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Properties of modern dust accumulating in the Uinta Mountains, Utah, USA, and implications for the regional dust system of the Rocky Mountains

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ABSTRACT: A growing body of work is illuminating the importance of dust as a component of soil development and biogeochemical cycling in alpine environments of the Rocky Mountains. Nonetheless, important questions remain about the dust system in this region due to a paucity of focused studies and direct measurements. This project involved deployment of modified marble dust traps in the alpine zone of the Uinta Mountains of Utah to trap modern atmospheric dust over a two year period. Results indicate that dust accumulation rates are similar to values previously reported for the Wind River Range of Wyoming, but less than values for southwestern Colorado, suggesting a south-to-north decrease in regional dust flux. The overall mean grain size of Uinta dust is similar to values reported by prior studies in Colorado, indicating a general uniformity in grain size distribution. Uinta dust is dominated by quartz, plagioclase, K-feldspar, and illite with trace amounts of kaolinite, chlorite, and amphibole. In contrast, only quartz and K-feldspar are present in the Uinta bedrock, confirming an exotic origin for the dust arriving in the alpine zone. Exotic mineralogies have also been reported in dust from other mountain ranges in the western United States, indicating that eolian delivery of allochthonous minerals is a widespread process. Geochemical analysis reveals that Bi, Na, P, Zn, Sn, Cu, Cd, Ba, Ni, W, Sb, Pb, and Tl in Uinta dust are elevated 10 to $>$ 80-times above their abundances in local bedrock. These results support reports of anthropogenic elemental enrichment in lake sediments from Colorado and Utah. Patterns of elemental loading suggest that certain elements are delivered by winds arriving from different directions, raising the possibility that some elements could be associated with unique source areas. Copyright © 2014 John Wiley & Sons, Ltd.

KEYWORDS: dust; alpine zone; geochemistry; mineralogy; Rocky Mountains

Introduction

Although the influence of atmospheric dust deposition on soil development has long been recognized in desert (e.g. Yaalon and Ganor, 1973; Reheis *et al.*, 1995; Reheis, 1999) and tropical environments (e.g. Dymond *et al.*, 1974; Kurtz *et al.*, 2001; Dia *et al.*, 2006), a growing body of work is illuminating the importance of dust as a component of soil development and biogeochemical cycling in alpine settings. Dust is generated in lowlands through a variety of natural and human-induced processes including off-road vehicle use, road construction, fossil fuel extraction, mining, and farming (e.g. Painter *et al.*, 2007; Neff *et al.*, 2008). Once delivered to high mountain environments by the wind, dust induces a multitude of effects including altering the pH and chemistry of surface water (e.g. Psenner, 1999), contributing to soil formation (e.g. Dahms, 1993; Lawrence *et al.*, 2011), and decreasing the albedo of snow, causing earlier snowpack meltout (e.g. Painter *et al.*, 2007; Painter *et al.*, 2010). In the Rocky Mountains of the western United States, several studies have documented pedologic and stratigraphic evidence for past dust deposition (e.g. Thorn and Darmody, 1980; Birkeland *et al.*, 1987; Litaor, 1987). A few have attempted to quantify rates of contemporary dust accumulation (e.g. Dahms and Rawlins, 1996; Lawrence *et al.*, 2010), and to identify possible dust source regions (e.g. Muhs and Benedict, 2006). Recent study of lake sediment records also suggests that rates of dust deposition (Neff *et al.*, 2008) and the geochemical composition of dust (Reynolds *et al.*, 2010) have changed in the past few centuries, linking human land use in lowland basins with dust deposition in the mountains.

Despite these observations, much uncertainty remains regarding past and modern dust deposition at high elevations in the Rocky Mountains. For instance, few measurements of modern dust deposition have been made, making it difficult to gauge regional variability in dust deposition rates. Similarly, only a small number of studies have successfully captured and analyzed samples of modern dust, meaning that little is known about the degree to which the grain size distribution and other properties of modern dust vary spatially. Furthermore, in most places where contemporary dust deposition has been documented, the geochemistry and mineralogy of dust have not been investigated, leading to uncertainty regarding dust source areas. Finally, only a few studies have investigated how human activities upwind may be influencing the properties of modern eolian sediment (e.g. Neff *et al.*, 2008; Reynolds *et al.*, 2010).

Given the growing evidence that dust deposition plays an important role in the geoecology of alpine systems, these questions are worthy of study and could generate results with implications for management of mountain ecosystems as well as the surrounding basins.

This study contributes to answering these questions by focusing on a representative sub-range of the Rocky Mountain system, the Uinta Mountains of north-eastern Utah (Figure 1). Prior work has documented that the Uinta Mountains (hereafter, the 'Uintas') exhibit a number of characteristics that make them an appropriate location in which to study contemporary dust deposition. Field study of alpine soils in the Uintas has documented a ubiquitous cap of fine sediment that has traditionally been interpreted as loess (Bockheim and Koerner, 1997; Bockheim *et al.*, 2000; Munroe, 2007b). Landscape positions with a thicker loess cap are typically mantled by forbs known to be active base cyclers, such as *Acomastylis rossii*, and tissue samples from these plants are significantly enriched in Ca (Bockheim *et al.*, 2000) suggesting that dust deposition has increased soil fertility and exerted a control on the distribution of plant species. Other studies have noted the circumneutral pH of Uinta surface waters, despite the acidity of precipitation and the apparent lack of an abundant buffering agent in Uinta bedrock (Christensen and Jewell, 1998), raising the possibility that dust deposition is playing a role in buffering surface water. More recent work has documented the presence of abundant ultra-fine (submicron size) material in lake sediment cores (Munroe *et al.*, 2009). This sediment, which has accumulated at varying rates over time, has a geochemical signature distinct from that of the rocks surrounding the studied lakes, suggesting that it was derived from outside the lake watersheds. Similarly, study of the magnetic properties and geochemistry of lake sediments deposited during the past few centuries has identified increases in heavy metal deposition attributed to upwind industrial activity (Reynolds *et al.*, 2010).

Despite the success of these studies, rates of modern dust deposition, and the properties and possible sources of dust in the Uintas, remain poorly understood. Focused study of the modern dust system in the Uintas, therefore, would provide the opportunity to address questions germane to this specific mountain range while simultaneously enhancing understanding of the regional dust system in the western United States.

This paper presents results from a two year study focused on contemporary dust deposition in the Uintas designed to quantify modern dust deposition rates; measure the grain size distribution of modern dust; evaluate the geochemical and mineralogical properties of modern dust; and investigate the spatial distribution of elemental loading in the alpine zone. Specially designed passive collectors were deployed at four locations to trap dust in the alpine zone. Results are considered in light of their implications for the Uintas as a specific locality, as well as for the dust system in the Rocky Mountain region.

