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GEOLOGICAL NOTE

Sizes and Shapes of 10-Ma Distal Fall Pyroclasts in the Ogallala Group, Nebraska

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ABSTRACT

Size distributions of distal ashfall particles from correlated 10-Ma layers in Nebraska, measured using laser diffraction methods, are lognormal with mode diameters of ~90 μm. This ashfall is ~100% bubble-wall shards of rhyolite glass and apparently represents a distal ashfall from an eruption 1400 km away. Measured terminal velocities of these ash particles are 0.2–18 cm/s, consistent with Stokes Law settling of spherical particles with diameters of 9–50 μm. Surface area of the ash particles, measured with gas adsorption, is 20–30 times the surface area of equivalent Stokes spheres. These results highlight the effects of shape and atmospheric drag in distal ashfalls. They also highlight atmospheric transport and fallout of distal ashfall particles, because these deposits resemble many other ashfalls preserved in the Great Plains of North America throughout the Tertiary and Quaternary. Because the ashfalls preserve major mammalian death assemblages, they demonstrate that deposits with modes of optical diameters >100 μm are still hazardous by aerodynamic definitions of lung disease risk and include particles substantially within hazardous PM10 ranges. The aerodynamically fine particle size may lead to substantial aeolian redistribution, causing local thicknesses of >2 m. Overall, the ashfall thicknesses observed are at least several times larger than would be expected based on exponential thinning from the volcano. Shape measurements of distal ash particles may be necessary to assess risk. The possible health risks in the central United States from a future rhyolitic eruption in the western United States may be significant.

Introduction

The Great Plains of America, covered by geological units such as the Ogallala Group (Darton 1903), have dozens of prominent Tertiary and Quaternary ashfall horizons (Wadsworth 1885; Izett 1981) that record distal fallout from volcanic eruptions >1000 km away, in and around the Great Basin. These fall deposits are found in North Dakota, South Dakota, Nebraska, Kansas, Colorado, Wyoming, New Mexico, Oklahoma, and Texas and host important fossil sites in the region (Voorhies and Thomasson 1979). Transport of ash by westerly prevailing winds at and near the tropopause, and rapid aggradation and preservation in the Ogallala, makes the Great Plains one of the world's best places to study distal ashfall deposits and their associated volcanic hazards. Ogallala ash horizons are known to local geologists and paleontologists but have not yet been well correlated (Perkins et al. 1995*a*, 1995*b*; Perkins 1998).

Distal fallout (distances >150 km) happens 1–24 h after emplacement in the atmosphere after most coarse (>500 μm) pyroclasts are already on the ground closer to the volcano (Rose et al. 2001). It results from aerodynamically small (spherical diameters of <500 μm) ash particles in the laminar flow regime, based on particle Reynolds number (Bonadonna et al. 1998), that fall as aggregates (Carey and Sigurdsson 1982; Sparks et al. 1997). Distal fallout is rarely mapped, but when this is done, secondary maxima in mass accumulations are found (Sarna-Wocjicki et al. 1981; McGimsey et al. 2001). A well-known occurrence of distal ashfall is the 2-m-thick deposit at Ashfall Fossil Beds State Historical Park in NE Nebraska, in the 1-Ma

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Cap Rock Member of the Ash Hollow Formation of the Ogallala Group, which contains a spectacular large-mammal fossil occurrence (Voorhies and Thomasson 1979). It represents a remarkable death assemblage of multiple whole skeletons of numerous species including rhinoceros, camels, and several kinds of horses. Lung disease conditions were the cause of death (Beck 1995). The deposit is correlated with occurrences in Morrill county, western Nebraska (Diffendal 1982, 1995; Diffendal et al. 1996), and has been tentatively associated with eruption from the Bruneau-Jarbridge Volcano of western Idaho (Perkins 1998), about 1400 km west (fig. 1). Work on fine ashfalls (Baxter et al. 1999) and on airborne particles and industrial health (Expert Panel on Air Quality Standards 2001) has heightened interest in the effects of fine particles on health. The aim of this article is to determine the sizes, shapes, and terminal velocities of the distal volcanic ash associated with the Ashfall Fossil Beds occurrence and its correlatives in Nebraska and to consider the implications of these data for ashfall hazards from future explosive eruptions in the western United States.

