Possible deposit of soil dust from the 1930's U.S. dust bowl identified in Greenland ice

J. Donarummo Jr.,[1] M. Ram,[2] and E. F. Stoermer[3]

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[1] We have identified a dust storm deposit in the GISP2 ice core that most likely originated from the Great Plains region of the United States during the 1930's 'Dust Bowl' era. These results indicate that the Central U.S. can be a significant source of dust to the Greenland ice sheet, especially when the source area is affected by intense drought conditions. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; 1812 Hydrology: Drought; 3655 Mineralogy and Petrology: Major element composition; 1827 Hydrology: Glaciology (1863). **Citation:** Donarummo, J., Jr., M. Ram, and E. F. Stoermer, Possible deposit of soil dust from the 1930's U.S. dust bowl identified in Greenland ice, *Geophys. Res. Lett.*, *30*(6), 1269, doi:10.1029/2002GL016641, 2003.

1. Introduction

[2] During the U.S. Dust Bowl of the 1930's, enormous quantities of soil dust were lofted into the atmosphere and deposited thousands of miles away [*Worster*, 1979]. The magnitude of the dust storms over the North American continent during those years was so large [*Goudie*, 1983] that it is reasonable to consider that some of the dust may have found its way to the Greenland ice sheet. Indeed, *Hammer* [1977] reports measuring large dust peaks in the Summit and Dye 3 ice cores from Greenland. The timing of the peaks (1935 for Summit and 1936 for Dye 3) led Hammer to conjecture that the dust might possibly be associated with the severe dust storms that occurred in the U.S. at that time. No dust composition measurements were reported so that it was not possible to substantiate the conjecture.

[3] In this paper, we report our observation of a very large peak (Figure 1) in the shallow (0 to 120 m) dust concentration profile from the Greenland Ice Sheet Project 2 (GISP2) ice core from Central Greenland. The remote location and high altitude (3.2 km) of the GISP2 drilling site make it unlikely that the dust was derived from local sources. In addition, this dust peak is not coincident with an increase in sulfate concentration, which rules out the possibility that it was of volcanic origin, nor with an increase in ammonium, which rules out the possibility that it originated from a forest fire (Figure 1). The dating of the core [*Meese et al.*, 1997] indicates that the dust associated with the peak was deposited in 1933, a year when the first severe dust storms of the Dust Bowl occurred over the continental U.S. [*Worster*, 1979]. The results presented in this paper support the conclusion that the peak is associated with a deposit of dust from a dust storm that most likely originated from the U.S. Great Plains region.

2. Methods

[4] All sample handling procedures were performed under Class 100 clean room conditions. The dust concentration profile shown in Figure 1 was obtained using the laser-light scattering (LLS) from meltwater technique [*Ram and Illing*, 1994].

[5] Two samples, labeled Holocene Dust Storm (HDS) and Holocene Background (HBG), were extracted from the GISP2 ice core at the depths indicated in Figure 1. The size distribution and concentration of dust particles in the samples were measured using an Elzone 280PC (Coulter-type) particle size analyzer fitted with a 20 μm orifice tube, which has an effective measuring range of 0.8 to 10 μm. Each sample was vigorously shaken prior to measurement to ensure suspension of the largest grains. Aliquots of the meltwater samples (4.35 g of HDS and 4.90 g of HBG) were filtered onto 0.08 μm pore diameter Nuclepore filters, which were subsequently mounted on sample stubs and coated with evaporated carbon. Particles recovered onto the filter from sample HDS were brownish-yellow in color. Sample HBG did not produce a filter that was suitable for measurement due to its low dust concentration. The morphology and major element (Na, Mg, Al, Si, P, S, K, Ca, Ti, Mn, Fe) chemical composition of particles on the HDS filter were measured using a Hitachi S-4000 field emission scanning electron microscope (SEM) equipped with an energy-dispersive X-ray spectrometer (EDS). The EDS system is limited to the analysis of particles larger than 1 μm. Randomly selected areas of the filter were photographed at 2000X magnification, and all particles within each field of view that were larger than 1 μm and were not overlapping adjacent particles were analyzed using EDS. The beam voltage was set at 20 kV and each EDS spectrum was collected for 100 s. Particles were rejected if their x-ray count rate fell below 100 counts per second. Diatom searches were performed by scanning the entire filter at 500X magnification.

