Two distinct seasonal Asian source regions for mineral dust deposited in Greenland (NorthGRIP)

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[1] A four-year, high-resolution (<2 mo) record of mineralogical and isotopic (Sr and Nd) characteristics of mineral dust deposited at NorthGRIP confirms the seasonal variability in the eastern Asian source regions providing dust to northern Greenland at present. Comparison of the Sr and Nd isotopic compositions of the dust with those of potential source area samples from China and Mongolia support that the Takla Makan desert is the primary source, supplying most if not all of the mineral particles during the dusty spring season. A different source area, however, plays a role during most of year and during the low-dust season (summer through winter) in particular. Inner Mongolian deserts of northern China, including the Tengger and the Mu Us, are likely candidates but the Mongolian Gobi is ruled out as a significant contributor to Greenland. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0322 Atmospheric Composition and Structure: Constituent sources and sinks; 0330 Atmospheric Composition and Structure: Geochemical cycles; 9315 Information Related to Geographic Region: Arctic region; 9320 Information Related to Geographic Region: Asia. **Citation:** Bory, A. J.-M., P. E. Biscaye, and F. E. Grousset, Two distinct seasonal Asian source regions for mineral dust deposited in Greenland (NorthGRIP), *Geophys. Res. Lett.*, *30*(4), 1167, doi:10.1029/2002GL016446, 2003.

1. Introduction

[2] By comparing mineralogical and isotopic (Sr and Nd) composition of the mineral dust extracted from ice cores with that of small particles in sediment samples in potential source areas (PSA) for Greenland dust, it has been shown that eastern Asia was the main source for Greenland dust during several intervals of the last Glacial period [*Biscaye et al.*, 1997; *Svensson et al.*, 2000] and in the Holocene [*Svensson*, 1998]. A recent study of mineral dust extracted from snow and firn deposited over the last decade at the NorthGRIP ice camp (75.1°N, 042.3°W) has confirmed the eastern Asian origin for central Greenland dust through the present day [*Bory et al.*, 2002]. Some of the results of that study suggested that the provenance of the dust varied seasonally within eastern Asia, and that the major source of the dust was the Takla Makan desert (hereinafter TM) of northwest China. These conclusions, however, were rather tentative since they were based on only 7 Greenland samples, representing a 1.4-year record sampled at ~2.4-mo resolution, and since no source area was determined for more than half of the yearly dust deposition. Here we present a new ~4-year record of the mineralogical and isotopic composition of dust with a ~1.9-mo resolution obtained at NorthGRIP during summer 2001. Results are discussed in the light of additional PSA sample analyses from China and Mongolia to better constrain present-day sources and transport patterns.

2. Methods

[3] Twenty three horizontal snow layers ~8 cm thick, ~60 cm wide and ~15-m long were collected for dust extraction from a snow-pit (i.e., ~150 kg of snow each), approximately 4 km south of NorthGRIP ice camp. Two additional large samples were taken at the surface (drifted snow in the vicinity of the pit). The snow pit was also sampled continuously at 3 cm intervals (i.e., a few g of snow each) down its entire depth for the analysis of $\delta^{18}O$ and $[Ca^{2+}]$. Mineral dust (carbonate-free fraction) was analysed by X-ray diffraction before undergoing complete acid digestion. Sr and Nd were then separated using exchange columns and analysed by thermal ionization mass spectrometry. Measured SRM987 standard $^{87}Sr/^{86}Sr$ and La Jolla Standard $^{143}Nd/^{144}Nd$ were 0.710280 (±9 10 − 6, 1 σ, N = 11) and 0.511836 (±14 10 − 6, 1 σ, N = 7), and data were normalized with respect to certified values 0.71024 and 0.51186, respectively, with propagating errors. Blanks were less than 1% of Sr and Nd weights, and were considered negligible. Fine fractions (<5 μm diameter) of eight PSA samples, 5 from the TM desert (all from 40.8°N, 084.3°E), 1 from the Gobi desert (43.5°N, 104.5°E), 1 from the Tengger desert (38.8°N, 105.5°E), and 1 from the Mu Us (39.5°N, 110.0°E), were also analyzed. All procedures are fully described elsewhere [*Bory et al.*, 2002].