Methods

We determined the size distribution of ash samples using laser diffraction techniques with a Microtrac instrument. Such devices determine optical diameters in the range of 700 μm to <1 μm. We also separated one of the ashes into terminal velocity groups, using a powder elutriation device called a Roller Analyzer (Roller 1931). Pyroclasts grouped by their terminal velocity were then imaged using a scanning electron microscope (fig. 2). We then used image analysis software (Clemex) to determine size and shape parameters such as average diameter (average of 64 diameters for each particle) and perimeter. The surface area of bulk ash samples was determined by N_2 gas adsorption using a Micrometeoritics BET Analyzer. These methods are discussed in detail by C. M. Riley, W. I. Rose, and G. J. S. Bluth (unpub. manuscript). Analysis of grain size data used schemes of Folk and Ward (1957) and Inman (1952), as well as the common techniques of aerosol science (Rhodes 1999; Friedlander 2000) that use standard statistical and mathematical approaches to get concentrations of particles, average particle diameter and surface areas (table 1).

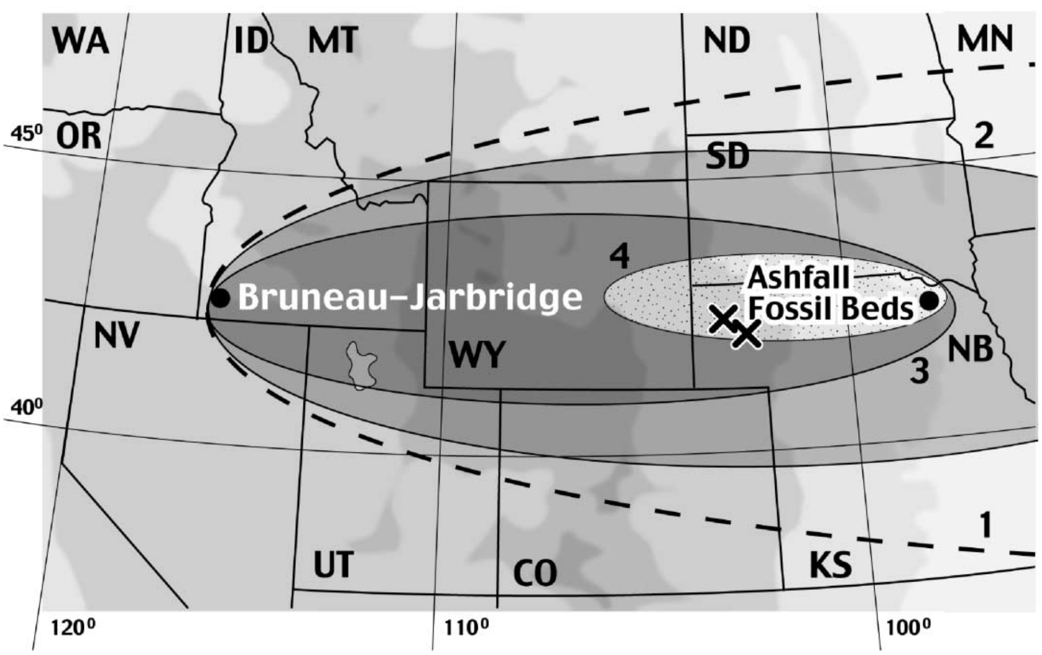


Figure 1. Location map showing Bruneau-Jarbridge volcano in SW Idaho and Ashfall Fossil Beds in NE Nebraska and two sampled ash localities in Morrill County, Western Nebraska (*x*). Possible elliptical shapes of distal isomass lines on the map are speculatively outlined, by analogy with other well-sampled distal fall deposit maps such as Sarna-Wojcicki et al. (1981) and McGimsey et al. (2001). Ellipsoidal lines 1–3 show the possible configuration of a deposit that exponentially thins away from the source, whereas ellipse 4 outlines a possible "secondary maximum" of deposition, such as that shown by well-mapped deposits.

