



Compositions of modern dust and surface sediments in the Desert Southwest, United States

Marith C. Reheis,¹ James R. Budahn,¹ Paul J. Lamothe,¹ and Richard L. Reynolds¹

Received 3 March 2008; revised 8 December 2008; accepted 24 December 2008; published 7 March 2009.

[1] Modern dusts across southwestern United States deserts are compositionally similar to dust-rich Av soil horizons (depths of 0–0.5 cm and 1–4 cm at 35 sites) for common crustal elements but distinctly different for some trace elements. Chemical compositions and magnetic properties of the soil samples are similar among sites relative to dust sources, geographic areas, and lithologic substrates. Exceptions are Li, U, and W, enriched in Owens Valley, California, and Mg and Sr, enriched in soils formed on calcareous fan gravel in southeast Nevada. The Av horizons are dominated by dust and reflect limited mixing with substrate sediments. Modern dust samples are also similar across the region, except that Owens Valley dusts are higher in Mg, Ba, and Li and dusts both there and at sites to the north on volcanic substrates are higher in Sb and W. Thus, dust and Av horizons consist of contributions from many different sources that are well mixed before deposition. Modern dusts contain significantly greater amounts of As, Cd, Cr, Cu, Ni, Pb, and Sb than do Av horizons, which record dust additions over hundreds to thousands of years. These results suggest that modern dust compositions are influenced by anthropogenic sources and emissions from Owens (dry) Lake after its artificial desiccation in 1926. Both modern dusts and Av horizons are enriched in As, Ba, Cu, Li, Sb, Th, U, and W relative to average crustal composition, which we interpret to indicate that the geologic sources of dust in the southwestern United States are geochemically distinctive.

Citation: Reheis, M. C., J. R. Budahn, P. J. Lamothe, and R. L. Reynolds (2009), Compositions of modern dust and surface sediments in the Desert Southwest, United States, *J. Geophys. Res.*, 114, F01028, doi:10.1029/2008JF001009.

1. Introduction

[2] Dust from distant sources is a major component of soils in both arid and humid areas [e.g., *Yaalon and Ganor*, 1973; *Reheis et al.*, 1995]. Dust provides nutrients needed for plant growth [e.g., *Swap et al.*, 1992; *Reynolds et al.*, 2006b], and influences hydrology by altering soil texture [*McDonald et al.*, 1995]. Inhalation of dust enriched in toxic metals such as antimony, arsenic, cadmium, and lead (the majority of which are considered anthropogenic in origin [e.g., *Galloway et al.*, 1982]) can be deleterious to health [e.g., *Ross et al.*, 1993; *Plumlee and Ziegler*, 2003; *Sheppard et al.*, 2006], and such dust when deposited may affect plants and soils. These effects of dust emphasize the need to understand sources of dust that are incorporated into soils and how these sources may change with climate and human impacts.

[3] A network of dust traps installed in southern Nevada and California (Figure 1) in 1984 samples deposited dust, including both wetfall and dryfall components. Additional traps were installed in Owens Valley in 1991 to investigate dust from Owens (dry) Lake [*Reheis*, 2003]. Previous studies using data from these sites showed that sparsely vegetated alluvial plains and distal alluvial fans are much

larger sources of modern dust than are playas in most years [*Reheis and Kihl*, 1995], but wet playas with shallow depths to groundwater may contribute large amounts of metal-rich dusts during and immediately following wet years [*Reheis*, 2006; *Reynolds et al.*, 2007c]. In this report, we use geochemical analyses to examine the relations between modern dust and the dust fraction of vesicular soil A (Av) horizons at the same dust trap sites.

[4] Modern dust deposited in the southern Basin and Range and Mojave Desert provinces, southwestern United States, is similar in major-element composition and mineralogy to previously deposited dust that has been incorporated into near-surface soil horizons (A and upper B horizon; [*Reheis et al.*, 1992, 1995; *McDonald*, 1994]). Modern dust samples are compositionally well mixed across the region with respect to these components [*Reheis and Kihl*, 1995], but do show variability in trace element contents that reflect mixing of dust sources from alluvium and playas as well as input of dust derived from Owens Valley, rich in As, Ba, Li, and Sb [*Reheis et al.*, 2002]. No previous studies have compared the trace element compositions of modern dust with those of dust-rich Av horizons characteristic of aridic soils [*McFadden et al.*, 1987, 1998; *Reheis et al.*, 1995] to investigate possible changes in dust sources from geologically recent (Holocene) periods to the present, although some papers have compared compositions of modern dust with those of the fine fraction of soil samples to determine their origin and effects on nutrient

¹U. S. Geological Survey, Denver, Colorado, USA.

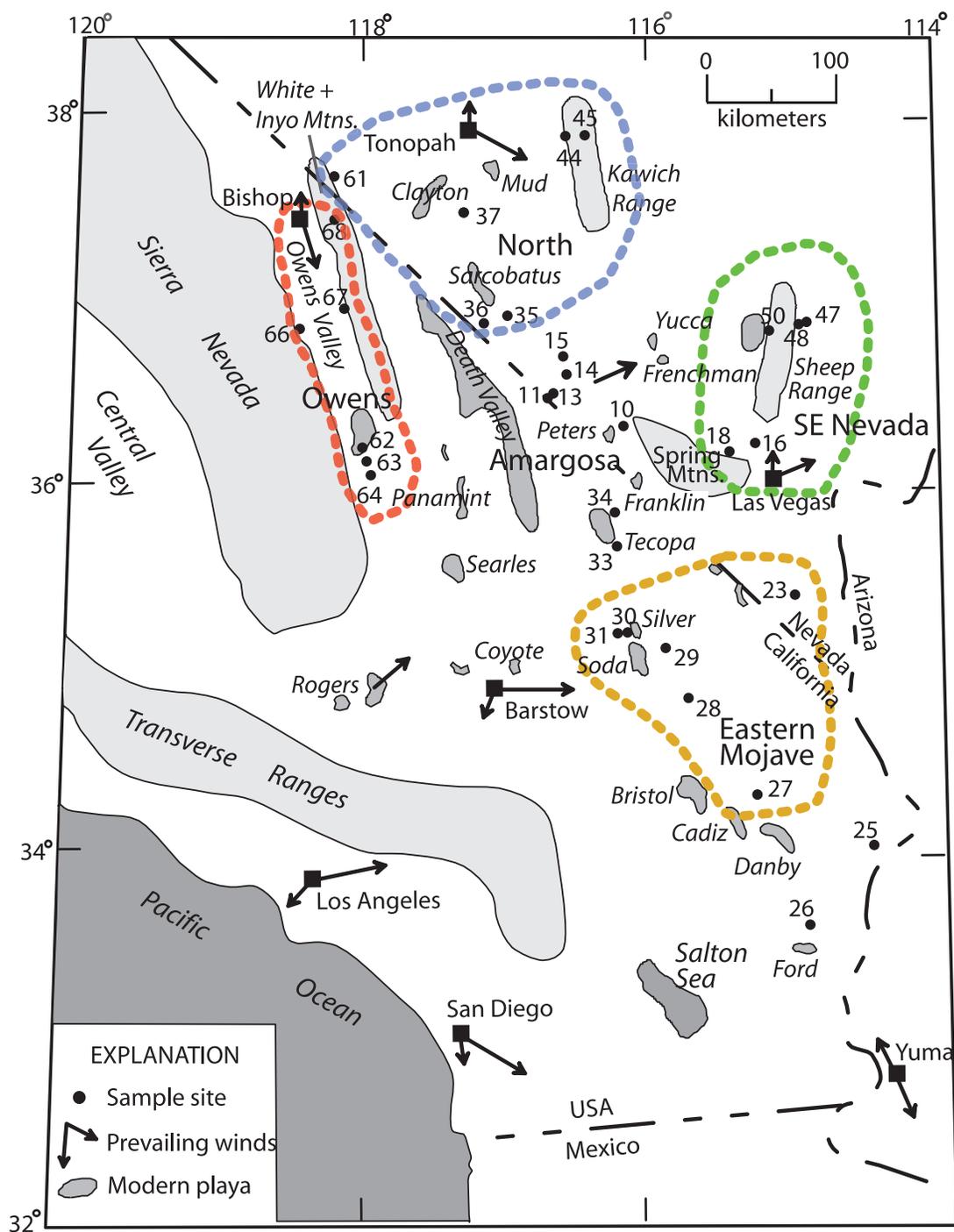


Figure 1. Map of sample locations, principal cities, prevailing wind directions, and playas. One to four analyses of dust samples from different years at each site were averaged to compare with soil samples. Colored dashed lines show regional groups of dust trap sites assigned by cluster analysis of the elemental data: North (blue), Owens Valley (red), Southeast Nevada (green), Eastern Mojave (gold), and Amargosa and two southern sites (no line).

supply [Muhs et al., 2007a, 2007b; Kennedy et al., 1998; Reynolds et al., 2006a, 2006b].

[5] In this paper, we compare samples of modern dust and surface (about 0–0.5 cm below the desert pavement or surface) and subsurface (about 1–4 cm below pavement or surface) Av horizons collected at 35 sites in the southern Great Basin and Mojave Deserts of California and Nevada

(Figure 1). The Av horizons are considered to represent a long-term archive of dust deposition over the past few hundreds to thousands of years [e.g., McFadden et al., 1987, 1998; Reheis et al., 1995; Keefer et al., 2004]. The laminated, platy character of well-developed Av horizons suggests that they thicken with time by upward accretion of dust [McFadden et al., 1998], although bioturbation or other

Table 1. Site Locations and Descriptions

Site	Name	Latitude (N)	Longitude (W)	Altitude (m)	Area Cluster	Local Substrate	Source Type
T10	Amargosa Flat	36.52	116.11	805	Amargosa/other	Limestone	Wet playa
T11	Funeral Range East	36.63	116.74	903	Amargosa/other	Metamorphic + mixed	Wet playa
T13	Amargosa Desert	36.67	116.67	793	Amargosa/other	Metamorphic + mixed	Wet playa
T14	Crater Flat	36.73	116.56	851	Amargosa/other	Metamorphic + mixed	Alluvium
T15	Bare Mountain	37.87	116.62	1171	Amargosa/other	Limestone	Alluvium
T16	Lower Kyle Canyon	36.38	115.32	839	SE Nevada	Limestone	Alluvium
T18	Upper Kyle Canyon	36.31	115.44	1318	SE Nevada	Limestone	Alluvium
T23	McCullough Mountains	35.54	115.07	1327	E Mojave	Rhyolite + granite	Alluvium
T25	Turtle Mountains	34.21	114.65	360	Amargosa/other	Metamorphic + mixed	Alluvium
T26	McCoy Mountains	33.74	115.93	190	Amargosa/other	Metamorphic + mixed	Dry playa
T27	Cadiz Lake	34.42	115.29	403	E Mojave	Rhyolite + granite	Alluvium
T28	Kelso Dunes	34.95	115.61	921	E Mojave	Rhyolite + granite	Alluvium
T29	Cima Volcanics	35.26	115.73	1257	E Mojave	Basalt	Wet playa
T30	Lower Silver Lake	35.32	116.12	290	E Mojave	Rhyolite + granite	Dry playa
T31	Upper Silver Lake	35.31	116.14	366	E Mojave	Rhyolite + granite	Dry playa
T33	Tecopa South	35.31	116.14	366	Amargosa/other	Metamorphic + mixed	Wet playa
T34	Tecopa East	35.97	116.23	525	Amargosa/other	Limestone	Wet playa
T35	Sarcobatus Flat	37.04	116.87	1244	North	Metamorphic + mixed	Wet playa
T36	Grapevine Mountains	37.02	117.01	1424	North	Rhyolite + granite	Wet playa
T37	Goldfield	37.69	117.26	1928	North	Basalt	Dry playa
T42	Tonopah	38.09	117.11	1629	North	Rhyolite + granite	Alluvium
T44	Bellehelen	38.15	116.63	1815	North	Rhyolite + granite	Alluvium
T45	Kawich Range	38.18	116.54	2277	North	Rhyolite + granite	Alluvium
T46	Reveille Valley	38.18	116.42	1760	North	Rhyolite + granite	Alluvium
T47	Coyote Springs	36.99	115.00	793	SE Nevada	Limestone	Alluvium
T48	Sheep Range E	37.04	115.05	906	SE Nevada	Limestone	Alluvium
T50	Sheep Range W	36.98	115.16	1208	SE Nevada	Limestone	Dry playa
T61	Trail Canyon	37.87	118.18	1431	North	Basalt	Alluvium
T62	Owens Lake	36.36	117.94	1087	Owens Valley	Metamorphic + mixed	Wet playa
T63	Haiwee Reservoir	36.22	117.95	1262	Owens Valley	Metamorphic + mixed	Wet playa
T64	Rose Valley	36.03	117.92	1021	Owens Valley	Rhyolite + granite	Wet playa
T66	Goodale Creek	36.97	118.31	1590	Owens Valley	Rhyolite + granite	Alluvium
T67	Stooge Range	37.02	118.17	1609	Owens Valley	Basalt	Alluvium
T68	White Mountains	37.35	118.18	2609	Owens Valley	Metamorphic + mixed	Alluvium

mixing may disturb stratification. We test for elemental differences that may be due to regional or lithologic substrates or to source types such as wet playas, dry playas, and alluvial plains. Finally, we test the hypotheses that differences in trace element composition between modern dust and the Av horizons could be caused by (1) global anthropogenic emissions; (2) new dust sources such as the 20th century desiccation of Owens (dry) Lake; (3) changes in dominant dust sources, perhaps due to recent drought or land-use change; and (or) (4) changes in wind strength during the Holocene.

2. Methods

2.1. Sample Collection

[6] The dust trap sites used in the present study comprise a subset of established sites in southern Nevada and southeastern California [Reheis and Kihl, 1995] and sites in Owens Valley [Reheis, 1997]. Sample sites were originally chosen on the basis of proximity to soil study locations and weather stations and on the need to answer specific questions about the relations of dust to local sources, distance from source, and climate (Figure 1 and Table 1). For details on trap construction, sample collection, and analytical procedures, see Reheis and Kihl [1995] and Reheis [2003]. Briefly, the trap consists of a coated angel food cake pan mounted on a post about 2 m above the ground. Glass marbles rest on metal mesh that is fitted into the pan so that it rests 3–4 cm below the rim. Thus, the samples integrate wet and dry deposition during the period

of accumulation, which ranged from 6 months to 2 years for this study.

