7). Three dune units (VI, VIII, and X) are dominantly vegetation-free (Figs. 6-8), and a fourth unit (III) is only partially vegetated (Fig. 6). The remaining dune units are all stabilized to one degree or another by desert psammophytic scrub vegetation, including big galleta grass (*Hilaria rigida*), dune panic grass (*Panicum urvilleaneum*), and creosote bush (*Larrea tridentata*) (Thorne et al., 1981) and experience little or no active sand transport at present (Figs. 5-8).

The three dominantly active units, VI, VIII, and X, exhibit the most distinctive suites of aeolian landforms and all are complex dunes. At the broadest scale, all three of these active dune units consist of southwest-to-northeast trending ridges that could be former linear dunes. If so, these orientations would imply winds dominantly from the southwest (or, less likely, from the northeast). Superimposed on these landforms are much smaller barchanoid ridges, parabolic dunes, and occasional star dunes; the latter are rare in North American dune fields. Although the large linear ridges in these units could imply southwesterly winds during their formation, the smaller (and younger) barchanoid ridges and parabolic dunes suggest winds from the west to west-northwest. The star dunes are also superimposed on (and are therefore younger than) the large linear dunes and imply variable paleowinds during their time of formation (Table 1).

Most stabilized dune units in the eastern part of the area (those east of Cottonwood Wash; Figs. 5-7) indicate that recent dune-forming paleowinds were from the west or west-northwest, based on geomorphology (Table 1). Unit I consists largely of sheet sands, but it and Unit V also have some degraded parabolic dunes that indicate westerly (unit I) or northwesterly (unit V) paleowinds. Landforms are better preserved in units II and III and consist of linear dunes with superimposed parabolic dunes, and the latter imply northwesterly or westerly paleowinds. Unit IV consists of degraded linear dunes and sand sheets, but unlike the other eastern dune units, has linear dune orientations that could indicate the possibility of paleowinds from the southwest.

Stabilized dune units in the western part of the area (west of Cottonwood Wash) for the most part imply past winds that were generally westerly. Units VII, XII, and XIV all consist of parabolic dunes that indicate winds from the northwest (VII) or west (XII and XIV). Units IX and XIII consist either of linear dunes with superimposed parabolic dunes (IX) or linear dunes that grade southeastward into parabolic dunes (XIII) that indicate dune-forming winds from the west (IX) or northwest (XIII). The major exception to the overall pattern of westerly or northwesterly paleowinds in this part of the Kelso Dunes is unit XI. This unit consists of linear dunes that grade eastward into parabolic dunes, but the orientations of both the linear dunes and the parabolic dunes indicate paleowinds from the west-southwest (Fig. 5).

4.2. Mineralogy of Kelso Dunes

There have been highly divergent estimates of the abundances of common minerals in the Kelso Dunes. Sharp (1966) identified quartz, K-feldspar, plagioclase, and a variety of heavy minerals in the Kelso Dunes, but did not make estimates of abundances of mineral species. However, Yeend et al. (1984), Paisley et al. (1991) and Ramsey et al. (1999) reported average quartz contents of 70-80%, ~90%, and ~42%, respectively. The wide range in estimates of mineral species abundances led us to re-examine the composition of the Kelso Dunes, and we conducted XRD analyses on 74 samples from 12 of the 14 dune units.

Based on our measurements of the Kelso Dunes, quartz averages 33.5% (± 7.8%, one sigma), K-feldspar content averages 24.8% (± 6.1), and plagioclase averages 41% (± 7.6%). Calcite was also detected in small amounts in a few samples, primarily in dune unit I. Based on the relative abundance of quartz, plagioclase, and K-feldspar, the Kelso Dunes have a bulk composition similar to that of granite (slightly more than half the samples) or granodiorite (slightly less than half the samples), based on the classification system of igneous rocks by Streckeisen (1976). Given the granitic composition of the most of the rocks in all the possible mountain ranges that could deliver sediments to the Kelso Dunes, these results are not surprising. In this regard, the Kelso Dunes have a mineralogical composition that is similar to other Mojave Desert dune fields, such as the Cadiz and Danby dunes, as well as the Sonoyta dunes, in Sonora, Mexico (Fig. 9). The Cadiz and Danby dunes are likely derived from nearby granitic mountain ranges (Muhs et al., 2003) and the Sonoyta dunes are likely derived in part from sediments of the Sonoyta River (Scheidt et al., 2011), which drains rock bodies composed of granite and gneiss in northern Sonora. In contrast, the Algodones dunes in southern California and the Parker dunes in western Arizona are both thought to be derived primarily from quartz-rich Colorado River sediments (Muhs et al., 1995, 2003) and show much lower concentrations of K-feldspar and plagioclase compared to the Kelso Dunes (Fig. 9). In good agreement with the mineralogy, concentrations of K_2O and CaO in Kelso Dunes (Fig. 10a) also fall within the ranges for these elements in granites and granodiorites (Nockolds, 1954). Concentrations of K_2O and CaO in Kelso Dunes are similar to other dune fields in the Mojave Desert, such as the Cadiz-Danby dunes and the Dale Lake sand sheet, but differ from the quartz-rich Algodones and Parker dunes (Figs. 10b, c, d).

A number of previous workers have noted the presence of lag concentrations of heavy minerals on the crests of the active portions of the Kelso Dunes (Sharp, 1966; Paisley et al, 1991; Lancaster, 1994). These concentrations of dark minerals are visually striking and can be observed from considerable distances in the field (Fig. 8c). Sharp (1966) and Yeend et al. (1984) identified a number of heavy minerals in the Kelso Dunes, including amphibole, pyroxene, zircon, biotite, epidote, apatite, sphene (titanite), garnet, rutile, tourmaline, monazite, ilmenite, magnetite and cassiterite. Yeend et al. (1984) also reported that the surface concentrations of heavy minerals consist largely of amphibole and magnetite, with magnetite concentrations of up to 10%. Geochemical data support previous interpretations of the presence of these minerals (Fig. 11). Concentrations of Ti (and Nb, correlated positively with Ti; note, however, that some samples approach the lower detection limit for Nb) could be due to the presence of sphene, rutile, ilmenite and magnetite (if present as titanomagnetite). Pyroxene, hornblende and biotite can also host trace amounts of Ti. The presence of zircon is confirmed with concentrations of Zr that are typically less than ~500 ppm, but range as high as ~2000 ppm in one sample. We also measured two of the light rare earth elements (REE), La and Ce, and Y- an element with properties similar to the REE. La, Ce and Y are often present in minerals such as sphene and zircon, and all three of these elements are positively correlated with concentrations of Ti and Zr. Abundances of these elements are extremely high in magnetite-rich surface lags (Fig. 11).

4.3. Geochemistry of Kelso Dunes

The relatively high concentrations of K-feldspar in the Kelso Dunes allow the use of K/Rb and K/Ba to distinguish geochemical signatures of possible source sediments. As a first step in testing some of the hypothesized source sediments for the Kelso Dunes, we examined the composition of the small dunes at Devils Playground, to the northwest of the main dune field. If Mojave River sediments were the main source of the Kelso Dunes, as proposed by many previous investigators, then the Devils Playground dunes should have a composition that is similar to the river sands, because this dune field is situated between the Mojave River sink and Kelso Dunes (Fig. 3). K/Ba and K/Rb values from these dunes are not significantly different from those in Mojave River sediments, which supports this hypothesis (Fig. 12a). Devils Playground dunes also show only partial overlap with the K/Rb and K/Ba fields defined by Providence Mountains fan alluvium and Budweiser Wash alluvium and no overlap with Kelso Wash alluvium (Figs. 12b, c). Nevertheless, Devils Playground dunes fall completely within the field defined by Granite Mountains fan alluvium (Fig. 12d).

To the southeast of the dunes in Devils Playground lie the western group of dune units in Kelso Dunes (units VI-XIV), situated west of Cottonwood Wash (Figs. 3, 5, 7). Aeolian sands from the western dune units have K/Ba and K/Rb compositions similar to Devils Playground dunes, Mojave River sands (Fig. 13a), Granite Mountains fan alluvium (Fig. 13b) and Budweiser Wash alluvium (Fig. 13d). As with the Devils Playground dunes, the western dune sands show only partial overlap with Providence Mountains fan alluvium (Fig. 13c), and no overlap at all with Kelso Wash alluvium (Fig. 13d).

The eastern dune units have compositions that differ significantly from both the Devils Playground dunes and western dunes. In contrast to the latter, the eastern dune units show somewhat less variable K/Rb, but much more variable K/Ba (Fig. 14). The eastern dune units show only a partial overlap with the composition of Mojave River sands (Fig. 14a) and no overlap with either Budweiser Wash or Kelso Wash (Fig. 14d). The dunes in this area do show, however, considerable overlap with the K/Ba and K/Rb fields defined by both Granite Mountains fan alluvium and Providence Mountains fan alluvium (Figs. 14b, c).

5. Discussion

5.1. Origin of the Kelso Dunes

One of the most fundamental differences between the results reported here and those of previous researchers is mineralogical composition. Our mineralogical results differ significantly from those of Yeend et al. (1984) and Paisley et al. (1991) but are close to those of Ramsey et al. (1999). We found that quartz averages ~33%, plagioclase averages ~41%, and K-feldspar content averages ~25%. If Kelso Dunes sands had quartz contents as high as ~90% (Paisley et al., 1991) or even ~80% (Yeend et al., 1984), they would be considered to be mineralogically mature. Many of the world's larger dune fields are in fact mineralogically mature (see review in Muhs, 2004), but based on processes whereby dune fields can achieve such a composition, we would not expect Kelso Dunes to be quartz-rich. Depletion of less-resistant minerals such as calcite, plagioclase, and even K-feldspar can take place by chemical weathering, while dunes are stabilized by vegetation under a humid climate. This mechanism is unlikely for many dune fields found in semiarid or arid regions, although it cannot be dismissed entirely, because in the past some deserts (including the Mojave Desert: see Spaulding, 1995) were more humid than they are now. However, a more likely mechanism of calcite, plagioclase, or K-feldspar depletion in dune fields is by mechanical breakdown, either from abrasion or ballistic impacts during aeolian transport. Silt-sized particles of calcite, plagioclase, or K-feldspar that result from this physical disintegration can then be removed from a dune field altogether by aeolian transport in suspension, leaving behind a residual, quartz-rich, sand grain population. This process can be important where there is either long-distance aeolian transport of sand particles far from the source or there is repeated reactivation and reworking of sand grains over long periods within a desert basin. Based on the setting of Kelso Dunes, long-distance transport does not apply and based on the IRSL chronology, reactivation and reworking of grains over many periods of dune activity does not seem likely. Inheritance of a quartz-rich sand population can also explain mineralogical maturity (see Muhs et al., 1995, 2003). However, both the bulk mineralogical composition of Kelso Dunes sands (Fig. 9) and their major element composition (Fig. 10) show that the dunes differ little from the composition of average granite or granodiorite. This, along with the granitic composition of the surrounding mountains, implies only short distances of aeolian transport and little or no reworking.

The *lack* of mineralogical maturity and abundance of K-feldspar in Kelso Dunes actually provides the key to assessing likely source sediments, through the use of K/Rb and K/Ba values. Geochemical data presented here do not provide a unique solution to the origin of Kelso Dunes. Nevertheless, although several scenarios of sediment transport pathways to the dunes can be envisioned, all of them require a revision of the simple, single-source, Mojave River wash model reported by numerous previous investigators.

Devils Playground dunes have K/Rb and K/Ba compositions that fall within the range of both Mojave River wash sediments and sediments from the Granite Mountains. The Providence Mountains and Budweiser Wash are less likely as sources for Devils Playground dunes and Kelso Wash does not appear to be an important source at all (Fig. 12). Granite Mountains fan alluvium as a source for Devils Playground dunes would require a dominance of winds from the southeast, which occur only during mid-to-late summer months (and with less frequency, in winter), whereas Mojave River wash sediments as a source would require westerly to northwesterly winds, which occur year-round. We infer that Devils Playground dunes are dominantly derived from Mojave River wash sediments, in agreement with hypotheses of many previous researchers.

The western dune units (VI-XIV) do not differ significantly in K/Rb and K/Ba composition from Devils Playground dunes or Mojave River sediments (compare Figs. 12 and 13). As with the Devils Playground dunes, Providence Mountains fan sediments and Kelso Wash sands can be eliminated as likely sources for the western dune units. The most straightforward interpretation is that the western dune fields are simply the downwind recipients in a sediment cascade from (1) the Mojave River sink to (2) the Devils Playground dunes to (3) the western dune units. The orientations of stable dunes in western dune units VII, IX, XIII, and XIV all imply winds out of the west or northwest, consistent with this interpretation. Furthermore, the orientations of the active, secondary barchanoid-ridge dunes, star dunes, and parabolic dunes of western dune units VI, VIII, and X also imply winds from the west or northwest. Winds from the west occur year-round in the Kelso Dunes (Fig. 4).

Although the concept of derivation of the western dunes exclusively from the Mojave River has appeal because of its simplicity, this explanation overlooks the fact that the western dune fields also have K/Rb and K/Ba compositions that fall within the ranges of both Granite Mountains fan alluvium and Budweiser Wash alluvium (Fig. 13). Because of where the western dunes are situated, these sources would require winds from the southwest, but winds from this direction do occur year-round (Fig. 4). Further, the southwest-to-northeast orientations of the large linear ridges of active dune units VI, VIII, and X (on which the barchanoid-ridge, star, and parabolic dunes are situated) and the stable linear dunes of unit XI are consistent with dune-forming winds dominantly from the southwest (Table 1). Thus, modern winds, dune orientations, and sand geochemistry would permit a model of aeolian delivery of sand from Budweiser Wash or fans of the Granite Mountains to the Kelso Dunes. It is worth noting that the alternative interpretations presented here for the origin of the western dunes are not mutually exclusive. Southwesterly winds transporting sand from Budweiser Wash or fans of the Granite Mountains could have alternated with westerly winds transporting sand from the Mojave River. The results reported here permit a departure from the simple, single-source Mojave River model advocated by most previous researchers.

The greater variability in K/Ba values in sands from the eastern dune units (I-V), east of Cottonwood Wash, contrasts with the composition of the western dunes and Devils Playground dunes (Fig. 14). There is only a partial compositional overlap of these dune fields with Mojave River sands and no overlap with Budweiser Wash or Kelso Wash sands. However, the eastern dunes have compositions that fall well within the range of alluvium from both the Granite Mountains and the Providence Mountains. From these observations, it can be inferred that the Mojave River certainly cannot be the sole source of the eastern dune units. A complex origin could be inferred if we interpret the eastern dune units to be derived from a mix of Budweiser Wash sands and Kelso Wash fans, a possibility permitted by the compositional array shown in Fig. 14d. We question this interpretation, however, because it is difficult to envision how sands from Budweiser Wash could be transported to the eastern dunes without being mixed with sands from the Mojave River. A simpler explanation is that the eastern dunes are derived from the easternmost fans of the Granite Mountains, an interpretation also permitted by the K/Rb and K/Ba data.

