Increasing eolian dust deposition in the western United States linked to human activity

J. C. NEFF[1,2]*, A. P. BALLANTYNE[1], G. L. FARMER[1,3], N. M. MAHOWALD[4,5], J. L. CONROY[6], C. C. LANDRY[7], J. T. OVERPECK[6,8,9], T. H. PAINTER[10], C. R. LAWRENCE[1] AND R. L. REYNOLDS[11]

[1]Geological Sciences Department, University of Colorado at Boulder, CB399, Boulder, Colorado 80309, USA
[2]Environmental Studies Program, CB397, University of Colorado at Boulder, Boulder, Colorado 80309, USA
[3]Cooperative Institute for Research in the Environmental Sciences (CIRES), CB 399, 80309, USA
[4]Department of Earth and Atmospheric Science, Snee Hall, Cornell University, Ithaca, New York 14853, USA
[5]Climate and Global Dynamics Division, National Center for Atmospheric Research, Boulder, Colorado 80304, USA
[6]Department of Geosciences, The University of Arizona, 1040 E 4th St, Tucson, Arizona 85721, USA
[7]Center for Snow and Avalanche Studies, PO Box 190, Silverton, Colorado 81443, USA
[8]Institute for the Study of Planet Earth, The University of Arizona, 715 N. Park Ave, 2nd Floor, Tucson, Arizona 85721, USA
[9]The Department of Atmospheric Sciences, The University of Arizona, 1118 E 4th St, Tucson, Arizona 85721, USA
[10]Department of Geography, 260 S. Central Campus Dr, University of Utah, 84112, USA
[11]Earth Surface Processes Team, US Geological Survey, MS980, Denver Federal Center, Denver, Colorado 80225, USA
*e-mail: neffjc@colorado.edu

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Mineral aerosols from dust are an important influence on climate and on marine and terrestrial biogeochemical cycles. These aerosols are generated from wind erosion of surface soils. The amount of dust emission can therefore be affected by human activities that alter surface sediments. However, changes in regional- and global-scale dust fluxes following the rapid expansion of human populations and settlements over the past two centuries are not well understood. Here we determine the accumulation rates and geochemical properties of alpine lake sediments from the western interior United States for the past 5,000 years. We find that dust load levels increased by 500% above the late Holocene average following the increased western settlement of the United States during the nineteenth century. We suggest that the increased dust deposition is caused by the expansion of livestock grazing in the early twentieth century. The larger dust flux, which persists into the early twenty-first century, results in a more than fivefold increase in inputs of K, Mg, Ca, N and P to the alpine ecosystems, with implications for surface-water alkalinity, aquatic productivity and terrestrial nutrient cycling.

Eolian dust is generated from a wide range of sources including industrial emissions and the wind erosion of soils[1]. Dust may affect ocean productivity[2,3], control terrestrial nutrient cycling[4] and alter regional and global climate[5,6]. Dust deposition onto snow cover in the western United States has recently been shown to accelerate melt and reduce snow-cover duration by approximately one month, a finding that has broad implications for water resources in mountainous regions of the United States[7]. At a global scale, the Sahara and Sahel deserts in Africa and the deserts of central Asia produce most of the world's mineral aerosol load[1]. Regional sources of dust, however, produce significant quantities of mineral aerosols with effects on soil fertility, air quality and human health[8,9]. Given the wide range of potential impacts of atmospheric dust, it is critical to improve our understanding of the past and present role of human activities on dust emission and deposition.

The Great Basin, Colorado Plateau, Mojave and Sonoran deserts of the southwestern United States are responsible for the majority of emissions in North America[1]. Like many arid environments, the drylands of the western United States have experienced widespread land-use change over the past two centuries, with rapid acceleration of agricultural and grazing activities following the westward expansion of the United States in the 1800s (ref. 10). Despite growing evidence of the impacts of land use on wind erosion of soils around the world[11–13], the history of human influences on atmospheric dust remains poorly documented. Records showing increased dust accumulation in Antarctic ice cores between the nineteenth and twentieth centuries[14], and evidence for changing chemistry of glacial dust during the twentieth century[15], suggest higher contemporary atmospheric mineral aerosol loads than during the pre-industrial period. Similar conclusions have been reached in studies of peat bogs in Europe[16]. Without more documentation of contemporary and palaeo-deposition rates, however, we are largely limited to speculation about how humans have altered regional and global dust emissions.

DUST PROXY RECORDS

We obtained proxy records of dust deposition from high-elevation lakes in the San Juan Mountains in southwestern Colorado to