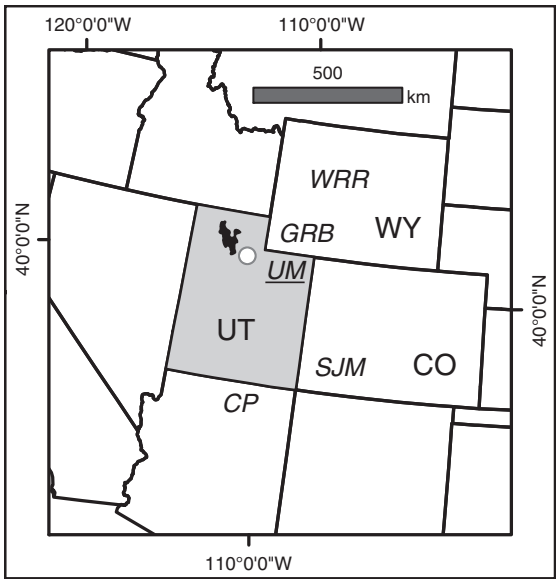

Figure 1. Location map for the study area. The state of Utah is highlighted in gray, with the Great Salt Lake (black) and location of Salt Lake City (white circle) shown for reference. UT: Utah, CO: Colorado, WY: Wyoming, UM: Uinta Mountains, SJM: San Juan Mountains, WRR: Wind River Range, GRB: Green River Basin, CP: Colorado Plateau.

Setting

The Uinta Mountains are a major range of the Rocky Mountain system located in north-eastern Utah. They extend ~200 km along an east–west axis parallel to the Utah–Wyoming border (Figure 1). The range is cored by a doubly-plunging anticline of Precambrian quartzite and shale that was uplifted during the Laramide Orogeny and extensively modified by alpine-style glaciation during the Quaternary Period (Sears *et al.*, 1982; Bradley, 1995; Dehler *et al.*, 2007; Munroe and Laabs, 2009). The Uintas contain the highest mountains in the state of Utah, culminating with Kings Peak at 4123 m above sea level (a.s.l.). Alpine treeline in the Uintas is at an elevation of ~3000 m, and several hundred square kilometers of the range are mantled by alpine tundra and peri-glacial deposits. Mapping of glacial landforms indicates that the Uintas contained over 2000 km^2 of active glacial ice during the Last Glacial maximum, *c.* 20 000 years ago (Munroe and Laabs, 2009). No glaciers remain in the Uintas today, and basal dates from lake sediment cores indicate that the range was essentially ice free by the beginning of the Holocene (Munroe, 2002).

Methods

Dust collector design

The collectors designed for this project are passive traps intended to collect dust suspended in the air (dry deposition) as well as aerosols forming the nuclei for raindrops and snowflakes (wet deposition). Simple passive collectors incorporating glass marbles have long been used to collect dust in arid environments (e.g. Reheis and Kihl, 1995; Wesely and Hicks, 2000; Sow *et al.*, 2006); however, the challenge in adapting these designs for the Uintas is the need to deal with large amounts of precipitation that could cause overflow, leading to loss of sediment. The collectors feature a clear polycarbonate tray measuring 56 cm × 56 cm by 7.5 cm deep (Figure 2). Each tray is divided into five 'V-shaped' troughs, each of which is filled with ~400, 1.75-cm diameter glass marbles (~7 kg per collector). The marbles form a rough surface that traps dust from the air, protects previously deposited dust from re-entrainment, and reduces the possibility of dust splashing out during precipitation events. The troughs inevitably collect water as well as dust, but the dark colored marbles allow for solar heating to evaporate water between precipitation events. If the troughs completely fill, a row of small (3 mm) holes near the top of each trough allows water to trickle out. Ideally dust trapped by the marbles settles to the base of each trough where it remains as water evaporates or overflows.

Emptying a collector involves removing the marbles from each trough and washing them through a sieve into an acid-washed bottle with distilled water (1 l per trough). After the

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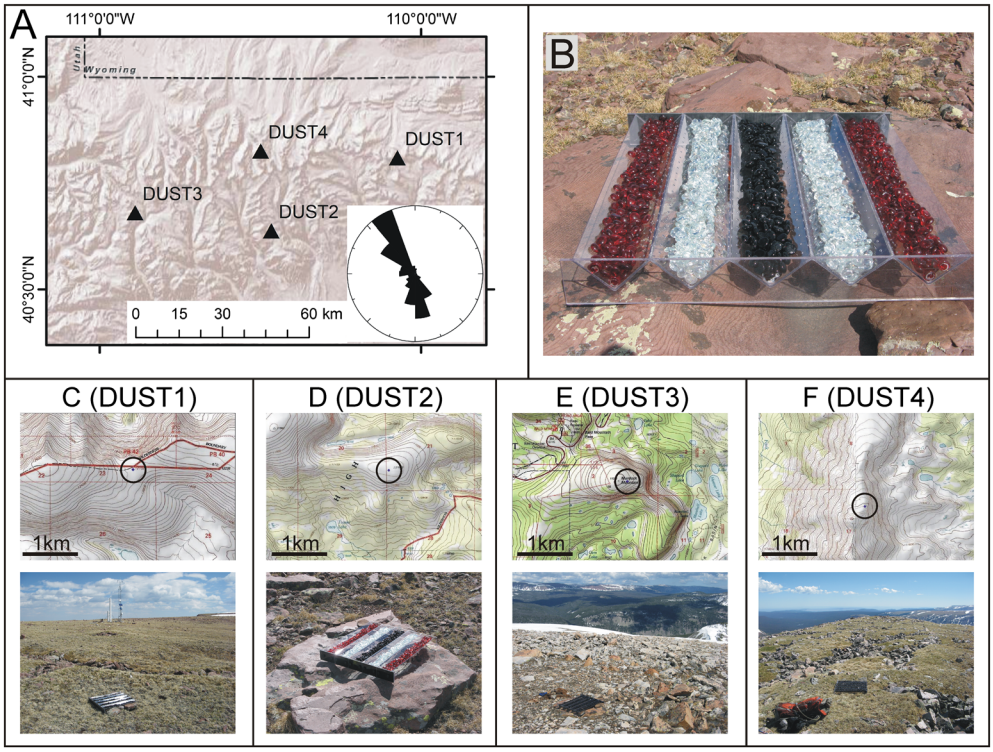

Figure 2. (A) Locations of dust collectors in the Uinta Mountains. Inset shows the wind rose for the Chepeta RAWS at the site of DUST1. (B) Close-up view of collector DUST2 showing the 'V-shaped' cross-section of the five, bead-filled troughs that trap dust from the air. This detector was originally deployed with a mixture of bead colors to test evaporation potential; all beads in the other collectors are black. (C–F) Topographic maps and landscape photographs of the four dust collectors. In (C) the Chepeta RAWS is visible in the background. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

marbles have been removed, the collector is tilted toward one end where a gasketed cap is removed. Remaining dust is then washed with distilled water directly from the trough into a bottle for transport.