Samples Studied

We studied samples from several localities each at three sites in Nebraska—the Ashfall Fossil Beds near Royal in NE Nebraska and sites in W Nebraska near Broadwater on the Fairchild and Gillespie ranches and ~15 km west at Greenwood Canyon in southern Morrill County (fig. 1). Each of these occurrences is thought to represent the same ashfall, and the descriptions of sample sites are described elsewhere (figs. 12 and 13 in Diffendal 1995; Perkins et al. 1995*a*). The exposures are found roughly parallel to contours in areas that span several square kilometers. Diffendal (1995, p. 72) has found more than 100 ashfall localities: "Their geometries vary from 'shoestring' channel fills that can be traced for up to 1 km, through lens shapes and irregular shapes, to broad blankets covering up to several sections." The samples we collected are quite pure, nearly 100% rhyolitic glass in the form of bubble-wall shards (fig. 2) sampled from blanket occurrences. Ash layers are silver-gray in color and either show no bedding or fine lamination with minor ripple scale cross lamination. Diatoms are found in some ash lentils, indicating a lacustrine depositional environment (Voorhies and Thomasson 1979). Thickness of ashfall layers varies from ~40 cm to 2 m. Ash thickens in apparent depressions and thins markedly within short distances, indicating reworking by wind or water after deposition. Above the ashfall there is mixed sediment and ash material, and at least minor ash is found in much of the overlying Ogallala beds. At the Ashfall Fossil Beds site, we sampled the deposit stratigraphically at regular 10-cm intervals across a 1.5-m thickness. At the western Nebraska localities, we sampled from the midpoint in apparently homogeneous layers.

Results

Optical diameters of pyroclasts are plotted in figure 3, and details of the data for two of the samples are in table 1. They show log normal distributions with peaks in modes ranging from 70 to 200 μm (2.3–3.8

Figure 2. Scanning electron microscopy images of the Broadwater ash sample from Western Nebraska showing the overall shapes of all the ash samples in this study. We interpret these as bubble wall shards. The image at the top illustrates the spontaneous aggregation of these ash particles that occurs in the Roller Analyzer during elutriation.

Table 1. Tabulated Size and Shape Parameters, 10-Ma Nebraska Ashfalls

Parameters	Western Nebraska (CR970401; 41°28′59″N, 102°52′05″W)	Northeastern Nebraska (NB-29-09; 42°22′32″N, 98°07′32″W)
BET specific surface area (m^2/g)	1.2291	1.9902
Bulk density (kg/m^3)	2300	2300
Metric scale parameters:		
First moment (arithmetic metric mean) (mm)	.0852	.0698
SD (metric sorting) (mm)	.0626	.0471
Specific surface area (m^2/m^3 or m^{-1})[a]	126,165.95	144,130.99
Specific surface area (m^2/g)[a]	.05485	.06267
ϕ scale parameters:		
Sixteenth fractile	2.82	3.12
Median, fiftieth fractile	3.84	4.12
Eighty-fourth fractile	5.01	5.24
Moment method:		
First moment (arithmetic ϕ mean)	3.94	4.18
Standard deviation (ϕ sorting)	1.10	1.04
Skewness[b]	.13	.14
Kurtosis[b]	2.90	2.82
Folk and Ward method:		
Mean	3.89	4.16
Sorting	1.57	1.53
Inman method:		
Mean	3.91	4.18
Sorting	1.09	1.06
Raw micrometric data (wt%):		
Bin size (μm):		
704	0	0
497.8	0	0
352	1.64	0
248.9	6.27	3.18
176	12.09	8.65
124.45	16.73	14.84
88	18.52	19.17
62.23	16.4	15.05
44	12.25	9.41
31.11	7.38	5.86
22	4.59	3.49
15.56	2.84	1.12
11	.94	.42
7.78	.35	0

[a] Calculated from the harmonic mean of the weight frequency grain-size distribution assuming spherical shape.
[b] Pearson's skewness (β_1) and kurtosis (β_2) (Kendall 1947).

ϕ) and metric sortings of 40–60 μm ($\sigma\phi$ of 1–1.6). Using ϕ-scale parameters, the samples are slightly positively skewed and show kurtosis of about 3. Samples from W Nebraska and from the base of the NE Nebraska section are coarser than the main part of the thick NE Nebraska section. To arrive in Nebraska from Idaho, the ash must have spent about 10–30 h in transit in the upper troposphere or stratosphere, if it traveled at typical North American tropopause wind speeds of 15–40 m/s. We would expect equidimensional particles of about 40–70 microns to fall out after this time from tropopause levels, but we instead see mostly grains with larger diameters. Overall, the optical diameter data describes a surprisingly coarse material considering the great distance from source. Scanning electronic microscopy (SEM) examination reveals a nonspherical shape (fig. 2), and as previous work (Wilson and Huang 1979) on pyroclast shape has revealed the importance of particle shape on atmospheric drag, we characterized the shape more thoroughly.