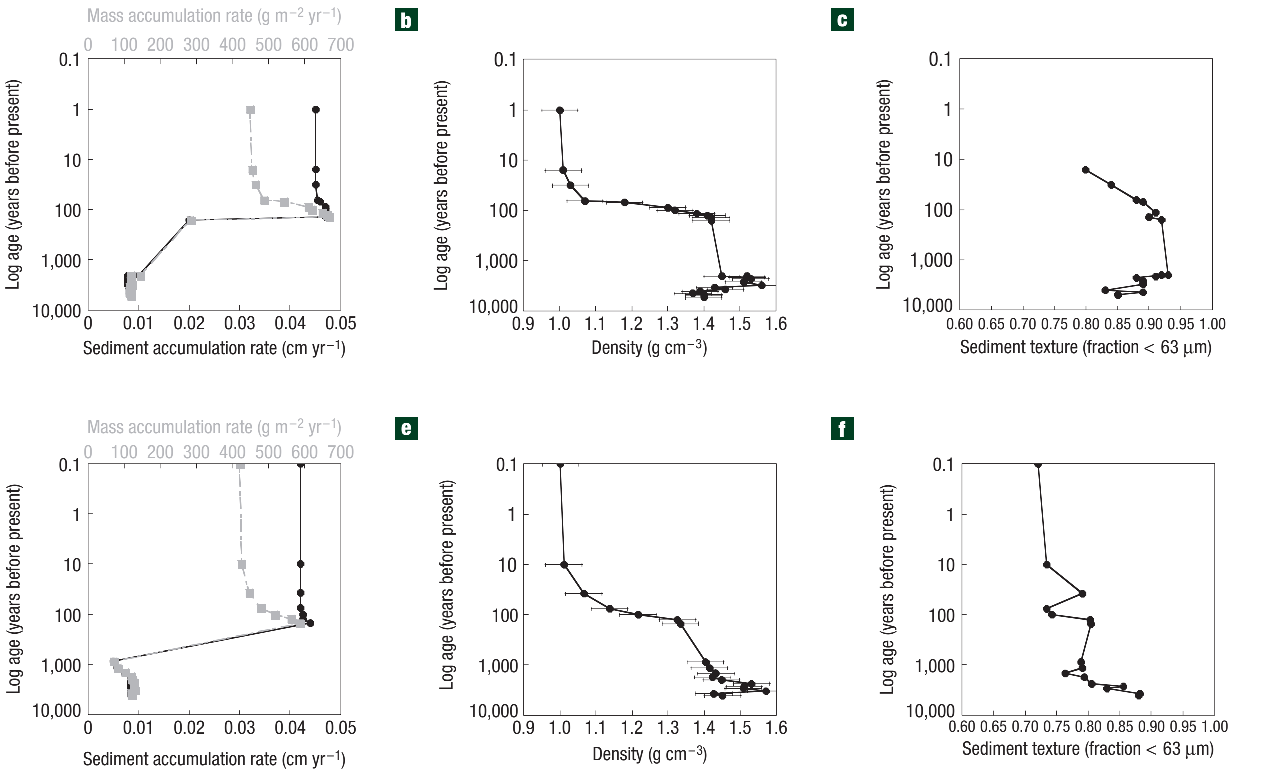

Figure 1 Sediment accumulation rates and physical properties. a–c, Sediments from Porphyry Lake including sediment and mass accumulation rates (**a**), density (**b**) and texture (**c**). **d–f**, Sediments from Senator Beck Lake, including sediment and mass accumulation rates (**d**), density (**e**) and texture (**f**). The age scale is on the basis of the depth–age model described in the supplementary online material, with age dates in the top 150 yr determined from ^{210}Pb measurements and those below from ^{14}C dating of terrestrial macrofossils. The error bars in **b** and **e** are estimated 95% confidence limits for density measurements.

examine the possibility of human-induced changes in atmospheric dust deposition. Located downwind of major western US deserts, this mountain range is prone to frequent eolian deposition events (see Supplementary Information, Fig. S1). The mountain range also contains a number of high-elevation lakes located above the tree line in areas with limited soil development. Given the frequent inputs of dust to snow cover[7], these alpine lakes provide ideal locations for studying changes in dust loading.

In two alpine lakes, sediment accumulation rates over the past ∼150 yr are more than five times greater than average accumulation rates over the past 5,000 yr, on the basis of radiogenic ^{210}Pb and ^{14}C dates (Fig. 1). These recently elevated sedimentation rates are supported by an independent study on a larger, nearby subalpine lake that also shows large increases (7–17-fold) in recent- versus late-Holocene sedimentation rates[17] (Table 1). Changes in sedimentation rates in these lakes occurred in the transition between age records derived from terrestrial macrofossils and those derived from ^{210}Pb (see Supplementary Information, Fig. S2). Although it is impossible to assign an exact date to the onset of increasing sedimentation rate, there is a clear and abrupt transition in sedimentation rate from old (∼1,000 yr before present) to recent (∼150 yr before present) sediment ages in one of our study lakes (Senator Beck Lake). The age and thickness of lake sediments also provide evidence that sedimentation rates peaked ∼100 yr before present. Taken together, these data strongly suggest that the period of increased sedimentation rate occurred within the past two centuries (Fig. 1, Supplementary Information, Tables S1,S2).

The San Juan Mountains currently experience four to seven large winter-time dust deposition events each year[7], and the recent increases in lake-sediment accumulation could be caused by these periodic deposition events. To test this possibility, we examined the physical and isotopic properties of dust, bedrock and lake sediments. The lake sediments are dominantly composed of fine-grained silts consistent with a far-travelled eolian origin rather than a local source[18]. To test further whether the sediment is dominantly dust derived, we compared the neodymium and strontium isotopic compositions of both the coarse- (>250 μm) and fine-grained (37–63 μm) lake sediments with those of the bedrock underlying their catchments. The range of ε_{Nd} values of ∼−5 to −9.8 from the bedrock (Oligocene silicic volcanic rocks of the San Juan volcanic field) underlying these basins contrasts with values from fine-grained lake sediment that range from ∼−10 to −11, despite similar values of ^{147}Sm/^{144}Nd ratios from ∼0.10 to 0.11 (Fig. 2a, Supplementary Information, Table S3). The ε_{Nd} values (from −10.4 to −10.8) and ^{147}Sm/^{144}Nd ratios from dust, collected from San Juan snowpack in 2005, are indistinguishable from those in the fine-grained sediment in the lakes (Fig. 2a). Strontium isotopes show similar patterns, with ^{87}Sr/^{86}Sr ratios (<0.708) from the residual fraction of the local volcanic bedrock consistently lower than those from lake sediments (>0.713). As with the Nd isotopes, the ^{87}Sr/^{86}Sr ratios for the 37–63 μm fraction of sediments are nearly identical to values for contemporary dust (Fig. 2b). The combination of Sr and Nd isotopes and sediment texture provides unambiguous evidence that the fine fraction of lake sediments (>75% of typical sediment mass in these cores) is derived from exogenous sources rather than locally eroded bedrock.

Table 1 Estimates of sediment accumulation rates for lakes in the San Juan Mountains, Colorado. The Mineral Basin, Senator Beck and Porphyry Lakes were sampled for this study, whereas the Molas Lake data are from ref. 17. Sediment accumulation rates are presented for dated intervals where information is sufficient to estimate sedimentation rates. Values in parentheses are standard errors estimated from propagation of analytical uncertainties through age/depth regression equations.