Study design

The dust collectors utilized in this project were deployed at four locations, selected to represent the east–west, as well as north–south, extent of the Uintas (Figure 2A). All of the collectors were located above treeline, at elevations > 3400 m a.s.l., in order to capture dust in the alpine zone (Table I). Collectors were intentionally positioned near other study sites of potential use for placing the dust results in context, including an existing remote automated weather station (the Chepeta RAWS), and lakes that were cored for previous projects (e.g. Munroe, 2007a). Collectors were placed in areas of flat to gently sloping topography, distant from cliffs or steep slopes that might perturb the local windfield. Because two collectors were deployed within the federally designated High Uintas Wilderness Area, it was not possible to install them on elevated structures such as poles or towers. Thus all collectors were placed on the ground or were elevated slightly (<20 cm) on rocks. This invariably made them vulnerable to locally-derived saltating sediment, however this compromise was necessary in order to position the collectors in the desired locations.

Collector 1 (hereafter, 'DUST1'), representing the eastern Uintas, was deployed immediately southwest of the Chepeta RAWS in a col along the Uinta ridgecrest (Figure 2C). The collector was located in the center of a peri-glacial stone polygon directly on the ground in an area of nearly continuous vegetation cover. A sample of surface pebbles was collected to represent the local bedrock.

Collector 2 (DUST2), representing the southern Uintas, was deployed on a convex ridge crest west of the Yellowstone River (Figure 2D). This collector was originally deployed with a mixture of bead colors to test evaporation potential (Figure 2B); it was converted to all black marbles in the second year. Ground cover is less continuous at this location, so the collector was positioned on a rock ~20 cm above the ground surface to reduce the possibility of collecting locally derived sediment. Large-diameter (~10 m) stone polygons are well-developed in the vicinity of the collector. Pebbles were gathered from the soil surface to represent local bedrock.

Collector 3 (DUST3), representing the western Uintas, was deployed just to the east of the summit of Murdock Mountain (Figure 2E). Vegetation cover is similar to the DUST2 site, so

Table I. Locations of dust collectors

Site	Sector	Easting[a] (m)	Northing[a] (m)	Elevation (m)	Vegetation cover (%)	Loess thickness (cm)	Position	Peri-glacial features
DUST1	East	578150	4518076	3692	100	30	On ground	10-m stone polygons
DUST2	South	545145	4498699	3413	75	15	Elevated 20 cm on rock	10-m stone polygons
DUST3	West	509330	4503295	3401	75	15	Elevated 20 cm on rock	8-m stone polygons
DUST4	North	542274	4519596	3782	100	15	On ground	2-m stone polygons

[a]Zone 12, WGS-84.

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the collector was located on a rock to elevate it slightly above the surrounding surface. Murdock Mountain is a popular destination for hikers, so the collector was positioned away from the actual summit where it was less likely to be disturbed. Large-diameter (~8 m) stone polygons dominate this location. Pebbles were collected to represent the local bedrock.

Collector 4 (DUST4), representing the northern Uintas, was deployed approximately 5 km south of Bald Mountain on the ridge between the East Fork Smiths Fork and the Little East Fork Blacks Fork (Figure 2F). Although the northern part of this ridge is subject to grazing, sheep rarely range this far south (Larry St Clair, Brigham Young University, personal communication). The vegetation cover in this location is continuous. Small diameter (<5 m) stone polygons are well-developed. Pebbles were collected from the soil surface, and a sample was also taken from the center of an active frost boil where deeper sediment is cryoturbating upward.

The four collectors were deployed in June 2011. They were emptied in October 2011, June 2012, and June 2013.

Laboratory methods

Emptying each collector generated five, 1 l bottles containing a mixture of dust and distilled water. These were shipped and stored upright until analysis less than one month later. In the laboratory, bottles were opened and sediment was concentrated through centrifuging and decanting. After the sediment from the five bottles representing an individual collector was concentrated into a single acid-washed 50-ml centrifuge tube, 20 ml of 35% hydrogen peroxide was added and allowed to react for several days to remove organic matter.

Once the reaction was complete, samples were stirred and sonified and the grain size distribution of the sediment was determined with a Horiba LA-950 grain size analyzer. This instrument has an effective range of 50 nm to 3 mm, and a refractive index of 1.54 with an imaginary component of 0.1i was used for calculation of the grain size distribution. Samples were washed through a 63-μm sieve with distilled water before grain size analysis. Because samples were discharged to a drain after each run, some sediment was consumed by the grain size analysis process. However, the mass of sample required by the instrument represents ~1% of the total sample mass.

After grain size analysis, an eyedropper was used to remove a small amount of each sample to make an oriented slide for X-ray diffraction (XRD) analysis. These oriented slides of dust samples, as well as random powders of crushed (<75 μm) rock samples from each study site, were analyzed with a Bruker D-8 XRD instrument, scanning from 2° to 40°, with a step of 0.05° and a step time of one second. Resulting XRD patterns were analyzed with Eva software.

Remaining sediment was dried for 48 hours at 60 °C in previously tarred containers to determine sample mass. These masses were converted to sedimentary fluxes (in g/m^2/yr) using the surface area of the collectors and the number of days between each collector visit.

Dried samples (with masses from ~1 to 3 mg), along with surface pebbles from the vicinity of each collector, were submitted for geochemical analysis with inductively coupled plasma mass spectrometry (ICP-MS) at SGS Minerals (Ontario, Canada) following a four-acid digestion. Elements measured, and their detection limits, are provided in Table II. Elemental enrichment of dust relative to bedrock was calculated for each sample and the bedrock composition at that location. These values were averaged for all sites to yield an overall enrichment for each element measured in the modern dust.

