Geochemical indicators of separate sources for eolian sands in the eastern Mojave Desert, California, and western Arizona

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ABSTRACT

Low, stabilized sand dunes cover much of the Cactus and La Posa Plains in western Arizona, near the town of Parker. The provenance of the dunes is not well defined, and it had been hypothesized that they were possibly related to extensive eolian sand deposits in the eastern Mojave Desert of California, on the other side of the Colorado River. Major oxide analyses of bulk sand samples collected from southeastern California and western Arizona show clear chemical differences. The Mojave sands all have $SiO_2 < 79$ wt%, $Al_2O_3 > 10$ wt%, and $Na_2O + K_2O > 5$ wt%, whereas the Colorado River and Arizona sands have $SiO_2 > 81$ wt%, $Al_2O_3 < 6$ wt%, and $Na_2O + K_2O < 4$ wt%. These results show that the stabilized dunes near Parker are chemically indistinguishable from Colorado River sands. The chemical differences between the southeastern California sands and the western Arizona sands are supported by X-ray diffraction results that indicate these two sand populations have significant differences in the relative abundance of quartz and feldspar. Our data also indicate a near-source origin for the Mojave sands, whereas the Colorado River and Arizona sands have undergone more prolonged chemical weathering. The major oxide results are consistent with published trace element studies by others that clearly distinguished between mature and immature sands in California and Colorado. The quartz/feldspar ratio may be amenable to measurement by some advanced remote-sensing instruments.

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INTRODUCTION

The southwestern United States consists of broad areas with arid to semiarid conditions and abundant eolian sand deposits, most of which are stabilized by vegetation. The broad expanse over which these eolian sands occur makes it difficult to evaluate the probable sources for the various sands. Trace element chemistry has been used successfully to identify distinct sources for eolian sand accumulations such as the Algodones Dunes east of the Salton Sea in southern California (Muhs et al., 1995) and eolian sands in eastern Colorado and western Nebraska (Muhs et al., 1996). Here we explore the discrimination potential of major oxide chemistry applied to bulk (>50 g) eolian sand samples from numerous locations throughout southeastern California and western Arizona (Fig. 1), as an extension of the trace element studies successfully applied by others. Our primary goal in this effort was to test the likely provenance of stabilized sand dunes near Parker, Arizona, which lack an obvious source in the surrounding mountains. Both the trace element and major oxide chemistry variations are related to the minerals that compose the individual sand grains, and thus the chemical trends should be related to the maturity and/or source of the sand deposits.

Eolian sand deposits in the eastern Mojave Desert occur along discrete pathways that cross drainage divides and follow the orientation of prevailing winds associated with winter storms (Zimbelman et al., 1995). Two prominent sand pathways, identified through remote-sensing data and field investigations of active and stabilized dunes, have been named for the Bristol Trough (crossing the drainage basins of the Bristol, Cadiz, and Danby Playas) and Clark's Pass (crossing the drainage basins of the Dale, Palen, and Ford Playas) (Fig. 1). A third eolian sand accumulation occurs east of the Colorado River, on the Cactus and La Posa Plains near Parker, Arizona (Zimbelman et al., 1995). The stabilized dunes near Parker show no obvious relationship to drainage from surrounding mountains, nor any well-defined association with the flood plain of the Colorado River. The close proximity of the terminus of the Bristol Trough sand path (at the Colorado River) with the Parker dunes led to the hypothesis that the Arizona sands were derived from Mojave sand in cutoff-meander deposits, stranded by migration of the river across its flood plain (Zimbelman et al., 1995). The trace element chemistry techniques described by Muhs et al. (1995, 1996) appeared to be particularly well suited to the testing of this hypothesis. We decided to evaluate the origin of the Parker sand dunes through selected trace element analyses, but we also wanted to explore the possibility that the chemical differences in the trace element abundance values might also be expressed in the major elements.

BACKGROUND

The eastern Mojave Desert and the surrounding areas are home to several well-studied eolian sand accumulations, as well as other dune fields in more obscure localities (e.g., Smith, 1982; Tchakerian, 1997). Major dune complexes at Kelso (Sharp, 1966; Smith, 1984; Lancaster, 1993, 1994) and at Mesquite Flat in Death Valley National Park (Smith, 1982) have been studied extensively, and the