Alpine lake	Dated interval	Dating method*	Sediment accumulation rate (mm yr^{-1})	Mass accumulation rate (g m^{-2})
Mineral Basin Lake	~1,890-present	^{210}Pb	0.6 (0.06)	ND
Senator Beck Basin Lake	~1,910-present	^{210}Pb	0.42 (0.04)	457 (18)
	~1,850–1,910	^{210}Pb	0.44 (0.04)	555 (20)
	1,750–1,150 BP	^{14}C	0.050 (0.001)	92 (10)
	2,580–1,750 BP	^{14}C	0.078 (0.001)	124 (2)
Porphyry Lake	~1,910 to present	^{210}Pb	0.45 (0.05)	501 (26)
	~1,850 to 1,910	^{210}Pb	0.47 (0.05)	576 (74)
	5,178–3,183 BP	^{14}C	0.092 (0.001)	119 (1)
Molas Lake[17]	~1,880-present	^{210}Pb	5.31	ND
	1260–120 BP	^{14}C	1.70	ND
	2760–1260 BP	^{14}C	0.32	ND
	5920–2760 BP	^{14}C	0.28	ND

* ^{210}Pb refers to the use of lead-210 dating techniques for recent sediments, whereas older sediments were dated through the measurement of the ^{14}C content of terrestrial macrofossils.

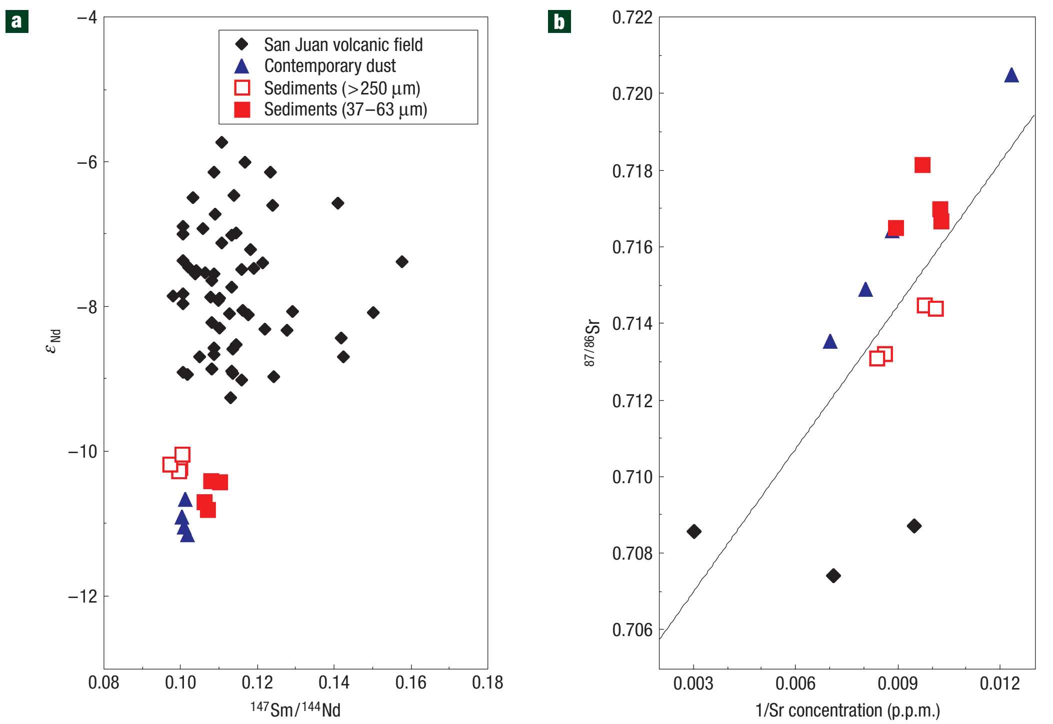

Figure 2 Dust, bedrock and sediment isotopic characteristics. a, The ε_{Nd} versus ^{147}Sm/^{144}Nd data, which illustrate the separation between local bedrock, dust and sediment. The bedrock values are from the San Juan volcanic field (referenced data in main text) plotted for comparison with contemporary dust and two size fractions from lake sediments. **b**, The strontium isotope values for dust, bedrock and sediments in the study area. All values are for residual fractions of samples (see Supplementary Information). Analytical errors for both Sr and Nd isotopic measurements are smaller than the marker size in the graphs.

SOURCES OF DUST TO THE SAN JUAN MOUNTAINS

There are a number of potential sources of dust to the San Juan Mountains including the deserts of the southwestern United States and desert sources in Asia that are known to contribute dust to the North American continent[19]. Although the precise provenance of San Juan dust samples is difficult to determine, the physical and isotopic properties of dust can be used to substantially narrow the potential source regions. The ε_{Nd} values of contemporary dust range from −10.4 to −10.8 at ^{147}Sm/^{144}Nd ratios between 0.106 and 0.110. These values overlap those of Palaeoproterozoic basement rocks that comprise the bulk of the continental crust underlying Arizona and New Mexico (Fig. 3a, Supplementary Information, Table S3)[20–27]. These isotopic compositions are

