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Alluvial sediment or playas: What is the dominant source of sand and silt in desert soil vesicular A horizons, southwest USA

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[1] Vesicular A (Av) soil horizons form beneath desert pavements from the accretion of aeolian sediment (dust) commonly thought to be derived primarily from desiccating pluvial lakes and playas, with contributions from ephemeral washes and alluvial fans. Particle size distributions of Av horizons are typically bimodal with primary modes of very fine silt and fine sand, suggesting that the horizon matrix is derived from multiple sources. Here we conduct detailed chemical and physical analysis of both Av horizon soil samples and potential sources of aeolian sediment to better constrain the relative contributions of dust associated with the development of Av horizons. Geochemical data from both sand (125–250 μm) and silt (2–32 μm) fractions in Av horizons and potential dust sources in the eastern Mojave Desert and western Sonora Desert, USA, point to large contributions from nearby sources including distal alluvial fans and washes, and comparably lower contributions from regional sources such as playas. The silt mode is derived from suspension transport of dust, and the fine sand mode is derived from saltating sand. The desiccation of pluvial lakes in the Mojave Desert is commonly believed to have driven episodes of aeolian activity, contributing to sand dunes and Av horizon formation. We propose that alluvial fans and washes are underappreciated as desert dust sources and that pulses of dust from late Pleistocene and Holocene alluvial fans dwarfed pulses of dust from desiccating pluvial lakes in the eastern Mojave Desert.

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1. Introduction

[2] Dust in many deserts primarily accumulates and forms vesicular A (Av) horizons beneath gravel desert pavements [*Wells et al*., 1985, 1995; *McFadden et al*., 1986, 1987, 1998; *Gerson and Amit*, 1987]. The dust that has formed Av horizons in the Mojave Desert in the southwest United States is thought to be largely derived from the deflation of desiccating pluvial lakes and playas [*Wells et al*., 1985; *McFadden et al*., 1986, 1992; *Reynolds et al*., 2006] because playas lack vegetation and contain abundant dust-sized sediment, and regional changes in climate and pluvial lake activity in the late Pleistocene and early Holocene contributed to increased sediment availability [*McFadden et al*., 1986, 1992; *Wells et al*., 1987a, 1987b; *Reheis et al*., 1995; *Lancaster and Tchakerian*, 1996, 2003; *Clarke and Rendell*, 1998; *Tchakerian and Lancaster*, 2002]. Many of these same studies also indicate that pulses of aeolian activity, primarily recorded in aeolian sand deposits and soils, occurred throughout the Holocene and are related to climatic fluctuations. Playas comprise only about 1% of most deserts [*Thomas*, 2000], are considered a primary source of dust from deserts [*Blackwelder*, 1931; *Young and Evans*, 1986; *Chadwick and Davis*, 1990; *Cahill et al*., 1996; *Gill*, 1996; *Prospero et al*., 2002; *Reheis et al*., 2002; *Mahowald et al*., 2003; *Pelletier and Cook*, 2005; *Washington and Todd*, 2005], and are the preferred source in some global dust models [*Ginoux et al*., 2001; *Tegen et al*., 2002; *Tegen*, 2003]. By comparison, studies of modern dust in the Mojave Desert reveal that, apart from anthropogenically influenced dust emissions, freshly deposited alluvial sediments (dry washes and distal alluvial fans) are the primary sources of dust today [*Gillette et al*., 1980; *Langford*, 1989; *Reheis and Kihl*, 1995; *Sweeney et al*., 2011].

[3] Extensive research has been conducted on the source and composition of modern and ancient dust in the Mojave Desert [*Reheis and Kihl*, 1995; *Reheis et al*., 1995, 2002, 2009; *Reheis*, 2006; *Reynolds et al*., 2006; *Goldstein et al*., 2008]. This previous work focused on determining sources of modern dust, comparing the composition of modern dust to ancient dust (Av horizons), comparing the composition of dust to potential bedrock sources, determining source regions of dust such as the Amargosa Desert and the eastern Mojave

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All Supporting Information may be found in the online version of this article.

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Desert, and tracing dust sources to anthropogenically modified landscapes, such as Owens Lake. In terms of identifying sources of dust, except for Owens Lake, dust compositions are compared to dry and wet playas and alluvial sources in general. Results of previous work have shown that Av horizons are composed of dust from multiple sources that has been thoroughly mixed during transport, and thus are chemically uniform [*Reheis et al.*, 1995; *Reynolds et al.*, 2006].

[4] Our approach seeks to identify *specific landforms* as aeolian sediment sources that dominate the signal in Av horizons. We combine sedimentological and geochemical techniques to fingerprint the source of dust and aeolian sand in Av horizons. Specifically, we use major and trace elements to determine which desert landforms, including playas, dry washes, alluvial fans, and sand dunes, contributed aeolian sediment to the formation of Av horizons. Grain size distributions and studies of grain roundness of the sand fraction provide additional evidence of potential sources, reveal aeolian transport processes involved in the accumulation of Av soil, and also elucidate local versus regional contributions of aeolian sediment. Our study focuses primarily in the eastern Mojave Desert of southern California but also evaluates dust sources in the western Sonora Desert near Yuma, Arizona.

[5] Av horizons have broad significance in deserts because they play a fundamental role in the pedogenic development of arid soils [*Yaalon and Ganoor*, 1973; *Reheis et al.*, 1989; *Wells et al.*, 1995; *McFadden et al.*, 1998; *Birkeland*, 1999]. Av horizons affect the hydraulic properties of desert soils and are dynamic in that their properties change with time as a function of aeolian influx [*McDonald et al.*, 1996; *McDonald*, 2002; *Young et al.*, 2004]. Their evolving soil properties in turn influence desert ecology [*McAuliffe and McDonald*, 1995; *Hamerlynck et al.*, 2002; *Shafer et al.*, 2007] and are a significant reservoir for nitrate [*Michalski et al.*, 2004; *Graham et al.*, 2008]. Av horizons are also essential in the formation and evolution of desert pavements [*Wells et al.*, 1985, 1995; *McFadden et al.*, 1987, 1998; *Wood et al.*, 2005].

[6] Our research, while confirming many of the previous results in general, demonstrates that local alluvial sources dominate the aeolian signal and point to alluvial fans and washes as major contributors of dust and aeolian sand in Av horizons in the eastern Mojave Desert (Figure 1) and the western Sonora Desert (Figure 2). While playas are clearly important sources of dust in some areas [*Chadwick and Davis*, 1990; *Gill*, 1996; *Mahowald et al.*, 2003; *Pelletier and Cook*, 2005], and do likely contribute to dust in Av horizons, a strong regional geochemical signal of playa-derived dust is absent in the Av horizons that we analyzed from the desert southwest United States.

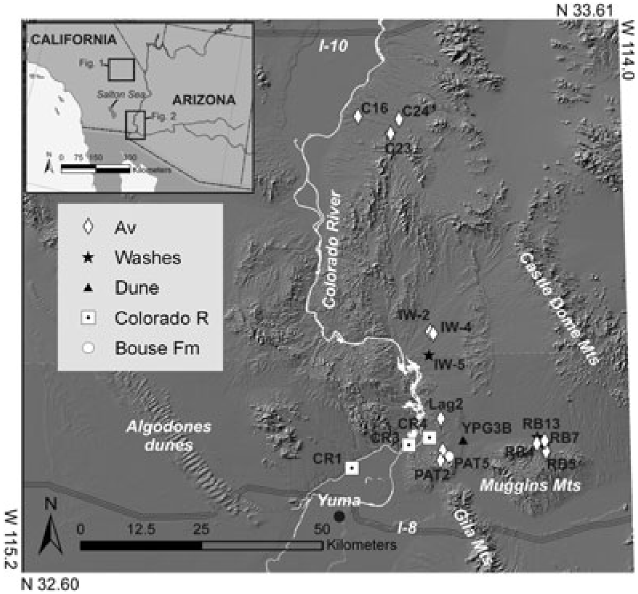

Figure 2. Location map for selected sampling sites, by landform type, near Yuma, Arizona. See Table 1 for all locations.

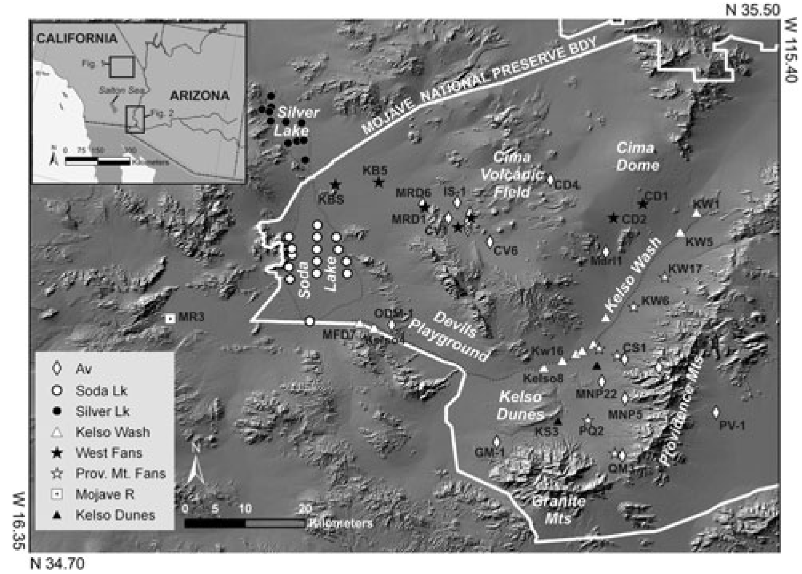

Figure 1. Location map for selected sampling sites, by landform type, in the Mojave National Preserve, southern California. See Table 1 for all locations.

2. Background

2.1. Formation of Av Horizons and Desert Pavements

[7] Av horizons form from the accumulation of dust and aeolian sand below desert pavements [*Wells et al.*, 1985, 1987b, 1995; *McFadden et al.*, 1986, 1987, 1998; *McDonald*, 1994]. The initial studies first proved the aeolian origin for Av horizons by recognizing the stark contrast in composition between the quartz-rich soil, underlying basalt, and overlying pavement at the Cima volcanic field. Dust and sand is trapped on gravel-covered bar and swale surfaces such as alluvial fans or volcanic terrains that have sufficient surface roughness to baffle the wind [*McFadden et al.*, 1998; *Valentine and Harrington*, 2006]. In the accretionary model for Av horizon development, dust particles work their way down between gravel clasts [*McFadden et al.*, 1987]. Over time, as clay content increases and shrink-swell processes develop, accumulated dust lifts a single layer of gravel, kept at the surface, forming desert pavement. The desert pavement evolves over time to an interlocking matrix of clasts that, together with the underlying dust, smoothens rough topography [*Amit and Gerson*, 1986; *McFadden et al.*, 1987, 1998; *Wood et al.*, 2005]. This model of desert pavement development has been broadly accepted; however, some recent texts still ignore this important process [*Gutiérrez*, 2001; *Huggett*, 2007]. Vesicles in the Av may form by expansion of the soil followed by multiple wetting and drying events [*Miller*, 1971; *McFadden et al.*, 1998]. Av peds contain strong columnar, prismatic, and platy structure that may assist in movement of particles from the surface into peds, resulting in textural zonation [*McDonald*, 1994; *Anderson et al.*, 2002]. As Av horizons and desert pavements co-evolve, thickness and silt-clay content of the Av horizon increases, the pavement becomes better developed, and bar and swale relief at the surface is smoothed [*McDonald et al.*, 1995; *Valentine and Harrington*, 2006]. Av horizon thickness in the eastern Mojave Desert typically ranges from <10 to 80 mm, but they may be as thick as 200 mm [*McFadden et al.*, 1998].