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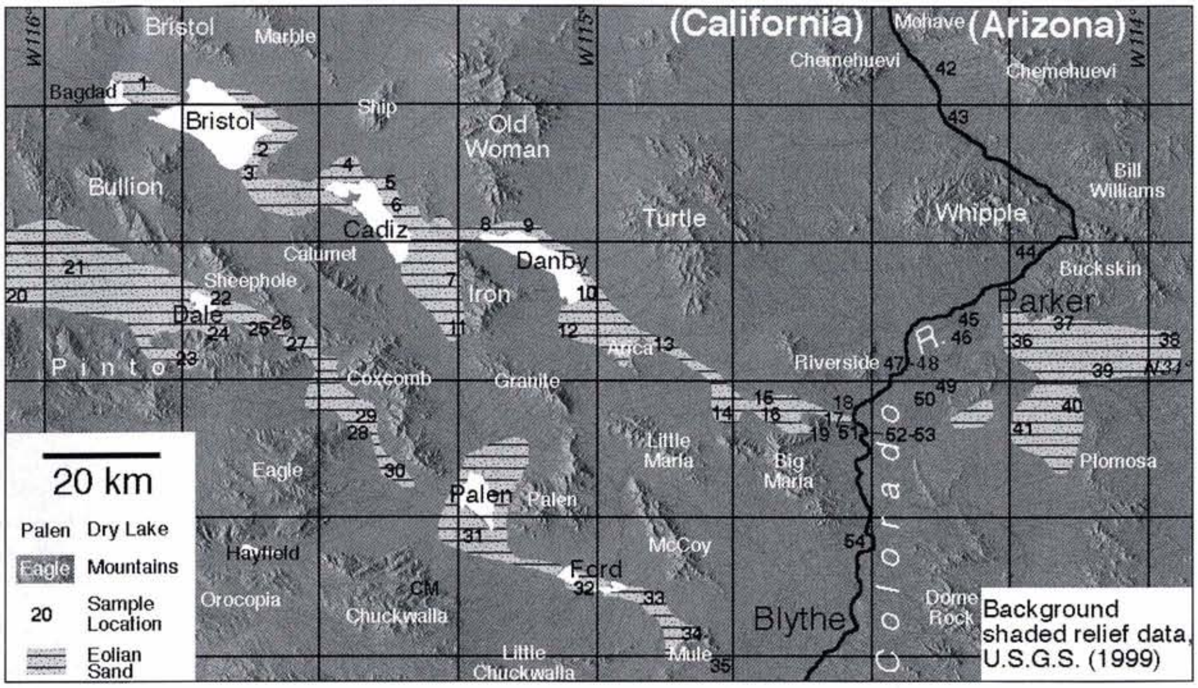

Figure 1. Location map for the study area in southeastern California and western Arizona. Principal mountains and dry lakes are labeled, and Mojave sand paths (Zimbelman et al., 1995) are shown by the areas with a lined pattern over shading. Sample locations are indicated by sample numbers (see Table 1). Sample 55, from the Algodones Dunes, is not shown because that locality is well south of the study area. Shaded-relief image is at 240 m/pixel resolution, with 15 × 15-minute block boundaries in solid black lines and faint drainage channels (data from U.S. Geological Survey, 1999).

dunes at Algodones (Sharp, 1979; Smith, 1982) and Dumont are extremely popular for off-road use. Less extensive, but still significant, active dunes are found in the Cadiz Valley, and semiactive dunes occur in Rice Valley and on the Cactus and La Posa Plains near Parker, in western Arizona (Zimbelman et al., 1995).

Eolian transport of sand in the region can operate on both local and regional scales. Some sand dunes and eolian sand sheets can be readily associated with the source of their sand supply, such as the barchan dunes on the western side of the Salton Sea (Sharp, 1964; Shelton et al., 1978). The Salton Trough, north of the Imperial Valley, was the northern extension of the present Gulf of California in Pliocene time (Dohrenwend and Smith, 1991). The upper gulf was cut off from the sea by the development of the Colorado River delta, and the basin eventually was occupied by a large freshwater lake (Lake Cahuilla) that existed intermittently in the late Holocene (Waters, 1983). The Salton Sea barchans and the much more extensive Algodones complex are primarily remobilized Lake Cahuilla beach deposits (Long and Sharp, 1964; Muhs et al., 1995; Winspear and Pye, 1995).

The study area (Fig. 1) has often been used as an analogue for assessing the effects of eolian and other geologic processes in comparative planetology (e.g., Greeley and Iversen, 1985). The eolian sand pathways just described are similar to sand accumulations observed on both Mars (Greeley and Iversen, 1985, p. 190–197; Greeley et al., 1992) and Venus (Greeley et al., 1997). The eolian sand pathways are particularly significant because of the wind's capacity to transport sand across topographic barriers, from one drainage basin to the next, and because they may contain paleoclimate information (Dohrenwend, 1987; Tchakerian, 1991; Zimbelman et al., 1995; Lancaster and Tchakerian, 1996; Rendell and Sheffer, 1996; Clarke et al., 1996). Field studies of the albedo contrast in individual Mojave wind streaks revealed the potential importance of both infrequent but intense rains (Williams and Zimbelman, 1994) and plant populations that favor the drainage properties of certain sediments (Zimbelman and Williams, 1996). Remotely sensed compositional information for sand accumulations is difficult to obtain at present, but recent spacecraft missions to Mars provided the first compositional clues for sand-sized materials, from both lander (Greeley et al., 1999; McSween et al., 1999) and orbiter spacecraft (Edgett and Christensen, 1994; Edgett, 1997; Christensen et al., 1999). The present study holds the potential to aid in identifying chemical properties that may be useful for assessing the history or maturity of eolian deposits on other planets.