The other alternative permitted by the data is derivation of the eastern dunes dominantly from fan sediments of the Providence Mountains. This would explain the distinctive composition of the eastern dunes as compared with the western dunes, but is a bit more difficult to reconcile with contemporary wind regimes. Fan sediments from the Providence Mountains are situated mostly to the east of the eastern dune fields (Figs. 3, 5, 7). Winds from the southeast occur only in late summer and, with less frequency, in late winter (Fig. 4). Although derivation of the eastern dune fields from Providence Mountains fan sediments under easterly winds is possible, stratigraphic and geomorphic studies by McDonald et al. (2003) suggest another explanation. Work by these investigators on the geomorphology and stratigraphy of Providence Mountains fan deposits shows that older fan sediments are found beneath some of the aeolian sands of the eastern dune fields. Further, aeolian sands and fan sediments are interbedded in parts of the eastern dune fields and in places fan sediments are found west of some of the eastern dunes (see Fig. 8d for an example). Thus, distal fan sediments from the Providence Mountains, found to the west of the eastern dune fields, could have been the source of these dunes and would require only winds from the west, which occur year-round (Fig. 4). We note that Sweeney et al. (2013) found that fans and dry washes from the Providence Mountains are an important source, via aeolian transport, of the sand fraction in eastern Mojave Desert soil Av horizons, which supports our interpretations.

Based on thermal infrared multispectral scanner (TIMS) data, Ramsey et al. (1999) also inferred that fan sediments from the Providence Mountains were an important source of sand for the Kelso Dunes. Of the eastern dune fields, Ramsey et al. (1999) inferred that the greatest influence of Providence Mountains fan sediments, with respect to K-feldspar inputs, was in dune unit V, with the least influence on dune unit II. With the data presented here, we agree with Ramsey et al. (1999) that Providence Mountains fan sediments were likely an important influence on the origin of the eastern dune fields.

We summarize our interpretations of the origin of the youngest aeolian sands in the Kelso Dunes region in two different scenarios shown on Landsat imagery (Figs. 15a,b). In the interpretation shown in Fig. 15a, western dunes are derived from Mojave River Wash sands from northerly (fall and winter) and westerly (year-round) winds, combined with possible inputs from Budweiser Wash from southwesterly winds (year-round). Eastern dunes are derived from Providence Mountain fan sediments from southeasterly winds (summer) and/or Granite Mountains fan sediments and Budweiser Wash sediments from southwesterly winds (year-round). In the interpretation shown in Fig. 15b, western dunes are derived from various sources as described in the first scenario. However, in this alternative sequence of events, the eastern dune units are derived from distal Providence Mountain fan sediments that were deposited close to Kelso Wash and then entrained by winds from the west (year-round) and transported back up onto proximal Providence Mountains fan sediments. This latter scenario would also imply that

Cottonwood Wash (Figs. 5-7) has been a significant barrier to sand transport from sources to the west and northwest (i.e., the Mojave River). Of the two scenarios, we favor the second, because the dominance of westerly winds in the region supports it and it is consistent with stratigraphic evidence of interbedded aeolian sand and Providence Mountains fan deposits, documented by McDonald et al. (2003). With either interpretation, however, it is clear that the origin of the Kelso Dunes is more complex than the single-source, Mojave River model that has been envisaged by most investigators for the better part of a century.

Information on the composition of Kelso Dunes provides constraints on the age of the dune field. Although local sources of sand are clearly important, the volume of sediment generated from them is likely insufficient compared to the volume of sand in the dune field, which is estimated to be ~1 km^3 (Lancaster, 1993). The lower reaches of the Mojave River have a complex history of drainage integration (Enzel et al., 2003), and recent studies indicate that the Mojave River reached the Soda Lake basin and present day Mojave River Sink via Afton Canyon sometime after 25 ka (Reheis and Redwine, 2008; Reheis et al., 2012). Based on sediment composition, it is likely that the dune field has accumulated episodically over the past ~25 ka, although small dune areas fed by local sources may have existed prior to that time.

5.2. Use of K/Rb and K/Ba to understand aeolian sand provenance in large sand seas on other continents

One conclusion from our studies is that even though the Kelso Dunes are a relatively small dune field, more than one source of sand is apparent from the data we present here. Thus, it seems likely that larger dune fields, and certainly ergs or large sand seas, also likely have complex origins. The use of K/Rb and K/Ba in K-feldspar as a provenance indicator leads us to propose that this method could be applied to investigations of dune origins in many of the world's large sand seas. Sand seas cover a significant amount of land area in the low-latitude deserts of Africa, Asia, and Australia and at higher latitudes of Asia where structural basins are rimmed by mountains that provide rain-shadowed topographic lows (Fig. 16). Here we present some examples of dune fields on other continents whose origins are not understood or are controversial and where we believe the methodology applied to the Kelso Dunes could be used for determination of sand provenance. In some cases, there are also good reasons why the approach would *not* be useful and we give examples of these as well.

5.2.1. Saharan and Sahel dunes of Mauritania and Senegal

Spectacular linear dunes are found over a large area of western Mauritania in the southern Sahara Desert (Fig. 16). Long axes of these dunes are aligned northeast-to-southwest, in good agreement with resultant drift directions (RDDs) computed by Fryberger and Ahlbrandt (1979) and Breed et al. (1979). Lancaster et al. (2002) documented at least three ages of dunes with luminescence dating in this region and showed that although all were generated by dominantly northeasterly winds, each phase of dune-building was associated with a slightly different wind regime. Many of these dunes are still active today (Figs. 17a, b). To the south in Senegal, dunes are also found but are stabilized by vegetation (Figs. 17a, c). In a now-classic paper, Grove and Warren (1968) hypothesized that the stabilized linear dunes in Senegal are continuations of what were once more extensive linear dunes originating farther north, in Mauritania. Further, they speculated that movement of aeolian sand would have blocked the Senegal River in its lower reaches, presumably filling the valley downstream and allowing aeolian sand migration to continue to the southwest. Mapping from early Landsat imagery by Breed et al. (1979) confirms the possibility of such a sequence of events. To our knowledge, this intriguing hypothesis has never been tested with any rigorous field and laboratory studies. An alternative explanation is that the stabilized dunes to the south derived their sand independently from the Senegal River at some hypothetical time or times when there was at least seasonally low discharge. Determination of K/Rb and K/Ba values in sands from the dunes in Mauritania, the Senegal River (upstream of the dunes, to avoid problems of fluvial reworking of dune sand from the north), and dunes in Senegal (the Ferlo-Cayor dune field) could provide a test of this hypothesis. Dunes in Mauritania contain 0.2-0.7% K_2O (Lancaster et al., 2002), indicating that they are likely mineralogically mature, or rich in quartz. Nevertheless, even this amount of K_2O indicates the likely presence of K-feldspar in sufficient amounts to allow a provenance study using K/Rb and K/Ba.

5.2.2. Namib Sand Sea, southwestern Africa

The Namib Sand Sea is a large (~34,000 km^2), active dune field along the coast of Namibia in southwestern Africa (Figs. 16, 18). A wide variety of aeolian landforms can be found in the Namib sand sea, including barchanoid ridges (particularly on the coast), linear dunes (inland, in the southern part), linear dunes with superimposed star dunes (inland in the southern part), and sheet sands (northern, eastern and southern margins) based on studies by Breed et al. (1979) and Lancaster (1989). Dune orientations indicate that major dune-forming winds came mainly from the south, which is consistent with modern resultant drift directions (Fig. 18). Lancaster (1989) has shown that physical properties of the dune sediments vary spatially: dunes are redder, and particles are more rounded and better sorted in a west-to-east direction (Fig. 18), suggesting that the youngest sediments are near the coast and older sediments are found inland. Based on data from cosmogenic isotopes, the Namib Sand Sea may have been in existence as a dune field for at least the past million years (Vermeesch et al., 2010).

The origin of dune sand in the Namib Sand Sea has been discussed for the better part of a century and debate continues to the present decade. Gevers (1936), Logan (1960), Hallam (1964) and Rogers (1977, 1979) all thought that sand in this dune field was ultimately derived from sediments of the Orange River, which is upwind of the Namib Sand Sea (Fig. 18). Besler and Marker (1979, p. 159) and Besler (1980, 1984), however, challenged this hypothesis and proposed that the Tsondab Sandstone (referred to as the Namib Sandstone by these investigators), which crops out to the east of the sand sea, below the Great Escarpment (Fig. 18), was the more likely source. These workers envisioned fluvial erosion of the sandstone with delivery to the west, followed by aeolian reworking to the north. Lancaster and Ollier (1983) conducted heavy mineral analyses of both dunes in the Namib Sand Sea and possible sources, including the Tsondab Sandstone, but not sands from the Orange River. They concluded that an Orange River source from the south was likely, but pointed out that their data would permit an interpretation that local additions from the Tsondab Sandstone could have been important in the eastern part of the dune field. These investigators note that the light mineral fraction of the Tsondab Sandstone is similar to that of the dune sands. Besler (1996), in a follow-up study, maintained her assertion that the Tsondab Sandstone is a significant source of Namib dune sand. White et al. (2007) took a different approach to studying the Namib dunes and used remote sensing of Fe-oxide content in the dunes to infer at least two sources of sand, one eroded from rocks of the Great Escarpment and the other derived from southern, coastal sources. Vermeesch et al. (2010) determined U-Pb ages of detrital zircons from both dunes of the Namib Sand Sea and one sample from sediments of the Orange River. Although they interpret their age spectra from the westernmost dunes to indicate an Orange River source, they also point out that dunes in the eastern part of the sand sea have age spectra that differ significantly from those in the western part of the dune field. These investigators did not provide data on the U-Pb ages of zircons from the Tsondab Sandstone, so it is not possible to know at present if contributions from this formation could be responsible for the difference in zircon age spectra. Garzanti et al. (2012) reiterated the U-Pb zircon age data of Vermeesch et al. (2010) and in addition provided detailed mineralogical data for four samples of Orange River sands and 12 Namib dune sands, as well as about a dozen sediment samples from rivers draining the Great Escarpment. These authors state that their mineralogical comparison of these samples 'proves' that most of Namib aeolian sand is derived from the Orange River. In making this rather categorical statement, the authors chose to ignore the larger heavy mineral data set presented by Lancaster and Ollier (1983), and even disregard the implications of the U-Pb zircon age spectra that they themselves presented. Finally, Stone (2013) presented a comprehensive review of all the previous studies and concluded that the majority of evidence pointed to the Orange River as the most important source, with local contributions from fluvial systems draining the Great Escarpment being secondary sources.

Lancaster and Ollier (1983) reported that the light mineral fractions of Namib Sand Sea sands consist of quartz, K-feldspar, and plagioclase. Garzanti et al. (2012) reported quartz contents of 66-79% and feldspar contents (presumably both plagioclase and K-feldspar) of 16-26%, with the remainder being rock fragments. The latter data agree with mineralogical and whole-sediment, major-element geochemical data reported by Muhs (2004). In that study, Muhs (2004) reported that quartz is the most important mineral in Namib dune sands, but all samples examined have abundant plagioclase, K-feldspar, and rock fragments. In addition, a few samples appear to have trace amounts of calcite and dolomite. Geochemical analyses of Muhs (2004) support the mineralogical data of Garzanti et al. (2012), as SiO_2 contents are 81-87%, Al_2O_3 contents are 5.0-6.8%, Na_2O contents are 1.0-1.4% and K_2O contents are 1.0-2.0%. Thus, K/Rb and K/Ba analyses could easily be conducted on sediments of the Namib Sand Sea as there is sufficient K-feldspar, based on both mineralogical and geochemical data. Such analyses, if conducted over a major part of the dune field, along with analyses of Orange River sands, fluvial sands draining the Great Escarpment, and sands from the Tsondab Sandstone, could potentially provide information about whether there is more than one source for the Namib Sand Sea.

5.2.3. Grand Erg Oriental, Algeria and Tunisia

The Grand Erg Oriental is one of the largest sand seas in North Africa and may cover as much as 192,000 km^2 (Wilson, 1973). Despite its large size and mostly active condition (Fig. 19), there have been remarkably few studies of its origins, likely because of the inaccessibility of much of the dune field. Nevertheless, there have been a handful of studies that have offered hypotheses for its origin. Bellair (1953) is one of the few investigators who did mineralogical analyses of the Grand Erg Oriental. He reported that the dunes are dominated by quartz, but also locally contain gypsum and anhydrite. Using heavy mineral separates from dune sands collected along a ~400 km transect between El Oued and Ghudamis (Fig. 19), he found that the composition changed significantly ~300 km southeast of El Oued, near Sif-Fatima. From this, Bellair (1953) concluded that the

Grand Erg Oriental was derived from diverse sources. Later researchers have based their hypotheses about dune origins in this large erg mainly on interpretations of maps, aerial photographs, and satellite imagery. Breed et al. (1979) interpreted Wilson (1973) to say that the Grand Erg Oriental was derived from alluvium in basins upwind of the dune field, but Wilson (1973) was actually not this specific. Although the Grand Erg Oriental was a major focus of his study, with regard to sources Wilson (1973) stated simply that ergs in most deserts are derived from alluvium. Fryberger and Ahlbrandt (1979), interpreting Landsat imagery, hypothesized that large wadi systems draining bedrock uplands to the northwest were likely contributors to sand in the Grand Erg Oriental. Mainguet (1978, p. 20), however, rejected the idea of local alluvium being a major source of sand for the Grand Erg Oriental (and for other Saharan ergs as well) and thought that sand was derived from distant sources, hundreds or perhaps thousands of kilometers away. In a later paper (Mainguet, 1984), it was emphasized that the Grand Erg Oriental was a *source* of sand for other ergs, namely the Erg Chech (to the southwest) and the Erg Issaousane (to the south).

All of these hypotheses can be tested with a systematic program of sampling alluvial sands found upwind of the Grand Erg Oriental, transects of dunes within the erg itself, local sources of alluvium to the east and west of the erg, and sand within the Erg Chech and Erg Issaouane to the southwest and south. Analyses of K/Rb and K/Ba in K-feldspar would help to test the hypotheses of (1) diverse local contributions to the Grand Erg Oriental (Bellair, 1953); (2) wadi sources upwind of this sand sea (Fryberger and Ahlbrandt, 1979); and (3) erg-to-erg sand transport, with the Grand Erg Oriental being a source as well as a sink for wind-blown sand (Mainguet, 1984). Such an approach requires, of course, that K-feldspar is present in sands of the Grand Erg Oriental. This is not a trivial issue, as some dune sands in the Sahara are mineralogically mature, and absolutely dominated by quartz. To test for the feasibility of doing further studies, we sampled nine dune sand samples in the northeastern margin of the Grand Erg Oriental, in southern Tunisia (three samples from a 10-meter high dune at N33°31'42.4"; E08°47'11.5" and six samples from 4-6-meter high dunes within a 200-meter radius of N33°26'58.2"; E08°51'57.0"). We analyzed these sediments for mineralogy (by XRD) and major-element geochemistry (by WD XRF). Results indicate, in broad agreement with Bellair (1953), that quartz is dominant in these dune sands, with subordinate amounts of calcite and gypsum. In addition, however, all Grand Erg Oriental samples we studied contain measurable amounts of K-feldspar and some even contain plagioclase. Concentrations of K_2O range from 0.7-0.9% and Na_2O contents are 0.13-0.19%, confirming the presence of both species of feldspar inferred from XRD. Thus, the potential for learning more of the provenance of sand in the Grand Erg Oriental is high and could benefit from K/Rb and K/Ba analyses of K-feldspar in these dunes and potential sources.

5.2.4. Sinai-Negev sand sea, Egypt and Israel

The Sinai-Negev sand sea (Fig. 19) is a single geomorphic entity, but both names are applied here because the dune body is found in both Egypt (Sinai) and Israel (Negev). As has been the case with the history of studies of the Kelso Dunes, essentially one sediment source alone has been proposed for the Sinai-Negev dune field, namely sand from the Nile Delta (see review in Muhs et al., 2013a). Interestingly, identification of the Nile as a source for the Sinai-Negev erg sands seems to have been both a working assumption as well as an untested hypothesis (Neev et al., 1987; Goring-Morris and Goldberg, 1990; Pye and Tsoar, 2009; Amit et al., 2011; Roskin et al., 2011, 2012). Indeed, Davis et al.