Table II. Elements analyzed

Element	Detection limit	Units
Silver Ag	0.02	ppm
Aluminum Al	0.01	%
Arsenic As	1	ppm
Barium Ba	1	ppm
Beryllium Be	0.1	ppm
Bismuth Bi	0.04	ppm
Calcium Ca	0.01	%
Cadmium Cd	0.02	ppm
Cerium Ce	0.05	ppm
Cobalt Co	0.1	ppm
Chromium Cr	1	ppm
Cesium Cs	5	ppm
Copper Cu	0.5	ppm
Iron Fe	0.01	%
Gallium Ga	0.1	ppm
Hafnium Hf	0.02	ppm
Indium In	0.02	ppm
Potassium K	0.01	%
Lanthanum La	0.1	ppm
Lithium Li	1	ppm
Lutetium Lu	0.01	ppm
Magnesium Mg	0.01	%
Manganese Mn	2	ppm
Molybdenum Mo	0.05	ppm
Sodium Na	0.01	%
Niobium Nb	0.1	ppm
Nickel Ni	0.5	ppm
Phosphorus P	50	ppm
Lead Pb	0.5	ppm
Rubidium Rb	0.2	ppm
Sulfur S	0.01	%
Antimony Sb	0.05	ppm
Scandium Sc	0.1	ppm
Selenium Se	2	ppm
Tin Sn	0.3	ppm
Strontium Sr	0.5	ppm
Tantalum Ta	0.05	ppm
Terbium Tb	0.05	ppm
Tellurium Te	0.05	ppm
Thorium Th	0.2	ppm
Titanium Ti	0.01	%
Thallium Tl	0.02	ppm
Uranium U	0.05	ppm
Vanadium V	2	ppm
Tungsten W	0.1	ppm
Yttrium Y	0.1	ppm
Ytterbium Yb	0.1	ppm
Zinc Zn	1	ppm
Zirconium Zr	0.5	ppm

Finally, the concentrations of the elements featuring the greatest enrichment were imported to a geographic information system (GIS) and used to generate maps illustrating the spatial pattern of elemental additions to the Uinta alpine zone.

Results and Discussion

Dust mass and flux

The dust collectors designed for this project were successful at trapping windblown sediment and dealing with precipitation. During field visits, glass marbles in the troughs were visibly dirty, and sediment was obvious along the trough walls and within the 'V' at the base of each trough. All collectors were dry when visited in October 2011, and most were dry in June 2012 and June 2013 despite rain within the previous 24 hours.

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This observation indicates that solar heating of the marbles was successful in evaporating water from the troughs. Moreover, there was no indication, either in the form of a high-water line or a drip line, that the troughs had overflowed. This does not rule out the possibility of overflow, but it suggests that any overflow events were infrequent, making it unlikely that appreciable sediment was removed by overflowing water.

Because the collectors were required to be located at ground level, material > 63 μm in diameter was assumed to represent locally derived material delivered to the collector by saltation, whereas material < 63 μm in diameter was considered more far-traveled dust. The amounts of local material accumulating in DUST2 and DUST3 during the first year were rather high, up to 2× the amount of dust, reflecting the reduced vegetation cover around these collectors (Table I). To reduce the amount of saltating sand ending up in these collectors, both were moved < 100 m in June 2012 to nearby locations surrounded by felsenmeer.

Table III presents the masses of < 63-μm dust recovered from each dust collector. During the summer of 2011, the collectors trapped an average of 0.5 g of dust. The greatest mass of dust accumulated in DUST2 and DUST3 (~0.7 g), with the smallest amount in DUST4 (0.2 g). Maximum accumulation during the following nine months (October 2011–June 2012) was greater (1.2 g), and DUST1 and DUST4 were the sites of the greatest accumulation. Total accumulations for the June 2011–June 2012 period ranged from 1.2 g (DUST2) to 1.8 g (DUST3), with a mean of 1.4 g. Accumulations during the second year (June 2012–June 2013) were lower at all collectors relative to the previous 12 months. Sampler DUST4 collected the minimum mass (0.4 g), whereas DUST3 collected the maximum (1.2 g). The mean from all four collectors during the second year was 0.8 g, roughly half the amount collected in the first year.

Using the dimensions of each collector and the length of time between each collector servicing, it is possible to calculate a flux of < 63-μm dust to each collector (Table III). During the 2011–2012 period, fluxes ranged from 3.6 (DUST2) to 5.5 (DUST3) g/m^2/yr with a mean of 4.4 g/m^2/yr. During the second year values were lower, ranging from 1.4 (DUST4) to 4.1 (DUST3) g/m^2/yr with a mean of 2.7 g/m^2/yr. The average for all four collectors over two years was 3.5 g/m^2/yr (Table III).

Three considerations suggest that these dust flux values for the Uintas may be underestimates. First, experiments intended to quantify the efficiency of marble dust collectors reveal that these devices have their limitations (Sow *et al.*, 2006). For instance, at wind speeds averaging 5 m/s (the average value at the Chepeta RAWS), the efficiency of a marble dust collector oriented parallel to the wind direction could be as low as 0.5 for the grain size range of Uinta dust. Thus, these values might underestimate the actual flux of dust to the Uinta alpine zone by a factor of two.

Second, even though the collectors were deployed in windswept locations, they were required to be positioned on the ground to make them less visible in this designated wilderness area. As a result, they likely spend at least part of the winter buried beneath the snowpack, reducing the total amount of dust they can collect. This situation may partially explain the greater dust accumulation during the 2011–2012 period, when SNOTEL sites throughout the Uintas recorded a snowpack 67–77% of normal (in contrast, the winter of 2012–2013 was near normal). Reduced snowcover would increase the amount of time each collector was exposed, resulting in a potentially greater mass of accumulated dust.

Finally, although there is no evidence for this, fine dust may have been lost to overflowing water if the collectors filled up to the level of their drain holes.

Despite these concerns, it is notable that these fluxes are similar to those measured in the Wind River Range (~3 g/m^2/yr) ~200 km farther north in Wyoming (Dahms and Rawlins, 1996), and at lower elevations (~5 g/m^2/yr) in northern Utah (Rosenbaum *et al.*, 2009). This convergence suggests a general consistency of dust flux in the central Rocky Mountains. In contrast, winter/spring dust fluxes of 5 to 10 g/m^2/yr have been reported from snowpack samples in the San Juan Mountains of Colorado (Lawrence *et al.*, 2010). Assuming that dust is also deposited in the San Juan Mountains during the summer and fall, overall annual dust fluxes there may be several times greater than in the Uintas and Wind River Range. This contrast suggests that dust flux to high-elevation environments in the Rocky Mountains may decrease in a general south-to-north direction, supporting previous studies that have suggested the Colorado Plateau as a likely source area for dust in this region (e.g. Lawrence *et al.*, 2010).

Dust grain size distribution

Grain size analysis reveals that dust in the alpine zone of the Uinta Mountains is dominated by very fine silt (Figure 3 and Table IV). On average, 31% of each sample is comprised of material from 2 to 7 μm in diameter (very fine silt), with another 27% between 7 and 14 μm (fine silt). Clay-sized (<2 μm) material makes up 7% of each sample on average, with ~4% falling in the < 1 μm size fraction. The samples are poorly sorted (graphic standard deviations ~2 Φ), with sub-modes of 0.3 μm and 2 μm, and a dominant mode of 11 μm (Figure 3A). The overall mean size of all samples is 13 μm (6.3 Φ), and the median is 9.1 μm (6.8 Φ).