Feldspars, one of the most abundant mineral groups of Earth's crust, are highly susceptible to chemical weathering into clays such as kaolinite, in contrast to the very slow dissolution rate of quartz (Siever, 1988, p. 20–26). The consequence of these differences is that the quartz/feldspar ratio is a good indicator of the general maturity of sediments, in terms of the relative effects of weathering and transport on the individual minerals (Blatt et al., 1972, p. 302–304). Muhs et al. (1995) used trace element concentrations, in conjunction with mineral evidence, to demonstrate that the Algodones dunes were not derived from sediments transported from the San Bernardino Mountains that lie to the north, but instead had strong affinities to sediments from Lake Cahuilla. The geochemical results correlate well with mineral data, indicating that the Algodones sands have higher quartz/feldspar ratios relative to alluvium from the San Bernardino Mountains, but very similar in relative abundance to Colorado River sediments (Muhs et al., 1995, their Figs. 8 and 9). The same geochemical approach was subsequently applied to an assessment of the likely sources for eolian sand deposits in northeastern Colorado (Muhs et al., 1996). Here we explore whether the geochemical technique can be extended beyond the trace elements to include the major elements as well.

PROCEDURE

Sand samples were collected during several field trips to the study area between 1990 and 1995 (Zimbelman and Williams, 1997). In many cases, Global Positioning System (GPS) coordinates were obtained at the site during sample collection; specific location information for individual samples is available.[1] Samples were collected to represent eolian sand paths in the eastern Mojave Desert of California, the dunes near Parker, Arizona, and remobilized fluvial sands from the Colorado River (Fig. 1, Table 1). Samples 1–19 are from eolian sands along 150 km of the Bristol Trough sand path. Samples 20–35 are from eolian sands along 125 km of the Clark's Pass sand path. Samples 36–41 are from dunes on the Cactus Plain and La Posa Plain near Parker, in western Arizona. Samples 42–54 are from deposits along the Colorado River from near Lake Havasu City, Arizona, in the north to near Blythe, California, in the south. Most samples are from active or stabilized dunes, but where dunes were absent, samples were obtained from eolian sand sheets (1, 2, 18, 19, 20, 26, 29, 32, 35, 42, 48), beaches (43, 52), and cutoff-meander deposits of the Colorado River (47, 53). Sample 55 (not shown in Fig. 1) comes from the center of the Algodones Dunes, located southeast of the Salton Sea and ~85 km due south of Palen Playa, at a pullout for off-road access from California Highway 78. This sample was included here because the Algodones Dunes were the focus of detailed study by Muhs et al. (1995), which concluded that the Algodones eolian sands were closely related to Colorado River sands.

Selected samples of rock and coarse alluvium from mountains around the Palen Playa were included to assess possible local contributions to the sand (see entries under "Other" in Table 1). Sample CM is coarse sand and gravel from the bed of a stream in the eastern part of the Chuckwalla Mountains that empties directly into the basin containing the Palen Playa and its surrounding sands. Sample CM2 is a granodiorite from the Chuckwalla Mountains adjacent to the stream at the CM location. Sample CX is grus (sieved particles > 1.4 mm) from the Coxcomb Mountains at the site of sample 29. Finally, sample MS is from an active dune in Monahans Sandhills State Park west of Midland, Texas, a large sand accumulation of nearly pure quartz resulting from eolian transport across the Southern High Plains east of the Rocky Mountains. This sample illustrates the end member of the mechanical and chemical degradation associated with reworking during extensive eolian transport of sand.

All samples, ranging in mass from 60 to 140 g, were submitted to Bondar Clegg, Inchcape Testing Services, for chemical analysis. Each sample was pulverized to pass through 200 mesh (<80 μm) to facilitate mixing during fusion to form a glass sample for analysis. X-ray fluorescence (XRF) spectrometry was performed on 47 samples to obtain whole-rock (i.e., bulk sample) major oxide abundances; results for the most abundant oxides (generally >1 wt%, which excluded TiO_2, MnO, MgO, and P_2O_5) are listed in Table 1. Eight samples (11, 20, 26, 28, 33, 40, 44, 50) had their major oxides determined by inductively coupled plasma (ICP) because this procedure is complementary to the instrumental neutron activation analysis (INAA) technique used to obtain trace element abundances for these samples (Table 2). Bondar Clegg reported a measurement precision of 0.01% for each oxide, and INAA results reproducible to <1%. We submitted one sample three separate times to assess variability in XRF results due to possible inconsistencies resulting from physical mixing and the fusion process; all oxides reproduced <0.1 wt% for multiple analyses except SiO_2, where the observed repeatability was ≤0.9 wt%.