2.2. Tracing Aeolian Sources

[8] Previous work on determining the sources of aeolian sediments in the Mojave Desert have demonstrated that (1) several dust sources exist, such as playa and fluvial sediments [*Reheis and Kihl*, 1995; *Reheis et al.*, 1995, 2002, 2009], and (2) sand sources for dune and sand ramps (aeolian sand accumulations on the upwind side of mountains) are related to extensive sand transport pathways [*Zimbelman et al.* 1995; *Zimbelman and Williams*, 2002; *Muhs et al.*, 2003; *Pease and Tchakerian*, 2003]. Major and trace element geochemistry of modern dust in the Mojave suggests that the sources of dust are mixed and broadly similar to granitic rocks [*Reheis and Kihl*, 1995; *Reheis et al.*, 2002, 2009]. Av horizons and other soils with incorporated dust have a similar major oxide composition to modern dust [*Reheis et al.*, 1995].

[9] Av horizons in the Mojave Desert are, for the most part, chemically uniform [*Reheis et al.*, 2009]; however, key elements point to a variety of landform or bedrock source areas including playas (Ca, Sr, Li), alluvium (Rb, K), and granite (Ti, Zr). *Reheis et al.* [2002, 2009] concluded that Av horizons have contributions of dust from multiple sources that become well-mixed before deposition and are distinguishable from modern dust by an anthropogenic signal from elements such as As, Cu, Ni, Pb, and Sb.

[10] Dust emission from playas lags behind ephemeral alluvial sources because the finer-textured playa sediments retain more water and therefore take longer to dry [*Reheis and Kihl*, 1995]. Peaks in dust flux from fluvial systems occur during dry years and especially during drought phases, whereas playas are large dust producers in years following high precipitation [*Reheis and Kihl*, 1995; *Okin and Reheis*, 2002]. Studies of modern dust production suggest that playa and alluvial sources produce about the same amount of dust per unit area, but the volume of dust from alluvial sources is greater because alluvial sources are more extensive [*Reheis and Kihl*, 1995]. Wind tunnel experiments, on the other hand, reveal that alluvial sources are potentially more potent dust producers per unit area compared to playas [*Sweeney et al.*, 2011].

[11] Major element geochemistry of sand in sand ramps shows variations in sources with time, suggesting that local sources are dominant in the formation of sand ramps [*Tchakerian and Lancaster*, 2002; *Muhs et al.*, 2003; *Pease and Tchakerian*, 2003]. These researchers downplay the role of sediment mixing and homogenization along sand transport pathways, as suggested by *Zimbelman et al.* [1995]. The Kelso dunes also show a variety of local sources feeding the dune field, including some sand derived from Providence Mountains alluvial fans downwind and to the east of the dunes [*Ramsey et al.*, 1999], perhaps incorporated as the dunes migrated over sand from underlying alluvial sediments.

[12] Aeolian systems with upwind sand and downwind silt accumulations are often genetically related to their source area and may form contemporaneously, provided there is a suitable downwind trap for the dust component [*Sweeney et al.*, 2007]. The diversity of potential sources in a small regional area may be obscured if aeolian sands continue to migrate further from their original source and incorporate new source material along the way, potentially generating a complex provenance.

3. Methods

[13] This study focuses on Av horizons and potential aeolian sediment sources in the eastern Mojave Desert, primarily in the Mojave National Preserve in southern California (Figure 1), and in the Sonora Desert within the US Army Yuma Proving Ground (hereafter ‘Yuma’) in southwestern Arizona and near the Salton Sea, southern California (Figure 2). Sediment samples were collected from potential sources including playas, large ephemeral washes, distal alluvial fans, and sand dunes. Av horizon samples were collected from different ages of alluvial fan terraces and basalt flows (Table 1).

[14] Geochemical data, especially contents of immobile elements, are useful in sedimentary provenance studies [*Taylor and McLennan*, 1985]. Provenance studies of loess and dust have utilized several key elemental tracers including Ce, La, Nb, Rb, Sc, Th, Ti, Y, and Zr where differentiation of potential sources can be revealed on ternary diagrams or bivariate plots [*Sun*, 2002; *Marx et al.*, 2005; *Muhs and Benedict*, 2006; *Muhs et al.*, 2008a, 2008b; *Reheis et al.*, 2009].

Table 1. Site Locations, Landform Classification, and Landform Ages for Collected Samples

Field ID	General Location and Geology	Landform	Age[a]	Easting	Northing	XRF sd/sl[b]
Mojave Desert						
QM3	Providence Mts; Qtz monzonite	Av	MP	626985	3856819	sl, sd
QM6	Providence Mts; Qtz monzonite	Av	LH	626642	3857005	sl, sd
PQ3	Providence Mts; Qtz monzonite	Av	MP	626289	3857411	sl, sd
CS1	Providence Mts; Limestone	Av	EMP	627111	3872814	sl, sd
CS2	Providence Mts; Limestone	Av	MP	626527	3873073	sl, sd
CS5	Providence Mts; Limestone	Av	LH	625998	3873486	sl, sd
CS11	Providence Mts; Limestone	Av	LH	631770	3871485	sl, sd
MNP4	Providence Mts; Mixed volcanic	Av	MP	625575	3868146	sl, sd
MNP5	Providence Mts; Mixed volcanic	Av	EMP	627238	3866269	sl, sd
MNP22	Providence Mts; Mixed volcanic	Av	P-H	624016	3869016	sl, sd
GM1	Granite Mts	Av	EMP	609815	3858810	sl
PV1	Providence Mts; west side	Av	LP	639674	3864150	sl
CV1	Cima Volcanic Field; basalt	Av	MP	602812	3895827	sl, sd
CV4	Cima Volcanic Field; basalt	Av	LP	605483	3894024	sl, sd
CV6	Cima Volcanic Field; basalt	Av	MP	608503	3891952	sl, sd
CD-4	Cima Volcanic Field; basalt	Av	MP	616567	3902365	sl
IS-1	Indian Springs; granite, basalt	Av	EMP	603973	3898462	sl
IS-4	Indian Springs; granite, basalt	Av	MP	605479	3894750	sl
IS-5	Indian Springs; granite, basalt	Av	MP	605527	3895413	sl
IS-7	Indian Springs; granite, basalt	Av	LP	605895	3896059	sl
IS-8	Indian Springs; granite, basalt	Av	LH	605750	3896550	sl
IS-9	Indian Springs; granite, basalt	Av	P-H	605823	3896296	sl
MRD-6	Old Dad Mts	Av	LH	599252	3898118	sl
MARL-1	Marl Mts	Av	MP	624292	3890506	sl
ODM-1	Devils Playground	Av	P-H	595271	3878050	sl
sle1	Soda Lake; east transect	Playa	Mod	589145	3886502	sl
sle3	Soda Lake; east transect	Playa	Mod	589009	3888504	sl
sle5	Soda Lake; east transect	Playa	Mod	587876	3890501	sl
sle7	Soda Lake; east transect	Playa	Mod	587602	3892500	sl
slc1	Soda Lake; central transect	Playa	Mod	584973	3886498	sl
slc3	Soda Lake; central transect	Playa	Mod	584962	3888510	sl
slc5	Soda Lake; central transect	Playa	Mod	584960	3890500	sl
slc7	Soda Lake; central transect	Playa	Mod	584967	3892501	sl
slc9	Soda Lake; central transect	Playa	Mod	585003	3894501	sl
slw1	Soda Lake; west transect	Playa	Mod	581338	3885515	sl
slw3	Soda Lake; west transect	Playa	Mod	581186	3887501	sl
slw5	Soda Lake; west transect	Playa	Mod	581623	3889538	sl
slw6	Soda Lake; west transect	Playa	Mod	581542	3890556	sl
slw8	Soda Lake; west transect	Playa	Mod	581148	3892510	sl
B5N	Soda Lake	Playa	Mod	587819	3891484	sl
C5N	Soda Lake	Playa	Mod	586751	3890000	sl
C1N	Soda Lake	Playa	Mod	582078	3885885	sd
A3N	Soda Lake	Playa	Mod	583953	3896240	sl
MFD-4	Soda Lake; southern point	Playa	Mod	584092	3878564	sl
SL1	Silver Lake	Playa	Mod	582941	3910743	sl
SLB-1	Silver Lake	Playa	Mod	578500	3915795	sl
SLB-5	Silver Lake	Playa	Mod	583238	3905285	sl
sv1	Silver Lake; south	Playa	Mod	580891	3908029	sl
sv2	Silver Lake; south	Playa	Mod	582083	3908393	sl
sv3	Silver Lake; south	Playa	Mod	582991	3908510	sl, sd
sv4	Silver Lake; central	Playa	Mod	582686	3911406	sl
sv5	Silver Lake; central	Playa	Mod	580548	3911563	sl
sv6	Silver Lake; central	Playa	Mod	578470	3911671	sl, sd
sv7	Silver Lake; north	Playa	Mod	577280	3913572	sl, sd
sv8	Silver Lake; north	Playa	Mod	578534	3913963	sl
sv9	Silver Lake; north	Playa	Mod	578291	3913219	sl
KW1	Kelso Wash	Wash	Mod	636514	3897263	sl
KW2	Kelso Wash	Wash	Mod	620177	3873703	sd
KW3	Kelso Wash	Wash	LH	620294	3873610	sd
KW4	Kelso Wash	Wash	Mod	620312	3873562	sd
KW5	Kelso Wash	Wash	Mod	634336	3894027	sl, sd
KW6	Kelso Wash	Wash	Mod	628200	3881508	sl
KW7	Kelso Wash	Wash	Mod	621928	3875139	sl
KW15	Kelso Wash	Wash	Mod	620334	3873563	sl
KW16	Kelso Wash	Wash	Mod	618575	3872477	sl
KW17	Kelso Wash	Wash	Mod	632378	3886533	sl
KW18	Kelso Wash	Wash	LH	620429	3873648	sl
KW19	Kelso Wash	Wash	Mod	621260	3874182	sl
Kelso-1	Kelso Wash	Wash	Mod	624413	3879702	sl

(continues)