[7] We sampled the dust-enriched uppermost soil horizons at 35 dust trap sites (Figure 1 and Table 1). Nearly all sites are located on alluvial fans or volcanic plateaus of varying ages; surficial deposits at these sites generally have a dust-derived Av horizon beneath a desert pavement. Exceptions are sites in well-vegetated areas at higher altitudes, including T66 in Owens Valley, T68 in the White Mountains, and T45 in the Kawich Range, and site T-62 on Owens Lake playa. Samples were taken at depths of 0–0.5 or (rarely) 0–1 cm (surface) and between 1 and 2 and 1–4 cm (subsurface) beneath the pavement or ground surface, by removing the gravelly desert pavement and then scraping an area of 300–500 cm² using a sharp-edged trowel to obtain 20–50 g of fine-grained sediment. Because Av horizons develop with time by accretion of dust beneath a surface layer of stones [McFadden *et al.*, 1987], young Holocene deposits tend to have weakly developed desert pavements and thin sandy Av horizons, whereas older Pleistocene deposits have well-developed pavements and thick silt- and clay-rich, laminated Av horizons [e.g., Reheis *et al.*, 1995; McFadden *et al.*, 1998]. Thus, the concentrations of dust-derived silt and clay particles, and the possibility of mixing with substrate sediments, varied from site to site depending on surface age. The sandy nature of some of the samples is evident in Data Set S1.¹

¹Auxiliary materials are available at <ftp://ftp.agu.org/apend/jf/2008/jf001009>.

2.2. Laboratory Analyses

[8] In the laboratory, dust samples were dried at about 35°C in large evaporating dishes and coarse organic material was removed. Following analyses of organic and inorganic carbon (using coulometry) and soluble salts (electroconductivity), organic matter was removed using hydrogen peroxide and particle size was measured using a laser particle size analyzer. This analyzer uses a laser-light-scattering method on samples suspended in water [Agrawal *et al.*, 1991], and has manufacturer-reported precision and accuracy of 1% or better. The remaining sample (if any) was separated into sand and silt-plus-clay (<53 μm) fractions by wet sieving. At five of the 35 sites, dust samples were not large enough to analyze geochemically; other sites are represented by multiple samples from different years (see Reheis *et al.* [1999] for details of combined samples). The <53 μm fractions of the 56 processed dust samples (Data Set S2) were then analyzed for geochemistry [Reheis *et al.*, 1999]. USDA particle size classes rather than Wentworth classes were used in this and all previous studies on the dust trap sites by the authors to facilitate comparison to most United States soil studies. Hence, particles in the range of 63–53 μm , which are abundant in wind-transported sediment, are excluded from geochemical analyses of both the dust and the soil samples. We note that it is possible that some elements that may be associated with water-soluble phases in dust samples may have been partially or completely removed (e.g., As and Na [Reynolds *et al.*, 2007c]) because geochemical analysis was done after leaching with deionized water. Soil samples were analyzed (Data Set S1) using the same techniques, except that carbonates were also removed using 10% HCl to eliminate pedogenic accumulations of CaCO_3 . Because of these pretreatments, we do not rely on statistical analyses of Na, Ca, or As to compare compositions of dust and soil samples. However, we do discuss the postpretreatment (nonwater-soluble) As values, because they are significant to Owens Valley as a dust source [Reheis *et al.*, 2002].

[9] Analytical techniques included instrumental neutron activation analysis (INAA), inductively coupled plasma atomic emission spectroscopy (ICP-AES), and inductively coupled plasma mass spectroscopy (ICP-MS). Most of the dust samples were analyzed using either INAA or ICP techniques depending on sample size, but some were analyzed using INAA, ICP-MS, and ICP-AES. These three techniques yield results for different, but overlapping, suites of elements and provide results with different levels of precision (see Reheis *et al.* [1999] for replicate analytical data of dust samples). Elements included Ag, Al, As, Au, Ba, Be, Bi, Ca, Cd, Ce, Co, Cr, Cs, Cu, Eu, Fe, Ga, Gd, Hf, Ho, K, La, Li, Lu, Mg, Mn, Mo, Na, Nb, Nd, Ni, P, Pb, Rb, Sb, Sc, Sm, Sn, Sr, Ta, Tb, Th, Ti, Tl, Tm, U, V, W, Y, Yb, Zn, and Zr (see Data Set S2 for method used for each reported element and estimates of precision and accuracy). For detailed information on analytical techniques, refer to Budahn and Wandless [2002]

for INAA, to Briggs [1996] for ICP-AES, and to Briggs and Meier [1999] for ICP-MS.

[10] Eolian dust within Av horizons in the study area contains silt-sized magnetic particles [Reynolds *et al.*, 2006b]. We used a combination of magnetic [Thompson and Oldfield, 1986; King and Channel, 1991] and reflected light petrographic methods to determine the types, amounts, and origins of magnetic minerals. Magnetic property measurements (Data Set S3), on dried bulk sediment packed into 3.2 cm^3 plastic cubes and normalized for sample mass, included: (1) isothermal remanent magnetization (IRM) acquired at -0.3 Tesla (T), a measure primarily of magnetite; (2) frequency-dependent magnetic susceptibility (FDMS, from magnetic susceptibility measurements at 600 and 6000 Hz), a measure of the amount of superparamagnetic (ultrafine, <30 nm) magnetite that may form in some settings by pedogenesis [Dealing *et al.*, 1996]; and (3) anhysteretic remanent magnetization (ARM). Hard IRM (HIRM), a measure of high-coercivity ferric oxide minerals such as hematite, is calculated: $(\text{IRM}_{1.2\text{T}} - \text{IRM}_{0.3\text{T}})/2$. The S parameter ($\text{IRM}_{0.3\text{T}}/\text{IRM}_{1.2\text{T}}$) is a measure of the relative proportion of magnetite to all ferric oxides, mostly hematite in these settings.

2.3. Numerical and Statistical Analyses

[11] To examine potential differences in dust source composition, we compared contents of Th, U, Rb, Sc, Sr, La, Ti, and Zr, elements that are commonly used to identify differences in crustal composition [e.g., Muhs and Benedict, 2006; Muhs *et al.*, 2007a, 2007b; Moreno *et al.*, 2006], and found only minor differences (discussed below). Th, Sc, La, Ti, and Zr are considered chemically immobile in normal weathering environments. We also calculated element enrichments in dust samples relative to average crustal composition (enrichment factor) using Fe as the reference element (crustal abundance data of Krauskopf and Bird [1995]). Most atmospheric dust studies calculate sample-to-crust ratios relative to Al [e.g., Zoller *et al.*, 1974; Galloway *et al.*, 1982]; our data show that of the elements analyzed, Al contents are the most similar among the samples and relative to crustal abundance (Data Set S2). However, Al is not usually analyzed by the INAA technique; its use would have resulted in rejection of nearly half of the dust data. Comparison of results using the two reference elements showed that the only difference is a slight increase in enrichment values for most elements relative to Fe because the dust and Av samples are slightly lower in Fe content than the crustal average value.

[12] Compositions of dust and Av horizons were grouped with respect to depth (dust, 0–0.5 cm—surface, and 1–4 cm—subsurface), lithologic substrate (bedrock or alluvium derived from: basalt, limestone, metamorphic + mixed lithologies, and rhyolite + granite), and type of primary dust source (alluvium, dry playa, and wet playa). These same lithologic and source-type subdivisions of the sites were used by Reheis *et al.* [2002] and Reheis [2006] to investi-

Figure 2. Result of cluster analyses of (a) modern dust samples and (b) Av samples using elemental data that were common to all samples (Data Set S2), including Al, Fe, K, Mg, Ti, Mn, Ba, Ce, Cr, La, Nd, Ni, Rb, Sb, Sc, Sr, Th, and U. Clusters that were grouped with respect to geographic area or lithologic substrate are identified by brackets on left side; single occurrences denoted with geographic area.

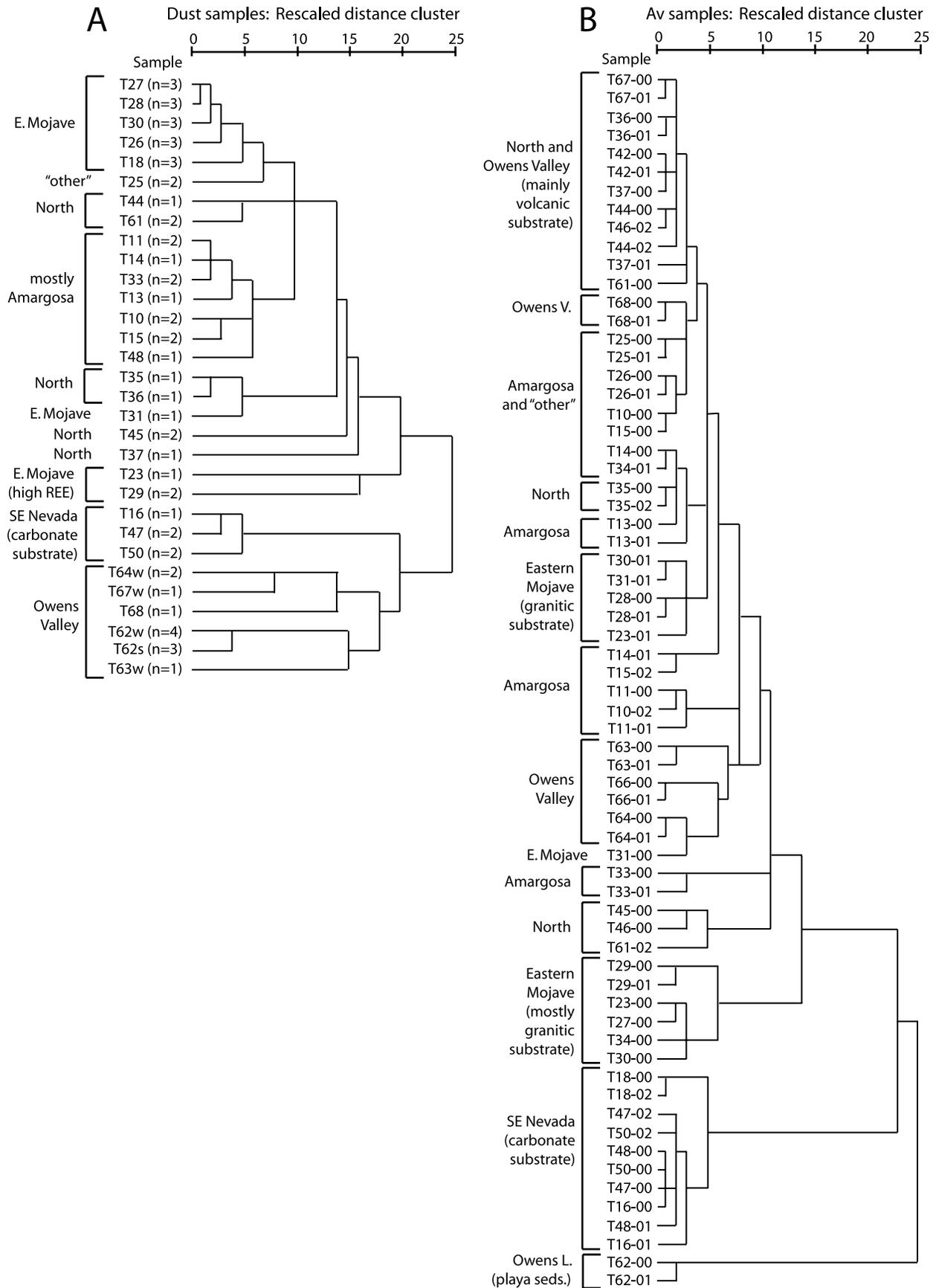


Figure 2

gate effects of these factors on dust geochemistry and deposition rates of different dust components. In addition, we explored possible geographic controls by cluster analysis on the elemental compositions of all the samples and of the dusts and A_v samples separately (Figure 2; groups shown on Figure 1). For the cluster analysis, we used all elements analyzed in common among all the samples (Data Set S2), except for Na, Ca, and As. The hierarchical cluster technique, using a standard statistical package (SPSS v. 11.0.1) used a squared Euclidean distance measure and between groups linkage on the sample values, which were standardized to a range of 0–1 because of the wide ranges in values of some elements (Data Set S2).

[13] Examination of the cluster results on all data (not shown) and on dust and A_v samples separately (Figure 2) suggested that many samples from different parts of the study area and with different lithologic substrates grouped into the same clusters. However, some geographically and (or) lithologically related samples exhibited distinct clusters, especially for the A_v samples, and in some large mixed groups there were subgroups of related samples (shown by labeled brackets on Figure 2). Dust samples from Owens Valley sites were most closely related to each other, but not as strongly (having higher distance-cluster values) as those of other groups. Among the A_v samples, sites in southeastern Nevada, all of which are located on limestone-derived alluvial fans, form a strong cluster; however, two dust samples from this area (T18 and T48) fall into other groups. One site on the northeast edge of Owens Valley (T67) and all the sites across the northern part of the study area, all of which are on volcanic substrates, form a subgroup, and the eastern Mojave Desert sites form two subgroups. We used these results, considering the dust and A_v clusters together and in combination (not shown), to modify the geographic groupings used in a previous paper [Reheis *et al.*, 2002] and to assign sites to geographic clusters as shown on Figure 1. Sites near cluster boundaries (e.g., T34, T67) sometimes changed membership in the cluster analyses, but were assigned to only one cluster. Note that the SE Nevada cluster has uniformly carbonate substrates, and the North cluster has volcanic substrates. Sites T25 and T26, farthest south (Figure 1) are closely related to each other; however, they have dust compositions that tend to cluster with those of the nearby eastern Mojave sites, and their A_v compositions overlap with Amargosa and North sites. Two sites would not yield a statistically viable cluster, so we arbitrarily grouped these with Amargosa sites (Amargosa/other) for statistical analysis. Site T62 in Owens Valley, composed of playa sediment rather than dust-rich soil, proved so distinctly different that it was removed from further statistical analyses.

[14] Tests of normality were applied to all samples and to dust and A_v samples separately. These tests showed that population distributions range from normal to lognormal to strongly skewed, making application of parametric statistical techniques problematic. Thus, the populations of element compositions and crustal enrichment values in different categories were compared using the nonparametric Kruskal-Wallis H test (three or four categories) and Mann-Whitney U test (two categories). These tests incorporate both central tendency and dispersion; thus, a population with a large range of values may be statistically different

than one with a small range, even if their modes or averages are similar. Because these tests do not require normally distributed populations, they provide a robust test of whether populations of different categories (i.e., dust samples in different geographic regions) are statistically different. Samples are assumed to be from different populations when significance levels are $\leq 5\%$.

3. Results

3.1. Elemental Composition of Dust and A_v Samples

[15] The major-element contents of modern dust and A_v samples are generally similar at the same site and among sites. Differences mainly reflect local sources of modern dust and some mixing of eolian dust with parent material sediment in A_v horizons. For example, the Kyle Canyon (T16) site in Nevada (Figure 1) is located on a carbonate-dominated alluvial fan, whereas the Cima (T29) site in California is on a basalt flow; thus, Ca and Mg are greater in both dust and A_v samples from site T16 (although pedogenic CaCO_3 was removed from the soil samples, all dolomite grains may not have completely dissolved, and CaCO_3 was not removed from dust samples), whereas Fe and Ti are greater in all T29 samples (Figure 3). Major elements that are higher in A_v samples compared to dust at a given site, including Fe, Ti, and Mn (Figures 3 and 4), are commonly contained in relatively high-density, iron-rich minerals.