Two samples (4 and 37), from the two sediment groups indicated by the geochemistry (see the next section), were analyzed with X-

TABLE 1. PRINCIPAL MAJOR OXIDE RESULTS

Sample*	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O
Bristol Trough sand path						
1	66.9	15.6	2.5	3.2	3.8	3.2
2	69.5	13.4	3.4	3.2	3.4	2.9
3	69.2	14.8	2.1	3.4	4.2	3.2
4	71.5	14.2	1.6	2.4	3.5	3.5
5	69.8	14.3	3.0	3.4	4.0	2.7
6	73.9	10.6	2.3	3.4	2.7	2.8
7	74.8	13.2	1.5	1.9	3.9	3.2
8	71.8	14.3	2.0	2.8	4.0	3.0
9	70.4	14.1	2.0	3.4	4.0	3.1
10	73.1	13.1	2.5	2.4	3.3	3.2
11	70.7	16.4	0.8	2.5	4.9	2.7
12	74.1	13.1	1.6	2.3	3.4	3.3
13	74.7	12.1	2.1	2.0	3.1	3.3
14	78.5	11.3	1.1	1.5	2.6	3.5
15	73.1	13.0	3.2	2.7	3.1	2.9
16	72.9	13.7	2.0	2.5	3.5	3.0
17	74.6	13.3	1.6	2.2	3.3	3.0
18	73.4	12.6	2.6	2.5	3.1	3.0
19	74.8	12.7	2.0	2.0	3.3	3.2
Clark's Pass sand path						
20	68.4	15.7	2.6	3.2	4.0	2.8
21	70.7	14.5	2.6	2.8	4.0	2.9
22	74.3	12.9	1.7	2.1	3.5	3.4
23	77.8	10.8	1.9	1.5	2.4	3.6
24	78.8	10.2	1.5	1.2	2.3	3.7
25	75.4	12.5	1.8	1.9	3.2	3.4
26	72.6	13.6	1.6	2.1	3.3	3.5
27	71.4	13.5	2.9	2.4	3.5	3.1
28	75.8	11.9	1.6	1.9	2.8	3.5
29	73.9	13.6	1.5	2.3	3.8	3.0
30	71.4	13.2	3.7	2.7	3.6	3.0
31	70.9	13.1	3.2	2.7	3.3	3.1
32	73.0	12.7	2.2	2.6	3.1	3.1
33	75.9	10.4	2.3	3.0	1.9	3.0
34	73.4	11.5	3.0	2.8	2.8	2.7
35	76.0	11.0	2.3	2.2	2.7	3.2
Dunes near Parker, Arizona						
36	85.1	5.2	1.2	1.7	1.0	1.8
37	88.0	4.5	1.4	0.9	0.8	1.6
38	88.1	4.5	1.8	0.6	0.8	1.7
39	87.2	4.9	1.8	1.0	2.0	1.7
40	89.3	4.4	1.3	0.7	0.7	1.6
41	89.1	4.2	1.4	0.5	0.8	1.5
Colorado River						
42	86.3	5.0	1.2	1.5	1.0	1.8
43	84.3	4.9	1.2	2.0	0.9	1.7
44	89.2	4.7	0.7	0.7	0.8	2.0
45	84.7	3.8	1.3	2.6	0.8	1.3
46	86.0	4.0	1.1	2.4	0.6	1.5
47	64.9	8.2	2.5	6.3	1.2	2.1
48	83.6	5.7	1.5	2.3	1.2	1.8
49	85.9	3.6	1.5	2.4	0.6	1.3
50	86.5	3.8	1.2	2.4	0.5	1.5
51	81.0	5.7	1.6	3.0	1.0	2.0
52	86.2	3.5	1.6	1.9	0.6	1.3
53	71.3	7.4	2.2	5.0	1.0	2.1
54	85.1	4.4	1.1	2.3	0.7	1.6
Algodones Dunes						
55	85.5	5.1	0.9	1.7	1.0	1.6
Other						
CM	74.0	12.7	2.0	2.1	2.9	4.0
CM2	66.3	15.6	4.6	3.7	3.5	3.3
CX	68.6	16.7	1.8	2.7	4.8	3.9
MS	97.6	0.7	0.3	0.0	0.0	0.2

Note: All measurements are in wt%.