The individual pyroclasts in one of the samples from western Nebraska separate into terminal velocity groups ranging from 0.6 to 18 cm/s. We note, using Stokes Law, that if the pyroclasts were spheres with the same terminal velocity and density (2300 kg/m^3), they would consist of particles with spherical diameters from 9 to 50 μm, finer than the observed optical diameters (fig. 4). Shapes of pyroclasts were examined directly in 2D using SEM and digital imaging. This verified the larger optical diameters and showed that the particles

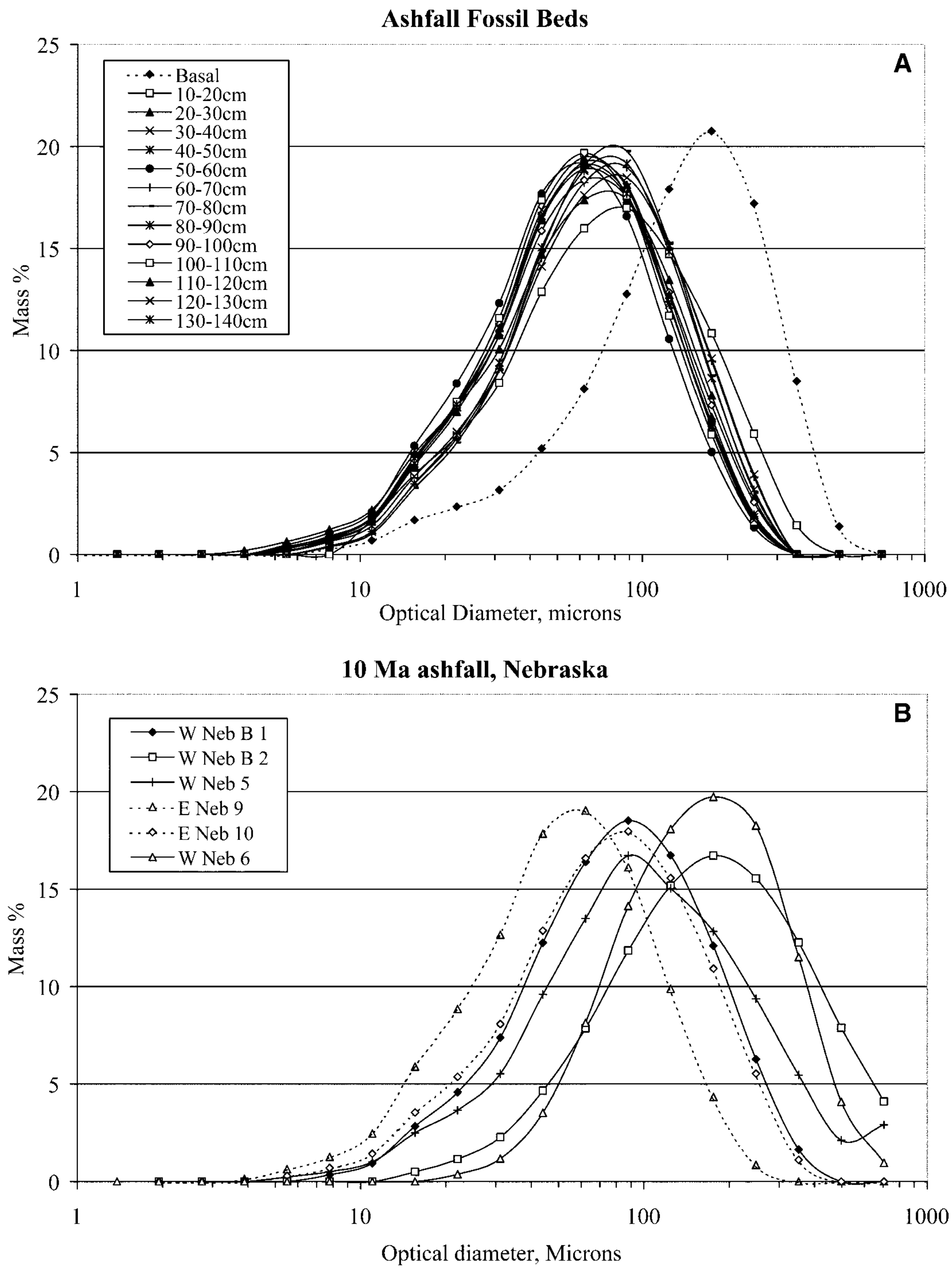


Figure 3. Optical diameter size distribution data for Nebraska 10-Ma ashfalls as determined by Microtrac laser diffraction. *A*, Data for a stratigraphic section collected at Ashfall Fossil beds in NE Nebraska; *B*, size differences between the localities in northeastern (*dashed lines*) and western Nebraska (*solid lines*).

have high aspect ratios of >2 and perimeters that exceed the perimeters of spheres with aerodynamically similar terminal velocities.