Table 1. *(continued)*

Field ID	General Location and Geology	Landform	Age[a]	Easting	Northing	XRF sd/sl[b]
Kelso-2	Kelso Wash	Wash	LH	624413	3879702	sl
Kelso-4	Kelso Wash	Wash	LH	592894	3877543	sl
Kelso-5	Kelso Wash	Wash	Mod	592894	3877543	sl
Kelso-8	Kelso Wash	Wash	LH	616089	3871311	sl
KW-W	Kelso Wash	Wash	LH	592894	3877543	sl, sd
KW-E	Kelso Wash	Wash	LH	624332	3879066	sd
KW-A	Kelso Wash	Wash	LH	616089	3871331	sd
MFD-7	Kelso Wash	Wash	LH	590890	3878417	sl
MR2	Mojave River	Wash	Mod	565102	3878801	sl
MR3	Mojave River	Wash	Mod	565110	3878836	sd
MR4	Mojave River	Wash	Mod	565090	3878922	sl
MR5	Mojave River	Wash	Mod	565080	3879016	sd
MR6	Mojave River	Wash	Mod	562059	3877248	sd
QM 7a	Providence Mts fans; Qtz monz.	Distal fan	LH	626987	3856807	sl
QM 7b	Providence Mts fans; Qtz monz.	Distal fan	LH	626642	3857005	sl, sd
PQ1	Providence Mts fans; Qtz monz.	Distal fan	Mod	621625	3862536	sl
PQ2	Providence Mts fans; Qtz monz.	Distal fan	Mod	622223	3862670	sl, sd
PQ4	Providence Mts fans; Qtz monz.	Distal fan	Mod	625941	3857255	sl, sd
CS-3	Providence Mts fans; Limestone	Distal fan	Mod	626062	3873439	sd
CS-4	Providence Mts fans; Limestone	Distal fan	Mod	625998	3873486	sd
CS-6	Providence Mts fans; Limestone	Distal fan	Mod	623596	3874575	sl, sd
CS7	Providence Mts fans; Limestone	Distal fan	Mod	622992	3874739	sl, sd
CS8	Providence Mts fans; Limestone	Distal fan	Mod	623115	3872536	sd
CS9	Providence Mts fans; Limestone	Distal fan	Mod	622780	3875254	sl, sd
CV2	Western fans; Indian Springs	Distal fan	Mod	602826	3895763	sl, sd
CV3	Western fans; Indian Springs	Distal fan	Mod	605362	3894201	sd
CV5	Western fans; Indian Springs	Distal fan	Mod	604562	3894097	sd
CV7	Western fans; Indian Springs	Distal fan	Mod	608615	3891804	sd
KB5	Western fans; Indian Springs	Distal fan	LH	593272	3901773	sl, sd
KB-S	Western fans; Indian Springs	Distal fan	LH	587366	3901279	sd
MO-2	Western fans; Indian Springs	Distal fan	LH	600146	3898217	sd
HSR	Western fans; Indian Springs	Sand ramp	Mod	587696	3894287	sd
IS-2	Western fans; Indian Springs	Distal fan	EMP	603973	3898462	sl
IS-3	Western fans; Indian Springs	Distal fan	Mod	604130	3894409	sl
IS-6	Western fans; Indian Springs	Distal fan	P-H	605909	3895998	sl
MRD-1	Western fans; Indian Springs	Distal fan	Mod	599581	3897686	sl
MRD-2	Western fans; Indian Springs	Distal fan	LH	599565	3897710	sl
MRD-3	Western fans; Indian Springs	Distal fan	LH	599565	3897710	sl
MRD-4	Western fans; Indian Springs	Distal fan	LH	599252	3898118	sl
CD-1	Western fans; Cima Dome	Distal fan	LH	629225	3898602	sl
CD-2	Western fans; Cima Dome	Distal fan	LH	625241	3896247	sl
KS1	Kelso dunes	Dune	Mod	623332	3871749	sd
KS2	Kelso dunes	Dune	Mod	618423	3862216	sd
KS3	Kelso dunes	Dune	Mod	618135	3862465	sd
MFD6	Soda Lake dune	Dune	Mod	584635	3878462	NA
MR1	Mojave River dune	Dune	Mod	565122	3878720	sd
Moja1	Mojave River dune	Dune	Mod	574252	3878407	NA
Sonora Desert						
RB1	Muggins Mts; Gneiss	Av	MP	763435	3634277	sl, sd
RB2	Muggins Mts; Gneiss	Av	LP	763117	3636461	sl, sd
RB3	Muggins Mts; Gneiss	Av	LH	761469	3635871	sl, sd
RB4	Muggins Mts; Gneiss	Av	MP	763364	3633729	sl, sd
RB7	Muggins Mts; Gneiss	Av	LH	763121	3635941	sl, sd
RB10	Muggins Mts; Gneiss	Av	MP	763353	3633825	sl, sd
RB11	Muggins Mts; Gneiss	Av	LH	761469	3635871	sl, sd
RB12	Muggins Mts; Gneiss	Av	MP	763303	3633802	sl, sd
IW2	East of Colorado R; volcanic	Av	LH	739367	3659173	sl, sd
IW4	East of Colorado R; volcanic	Av	P-H	740094	3658749	sl, sd
IW3-C	East of Colorado R; volcanic	Av	P-H	745512	3667463	sl, sd
PAT1a	East of Colorado R; volcanic	Av	LP	742018	3634458	sl, sd
PAT1b	East of Colorado R; volcanic	Av	LP	742018	3634458	sl, sd
PAT2	East of Colorado R; volcanic	Av	MP	741595	3632374	sl, sd
PAT4	East of Colorado R; volcanic	Av	MP	742691	3633223	sl, sd
LAG2	East of Colorado R; volcanic	Av	LP	741636	3641087	sl, sd
C23	East of Colorado R; volcanic	Av	LP	729862	3701165	sl, sd
C24	East of Colorado R; volcanic	Av	P-H	730598	3703526	sl, sd
C16	East of Colorado R; volcanic	Av	LH	723112	3703723	sl, sd
A-32	Salton Sea	Playa	LH	630171	3682992	sl
A-34	Salton Sea	Playa	LH	596176	3690337	sl
SS-17	Salton Sea	Playa	Mod	618997	3691282	sl

(continues)

Table 1. *(continued)*

Field ID	General Location and Geology	Landform	Age[a]	Easting	Northing	XRF sd/sl[b]
A-101	Salton Sea	Playa	Mod	625101	3690917	sl
A-31	Salton Sea	Playa	Mod	624022	3692186	sl
PAT5	Bouse Fm; Fluviolacustrine	Playa	MiPl	743166	3633194	sl, sd
RB5	Muggins Mts; Gneiss	Distal fan	Mod	763069	3635223	sd
RB-6	Muggins Mts; Gneiss	Distal fan	Mod	763069	3635223	sl, sd
RB8	Muggins Mts; Gneiss	Distal fan	Mod	763295	3635867	sd
RB-9	Muggins Mts; Gneiss	Distal fan	Mod	763295	3635867	sl, sd
RB13	Muggins Mts; Gneiss	Distal fan	Mod	761605	3637231	sd
IW-1	East of Colorado R; volcanic	Distal fan	Mod	739407	3659212	sl, sd
IW-5	East of Colorado R; volcanic	Distal fan	Mod	739194	3654335	sl, sd
GO1	East of Colorado R; volcanic	Distal fan	Mod	731252	3700199	sd
C26	East of Colorado R; volcanic	Distal fan	Mod	729562	3700606	sd
CR1	Colorado River	Wash	LP	723236	3630783	sd
CR2	Colorado River	Wash	Mod	723045	3630644	sd
CR3	Colorado River	Wash	Mod	735043	3635566	sl
CR4	Colorado River	Wash	Mod	739285	3637089	sl, sd
YPG3B	East of Colorado R	Dune	Mod	746223	3636643	sd
YPG3C	East of Colorado R	Dune	Mod	750583	3645660	sl, sd
PAT3	East of Colorado R	Dune	Mod	741961	3633183	sd

[a] Ages of Mojave landforms from *McDonald et al*. [2003]; Cima volcanic flow ages from *McFadden et al*. [1986]. Ages of Sonora landforms from *Bacon et al*. [2010]; Bouse Fm. from *Spencer and Patchett* [1997]; Lake Cahuilla from *Waters* [1983]. Ages for Av horizons are for the landform on which they accumulated. MiPl = Miocene-Pliocene, EMP = early to middle Pleistocene, MP = middle Pleistocene, LP = late Pleistocene, P-H = Pleistocene-Holocene transition, LH = late Holocene, Mod = modern surface.

[b] XRF on the silt (sl) or sand (sd) fraction; NA = not analyzed for XRF.

These tracers along with other commonly used trace elements (such as Sr, Ba, Ni, and Cu) and major oxides (SiO_2, K_2O, Na_2O, CaO, MgO) are used here to determine specific landforms that are potential sources of aeolian sediment for Av horizons.

[15] Bulk chemical analysis of Av horizons and potential sources may mask geochemical signals from diverse sources, so we chose to analyze two distinct grain size intervals of the aeolian sediment and potential sources. In addition, this allows us to identify aeolian processes involved in the contribution of aeolian sediment from local and far-traveled sources: medium to very fine silt (2–32 μm) is considered the suspended load component and fine sand (125–250 μm) is considered the saltation component. Coarse silt and very fine sand can in many cases be temporarily transported in modified saltation and suspension [*Tsoar and Pye*, 1995], and so was not analyzed for chemistry in this study. This differs from previous studies that determined the dust composition of bulk samples (<2 mm) or <50 μm fraction [*Reheis et al*., 1995, 2002, 2009].

[16] Av horizons were sampled by removing the surface layer of desert pavement clasts and excavating intact soil peds. Potential dust sources were sampled by collecting fine-grained surface samples adjacent to and upwind of Av sample sites or along transects. For example, several samples from Kelso Wash were collected along its profile. The Soda and Silver Lake playas were sampled along transects, the purpose being to capture any variability in surface composition of landforms. GPS locations were recorded for each sampling site (Table 1).

[17] All samples were weighed and then dried for 24 hours at 105 °C before laboratory analysis. Particles greater than 1 mm were removed using nested sieves to determine the percent of coarse sand, very coarse sand, and gravel. The grain size distribution of particles smaller than 1 mm was determined using laser diffraction in a Saturn Digisizer 5200 (Micromeritics, Norcross, GA). Samples were sonicated in deionized water with 0.005% surfactant (sodium metaphosphate) before analysis. Carbonates were not removed before analysis.

[18] Sample geochemistry was determined using X-ray fluorescence on segregated fine sand (125–250 μm) and medium to very fine silt (2–32 μm) subsamples of at least 5 g, if possible. Some samples did not contain appreciable fine sand and fine silt, in which case only the subsample with ample sediment was prepared (Table 1). The fine sand subsamples were obtained by wet sieving the samples through 125 and 250 μm sieves. The medium to very fine silt subsamples were obtained by dispersing the sample overnight with sodium metaphosphate solution, and wet sieving the sample through a 32 μm sieve. The liquid sample was centrifuged to settle the silt fraction [*Jackson*, 2005]. The clay fraction was decanted, and the fine silt fraction was collected and dried. The combination of wet sieving and centrifugation washed the samples of dispersant, which we found contaminated results with elevated Na and P unless they were adequately washed. Samples were sent to the Washington State University Geoanalytical Lab and prepared using a double fusion method [*Johnson et al*., 1999] and analyzed in a ThermoARL Advant'XP+ sequential X-ray fluorescence spectrometer (Thermo Scientific, Waltham, GA). Normalized results are presented here for the major elements in weight percent and trace elements in ppm (supporting information).

[19] Statistical analyses were performed using SigmaPlot software (Systat Software Inc., San Jose, CA) to compare compositions of potential sources and Av horizons. The compositional data are not normally distributed, so one-way analysis of variance on ranks using the Kruskal-Wallis method, a nonparametric test, was used. Pairwise multiple comparison using Dunn's method for nonnormal data further elucidated differences between potential sources and Av horizons at the 95% confidence interval. Cluster analysis, using all measured elements, detects natural groupings of data and is used here as an additional check to gauge the similarity of Av soil to potential dust sources.