*Sample numbers are keyed to locations in Figure 1, except that 55 is from the middle of the Algodones Dunes, east of the Salton Sea, off the bottom of Figure 1. See text (Procedures section) for descriptions of the lettered samples.

TABLE 2. TRACE ELEMENT ABUNDANCES

Sample	Rb	Sr	Y	Zr	Nb	Ba	La	Ce	Sc	Sm
Bristol Trough sand path										
11	74	541	14	75	2	898	13	24	1.6	1.8
Clark's Pass sand path										
20	96	440	27	148	9	708	34	69	6.9	5.1
26	96	383	21	130	5	972	25	49	3.9	3.6
28	98	331	23	132	6	939	27	54	4.3	4.0
33	115	206	34	200	15	657	42	91	6.2	6.1
Dunes near Parker, Arizona										
40	51	118	14	135	5	542	15	29	2.2	1.9
Colorado River										
44	61	107	14	75	2	655	11	21	1.2	1.5
50	44	104	15	233	3	527	13	26	2.2	2.1

Note: All measurements in ppm.

[1]GSA Data Repository item 2002050, Geographical location information, keyed to the sample numbers, is available on the Web at http://www.geosociety.org/pubs/ft2002.htm. Requests may also be sent to editing@geosociety.org.

ray diffraction (XRD) by J. Post at the National Museum of Natural History. Using the Rietveld full-pattern-fitting method (Bish and Post, 1993) allowed a quantitative mineral assessment to be obtained; such assessments are reproducible to $\leq$3% by the pattern-fitting method.

RESULTS

The major oxide results reveal clear distinctions between sediments from various regions (Table 1). SiO_2 abundances divide the samples into two major groups: Samples 1–35 (the Bristol Trough and Clark's Pass sand paths) have $SiO_2 < 79$ wt%, whereas samples 36–55 (the dunes near Parker, the Colorado River sands, and the Algodones Dunes) have $SiO_2 > 81$ wt%. The only exceptions to this SiO_2 subdivision are samples 47 and 53, both of which come from cutoff-meander deposits by the Colorado River (discussed in the next section). SiO_2 content increases to the east (toward the Colorado River) along both of the two sand paths; Figure 2 illustrates this trend for the Bristol Trough path. Peaks in SiO_2 abundance along the path correspond to dunes ramped against the western (windward) slopes of mountains (e.g., by the Arica Hills in Fig. 2), which may represent localized extensive reworking of the sand relative to other stabilized dunes along the path. The eastward-increasing SiO_2 content along both sand paths is consistent with increased destruction of feldspar during transport. In contrast, the Colorado River and Arizona sands show no apparent trend in SiO_2 content. The SiO_2 content of the Colorado River materials is still well below the nearly pure SiO_2 (> 97 wt%) present in eolian sands from the Monahans dunes (sample MS in Table 1). Such nearly pure quartz sands may represent multigeneration sands derived from erosion of sandstone sources, especially those grains that are well rounded, and intense chemical weathering in place is unlikely (Siever, 1988, p. 34). Alternatively, quartz-rich eolian sands can be attributed to ballistic impact destruction of feldspars over an extended period of time (Muhs et al., 1997).

The two cutoff-meander samples consist of very fine sand to silt, in contrast to the medium sand that dominates all other samples. The reduced SiO_2 content (relative to the Colorado River sands) of the fine fraction from the meander samples may indicate that some of the small weathered feldspar products removed from the coarse size fractions during transport down river may be enhanced in the fine fraction deposited in the low-energy environment within river meanders. Alternatively, the meander deposits may simply contain less quartz, because their major element chemical content is generally consistent with that of the Colorado River sands, except for their relatively low SiO_2 abundance.

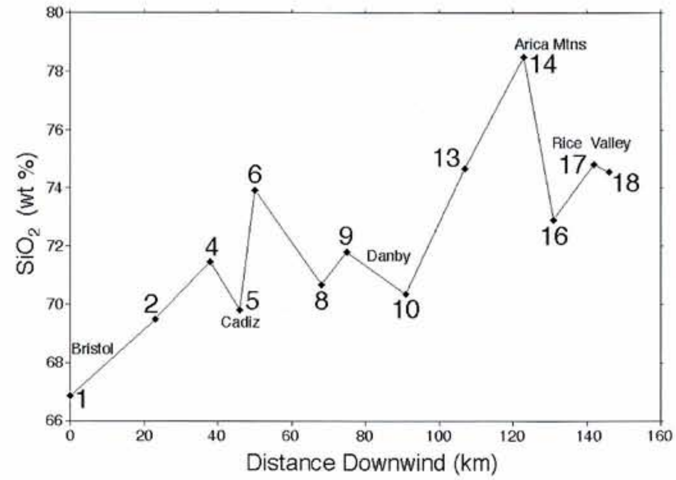

Figure 2. SiO_2 vs. distance downwind, along the Bristol Trough sand path. Distance is measured relative to the location of sample 1, east of the Bristol Playa (Fig. 1). The approximate locations of playas and mountains along the path are indicated by label position. Points correspond to indicated sample numbers.