3. Results and Discussion

3.1. Eastern Asian Origin of North Greenland Dust

[4] All mineral compositions of the 2001 snow pit dust samples are characterized by low (0.10–0.61) kaolinite/chlorite ratios, and are similar to those obtained in previous snow pit [*Bory et al.*, 2002] and ice core [*Biscaye et al.*, 1997; *Svensson et al.*, 2000] studies in Greenland. Such mineralogical signatures are typical of east Asian source areas and rule out the two other main candidates, North America and northern Africa, as significant contributors for Greenland dust as discussed in *Bory et al.* [2002] on the basis of 310 PSA samples (202 from Eastern Asia, 91 from North America, and 17 from Africa). Although Texas dust has been observed in north-eastern USA, as well as Saharan dust, which also makes it regularly to northern Europe,

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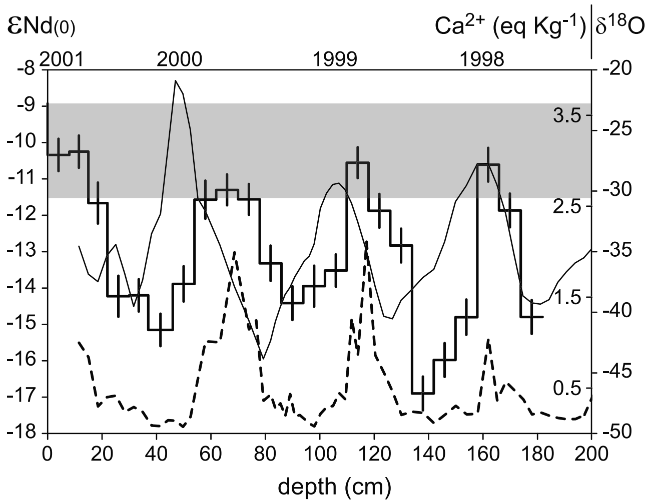

Figure 1. εNd(0) of the dust (step-like line), $\delta^{18}O$ (solid line) and Ca^{2+} concentration (dashed line) versus depth in the NorthGRIP 2001 snow-pit. $\delta^{18}O$ and $[Ca^{2+}]$ are proxies for temperature and dust, respectively. $\delta^{18}O$ provides the basis for a seasonal stratigraphy. Corresponding years are indicated above the summer peaks. Because the $\delta^{18}O$ stratigraphy, obtained along one vertical profile a few cm wide down the side of the pit, might not be representative exactly of the 15 m-long large-volume samples stratigraphy (due to uneven horizontal snow distribution and/or possibly imperfect horizontal sampling), εNd(0) and $\delta^{18}O$ times series were synchronized using the dust concentration in the snow-pit layer (not shown) which was correlated with the $[Ca^{2+}]$ using the AnalySeries 1.2 software from D. Paillard (http://www.agu.org/eos_elec/96097e.html). Dust concentration varies from $\geq\sim 140$ μg kg^{-1} in the spring to $\geq\sim 20$ μg kg^{-1} in the autumn.

transport patterns must prevent these from reaching the ∼3000 m-high Greenland ice-sheet.

[5] Both the timing of the annual main dust fallout in Greenland and the transport patterns are also consistent with an eastern Asian origin. The marked spring increase in dust concentration in Greenland (Figure 1), which has been known for some time [*Hamilton and Langway*, 1967], coincides with the most active period for dust storms in eastern Asia. During the spring, cold air outbreaks emerge from Siberia causing cold fronts and cyclonic activity, and huge amounts of lithogenic material are lifted to high altitude (up to 8000 m) over Asia [*Sun et al.*, 2001]. This dust is transported in the westerlies towards the Pacific, often reaching remote Islands [*Merrill et al.*, 1989], the western U.S.A. coast [*Husar et al.*, 2001], and Alaska and the central Canadian arctic [*Barrie*, 1995]. Satellite observations of Asian dust have even been recently reported in the spring over North America's Atlantic coast (http://visibleearth.nasa.gov/cgi-bin/viewrecord?7721). Air-mass back-trajectories from Greenland indicate that eastern Asian air masses regularly reach the ice cap, especially during the winter and spring seasons [*Kahl et al.*, 1997].