[20] A subsample of the sand grains separated for XRF was collected to evaluate grain roundness. Digital photos of grains were taken using a camera-mounted binocular stereoscope. Individual sand grains along a line transect on the photos were described using the grain roundness criteria of *Powers* [1953]. Six roundness classes from very angular to well-rounded were described for individual grains using visual estimation. Twenty-three different samples comparing the roundness of fine sand from Av horizons (Mojave $n = 3$, Yuma $n = 3$) and potential sources including sand dunes ($n = 6$), ephemeral washes and distal alluvial fans ($n = 7$), and playas ($n = 4$) were analyzed. At least 200 individual grains were described per sample to determine significant roundness differences [*Folk*, 1955; *El-Sayed*, 1999]. To help maintain an unbiased interpretation of depositional environment and roundness, each sample was assigned a number so that the location and type of the sample was unknown at the time of the roundness description.

4. Results

4.1. Grain Size

[21] Most sampled Av horizons in both the Mojave and Yuma areas have a loam to clay-loam texture, although Av texture can be as coarse as loamy sand (>70% sand) or as fine as silty clay loam (<20% sand) (Figure 3). Grain size distributions of Av peds are typically bimodal, with the coarser mode falling in the coarse silt to very fine sand range (50–200 μm), and the fine mode in the clay to fine silt range (1–4 μm) (Figures 4a and 5a). The dip in the distribution between the coarse and fine modes is centered at about 20 μm. Occasionally, Av horizons are polymodal, containing an additional fine to medium sand mode (Pat1b). The ubiquitous presence of a coarse and fine mode in Av horizons justifies our approach of analyzing two grain size fractions for composition.

[22] Alluvial sources in the Mojave (Kelso Wash, Mojave River, and distal alluvial fans) contain abundant sand with some facies that are silt-rich (KW7, IS2). The Mojave River (MR5, MR4) contains sand modes ranging from 100 to 400 μm but also contains silt modes from 40 to 60 μm. Kelso Wash (KW7, KW2) has modes similar to those of the Mojave River on the coarse end, but much more abundant and finer grains with dominant modes from 3 to 30 μm (Figure 4b). Soda and Silver Lake playas contain abundant fine sediment with modes from 2 to 7 μm as well as fine silt and very fine sand modes (Figure 4c). Dunes are unimodal from 125 to 250 μm with less than 6% silt and clay (Figure 4d).

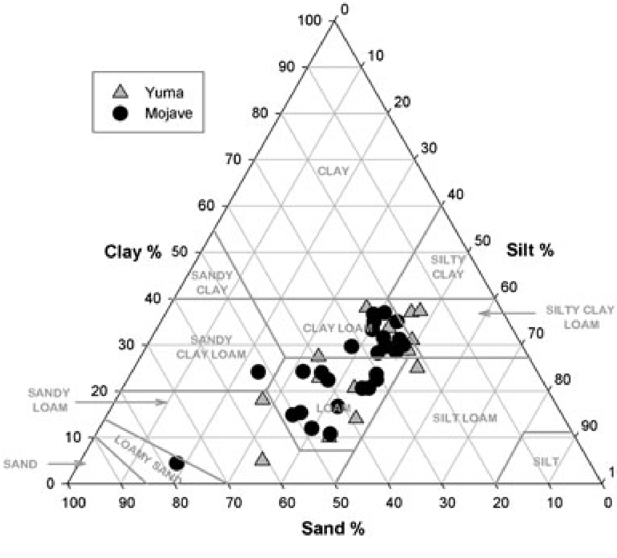

Figure 3. Ternary diagram depicting soil texture of Av horizons from the Mojave and Yuma sampling sites.

[23] Alluvial sediment at Yuma, derived from ephemeral washes draining alluvial fans (C26, GO1), and from the Colorado River (CR1, 3, 4), contains very fine to medium sand modes (70 to >300 μm) and localized silt-rich facies that have a mode centered over 3 μm (Figure 5b). The Bouse Formation (Miocene-Pliocene Colorado River [*Spencer and Patchett*, 1997]) is locally exposed and exhibits badland-style erosion due to its fine-grained nature. Our sample is predominantly fine silt with a mode centered over 3 μm with a secondary mode at 40 μm (Figure 5d). Sediment from the margins of the Salton Sea, considered here as a potential source for far-traveled dust to the Yuma area, is variable in texture but contains abundant silts with modes from 2 to 62 μm (Figure 5c). Dunes are similar to the samples from the Mojave with modes from fine to medium sand (Figure 5d).

[24] On average, about 50% of grains in Av horizons are <20 μm, and 30% of the grains are 5 μm and less (Table 2). Playas have a similar distribution of fine grains compared to Av horizons. Alluvial sources have, on average, lower percentages of fines; however, all potential sources except dunes have a high variability in the percent of fines.

4.2. Geochemistry—Medium to Very Fine Silt (32–2 μm)

[25] Most of the elemental ratios show distinct separation between Av horizon composition from soils and certain landforms in the Mojave Desert that are potential dust sources (Figure 6). Ratios including Ti/Zr, Rb/Sr, Ce/Y, K/Rb, Ti/Nb, and Ba/Sr show that Av horizon composition overlaps with Kelso Wash and distal fans of the Providence Mountains and other regional fans (referred to as western fans in figures; Figure 6a–c). Distal alluvial fans seem to have the most in common with Av horizons (Figure 6a, c), followed by Kelso Wash, which distinctly matches Av horizons in Rb/Sr versus Ba/Sr (Figure 6d) but also shares a similar composition to playas (Figure 6b, c). Soda Lake playa shows some modest overlap in composition with Av horizons in K/Rb versus Ti/Nb and Ce/Y versus Th/Sc, but Silver Lake playa clearly does not match Av horizons (Figure 6b, c). Rb-Sr-Ba/10 shows separation of Soda and Silver Lake playas from Av horizon composition (Figure 7b). Major elements are less likely to show differences in potential sources, although $CaO + MgO\text{-}SiO_2/10\text{-}Na_2O + K_2O$ reveal differences between Soda Lake playa and all other samples (Figure 7a).

[26] Box plots of single elements comparing Av silt to potential silt sources by landform depict not only the compositional ranges of landforms with respect to certain elements, but also reveal where similarities or differences exist in composition (Figure 8). For the most part, silt compositions of Av dust and playa sources are statistically different using key elemental tracers, whereas Av silt is

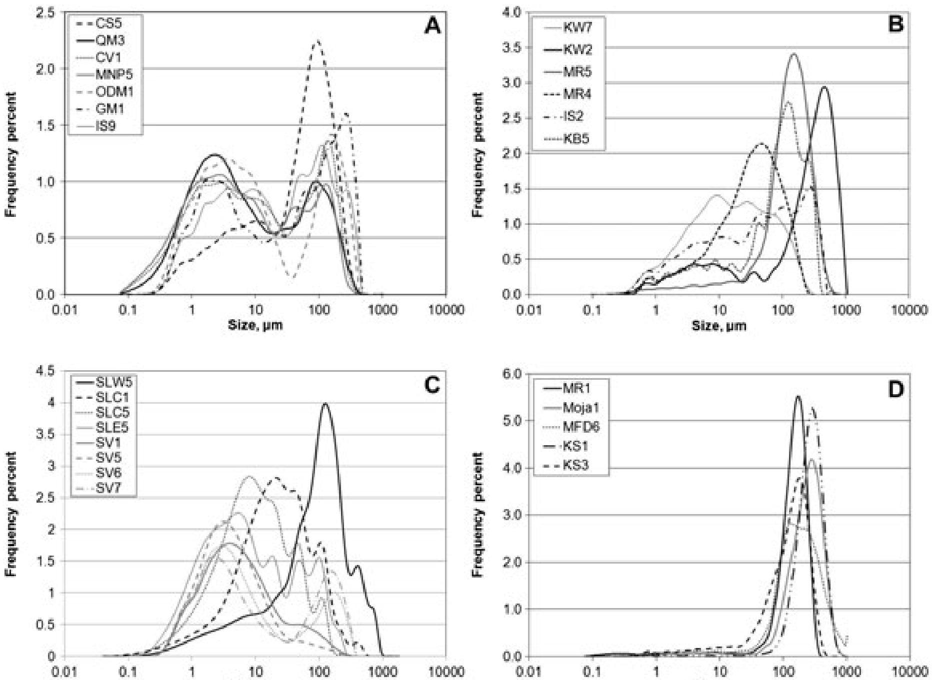

Figure 4. Representative grain size distributions of the <1 mm fraction of samples from the Mojave Desert including (a) Av horizons, (b) alluvial sources including distal fans and washes, (c) playas, and (d) sand dunes. Abbreviations in legend correspond to sampling sites in Table 1.

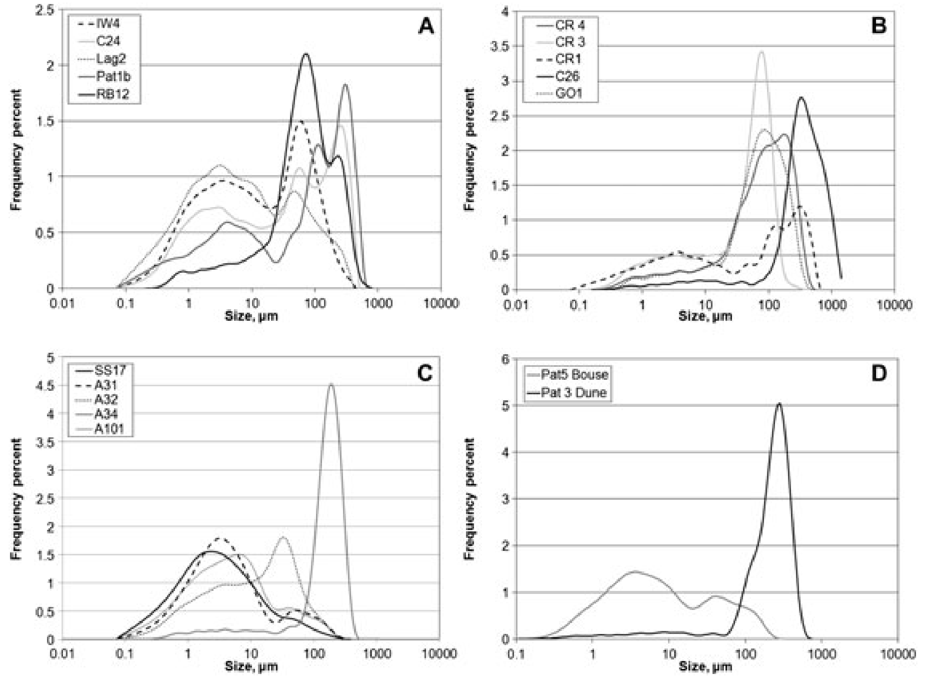

Figure 5. Representative grain size distributions of the <1 mm fraction of samples from the Yuma area including (a) Av horizons, (b) alluvial sources including distal fans and washes (C26 is <2 mm fraction), (c) Salton Sea, and (d) Bouse Formation and sand dunes. Abbreviations in legend correspond to sampling sites in Table 1.

statistically similar to Kelso Wash and nearby distal alluvial fan deposits. Those elements that separate playa and Av silt include Sr, Nb, Zr, Ce, La, Y, and Ti. Those that have no statistical difference include Th, Sc, Ni, and Cu. It is clear from the data that alluvial sources are favored in the formation of Av horizons in the Mojave Desert, but that other landforms, including playas, also contribute aeolian sediments.