The division evident in the SiO_2 content is also reflected in variations of the Al_2O_3 abundance: Distinct fields result for the Mojave and Colorado-Parker sands in a plot of SiO_2 versus Al_2O_3, as well as for the cutoff-meander deposits (Fig. 3). The higher abundance of Al_2O_3 in the Mojave samples (>10 wt%) probably reflects an increased relative abundance of feldspars in these samples, indicating that they are less mature than the sands transported down the Colorado River. The Fe_2O_3 and CaO contents do not show clear group separations like that shown by the Al_2O_3 contents, but total alkali-metal oxides ($Na_2O + K_2O$) show fields very similar to those of Al_2O_3 (compare Figs. 3 and 4), consistent with the trace element interpretation discussed in the next section. The differences in major oxide chemistry of material transported down the Colorado River compared to that derived from mountains in southern California parallel the differences between the

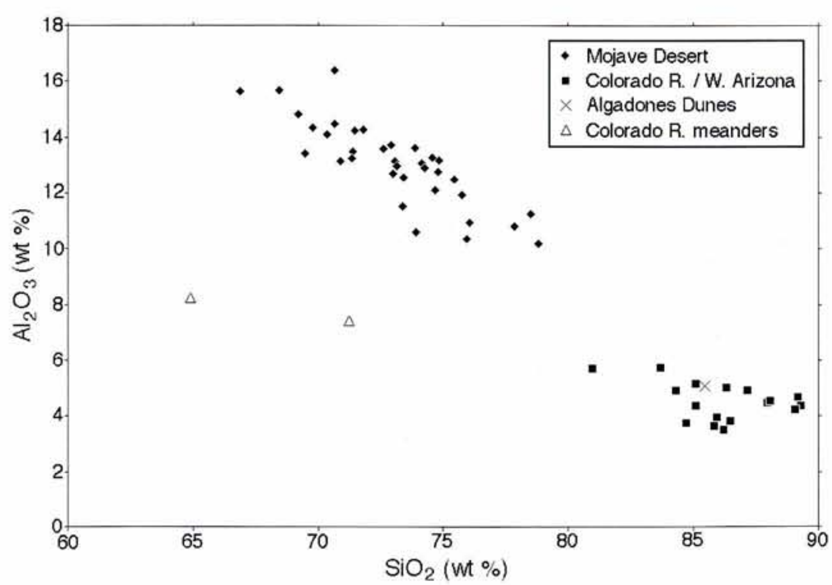

Figure 3. Plot of SiO_2 (wt%) vs. Al_2O_3 (wt%) for 55 sand samples. The samples fall into distinct fields corresponding to locations identified in the inset box.

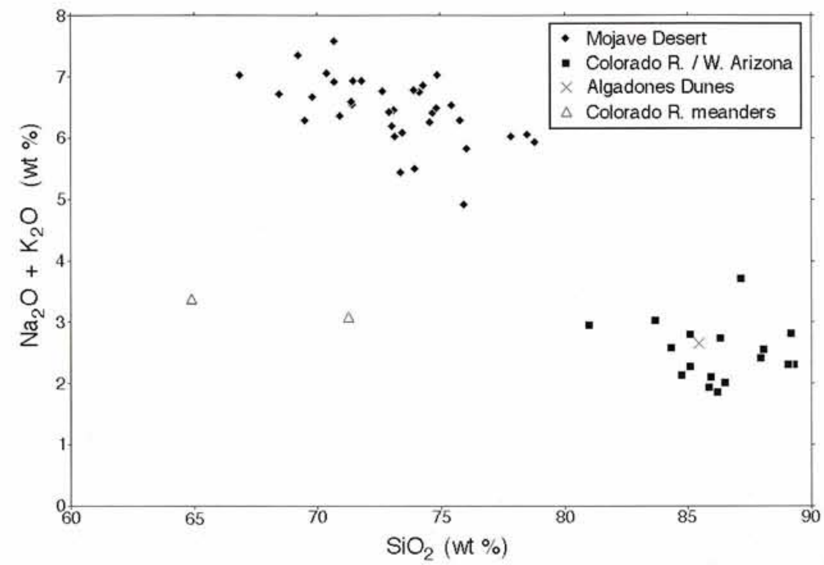

Figure 4. Plot of SiO_2 (wt%) vs. total alkali metal oxides ($Na_2O + K_2O$; wt%) for 55 sand samples. The samples fall into distinct fields corresponding to locations identified in the inset box.