(2012) even proposed that the Nile has been a major source for aeolian sediments in Israel for the past ~2.5 million years, based on cosmogenic isotope evidence from quartz. And, in point of fact, the best argument for a Nile Delta source is the simple lack of evidence for other likely sources (Tsoar et al., 2008), although this does not in and of itself constitute proof.

Other possible quartz-rich sources for the Sinai-Negev erg are, however, very limited. Areas in central Sinai within the Wadi El Arish drainage basin (Fig. 19) have bedrock dominated by Cretaceous or Eocene rocks. Although these rocks are composed mostly of carbonate facies, Bartov (1990) reports that sandstone facies are also present in two of the Cretaceous units. These rocks are situated in the upper drainage basin area of Wadi El Arish and thus provide a source that is upstream and upwind of much of the Sinai-Negev dune field. Farther north, in north-central Sinai, Lower Cretaceous sandstones, now part of what is called the Kurnub Group (Bartov, 1990), were formerly referred to as 'Nubian Sandstone.' These rocks are downwind of many of the dunes in the erg, however, so at most they constitute a potential source for only part of the erg.

Muhs et al. (2013a) conducted mineralogical and geochemical studies of the Sinai-Negev dune field, sand-sized particles from the Nile Delta, and sand-sized alluvium from Wadi El Arish. They report that ternary diagrams of Fe_2O_3-MgO-TiO_2, a geochemical proxy for heavy mineral assemblages, show that Nile Delta sands and Wadi El Arish alluvial sands in Sinai have distinctive compositions, with no overlap. Sinai-Negev dune sands fall mostly within or close to the field defined by Nile Delta sands, although some samples fall within the range of Wadi El Arish alluvial sands. Furthermore, most Sinai-Negev dune sands contain calcite, which is largely absent from Nile Delta sands, but is abundant in sands from Wadi El Arish. Thus, although the evidence points to the Nile Delta as the major source of heavy minerals in the Sinai-Negev dune field, Wadi El Arish has likely contributed most of the calcite to the dunes. An interesting question that arises, therefore, what the relative contributions of Nile Delta sands and Wadi El Arish sands are to the light, silicate mineral fraction (quartz, plagioclase, K-feldspar) of Sinai-Negev dunes. Geochemical plots of mineralogical maturity (Log [Na_2O/K_2O] vs. Log [SiO_2/Al_2O_3]) that measure feldspar depletion relative to quartz show that many Sinai-Negev dunes have compositions that fall within the range of Nile Delta sands, but some fall within the range of Wadi El Arish sands, and some could have had contributions from both sources. Investigations by Muhs et al. (2013a) show that K-feldspar is present in measurable amounts in Nile Delta sands, Wadi El Arish sands, and Sinai-Negev dune sands, and concentrations of K_2O in these sediments, with a couple of exceptions, range from 0.4-1.4%. A worthwhile effort, therefore, would be to analyze both Nile Delta sands and Wadi El Arish sands for K/Rb and K/Ba. If these two sand sources show distinctive K/Rb and K/Ba compositions, then it should be possible to determine the relative contributions of each source to the light, silicate mineral fraction of Sinai-Negev dunes.

5.2.5. Problems in applying the method to certain other dune fields

Although we propose here that K/Rb and K/Ba data from K-feldspars might yield much new significant information about the sources of dunes in many sand seas, we recognize that there are a number of places where such studies would not be feasible. The limiting factor in many dune fields worldwide is simply lack of K-feldspar. Dunes in many of the world's great sand seas are mineralogically mature, dominated by quartz, and of course at least some minimum amount of K-feldspar is required for K/Rb and K/Ba studies. As an example, consider the arid interior of Australia, where much of the landscape is covered with large fields of predominantly linear dunes (Fig. 16). Mineralogical analyses by both microscopic examination of grains and X-ray diffraction show that only one sample from the Great Sandy Desert had even the slightest trace of feldspar, with all others showing only quartz (Muhs, 2004), confirming earlier findings of Goudie et al. (1993). Geochemical analyses support these findings, as all samples have SiO_2 contents of 95-98% and K_2O contents of only 0.03-0.08%. It is likely, given that quartz was essentially the only sand-sized grain observed, that the small amounts of Al_2O_3 (0.5-1.7%) and K_2O do not represent feldspar but are reflecting the presence of clay mineral coatings that were not completely removed in the pre-treatment process. Thus, we propose that use of U-Pb age spectra of detrital zircons, such as those conducted by Pell et al. (1999, 2000) for the Great Victoria, Simpson, Strzelecki, and Tirari Deserts (Fig. 16) is a more appropriate method for provenance studies of mineralogically mature Australian dunes.

Although we presented data to show that the Grand Erg Oriental has sufficient K-feldspar to make K/Rb and K/Ba studies feasible, this is not true for all dune fields in the Sahara. The Zallaf sand sea, the easternmost arm of the larger Ubari dune field of Libya (McKee and Tibbitts, 1964; Walker, 1979; Breed et al., 1979), is such an example (Fig. 16). Muhs (2004) showed that in this dune field, quartz is the only mineral in some samples and K-feldspar is present only in very small amounts in other samples. The dominance by quartz with only minor amounts of (or no) K-feldspar in sands from the Zallaf sand sea is supported by major element geochemistry, with SiO_2 contents of 97.9-98.5% and K_2O contents of only 0.12-0.17%.

6. Summary and conclusions

The Kelso Dunes are unusual among dune fields of the western USA in that there is a wide variety of dune forms occupying a small area. In addition, they are also partially active, which is rare among dune fields in the deserts of the western USA. Over eight decades, there has been much speculation about the origin of the dunes, but the majority of investigators have favored a simple, Mojave-River-dominated source. Nevertheless, with a couple notable exceptions, these studies have not presented mineralogical or geochemical data to ascertain possible dune sources and thus are of a speculative nature.

Analysis of the geomorphology of Kelso Dunes suggests the possibility of derivation from more than one source. Many of the dunes have orientations indicating dominantly westerly or northwesterly winds during their formation, consistent with a Mojave River source. On the other hand, other dunes show an orientation indicating southwesterly winds or have a complex nature, with the earlier phase of dune development indicating formation under southwesterly winds.

In previous studies that have presented mineralogical data, two report that the Kelso Dunes are quartz-rich. Given the likelihood of short transport distances and the granitic composition of all the surrounding mountain ranges, a dominance of quartz in Kelso Dunes, indicating mineralogical maturity, would be surprising. Mineralogical and geochemical data presented here indicate that the dunes are far less quartz-rich than previous studies have indicated, with relatively high abundances of plagioclase and K-feldspar. The presence of K-feldspar can be used to identify the source or sources of aeolian sand in Kelso Dunes, through K/Rb and K/Ba values in this mineral. These values reflect compositions of K-feldspars from different alluvial sources and ultimately

K-feldspars from different source rocks. Although there is some overlap among different alluvial sources, several of these can be distinguished from one another, allowing some inferences about what fed the Kelso Dunes. Comparison of K/Rb and K/Ba in aeolian sands with alluvial sources indicates that sands in the nine western dune groups have compositions that are indistinguishable from Mojave River alluvium and Budweiser Wash alluvium. Mojave River alluvium would require northwesterly or westerly winds whereas Budweiser Wash alluvium would require southwesterly winds to build dunes. Thus, whereas many previous interpretations have inferred a single Mojave River source, the new results indicate that two sources could have supplied sand to the western dune fields. 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 southeast or, more likely, aeolian reworking of distal Providence Mountain fan sediments by winds from the west, at a rate greater than that from Mojave River or other western source inputs. Overall, the results indicate that even a small dune field can have a complex origin, either from seasonally varying winds or complex fan-dune interaction. Our case study of the Kelso dunes demonstrates the potential of using K/Rb and K/Ba in K-feldspar as an indicator of sand provenance that can be applied to understand sediment sources and transport pathways in many sand seas worldwide.

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Figure captions

FIGURE 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).

FIGURE 2. Map showing a part of eastern California and adjacent Nevada, the location of Mojave National Preserve (brown shading – online version), major towns and highways, and location of the Devils Playground dune field and Kelso Dunes.

FIGURE 3. Landsat ETM+ image (Path 39; Row 36), 20 May 2006, band 1, showing the Kelso Dunes and surrounding area. Numbered features indicate hypothesized source sediments; PM, Providence Mountains; GM, Granite Mountains.

FIGURE 4: Wind roses for four representative months of the year from the Mojave 'Sink' area (see Fig. 3 for location); period of record, 1988-2009. Only shown are frequencies of winds above the threshold velocity for medium sand (~5 m/s) when considered at an instrument measurement height of 10 m. Note scale change for the month of May. Graphs compiled from data from the Western Regional Climate Center of the Desert Research Institute, Reno, Nevada USA (http://www.wrcc.dri.edu).

FIGURE 5. Enlargement of a portion of the Landsat ETM+ image shown in Fig. 3, showing aeolian landform groups (Roman numerals) in the Kelso Dunes identified by Lancaster (1993, 1994) on the basis of geomorphology.

FIGURE 6: U.S. Geological Survey aerial photograph (National Aerial Photography Program or NAPP, acquired 24 July 1989) of a portion of the Kelso Dunes area; Roman numerals designate aeolian landform groups identified by Lancaster (1993, 1994; see also Lancaster and Tchakerian, 2003). Cottonwood Wash, in the

center of the photograph, divides what is designated herein as 'western dune groups' and 'eastern dune groups.'

FIGURE 7: Oblique aerial photograph (acquired at an altitude of ~10,000 m), looking south, of the Kelso dunes and adjacent mountain ranges and drainages. Roman numerals designate aeolian landform groups identified by Lancaster (1993, 1994; see also Lancaster and Tchakerian, 2003). Photo courtesy of Tracy Rowland.

FIGURE 8: Ground photographs of the Kelso Dunes, showing some of the major dune groups shown in Figs. 5-7 and surrounding mountain ranges. In photograph (c), red arrows point to heavy mineral concentrations on dune crests. Photos by D. Muhs.

FIGURE 9: Ternary plots of percentages of quartz, K-feldspar, and plagioclase (calculated as a sum of 100% for these three mineral species) for the Kelso Dunes, shown in all four diagrams as red squares. See text for methods of estimating mineral content percentages. Shown for comparison are ranges of compositions for these three minerals for (a) the Algodones Dunes, California (mineralogical data from this study; samples from Muhs et al., 1995); (b) San Nicolas Island, California dunes and the Parker Dunes, Arizona; (c) the Cadiz/Danby Dunes, California (mineralogical data from this study; samples from Muhs et al., 2003); and (d) the Soynota dunes, Sonora, Mexico (mineralogical data and samples from this study, but see Scheidt et al., 2011 for additional data).

FIGURE 10: Plots showing weight-percent concentrations of K_2O (representing mostly K-feldspar) and CaO (representing mostly plagioclase possibly with minor

amphibole and calcite) from the Kelso Dunes, shown as red squares in all graphs. (a) Concentrations of K_2O and CaO in Kelso Dunes compared to ranges in granites and granodiorites (data from Nockolds, 1954); and (b), (c), (d) Concentrations of K_2O and CaO in Kelso Dunes compared to similar data for the Algodones Dunes, California (data from Muhs et al., 1995), the Parker Dunes, Arizona, the Cadiz/Danby Dunes, California, and the Dale Lake sand sheet, California (data from Muhs et al., 2003).

FIGURE 11: Plots of concentrations of Ti vs. Ce ,Y, and Nb, and Zr vs. Ce and Y in the Kelso dunes, all geochemical indicators of the heavy mineral suite.

FIGURE 12: Plots of K/Ba vs. K/Rb, representing mostly K-feldspar compositions, for aeolian sands from Devils Playground (Fig. 3), shown as solid green circles, compared to range of compositions for these element ratios for hypothesized source sediments, shown in Fig. 3.

FIGURE 13: Plots of K/Ba vs. K/Rb, representing mostly K-feldspar compositions, for dune sands from the western groups of Kelso Dunes (units VI through XIV on Figs. 5-7), shown as open black circles, compared to range of compositions for these element ratios for hypothesized source sediments, shown in Fig. 3.

FIGURE 14: Plots of K/Ba vs. K/Rb, representing mostly K-feldspar compositions, for dune sands from the eastern groups of Kelso Dunes (units I through V shown on Figs. 5-7), shown as open blue circles, compared to range of compositions for these element ratios for hypothesized source sediments, shown in Fig. 3.

FIGURE 15: Alternative interpretations of the origin of the eastern dunes in the Kelso Dunes region based on geochemical data presented in Figs. 12-14. Blue arrows in both (a) and (b) (see online version) represent sand-transporting winds, as shown in Fig. 4. In interpretation (a), western dunes are derived from the Mojave River by western winds (year-round) and Granite Mountain fans and Budweiser Wash sediments by southwesterly winds (year-round). Eastern dunes are derived from Providence Mountain fan sediments from southeasterly winds (summer only). In interpretation (b), western dunes are derived as in (a), but eastern dunes are derived from distal Providence Mountain fan sediments deposited close to Kelso Wash and then entrained by winds from the west and blown back up onto proximal Providence Mountains fan sediments. Images in both (a) and (b) are from Landsat ETM+ (Path 39; Row 36), 20 May 2006, band 1, as in Fig. 3.

FIGURE 16: Map showing the distribution of aeolian sand, whether active or stabilized, in Africa, Asia, and Australia. Sources of information: northern Africa: Wilson (1973); southern Africa: Lancaster (1988, 1989) and Thomas and Shaw (1991); Sinai-Negev: Muhs et al. (2013a); Arabian Peninsula and India: Wilson (1973); Central Asia: Maman et al. (2011); China: Sun and Muhs (2007) and sources therein; Australia: Bowler et al. (2001).

FIGURE 17: (a) Moderate Resolution Imaging Spectrometer (MODIS) natural-color image from NASA's Terra satellite, acquired 14 January 2015, showing mostly active dune fields (Azefal, Akchar, and Aoukar) in Mauritania (north of the Senegal River) and the stabilized Ferlo-Cayor dune field in Senegal (south of the Senegal River). Blue arrows show resultant drift directions (RDDs) for aeolian

sand, from Fryberger and Ahlbrandt (1979) and Breed et al. (1979). Image courtesy of Jeff Schmaltz, LANCE MODIS Rapid Response Team at NASA Goddard Space Flight Center. (b) Ground photo (by N. Lancaster) of active linear dune in the Azefal sand sea of Mauritania. (c) Ground photo (by D. Muhs) of stable dune in the Ferlo-Cayor dune field, just north of Dakar, Senegal.

FIGURE 18: (a) MODIS natural-color image from NASA's Terra satellite, acquired on 26 June 2011, showing the Namib Sand Sea of Namibia, southwestern Africa, and rivers to the north and south. Light blue arrows show RDDs, from Breed et al. (1979) and Lancaster (1989). Dark blue arrows mark drainages from possible bedrock sources of sand adjacent to the Great Escarpment. Image courtesy of MODIS Rapid Response Team at NASA Goddard Space Flight Center (b) Ground photo of Namib dunes at their southernmost occurrence, near possible source areas, Elizabeth Bay area, just south of Luderitz (c) Ground photo of dunes in the Namib Sand Sea farther north in the main body of the dune field, where sand is redder (both ground photos by N. Lancaster).

FIGURE 19: (a) False-color Landsat ETM+ mosaic of parts of Algeria, Libya, and Tunisia showing the Grand Erg Oriental. Mosaic constructed from individual Landsat ETM+ images acquired from 1999-11-11 to 2001-06-97; image is N-32-30, courtesy of the University of Maryland. Blue arrows (see online version) show RDDs, from Fryberger and Ahlbrandt (1979) and Breed et al. (1979). (b) Ground photograph (by D. Muhs) of active dunes on the northeastern margin of the Grand Erg Oriental (N33°26'58.2"; E08°51'57.0"), southeast of Chott El Jerid.