3.2. Range of Dust Isotopic Signatures

[6] The Sr and Nd isotopic composition of the new snow-pit dust samples ($^{87}Sr/^{86}Sr$ from ∼0.720 to ∼0.725 and εNd(0) from ∼−9.0 to ∼−17.0) falls largely within the range obtained from previous snow pit studies at North-GRIP (Figure 2). Two very negative εNd(0) values (−15.9 ± 0.6 and −16.8 ± 0.6) support the existence of a strongly non-radiogenic end-member (source area) as suggested by a snow-pit dust εNd(0) of −17.2 ± 0.4 in *Bory et al.* [2002]. The new snow pit samples, on the other hand, show a rather narrower range in Sr isotopic ratios than previously reported, probably reflecting a lesser contribution of volcanogenic material during 1998–2001 than over some periods of the 1989–1998 decade.

3.3. Seasonal Variability of Dust Provenance

[7] The temporal variability of the mineralogical and isotopic composition shows a distinct seasonal trend throughout the ∼4 year record, as best illustrated by the Nd isotopic composition (Figure 1). This confirms earlier findings which were based on a shorter time-series [*Bory et al.*, 2002], that dust provenance in northern Greenland varies seasonally.

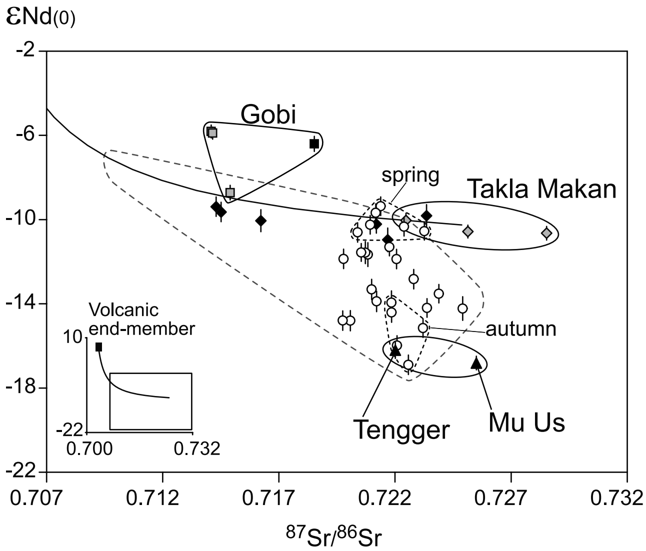

Figure 2. εNd(0) versus $^{87}Sr/^{86}Sr$ of the 2001 snow-pit samples (open circles) and of the PSA samples from China and Mongolia (gray squares: *Biscaye et al.* [1997]; gray diamonds: *Bory et al.* [2002]; black symbols: this study), together with the mixing curve (solid line) between the TM desert end-member (average of the 4 TM samples enclosed in the TM domain) and the volcanogenic end-member used in *Biscaye et al.* [1997]. The contour of the snow-pit dust isotopic compositions obtained in previous snow-pit work [*Bory et al.*, 2002] is shown by the dashed line. The re-analysis of one TM sample from *Bory et al.* [2002] (40.11°N, 088.3°E) which presented an unusually high analytical uncertainty gave a much less negative εNd(0) value, contracting the TM domain compared to the one originally estimated for this desert. The 5 additional PSA samples from the TM presented here are atmospheric dust samples (black diamonds outside the TM domain). Because of their small size, analyses were carried out on the bulk fraction (carbonate was thus not removed), resulting in lower $^{87}Sr/^{86}Sr$ ratios; considering the extremely low Nd concentration in carbonates, the latter's effect on εNd(0), however, is negligible.