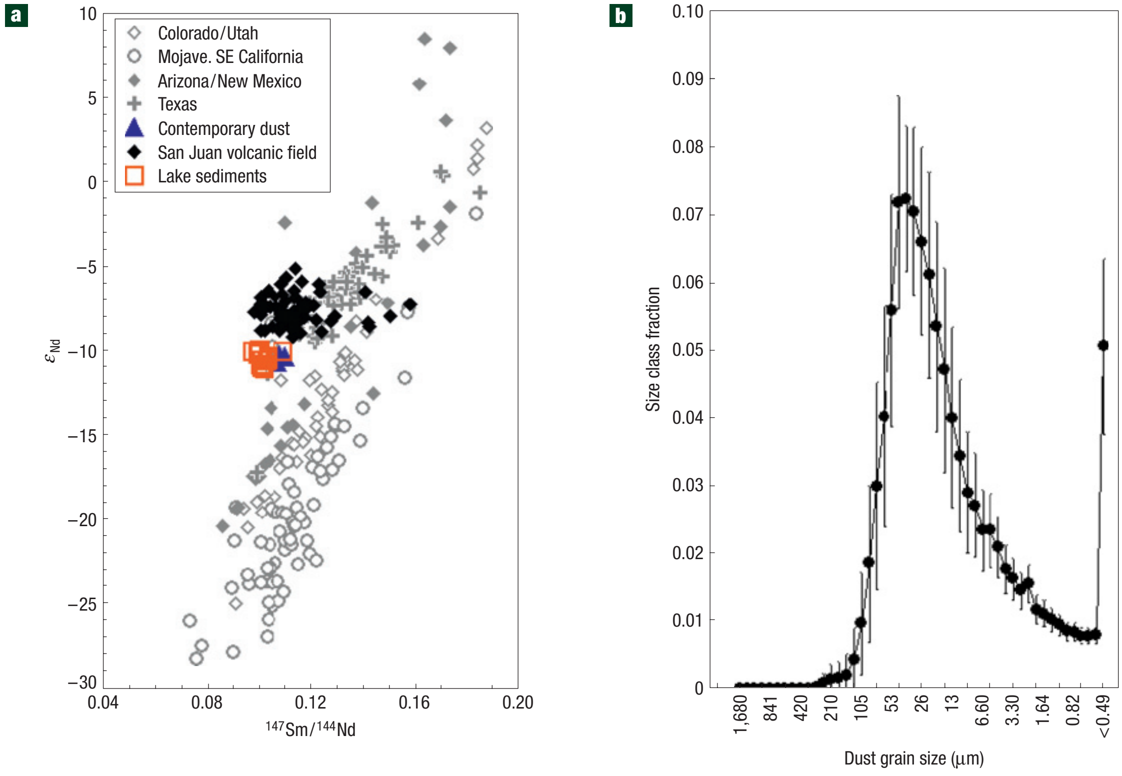

Figure 3 Dust isotopic properties and texture. a, ε_{Nd} and $^{147}Sm/^{144}Nd$ for potential sources of dust to the San Juan mountains. Except where otherwise noted, data in the graph are for Precambrian basement rocks for various portions of the western United States as cited in the main text. Analytical errors are smaller than the graph symbols. **b**, The average grain-size distribution for modern dust collected from five separate deposition events in 2005. Bars on the graph represent the 95% confidence interval.

consistent with dust sources to the south and/or southwest of the study area. Satellite detection of dust plumes and atmospheric back-trajectory modelling for this region also link wintertime dust deposition in the San Juan Mountains to dust plumes that originate in the deserts of the southwestern United States, further supporting a dust source indigenous to western North America[7].

Although Asian dust periodically falls on the San Juan Mountains, the textural distribution of dust samples also provides strong evidence for a regional source of dust. Nearly 40% of the mass of dust sampled from the snowpack occurs in the 10–37 μm size class, 26% in the 37–63 μm size class and 17% in the 63–180 μm size class (Fig. 3b). The relatively large proportion of particles over 37 μm is evidence for particles that have been transported hundreds, rather than thousands, of kilometres[28]. This result suggests that the dominant source of wintertime dust inputs to the San Juan Mountains is the western United States rather than far-travelled Asian dust, which would be much finer (that is, in the less than 10 μm size classes)[29].

CAUSES OF INCREASED DUST LOADING

Increased sedimentation in lakes in recent decades or centuries is generally attributed to catchment-scale disturbance[30] or changes in regional climate[31]. In the high-elevation setting sampled here, the lakes are surrounded by talus fields, with limited soil and vegetation development and no evidence of modern human disturbance. These factors together effectively rule out a local cause for the observed increase in lake sedimentation rates. Combined with the isotopic evidence for predominantly eolian sources for the lake sediments, we suggest that the large, recent increases in sedimentation rates are related to increased eolian deposition. Both lake-sediment core records indicate that increased dust loading began between 200 and 100 yr ago with peak deposition rates in the first half of the twentieth century (Fig. 1). Drought is a potential cause of increased wind erosion of soils. Although there have been multiple drought events during the nineteenth and twentieth centuries in the western United States, these droughts have been considerably shorter and less severe than several drought events that have occurred over the past 2,000 yr in the region[32], making it unlikely that drought is the primary cause for the increased dust loading observed in this study. Instead, the period of increased sedimentation rate is contemporaneous with an intensification of western US land use, and particularly livestock grazing activities, that began in the early 1800s.

The migration of settlers of European descent into the western United States led to widespread expansion of grazing, mining and agricultural activities in the nineteenth and twentieth centuries. In the period following the development of railroad lines (and heavy transport capabilities for livestock) in the late 1860s, cattle and sheep grazing greatly intensified across the western United States[10,33–35]. In the Navajo Nation tribal lands to the south and southwest of the San Juan Mountains, high animal densities and impacts of overgrazing became a major issue by the early 1890s. By the early 1930s, two-thirds of the land area in northeast Arizona had been significantly disturbed by heavy livestock use[36]. Overall, nearly 70% of the natural ecosystems of the western United States have been affected by livestock grazing[37], resulting in loss of soil stability and increases in wind erosion of soil[9,11]. The extensive degradation of western US rangelands led to the Taylor Grazing Act of 1934, which imposed regulations and restrictions on grazing activities in