Bulk surface area for these ashes was determined directly by BET and found to range from 1.3 to 2.0 m^2/g (table 1). These values are about 22–32 times the surface areas expected for aerodynamically equivalent spherical particles (fig. 4; table 1).

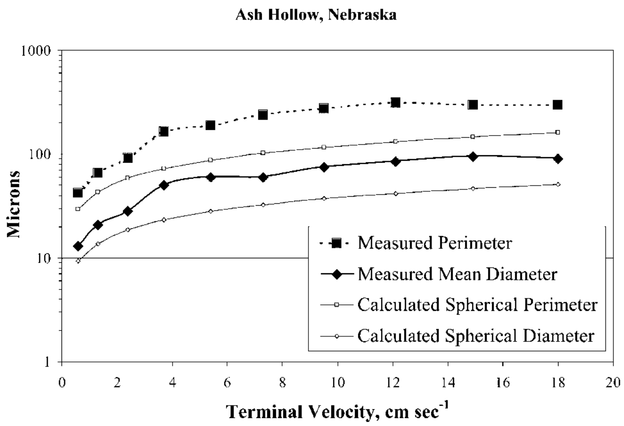


Figure 4. Measured average diameters and perimeters for particles in the separated terminal velocity groups from the western Nebraska ash sample (*bold curves*) contrasted with calculated values for spheres of the same density that would have the same terminal velocity in the atmosphere (*fine lines*). The spherical calculated values are based on laminar flow equations, as is appropriate for their small diameter (Bonadonna et al. 1998). The observed values of diameter and perimeter for the ash are 0.5–1 order of magnitude larger than spheres.

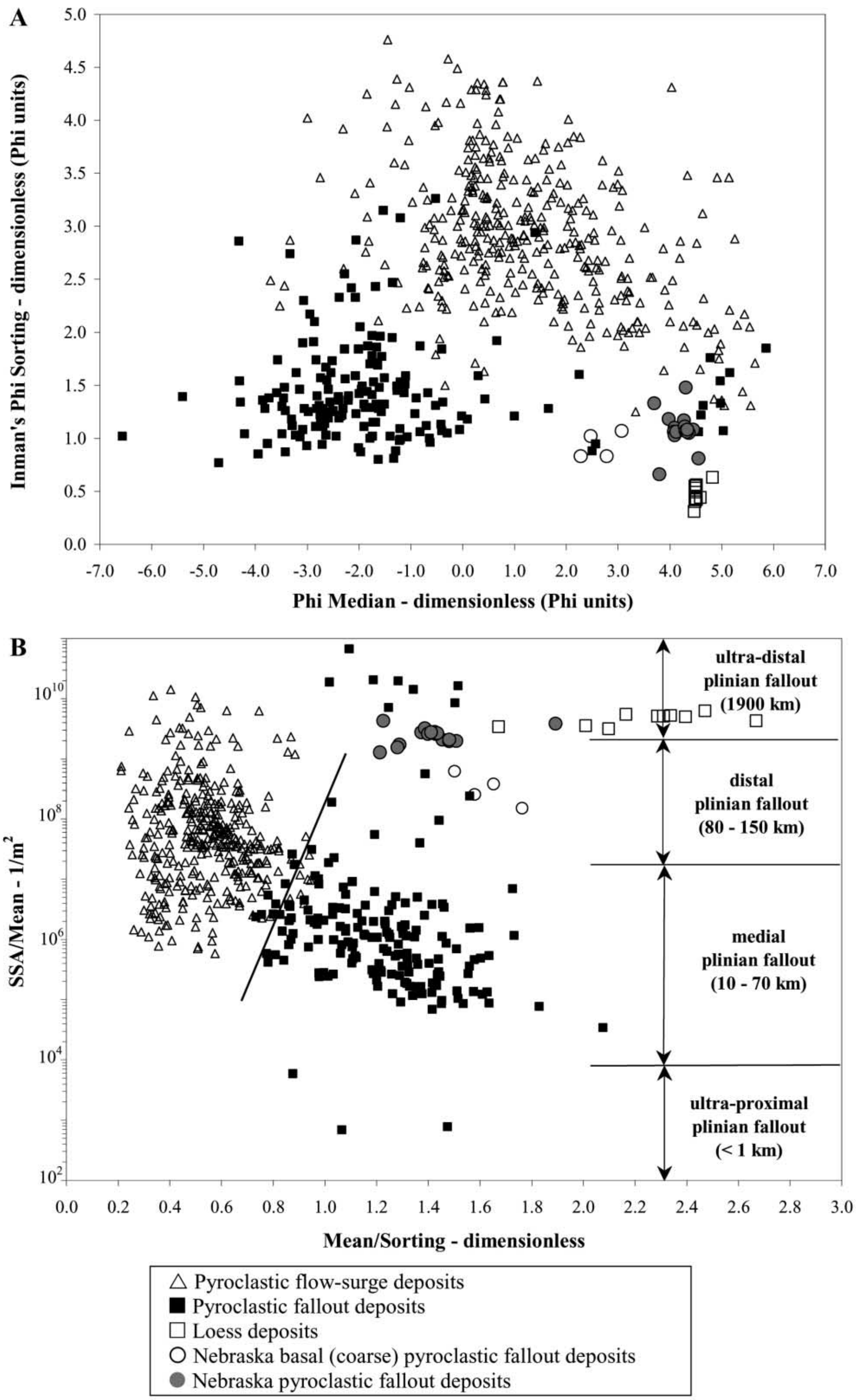
In summary, our results show that distal rhyolitic fall materials can be surprisingly coarse (75–200 μm in diameter), the terminal velocity of these materials is the same as spheres one-third to one-eighth as large, the surface area of this material is 22–32 times larger than similarly sorted spheres, and the more proximal ashes and the pyroclasts that deposited first are coarser by about a factor of 2.