FIGURE 20: (a) MODIS image of the Sinai-Negev dune field of Egypt and Israel, acquired from the NASA Aqua satellite on 6 February 2003. Also shown are possible source sediment areas for this dune field, the Nile Delta and the Wadi El Arish drainage basin. MODIS image courtesy of Jeff Schmaltz, MODIS Rapid Response Team, NASA Goddard Space Flight Center. Blue arrows indicate RDDs (from Muhs et al., 2013a). (b) Ground photograph (by D. Muhs) showing dunes of the Sinai-Negev dune field along the Egypt-Israel border, west of Halamish, Israel.

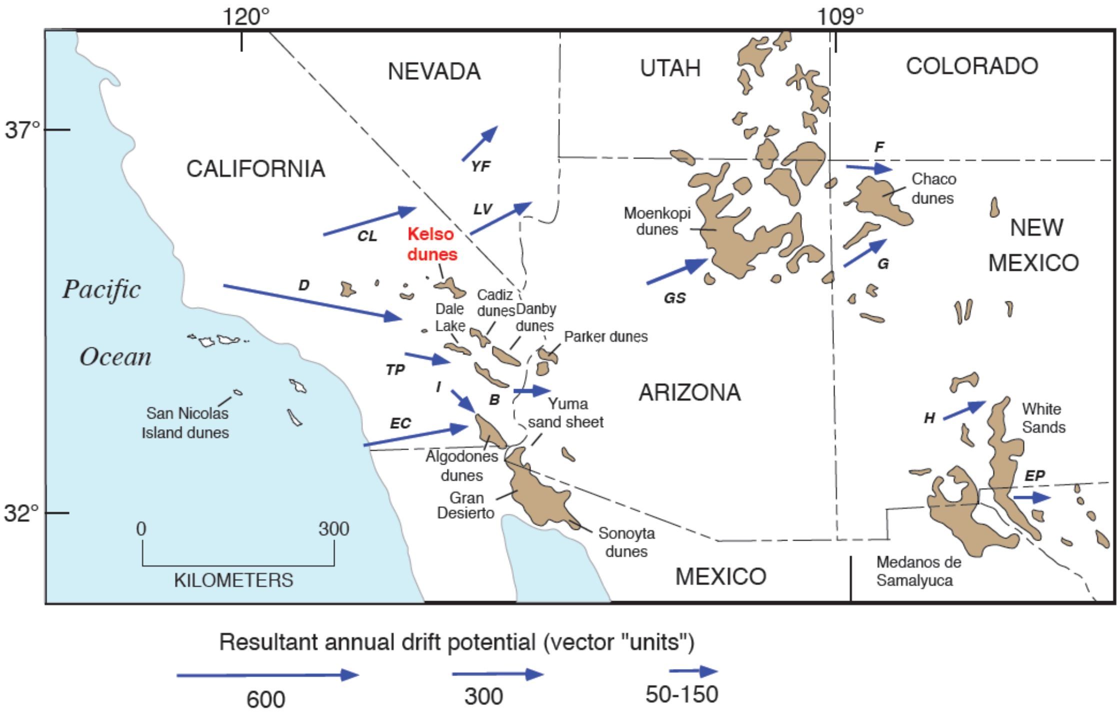

120°
109°
37°
32°
NEVADA
UTAH
COLORADO
CALIFORNIA
YF
LV
CL
Kelso dunes
F
Chaco dunes
Moenkopi dunes
NEW MEXICO
G
GS
D
Pacific
Ocean
Dale Lake
Cadiz dunes
Danby dunes
Parker dunes
TP
I
B
Yuma sand sheet
ARIZONA
San Nicolas Island dunes
EC
H
White Sands
Algodones dunes
EP
Gran Desierto
Sonoyta dunes
0
300
KILOMETERS
MEXICO
Medanos de Samalyuca
Resultant annual drift potential (vector "units")
600
300
50-150

Fig. 1

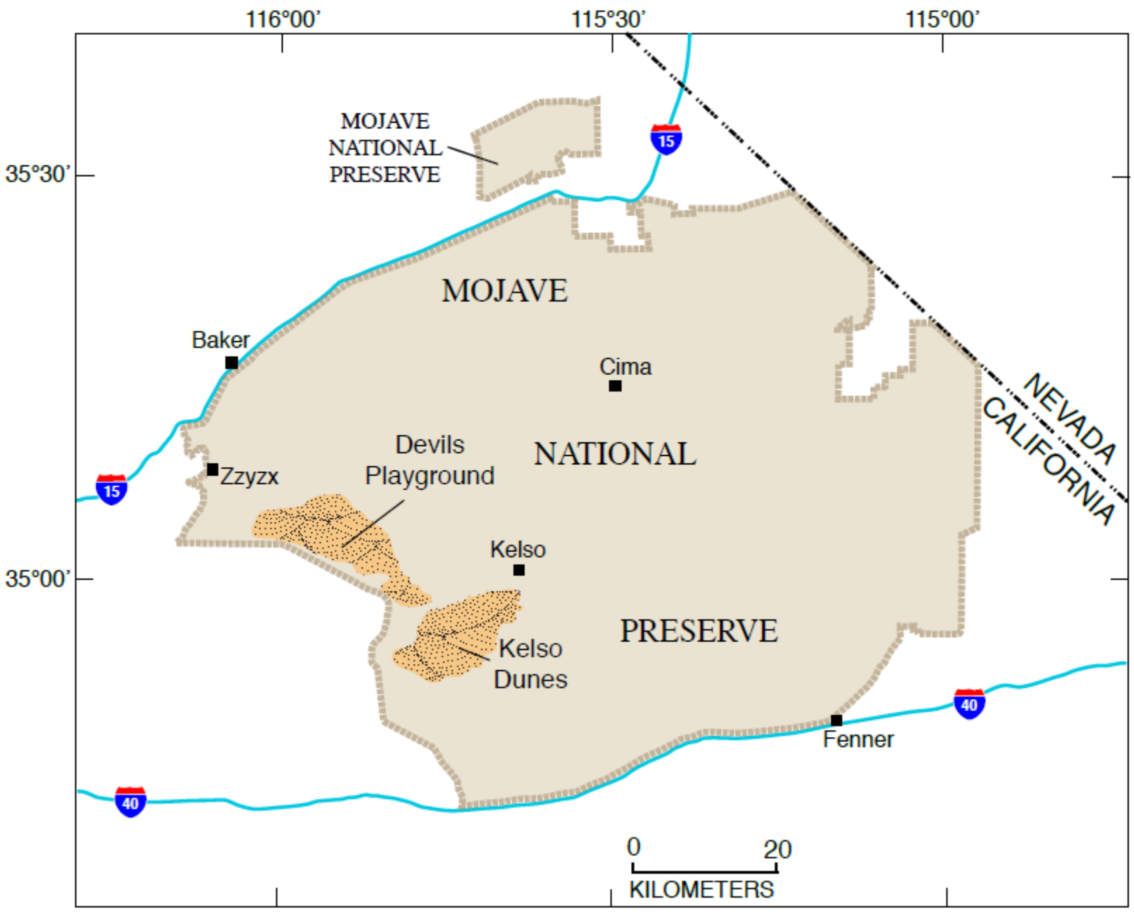

116°00'
115°30'
115°00'
35°30'
35°00'
MOJAVE
NATIONAL
PRESERVE
15
Baker
MOJAVE
Cima
NEVADA
CALIFORNIA
Zzyzx
Devils
Playground
NATIONAL
Kelso
Kelso
Dunes
PRESERVE
40
Fenner
0
20
KILOMETERS

Fig. 2

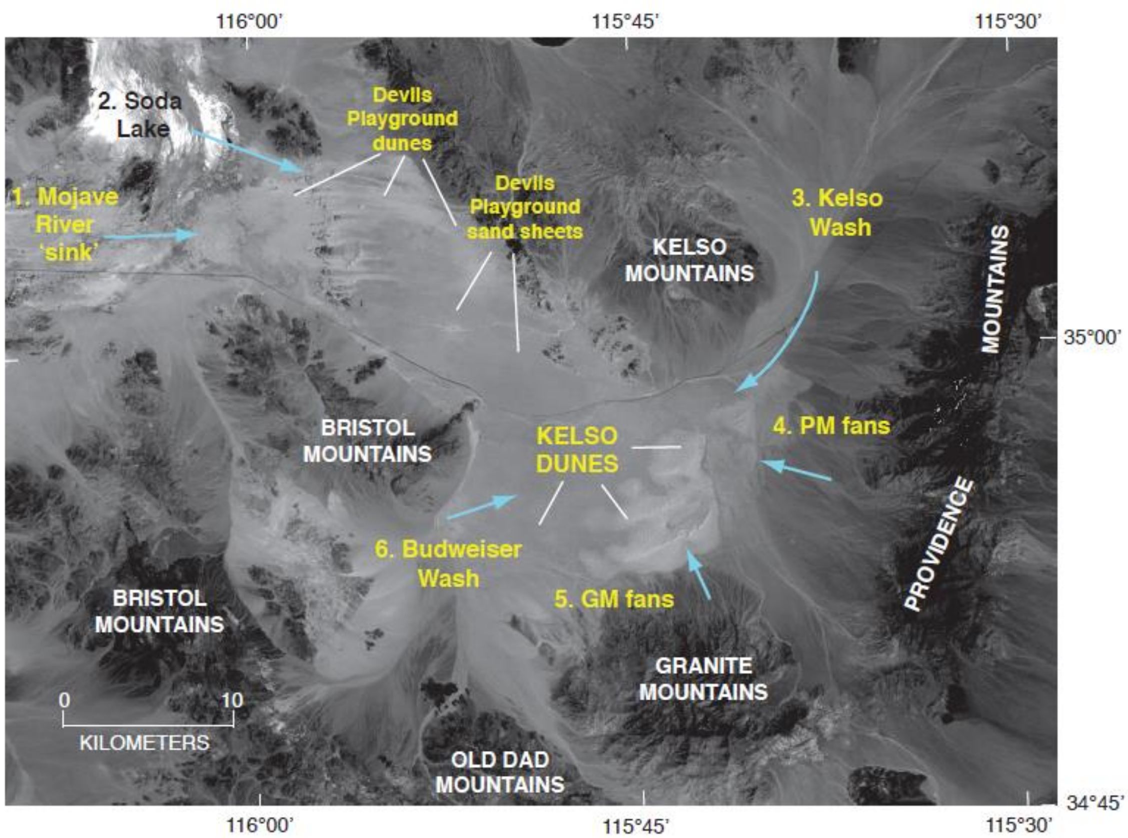

116°00'
115°45'
115°30'
2. Soda Lake
Devils Playground dunes
Devils Playground sand sheets
1. Mojave River 'sink'
3. Kelso Wash
KELSO MOUNTAINS
MOUNTAINS
35°00'
BRISTOL MOUNTAINS
KELSO DUNES
4. PM fans
6. Budweiser Wash
5. GM fans
PROVIDENCE
BRISTOL MOUNTAINS
GRANITE MOUNTAINS
0
10
KILOMETERS
OLD DAD MOUNTAINS
34°45'

Fig. 3

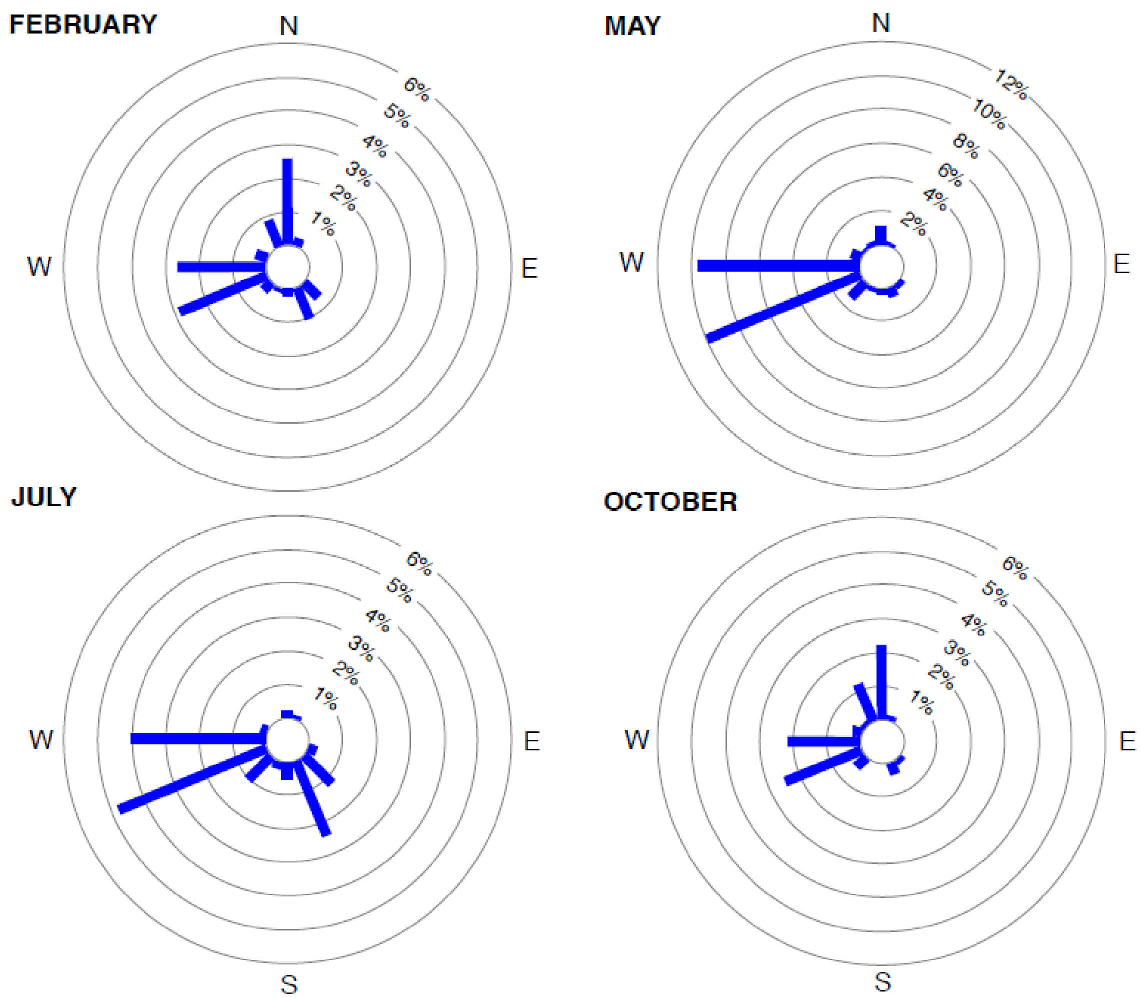

FEBRUARY
N
W
E
1%
2%
3%
4%
5%
6%
MAY
N
W
E
2%
4%
6%
8%
10%
12%
JULY
W
E
S
1%
2%
3%
4%
5%
6%
OCTOBER
W
E
S
1%
2%
3%
4%
5%
6%