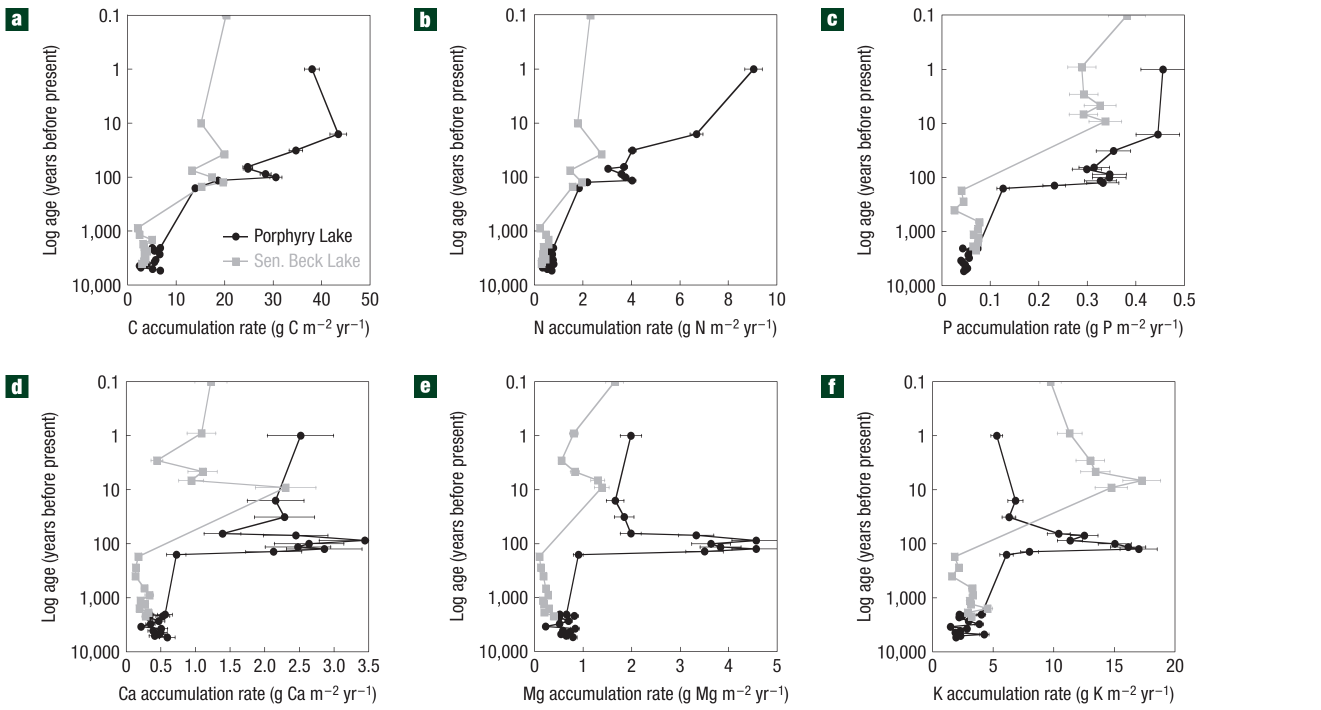

Figure 4 Elemental fluxes for two alpine lakes in the San Juan Mountains, Colorado. a–c, C, N and P fluxes, respectively, for Senator Beck and Porphyry Lakes. **d–f**, Ca, Mg and K loading, respectively, for Senator Beck and Porphyry Lakes. Element accumulation rates were calculated by multiplying mass accumulation rates by sediment elemental abundance and are expressed on an area basis. Error bars are on the basis of the propagation of error in density and element abundance measurements. Sediment ages for the top 150 yr were determined from ^{210}Pb measurements and those below from ^{14}C dating of terrestrial macrofossils.

these rangelands. At about this time the mass accumulation rates of the lake sediments begin a moderate decline, which persists through the second half of the twentieth century (Fig. 1).

BIOGEOCHEMICAL IMPLICATIONS OF INCREASED DUST DEPOSITION

Eolian dust mobilized from arid-land soils generally contains high concentrations of base cations, and dust typically has high concentrations of N and P, as well as elevated concentrations of a range of atmospheric pollutants[4,38]. High-elevation lakes and tundra ecosystems are generally low in nutrient content and vulnerable to increases in atmospheric deposition[39]. There is strong evidence for the impacts of changing N deposition in high-elevation settings[40], as well as suggestions of increasing P and base-cation deposition into high-elevation settings[39,41,42].

To evaluate the changes in element loading in the lake sediments examined here, we combined sediment mass-accumulation rates with geochemical analyses to estimate sediment element-accumulation rates in the two lakes. For the elements N, P, Ca, Mg and K, both lakes show large increases in element accumulation rates over the past 150 yr compared with background fluxes (Fig. 4). Element accumulation rates for the base cations, Ca, Mg and K, generally show a peak ~100 yr ago, with some decline to present and some variation (particularly with Mg) between the lakes. These early-twentieth-century peaks provide additional evidence that land-use change in the western United States led to a large destabilization of base-cation-rich, desert soils in the early twentieth century. There is evidence from a range of other settings that base-cation loading via dust deposition can change precipitation and surface-water alkalinity[43,44]. The relatively large perturbation to base-cation loading to these lakes suggests that dust inputs could be one factor mitigating the lake impacts of generalized regional increases in acid deposition[45].

Both lake-sediment records show an increase in C and N accumulation rates during the nineteenth and twentieth centuries. These records are complicated to interpret, both because of some variability between the lakes and because changes in the accumulation of these elements could be a product of either diagenesis in the sediment profile[46] or increases in aquatic productivity resulting from elevated dust and nitrogen deposition. For Porphyry Lake, the sediment N and organic C record shows increasing accumulation through the twentieth century, although this is less pronounced in Senator Beck Lake. Nitrogen deposition to alpine settings is the result of multiple potential sources, probably dominated by gas-phase emissions of nitrogen oxides during fossil-fuel combustion[47]. The timing and magnitude of N deposition changes to these lake sediments is generally reflective of global perturbations to the N cycle[48] although both lakes also show peaks in C and N accumulation that are consistent with the apparent dust deposition peak ~100 yr ago and suggest a potential stimulatory effect of this dust on lake productivity.

Phosphorus sedimentation accumulation rates show a large and sustained increase through the modern record in both cores, which indicates a more complex change in element loading than observed for the base cations. Phosphorus, like the base cations, shows elevated element accumulation rates early in the twentieth century in addition to more recent increases in loading rates. Phosphorus deposition is also subject to the diagenesis issues for C and N mentioned above. Nonetheless, the continued increase of P sedimentation rates through the twentieth century is contemporaneous with the widespread expansion of the use of P fertilizers in the second half of the twentieth century[49]. This increase is caused by both elevated rates of sediment accumulation and increasing P concentrations in sediments. The possibility of human disruption to the P cycle through agricultural activity and dust emission is a potentially significant finding, as relatively little is known about anthropogenic changes in P deposition rates to ecosystems. Although intriguing, more work is needed to establish the causes of these changes in P accumulation rates.

CONCLUSIONS

Land-use change in the western US over the past 200 yr is similar to agricultural intensification in semi-arid regions around the world, which often results in increased wind erosion of soils[12,14,50]. Recent studies of dust deposition records from Antarctica[14] suggest that the patterns observed in our study may be replicated elsewhere and may be indicative of a significant human role in regional dust generation. If human land-use change has altered the flux of dust between the biosphere and the atmosphere to the degree implied by our study, then there have also been substantial changes in elemental fluxes to ecosystems, with broad implications for nutrient deposition and biogeochemical cycling. In addition to its role in nutrient and contaminant transport, dust can also influence regional snowpack and climate. Effects on snowpack include accelerated spring snowmelt and decreased late-spring snowpack depth[7]. In the atmosphere, mineral aerosols play an important and highly uncertain role in climate change[51]. Most studies of mineral aerosols focus on the less than 10 μm size classes generated in, and transported from, Asia and Africa. The results of this study suggest the importance of regional sources for mineral aerosol fluxes in the western United States, and imply a strong and changing human role in controlling these fluxes. To the degree that these results are replicated in other areas with extensive, recent land-use change, human-caused changes in dust production and deposition may be far more important than previously thought.