Discussion

Figure 5 compares pyroclastic deposits from Dartevelle et al. (2002) (surge, flow, fallout) and loess deposits within Walker's (1971) traditional ϕ-scale diagram (ϕ sorting vs. ϕ median; fig. 5*A*) and the diagram of two grain-size ratios in the metric scale (specific surface area/mean ratio vs. mean/sorting ratio; fig. 5*B*). In both diagrams, Nebraska ashfalls are similar to ultradistal falls such as Askja plinian fallout collected at 1900 km from source (Dartevelle et al. 2002). For instance, F median of the Nebraska fallout is about 4 (fig. 5*A*), and specific surface area (SSA)/mean > 10^9 (fig. 5*B*), which indicates that they consist of very fine micrometric materials. Nebraska ashes resemble the sizes and the shapes described for distal (3000 km) ashfall from Toba's YTT (Youngest Toba Tuff) eruption (Rose and Chesner 1987). Other silicic eruptions probably produce ashes with similar characteristics (high surface area and aspect ratios, enhanced atmospheric drag). The diagram of the two grain-size ratios (fig. 5*B*) has been initially used to discriminate coignimbrite from plinian fallouts (Dartevelle et al. [2002]. In figure 5*B*, Nebraska deposits occupy a position equivalent to the plinian ultradistal fallout (e.g., mean/sorting > 1). However, we cannot conclude that those deposits have a plinian origin, as it is very likely that their mean/sorting ratios have been modified and increased by the action of water and/or wind, which are both excellent sorting agents (decrease the sorting values) (Udden 1898, 1914). Therefore, a coignimbrite origin for those Nebraska fallouts cannot be excluded. Their anomalous thickness, presence of ripple cross lamination, and coarser basal layer are consistent with deposition in water. In figure 5*B*, eolian loess deposits (Udden 1898) have higher mean/sorting values than the utmost ultradistal plinian fallouts, which indicates an extreme aerial sorting by the action of wind (Porter 2001). In addition, Nebraska fallout ashes, Askja ultradistal plinian fallouts, and loess deposits have very similar SSA/mean values (>10^9), consistent with their distal origin (a few thousand kilometers).

Thicknesses of distal fall deposits sampled here are 40 cm to 2 m, which is perhaps an order of magnitude more than what would be expected for a fall deposit based on data from isopach mapping (fig. 6). A recent compilation of ashfall thicknesses from the Yellowstone hotspot (Perkins and Nash 2002, fig. 10) shows that anomalous thicknesses are present in many Neogene Great Plains fall deposits. There is no clear evidence to explain the cause of these greater thicknesses. Redeposition or redistri-