Given these values, modern Uinta dust is similar to eolian sediment collected from the snowpack surface in the Colorado Front Range, which has a mean (determined through hydrometer analysis) of 4.6 to 5.7 Φ (Thorn and Darmody, 1985). A mean of 6.1 Φ was also reported for eolian sediment collected from snow in the San Juan Mountains using a laser scattering methodology similar to that employed here (Lawrence *et al.*, 2010). Lawrence *et al.* (2010) do report that 28% of their

Table III. Masses and fluxes of < 63-μm material accumulating in Uinta Mountain dust collectors

	Units	DUST1	DUST2	DUST3	DUST4	Mean
June 2011 to October 2011	g	0.359	0.686	0.859	0.194	0.525
October 2011 to June 2012	g	1.170	0.469	0.902	1.063	0.901
June 2011 to June 2012	g	1.530	1.155	1.761	1.257	1.426
Duration	days	375	375	376	374	—
2011–2012 Flux	g/m^2/yr	4.7	3.6	5.5	3.9	4.4
June 2012 to June 2013	g	0.673	0.868	1.228	0.431	0.800
Duration	days	345	350	349	351	—
2012–2013 Flux	g/m^2/yr	2.3	2.9	4.1	1.4	2.7
Overall mean flux	g/m^2/yr	3.5	3.2	4.8	2.7	3.5

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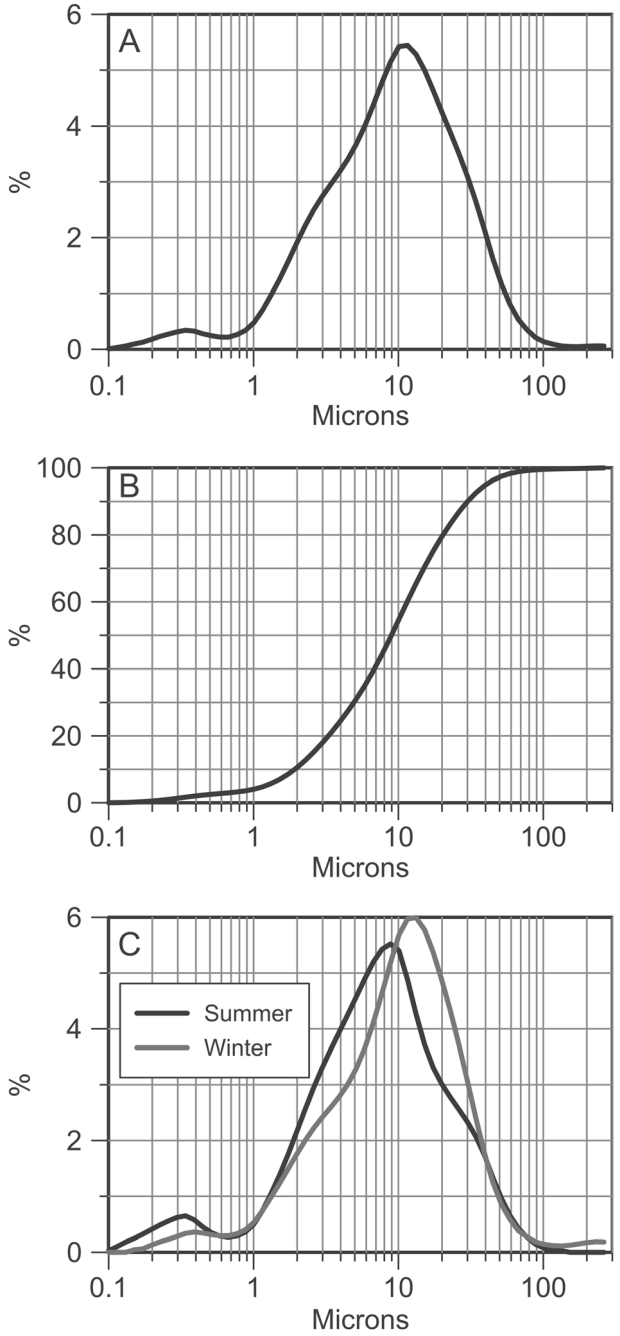

Figure 3. (A) Average grain size distribution of dust arriving in the Uinta alpine zone between June 2011 and June 2013. Samples were wet-sieved to 63 μm before analysis to remove any sediment delivered to the collector as local saltating load. (B) Cumulative frequency plot of the distribution presented in (A). (C) Comparison of the October 2011 sample (representing summer) and the June 2012 sample (representing winter) demonstrating that winter dust is slightly coarser.

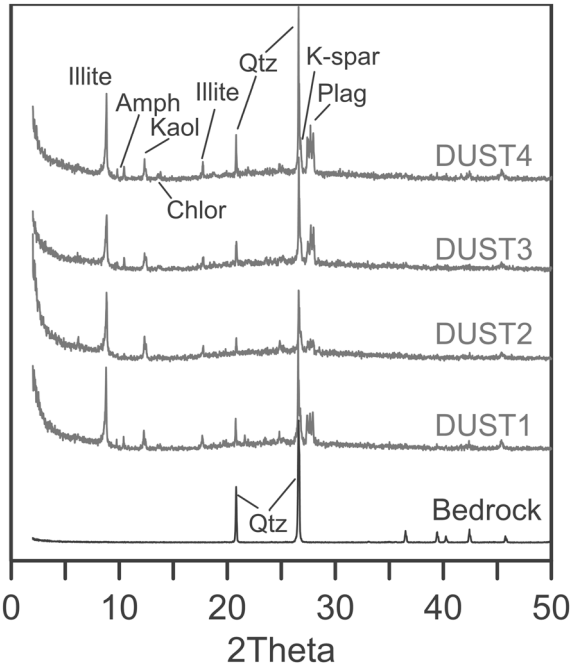

Figure 4. X-ray diffraction patterns for Uinta bedrock and the dust from the four collectors. Bedrock is composed primarily of quartz. In contrast, dust contains detectable feldspar, illite, chlorite, kaolinite, and amphibole.

samples had diameters < 9.3 μm, and $14\% < 2.8$ μm, whereas corresponding values are 64% and 18% in Uinta dust, however this difference likely stems from the fact that the Uinta samples were wet-sieved to 63 μm prior to analysis, whereas analysis of samples from the San Juan Mountains was conducted on the 250 μm fraction. For all of these studies it is worth noting that eolian sediment could be transported as agglomerations of smaller particles, thus grain size measurements made on dispersed samples may underestimate the grain size distribution of the sediment as it was transported. Nonetheless, the consistence of grain size distributions measured on samples from three different mountain ranges distributed across an area of $\sim 2.5 \times 10^5$ km^2 indicates that atmospheric dust is well mixed in this region, and that local sources are rapidly homogenized within the overall eolian flux.