[16] Trace element contents show much more variability between modern dust and A_v samples. Concentrations of As, Cd, Cu, Pb, and Sb are significantly higher in dusts (positive sign in Figure 3), whereas Hf, Th, Zr, and rare earth elements are higher in soils (negative sign). Elements that are enriched in dusts are commonly attributed to anthropogenic sources, although As, Ba, and Sb are also enriched in modern dusts derived from Owens Valley [Reheis *et al.*, 2002]. Notably, Cu and Pb are commonly an order of magnitude more abundant in dusts than in A_v horizons.

[17] Differences in composition between samples of modern dust and dust-derived surface soil horizons are demonstrated by their population distributions (Figure 4). The top row of plots in Figure 4 represents elements (Fe, K, and Cs) that show little or no difference between modern dust and A_v horizons. In the second row, modern dusts are depleted in Ti and Zr whereas Ba is slightly enriched with several outliers of very high Ba values, nearly all from Owens Valley. The third row represents elements (As, Cu, and Pb) that are moderately to strongly enriched in modern dust, whereas the fourth row represents elements (Th, Eu, and Lu) that are depleted in modern dust compared to A_v horizons. Note that Eu, representing the light rare earth elements (REE), is somewhat less depleted in the dust samples than is Lu, representing the heavy REE. No differences are apparent between surface samples and subsurface samples.

3.2. Comparison of Immobile Crustal Elements

[18] To investigate whether modern dust samples and associated A_v horizons across the region are derived from compositionally different crustal sources, we compared contents of Th, U, Rb, Sr, La, Sc, Ti, and Zr, elements that

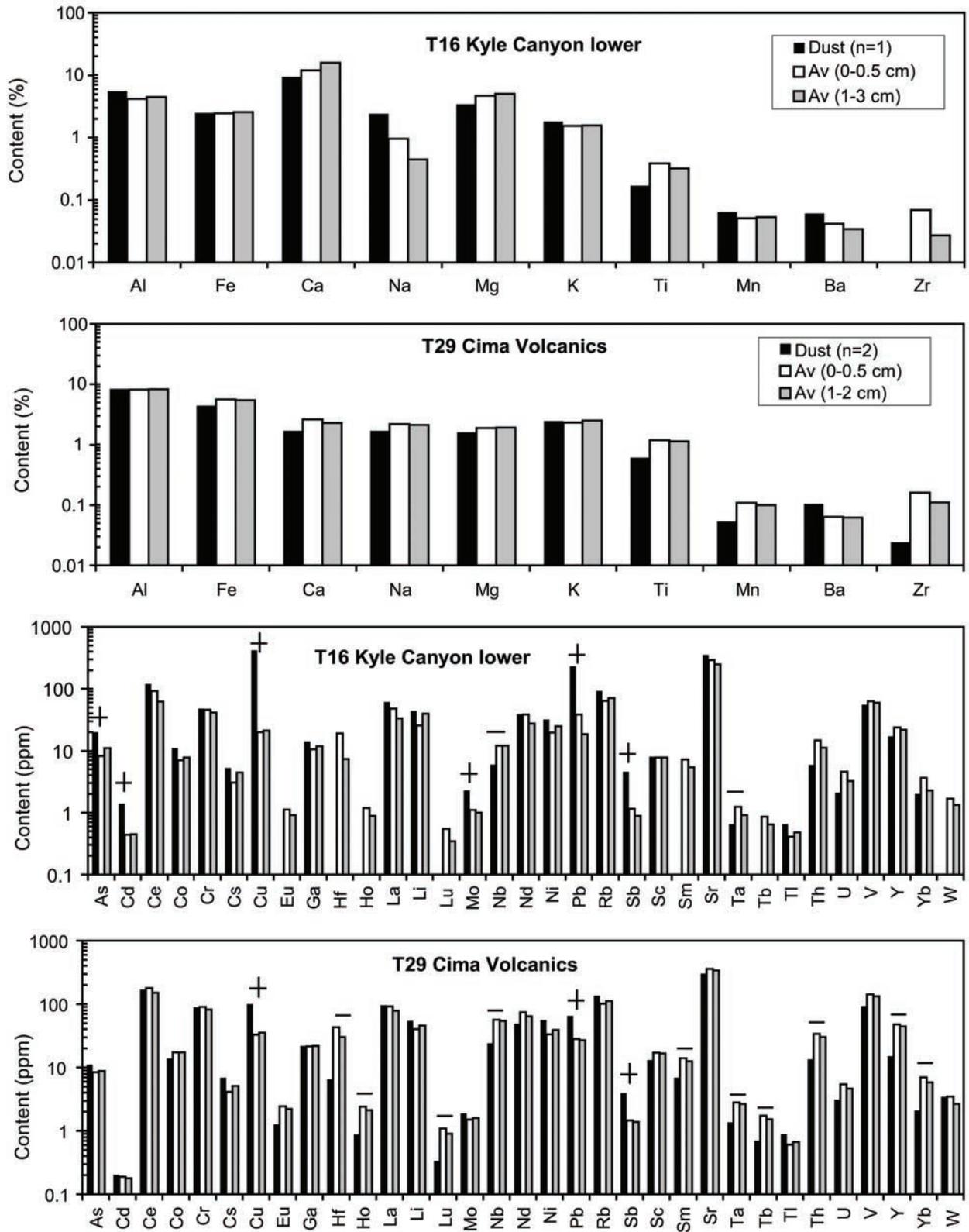


Figure 3. Major and trace element contents of modern dust and Av horizons at two sites. Plus symbol indicates notable enrichment in dust relative to surface soil (typically a factor of 2 or greater); minus symbol indicates notable depletion. Analytical errors for each element are too small to depict.

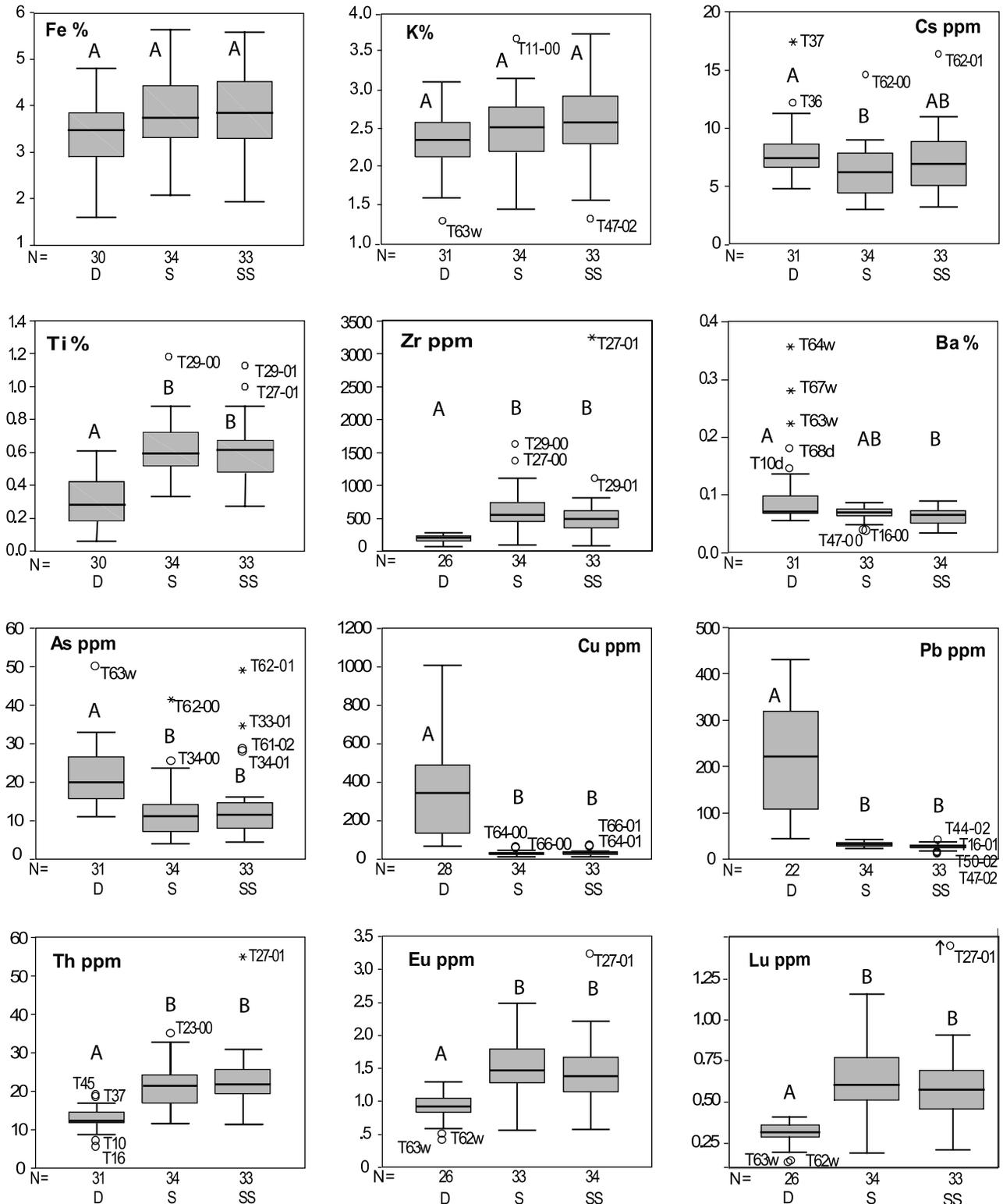


Figure 4. Boxplots of representative elements for populations of modern dust and surface soil samples grouped by depth. Shown are the median (black bar), interquartile range (solid box), expected range (brackets, $1.5 \times$ interquartile range), outlier values (circles, $1.5\text{--}3.0 \times$ interquartile range), and extreme values (stars, $>3.0 \times$ interquartile range) annotated with sample numbers (00, surface sample, ~0–1 cm; 01, subsurface sample, ~1–4 cm; wd, winter dust), for representative elements. Letters designate lithologic groups with statistically different populations based on nonparametric tests; combined letters indicate population of group overlaps with other groups.

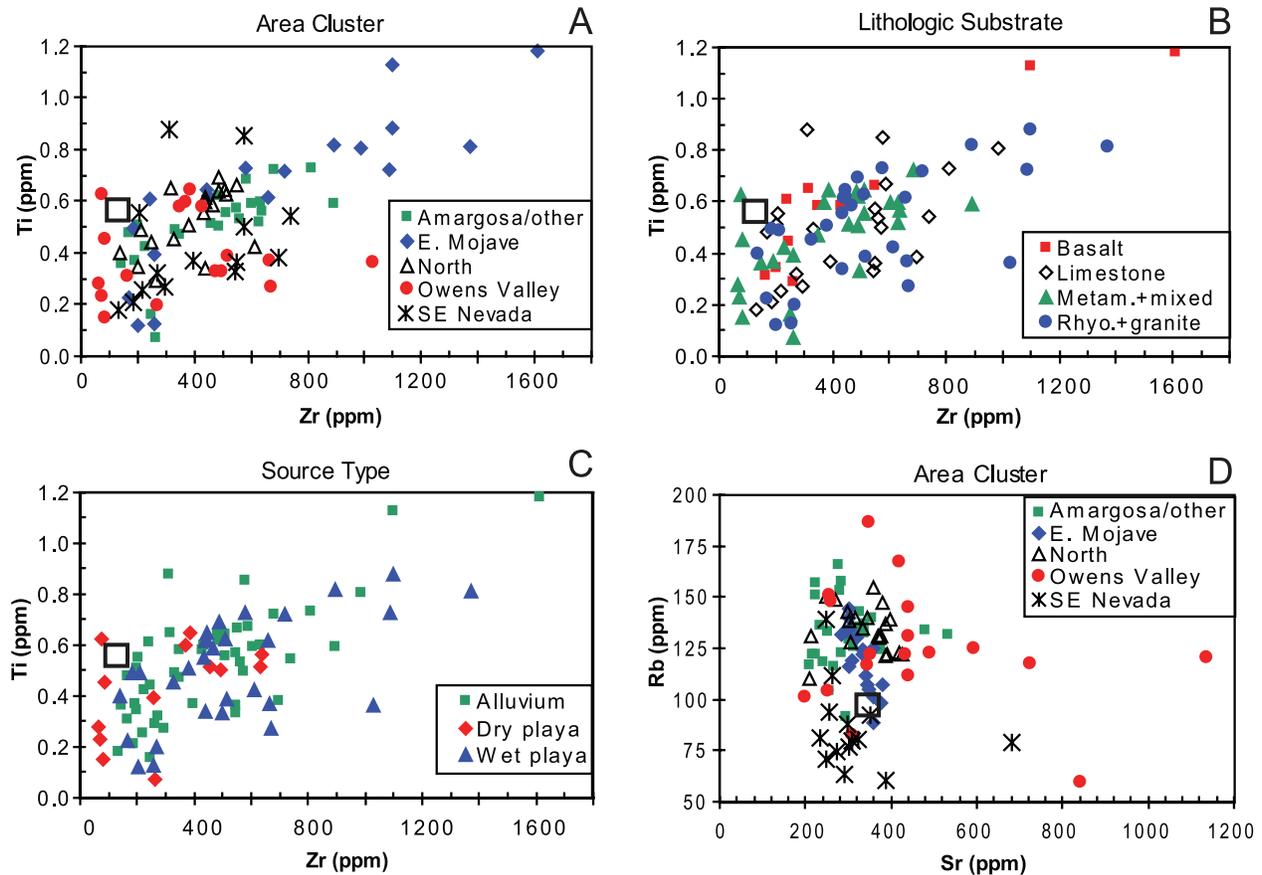


Figure 5. Element scatterplots. Ti and Zr contents of modern dust and surface soil samples grouped according to (a) area cluster, (b) lithologic substrate, and (c) source type. (d) Rb and Sr contents versus geographic cluster. Large squares indicate average crustal composition [Krauskopf and Bird, 1995].

are commonly used to distinguish sediments from different source rocks [e.g., Muhs and Benedict, 2006; Moreno et al., 2006; Muhs et al., 2007a, 2007b]. Most of these, except Rb, Sr and U, are considered chemically immobile in normal weathering environments. Samples were grouped in several different ways: (1) by depth (dust, surface, and subsurface), (2) by lithologic composition of the site substrate, (3) by dominant local dust source, and (4) by geographic cluster (Figure 1 and Table 1).

[19] Plots of Ti and Zr according to these groupings (Figures 5a–5c) show that dust and soil compositions are similar among areas, lithologies, and source types, except that some sites in the Eastern Mojave group tend to have higher contents of Zr and Ti in the Av horizons. However, modern dust samples are relatively depleted in Ti and especially Zr compared to Av horizons (Figure 4). This may be caused in part by a component of parent material within the soil samples, because Zr is dominantly contained in relatively high-density zircons that can be depleted in dusts by winnowing during transport [Reheis, 1990; Mason and Jacobs, 1998; Muhs and Bettis, 2000]. Alternatively, this depletion may also indicate an overall change in dust source or wind erosion in modern times since the deposition of the dust contained in most Av horizons.