Fig. 4

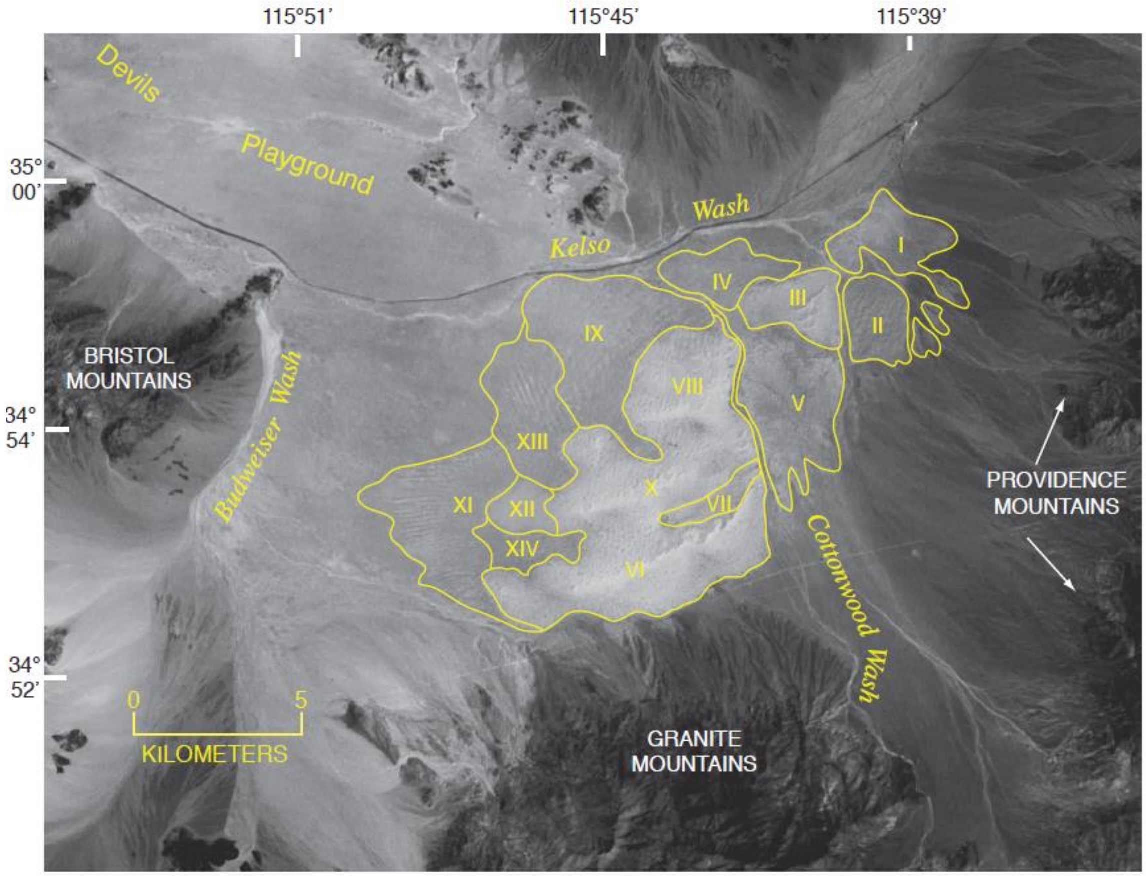
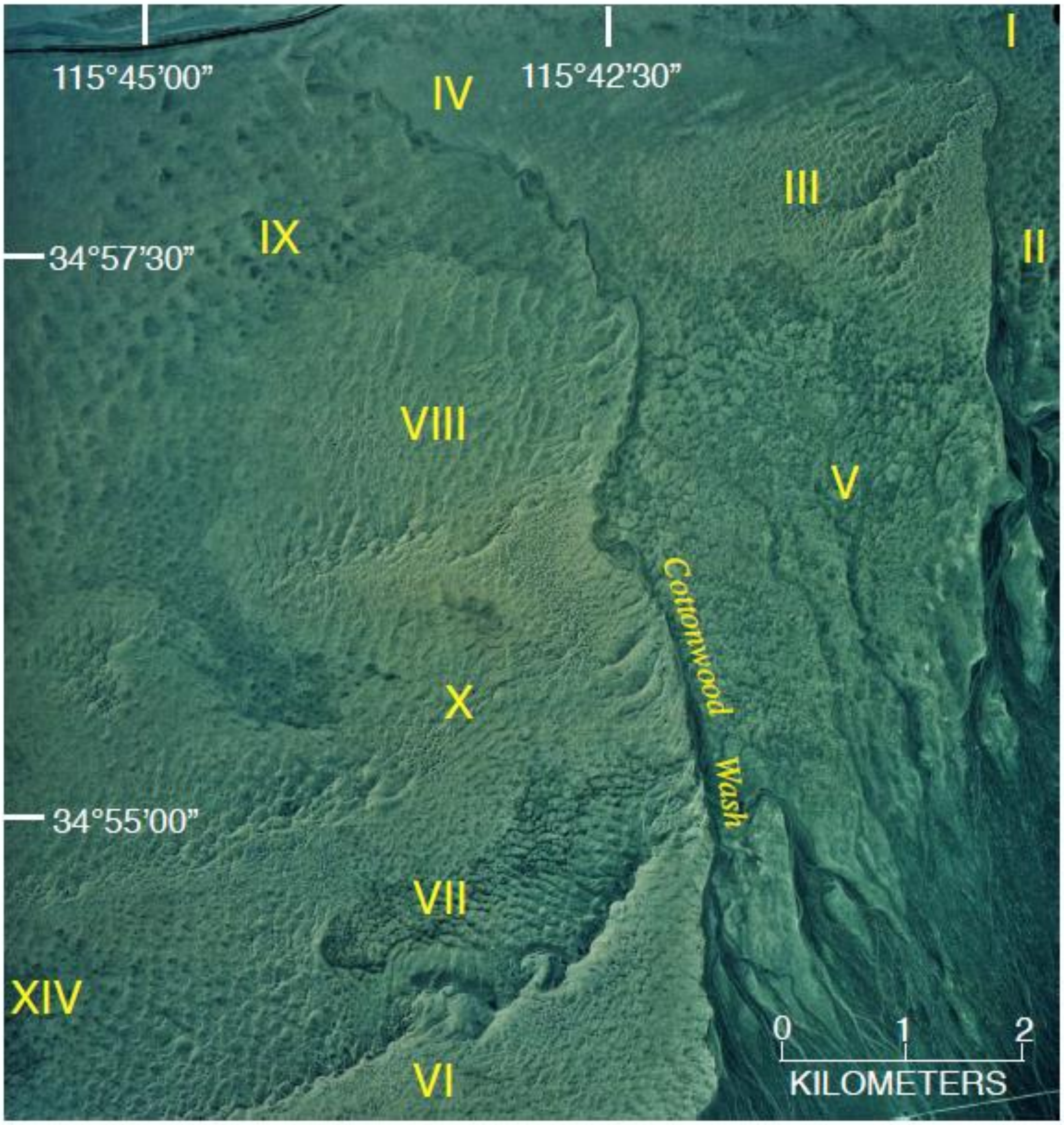

115°51'
115°45'
115°39'
35° 00'
34° 54'
34° 52'
Devils
Playground
Kelso
Wash
BRISTOL MOUNTAINS
Budweiser Wash
Cottonwood Wash
PROVIDENCE MOUNTAINS
GRANITE MOUNTAINS
0
5
KILOMETERS
I
II
III
IV
V
VI
VII
VIII
IX
X
XI
XII
XIII
XIV

Fig. 5



115°45'00"
115°42'30"
34°57'30"
34°55'00"
I
II
III
IV
V
VI
VII
VIII
IX
X
XIV
Cottonwood Wash
0
1
2
KILOMETERS

Fig. 6

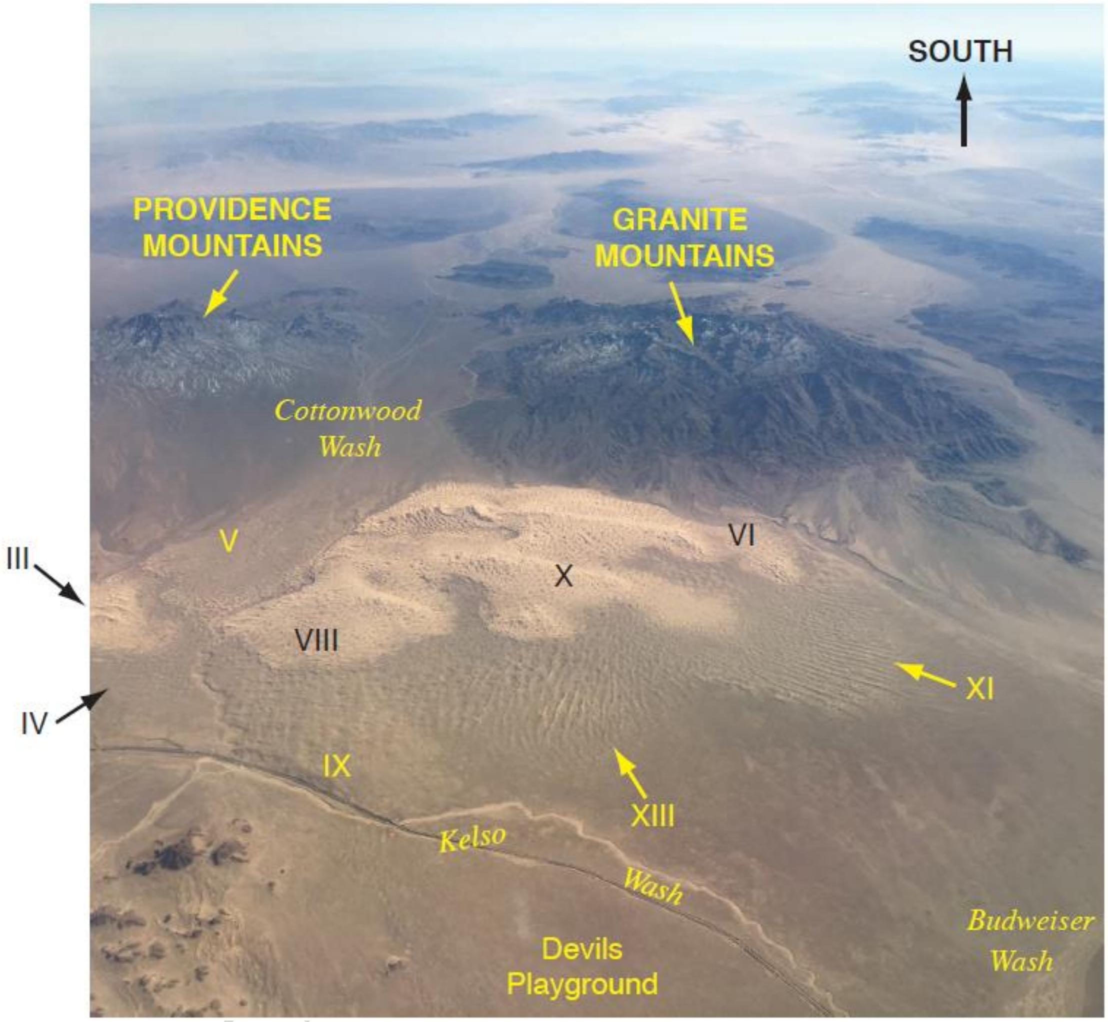

SOUTH
PROVIDENCE MOUNTAINS
GRANITE MOUNTAINS
Cottonwood Wash
III
V
VI
X
VIII
IV
XI
IX
XIII
Kelso Wash
Budweiser Wash
Devils Playground

Fig. 7

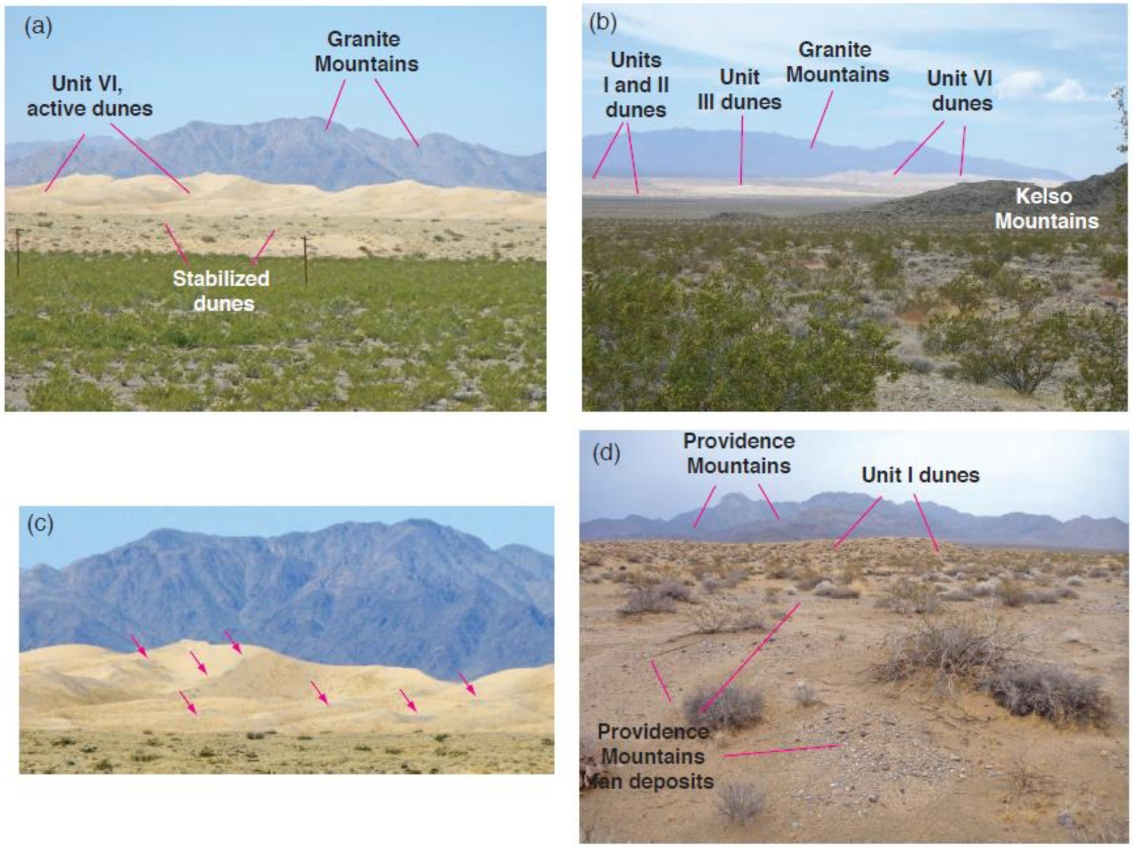

(a)
Granite Mountains
Unit VI, active dunes
Stabilized dunes
(b)
Units I and II dunes
Unit III dunes
Granite Mountains
Unit VI dunes
Kelso Mountains
(c)
(d)
Providence Mountains
Unit I dunes
Providence Mountains fan deposits