METHODS

The alpine lakes sampled in this study are located between Silverton and Telluride, Colorado, USA. The lakes were located at ∼3,500 m in alpine glacial cirques with shallow surrounding soils and limited vegetation development (grasses and small shrubs). Sediment cores were extracted using a Universal Core Head Corer from shallow alpine lakes (1–2 m depth). In the laboratory, the cores were subsampled into 0.5–1 cm increments. Terrestrial macrofossils were picked from the sediments during this initial sectioning procedure. We obtained as many macrofossils as possible for this study; however, these samples are limited owing to the high elevation and limited vegetation cover. All samples were freeze-dried and separated using a splitter to yield homogenous samples. Dust samples were collected from snowpack within 2–3 weeks of deposition in Senator Beck Basin. These samples were melted, evaporated and freeze-dried. Several samples of representative bedrock were also taken from Senator Beck Basin.

Surface sediments from lakes in all basins were dated using the radiogenic nuclide ^{210}Pb, and sediments at depth were dated by measuring ^{14}C of macrofossils. The sediment accumulation rate was estimated using the constant-rate-of-supply model fitted to measurements of unsupported ^{210}Pb activity[52] (see Supplementary Information, Table S1 and Methods). For each sediment core, we present two periods of accumulation related to the time intervals from the mid-1800s to early 1900s and from the early 1900s to the present. Our selection of these intervals enables the use of at least three ^{210}Pb measurements per period, with the intent of providing a relatively conservative estimate of recent temporal variation in sediment loading. The surface sample from Porphyry Lake was excluded from the sedimentation estimates because of a suggestion of disturbance of the top 1 cm during sampling. Inclusion of this sample point doubles recent sedimentation estimates, but with sufficient uncertainty to warrant a more conservative approach.

Terrestrial macrofossils, identified as roots or woody material, were sampled in Senator Beck and Porphyry lake sediments for ^{14}C analysis. Each macrofossil was sonicated and then freeze-dried. The samples were analysed for ^{14}C at the UC Irvine Keck Accelerator Mass Spectroscope facility (see Supplementary Information, Table S2). An oxalic acid standard of known ^{14}C age was also freeze-dried and analysed for ^{14}C content, yielding values within the range of analytical uncertainty, indicating that this method produces accurate radiocarbon ages. A depth-to-age model was constructed using the ^{210}Pb- and ^{14}C-based chronologies (see Supplementary Information, Fig. S2), and this model was used in combination with density and chemistry measurements described below to estimate mass and elemental accumulation rates through time. The offset between ^{210}Pb and ^{14}C records make it impossible to precisely constrain the timing of increased sedimentation; however, the record from Senator Beck Lake suggests that this period probably began in the 200 yr before present (see Supplementary Information for more information)

The density and texture of each core were also measured using methods described in the Supplementary Information. The elemental content of bedrock, sediments and dust were determined using inductively coupled plasma atomic emission spectroscopy and inductively coupled plasma mass spectroscopy. Samples were dissolved in HF using a microwave-assisted digestion method. Two bedrock standards and one soil standard were also analysed, yielding values within 5–7% of the expected values. We analysed five duplicate samples across the two cores, with the following coefficients of variation: Ca, 16%; K, 6%; Mg, 8%; P, 7%; Fe, 3%; Si, 13%. Relative elemental concentrations were measured for a duplicate core from Porphyry Lake using an EDAX Eagle III X-ray fluorescence analyser following methods described in the Supplementary Information. Carbon and nitrogen content was measured with a CNS combustion analyser. Carbon and nitrogen measurements were accurate to ∼1%, with an average variance on duplicate samples of less than 1%.

Measurements of Sr, Sm and Nd were made on dust, bedrock and sediment samples from Senator Beck Basin. Samples were dissolved in concentrated HF and $HClO_4$ following removal of ammonium-acetate-soluble materials. For sediments, we analysed two distinct size fractions, 37–60 μm and over 250 μm. Strontium was separated from the solution using SrSpec resins, whereas Sm and Nd are obtained using reverse-phase chromatographic techniques[53]. Isotope dilution concentration and Sr and Nd isotopic determinations were obtained using a Finnigan-MAT 261 thermal ionization mass spectrometer. Isotope dilution concentrations were accurate to ∼1% for Sr, and 0.5% for Sm and Nd. Total procedural blanks averaged ∼1 ng for Sr, and 100 pg for Nd, during the study period. Thirty measurements of SRM-987 during the study period yielded mean $^{87}\mathrm{Sr}/^{86}\mathrm{Sr} = 0.71032 \pm 2$. Analyses were corrected to the SRM-987 value of 0.71028. Measured $^{143}\mathrm{Nd}/^{144}\mathrm{Nd}$ were normalized to $^{146}\mathrm{Nd}/^{144}\mathrm{Nd} = 0.7219$. Thirty-three measurements of the La Jolla Nd standard during the study period yielded a mean $^{143}\mathrm{Nd}/^{144}\mathrm{Nd} = 0.511838 \pm 8$ (2-σ mean). $\varepsilon_{\mathrm{Nd}}$ ($\varepsilon_{\mathrm{Nd}} = \{[(^{143}\mathrm{Nd}/^{144}\mathrm{Nd})(\mathrm{sample})/(^{143}\mathrm{Nd}/^{144}\mathrm{Nd})(\mathrm{CHUR})] - 1\} \times 10^4$) values were calculated using a present-day $^{143}\mathrm{Nd}/^{144}\mathrm{Nd}(\mathrm{CHUR}) = 0.512638$ (see Supplementary Information, Table S3).