2.1. Particle Identification

[6] Mineral identifications were made using the elemental peak intensity ratio method [*Mudroch et al.*, 1977; *Maggi*, 1997], modified to account for operating conditions of our SEM/EDS system. Powdered mineral standards were selected to represent mineral groups that have previously been identified in Greenland ice core samples [*Biscaye et*

[1]Department of Geology, University at Buffalo, Buffalo, New York, USA.
[2]Department of Physics, University at Buffalo, Buffalo, New York, USA.
[3]Herbarium, University of Michigan, Ann Arbor, Michigan, USA.

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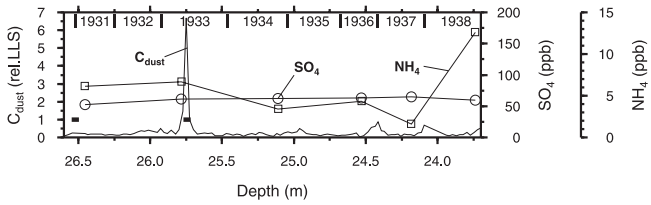

Figure 1. The GISP2 dust profile, 23 to 27 m depth. The thin line shows the raw LLS data. Dating in year A.D. [*Meese et al.*, 1997] is shown at the top of the plot. The thick lines at 25.75 and 26.5 m indicate the positions of meltwater samples HDS (4.5 cm long) and HBG (9.5 cm long), respectively, that were extracted from the core for this study.

al., 1997; *Maggi*, 1997; *Svensson et al.*, 2000]. Peak ratios calculated from the standards were used to separate the GISP2 dust particles into the standard mineral groups. Particles with simple chemistry (i.e. one or two dominant elements) were identified as follows: high Si = quartz; high Fe + Ti = Fe/Ti oxide. Particles with complex chemistry were identified using the peak ratio sorting scheme shown in Figure 2. The relative oxide percentages for each particle were calculated from the measured atomic percentage and compared with literature values [*Deer et al.*, 1992; *Newman*, 1987; *van Olphen and Fripiat*, 1979; *Weaver and Pollard*, 1973] to verify that the mineral identifications were accurate. Particles that did not match any of the standard mineral groups were sorted into separate unknown bins, labeled U-A to U-F in Figure 2.

3. Results

3.1. Size Distribution

[7] The size distribution of sample HDS (Figure 3) is consistent with a deposit of dust that has been transported in a dust storm [*Duce*, 1995], whereas the size distribution of sample HBG is representative of the background dust aerosol. The mean diameter of particles from sample HDS is 1.39 μm and from sample HBG is 1.23 μm. Both samples have equal volume modes at 2.4 μm, and are lognormal in the diameter range 0.9–2.5 μm.

[8] The size distributions of both samples converge at diameters greater than 4 μm, where gravitational settling exerts an increasing influence on suspended particles. In sample HDS, there is an excess of particles in the diameter range 1.2 to 4 μm, which corresponds to a soil-derived aerosol mode [*Patterson and Gillette*, 1977]. The maximum particle size identified in sample HDS, detected using the SEM, is 10 μm. The concentration of particles in HDS is 5.13 μg dust/cc meltwater and in HBG is 2.44 μg dust/cc meltwater.

3.2. Particle Morphology and Mineralogy

[9] Particles in sample HDS have a morphology that is typical of airborne soil dust. Platy particles are the most numerous type in the sample and are concentrated in the finer size range, whereas blocky particles tend to be concentrated in the coarser size range. Platy dust particles are often transported as aggregates that dissociate upon deposition and/or sampling, or are attached to the surfaces of large particles [*Gomes et al.*, 1990]. Although we could not verify the presence of fine-grained aggregates in our dust samples, we have observed numerous small (less than 0.5 μm), platy particles adhering to the surfaces of large particles.