Fig. 8

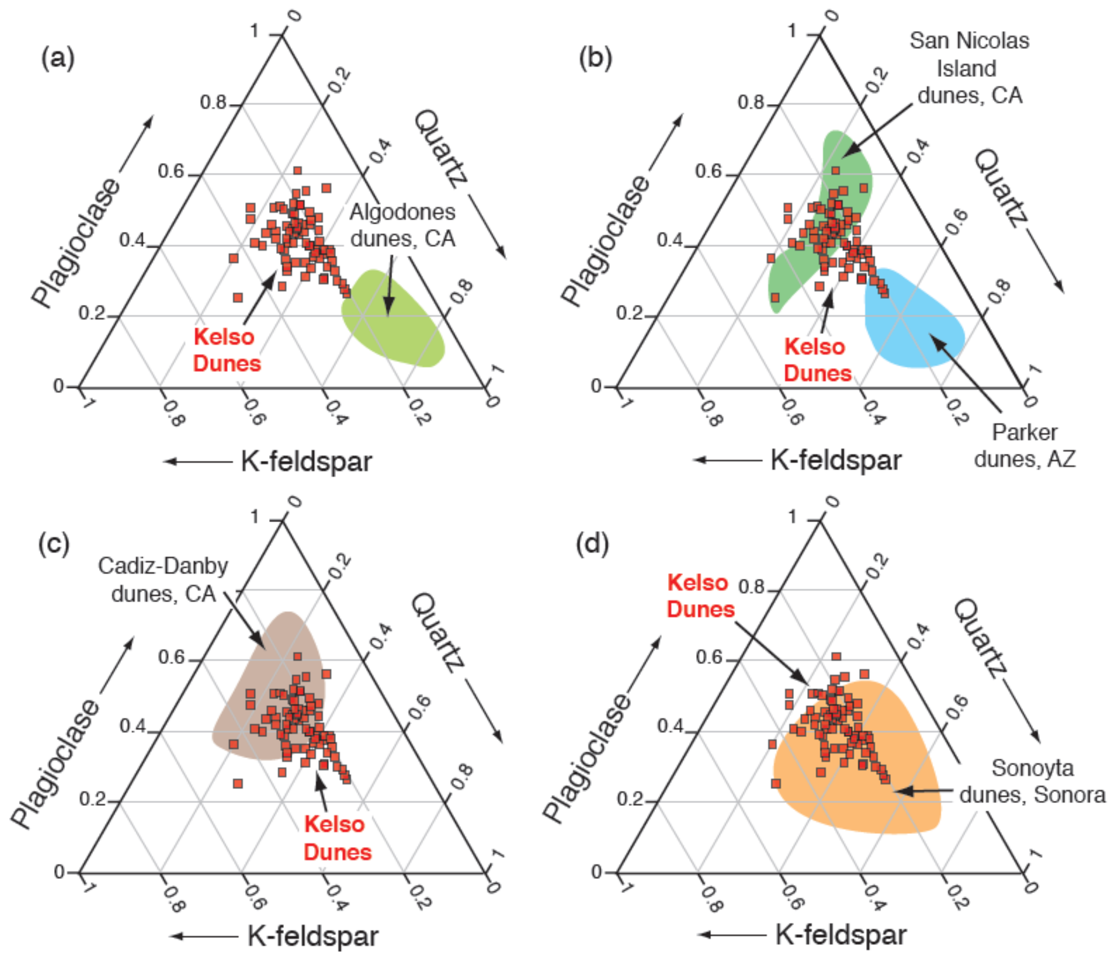

(a)
Plagioclase
Quartz
K-feldspar
Algodones dunes, CA
Kelso Dunes
(b)
San Nicolas Island dunes, CA
Kelso Dunes
Parker dunes, AZ
(c)
Cadiz-Danby dunes, CA
Kelso Dunes
(d)
Kelso Dunes
Sonoyta dunes, Sonora

Fig. 9

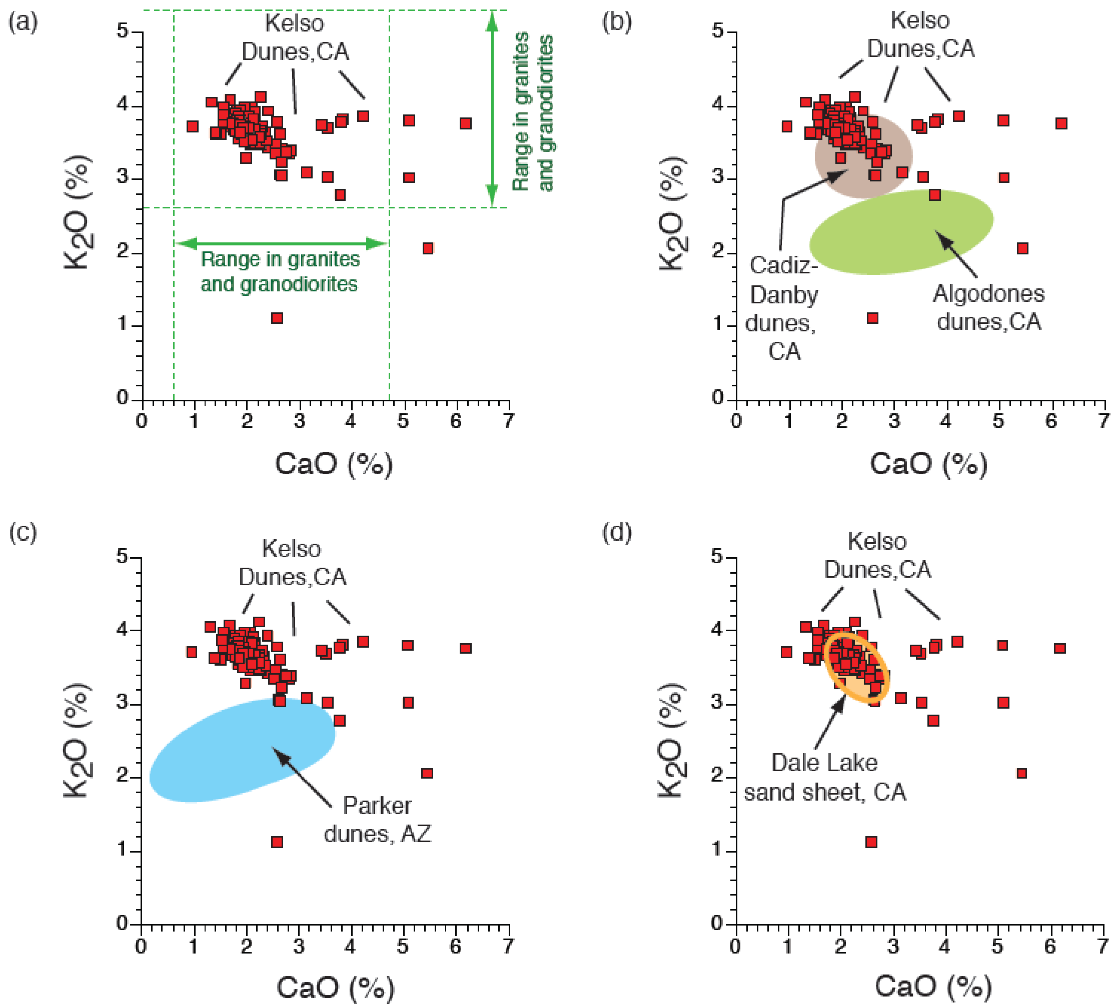

(a)
Kelso Dunes,CA
Range in granites and granodiorites
Range in granites and granodiorites
K2O (%)
CaO (%)
(b)
Kelso Dunes,CA
Cadiz-Danby dunes, CA
Algodones dunes,CA
K2O (%)
CaO (%)
(c)
Kelso Dunes,CA
Parker dunes, AZ
K2O (%)
CaO (%)
(d)
Kelso Dunes,CA
Dale Lake sand sheet, CA
K2O (%)
CaO (%)

Fig. 10

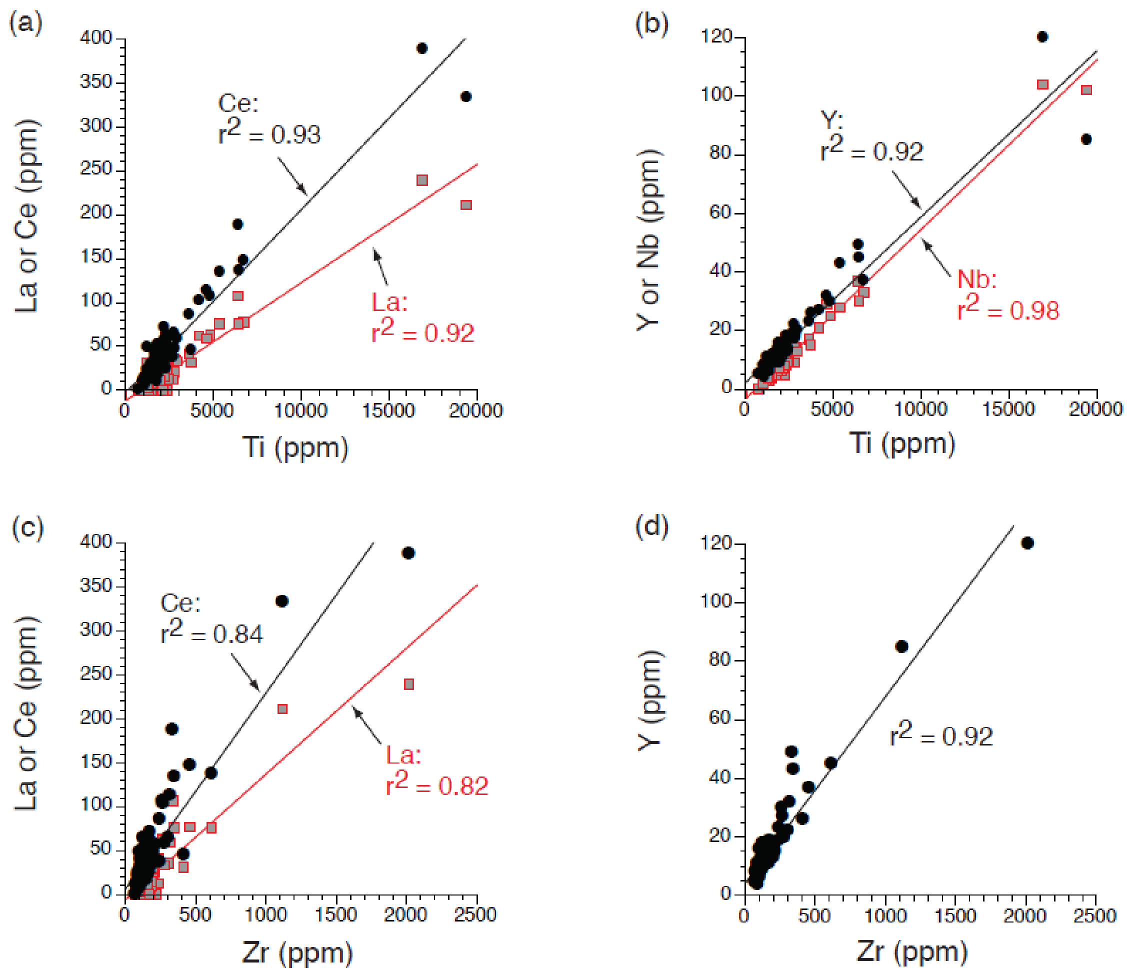

(a)
La or Ce (ppm)
Ti (ppm)
Ce:
r2 = 0.93
La:
r2 = 0.92
(b)
Y or Nb (ppm)
Ti (ppm)
Y:
r2 = 0.92
Nb:
r2 = 0.98
(c)
La or Ce (ppm)
Zr (ppm)
Ce:
r2 = 0.84
La:
r2 = 0.82
(d)
Y (ppm)
Zr (ppm)
r2 = 0.92

Fig. 11

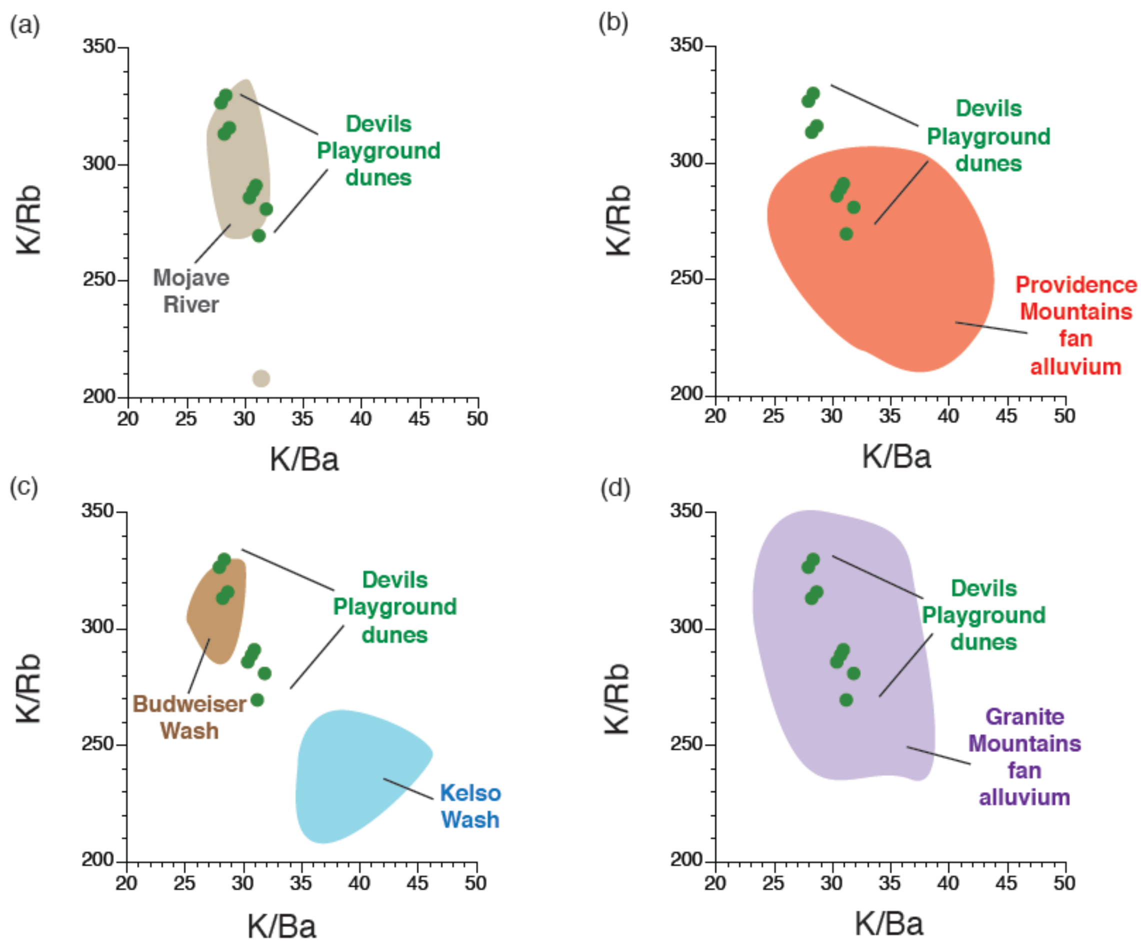

(a)
350
300
250
200
20 25 30 35 40 45 50
K/Rb
K/Ba
Devils
Playground
dunes
Mojave
River
(b)
Devils
Playground
dunes
Providence
Mountains
fan
alluvium
(c)
Devils
Playground
dunes
Budweiser
Wash
Kelso
Wash
(d)
Devils
Playground
dunes
Granite
Mountains
fan
alluvium

Fig. 12

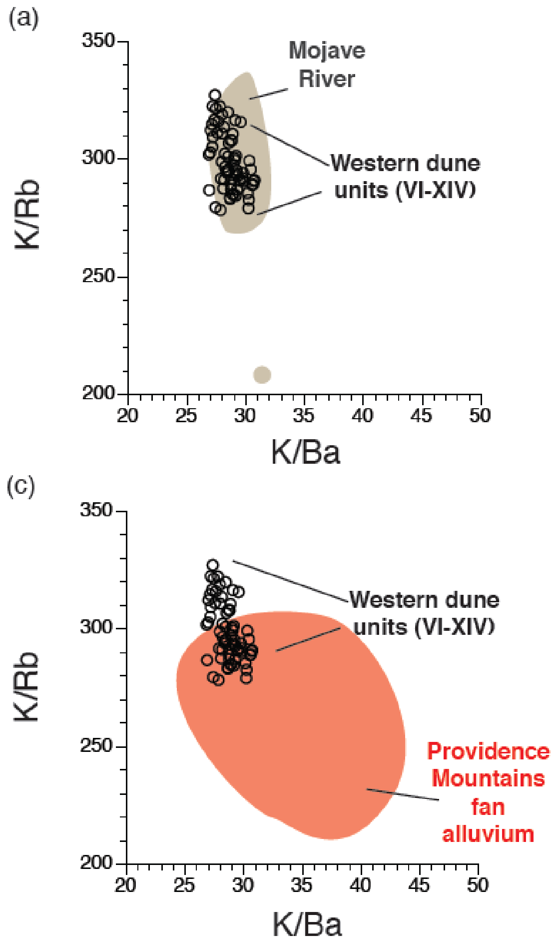

(a)
350
300
250
200
20 25 30 35 40 45 50
K/Rb
K/Ba
Mojave River
Western dune units (VI-XIV)
(b)
350
300
250
200
20 25 30 35 40 45 50
K/Rb
K/Ba
Western dune units (VI-XIV)
Granite Mountains fan alluvium
(c)
350
300
250
200
20 25 30 35 40 45 50
K/Rb
K/Ba
Western dune units (VI-XIV)
Providence Mountains fan alluvium
(d)
350
300
250
200
20 25 30 35 40 45 50
K/Rb
K/Ba
Budweiser Wash
Western dune units (VI-XIV)
Kelso Wash