[20] Plots of Th, U, Rb, Sr, and La, like those of Ti versus Zr, also show that the various groupings by dust source, substrate lithology, and area occupy similar compositional

ranges. Two exceptions are some sites in Owens Valley, which have relatively high Sr and low La values (Figures 5d and 6). Dust samples are distinguished from Av samples by low Th and higher La values (Figures 4 and 6). Overall, these plots indicate that both modern dust samples and Av samples are compositionally similar and well mixed, despite being located in different parts of the study area, on dissimilar lithologic substrates, and downwind of different primary dust source types. These results support the interpretation that Av horizons in the study area consist primarily of eolian dust derived from lithologic sources similar in composition to modern dust sources, except for Th, Ti, and Zr. Compared to average crustal composition and to samples of Mississippi loess and dusts from Africa and Asia, these southwestern dusts and soils tend to be lower in Sc; they are also higher in La relative to average crust and Asian dusts, but similar to Mississippi loess and African dust. Significantly, the modern southwestern dusts are nearly identical in composition to that of sediment from high-altitude lakes in the Uinta Mountains of northeastern Utah, interpreted to consist mainly of eolian dust deposited in these lakes [Reynolds et al., 2007a; R. Reynolds, unpublished data, 2008].

3.3. Dust and Av Samples: Crustal Enrichment Values

[21] A commonly used technique to compare sample compositions, especially in analyses of aerosols, is the

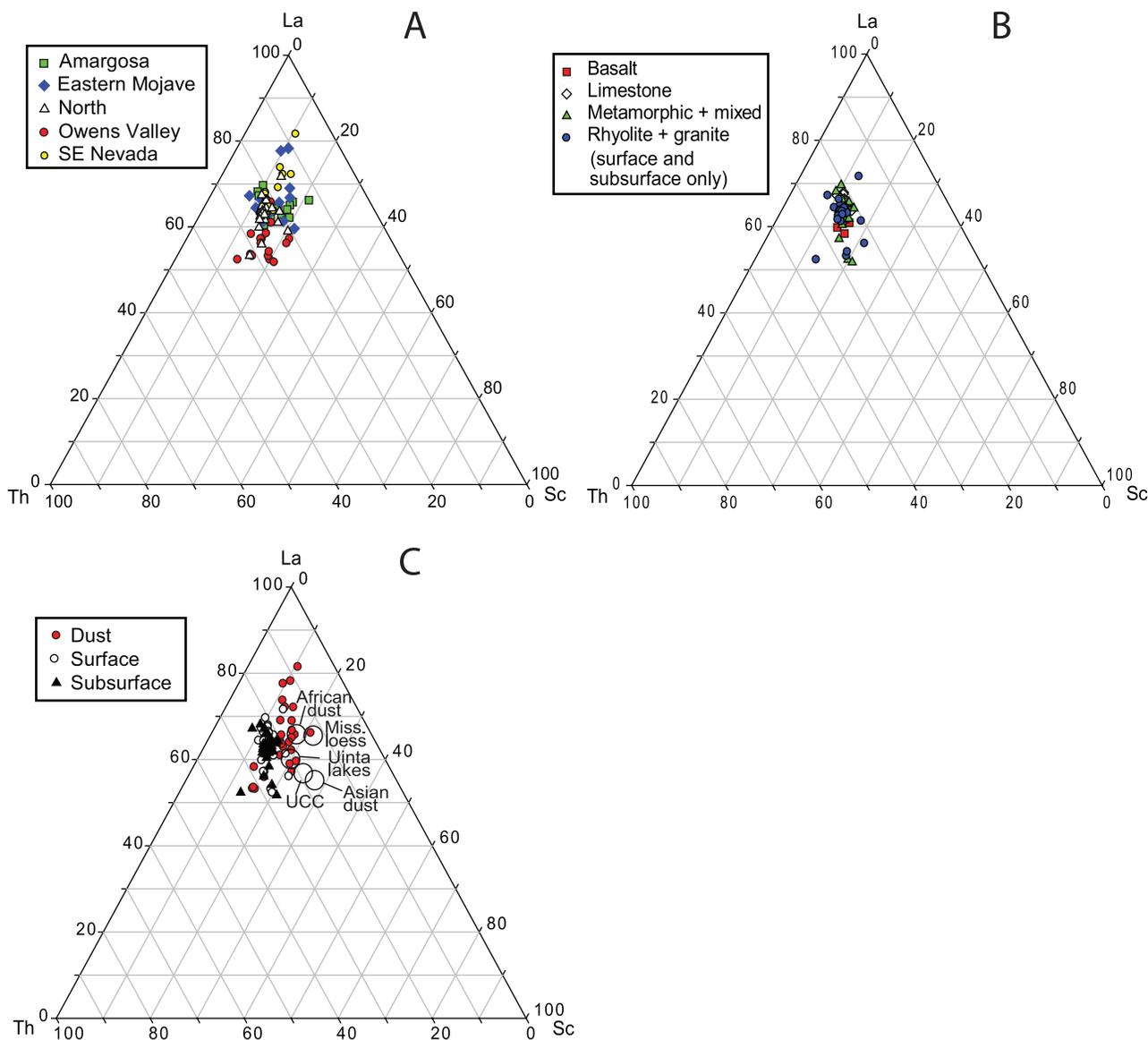


Figure 6. Ternary plots of Th, La, and Sc contents grouped by (a) area, (b) lithologic substrate (only Av samples plotted), and (c) dust and sample depth. In Figure 6c, average compositions of upper continental crust [Krauskopf and Bird, 1995], Asian dust [Zdanowicz *et al.*, 2006], African dust [Muhs *et al.*, 2007a], Mississippi loess [Muhs and Bettis, 2000], and dust in Uinta Mountains lakes (R. Reynolds, unpublished data, 2008) are shown by open circles.

crustal enrichment (CE) value [Zoller *et al.*, 1974; Galloway *et al.*, 1982] in which the concentration of an element divided by a reference element is divided by the same element ratio in average crustal rocks (a value of 1 indicates no crustal enrichment). The values herein, calculated relative to Fe, slightly overestimate crustal enrichment compared to calculations relative to Al, but do not change the overall trends in enrichment or depletion or the population distributions of sample groups.

[22] CE values of modern dust and surface samples are similar with respect to major elements, but trace element values are commonly very different. The CE values in Figure 7 are represented by plus or minus one standard deviation of selected major and trace elements. Some of the populations have normal or lognormal distributions, but some, especially Ba, Cd, Cu, Li, Ni, and Pb, do not (see

examples in Figure 4). Most of the major elements are not enriched or are only slightly enriched relative to crustal values; this slight difference is mostly due to the use of Fe as a reference element. In contrast to the major elements, many trace elements in dust are significantly enriched. Elements such as Cu, Cd, Li, Pb, and Sb are enriched in modern dust samples as much as 1–2 orders of magnitude above average crustal values; they are also enriched in Av samples, but by smaller factors of typically 2 to 6. The REE (Ce, Eu and La shown in Figure 7) are also slightly enriched in dust and Av samples relative to crustal averages, in part because of the use of Fe as a reference element.

3.4. Magnetic Properties of Surface Sediment

[23] Magnetic properties of surface sediment samples are essentially uniform with depth (Figure 8; data for modern

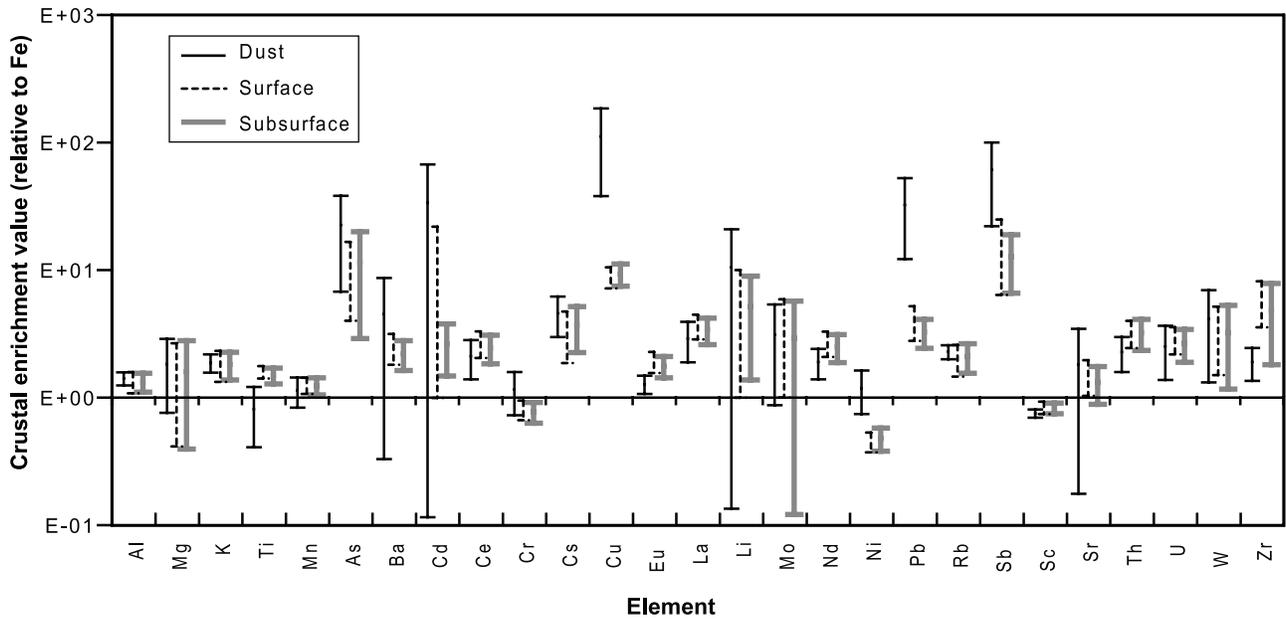


Figure 7. Crustal enrichment values for selected elements calculated relative to Fe for populations of modern dust and surface soil samples grouped by depth. Bars represent range of 1 standard deviation from mean.

dust samples are lacking at most sites). The main exception is samples grouped by substrate lithology; the higher IRM (a proxy for magnetite) and HIRM (a proxy for hematite) values in the subsurface samples on basaltic (B) substrates

compared to other lithologies clearly indicate that in these samples, eolian dust is diluted with parent sediment at depth. In addition, some of the magnetite in basaltic sediment may have been converted to hematite through

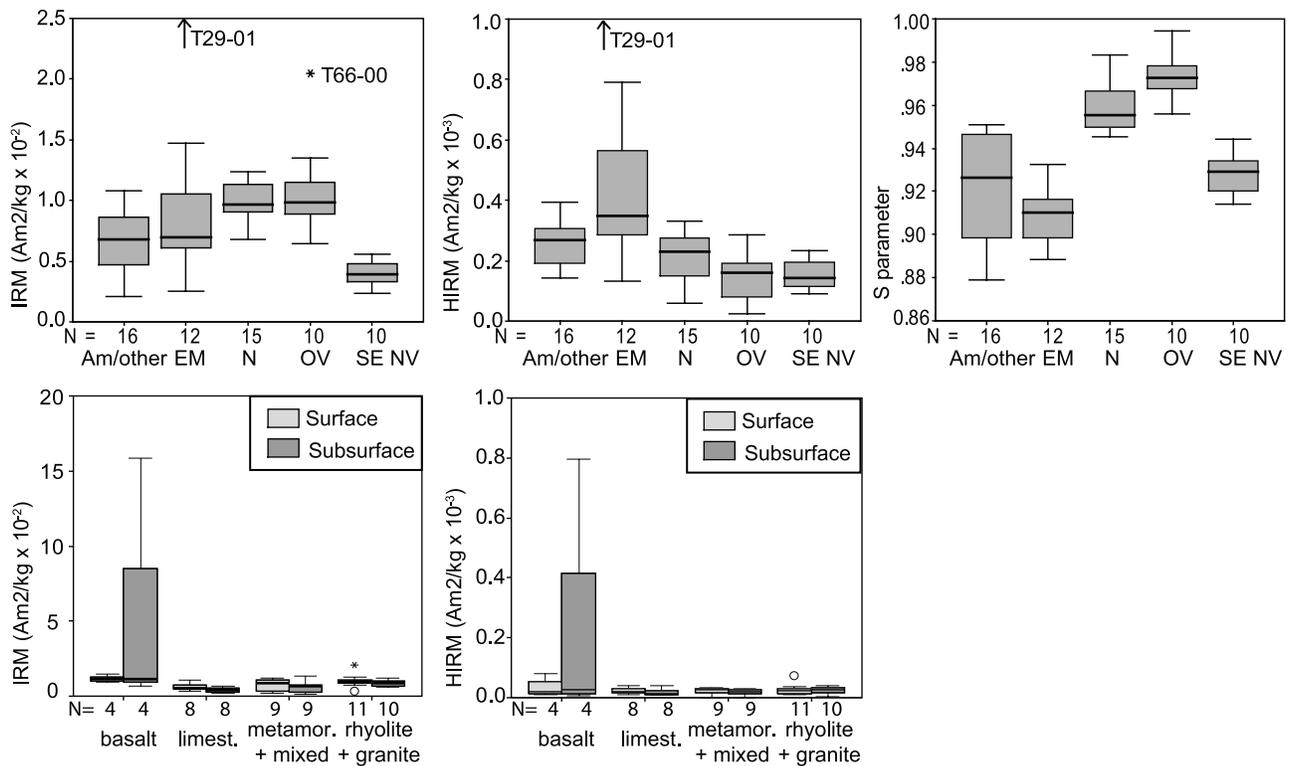


Figure 8. Boxplots of magnetic properties of soil samples grouped by geographic area, lithologic substrate, and primary dust source. Note scale change on lithologic plots to incorporate the extreme outlier of subsurface sample T29; on other plots this point is indicated by arrows.

subsurface weathering. Also, sites in SE Nevada have lower IRM values than sites elsewhere, likely because these sites are entirely on carbonate gravels and are most distant from potential eolian sources of magnetite (Figure 1). The S parameter (essentially a measure of relative magnetite-hematite abundances) shows little difference among groups of substrate lithologies and dust sources. However, the North and Owens Valley clusters have higher S parameter values than the other clusters, possibly because of a larger component of local bedrock that is volcanic in origin, hence likely to be richer in magnetite particles.

4. Discussion

[24] Many previous studies have shown that Av horizons of aridic soils in the southwestern United States are essentially composed of eolian dust [McFadden *et al.*, 1987, 1998; McDonald *et al.*, 1995; Reheis *et al.*, 1995] on the basis of particle size, mineralogy, and major- and minor-element composition. Pedogenic carbonates in these soils exhibit Sr isotopic compositions that represent contribution from a far-traveled and well-mixed eolian dust [e.g., Naiman *et al.*, 2000; Van der Hoven and Quade, 2002]. Previous work by the present authors has shown that the elemental composition of most modern dust in southeastern California and southern Nevada represents well-mixed contributions from lithologically and geographically diverse sources across the region [Reheis *et al.*, 2002]. An exception is Owens Valley dust, which is enriched in As, Ba, Li, Sb, Sr, and other elements because of an unusual combination of geochemically distinct sources in the flanking mountain ranges and to voluminous dust production by Owens (dry) Lake, a large wet playa with shallow groundwater beneath most of the dry lake bed [Tyler *et al.*, 1997; Levy *et al.*, 1999]. Of these elements, only As, Sb, and to a lesser extent Ba, appear to be exported in detectable amounts as shown by downwind decreases (i.e., away from Owens Valley) in their concentrations in modern dust [Reheis *et al.*, 2002].