Figure 5. Grain size properties of >600 pyroclastic deposits (Dartevelle et al. 2002): pyroclastic flow and surge deposits (*open triangles*) and plinian, subplinian, strombolian fallout deposits (*filled squares*); coarse basal Nebraska fallout deposits (*open circles*), upper fine-grained Nebraska fallout deposits (*gray filled circles*), and loess deposits (*open squares*; Udden 1898, 1914). *A*, ϕ-sorting versus ϕ-median diagram after Walker (1971). *B*, Metric two-grain-size-ratios diagram (Dartevelle et al. 2002). The vertical axis is the ratio of specific surface area over mean (SSA/mean, m^{-2}), and the horizontal axis is the ratio of mean over sorting (mean/sorting, dimensionless). The bulk specific



surface area is the total surface area of a set of grains to their total volume (in m^{-1}) and is sensitive to the bulk grain size (e.g., it decreases with increasing grain size). Hence, SSA/mean distinguishes coarse-grained from fine-grained deposits (e.g., proximal fall from distal fall deposits), and the mean/sorting ratio discriminates deposits with high relative sorting (e.g., flow, surge, coignimbrite) from those with low relative sorting (e.g., pure plinian fall deposits, loess). The distance indication on the right side of *B* pertains only to plinian fallout deposits.

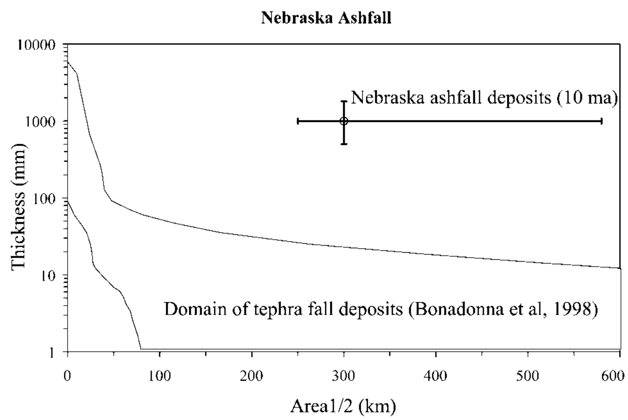


Figure 6. Thickness/area plots from isopach maps of ashfall deposits (Bonadonna et al. 1998) compared with Nebraska occurrences. Area estimates for Nebraska come from a hypothetical analogous area such as ellipse 3 or 4 in figure 1 and are likely minima, as the distribution of these deposits are not well known. Thicknesses are observed but could be affected by redistribution after deposition.

bution of the ash after initial fall clearly occurred, however. We observed ripple scale laminations in the upper part of the Ashfall Fossil Beds locality and at some of the western Nebraska localities (see Diffendal 1982, 1995; Diffendal et al. 1996 for details), which are suggestive of deposition in water. The variability of thickness is significant on a local scale. At Ashfall Fossil Beds the thickness of the ash varies from less than 0.5 m to more than 2 m within a lateral distance of less than 1 km. Whether redeposition occurred by fluvial or aeolian processes is unclear. The aerodynamic sizes of the ash particles means that they would have been susceptible to aeolian transport, and it is likely that airborne ash was abundant for at least several months after deposition. Because the Great Plains is an important region for loess redeposition, particularly during glacial episodes, we know about the patterns of aeolian redeposition of loess. Kohfeld and Harrison (2001) show that Wisconsin age loess in Nebraska thins markedly (>30 m to 1 m in ~100 km), moving away from its source regions (along glacial termini and river valleys). This pattern of loess thinning does not help explain the overall anomalous observed thickness of the 10-ka ash in all its Nebraska occurrences. Scasso et al. (1994) observed significant aeolian redeposition in the fall deposits of the 1991 Hudson eruption, which showed aeolian dune features and other obvious signs of aeolian redistribution. We suggest that aeolian redistribution might be able to account for the large local changes in ash thickness seen in Nebraska, and perhaps ash accumulated in valleys where water may have helped trap the fine particles. Overall, the Nebraska occurrences may not be part of an exponentially thinning blanket deposit but, instead, are probably a secondary maximum, as schematically shown in figure 1, ellipse 4. Data from Perkins and Nash (2002, fig. 10) strongly indicate that this anomalous distal thickness is a feature of many large Neogene eruptions.

Figure 7 shows the fall rates of spherical particles in the atmosphere from an arbitrary 32 km, representing a stratospheric level. Upper air flow from western North America is typically westerly in the range of 15–40 m/s, which would deliver air parcels from Idaho to Nebraska in 10–30 hrs. Pyroclasts aerodynamically similar to the Nebraska fall (9–50 mm diameter spheres) would fall out in 20–500 h if they fell as individual particles. Thus, simple fall can explain only the very coarsest particles in the Nebraska case, and most of the particles were affected by clustering or aggregation processes, as observed by Sorem (1982) and suggested by Carey and Sigurdsson (1982) Scasso et al. (1994) and Sparks et al. (1997). Particle aggregation may be enhanced by atmospheric turbulence (R. A. Shaw, C. M. Riley, and W. I. Rose, unpub. manuscript), and in this case, the location downwind of the Rocky Mountains is suggestive of the influence of turbulence induced as a mountain wave. Alternatively, the occurrence of a thunderstorm and convective air movement could also have enhanced aggregation. We speculate that meteorological observations could be critical in the accurate forecasting of distal fall and anomalous distal fall thickness.