Table 2. Grain Size Attributes of Av Horizons and Potential Aeolian Sediment Sources[a]

		% < 20 μm				% < 5 μm				% Sand	
	n	Avg	SD	Max	Min	Avg	SD	Max	Min	Avg	SD
Av horizon	42	51.2	12.5	69.0	14.8	34.1	10.1	47.0	7.0	32.4	11.2
Fluvial wash and fan	44	17.6	13.1	58.7	3.4	9.4	7.0	28.7	1.8	70.8	20.8
Kelso Wash	14	23.4	16.5	58.7	5.5	12.5	8.3	28.7	3.1	63.8	22.7
Playa	29	60.2	23.0	91.3	9.4	35.2	18.5	65.9	5.8	27.8	18.8
Dune	6	5.6	2.7	8.9	1.0	3.4	1.4	4.5	0.7	91.7	4.0

[a] Data for table include Mojave and Yuma samples, except for Kelso Wash, which is in the Mojave.

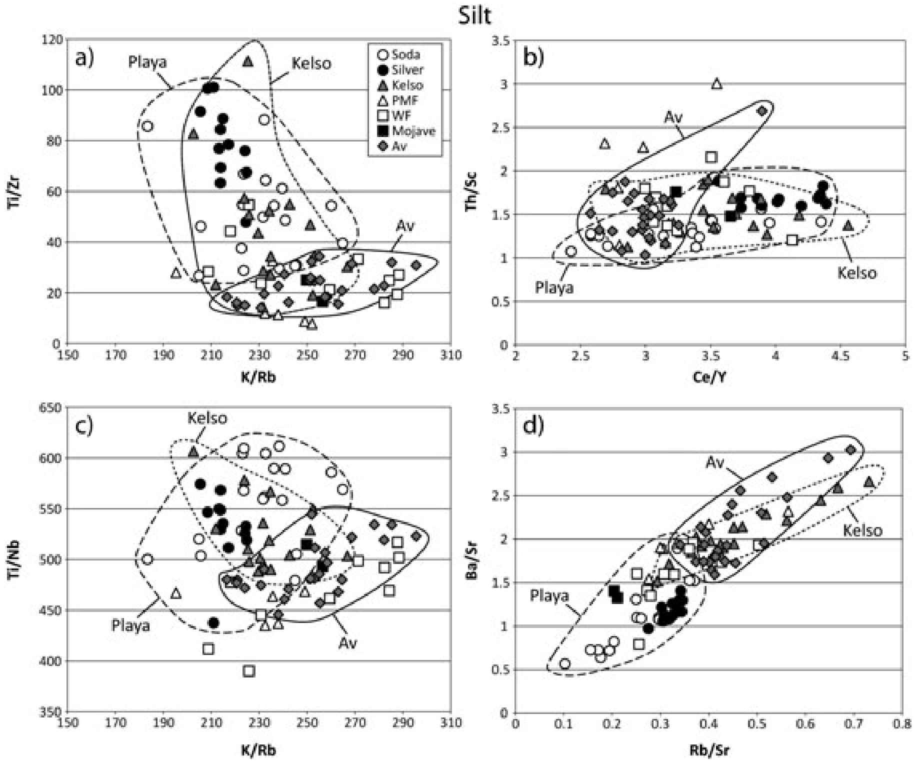

Figure 6. Bivariate plots of elemental ratios comparing the silt fraction (32 to 2 μm) of Av horizons and potential dust sources in the Mojave Desert. Three fields depict compositional zones of Av horizons, playas, and the Kelso Wash.

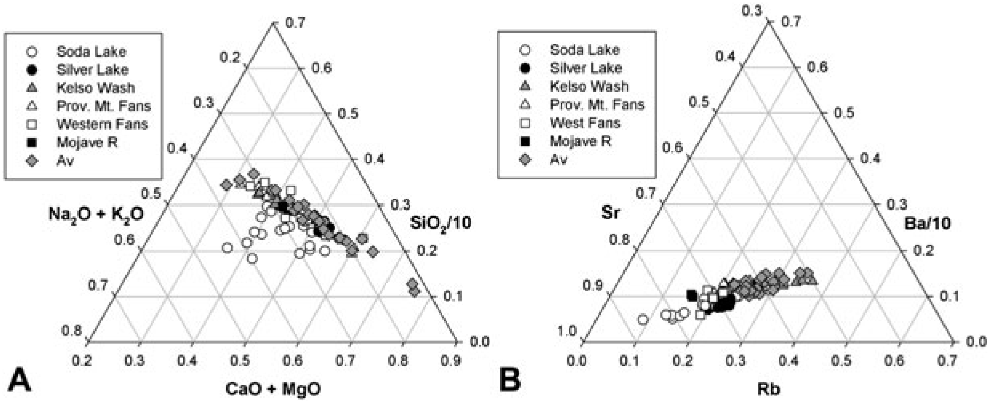

Figure 7. Ternary plots of (a) major elements in weight percent and (b) trace elements in ppm comparing the silt fraction (32–2 μm) of Av horizons and potential dust sources in the Mojave Desert.

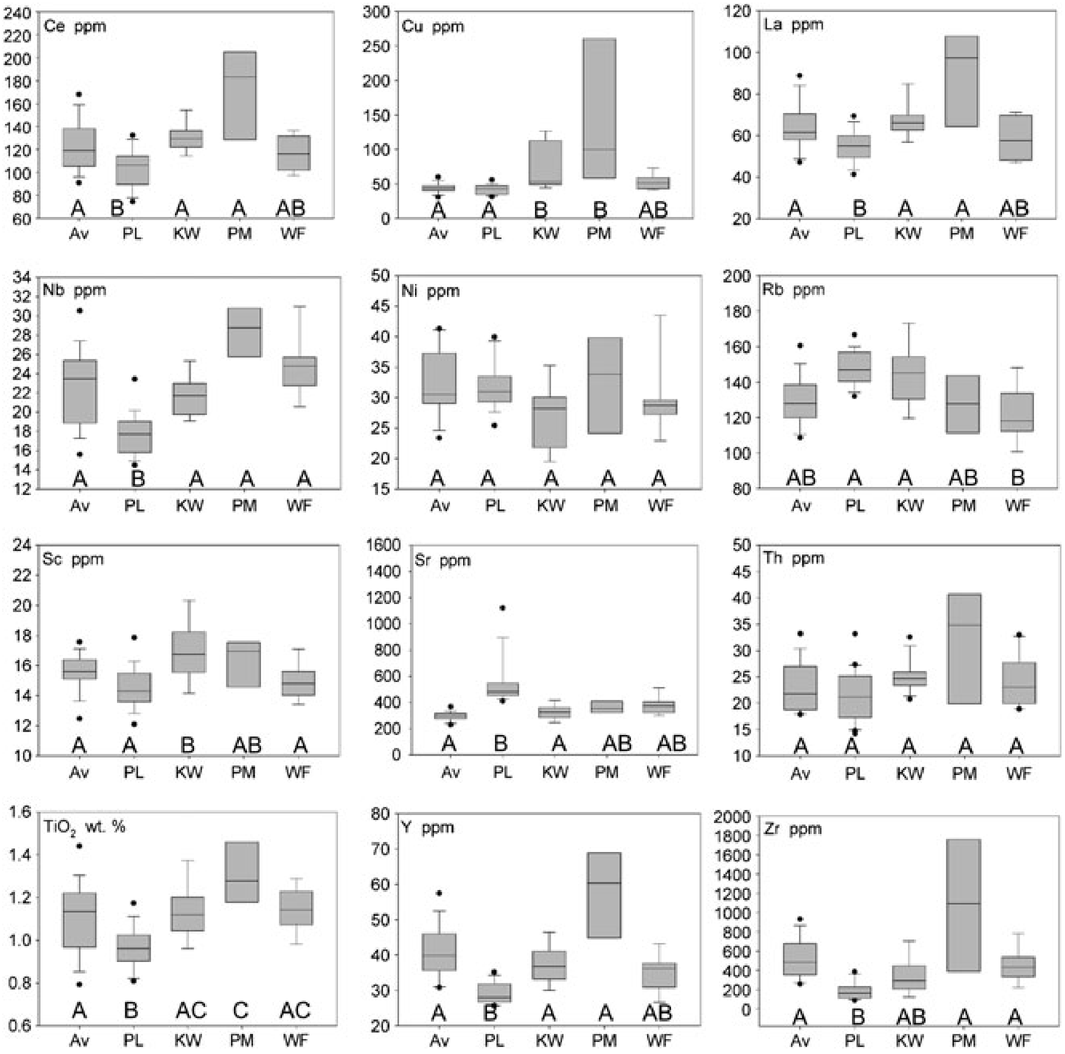

Figure 8. Box plots of selected elements depicting the compositional variability of the silt fraction (32 to 2 μm) of Av horizons and potential dust sources in the Mojave Desert. The grey boxes represent the 25th to 75th percentiles and the whiskers capture the 10th to 90th percentiles. Bottom and top dots represent minimum and maximum values, respectively. The line in each box represents the median value. Nonparametric statistical analysis using Kruskal-Wallis method with a pairwise multiple comparison analysis using Dunn's method reveal which landforms are statistically similar in composition to Av horizons. Shared letters A, B, or C are used to identify statistical similarities in composition. Av is soil dust, PL is playas, KW is Kelso Wash, PM is Providence Mountains alluvial fans, and WF are western fans (Indian Springs and others).

[27] Plots of elemental ratios from the Yuma area reveal broad overlap between potential sources and Av soils (Figure 9). Av silts compositionally overlap with samples from adjacent local washes, the nearby Colorado River sediment, and local outcrops of the Bouse Formation indicating that all three are dust contributors to regional Av horizons. By comparison, the composition of sediments along the margins of Lake Cahuilla and the Salton Sea only partially overlap with Av horizons indicating that dust derived from Salton Trough is a minor contributor to Av development in the region (Figure 10). Playas are less abundant in the western Sonora Desert compared to the Mojave Desert study area; however, before the flooding of the Salton Trough by the Colorado River in 1905, the trough was a vast desiccated lake plain containing sediments of ancient Lake Cahuilla [*Dohrenwend and Smith*, 1991]. Box plots also indicate broad similarities between most potential dust sources and Av horizons at the Yuma locations (Figure 11) but that Salton Sea sediments are statistically different when comparing most key elements.

[28] Cluster analysis using all measured elements in the silt fraction reveals that in the Mojave Desert, Av horizons are chemically most similar to Kelso Wash and distal alluvial fans, followed by Mojave River and then Soda and Silver lakes (Figure 12a). At Yuma, Av horizons are most chemically similar to the Colorado River, Bouse Formation, and ephemeral washes, and least similar to the Salton Sea sediment (Figure 12b). The results of the cluster analysis agree with many of the statistical comparisons described above.