Comparing the samples collected in October 2011 (representing summer) and June 2012 (representing winter), the winter dust sample was coarser (14.6 μm) than the summer sample (10.9 μm) at all four sites (Table IV and Figure 3C). This increase in average grain size was primarily driven by an increase in the abundance of medium silt (30–14 μm) and a drop in the abundance of very fine silt (Table IV). The lack of winter versus summer samples from other studies in the region, combined with the short period of collection in the Uintas, limits extrapolation from this single set of paired samples. However, the possibility that seasonal contrasts in windspeed and/or seasonal changes in dust source areas could affect the properties of dust arriving in the mountains could be explored by sub-annual sampling and future projects.

Dust mineralogy

XRD analysis reveals that the dust accumulating in the alpine zone of the Uintas is dominated by quartz, plagioclase, K-feldspar, and illite with trace amounts of kaolinite, chlorite, and amphibole (Figure 4). Although the sampling interval is relatively short, no difference in the overall mineralogical make-up of the dust in the four samplers each year, or between years, was detectable with XRD analysis (Figure 4), suggesting that the overall composition of the dust arriving in the Uintas is similar throughout the alpine zone.

In contrast, XRD analysis of the pebbles collected from the soil surface in the vicinity of each dust collector reveals that Uinta bedrock is dominated by quartz, with trace amounts of K-feldspar (Figure 4). The presence of plagioclase, illite, chlorite, kaolinite, and amphibole in the dust, therefore, confirms that at least part of the fine eolian sediment arriving in the Uinta alpine zone is exotic. Similar mineralogical compositions have been reported for dust accumulating in other ranges of the Rocky Mountains, indicating a regionally well-mixed dust system (e.g. Thorn and Darmody, 1980; Dahms, 1993; Lawrence

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et al., 2010; Lawrence *et al.*, 2011). Plagioclase, illite, chlorite, and kaolinite are common minerals that may have been entrained from numerous locations in the western United States. In contrast, sources of amphibole are somewhat more restricted, although Dahms (1993) concluded that eolian amphibole in the Wind River Range, 200 km north of the Uintas, was derived from the Bridger and Green River Formations in south-western Wyoming. Given that these formations crop out along the north flank of the Uintas, it seems plausible that the same rocks may be the source for the amphibole identified in Uinta alpine dust. Trace amounts of amphibole were also detected in dust accumulating in south-western Colorado (Lawrence *et al.*, 2010).

Dust geochemistry

Geochemical analysis reveals that Al (mean of 7%), Fe (3%), and K (2.4%) are the most abundant major elements (of those measured, Table II) in dust collected in the Uinta alpine zone between 2011 and 2013. These same elements are dominant in Uinta bedrock, but at average concentrations 2% (Table V). The five most abundant trace elements in these dust samples are Ba (mean of 706 pm), Mn (491 ppm), Zn (420 ppm), Cu (315 ppm), and Sr (180 ppm). Some of these elements are also in the top five most abundant in Uinta bedrock, but at lower levels: Mn (mean of 118 ppm), P (112 ppm), S (100 ppm), Ba (61 ppm), and Sr (39 ppm). Of the elements measured, only Se was generally below detection limits in Uinta dust, whereas Cs, In, Se, and Te were undetectable in Uinta bedrock.

The general pattern of elemental abundances is similar between dust samples, although there are a few notable exceptions (Table V). The abundance of Cu, for instance, was very high in the samples from October 2011, reaching 1290 ppm in DUST1. In contrast, Cu concentrations averaged 125 ppm in the two subsequent June collections. Similarly, values of Zn in all collectors in October 2011 were approximately double those from the June collections. However, Ni values were greatly elevated in June 2013, reaching 411 ppm in DUST1, compared with a mean of 25 ppm in October 2011 and June 2012. Values of Sn in June 2012 were ~4× higher than October 2011 or June 2013.

The October 2011 and June 2012 samples can be utilized to compare seasonality of dust composition (Figure 5A). Several elements are notably more abundant in the summer (i.e. October 2011) sample, including Cu (7×), Cd (3×), Zn (3×), Pb (2×) and Be (2×). In contrast, Nb (0.33×), Ta (0.3×) and Sn (0.23×) are somewhat more abundant in the winter sample (June 2012). The other measured elements have abundances that are essentially equal between these two samples. These observations would be bolstered by acquisition of additional samples representing separate seasons, but the existing data nonetheless suggest that certain elements are preferentially delivered at different times of year. This situation may reflect prevailing wind patterns associated with different seasons, or the presence of snowcover in some source areas during the winter.

Comparison of the geochemical results for dust samples with pebble samples representing the bedrock at each collector site reveals that Uinta dust is notably enriched in many elements (Figure 5B). This enrichment is particularly dramatic in Bi (83×) and Na (53×), although P, Zn, Sn, Cu, Cd, Ba, Ni, W, Sb, Pb, and Tl are all elevated 10–40× above their concentrations in local bedrock. Some of these elements may be derived from past and present mining activities in the regions surrounding the Uintas. Bismuth, for instance, is present in the Tintic mining district in the Wasatch Mountains (Lindgren *et al.*, 1919), Cu is currently mined at Bingham Canyon near Salt Lake City (Lanier *et al.*, 1978), and Na is extensively mined as trona in south-western Wyoming (Culbertson, 1966). Sodium is also present at the surface over widespread areas in western Utah surrounding the Great Salt Lake. Cadmium, which is elevated ~18× in Uinta dust, Cu (27×), and Bi are also enriched in some lake sediments in the Uintas deposited after AD 1870, providing additional support for an anthropogenic source for these elements (Reynolds *et al.*, 2010). Furthermore, Cd and Cu are elevated above average crustal values (Wedepohl, 1995) in modern dust accumulating in the San Juan Mountains (Lawrence *et al.*, 2010) and in the desert south-western United States (Reheis *et al.*, 2009), suggesting that this is a regional signal.

Importing the geochemical results to a GIS yielded loading maps for the 15 elements most enriched in the June 2012 sample period, which was the only one for which the DUST4 collector contained sufficient material for ICP-MS analysis. In Figure 6 these maps are displayed for each element with their measured abundances (Table V) replaced by ratios to the mean to illustrate the pattern of elemental deposition. An obvious limitation of this approach is that the dust collectors represent just four points. With this caveat in mind, yet in recognition of the fact that the collectors were intentionally positioned to capture possible spatial variations in dust properties across the Uintas, the 15 most-enriched elements can be assigned to three groups with contrasting patterns.