[25] Here, we extend these geochemical analyses to compare the compositions of dusts to Av horizons developed on different lithologic substrates, in different geographic areas, and near different principal dust source types. Observed differences could be caused by the following: (1) Globally distributed anthropogenic emissions such as power plants and automobiles, which should be observed as a uniform geochemical signal across the study area. (2) New dust sources such Owens (dry) Lake, desiccated in the 20th century, and mining and smelting waste piles, which should manifest as enrichment close to the probable source and decreasing away from the source. (3) Changes in dominant dust source types due to recent drought or land-use change. Drought and land uses such as grazing should both lead to greater wind erosion and deflation of alluvial surfaces, which are more susceptible to drought and grazing pressure [e.g., Reheis, 2006; Reynolds *et al.*, 2007b]. Such changes should be reflected by concentrations in surface samples of elements such as Sc, Th, and Zr, which are associated with denser minerals, and depletions of these elements in dusts. In addition, such effects might be restricted to alluvial substrates or certain geographic areas. (4) Changes in wind strength or direction. Either would be difficult to detect with our methods, although an increase

in wind strength would likely have the same effect as (3) above but be expressed across the entire study area.

[26] Comparison of immobile crustal elements (Figures 4–6) strongly suggests that the most important differences among the samples are related to dust versus sample depth, with a secondary control by geochemically distinctive dust derived from Owens Valley. However, recent studies indicate that primary dust source type may affect the composition of modern dust. For example, salt-rich dust derived from wet playas [Reheis, 2006] may be enriched in trace metal contents [Goldstein *et al.*, 2007]. Lithologic effects seem to be expressed by some magnetic properties (Figure 8) and by some of the clusters (Figures 1 and 2), particularly the SE Nevada sites on carbonate alluvial fans and the North sites on volcanic gravels (Table 1). To explore further the possible complicating effects of dust source, lithologic, and geographic factors, we subdivided the samples by modern dust versus depth categories, and by lithologic substrate, primary dust source type, and geographic cluster, yielding three matrices whose populations were tested for statistically significant differences.

4.1. Lithologic Factors

[27] In general, few significant differences exist between populations of the dust, surface, and subsurface samples with respect to lithologic substrate (Figure 3). The deeper samples (1–4 cm) are most likely to show a lithologic control exerted by the soil substrate that may be admixed with eolian dust to form Av horizons, yet even these differences are minor (Figure 9). Among the various lithologic groups (basalt, limestone, mixed + metamorphic, and rhyolite + granite), Av horizons on basaltic sediment have CE values that are higher in Ti than the other groups. This result is consistent with higher IRM values for basaltic substrates (Figure 8), because Fe-Ti oxides are abundant in Mojave dusts [Reynolds *et al.*, 2006a, 2006b]. The uniformity of magnetic properties of Av horizons, except for basalt substrates, across the study area confirms and extends results of Reynolds *et al.* [2006a, 2006b] on the basis of a few of our sites and also many samples of eolian sediment in natural pockets and crevices on high ridges and peaks in the Mojave Desert. In addition, the range of values for HIRM and IRM in our samples is identical to the range reported by Reynolds *et al.* [2006a, 2006b]. Av horizons on limestone and carbonate-rich sediment (playas) are higher in Mg and Ni than on other substrates. No other differences are statistically significant. These results confirm the eolian source and geochemically uniform nature of Av horizons reported previously [e.g., Reheis *et al.*, 1995; McFadden *et al.*, 1998].

4.2. Dust Source Factors

[28] Populations of dust and Av samples are similar with respect to primary dust source type (alluvium, dry playa, and wet playa). Most of these groupings are statistically indistinguishable. Li is enriched in many dust and Av samples downwind of wet playa sources (though the populations are not statistically distinct because of overlapping value ranges in the different groups; Figure 10), probably because several wet playas in the study area, including Owens (dry) Lake and Franklin Playa, have high levels of Li in the shallow groundwater that can be concentrated at

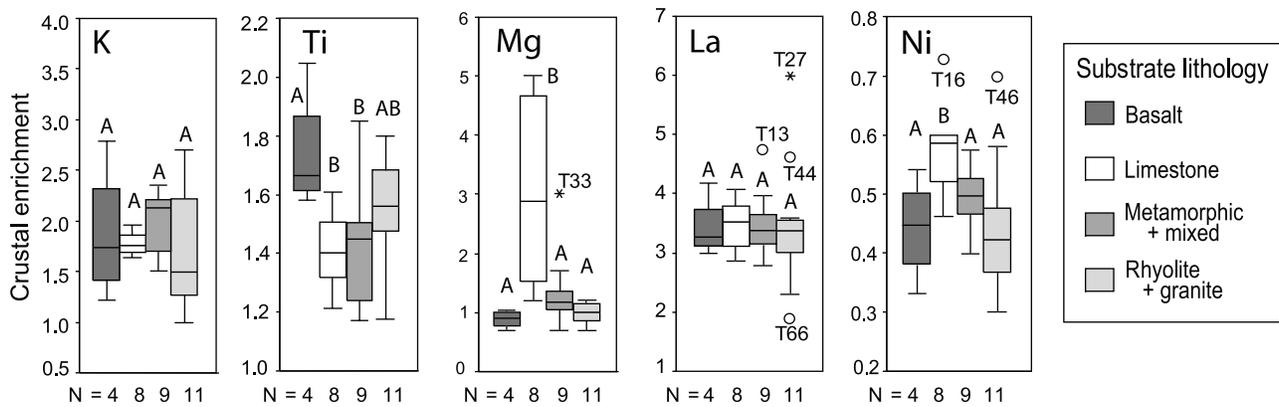


Figure 9. Boxplots of crustal enrichment values of selected elements calculated relative to Fe for soil samples between depths of 1–4 cm grouped by lithologic substrate. Most elements show no statistical differences among lithologic groups. Symbols same as in Figure 3.

the surface by evaporation and subsequently deflated [Levy *et al.*, 1999; Goldstein *et al.*, 2007]. The smectite clays that are abundant in surface sediments of Owens Lake are also Li rich [Bischoff and Cummins, 2001]. Sr and W are somewhat enriched in samples with wet playa sources, and W is also enriched in samples with alluvial sources. The outliers and extreme values of Sr are all associated with Owens Valley or in SE Nevada on carbonate substrates (T47, T50), and those of W are mainly at sites in Owens Valley (Data Set S2), suggesting that these enrichments are influenced by factors other than a wet playa dust source.

[29] We anticipated more distinct differences among source types because of the known enrichment of many trace metals such as As, Sb, Li, Pb, Cr, and W in wet playa sediment in the study area [Goldstein *et al.*, 2007]. The subdued expression of these metal-rich dust emitters at sites downwind may be due to the redistribution and mixing of dusts from multiple sources by deposition and reentrainment, and to the fact that many of the dust trap sites receive dust from more than one source type. For example, the nearest dust sources to sites T66 and T67 in Owens Valley are alluvial, but both sites are known to receive some dust derived from Owens (dry) Lake [Reheis, 1997]. In addition, these two sites may receive dust that is more enriched in Ba than other Owens Valley sites (Data Set S2) because of contributions of Ba-rich feldspars in alluvial fan sediment derived from Sierran plutons [Hinkley, 1974]. We conclude that the observed geochemical patterns do not support an overall shift in dominant dust source type since formation of most Av horizons in the study area; a single new source, Owens Lake, is indicated.

4.3. Geographic Factors

[30] Many of the elements we examined are uniformly distributed in dusts and in samples from the same depths across the region (Figure 11). For example, only minor differences exist among enrichment values of Al, K, Cs, Eu, Ni, Rb, Ti, and Mn (not shown) among samples at the same depths in different areas. However, some elements are strongly enriched in both modern dust and surface samples in Owens Valley, whereas other elements are enriched in other areas but not in both dusts and Av horizons.

[31] Compared to other areas, both dust and Av samples from Owens Valley sites have anomalous metal enrichments. All Owens samples are significantly enriched in Mg, Li, and W (Figure 11), suggesting long-term local sources of these trace elements that persist today. W is also enriched in dust samples from the North area. As and Sb are enriched in dust samples across the entire region compared to surface samples, and Sb is much higher in dusts from Owens Valley and the North area; both elements have been documented as derived from Owens Valley and exported regionally in dusts [Reheis *et al.*, 2002; Gill *et al.*, 2002], in large part because of the desiccation of Owens Lake in the 20th century [Saint Amand *et al.*, 1986; Gill, 1996]. Li is strongly enriched in Owens Valley dusts but much less so in Av samples. The Li enrichment in Owens Valley dusts is likely caused by Li abundance in shallow groundwater around Owens playa and in exposed lake sediments [Levy *et al.*, 1999; Bischoff and Cummins, 2001]. Ba and Sr are known to be concentrated in Owens Valley, and in the area of Owens (dry) Lake in particular, because of contributions from surrounding mountains, and for Sb, from mining wastes (discussed by Reheis *et al.* [2002]). Although we do not report modern dust data for Zn in this paper because of contamination problems (see Reheis *et al.* [2002] for explanation), others have reported high levels of Zn (ranging from 700 to 2100 ppm) in Owens Valley dusts and surface sediments near milling areas [Barone *et al.*, 1979; Cahill *et al.*, 1994; Reid *et al.*, 1994]. Such high values are an order of magnitude higher than Zn concentrations present in our Av horizons (Data Set S2), and support a mining-waste source.

[32] Tungsten mineralization is common in the southern Sierra Nevada and in an arc trending from there northeast through west-central Nevada, a belt that includes the Owens Valley and North sites delineated in Figure 1 (USGS minerals database: <http://tin.er.usgs.gov/mrds>). Although ore minerals containing W are dense and less likely to be entrained by wind, mine dumps and ore-processing facilities generally may act as local dust sources (e.g., sites in the western Mojave Desert [Chaffee and Berry, 2006]). Many abandoned or closed tungsten mines are present in the Owens Valley and North areas. Elevated W has been measured in airborne dusts in Fallon, Nevada (about 200 km

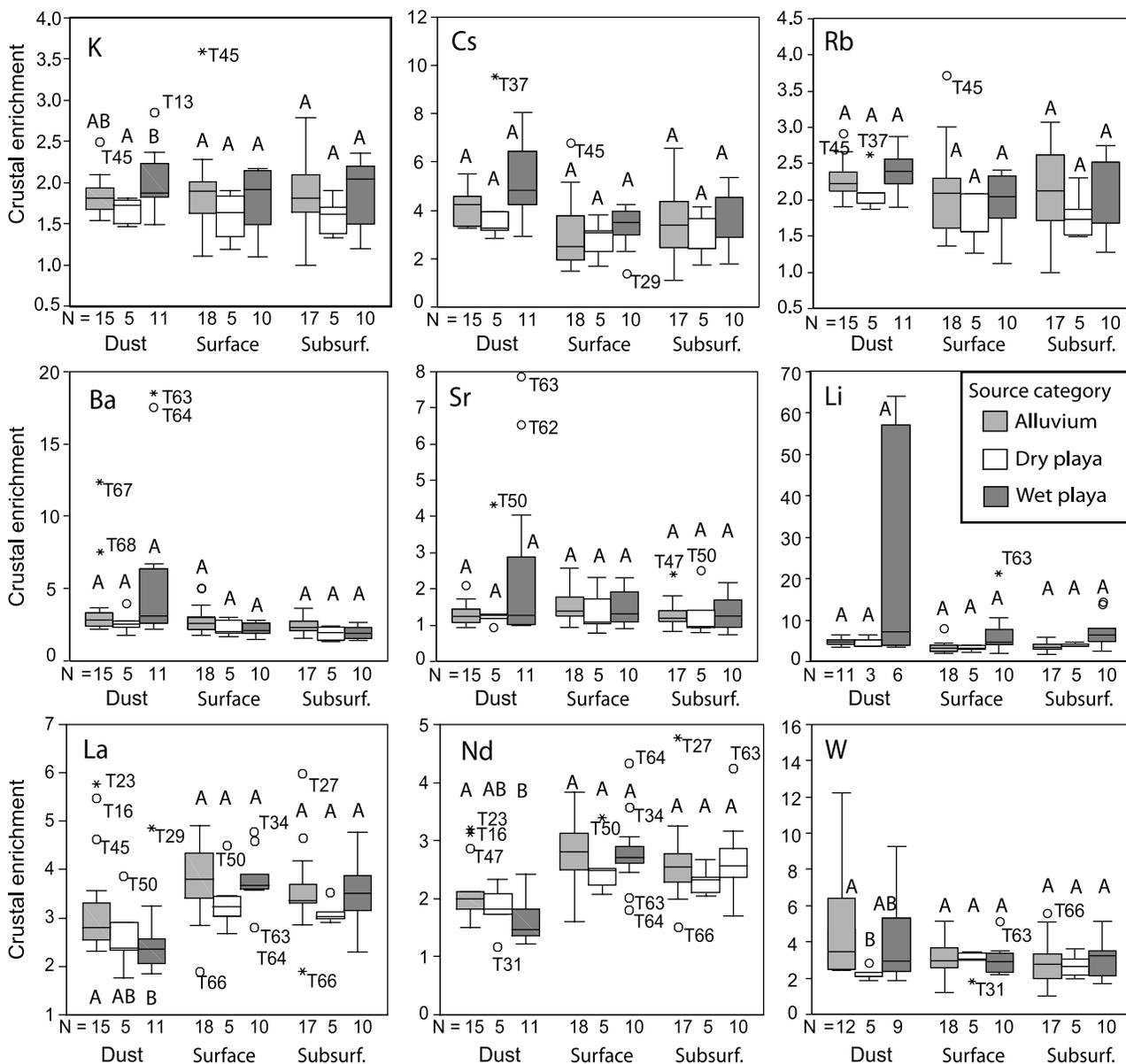


Figure 10. Boxplots of crustal enrichment values of selected elements calculated relative to Fe for dust and soil samples grouped by primary dust source. Symbols same as in Figure 3; only selected outlier values are annotated with sample numbers.

north of Tonopah), in studies investigating the causes of a recent childhood leukemia cluster, and may be related to a hard metal processing plant nearby [Sheppard *et al.*, 2006].

[33] Samples from other geographic areas show few differences. Ni and Cr are enriched (also Co and Cd, not shown) in Av samples in the SE Nevada area (Figure 11). These elements are close geochemical associates and in these samples are probably derived from weathering of dolomitic gravels in the substrates. Ti and Zr are notably enriched in Av samples of the Eastern Mojave cluster (Figure 5; enrichments are less distinct in the CE values, Figure 11). Although CE values of Al and K (and Cs and

Rb, close geochemical associates of K) appear to be relatively lower in Eastern Mojave dust and surface samples, this is in part due to the use of Fe as a reference element, because Fe is enriched in this geographic cluster compared to other areas (Data Set S2).