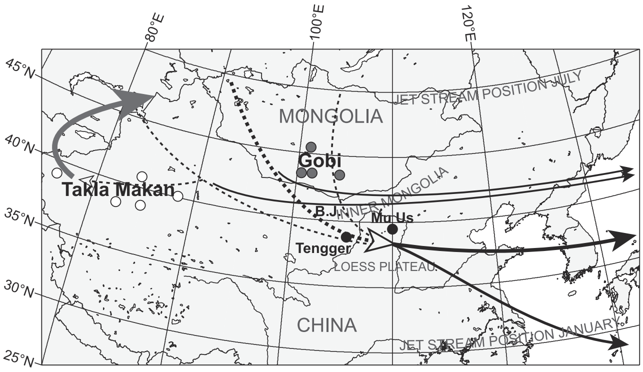

Figure 3. Location of the PSA samples presented on Figure 2, and schematic winds and dust transport pathways in the spring (adapted from *Sun et al.* [2001]). Dotted lines: route of cold air outbreaks; solid black lines: dust route at low atmospheric level; solid gray line: dust route at higher atmospheric level. The relative thickness of the lines indicates the relative importance of the winds/transport pathways. The location of the Badain Jaran (B.J.) is given for reference.

[8] The reliable stratigraphy obtained in this study (see caption, Figure 1) clearly indicates that the isotopic composition of the dust varies together with the dust concentration. The least negative εNd(0) values are observed during the spring dust concentration peaks while the most negative εNd(0) values are recorded in the autumn when dust concentration is minimal.

3.4. The Major North Greenland Dust Source: The Takla Makan Desert

[9] The mineralogical and isotopic characteristics of two major eastern Asian dust sources, the TM (Xingjiang province, northwestern China) and the Gobi (southern Mongolia) deserts, were investigated in *Biscaye et al.* [1997] and *Bory et al.* [2002]. The additional PSA samples from both deserts presented here in Figure 2 (locations in Figure 3) show isotopic compositions which are largely consistent with those previously reported. The isotopic signature of the Gobi desert, however, which is characterized by relatively less negative εNd(0), is stretched slightly towards more radiogenic $^{87}Sr/^{86}Sr$, and the Nd isotopic composition of the TM desert is circumscribed by a narrower range of values (−9.4 to −11.0) than stated in *Bory et al.* [2002] (see caption, Figure 2). The snow-pit samples fall either on or below the TM-volcanogenic end-member mixing curve. Those on or close to the TM mixing curve are all from the spring season. These results confirm that the Gobi desert of Mongolia is not a significant provider of present-day mineral dust to northern Greenland (although a minor contribution cannot be completely excluded), and that the TM is the main source during the dustiest period of the year and therefore by far the dominant contributor of mineral particles deposited onto the ice cap.

[10] This is consistent with the fact that the TM, the largest desert in China, is thought to be the most active dust source in eastern Asia at present [*Prospero et al.*, 2002], especially with respect to long-range transport. Indeed, dust from the TM is entrained to elevations >5000 m and often takes a northern route before being transported in the westerlies (Figure 3). By comparison, the dust from the Gobi is first transported southeastwards at lower tropospheric levels, generally <3000 m (see *Sun et al.* [2001] for details). The dust transport from the TM, often unaccounted for at the downwind meteorological stations in China due to its high altitude, has been clearly evidenced in recent satellite observations. In the spring, large scale dust storms taking place simultaneously in both the TM and the Gobi can actually be superimposed over the Pacific ocean but at two distinct tropospheric levels, kilometers apart [*Iwasaka et al.*, 1983]. Both differences in elevations and pathways make it therefore more likely for the dust originating from the TM to be transported farther and to higher latitudes, eventually reaching Greenland.