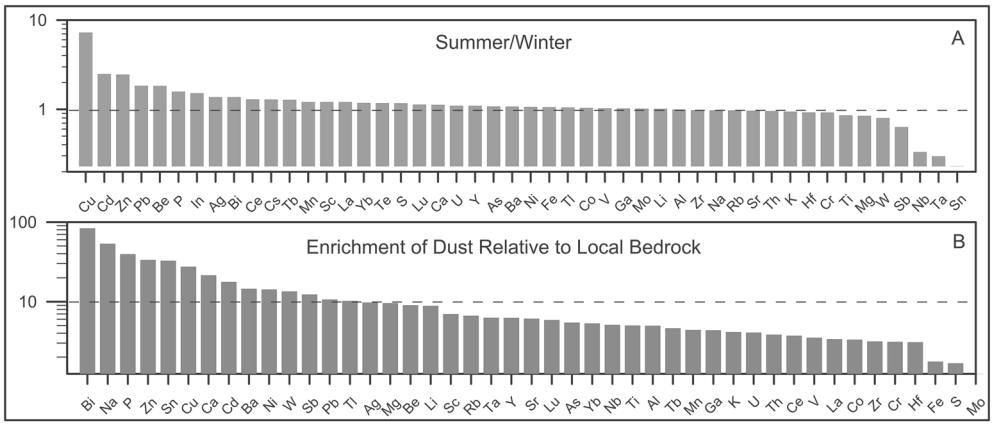

Figure 5. (A) Ratio of mean elemental abundance in summer (October 2011) and winter (June 2012) dust at the four collectors. Most elements are relatively evenly distributed between the seasons, however Cu, Cd, and Zn are notably more abundant in the summer sample, whereas Nb, Ta, and Sn are more abundant in the winter. (B) Mean enrichment of elemental abundances in Uinta dust compared with bedrock at each collector site. Abundances of Bi, Na, P, Zn, Sn, Ca, Cd, Ba, Ni, W, and Sb are enriched > 10× in dust compared to bedrock likely reflecting mining, agriculture, and other land-use practices in regions upwind of the Uintas.

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Group 1 elements include Ag, Ba, Ca, Cd, Sb, and Tl, all of which exhibit generally higher values at DUST3 (west) and DUST4 (north), suggesting delivery from the northwest. This is the most common wind direction at the Chepeta RAWS site (Figure 2A). During the period considered here, winds were from the northwest (azimuth of 270° to 360°) 50% of the time, with a mean velocity of 6 m/s (data from < raws.wrh.noaa.gov/roman>).

Group 2 elements, including Na, Pb, and Sn, tend to have higher concentrations at DUST2 (south) and DUST3 (west). Nickel and P are also included in Group 2 because their measured abundances are relatively high at DUST1, DUST2, and DUST3, and low on the north side of the range (DUST4). This pattern suggests delivery from the south or southwest. During the collection period winds were from the south-southeast (azimuth of 135° to 180°) 25% of the time with a mean velocity of 9 m/s, and the south-southwest (azimuth of 180° to 225°) 18% of the time, with a mean of 6 m/s. The source of Ni to the south of the Uintas is unknown; however, P is often considered a signature of agricultural activity, and study of sedimentary records from two lakes on the south slope of the Uintas has documented a correspondence between increasing P over the past century and expanded use of phosphate in the western United States (Reynolds *et al.*, 2010). Thus, the high values of P at DUST2 and DUST3 may reflect farming and fertilizing upwind. The relatively high concentration of P at the eastern end of the range (DUST1) may reflect the presence of an active open-pit phosphate mine 50 km to the southeast.

The pattern for Group 3 elements is less consistent; however, most have relatively low concentrations at DUST1 (east), and greater concentrations in the central and western Uintas, suggesting delivery from the west (Figure 6). This pattern is well-expressed by Bi, W, and Zn. Copper is also included in this group because of its high concentration at DUST3, although

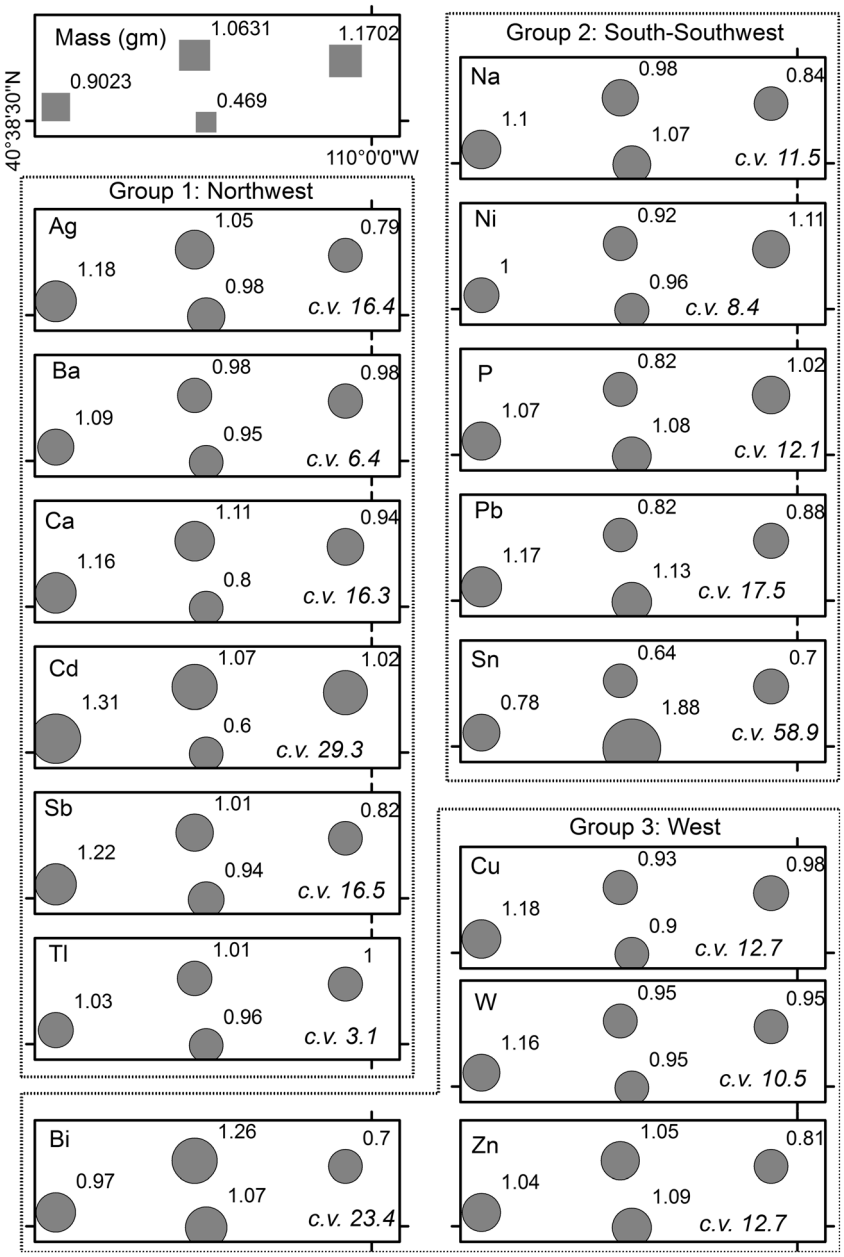

Figure 6. Maps of elemental loading in the June 2012 sample for the 15 elements most enriched in Uinta dust. Panel in the upper left shows the locations of the four dust collectors. These are replaced with proportionally scaled circles in the other panels. Values are ratios of elemental abundance at each collector relative to the mean. CV is the coefficient of variation in percent to represent dissimilarity of the elemental abundances at the four collector sites. Group 1 elements have patterns suggesting delivery from the northwest. In contrast, Group 2 elements appear to be derived from sources to the south of the Uintas. Group 3 elements have values that are generally low to the east and high to the west, suggesting a westerly source.