[10] Sample HDS contained many diatom frustules and frustule fragments as well as chrysophyte cysts and other plant fragments. Table 1 lists the relative abundance of all diatom frustules and fragments that were identifiable to species or genus. They are consistent with, but not specific to, the U.S. Great Plains region. They appear to be common soil forms, or diatoms that grow in shallow water bodies (such as prairie pot hole ponds or playas, for example). The most abundant species present, *Luticola cohnii* (Figure 4), is common in soils or harsh subaerial habitats.

[11] The mineral assemblages in the samples analyzed are typical of what we expect to find in a population of soil dust particles, with high amounts of stable minerals such as quartz, clays, orthoclase and albite, and low amounts of unstable minerals such as pyroxenes, amphiboles and high-Ca plagioclase (Table 2). Calcite and other highly soluble minerals dissolve in the meltwater and are lost during filtration [*Steffensen*, 1997; *Biscaye et al.*, 1997]. In Table 2, we show the mineralogy of particles recovered from two Wisconsinan samples for comparison with sample HDS. The sample labeled Wisconsinan High Dust (WHD)

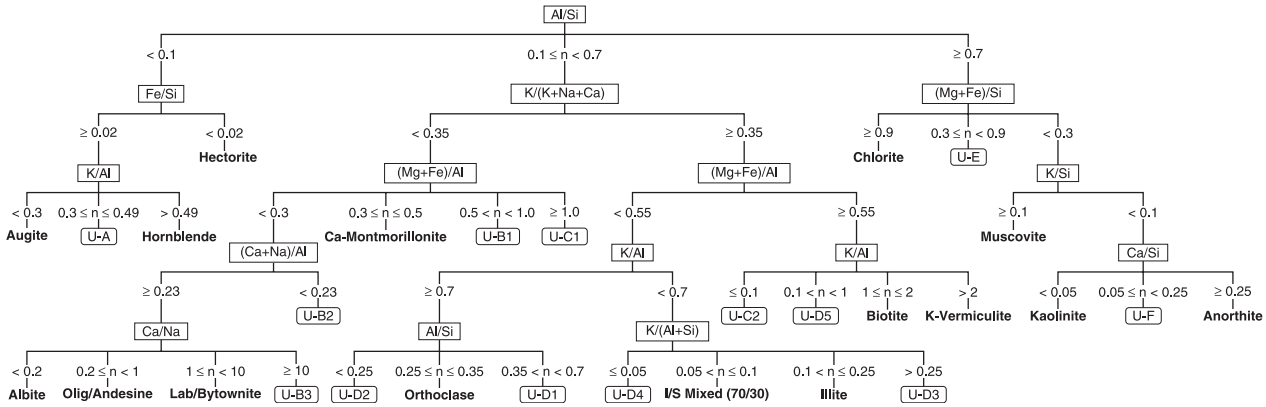

Figure 2. Peak intensity ratio sorting scheme used to identify mineral particles in the GISP2 dust samples. Standards used to define the sorting limits are indicated in bold. The ratios indicated in the flowchart are calculated at each step and the particle is sorted accordingly.

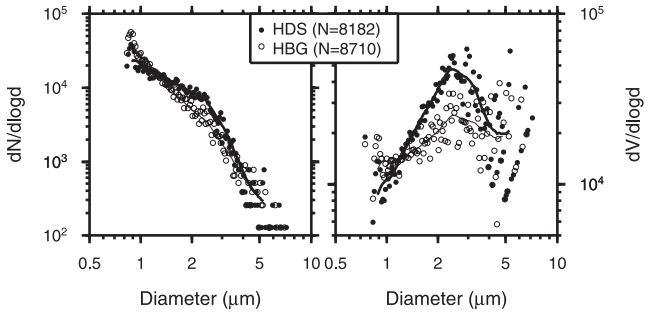

Figure 3. Size distributions of GISP2 dust particles. The solid lines represent 20 point moving averages of the data.

is from a cold, glacial period when atmospheric dust concentrations were very high. The sample labeled Wisconsinan Low Dust (WLD) is from a warm, interstadial period when atmospheric dust concentrations were very low. There is sufficient evidence [*Biscaye et al.*, 1997; *Svensson et al.*, 2000; *Bory et al.*, 2002] to suggest that both WHD and WLD are most likely derived from Asian dust source areas. The significant differences between the Wisconsinan samples and sample HDS would seem to indicate that HDS was derived from a source area other than Asia.