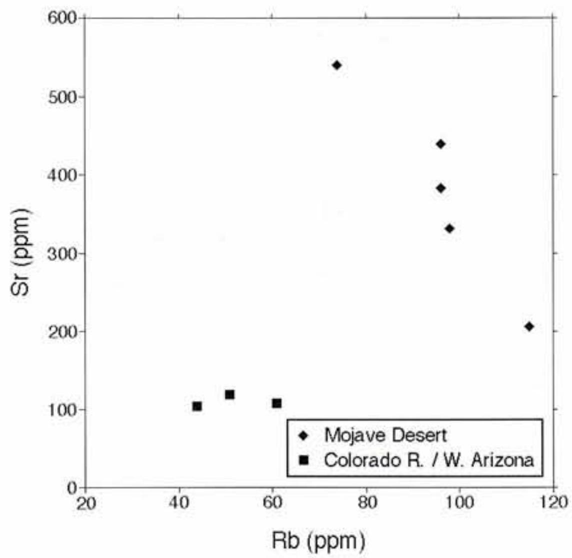

Figure 5. Plot of rubidium vs. strontium content for eight samples for which trace element abundances were determined (see Table 2). The samples fall into the same two major sediment groups shown in Figures 3 and 4. The locations of the two groups in this plot correspond to fields published previously in Rb vs. Sr plots for samples from the southern Mojave Desert and the Algodones Dunes–Colorado River (Muhs et al., 1995, their Fig. 14).

chemical groups recognized through trace element analysis in the Algodones Dunes region (Muhs et al., 1995), south of our study area. Our trace element results (Table 2), although few in number, reveal distinct separations between the two major eolian sand types already discussed (Fig. 5). Our Sr and Rb values fall within the same general fields identified in the comparison between the Algodones Dunes and San Bernardino Mountains alluvium (Muhs et al., 1995, their Fig. 14). Other trace element values show similar separations between the two sediment groups, again consistent with results reported by Muhs et al. (1995). Sample 55, from the Algodones Dunes, has major oxide abundances very consistent with those of our samples from the Colorado River and Parker areas (X in Figs. 3 and 4). Muhs et al. (1995, their Fig. 16) showed that the Algodones Dunes are indistinguishable from lower Colorado River sediments; our results now extend the recognition of this distinct sediment group farther upstream within the Colorado River, to near the Nevada border.

The geochemical results indicate two principal compositional groups (excluding the small cutoff-meander field), which led us to examine the minerals constituting the two sediment groups. Published ternary diagrams of quartz–plagioclase–K-feldspar abundances show clear separation between the quartz-rich Algodones Dunes and the plagioclase-rich San Bernardino Mountains alluvium (Muhs et al., 1995, their Fig. 9a) and coincidence between the Algodones Dunes and Colorado River sediments (Muhs et al., 1995, their Fig. 8a). Our XRD analyses confirm the distinct mineralogical differences between the two sediment groups. A sample (37) from the Parker dunes has 68% quartz, 18% microcline, and 14% low-Ca, whereas (4), a sample from the Cadiz Dunes, has 29% quartz, 28% microcline, and 43% low-Ca albite. Not only is the quartz abundance drastically different in the two groups, but also the proportions of microcline and albite in the Parker sand (relative to their abundances in the Cadiz sand) are consistent with the greater resistance to weathering of microcline because of its relatively highly ordered crystal structure and consequent increased stability at low temperatures (Blatt et al., 1972, p. 304). Both samples may have $<3\%$ amphibole, pyroxene, and mica combined, but these low abundances are below the detection limit of the XRD analysis technique (Bish and Post, 1993). The XRD results are consistent with the generally accepted use of the quartz/feldspar ratio in sediments as an index of chemical to mechanical weathering (Siever, 1988, p. 29). The Mojave sands are interpreted to be relatively immature and not far from their sources, whereas the Colorado River sands are relatively mature owing to weathering during transport down river and/or owing to derivation from quartz-rich sedimentary rocks.

Geochemical results for samples from the mountains around the Palen dry lake strengthen the inference that the Mojave sand path results (samples 1–35) reflect mineralogically immature sands. Dunes on the southern margin of the Palen Playa (sample 31) have chemical compositions that are generally intermediate between those of stream sand and alluvium (sample CM) and granodiorite bedrock (sample CM2) from the Chuckwalla Mountains (located near the bottom of Fig. 1), 15 km upslope from the dunes south of Palen Playa dunes. The stream sample probably includes some contribution from rock types upstream that are quite different from the granodiorite outcrops at the margin of the Palen basin. Grus sieved from detritus of the Coxcomb Mountains (sample CX), west of the Palen Playa (Fig. 1), is distinct chemically from sand collected at the same location (sample 29), but these two samples show general trends similar to those between the Palen sand and the Chuckwalla granodiorite. We interpret these results to indicate that the Mojave sands have general affinities with the local bedrock. Moreover, these sands are relatively immature when compared to the sands from the Colorado River and western Arizona.