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References

1. Tanaka, T. Y. & Chiba, M. A numerical study of the contributions of dust source regions to the global dust budget. *Glob. Planet. Change* **52**, 88–104 (2006).
2. Blain, S. *et al.* Effect of natural iron fertilization on carbon sequestration in the Southern Ocean. *Nature* **446**, 1070-U1 (2007).
3. Kawahata, H., Okamoto, T., Matsumoto, E. & Ujiie, H. Fluctuations of eolian flux and ocean productivity in the mid-latitude North Pacific during the last 200 kyr. *Quat. Sci. Rev.* **19**, 1279–1291 (2000).
4. Chadwick, O. A., Derry, L. A., Vitousek, P. M., Huebert, B. J. & Hedin, L. O. Changing sources of nutrients during four million years of ecosystem development. *Nature* **397**, 491–497 (1999).
5. Tegen, I., Lacis, A. A. & Fung, I. The influence on climate forcing of mineral aerosols from disturbed soils. *Nature* **380**, 419–422 (1996).
6. Yoshioka, M., Mahowald, N., Dufresne, J. L. & Luo, C. Simulation of absorbing aerosol indices for African dust. *J. Geophys. Res.-Atmos.* **110** (2005).
7. Painter, T. H. *et al.* The impact of disturbed desert soils on duration of mountain snow cover. *Geophys. Res. Lett.* **34** doi:10.1029/2007GL030284 (2007).
8. Mohamed, A. M. O. & El Bassouni, K. M. Externalities of fugitive dust. *Environ. Monit. Assess.* **130**, 83–98 (2007).
9. Neff, J. C., Reynolds, R. L., Belnap, J. & Lamothe, P. Multi-decadal impacts of grazing on soil physical and biogeochemical properties in southeast Utah. *Ecol. Appl.* **15**, 87–95 (2005).
10. Abruzzi, W. S. The social and ecological consequences of early cattle ranching in the Little-Colorado River Basin. *Hum. Ecol.* **23**, 75–98 (1995).
11. Belnap, J. & Gillette, D. A. Vulnerability of desert biological soil crusts to wind erosion: The influences of crust development, soil texture, and disturbance. *J. Arid Environ.* **39**, 133–142 (1998).
12. Liu, L. Y. *et al.* Wind erodibility of major soils in the farming–pastoral ecotone of China. *J. Arid Environ.* **68**, 611–623 (2007).
13. Neff, J. C., Harden, J. W. & Gleixner, G. Fire effects on soil organic matter content, composition, and nutrients in boreal interior Alaska. *Can. J. Forest Res.-Revue Canadienne De Recherche Forestiere* **35**, 2178–2187 (2005).