4.4. Modern Dust Versus Av Horizons

[34] The major- and minor-element contents of modern dust and Av samples are generally similar at the same site and among sites, supporting the interpretation that Av horizons in the study area consist primarily of eolian dust derived from geologic sources similar in composition to

Figure 11. Boxplots of crustal enrichment values of selected elements calculated relative to Fe for dust and soil samples grouped by geographic area. Elements with similar patterns of enrichment are annotated on some plots, though ranges of values differ. Symbols same as in Figure 3; only selected outlier values are annotated with sample numbers.

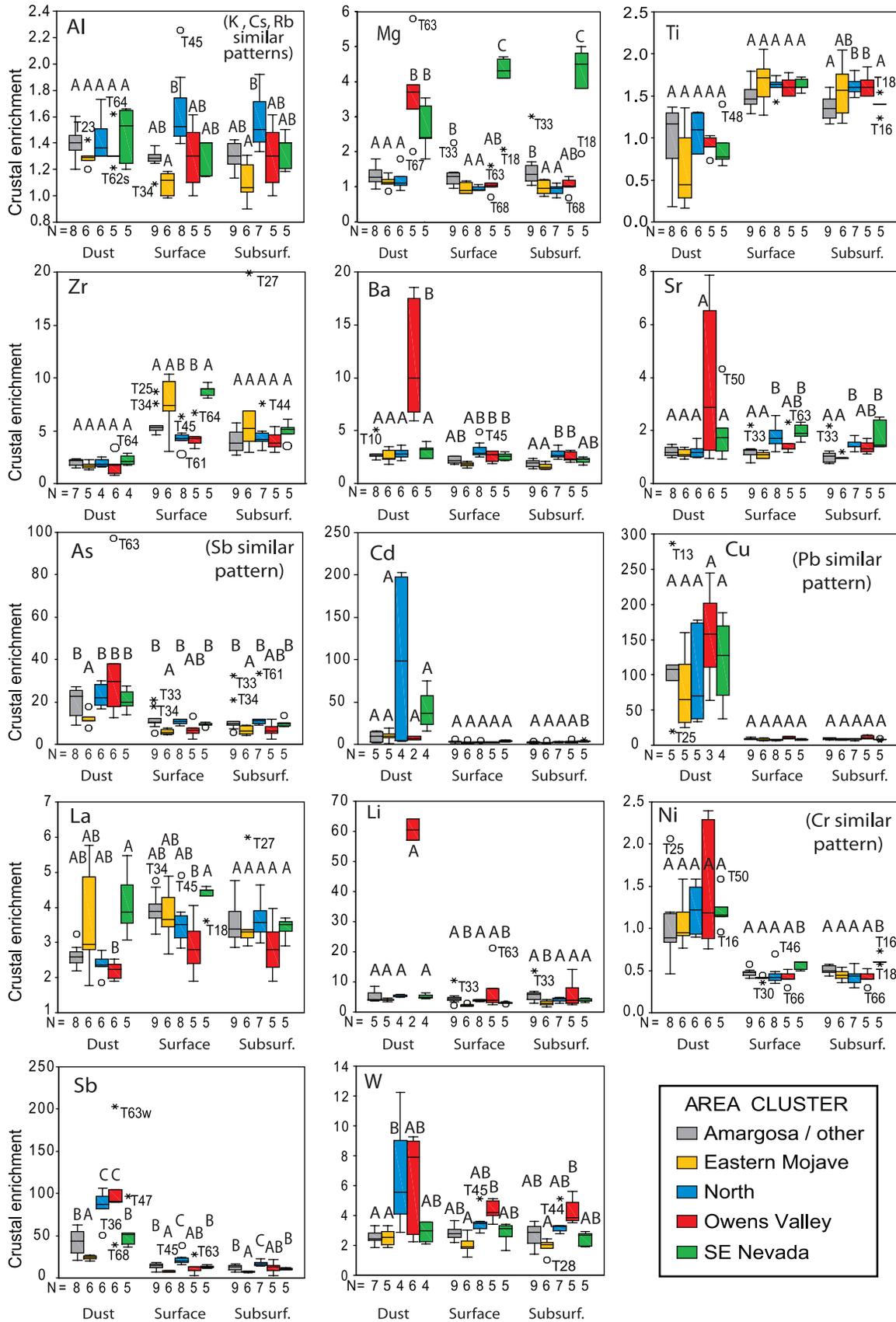


Figure 11

modern dust sources. Differences mainly reflect local dust sources and some mixing of eolian dust with parent material sediment. These relations are supported by comparison of immobile crustal elements (Figures 5 and 6), which shows that groupings by dust source, substrate lithology, and area occupy similar compositional ranges, with the following exceptions: some sites in Owens Valley have higher Sr content and lower La content, some Eastern Mojave substrates have elevated Ti and Zr contents, and SE Nevada sites are lower in Rb.

4.4.1. Ti, Zr, and REE

[35] Modern dusts are distinguished from Av samples by lesser amounts of Mn, Th, Ti, Zr, Hf, and REE (Figures 3, 4, and 6c). Elements that are higher in Av samples compared to dust at a given site (Figure 3) are commonly contained in relatively high-density zircons and iron-rich minerals. Small differences in some elements, especially Fe and Mn, can be ascribed to mixing of dust with local substrate sediment to form the Av horizons. However, the consistent depletion in Th, Ti, Zr, Hf, and REE in dusts relative to Av horizons across the study area (Figures 11 and 12) suggests either (1) a dust source change, (2) a wind strength change since accretion of most of the Av sediment, or (3) that modern dusts are in part produced by winnowing of lighter grains from the surface Av sediment. The only new major local dust source is Owens Lake. However, the Owens Valley area is actually enriched in Th (Figure 6) and is not depleted in Ti and Zr relative to other areas, except for the eastern Mojave sites (Figure 5a), and thus cannot account for this depletion in modern dusts.

[36] Most workers think that Av horizons grow by upward vertical accretion of dust (discussed earlier [McFadden *et al.*, 1998]), although mixing may occur within Av sediments during wetting and drying or through bioturbation. Thus, the thin sandy surface samples could represent relatively younger eolian sediment than the subsurface, siltier sediment; certainly, the surface samples have been subjected to eolian processes more recently. We have no chronologic age control on our samples. However, Av horizons have been dated by others using luminescence techniques at several locations within the study area [McFadden *et al.*, 1998; Keefer *et al.*, 2004], generally at depths several cm below the surface, and have obtained ages ranging from about 5 to 15 ka. Reheis *et al.* [1995] showed that rates of dust deposition, as recorded by silt-rich Av horizons in the Mojave Desert, were much higher during the latest Pleistocene and early Holocene than in the later Holocene. Major episodes of dune construction within dune fields along the Mojave River-Kelso Dunes sand transport corridor also occurred during the latest Pleistocene and early Holocene, followed by minor dune reactivation during the past 2000 years [Rendell and Sheffer, 1996; Tchakerian and Lancaster, 2002]. Our surface sediment samples might record either a late Holocene period of higher average wind velocity sufficient to move coarser grains and denser sediment enriched in Ti, Zr, and REE, or more likely, deflation of less dense fines as a result of historic drought or grazing pressures. A recent study of cores from high-altitude lakes in southwestern Colorado by Neff *et al.* [2008] documented a 500% increase in dust deposition rates beginning in the late 19th century and attributed this to wind erosion caused by the great expansion of livestock grazing in the western United States.

[37] Previous research indicates that Ti in midcontinent loess (and presumably, dust) is concentrated in the fine silt fraction and increases with distance downwind from a source, whereas Zr is concentrated in the coarse silt fraction and decreases downwind [Muhs and Bettis, 2000]. In loess, Ti and Zr generally occur as microinclusions of accessory minerals such as rutile and zircon in quartz grains [Drees and Wilding, 1978]. Eolian winnowing from such source sediment should not produce Av samples with high Ti and Zr values and dust samples with low values. However, Reynolds *et al.* [2006a, 2006b] found that in some of these same Av samples as well as many other dust samples that accumulated on high, isolated surfaces in the Mojave Desert, Ti in the silt-plus-clay fraction correlates well with magnetic, high-density Fe-Ti oxides. Zr contents in this study are only slightly higher in the surface samples compared to subsurface samples (Figure 4), but in the Eastern Mojave, SE Nevada, and Amargosa/other clusters, the differences are more pronounced (Figure 11). In addition, the surface samples at many sites consist of sediment with a higher proportion of fine and very fine sand, sometimes twice as much as that present in the subsurface, much siltier samples (Data Set S1). On balance, these considerations tend to support the hypothesis that the surface samples have been affected by winnowing rather than by a change in dust source. Also, the sorting is more noticeable in certain areas, rather than across the region as would be expected if a change in wind strength had occurred.

[38] Ti, Zr, and REE are most enriched in the Eastern Mojave samples, and especially at site T29 and surrounding sites (Figures 1, 5, and 12 and Data Set S2). To compare these samples with those in the rest of the region, we calculated averages of chondrite-normalized REE contents for modern dust and Av samples for (1) sites between Cadiz Lake and Silver Lake in the Eastern Mojave group ("Mojave dust," Figure 12b), and (2) sites farther southeast and sites to the north (Figure 12a); we excluded sites with high Ca contents (T33, T34, T16, T18, T47, T48, and T50), as well as Owens Valley sites. The chondrite-normalized values are volatile-free (i.e., C- and H₂O-free) C1 chondritic values obtained by multiplying 1.32 times the C1 compiled data of Anders and Ebihara [1982]. The REE values are very similar to those reported by Boynton [1985].

[39] All dusts are depleted in Th, Zr, and REE compared to Av samples. Av samples from Eastern Mojave sites are distinctly enriched in all REE, Th, and Zr compared to the Av samples from elsewhere in the study area, but the Eastern Mojave dust samples have even lower REE contents than other dusts. The highest REE values in the Eastern Mojave group are in surface samples from 0 to 0.5 cm depth (Data Set S2). These results suggest that the Eastern Mojave surface samples and dusts reflect more aerodynamic sorting, hence more frequent or severe historic wind erosion, than other sites.

[40] The Eastern Mojave region is notable for several geologic features that may explain the local enrichments of Ti, Zr, and REE in Av samples: (1) the granitic-dominated sand transport corridor that begins near the southwestern edge of Soda Lake and extends east through Kelso Dunes past site T-28 [Lancaster, 1993; Zimbelman *et al.*, 1995], (2) the extensive volcanic plateaus and cinder cones of the

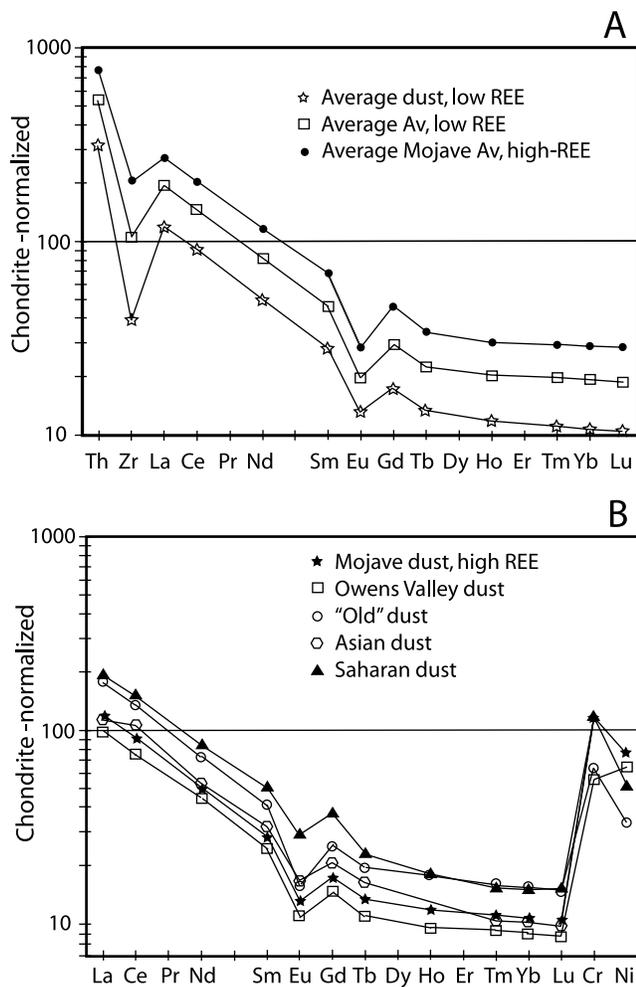


Figure 12. Chondrite-normalized REE and other element abundances. (a) Comparison of REE, Th, and Zr values of average low-Ca modern dust and surface samples (sites T11, T13, T14, T25, T26, T35, T36, T37, T44, T45, and T61) and the high-REE surface samples (sites T23, T27, T28, T29, T30, and T31). (b) Comparison of REE, Cr, and Ni values of Mojave dust; Owens Valley dust (sites T62–T67); “old dusts” from Yucca Mountain, Nevada [Reheis *et al.*, 2002]; Asian dust [Zdanowicz *et al.*, 2006]; and African dust [Muhs *et al.*, 2007a].

Cima Volcanic Field surrounding site T-29, and (3) an REE-enriched region between sites T-29 and T-23, exemplified by the carbonatite-hosted rare earth mine at Mountain Pass on the California-Nevada border [Woolley, 1987]. Analyses of Jurassic plutons that are widespread in the Mojave Desert [Miller and Glazner, 1995] and a few analyses of Mojave River sand from upstream of Soda Lake (J. R. Budahn, unpublished data, 2008) have Zr contents ranging from 100 to 400 ppm, not high enough to account for the Zr contents in Av samples of the Eastern Mojave group. However, the eolian sand transport corridor could concentrate Zr in resistant zircon grains. The Cima volcanic flows are enriched in Ti and may be the source of the high Ti values in Av horizons. However, REE values of the flows are not

very high [e.g., Farmer *et al.*, 1995] and they do not possess a negative Eu anomaly that is present in the modern dust and Av samples (Figure 12). Haxel [2005] summarized the geochemistry of REE-rich rocks from Mountain Pass; however, these samples cannot be direct sources of this component because of discrepancies in several REE ratios (i.e., La/Yb and Eu*).

[41] REE values of modern dust samples in the study area, especially in Owens Valley, are lower than those reported for typical Asian and Saharan dust samples [Zdanowicz *et al.*, 2006; Muhs *et al.*, 2007a] (Figure 12b). In contrast, samples of “old dust” from natural dust traps on the crest of Yucca Mountain (east of site 14 on Figure 1, discussed by Reheis *et al.* [2002]), long protected from grazing, have higher REE values that are comparable to those of Saharan dust and similar to those of the low-REE Av samples from the surrounding area (compare Figures 12a and 12b), although with a larger negative Eu anomaly. The similarity in these compositions of the “old dust” and Av samples is consistent with the hypothesis that increased wind erosion due to historic surface disturbance has produced modern dusts by winnowing surface samples.