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DUST1 (east) recorded the second highest value. The significance of relatively high Cu values at both the eastern and western ends of the Uintas is unclear.

Previous work has identified the Colorado Plateau to the south of the Uintas (e.g. Neff *et al.*, 2008; Lawrence *et al.*, 2010), industrial activity to the southwest of the Uintas (Reynolds *et al.*, 2010), and the deserts of western Utah (Steenburgh *et al.*, 2012) as likely sources of dust to the central Rocky Mountains. The Group 2 and 3 elements in this analysis have a pattern of deposition consistent with delivery from these sources. Furthermore, meteorological data from Salt Lake City, ~100 km to the west of the Uintas, document that the greatest dust flux at lower elevations arrives with southerly winds (Steenburgh *et al.*, 2012). However, the elemental loading patterns for Group 1 elements suggest that some dust is arriving in the alpine zone of the Uinta Mountains from source areas to the northwest. Support for this conclusion is provided by the wind direction data gathered by the Chepeta RAWS, where northwesterly winds are more common than southerly winds, although at lower mean velocities.

Limitations and Implications of the Dataset

The data reported here provide the first year-round field measurements of the contemporary eolian flux to an alpine zone in the Rocky Mountains for a multi-year period, as well as the first direct determination of dust grain size distribution, geochemistry, and mineralogy for the Uinta Mountains. Despite this success, the dataset has some limitations which require consideration. For instance, extrapolations from these data are limited by the length of time for which the collectors were deployed. Insight into the seasonality of dust composition is further compromised by the fact that a summer sample was only collected in 2011, and interpretations of the spatial patterns of elemental loading are restricted by the reality that the sample from DUST4 was too small for ICP-MS analysis in two of the three collections. The passive collectors utilized in this project inevitably combine multiple dust-delivery events over many months in a single sample, precluding more specific tracing of dust components back to their source areas. The exposed nature of the samplers, and the wet-methods used to wash and concentrate dust, obviate the possibility of collecting soluble mineral phases. And the wind data from the Chepeta RAWS may not be representative of high-elevation winds throughout in the Uintas.

Despite with these concerns and limitations, this new dataset from the Uintas offers several strengths that improve understanding of the regional dust system in the Rocky Mountains. First, the newly designed dust collectors permit sampling of dust throughout the year, not just during the season in which snow accumulates. This advance supports a more accurate picture of annual dust flux in this region. Second, the dataset represents two complete years of dust collection, providing the opportunity for internal checks on the consistency of results. This redundancy permits a more rigorous comparison with results purported from elsewhere in the region, and allows the uniformity of dust properties to be more thoroughly assessed. Finally, the broad distribution of dust collector sites within the Uintas allows consideration of elemental loading patterns, which could be utilized as a check on models of atmospheric circulation and dust transport.

Conclusion

Delivery of dust by eolian transport is increasingly recognized as an important process in alpine ecosystems of the Rocky Mountains. However, questions remain about variability of the dust system in the Rocky Mountain region, primarily due to the small number of prior studies and the lack of continuous year-round collections of modern dust. This project contributed to the development of a more comprehensive picture of the dust system in this region by collecting and analyzing contemporary eolian sediment accumulating in the alpine zone of the Uinta Mountains of northern Utah. Passive dust collectors deployed at four locations in the alpine zone in June 2011 accumulated an average of 1.1 g/yr of material 63 μm in diameter. Given the dimensions of the dust collectors, this mass corresponds to an overall mean flux of 3.5 g/m^2/yr. Although this value is likely an underestimate given inherent limitations of marble dust collectors and the possibility of short-term burial of the collectors by winter snow, this flux is notably consistent with values reported by other studies from the Wind River Range (Dahms and Rawlins, 1996), but is lower than fluxes reported for south-western Colorado (Lawrence *et al.*, 2010). This pattern suggests the operation of a south-to-north gradient of decreasing dust flux away from the Colorado Plateau. The grain size distribution of dust arriving in the Uinta alpine zone is dominated by very fine silt (~30% by volume), and has an overall mean of 13.0 μm (6.3 Φ). This is nearly identical to the mean of 6.1 Φ reported for eolian sediment collected from snow in the San Juan Mountains (Lawrence *et al.*, 2010), and is similar to dust from snow in the Colorado Front Range (Thorn and Darmody, 1985). This consistency suggests that the regional dust system in the Rocky Mountains is well-mixed, and that local sources are rapidly incorporated into the background dust flux.

The bedrock of the Uintas is dominated by quartz, with minor amounts of K-feldspar, yet dust samples contain plagioclase, illite, kaolinite, chlorite, and amphibole, confirming an exotic source for this material. Similar mineralogical compositions reported for dust elsewhere in the Rocky Mountains demonstrate general consistency in the delivery of allochthonous material by eolian processes in this region.

Geochemically, dust in the Uinta Mountains is dramatically enriched (relative to Uinta bedrock) in Bi (83×), Zn (33×), Sn (33×), Cu (27×), and Cd (18×), which may reflect mining and industrial activity upwind. Investigating the spatial pattern of elemental abundance in the October 2011 through June 2012 collection reveals that Na, Ni, P, Pb, and Sn are preferentially deposited on the southern flank of the Uintas, suggesting transport from that direction. In contrast, Ag, Ba, Ca, Cd, Sb, and Tl have distributions suggesting delivery from the northwest, which is the primary wind direction at the lone weather station operating in the alpine zone of the Uintas. The distributions of Bi, W, and Zn fall from west to east across the Uintas, suggesting delivery from the west. Copper concentrations are also highest at the western end of the Uintas, closest to a large open-pit copper mining operation. The abundance of some elements also varies seasonally, particularly in the case of Cu, Cd, and Zn which are several times more abundant in dust accumulating in the summer months.

The results of this study confirm that eolian sediment of exotic origin is accumulating in the Uinta alpine zone today at rates, and with properties, equivalent to those reported from other ranges in the central Rocky Mountains. These results contribute to an emerging picture of a regionally well-mixed dust system in which substantial amounts of allochthonous material are delivered to alpine zones each year. Deposition of this sediment may exert a substantial forcing on the functioning of alpine geoecosystems in this region (e.g. Lawrence *et al.*, 2010; Lawrence *et al.*, 2011).

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