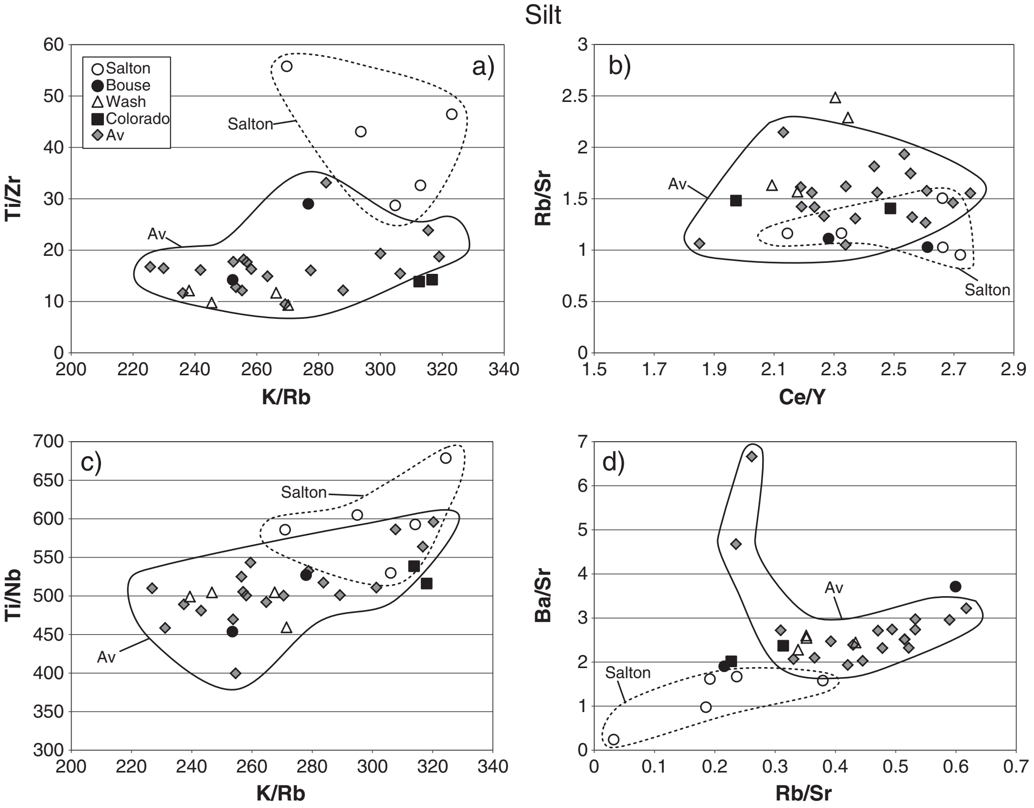

Figure 9. Bivariate plots of elemental ratios comparing the silt fraction (32 to 2 μm) of Av horizons and potential dust sources near Yuma, western Sonora Desert. Two fields depict the compositional ranges of Av horizons and the Salton Sea. Other landforms almost entirely overlap with Av horizons.

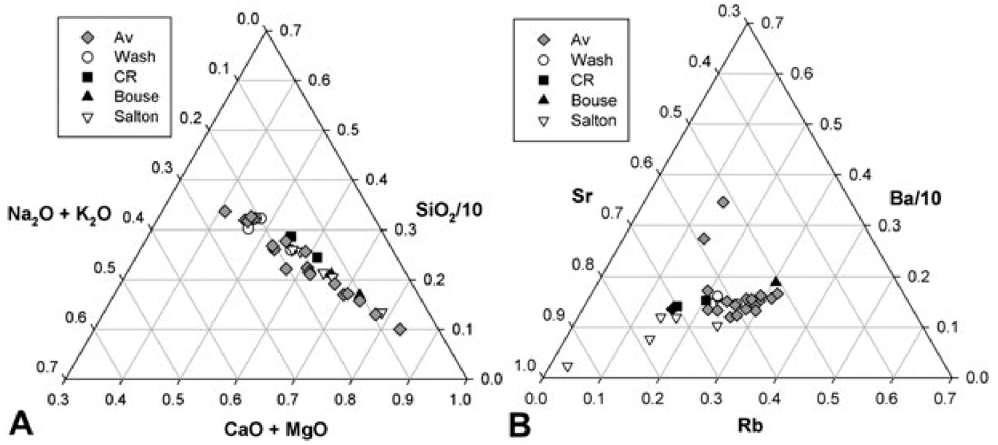

Figure 10. Ternary plots of (a) major elements in weight percent and (b) trace elements in ppm comparing the silt fraction (32 to 2 μm) of Av horizons and potential dust sources near Yuma, western Sonora Desert.

4.3. Geochemistry—Fine Sand (250–125 μm)

[29] Bivariate and ternary plots of the composition of the fine sand fraction appear to reveal broad overlap between potential sources and Av soils. Closer examination reveals compositional fields where Av sand at certain sites closely resembles nearby washes draining alluvial fans. For example, Providence Mountains alluvial fan washes and associated Av horizons appear to be closely related (Figure 13a, b; samples PM, QM, and CS in Figure 1). Av horizons on limestone substrate and samples from adjacent washes plot separately from the rest of the data due to locally derived calcium carbonate (Figure 14a). Sands from the Mojave River, Kelso Wash, and Kelso dunes plot in a broad zone encompassing the composition of most Av horizon sand. Despite the observed compositional fields, there is limited statistical difference of sand composition related to

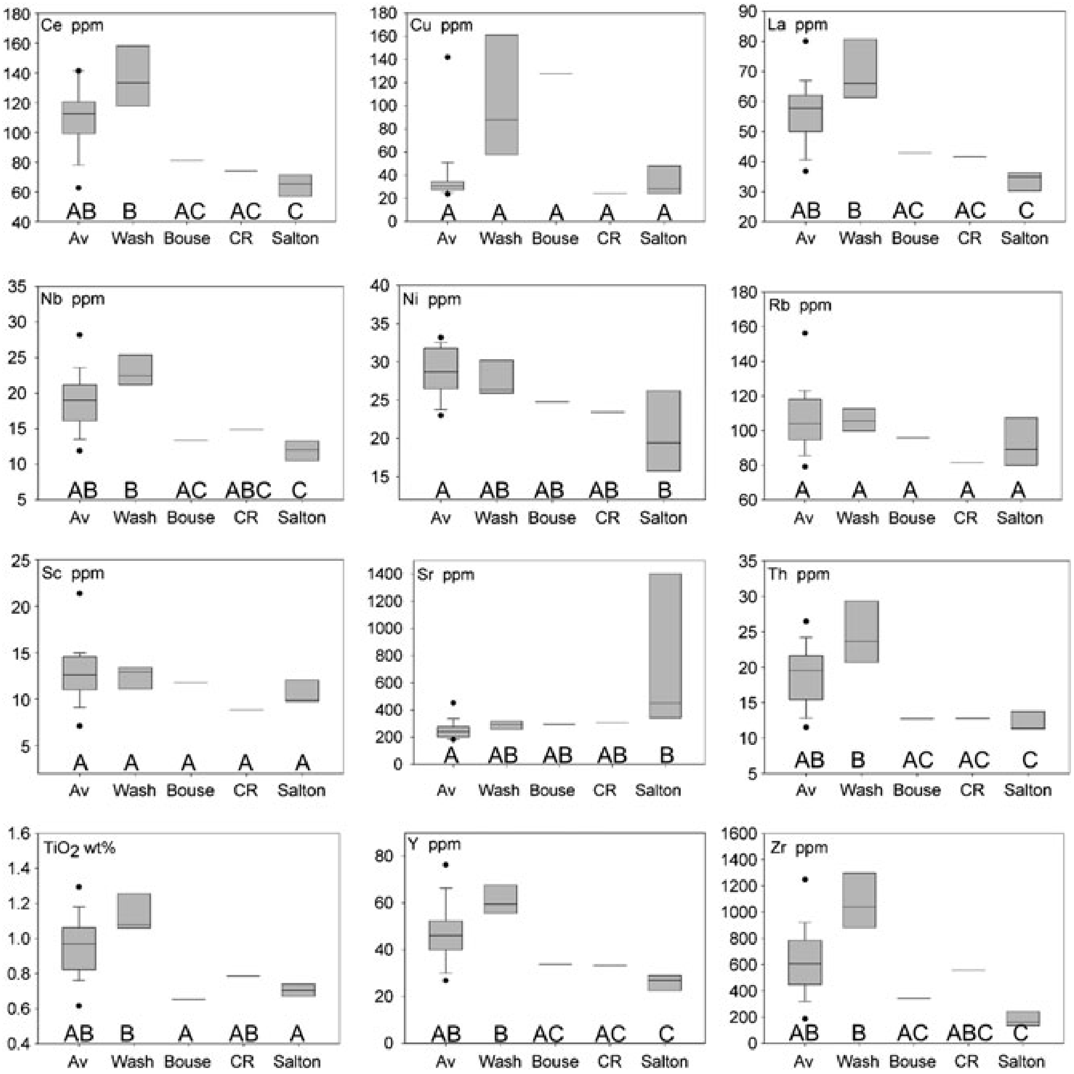

Figure 11. Box plots of selected elements depicting the compositional variability of the silt fraction (32 to 2 μm) of Av horizons and potential dust sources near Yuma, western Sonora Desert. The grey boxes represent the 25th to 75th percentiles and the whiskers capture the 10th to 90th percentiles. Bottom and top dots represent minimum and maximum values, respectively. The line in each box represents the median value. Nonparametric statistical analysis using Kruskal-Wallis method with a pairwise multiple comparison analysis using Dunn's method reveal which landforms are statistically similar in composition to Av horizons. Shared letters A, B, or C are used to identify statistical similarities in composition. Av is soil dust, Wash is distal alluvial fan washes, Bouse is the Miocene-Pliocene Bouse Fm., CR is Colorado River, and Salton is Salton Sea.

local lithology when comparing elemental ratios such as Rb/Sr (Figure 14b), and no statistical difference in the single elemental composition of any sand source compared to the Av horizon sand.

[30] A similar relation is seen at Yuma where local sand supply has a strong influence on the sand composition in Av horizons. Sand from washes draining gneiss or volcanic bedrock matches sand from Av horizons mantling adjacent alluvial fans (Figures 13c, d and 14c). Western fans appear to be strongly influenced by sand from the nearby Colorado River. There is a significant statistical relation between local lithology and sand composition in Av horizons for some elemental ratios such as K/Rb (Figure 14d), but no statistical difference in the single elemental compositions of sand.

4.4. Grain Roundness

[31] Individual sand grains were described as well rounded, rounded, subrounded, subangular, angular, and very angular, and averages for samples were calculated following *Powers* [1953]. Sand from washes and distal fans are classified as subangular. Av horizons and dune sand are classified as subrounded, and playa sands are also classified as subrounded, but are more variable. Dunes have the highest proportion of rounded grains, whereas washes have the highest proportion of angular grains (Figure 15).

5. Discussion

[32] The geochemical data make a strong case for local alluvial deposits being important sources of aeolian

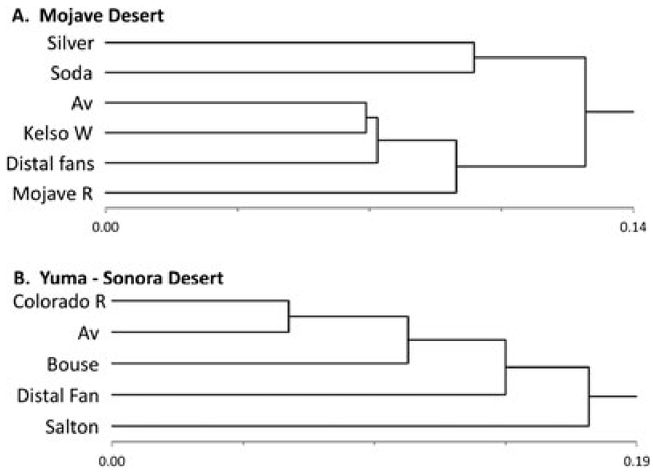

Figure 12. Cluster analysis revealing similarities in the silt fraction of all elements between Av horizons and potential dust sources in (a) Mojave Desert and (b) Yuma.