Fig. 13

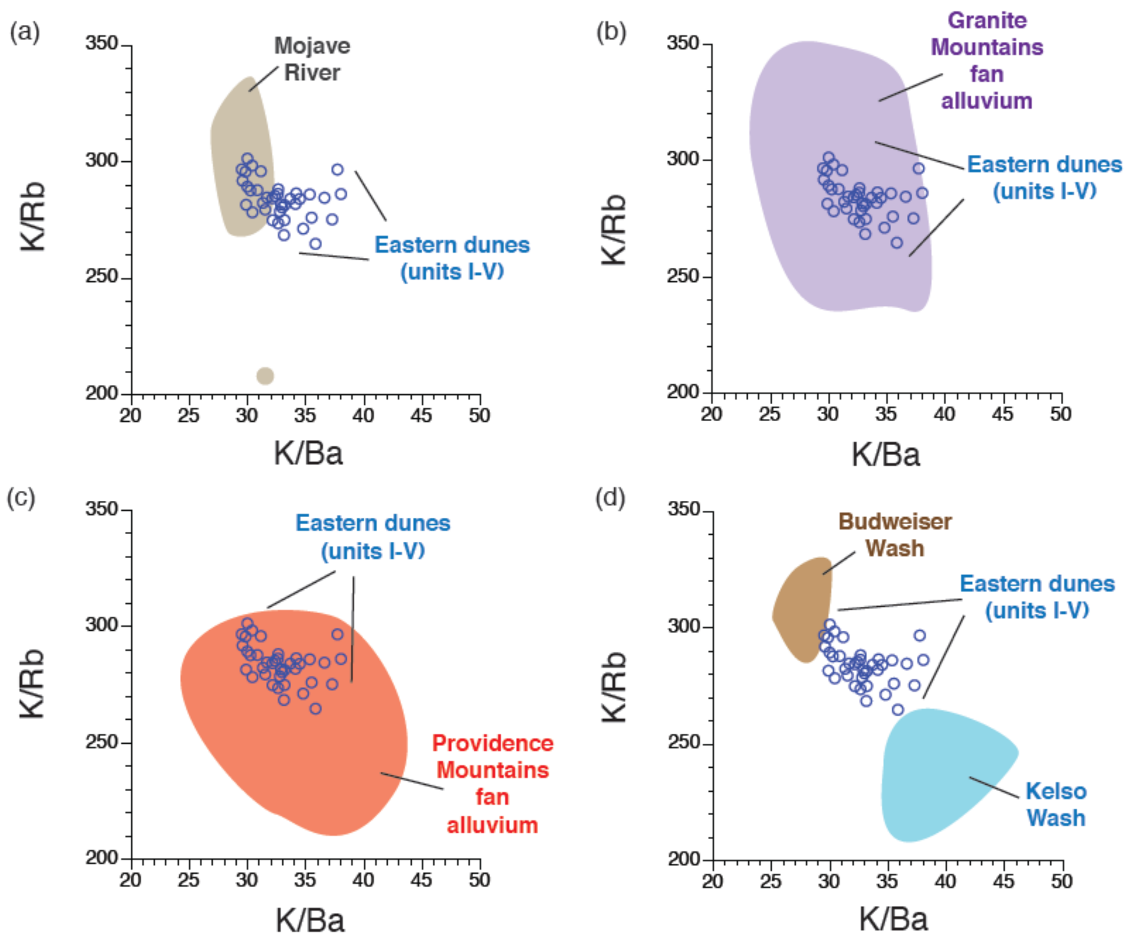

(a)
Mojave River
Eastern dunes (units I-V)
K/Rb
K/Ba
(b)
Granite Mountains fan alluvium
Eastern dunes (units I-V)
K/Rb
K/Ba
(c)
Eastern dunes (units I-V)
Providence Mountains fan alluvium
K/Rb
K/Ba
(d)
Budweiser Wash
Eastern dunes (units I-V)
Kelso Wash
K/Rb
K/Ba

Fig. 14

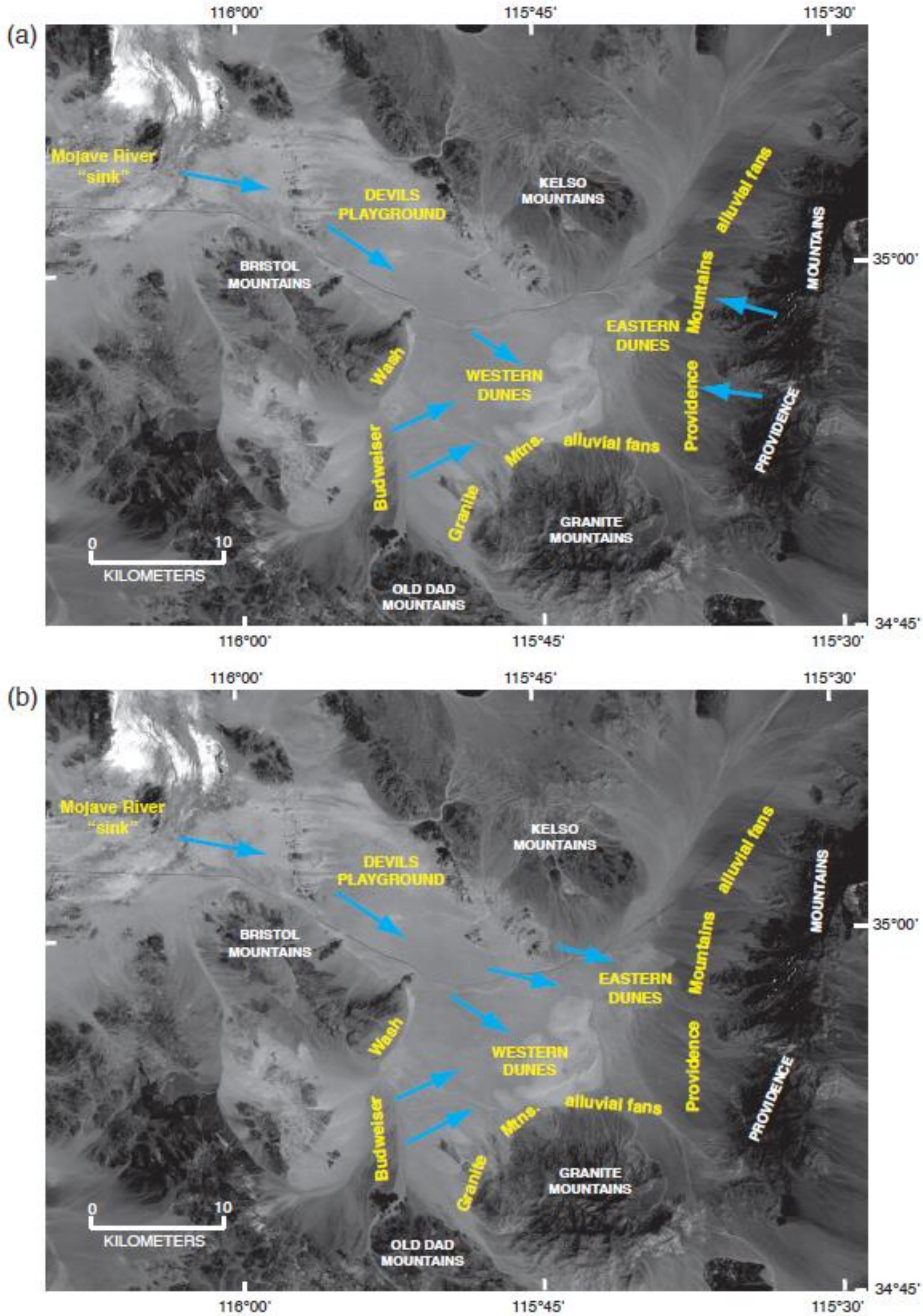

(a)
116°00'
115°45'
115°30'
35°00'
34°45'
Mojave River "sink"
DEVILS PLAYGROUND
KELSO MOUNTAINS
BRISTOL MOUNTAINS
alluvial fans
MOUNTAINS
EASTERN DUNES
Mountains
Wash
WESTERN DUNES
Providence
PROVIDENCE
Budweiser
Mtns.
alluvial fans
Granite
GRANITE MOUNTAINS
0 10 KILOMETERS
OLD DAD MOUNTAINS
(b)
116°00'
115°45'
115°30'
35°00'
34°45'
Mojave River "sink"
DEVILS PLAYGROUND
KELSO MOUNTAINS
BRISTOL MOUNTAINS
alluvial fans
MOUNTAINS
EASTERN DUNES
Mountains
Wash
WESTERN DUNES
Providence
PROVIDENCE
Budweiser
Mtns.
alluvial fans
Granite
GRANITE MOUNTAINS
0 10 KILOMETERS
OLD DAD MOUNTAINS

Fig. 15

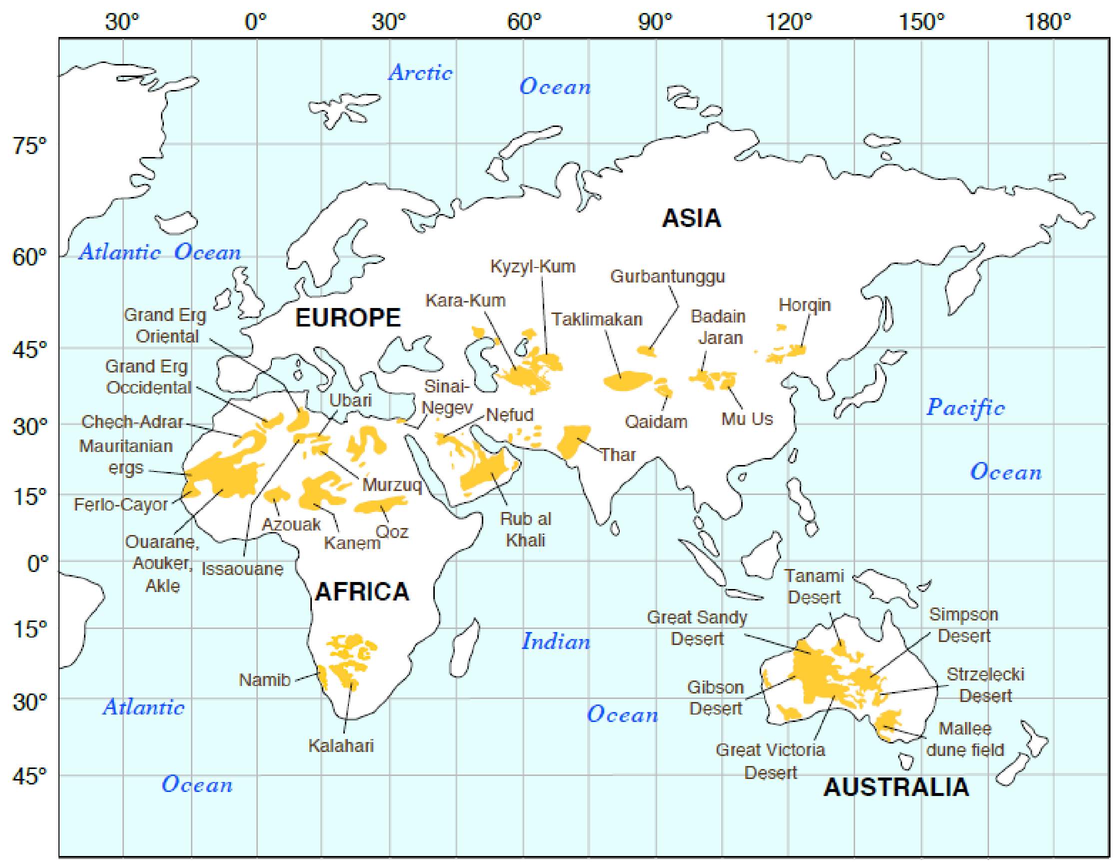

30°
0°
30°
60°
90°
120°
150°
180°
75°
60°
45°
30°
15°
0°
15°
30°
45°
Arctic
Ocean
ASIA
Atlantic Ocean
EUROPE
Kyzyl-Kum
Gurbantunggu
Kara-Kum
Taklimakan
Badain Jaran
Horqin
Grand Erg Oriental
Grand Erg Occidental
Ubari
Sinai-Negev
Nefud
Qaidam
Mu Us
Thar
Pacific
Ocean
Chech-Adrar
Mauritanian ergs
Murzuq
Ferlo-Cayor
Azouak
Qoz
Kanem
Rub al Khali
Ouarane, Aouker, Akle
Issaouane
AFRICA
Tanami Desert
Great Sandy Desert
Simpson Desert
Indian
Ocean
Namib
Gibson Desert
Strzelecki Desert
Atlantic
Kalahari
Mallee dune field
Great Victoria Desert
Ocean
AUSTRALIA