4.4.2. Trace Metal Enrichments

[42] Trace element contents of modern dust and Av samples are much more variable than major-element contents (Figures 2 and 7). As, Cu, Ni, Pb, and Sb are much higher in dusts. Notably, Cu and Pb are commonly an order of magnitude more abundant in dusts than in Av horizons, and As, Ni, and Sb are about 2–3 times as abundant. All of these elements are widely considered to be enriched in modern dust and aerosols because of anthropogenic emissions [Lantzy and Mackenzie, 1979; Nriagu, 1979; Galloway *et al.*, 1982]. Average crustal enrichment values of these elements support these relations (Figures 7 and 11): Cu, Pb, and Sb in dusts are enriched 1–2 orders of magnitude above average crustal values, and in Av samples by smaller factors of typically 2 to 6.

[43] Compared to other areas, dusts from Owens Valley sites are more enriched in As, Mg, Ba, Li, Sb, Sr, U, and W (Figure 11). Owens Av horizons are also enriched in Li, U, and W, suggesting long-term local sources of these trace elements that persist today. W is enriched in North area dusts, which also exhibit several high Cd values (Figure 11 and Data Set S2). Of these elements, As, Ba, and Sb are enriched in dust samples across the entire region compared to surface samples; these elements have been documented as derived from Owens Valley and exported regionally [Reheis *et al.*, 2002]. Mg, Li, and Sr are abundant in Holocene Owens Lake sediment [Bischoff *et al.*, 1997; Bischoff and Cummins, 2001]. Such effects on modern dusts but not on the older dust-derived Av horizons in the study area are probably caused by the 20th century desiccation of Owens Lake. From previous investigations and cores, the only time Owens Lake is known to have desiccated during the past ~800,000 years is for a brief period in the late Holocene [Smith *et al.*, 1997; Stine, 2004]. Sb and W in dusts, as discussed above, are likely derived from mining and milling wastes.

[44] We infer that elements that are distinctly enriched in dust samples compared to Av samples across all geographic regions, including Cu, Pb, and Ni (Cd is also enriched in

dusts, though the values are quite variable; Figures 7 and 11) represent a far-traveled, possibly global, component of the dustfall. One possible source of Ni and Cr in dusts in the study area is sediments and soils derived from ultramafic rocks (M. Goldhaber, United States Geological Survey, written communication, 2008) that are exposed along both sides of the Central Valley of California (Figure 1). The Central Valley is well known for its dust storms [e.g., *Wilshire et al.*, 1981]. Air-sampling data show that Cr content is commonly elevated in the dry summer months and also spikes during wind events during the winter (M. Goldhaber, written communication, 2008). However, Cr and Ni are enriched in nearly all of the dust samples, irrespective of location relative to the Central Valley.

4.4.3. Anthropogenic Aerosols

[45] We attribute the most notable differences between modern dusts and surficial dust-derived samples, namely the dramatic enrichments of Cu and Pb, to anthropogenic pollutants. At some sites, additional sources such as mining and smelting wastes contribute Cd and W to modern dusts. Such results are consistent with conclusions of other studies in the region [e.g., *Moyers et al.*, 1977; *Barbaris and Betterton*, 1996; *Reheis et al.*, 2002] and globally [*Galloway et al.*, 1982; *Arimoto et al.*, 1990; *Sherrell et al.*, 2000], which attributed these metal enrichments to background levels of emissions worldwide. In addition, Cr and Ni are enriched in modern dusts compared to Av horizons by factors of 2–3 (Figures 7 and 11). Modern Saharan dusts have similar amounts of Cr and Ni (Figure 12b), supporting a global anthropogenic effect. Pb, Cu and Cd are also notably enriched in the upper 10 cm high-altitude lake sediments from the Uinta Range, which record historic (~150 years) dust inputs to these lakes, compared to the background levels of these components at greater, prehistoric depths. Cr, but not Ni, also increases in the upper 10 cm of these sediments [*Reynolds et al.*, 2007a; R. Reynolds, unpublished data, 2008]. However, the fact that Cd, Cu, Pb, and other metals such as As, Ba, Cs, Li, Sb, and W are enriched above crustal average values in both modern dusts and Av horizons (Figure 7) in our study area shows that an important component of dusts in the region is derived from geologic sources that have been active for thousands of years.

[46] These results from the desert Southwest are consistent with, and expand upon, observations of the importance of a locally derived windblown component to the <10 μm fraction of dust measured at IMPROVE sites in the same region [*Kavouras et al.*, 2007]. They based this conclusion on comparison of wind data, visibility data, and soil dust concentrations partly estimated from major-element concentrations. Our data suggest that local dust sources may also be significant contributors of trace metals in dusts, at least within the study area. Such effects are not restricted to relatively low-altitude valley settings, because some of our sites (T29, T37, T45, and T68, Figure 1) lie on the crests of mountain ranges or plateaus. Furthermore, the southwestern dusts of this study are nearly identical in crustal composition to dust-delivered sediment in high-altitude Uinta lakes (Figure 6), indicating a broad regional distribution of these dusts. Ascribing a significant component of Southwestern United States dusts to local sources also suggests that models that estimate a large effect of Asian-derived fine

dust on aerosols in western North America [e.g., *Wells et al.*, 2007; *Zhao et al.*, 2007] may be overstated for the southwestern desert region.

5. Conclusions

[47] Modern dusts across deserts of southeastern California and southern Nevada are compositionally similar to surficial sediments for common crustal elements, but are distinctly different in elements such as Pb, Cu, Cr, and Ni, attributed to anthropogenic sources. Comparisons show that chemical compositions and mineral magnetic properties of the shallower and deeper sediment samples are very similar at individual sites and among sites associated with different primary dust sources (wet playas, dry playas, and alluvium), geographic areas, and lithologic substrates; the exceptions are certain elements such as Li, U, and W that are more abundant in Owens Valley sites because of the distinctive compositions of bedrock in the drainage basin. Av horizons do reflect some mixing of dust-derived and substrate sediments, including such effects as higher Ti and magnetic mineral contents on basaltic substrates and higher Mg and Sr contents on carbonate substrates. In addition, Av horizons in general and especially surface (0–0.5 cm) samples in the Eastern Mojave area are enriched in Zr, Ti, Th, and REE compared to modern dust samples. We propose that this enrichment of surface samples occurred because of winnowing of less dense particles, most likely caused by enhanced wind erosion related to historic grazing pressure, or less likely by a late Holocene episode of higher average wind speed.

[48] Modern dust samples are also nearly identical across the region relative to substrates and nearby dust sources, except that dusts within Owens Valley, Calif., are higher in Mg, Ba, Li, Sb, Sr, U, and W than at most other sites. Contributions from substrate lithologies and mineral components are minor and localized. Thus, apart from Owens Valley, contributions from many different dust sources are well mixed before deposition. Relative to average crustal values, modern dusts and surface samples are moderately enriched in most trace elements ratioed to Fe. However, at nearly every site, modern dust contains significantly greater amounts of trace elements, such as Cu, Cd, Cr, Ni, and Pb, than do surface samples. Because the surface samples probably record long-term dust additions over several hundreds to thousands of years, these results suggest that modern dust compositions are influenced by anthropogenic sources, including globally distributed emissions and local mining sources, as well as emissions from Owens (dry) Lake after 1926.

[49] **Acknowledgments.** Eric Fisher (United States Geological Survey) performed the particle size analyses shown in Data Set S1 and collected many of the dust and surface samples. We thank Harland Goldstein and Jiang Xiao (USGS) for magnetic property analyses. We very much appreciate the helpful suggestions and insightful reviews on earlier drafts of this paper by Dan Muhs and Marty Goldhaber (USGS), as well as two anonymous reviewers.

References

- Agrawal, Y. C., I. N. McCave, and J. B. Riley (1991), Laser diffraction size analysis, in *Principles, Methods, and Application of Particle Size Analysis*, edited by J. P. M. Syvitski, pp. 119–129, Cambridge Univ. Press, New York.

- Anders, E., and M. Ebihara (1982), Solar-system abundances of the elements, *Geochim. Cosmochim. Acta*, *46*, 2363–2380, doi:10.1016/j-7037(82)90208-3.
- Arimoto, R., B. J. Ray, R. A. Duce, A. D. Hewitt, R. Boldi, and A. Hudson (1990), Concentrations, sources, and fluxes of trace elements in the remote marine atmosphere of New Zealand, *J. Geophys. Res.*, *95*, 22,389–22,405, doi:10.1029/JD095iD13p22389.
- Barbaris, B., and E. A. Betterton (1996), Initial snow chemistry survey of the Mogollon Rim in Arizona, *Atmos. Environ.*, *30*, 3093–3103, doi:10.1016/1352-2310(95)00293-6.
- Barone, J. B., B. H. Kusko, L. L. Ashbaugh, and T. A. Cahill (1979), A study of ambient aerosols in the Owens Valley area, *Final Rep. A7-178-30*, 37 pp., Air Qual. Group, Univ. of Calif., Davis, Calif.
- Bischoff, J. L., and K. Cummins (2001), Wisconsin glaciation of the Sierra Nevada (79,000–15,000 yr B. P.) as recorded by rock flour in sediments of Owens Lake, California, *Quat. Res.*, *55*, 14–24, doi:10.1006/qres.2000.2183.
- Bischoff, J. L., J. P. Fitts, and J. A. Fitzpatrick (1997), Responses of sediment geochemistry to climate change in Owens Lake sediments: An 800-k.y. record of saline/fresh cycles in core OL-92, in *An 800,000-Year Paleoclimatic Record From Core OL-92, Owens Lake, Southeast California*, edited by G. I. Smith and J. L. Bischoff, pp. 143–160, Geol. Soc. of Am., Boulder, Colo.
- Boynton, W. V. (1985), Geochemistry of the rare Earth elements: Meteorite studies, in *Developments in Geochemistry 2: Rare Earth Element Geochemistry*, edited by P. Henderson, pp. 115–152, Elsevier, Amsterdam.
- Briggs, P. H. (1996), Forty elements by inductively coupled plasma-atomic emission spectrometry, in *Analytical Methods Manual for the United States Geological Survey*, edited by B. F. Arboast, *Open-File Rep. 96-525*, pp. 77–94, U. S. Geol. Surv., Reston, Va.
- Briggs, P. H., and A. L. Meier (1999), The determination of 42 elements in geological materials by inductively coupled plasma mass spectrometry, *Open-File Rep. 99-166*, 15 pp., U. S. Geol. Surv., Reston, Va.
- Budahn, J. R., and G. A. Wandless (2002), Instrumental neutron activation by long count, in *Analytical Methods for Chemical Analysis of Geologic and Other Materials*, edited by J. E. Taggart Jr., *Open-File Rep. 02-0223*, pp. 1–13, U.S. Geol. Surv., Reston, Va.
- Cahill, T. A., T. E. Gill, D. A. Gillette, E. A. Gearhart, J. S. Reid, and M.-L. Yau (1994), Generation, characterization, and transport of Owens (Dry) Lake dusts, *Final Rep. A132-105*, 166 pp., Air Qual. Group, Univ. of Calif., Davis, Calif.
- Chaffee, M. A., and K. H. Berry (2006), Abundance and distribution of selected elements in soils, stream sediments, and selected forage plants from desert tortoise habitats in the Mojave and Colorado deserts, USA, *J. Arid Environ.*, *67*, 35–87, doi:10.1016/j.jaridenv.2006.09.018.
- Dealing, J. A., K. L. Hay, M. J. Baban, A. S. Huddleston, E. M. Wellington, and P. J. Loveland (1996), Magnetic susceptibility of soil: An evaluation of conflicting theories using a national data set, *Geophys. J. Int.*, *127*, 728–734, doi:10.1111/j.1365-246X.1996.tb04051.x.
- Drees, L. R., and L. P. Wilding (1978), Elemental distribution in the light mineral isolate of soil separates, *Soil Sci. Soc. Am. J.*, *42*, 976–978.
- Farmer, G. L., A. F. Glazner, H. G. Wilshire, J. L. Wooden, W. J. Pickthorn, and M. Katz (1995), Origin of late Cenozoic basalts at the Cima volcanic field, Mojave Desert, California, *J. Geophys. Res.*, *100*, 8399–8415, doi:10.1029/95JB00070.
- Galloway, J. N., J. D. Thornton, S. A. Norton, H. L. Volchok, and R. A. N. McLean (1982), Trace metals in atmospheric deposition: A review and assessment, *Atmos. Environ.*, *16*, 1677–1700, doi:10.1016/0004-6981(82)90262-1.
- Gill, T. E. (1996), Eolian sediments generated by anthropogenic disturbance of playas: Human impacts on the geomorphic system and geomorphic impacts on the human system, *Geomorphology*, *17*, 207–228.
- Gill, T. E., et al. (2002), Elemental geochemistry of wind-erodible playa sediments, Owens Lake, California, *Nucl. Instrum. Methods Phys. Res. Sect. B*, *189*, 209–213.
- Goldstein, H. L., G. N. Breit, J. C. Yount, and R. L. Reynolds (2007), Trace-metal accumulation in brines and salts of Franklin Lake playa and the Ash Meadows area of Nevada and California, *Geol. Soc. Am. Abstr. Programs*, *39*(6), 188.
- Haxel, G. B. (2005), Ultrapotassic mafic dikes and rare earth element- and barium-rich carbonatite at Mountain Pass, Mojave Desert, Southern California: Summary and field trip localities, *Open-File Rep. 2005-1219*, 56 pp., U. S. Geol. Surv., Reston, Va.
- Hinkley, T. K. (1974), Alkali and alkaline earth metals: Distribution and loss in a high Sierra Nevada watershed, *Geol. Soc. Am. Bull.*, *85*, 1333–1338, doi:10.1130/0016-7606(1974)85<1333:AAAEMD>2.0.CO;2.
- Kavouras, I. G., V. Etyemezian, J. Xu, D. W. DuBois, M. Green, and M. Pitchford (2007), Assessment of the local windblown component of dust in the western United States, *J. Geophys. Res.*, *112*, D08211, doi:10.1029/2006JD007832.
- Keefe, W. R., J. W. Whitney, and E. M. Taylor (2004), Quaternary paleoseismology and stratigraphy of the Yucca Mountain area, Nevada, *Prof. Pap. 1689*, 212 pp., U. S. Geol. Surv., Reston, Va.
- Kennedy, M. J., O. A. Chadwick, P. M. Vitousek, L. A. Derry, and D. M. Hendricks (1998), Changing sources of base cations during ecosystem development, Hawaiian islands, *Geology*, *26*, 1015–1018, doi:10.1130/0091-7613(1998)026<1015:CSOBCD>2.3.CO;2.
- King, J. W., and J. E. T. Channel (1991), Sedimentary magnetism, environmental magnetism, and magnetostratigraphy, *Rev. Geophys.*, *29*, 358–370.
- Krauskopf, K. B., and D. K. Bird (1995), *Introduction to Geochemistry*, 3rd ed., 647 pp., McGraw-Hill, New York.
- Lancaster, N. (1993), Kelso Dunes, *Natl. Geogr. Res. Explor.*, *9*, 444–459.
- Lantzy, R. J., and F. T. Mackenzie (1979), Atmospheric trace metals: Global cycles and assessment of man's impact, *Geochim. Cosmochim. Acta*, *43*, 511–525, doi:10.1016/0016-7037(79)90162-5.
- Levy, D. B., J. A. Schramke, K. J. Esposito, T. A. Erickson, and J. C. Moore (1999), The shallow ground water chemistry of arsenic, fluorine, and major elements: Eastern Owens Lake, California, *Appl. Geochem.*, *14*, 53–65, doi:10.1016/S0883-2927(98)00038-9.
- Mason, J. A., and P. M. Jacobs (1998), Chemical and particle-size evidence for addition of fine dust to soils of the midwestern United States, *Geology*, *26*, 1135–1138, doi:10.1130/0091-7613(1998)026<1135:CAPSEF>2.3.CO;2.
- McDonald, E. V. (1994), The relative influence of climatic change, desert dust, and lithological control on soil-geomorphic processes and hydrology of calcic soils formed on Quaternary alluvial-fan deposits in the Mojave desert, California, Ph.D. thesis, 383 pp., Univ. of N. M., Albuquerque, N. M.
- McDonald, E. V., L. D. McFadden, and S. G. Wells (1995), The relative influences of climate change, desert dust, and lithologic control on soil-geomorphic processes on alluvial fans, Mojave Desert, California: Summary of results, *San Bernardino County Mus. Assoc. Q.*, *42*, 35–42.
- McFadden, L. D., S. G. Wells, and M. J. Jercinovich (1987), Influences of eolian and pedogenic processes on the origin and evolution of desert pavement, *Geology*, *15*, 504–508, doi:10.1130/0091-7613(1987)15<504:IOEAPP>2.0.CO;2.
- McFadden, L. D., E. V. McDonald, S. G. Wells, K. Anderson, J. Quade, and S. L. Forman (1998), The vesicular layer and carbonate collars of desert soils and pavements: Formation, age and relation to climate change, *Geomorphology*, *24*, 101–145, doi:10.1016/S0169-555X(97)00095-0.
- Miller, J. S., and A. F. Glazner (1995), Jurassic plutonism and crustal evolution in the central Mojave Desert, California, *Contrib. Mineral. Petrol.*, *118*(4), 379–395.
- Moreno, T., X. Querol, S. Castillo, A. Alastuey, E. Cuevas, L. Herrmann, M. Mounkaila, J. Elvira, and W. Gibbons (2006), Geochemical variations in aeolian mineral particles from the Sahara-Sahel dust corridor, *Chemosphere*, *65*, 261–270, doi:10.1016/j.chemosphere.2006.02.052.
- Moyers, J. L., L. E. Ranweiler, S. B. Hopf, and N. E. Korte (1977), Evaluation of particulate trace species in southwest desert atmosphere, *Environ. Sci. Technol.*, *11*, 789–795, doi:10.1021/es60131a002.
- Muhs, D. R., and J. B. Benedict (2006), Eolian additions to late Quaternary alpine soils, Indian Peaks Wilderness area, Colorado Front Range, *Arct. Antarct. Alp. Res.*, *38*, 120–130, doi:10.1657/1523-0430(2006)038[0120:EATLQA]2.0.CO;2.
- Muhs, D. R., and E. A. Bettis III (2000), Geochemical variations in Peoria Loess of western Iowa indicate paleowinds of midcontinental North America during last glaciation, *Quat. Res.*, *53*, 49–61, doi:10.1006/qres.1999.2090.
- Muhs, D. R., J. R. Budahn, J. M. Prospero, and S. N. Carey (2007a), Geochemical evidence for African dust inputs to soils in western Atlantic islands: Barbados, the Bahamas, and Florida, *J. Geophys. Res.*, *112*, F02009, doi:10.1029/2005JF000445.
- Muhs, D. R., J. Budahn, M. Reheis, J. Beann, G. Skipp, and E. Fisher (2007b), Airborne dust transport to the eastern Pacific Ocean off southern California: Evidence from San Clemente Island, *J. Geophys. Res.*, *112*, D13203, doi:10.1029/2006JD007577.
- Naiman, Z., J. Quade, and P. J. Patchett (2000), Isotopic evidence for eolian recycling of pedogenic carbonate and variations in carbonate dust sources throughout the southwest United States, *Geochim. Cosmochim. Acta*, *64*, 3099–3109, doi:10.1016/S0016-7037(00)00410-5.
- Neff, J. C., A. P. Ballantyne, G. L. Farmer, N. M. Mahowald, J. L. Conroy, C. C. Landry, J. T. Overpeck, T. H. Painter, C. R. Lawrence, and R. L. Reynolds (2008), Increasing eolian dust deposition in the western United States linked to human activity, *Nat. Geosci.*, *1*, 189–195, doi:10.1038/ngeo133.
- Nriagu, J. O. (1979), Global inventory of natural and anthropogenic emissions of trace metals to the atmosphere, *Nature*, *279*, 409–411, doi:10.1038/279409a0.