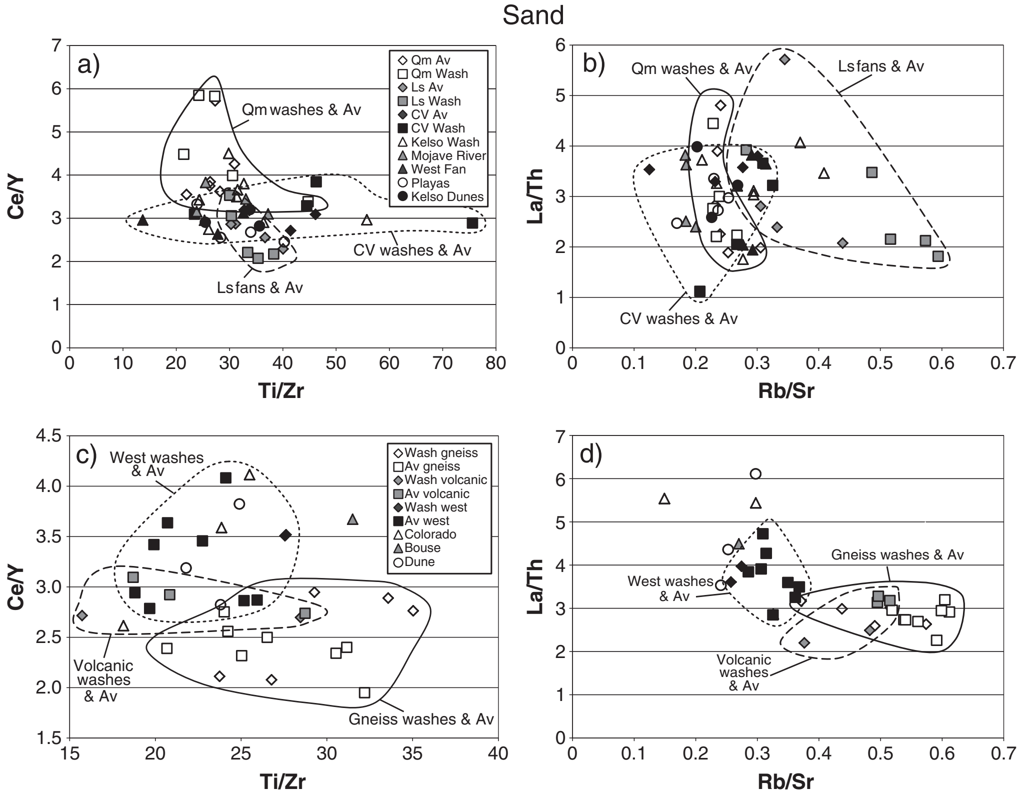

Figure 13. Bivariate plots of elemental ratios comparing the fine sand fraction (250 to 125 μm) of Av horizon sand and potential sand sources in (a and b) the Mojave Desert and (c and d) Yuma. Fields are drawn to depict similarities in Av sand composition to nearby washes draining distal alluvial fans. See Table 1 for sample locations.

sediment in the formation of Av horizons. Grain size and sand roundness data are more ambiguous in terms of elucidating potential sources, but they reinforce that local sources are contributors of aeolian sediment. We make the arguments below that our data demonstrate the dual role of aeolian suspension and saltation transport in the development of Av horizons and that the primary sources of aeolian sediment are proximal alluvial washes draining alluvial fans and axial drainages. Playas certainly play a role in dust formation in the desert, but they lack a significant geochemical fingerprint in the Av horizons studied.

5.1. Bimodality of Av Horizons

[33] The aeolian origin of Av horizons has been previously documented [*Wells et al.*, 1985], but the Av horizons are not just accumulations of dust. Grain size and shear velocity

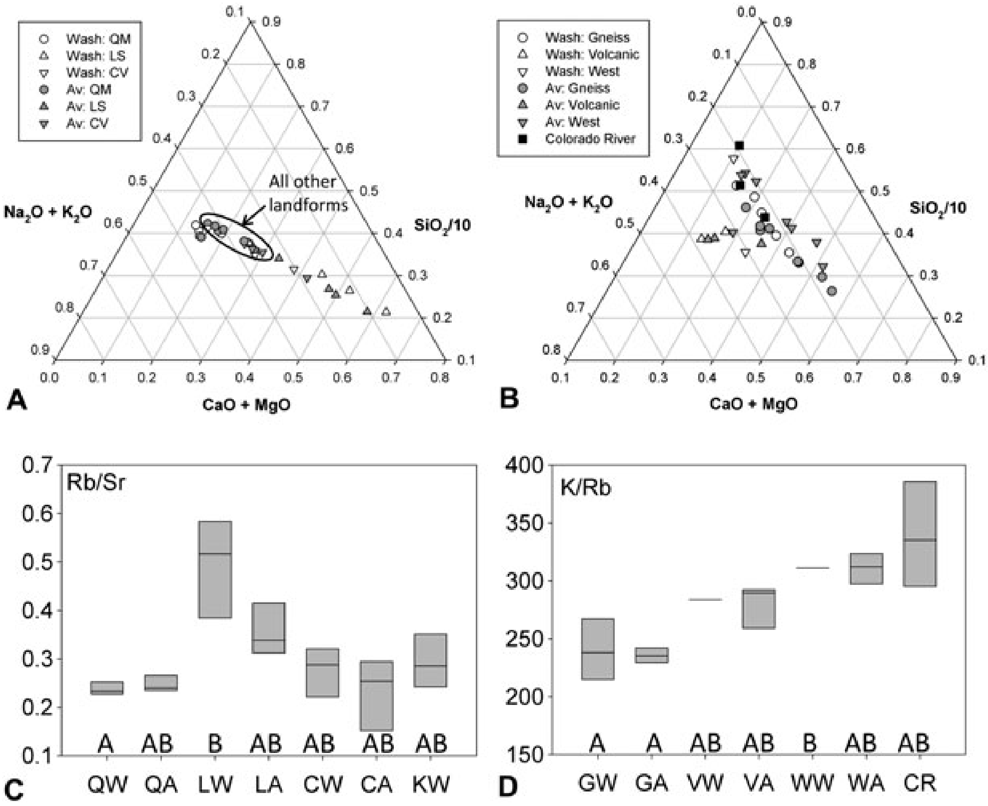

Figure 14. Ternary plots of major elements comparing the sand fraction (125 to 250 μm) of Av horizons and potential local sand sources in (a) Mojave Desert and (b) Yuma, both in weight percent. Oval in panel a encompasses the composition of all data from other landforms. In panel a, QM = quartz monzonite, LS = limestone, CV = Cima volcanics. Box plots of Rb/Sr of sand in (c) the Mojave Desert, and of K/Rb in (d) Yuma, reveal the influence of local lithology on sand composition in potential sources and Av horizons. Sample groups are named for the dominant bedrock in the area or for a significant geographic feature. In panel c, QW = quartz monzonite wash, QA = quartz monzonite Av, LW = limestone wash, LA = limestone Av, CW = Cima volcanic wash, CA = Cima volcanic Av, KW = Kelso Wash. In d, GW = gneiss wash, GA = gneiss Av, VW = volcanic wash, VA = volcanic Av, WW = western wash, WA = western Av, CR = Colorado River.

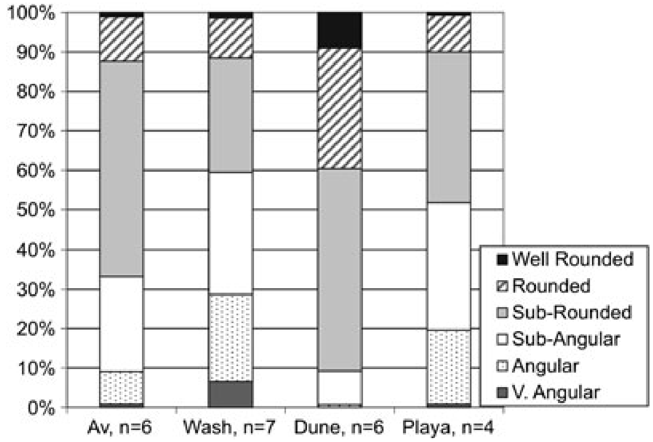

Figure 15. Grain roundness for fine sand (250 to 125 μm) comparing Av horizons, dunes, ephemeral washes, and playas. Roundness scale is from *Powers* [1953].

ultimately control whether certain particles are transported by suspension or saltation. Studies have shown that sand grains smaller than about 100 μm are transported by modified saltation or suspension, whereas larger grains are transported by saltation [*Nalpanis*, 1985] and sand grains larger than 100 μm rarely go into suspension [*Pye*, 1987]. Considering that Av horizons contain abundant grains greater than and smaller than 100 μm, we attribute their origin to both saltation and suspension transport. Furthermore, saltation bombardment plays a critical role in dust formation by liberating dust-sized particles for suspension transport [*Shao et al.*, 1993].

[34] Textural variability of Av horizons (Figure 3) is partly associated with soil age: the older the Av horizon, the more clay it contains [*McDonald*, 1994; *McDonald et al.*, 1995; *Young et al.*, 2004]. Younger (i.e., Holocene) Av horizons contain less clay and more sand such that as the horizon develops over time, it accumulates more clay into the ped interior and maintains a coarser, sandy exterior [*McDonald*, 1994; *Anderson et al.*, 2002]. Clay-sized particles, which comprise 20–40% of many Av horizons (Figure 3), were not analyzed in this study and could plausibly be derived from desiccating pluvial lakes and playas. The link between Av horizon age and clay content suggests clay is added gradually over time, so it is also plausible that clay-sized particles are derived from proximal alluvial landforms as well. Proximity to source may also influence the proportion of sand in Av horizons. *Wells et al.* [1985] noted that Av horizons are coarser than typical desert dust and that the sand fraction was derived from local saltating sediments.

[35] The bimodal to polymodal character of Av horizons (Figures 4a and 5a) clearly defines suspension- versus saltation-derived components in their genesis. Fine- to medium-sized sand contained in Av horizons is likely transported via saltation from nearby distal alluvial fans, washes, and dunes and incorporated into the Av horizon via vertical cracks along ped faces. The ubiquitous 3 μm mode found in Av horizons could be an indicator of far-traveled dust, carried in suspension only. According to *Gomes et al.* [1990], typical, proximal desert dust is bimodal with a coarse mode around 60 μm and a fine mode between 1 and 20 μm. The finer mode represents long-range transport and the coarse mode represents a local source. Desert dust commonly contains a mode of 3 μm produced by sandblasting and disaggregation of soil aggregates. Asian dust that has reached the western United States is typically between 2 and 4 μm [*VanCuren and Cahill*, 2002; *Muhs et al.*, 2008b] and could possibly supply some of the fine mode seen in Av horizons. Alternatively, local alluvial sources that we have documented as typically containing silt including a 2 to 4 μm mode could also have contributed this mode to Av horizons as well (Figures 4b and 5b, Table 2). The fine-grained compositional data (32–2 μm) capture the coarse half of the fine mode, but playas are not strongly represented in the compositional data, whereas silt from local alluvial sources is well represented (Figures 6 and 7). These data suggest that the bulk of the finer component of Av horizons is from a proximal source with a smaller component derived from deflating playas and other far-traveled dust.