Fig. 16

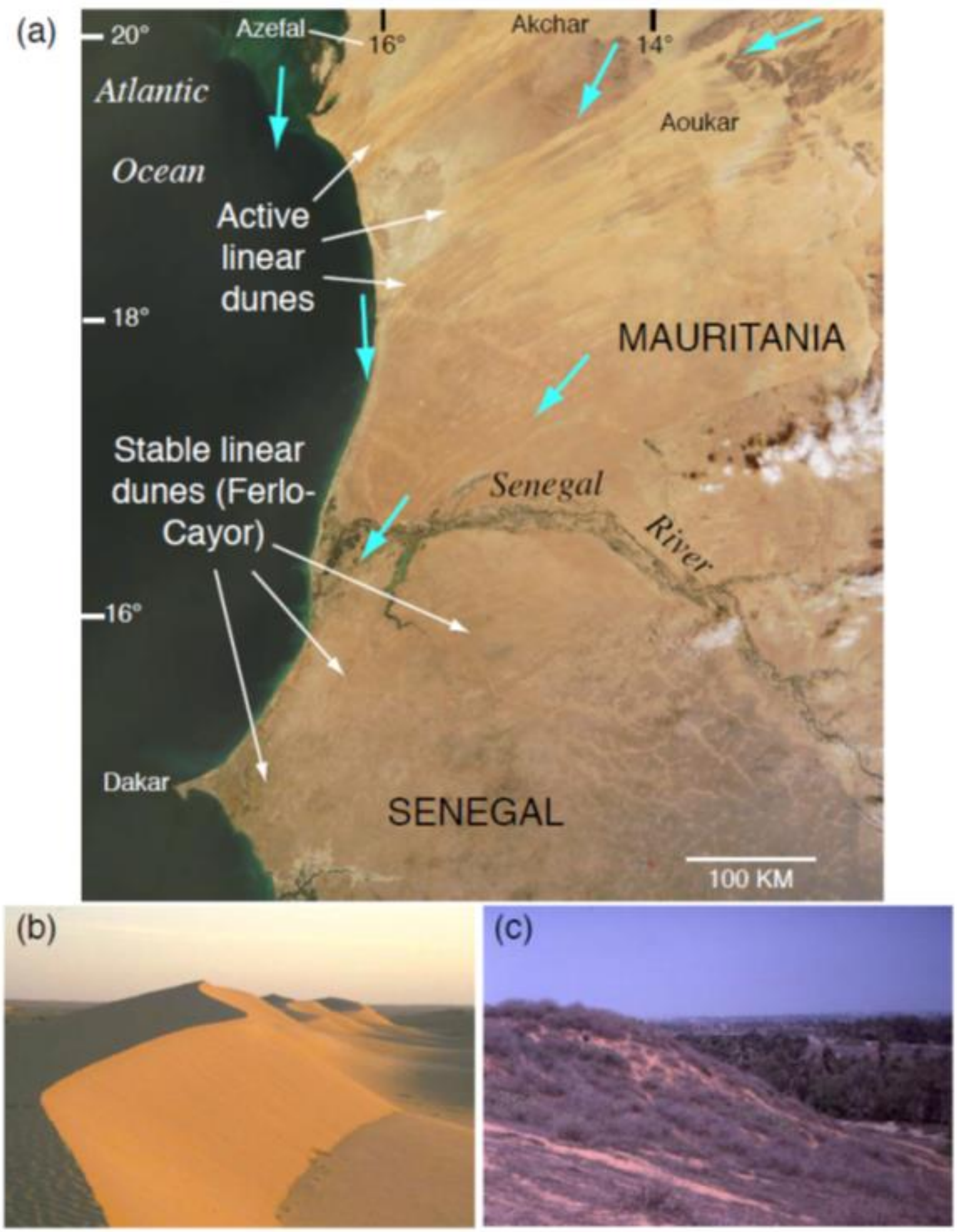

(a)
20°
Azefal
16°
Akchar
14°
Atlantic
Ocean
Aoukar
Active
linear
dunes
18°
MAURITANIA
Stable linear
dunes (Ferlo-
Cayor)
Senegal
River
16°
Dakar
SENEGAL
100 KM
(b)
(c)

Fig. 17

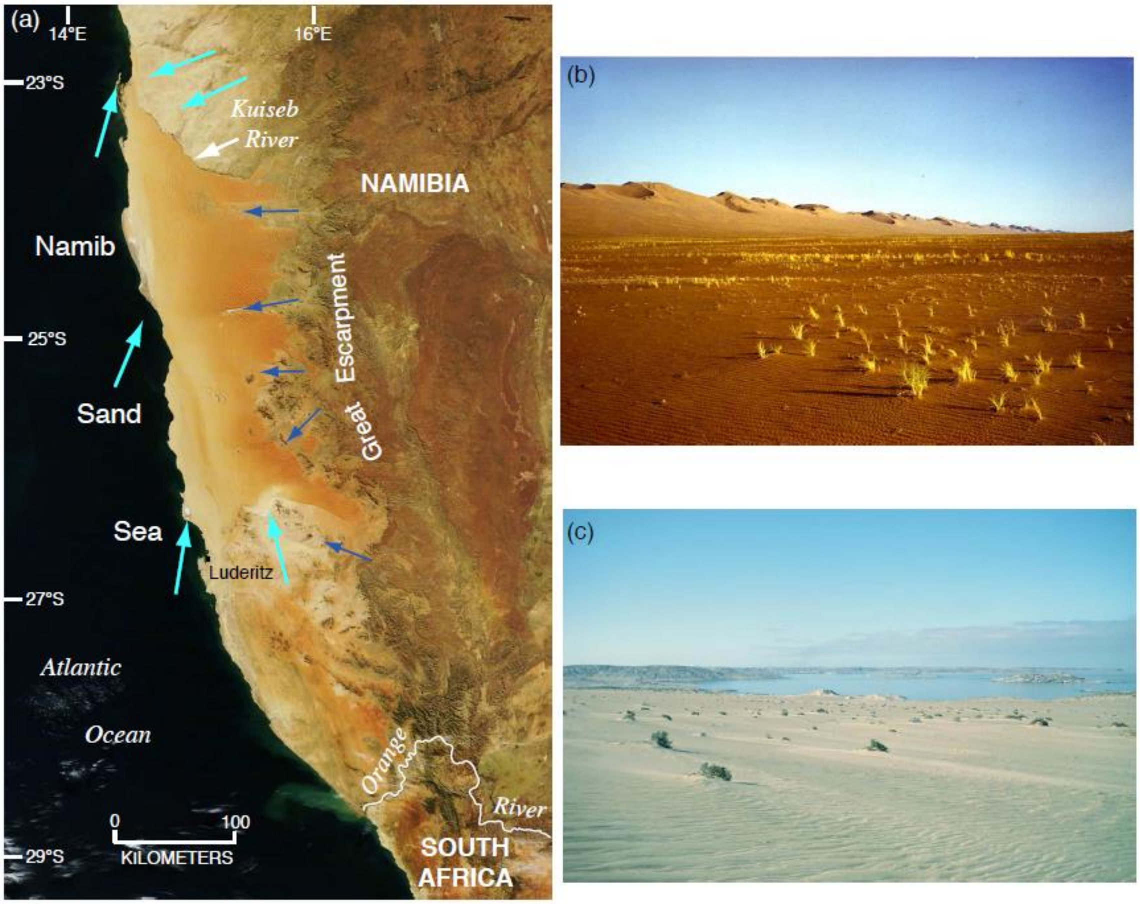

(a)
14°E
16°E
23°S
25°S
27°S
29°S
Kuiseb
River
NAMIBIA
Namib
Sand
Sea
Great
Escarpment
Luderitz
Atlantic
Ocean
Orange
River
SOUTH
AFRICA
0
100
KILOMETERS
(b)
(c)

Fig. 18

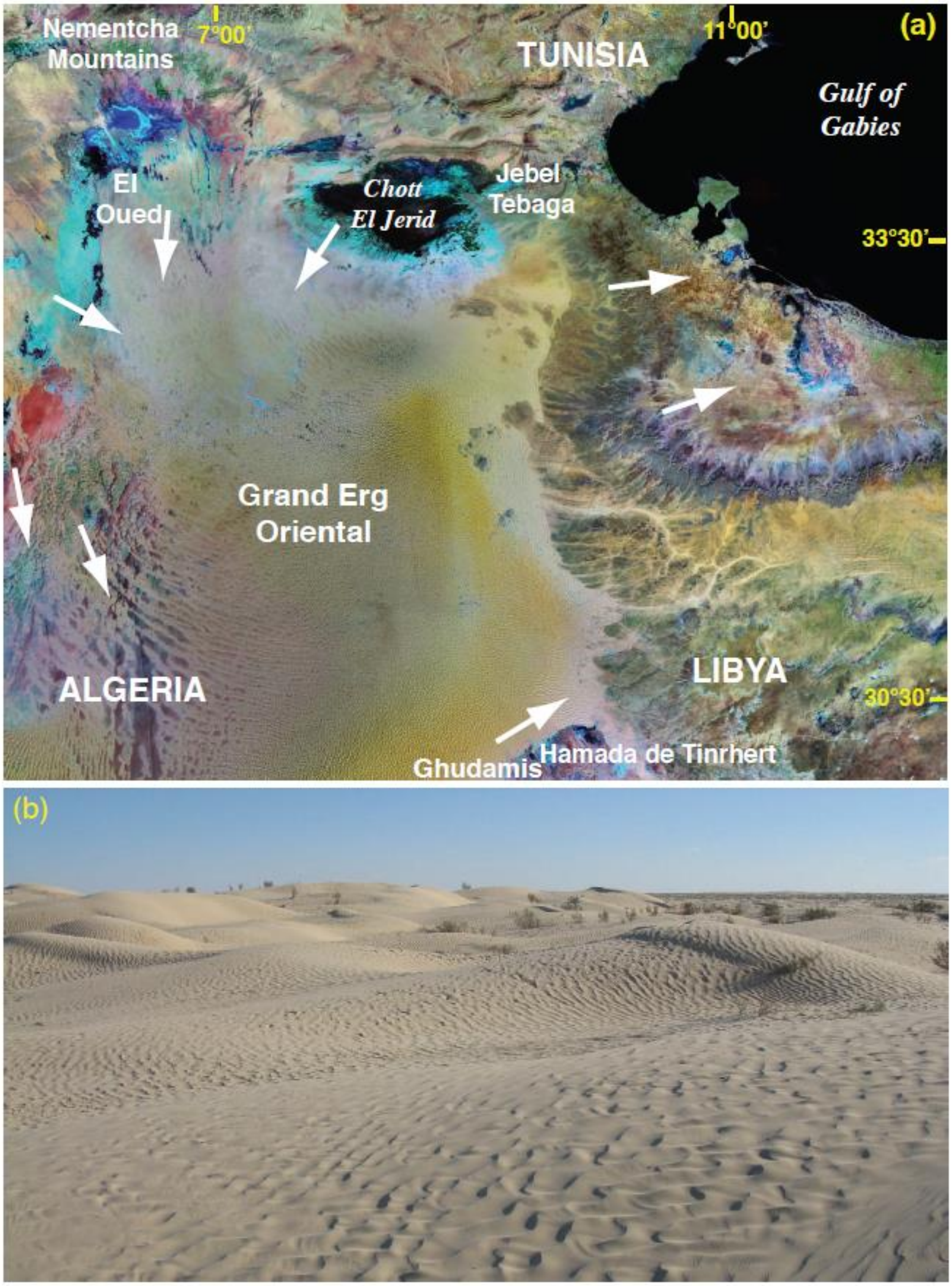

Nementcha
Mountains
7°00'
TUNISIA
11°00'
(a)
Gulf of
Gabies
El
Oued
Chott
El Jerid
Jebel
Tebaga
33°30'
Grand Erg
Oriental
LIBYA
30°30'
ALGERIA
Ghudamis
Hamada de Tinrhert
(b)

Fig. 19

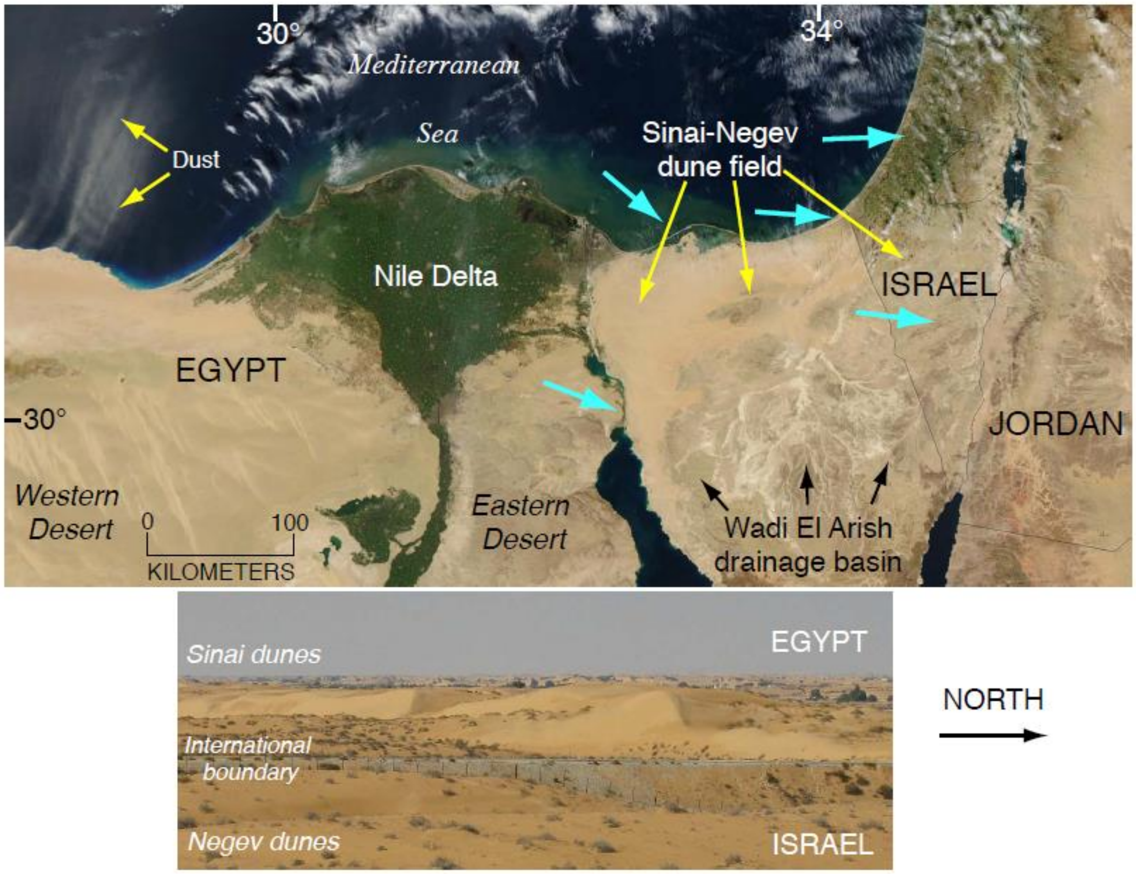

30°
34°
Mediterranean
Sea
Dust
Sinai-Negev
dune field
Nile Delta
ISRAEL
EGYPT
-30°
JORDAN
Western
Desert
0
100
KILOMETERS
Eastern
Desert
Wadi El Arish
drainage basin
Sinai dunes
EGYPT
International
boundary
Negev dunes
ISRAEL
NORTH

Fig. 20

Table 1. Geomorphology of the Kelso Dunes

Unit from Lancaster (1993, 1994)	Geography	Condition	Geomorphology	Most recent paleowind	Samples for XRF (n)	Samples for XRD (n)
I	Eastern	Stabilized	Degraded parabolic dunes and sand sheets	W?	9	5
II	Eastern	Stabilized	Linear dunes with superimposed parabolic dunes	WNW	9	6
III	Eastern	Active; stabilized	Linear dunes with superimposed parabolic dunes	W	5	4
IV	Eastern	Stabilized	Degraded linear dunes and sand sheets	SW?	10	8
V	Eastern	Stabilized	Degraded parabolic dunes	NW, W	5	1
VI	Western	Active	Linear dune with superimposed parabolic dunes, barchanoid ridges, and star dunes	SW;W or WNW	25	19
VII	Western	Stabilized	Degraded parabolic dunes	NW?	7	6
VIII	Western	Active	Linear dune with superimposed barchanoid ridges, star dunes and parabolic dunes	SW; W, WNW	0	0
IX	Western	Stabilized	Degraded linear dunes with superimposed, degraded parabolic dunes	W	9	4
X	Western	Active	Linear dune with superimposed barchanoid ridge, star, and parabolic dunes	SW; W, WNW	0	0
XI	Western	Stabilized	Linear dunes grading eastward into parabolic dunes	WSW	9	9
XII	Western	Stabilized	Parabolic dunes	W	3	1
XIII	Western	Stabilized	Linear dunes grading southeastward into parabolic dunes	NW	9	8
XIV	Western	Stabilized	Parabolic dunes	W	4	3
Devils Playground	Western	Stabilized	Sand sheets, streaks	W	9	0

Highlights

* The Kelso Dunes of desert California have a complex geomorphology

*Past studies suggest the dunes are quartz-rich, derived from the Mojave River

*The dunes are much richer in K-feldspar than previously supposed

*Alluvial sources can be distinguished using K/Rb and K/Ba in K-feldspar

*The dunes have a complex origin, with possibly three alluvial sources

*Methods employed here could be applied to dune provenance studies worldwide