- Plumlee, G. S., and T. L. Ziegler (2003), The medical geochemistry of dusts, soils, and other Earth materials, in *Treatise on Geochemistry*, vol. 9, edited by B. S. Lollar, pp. 263–310, Elsevier, New York.
- Reheis, M. C. (1990), Influence of climate and eolian dust on the major-element chemistry and clay mineralogy of soils in the northern Bighorn basin, U.S., *Catena*, 17, 219–248, doi:10.1016/0341-8162(90)90018-9.
- Reheis, M. C. (1997), Dust deposition downwind of Owens (dry) Lake, 1991–1994: Preliminary findings, *J. Geophys. Res.*, 102, 25,999–26,008, doi:10.1029/97JD01967.
- Reheis, M. C. (2003), Dust deposition in Nevada, California, and Utah, 1984–2002, *Open-File Rep. 03–138*, 66 pp., U.S. Geol. Surv., Reston, Va.
- Reheis, M. C. (2006), 16-year record of dust deposition in southern Nevada and California, USA, *J. Arid Environ.*, 67, 487–520, doi:10.1016/j.jaridenv.2006.03.006.
- Reheis, M. C., and R. Kihl (1995), Dust deposition in southern Nevada and California, 1984–1989: Relations to climate, source area, and source lithology, *J. Geophys. Res.*, 100, 8893–8918, doi:10.1029/94JD03245.
- Reheis, M. C., J. M. Sowers, E. M. Taylor, L. D. McFadden, and J. W. Harden (1992), Morphology and genesis of carbonate soils on the Kyle Canyon fan, Nevada, U.S., *Geoderma*, 52, 303–342, doi:10.1016/0016-7061(92)90044-8.
- Reheis, M. C., J. C. Goodmacher, J. W. Harden, L. D. McFadden, T. K. Rockwell, R. R. Shroba, J. M. Sowers, and E. M. Taylor (1995), Quaternary soils and dust deposition in southern Nevada and California, *Geol. Soc. Am. Bull.*, 107, 1003–1022, doi:10.1130/0016-7606(1995)107<1003:QSADDI>2.3.CO;2.
- Reheis, M. C., J. R. Budahn, and P. J. Lamothe (1999), Elemental analyses of modern dust in southern Nevada and California, *Open-File Rep. 99–0531*, U.S. Geol. Surv., Reston, Va.
- Reheis, M. C., J. R. Budahn, and P. J. Lamothe (2002), Geochemical evidence for diversity of dust sources in the southwestern United States, *Geochim. Cosmochim. Acta*, 66, 1569–1587, doi:10.1016/S0016-7037(01)00864-X.
- Reid, J. S., R. G. Flocchini, T. A. Cahill, R. S. Ruth, and D. P. Salgado (1994), Local meteorological, transport, and source aerosol characteristics of late autumn Owens Lake (dry) dust storms, *Atmos. Environ.*, 28, 1699–1706, doi:10.1016/1352-2310(94)90315-8.
- Rendell, H. M., and N. L. Sheffer (1996), Luminescence dating of sand ramps in the eastern Mojave Desert, *Geomorphology*, 17, 187–197, doi:10.1016/0169-555X(95)00102-B.
- Reynolds, R. L., J. Neff, M. Reheis, and P. Lamothe (2006a), Atmospheric dust in modern soil on aeolian sandstone, Colorado Plateau (USA): Variation with landscape position and contribution to potential plant nutrients, *Geoderma*, 130, 108–123, doi:10.1016/j.geoderma.2005.01.012.
- Reynolds, R. L., M. Reheis, J. Yount, and P. Lamothe (2006b), Composition of aeolian dust in natural traps on isolated surfaces of the central Mojave Desert—Insights to mixing, sources, and nutrient inputs, *J. Arid Environ.*, 66, 42–61, doi:10.1016/j.jaridenv.2005.06.031.
- Reynolds, R. L., H. Goldstein, J. Mordecai, K. Moser, J. C. Neff, M. C. Reheis, J. G. Rosenbaum, and J. C. Yount (2007a), Changes in dust composition in the western United States related to human activities over the past ca. 150 years, *Quat. Int.*, 167–168, 341.
- Reynolds, R. L., J. Neff, F. Urban, H. Goldstein, D. Fernandez, M. Reheis, and J. Belnap (2007b), Nutrients in grassland soils of the central Colorado Plateau—Spatial controls by substrate composition, geomorphic setting, and land-use effects, *Geol. Soc. Am. Abstr. Programs*, 39(6), 425.
- Reynolds, R. L., J. C. Yount, M. Reheis, H. Goldstein, P. Chavez Jr., R. Fulton, J. Whitney, C. Fuller, and R. M. Forester (2007c), Dust emission from wet and dry playas in the Mojave Desert, USA, *Earth Surf. Processes Landforms*, 32, 1811–1827, doi:10.1002/esp.1515.
- Ross, M., et al. (1993), Health effects of mineral dusts other than asbestos, in *Health Effects of Mineral Dusts*, edited by G. D. J. Guthrie and B. T. Mossman, pp. 361–407, Mineral. Soc. of Am., Washington, D. C.
- Saint Amand, P., L. Mathews, C. Gaines, and R. Reinking (1986), Dust storms from Owens and Mono Lakes, *Tech. Publ. 6731*, 79 pp., Nav. Weapons Cent., China Lake, Calif.
- Sheppard, P. R., G. Ridenour, R. J. Speakman, and M. L. Witten (2006), Elevated tungsten and cobalt in airborne particulates in Fallon, Nevada: Possible implications for the childhood leukemia cluster, *Appl. Geochem.*, 21, 152–165, doi:10.1016/j.apgeochem.2005.09.012.
- Sherrell, R. M., E. A. Boyle, K. K. Falkner, and N. R. Harris (2000), Temporal variability of Cd, Pb, and Pb isotope deposition in central Greenland snow, *Geochem. Geophys. Geosyst.*, 1(5), 1002, doi:10.1029/1999GC000007.
- Smith, G. I., J. L. Bischoff, and J. P. Bradbury (1997), Synthesis of the paleoclimatic record from Owens Lake core OL-92, in *An 800,000-Year Paleoclimatic Record From Core OL-92, Owens Lake, Southeast California*, edited by G. I. Smith and J. L. Bischoff, pp. 143–160, Geol. Soc. of Am., Boulder, Colo.
- Stine, S. (2004), Climate change in wildland management, *For. Serv. Gen. Tech. Rep. PSW-GTR-193*, pp. 51–55, U.S. Dep. of Agric., Washington, D. C.
- Swap, R., et al. (1992), Saharan dust in the Amazon Basin, *Tellus Ser. B*, 44, 133–149.
- Tchakerian, V. P., and N. Lancaster (2002), Late Quaternary arid/humid cycles in the Mojave Desert and western Great Basin of North America, *Quat. Sci. Rev.*, 21, 799–810, doi:10.1016/S0277-3791(01)00128-7.
- Thompson, R., and F. Oldfield (1986), *Environmental Magnetism*, 227 pp., Allen and Unwin, London.
- Tyler, S. W., S. Kranz, M. B. Parlange, J. Albertson, G. G. Katul, G. F. Cochran, B. A. Lyles, and G. Holder (1997), Estimation of groundwater evaporation and salt flux from Owens Lake, California, USA, *J. Hydrol.*, 200, 110–135, doi:10.1016/S0022-1694(97)00007-3.
- Van der Hoven, S. J., and J. Quade (2002), Tracing spatial and temporal variations in the sources of calcium in pedogenic carbonates in a semiarid environment, *Geoderma*, 108, 259–276, doi:10.1016/S0016-7061(02)00134-9.
- Wells, K. C., M. Witek, P. Flatau, S. M. Kreidenweis, and D. L. Westphal (2007), An analysis of seasonal surface dust aerosol concentrations in the western US (2001–2004), Observations and model predictions, *Atmos. Environ.*, 41, 6585–6597, doi:10.1016/j.atmosenv.2007.04.034.
- Wilshire, H. G., N. K. Nakata, and B. Hallet (1981), Field observations of the December 1977 wind storm, San Joaquin Valley, California, in *Desert Dust: Origin, Characteristics, and Effect on Man*, edited by T. L. Pewe, pp. 233–251, Geol. Soc. of Am., Boulder, Colo.
- Woolley, A. R. (1987), *Alkaline Rocks and Carbonates of the World: Part I, North and South America*, 216 pp., Br. Mus., London.
- Yaalon, D. H., and E. Ganor (1973), The influence of dust on soils in the Quaternary, *Soil Sci.*, 116, 146–155.
- Zdanowicz, C., G. Hall, J. Vaive, Y. Amelin, J. Percival, I. Girard, P. Biscaye, and A. Bory (2006), Asian dustfall in the St. Elias Mountains, Yukon, Canada, *Geochim. Cosmochim. Acta*, 70, 3493–3507, doi:10.1016/j.gca.2006.05.005.
- Zhao, T. L., S. L. Gong, X. Y. Shang, and D. A. Jaffe (2007), Asian dust storm influence on North American ambient PM levels: Observational evidence and controlling factors, *Atmos. Chem. Phys. Discuss.*, 7, 9663–9686.
- Zimelman, J. R., S. H. Williams, and V. P. Tchakerian (1995), Sand transport paths in the Mojave Desert, southwestern United States, in *Desert Aeolian Processes*, edited by V. P. Tchakerian, pp. 101–130, Chapman and Hall, New York.
- Zoller, W. H., E. S. Gladney, and R. A. Duce (1974), Atmospheric concentrations and sources of trace metals at the South Pole, *Science*, 183, 198–200, doi:10.1126/science.183.4121.198.

J. R. Budahn, P. J. Lamothe, M. C. Reheis, and R. L. Reynolds, U. S. Geological Survey, Mail Stop 980, Federal Center, Box 25046, Denver, CO 80225, USA. (mreheis@usgs.gov)