[36] Similar bimodal grain size distributions have been documented in loess of the Negev in Israel [*Crouvi et al.* 2008; *Enzel et al.*, 2010]. These authors note the lack of silt sources and the abundance of dunes upwind. Their explanation of the fine and coarse modes relates to the abrasion of sand grains during aeolian transport of dune sand, not from the liberation of silt-sized particles via saltation bombardment of a silt-rich source [*Crouvi et al.*, 2008, 2012]. This hypothesis for silt generation is compelling and may help to explain dust formation in the desert southwest United States. Many of the Av horizons in the eastern Mojave Desert sampled for this project lie downwind of the extensive Mojave River-Devils Playground-Kelso dunes sand transport corridor (Figure 1) driven by prevailing winds from the west and northwest. The process proposed by *Crouvi et al.* [2008], however, cannot explain the bimodal character of Av horizons in all settings in the eastern Mojave. For example, the Indian Springs-Cima volcanic field seems to lack an upwind dune field. At Yuma, sand-transporting winds are predominantly from the northwest, with a temporary reversal during the summer monsoon season [*Muhs et al.*, 1995; *Helm and Breed*, 1999]. Well-defined areas of sand dunes are uncommon in this area except for the Algodones dunes to the west (Figure 2) and dunes in the Gran Desierto (not shown) that are south of Yuma. Sand-transporting winds for the Gran Desierto dunes are from the south [*Muhs et al.*, 2003], therefore potentially providing a source of dust from dune sand abrasion. Our study does not have enough data to evaluate the Negev model, and more research must be conducted to demonstrate whether this is a viable process for dust generation in the desert southwest United States.

5.2. Alluvial Landforms as Sources of Aeolian Sediment

[37] Evaluation of the geochemistry data from multiple possible aeolian sources is important because based only on grain size comparisons, one could conclude that fine-grained playas were the primary source of dust (Figure 4c, Table 2). Several researchers have suggested that Soda and Silver Lake playas were the primary dust sources for Av horizons on top of Cima lava flows [*Wells et al.*, 1985; *McFadden et al.*, 1986; *Reynolds et al.*, 2006]. *Reynolds et al.* [2006] assumed the fine silt flux at Cima is from playas because of their similarity in grain size. In addition, they found low magnetite content in Mojave playas and in dust, leading to the interpretation that playas were large dust sources. Av samples from the Cima volcanic field and Indian Springs area are downwind of Soda and Silver Lake playas (Figure 1), yet our data suggest that their composition has a strong affinity toward alluvial fan deposits rather than these playas.

[38] Rapid accumulation rates of dust in the Mojave Desert in the early Holocene have also been attributed to desiccating pluvial lakes and playas [*Reheis et al.*, 1995]. Sr concentrations of dust suggest that the primary influence of dust from playas on soils is within 10 km [*Reheis et al.*, 2002], whereas salt contributions from playa dust to soils may reach up to 20 km or more [*Quick and Chadwick*, 2011]. The silt (32–2 μm) fraction analyzed for composition in this study biases the results toward playas, considering that about 50% of playa sediment samples fall into this grain size range (Table 2). Despite this bias, the compositional data do not support the idea that playas are large contributors of dust to Av horizons (Figures 6–8).

[39] One key observation in the Mojave Desert is the notable compositional similarity of distal alluvial fans, Kelso Wash silts, and most Av horizons (Figure 8). From a geomorphic standpoint, this is reasonable because sand dunes intercept Kelso Wash and distal alluvial fan deposits, providing ample saltating grains to liberate silts from these landforms.

[40] At Yuma, Av sediment in general matches a variety of potential sources likely due to of the overriding influence of the Colorado River on local sediments, the Bouse Formation, and Salton Sea. *Muhs et al.* [1995] noted the compositional similarities of sands from the Colorado River, ancient Lake Cahuilla in the Salton Trough, and the Algodones dunes.

5.3. Implications of Grain Roundness

[41] Grain roundness reflects the textural maturity of the sand source: the longer the sediment has been transported or recycled in the sedimentary system, the more rounded the grains become. Angular grains tend to suggest recent weathering from source rocks and limited distance of transport. Grains transported by aeolian processes tend to be more rounded because angular corners of grains are broken off during transport and grain collisions. Experiments by *Kuenen* [1960] suggest that the wind rounds grains 100–1000 times faster than fluvial processes. Grain rounding by aeolian processes clearly has implications for dust formation via grain-to-grain bombardment [*Bullard et al*., 2007; *Crouvi et al*., 2012]. Rounding is also a function of grain size; coarse sand-size fractions tend to be more rounded than finer fractions [*Khalaf and Gharib*, 1985]. Grain roundness alone is not an indicator of aeolian transport [*Goudie and Middleton*, 2006], but roundness as an indicator of transport distance is useful in determining the origin of sand in Av horizons.

[42] Our grain roundness data from Av soil horizons are most similar to dune sand and playas and least similar to alluvial sand, which has a larger angular component (Figure 15). The degree of roundness alone implies that the rounded grains in Av horizons are derived from dunes and playas; however, the chemistry of the sand suggests the grains are from nearby washes. We conclude from these results that rounded grains in Av horizons were primarily introduced from local alluvial sources by aeolian saltation, which rounded the angular fluvial grains to resemble those found in dunes. Dunes could also be sources of rounded sands in some cases. The rounded sand grains in playas are best explained by sand blown into the playa or recycling of eroded wind-blown sand transported to the playas by washes during periodic lake-filling events.

[43] Can the similarity in sand compositions between the Av horizon and nearby washes be explained by another process? Two possibilities include derivation of the sand grains from the alluvial fan itself, or by weathering of alluvial fan sediments or bedrock. The large component of rounded grains in Av horizons precludes weathering as a primary generator of sand grains in Av horizons, as also supported by previous studies documenting that limited chemical weathering of these soils has occurred [*McFadden et al*., 1986, 1998; *Reheis et al*., 1989, 1992]. Despite documented pavement clast fracturing [*Wood et al*., 2005] by diurnal thermal expansion and contraction [*McFadden et al*., 2005], physical weathering processes, which would create angular grains, likely only contribute minor amounts of sand ($<$10%, Figure 15) to Av horizons. The small proportion of angular grains found in Av horizons could be derived from short-distance aeolian transport, bioturbation, or by modest amounts of in situ weathering [*McFadden et al*., 1986, 1998]. Furthermore, the dominance of rounded grains in Av horizons is not consistent with the short alluvial transport distance on alluvial fans; therefore, we conclude that the rounded sand grains in Av horizons are introduced by aeolian saltation. The large proportion of rounded grains in Av horizons could also suggest that the sands, as well as silts, have been recycled numerous times via erosion and transport down alluvial fans followed by aeolian processes that transport the sand grains back up the fans into Av horizons time and again.

5.4. The Role of Alluvial Landforms in Dust Production

[44] We agree with *Okin et al*. [2011] that alluvial sources are a larger contributor of aeolian sediment overall compared to playas, especially in the Mojave Desert. Playas contain crusts and some have shallow water tables that provide enough soil moisture that inhibit dust formation. Ephemeral, efflorescent salts [*Reynolds et al*., 2007; *Zlotnik et al*., 2012] and playa margins [*Sweeney et al*., 2011] can provide dust, but because these areas are not laterally extensive, they generate only small volumes of dust compared to alluvial sources in the Mojave under the modern and Holocene climatic and geomorphic conditions. By comparison, washes are extensive and dynamic, eroding and depositing sediment during large floods in response to climate change [*Ely et al*., 1993]. Although the amount of suspended load an ephemeral wash carries varies dramatically on an annual basis, suspended load typically comprises $>$90% of sediment totals [*Powell et al*., 1996; *Alexandrov et al*., 2003]. Flooding and deposition of fine suspended load provides a significant source of dust.

[45] Periodically active alluvial fans cover expansive areas of the eastern Mojave Desert. Alluvial fans and desert flats [cf. alluvial flats; *Peterson*, 1981] comprise about 60% of the southwest US desert landscape [*Goudie*, 2002]. Distal reaches of these fans may have provided ample sand and dust for the formation of Av horizons on older fan surfaces and landscapes. Major pulses of alluvial fan activity have been documented at the Pleistocene-Holocene transition, ca. 14 to 9 ka [*McDonald et al*., 2003; *Miller et al*., 2010] and in the late Holocene, ca. 6 to 3 ka [*McDonald et al*., 2003; *Miller et al*., 2010; *Bacon et al*., 2010], but these deposits have been overlooked as a major source of dust because they are currently stabilized by crusts, vegetation, and gravel lags or incipient desert pavements today. For example, during the Holocene, the Kelso dunes migrated up the alluvial fan slopes of the Providence Mountains and covered mid-Holocene distal alluvial fan deposits [*McDonald et al*., 2003]. The advance of saltating sand grains over fine-grained, unvegetated distal alluvial fan sediments would have likely produced large amounts of dust that was trapped by desert pavement on older alluvial fan terraces. Formation of a deflational gravel lag or the expansion of wind-baffling vegetation may have shut down dust generation on distal fan environments; meanwhile, bare landscapes such as ephemeral washes and playas continued to produce modest amounts of dust. We argue that the proposed early Holocene pulse of dust from desiccating pluvial lake margins [*Reheis et al*., 1995] is drowned out by even larger pulses of dust from alluvial sources. Alluvial fans and major axial drainages are even more important to the origin of dust contained in Av horizons in regions where playas are rare or absent, such as in the Sonora Desert near Yuma, Arizona, and the Negev in Israel. The results presented here are also supported by wind tunnel studies revealing that alluvial sources potentially are some of the largest dust producers in the eastern Mojave Desert, exceeding contributions from playas by one or two orders of magnitude [*Sweeney et al*., 2011].

6. Conclusions

[46] Geochemical data indicate that proximal alluvial sources, including fine sand and very fine to medium silt

from ephemeral washes and distal alluvial fan deposits, are the primary contributor of aeolian sediment to Av horizons accumulating beneath desert pavements in the desert southwest United States. Playas, as well as other landforms, are considered secondary sources of aeolian sediments. Playas are not required to generate large volumes of dust in desert environments because regional alluvial sediments contain adequate sand and silt and cover greater than 60% of the landscape in the eastern Mojave and western portions of the Sonora deserts, compared to about 1% for playas. Av soil horizons contain the record of dust flux in the Mojave and Sonora deserts, and determining the sources of dust provides an indicator for the geomorphic response of desert landforms to climate change.

[47] From a geomorphic standpoint, it is reasonable to conclude that alluvial sources can be major producers of aeolian sediment. Alluvial fans and washes have been periodically active, depositing vast amounts of fine-grained sediments available for aeolian reworking until such a time when the formation of a gravel lag at the surface or vegetation limited dust production. At Yuma, numerous sources, including alluvial fans and Colorado River-derived sediments, have likely generated dust. Bimodality of grain size distributions in Av horizons points to a combination of local saltation-derived sand and suspension-derived silt and clay in their genesis. This work suggests that the geomorphic evolution of deserts over time provides more complex, temporally and spatially changing sources of dust.

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