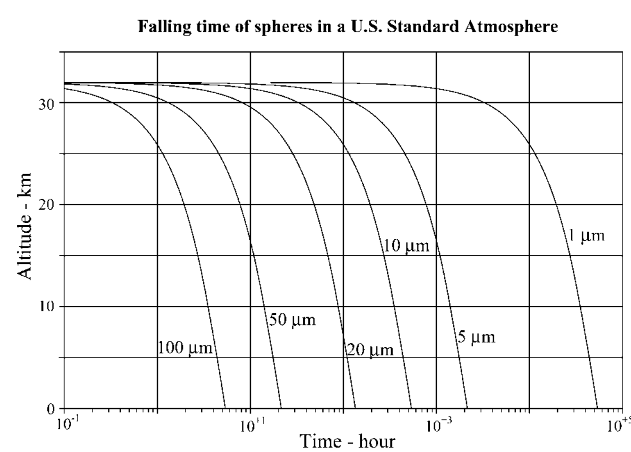


Figure 7. Fall times for spherical particles with a density of 2300 kg/m³ from 32 km in the atmosphere.

Current focus of airborne particle hazards is on concentrations of particles smaller than 10 μm or 2.5 μm (PM 10 and PM 2.5) (Expert Panel on Air Quality Standards 2001). Although the Nebraska particles are mostly larger than 10 mm, they had lethal impact on large mammals. Medical hazards of fine ash to humans have been related to size and concentrations in three categories, inhalable, thoracic, and respirable, depending on whether the small particles would penetrate beyond the nose, throat, or fine lung channels. As this hazard is related to aerodynamics and channels of air flow (injection of particles into the lung), it is important to consider particle shape in this assessment. Although the proportions of PM 10 and PM 2.5 in the samples we examined are small (3%–9% PM 10), they would be larger if we considered aerodynamically equivalent diameter cutoffs (about 10%–30% equivalent PM 10). Because these particles have extreme shapes, we speculate that it may be important to revise health hazard assessments of distal ash to include shape.

The geological description of the environment at the Ashfall Fossil Beds concludes that the large number of animals found concentrated in the area was because it was a local waterhole (Voorhies and Thomasson 1979), and the observed laminations in the deposit suggest ripple marks. Thus, ash deposition may have occurred in water. Studies of ash settling through shallow water columns are rare, although deep-sea conditions have been studied (Cashman and Fiske 1991; Carey 1997). Coarser pyroclasts would be expected at the base of fall deposits that accumulate underwater, as the higher viscosity of the water separates particles at the beginning of fall. Application of this principle by Ledbetter and Sparks (1979) determined the duration of eruptions where a deep-sea ashfall was preserved. Effects of deposition on a water surface and subsequent fall through a shallow water column could explain the basal coarse layer, because the behavior of the finer, initially hydrophobic, nonhydrated glass bubble-wall shards may have tended to float and might have settled more slowly than larger grains, especially during the initial fallout.

Conclusions

Rhyolitic ashfalls of ages ranging from Miocene to Pleistocene at distances of 1000 km or more from the vent are common in the Great Plains of the United States. One 10-Ma layer in Nebraska contains particles ~100 μm in diameter. The terminal velocities of these same particles are much less than 100-μm spheres because these particles have platy shapes and high surface areas and atmospheric drag—their terminal velocities are equivalent to spheres with diameters of only 9–50 μm. The particles are preserved in well-sorted layers that fell prematurely as aggregates and would possibly be carried thousands of kilometers farther if they had remained as simple particles. The cause of their aggregation and fallout may be meteorological turbulence or thunderstorms. The observed thickness of these fall deposits are an order of magnitude or more than data on proximal falls would suggest, and they likely represent secondary mass maxima. There is evidence for substantial aeolian and fluvial redistribution of these ashes on at least a local scale. More comprehensive work on these distal ash occurrences may be needed because of their unusual shape characteristics and their obvious potential for health hazards.

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