[12] Particles from the unknown groups U-C1 and U-C2 have EDS spectra that are characteristic of chlorite. When the oxide relative weight percentages of these particles are recalculated in terms of the general formula $(Mg,Fe,Al)_6(Al,Si)_4O_{10}(OH)_8$, a number of particles in U-C1 and U-C2 can be positively identified as chlorite.

[13] An interesting result of our work is the high concentration of dust particles in just two of the unknown groups in Figure 2, U-D4 and U-D5. The particles in U-D4 all contain Si, Al, and small amounts of Mg and/or Fe, and most likely represent an illite/smectite mixed layer clay with high percentages of Fe. The particles in group U-D5 all contain Si, Al, and high amounts of Mg and/or Fe. They most likely represent a mixed layer clay from the biotite/chlorite weathering series. These findings are consistent with the results of *Svensson et al.* [2000], who identified mixed layer clays in the Greenland samples they analyzed.

4. Discussion

[14] *Bory et al.* [2002], and references therein, have used the kaolinite/chlorite (K/C) ratio as a latitudinal indicator of dust source area. They measured the K/C ratio of soil samples from the three main dust source areas in the Northern Hemisphere (Eastern Asia, North America and Northern Africa) using X-ray diffraction of bulk samples. Their results indicate that soils from Eastern Asia have a K/C ratio range of 0.1 to 1, whereas both North American and Northern African soils have K/C ratios that range from 1 to 10. Our results indicate that sample HDS has a K/C ratio of 3.5, which is consistent with a North American or Northern African source area. In contrast, the K/C ratio of sample WHD is 0.6 and sample WLD is 0, both of which are consistent with an East Asian source area. Based on the evidence presented here, we cannot exclude Northern Africa as a possible dust source area for sample HDS.

[15] The transport of aerosols from North America to Summit, Greenland, is a viable atmospheric pathway. *Dibb et al.* [1996] tracked the transport of a biomass burning plume from the Hudson Bay lowlands region of Canada to Summit, Greenland. *Slater et al.* [2001] showed that at least 50% of the air masses transported to Summit during May/June of 1992–1996 had origins in the North American sector, which included regions down to 40°N latitude. Their evidence included increased soil dust aerosols (as represented by Ca and Mg soluble ions) during 1995 that could

Table 1. Relative Abundance of Diatoms in Sample HDS

Diatom Species	Number (%)	Mean Length, μm (±1σ)
Luticola cohnii (Hilse) D.G. Mann	16 (30.8)	10.6 (1.5)
Hantzschia or Nitzschia	7 (13.5)	[a]
Camaepinnularia sp.	7 (13.5)	15.8 (1.4)
Pinnularia borealis	2 (3.8)	[a]
Fragilariaforma	1 (1.9)	>20 (a)
Total	52(100.0)	

[a]No size information is included since no whole frustules were found.

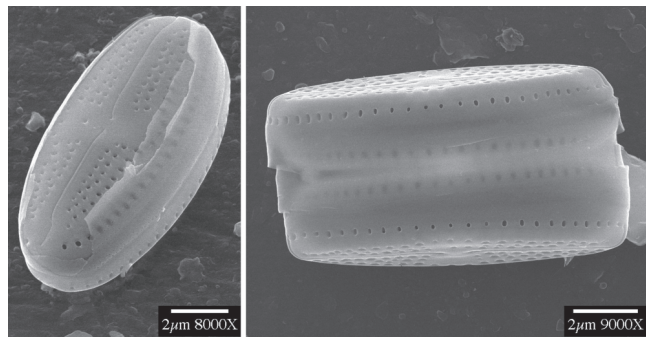

Figure 4. SEM micrographs of *Luticola cohnii (Hilse) D.G. Mann*. The specimen on the left has a partially intact outer membrane. The specimen on the right had completed cell division and was in the process of secreting new frustules when it died. The rows of areolae along the edges of the new frustules are clearly visible.