DISCUSSION

The geochemical results indicate that the Colorado River dominates the sediment supply along and immediately around the river, both in the past and at present. In contrast to this, the eolian sand pathways in the eastern Mojave Desert cross drainage divides between adjacent basins, but this transport occurs where no throughgoing river has been active in the recent past. The close proximity of the terminus of the Bristol Trough sand pathway at the Colorado River to sand-rich river meander deposits, as well as the Parker dunes, led to the hypothesis that river meander loops might allow discrete batches of Mojave sand to traverse the river (Zimbelman et al., 1995). The hypothesis is shown here to be unlikely for the dunes near Parker, Arizona. It is interesting that our conclusion is in agreement with a completely independent test of the hypothesis by mineralogical and chemical investigations carried out by another research group (Muhs et al., 2000). We now conclude that the Arizona dunes are likely related, directly or indirectly, to fluvial sediments derived from the Colorado River.

Our results also suggest that it will be difficult to use major oxide chemical composition alone to identify specific bedrock sources for sands, even if the sands are relatively immature. There is considerable evidence that zircon U-Pb ages and quartz oxygen isotope analyses (e.g., Pell et al., 1997, 1999, 2000) as well as Pb isotope studies (e.g., Aleinikoff et al., 1999) can identify specific sources for some sand or loess grains. However, here we were investigating the capabilities of bulk-sample chemical analyses as a discriminating tool. Our results show evidence of resolving large variations associated with maturity factors such as the quartz/feldspar ratio for bulk samples, but this capability likely will not extend to small samples ($<<50$ g) or individual grains. The sands in the Palen basin have affinities to the samples from the Chuckwalla and Coxcomb Mountains, but there is no clear indicator of the specific local source from our data. The chemical studies discussed here will be most applicable to situations where the potential sources and maturities of the sands in question are sufficiently distinct that mineral differences are reflected in the bulk chemistry of a composite of many thousands of grains. As a sand supply weathers and easily weathered minerals are lost, illustrated by the Colorado River and Parker area sands, the bulk sand will tend toward pure quartz like that of the Monahans Sandhills (sample MS). Individual grains of distinctive minerals (like zircon or garnet) can provide valuable information about sources, but the sands in our study are sufficiently heterogeneous to make it difficult to characterize their unique source areas from single grains without use of the isotopic studies cited previously.

The quartz/feldspar ratio in a large sand sheet or dune field may be detected by remote-sensing techniques. Quartz and the plagioclase solid-solution series of feldspar minerals have distinct adsorption features in the thermal infrared band (Hunt, 1980). Sensors on aircraft or spacecraft detect signatures averaged over the surface area of an individual detector element, a homogenization process that may be analogous to the effect of obtaining chemical properties from a fused glass bead composed of many thousands of individual grains. Sensor precision has improved so that the cumulative spectral information may allow a quantitative deconvolution of certain mineral abundances, analogous to the Rietveld full-pattern-fitting method applied to XRD patterns (Bish and Post, 1993). For example, the Thermal Emission Spectrometer (TES) on the *Mars Global Surveyor* spacecraft can identify mineral abundances to about the 10% level through a spectral matching algorithm based on a reference library of thermal-emission spectra (Bandfield et al., 1999, 2000). Quartz has yet to be identified definitively anywhere on Mars (Christensen et al., 2000), so the sands on Mars likely will not reveal a remotely determined quartz/feldspar ratio. However, there is no reason why the quartz/feldspar ratio may not eventually be measured remotely over Earth with instruments of sufficient spectral and spatial resolution. The geochemical results presented here suggest that a thermal-infrared hyperspectral sensor may have considerable utility for investigations of eolian sand deposits in arid regions of the world.

CONCLUSIONS

Bulk-sample major oxide abundances (primarily SiO_2, Al_2O_3, and $Na_2O + K_2O$) of 55 eolian sand samples indicate distinct differences between sands from the eastern Mojave Desert and those from the Colorado River and western Arizona. The close chemical affinity between the Colorado River sands and the dunes near Parker indicates that the eolian dunes in western Arizona are derived from river sediments. The major oxide results are consistent with a more limited number of trace element results, which in turn are consistent with previously published results demonstrating a similar source (Colorado River sediments) for the Algodones dunes (Muhs et al., 1995). X-ray diffraction results for samples from each sediment group demonstrate that the chemical differences are a result of low quartz/feldspar ratios in the immature eolian sands of the Mojave Desert, as compared to high quartz/feldspar ratios in sands from both the Colorado River and the eolian dunes near Parker, Arizona.

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