14. McConnell, J. R., Aristarain, A. J., Banta, J. R., Edwards, P. R. & Simoes, J. C. 20th-Century doubling in dust archived in an Antarctic Peninsula ice core parallels climate change and desertifications in South America. *Proc. Natl Acad. Sci. USA* **104**, 5743–5748 (2007).
15. Kang, S. C. *et al.* Dust records from three ice cores: Relationships to spring atmospheric circulation over the Northern Hemisphere. *Atmos. Environ.* **37**, 4823–4835 (2003).
16. Steinmann, P. & Shotyk, W. Geochemistry, mineralogy, and geochemical mass balance on major elements in two peat bog profiles (Jura Mountains, Switzerland). *Chem. Geol.* **138**, 25–53 (1997).
17. Toney, J. L. & Anderson, R. S. A postglacial paleoecological record from the San Juan Mountains of Colorado: Fire, climate and vegetation history. *The Holocene* **16** doi:10.1191/0959683606hl946rp (2006).
18. Muhs, D. R. & Benedict, J. B. Eolian additions to late Quaternary alpine soils, Indian Peaks Wilderness Area, Colorado Front Range. *Arctic Antarctic Alpine Res.* **38**, 120–130 (2006).
19. Wells, K. C., Witek, M., Flatau, P., Kreidenwei, S. M. & Westphal, D. L. An analysis of seasonal surface dust aerosol concentrations in the western US (2001–2004): Observations and model predictions. *Atmos. Environ.* **41**, 6585–6597 (2007).
20. Bennett, V. C. & DePaolo, D. J. Proterozoic crustal history of the western United States as determined by neodymium isotopic mapping. *Geol. Soc. Am. Bull.* **99**, 674–685 (1987).
21. DePaolo, D. J. Neodymium isotopes in the Colorado front range and crust–mantle evolution in the proterozoic. *Nature* **291**, 193–196 (1981).
22. Kempton, P. D., Harmon, R. S., Hawkesworth, C. J. & Moorbath, S. Petrology and geochemistry of lower crustal granulites from the Geronimo Volcanic Field, Southeastern Arizona. *Geochim. Cosmochim. Acta* **54**, 3401–3426 (1990).
23. Nelson, B. K. & Depaolo, D. J. 1,700-Myr greenstone volcanic successions in Southwestern North-America and isotopic evolution of Proterozoic mantle. *Nature* **312**, 143–146 (1984).
24. Nelson, B. K. & Depaolo, D. J. Rapid production of continental-crust 1.7 to 1.9 b.Y. ago—Nd isotopic evidence from the basement of the North-American mid-continent. *Geol. Soc. Am. Bull.* **96**, 746–754 (1985).
25. Norman, D. I., Condie, K. C., Smith, R. W. & Thomann, W. F. Geochemical and Sr and Nd isotopic constraints on the origin of late Proterozoic volcanics and associated tin-bearing granites from the Franklin Mountains, West Texas. *Can. J. Earth Sci.* **24**, 830–839 (1987).
26. Patchett, P. J. & Ruiz, J. Nd isotopes and the origin of Grenville-age rocks in Texas—implications for Proterozoic evolution of the United-States mid-continent region. *J. Geol.* **97**, 685–695 (1989).
27. Ramo, O. T. & Calzia, J. P. Nd isotopic composition of cratonic rocks in the southern Death Valley region: Evidence for a substantial Archean source component in Mojavia. *Geology* **26**, 891–894 (1998).
28. Middleton, N. J., Betzer, P. R. & Bull, P. A. Long-range transport of 'giant' aeolian quartz grains: linkage with discrete sedimentary sources and implications for protective particle transfer. *Mar. Geol.* **177**, 411–417 (2001).
29. Olivarez, A. M., Owen, R. M. & Rea, D. K. Geochemistry of eolian dust in Pacific pelagic sediments—Implications for paleoclimatic interpretations. *Geochim. Cosmochim. Acta* **55**, 2147–2158 (1991).
30. Plater, A. J., Boyle, J. F., Mayers, C., Turner, S. D. & Stroud, R. W. Climate and human impact on lowland lake sedimentation in Central Coastal California: The record from c. 650 AD to the present. *Reg. Environ. Change* **6**, 71–85 (2006).
31. Andresen, C. S., Björck, S., Bennike, O. & Bond, G. Holocene climate changes in southern Greenland: Evidence from lake sediments. *J. Quat. Sci.* **19**, 783–795 (2004).
32. Cook, E. R., Woodhouse, C. A., Eakin, C. M., Meko, D. M. & Stahle, D. W. Long-term aridity changes in the western United States. *Science* **306**, 1015–1018 (2004).
33. Abruzzi, W. S. Ecology resource redistribution, and Mormon settlement in Northeastern Arizona. *Am. Anthropol.* **91**, 642–655 (1989).
34. Floyd, M. L., Fleischner, T. L., Hanna, D. & Whitefield, P. Effects of historic livestock grazing on vegetation at Chaco Culture National Historic Park, New Mexico. *Conserv. Biol.* **17**, 1703–1711 (2003).
35. Sayre, N. The cattle boom in southern Arizona: Towards a critical political ecology. *J. Southwest* **41**, 239–271 (1999).
36. Grahame, J. D. & Sisk, T. D. (eds) *Canyons, Cultures and Environmental Change: An Introduction to the Land-use History of the Colorado Plateau* (2002) (accessed November 5, 2007) http://www.cpluhna.nau.edu/index.htm.
37. Fleischner, T. L. Ecological costs of livestock grazing in Western North-America. *Conserv. Biol.* **8**, 629–644 (1994).
38. Prospero, J. M. Long-range transport of mineral dust in the global atmosphere: Impact of African dust on the environment of the southeastern United States. *Proc. Natl Acad. Sci. USA* **96**, 3396–3403 (1999).
39. Sickman, J. O., Melack, J. M. & Clow, D. W. Evidence for nutrient enrichment of high-elevation lakes in the Sierra Nevada, California. *Limnol. Oceanogr.* **48**, 1885–1892 (2003).
40. Wolfe, A. P., Baron, J. S. & Cornett, R. J. Anthropogenic nitrogen deposition induces rapid ecological changes in alpine lakes of the Colorado Front Range (USA). *J. Paleolimnol.* **25**, 1–7 (2001).
41. Jassby, A. D., Reuter, J. E., Axler, R. P., Goldman, C. R. & Hackley, S. H. Atmospheric deposition of nitrogen and phosphorus in the annual nutrient load of Lake Tahoe (California Nevada). *Wat. Resour. Res.* **30**, 2207–2216 (1994).
42. Kopáček, J., Stuchlik, E. & Hardekopf, D. Chemical composition of the Tatra Mountain Lakes: Recovery from acidification. *Biologia* **61**, S21–S33 (2006).
43. Larssen, T. & Carmichael, G. R. Acid rain and acidification in China: The importance of base cation deposition. *Environ. Pollut.* **110**, 89–102 (2000).
44. Rogora, M., Mosello, R. & Marchetto, A. Long-term trends in the chemistry of atmospheric deposition in Northwestern Italy: the role of increasing Saharan dust deposition. *Tellus B* **56**, 426–434 (2004).
45. Meixner, T. *et al.* Multidecadal hydrochemical response of a Sierra Nevada watershed: Sensitivity to weathering rate and changes in deposition. *J. Hydrol.* **285**, 272–285 (2004).
46. Patience, A. J., Lallier-Vergès, E., Alberic, P., Desprairies, A. & Tribovillard, N. Relationships between organo-mineral supply and early diagenesis in the lacustrine environment: A study of surficial sediments from the Lac du Bouchet (Haute Loire, France). *Quat. Sci. Rev.* **15**, 213–221 (1996).
47. Burns, D. A. The effects of atmospheric nitrogen deposition in the Rocky Mountains of Colorado and southern Wyoming, USA—a critical review. *Environ. Pollut.* **127**, 257–269 (2004).
48. Galloway, J. N. *et al.* Nitrogen cycles: Past, present, and future. *Biogeochemistry* **70**, 153–226 (2004).
49. Mikkelsen, R. L. & Bruulsema, T. W. Fertilizer use for horticultural crops in the US during the 20th century. *Horttechnology* **15**, 24–30 (2005).
50. Moulin, C. & Chiapello, I. Impact of human-induced desertification on the intensification of Sahel dust emission and export over the last decades. *Geophys. Res. Lett.* **33** doi:10.1029/2006GL025923 (2006).
51. Mahowald, N. M. *et al.* Climate response and radiative forcing from mineral aerosols during the last glacial maximum, pre-industrial, current and doubled-carbon dioxide climates. *Geophys. Res. Lett.* **33** doi:10.1029/2006GL026126 (2006).
52. Appleby, P. G. & Oldfield, F. The assessment of Pb-210 data from sites with varying sediment accumulation rates. *Hydrobiologia* **103**, 29–35 (1983).
53. Farmer, G. L., Broxton, D. E., Warren, R. G. & Pickthorn, W. Nd, Sr, and O isotopic variations in metaluminous ash-flow tuffs and related volcanic-rocks at the Timber Mountain Oasis-Valley Caldera, Complex, SW Nevada—Implications for the origin and evolution of large-volume silicic magma bodies. *Contrib. Mineral. Petrol.* **109**, 53–68 (1991).

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Correspondence and requests for materials should be addressed to J.C.N.

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Author contributions

All authors commented on the manuscript and participated in the analysis of project results. J.C.N. and A.P.B. designed and carried out the study and J.C.N. developed the paper. G.L.F. carried out the isotopic analysis and aided in the interpretation of sediment isotopic chemistry. N.M.M. provided assistance in evaluating project results in comparison with global patterns in dust deposition. J.L.C., J.T.O., C.R.L. and R.L.R. analysed sediment core and dust chemistry. T.H.P. and C.C.L. developed and implemented dust sampling protocols for snowpack and assisted in sampling.