Table 2. Relative Abundance of Mineral Groups in the GISP2 Dust Samples

Mineral Group	HDS (%)	WHD[a] (%)	WLD[b] (%)
Quartz	34.1	26.4	27.9
Kaolinite	2.36	1.65	0
Illite	10.8	12.6	14.2
I/S Mixed (70/30)	13.2	16.5	9.84
Smectite: Ca-Montmorillonite	0.34	0.55	0.55
Chlorite	0	0.55	3.28
Muscovite	2.7	4.4	6.01
Orthoclase Feldspar	4.39	1.65	1.64
Plagioclase: Albite	4.05	5.49	5.46
Plagioclase: Olig/Andesine	3.72	1.1	1.09
Plagioclase: Lab/Bytownite	0.34	0.55	2.19
Augite	0.68	0	0
Fe/Ti Oxide	1.35	1.65	1.64
U-C1: Si, Al, high Mg + Fe	0.34	1.1	1.64
U-C2: Si, Al, high Mg + Fe	1.01	1.65	1.09
U-D4: Si, Al, low Mg + Fe	10.1	11.5	3.28
U-D5: Si, Al, K, high Mg + Fe	9.12	9.89	18.0
Other unknowns	1.36	2.75	2.18
Total	99.96	99.98	99.99
	(N = 296)	(N = 182)	(N = 183)

[a]Wisconsinan High Dust, 2055.0–2055.2 m, 27,790 (±10%) yr B.P.
[b]Wisconsinan Low Dust, 2060.0–2060.2 m, 28,143 (±10%) yr B.P.

only have come from snow-free areas south of 60°N latitude. Direct evidence for the transport of soil dust from North America to Greenland was presented by *Gayley et al.* [1989]. They observed diatoms of the species *Stephanodiscus niagarae*, which are indigenous to North America, in dust retrieved from the Crête ice core from Central Greenland.

[16] During the early 1930's, a number of dust storms that were generated in the Central U.S. transported dust over thousands of miles. A severe sand storm that occurred on January 18, 1933 in eastern Wyoming [*Disterdick*, 1933] is associated with the same weather system that transported dust from Kansas over Illinois, Indiana, Michigan and as far east as Quebec (Canada) [*Andrus*, 1933]. In mid-November, 1933, a large storm carried dust from the Northern Great Plains to the Atlantic coast [*Miller*, 1934]. A month later another storm occurred, and was determined [*Page and Chapman*, 1934] to be the source of an unusual dustfall that was reported in numerous locations from Sault St. Marie, Michigan to Quebec. *Page and Chapman* [1934] concluded that the dust was most likely picked up from an area centered on the Oklahoma panhandle region in the Southern Plains. Dust that was observed over Baton Rouge, Louisiana on April 12, 1934 [*Russell and Russell*, 1934] is most likely related to a dustfall that was reported from the Dakotas to Florida [*Mattice*, 1935]. In May of 1934, a severe storm scoured dust from the Northern Great Plains region and transported it towards the southeast, causing a dustfall that was reported across the Atlantic coast of the U.S. from Maine to Georgia [*Hand*, 1934; *Kellogg*, 1935; *Mattice*, 1935]. These reported occurrences lend credence to the idea that Dust Bowl dust could have been transported all the way to Central Greenland.

5. Conclusions

[17] Our results indicate that the Central U.S. may contribute significant amounts of dust to the Greenland ice sheet, especially under severe drought conditions. There is evidence [*Woodhouse and Overpeck*, 1998] that the Central U.S. has experienced drought conditions in the past 2,000 years that were more intense, more frequent and longer in duration than the drought that caused the U.S. Dust Bowl of the 1930's, and we suspect that large amounts of dust were transported from the Central U.S. to the Greenland ice sheet at these times.

[18] **Acknowledgments.** Figures 1, 2, and 3 were made using GMT [*Wessel and Smith*, 1991]. This work was supported in part by the National Science Foundation.

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J. Donarummo Jr., Department of Geology, University at Buffalo, 876 Natural Sciences Complex, Buffalo, NY 14260, USA. (jd2@buffalo.edu)

M. Ram, Department of Physics, University at Buffalo, 303 Fronczak Hall, Buffalo, NY 14260, USA. (phymram@physics.buffalo.edu)

E. F. Stoermer, Herbarium, University of Michigan, Ann Arbor, MI 48109, USA. (stoermer@umich.edu)