3.5. Evidence for Additional Source(s) in Inner Mongolia

[11] On the εNd(0) versus $^{87}Sr/^{86}Sr$ plot (Figure 2), most snow-pit samples, however, fall below the TM mixing curve, implying the role of at least one other dust source as first suggested by *Bory et al.* [2002]. Furthermore, based on the εNd(0), it is now apparent that the other source(s) may not play a role solely during the lowest dust season in Greenland (autumn), but most likely in the winter and summer also. Indeed, relatively few samples, those corresponding to peaks in dust concentration, have a εNd(0) consistent with 100% TM origin (Figures 1 and 2). There is growing evidence that some of the northern Chinese deserts in the Inner Mongolia province, between the Mongolian Gobi desert (to the north) and the Chinese Loess Plateau (to the south), could also be significant dust sources [*Derbyshire et al.*, 1998; *Sun et al.*, 2001]. Based on records from 174 meteorological stations in Mongolia and China, *Sun et al.* [2001] report that this region is where most dust storms have occurred during the 1960–1999 period. For example, the huge transport events of April 1998, which yielded high dust concentration over the U.S.A. west coast [*Husar et al.*, 2001], originated in part in the region enclosing in particular the Badain Jaran, Tengger, and Mu Us deserts of northern China [*Sun et al.*, 2000]; the Tengger desert is also thought to contribute to 'Kosa' event (i.e., dust fall over Japan) [*Kanayama et al.*, 2002].

[12] The analysis of two samples, one from the Tengger desert and one from the Mu Us (Figure 3), shows them to have a much less radiogenic neodymium signature (more negative εNd(0)) than the Gobi or the TM deserts. The Tengger and Mu Us samples' isotopic compositions are similar to the snow-pit samples presenting the most negative εNd(0) (Figure 2), making these deserts possible candidates for the missing end-member. This supports the hypothesis that Chinese Inner Mongolian deserts export mineral dust to Greenland and could be the dominant source during the low-dust season.

3.6. Relation of Dust Source to Transport Patterns

[13] Although dust storms in China and Mongolia increase dramatically in frequency and intensity in the spring, they occur all year round, both in the TM and in Inner Mongolia, and dust events are still reported in remote Pacific sites during the less-intense seasons for dust storms in eastern Asia [*Merrill et al.*, 1989]. Why then would Inner

Mongolia and not the TM export dust to Greenland in the low-dust season in particular? This may be related to the extreme topography surrounding the TM. Indeed, the TM, located in the Tarim basin, is bounded by high mountains (average elevation >5000 m): the Tibet plateau to the south, the mountains of the Hindu Kush to the west and the Tien Shan range to the north. Only the strong upwards wind created by highly unstable synoptic systems during the spring may provide favorable conditions for the dust to easily escape the basin [*Sun et al.*, 2001]. The Tengger is also bounded by mountains, albeit of lesser heights, such as the Helan mountains to the east and Qilian mountains to the south-west. It is not, however, in an enclosed basin, and it is located immediately at the leeward (southwestern) end of the Hexi Corridor, which is one of the most common route for cold-air outbreaks. These can continue their southeasterly route either north or south of the Helan mountains towards the Ordos plateau, where the Mu Us desert is located, or towards the Loess plateau, respectively [*Derbyshire et al.*, 1998]. Although dust entrained in this region is usually transported at relatively low elevations (<3000 m), it is known to occasionally reach the middle troposphere and then be transported long distances [*Sun et al.*, 2001]. The southward shift of the Jet Stream between its summer (∼50°N lat.) and winter (∼30°N lat.) positions (Figure 3) may also facilitate the long-range transport of the dust from this region during autumn and winter. This is supported by back trajectory analyses which show that eastern Asian air masses reaching Greenland in winter originate, on average, from lower latitudes than in the summer [*Kahl et al.*, 1997]. The fact that dust from the Gobi does not reach Greenland in the low-dust season might be due to the weakness of storms in Mongolia during this period of the year, the presence of snow cover, or the nature of the Gobi [*Middleton*, 1991]. The 'Gobi' (meaning 'gravel/pebble pavement') might indeed only be a significant source for long range transport occasionally during the strong storm conditions in the spring when low-pressure frontal system pass across the country. During this season, however, the initial direction of the dust transport from the Gobi is southerly [*Sun et al.*, 2001], away from the stronger westerlies associated with the more northerly Jet Stream. As a result, Gobi (and Inner Mongolia) dust is likely to be transported not as fast and as far in the westerlies and at lower latitude, and primarily TM dust is transported to Greenland as discussed above.

[14] These results imply that, in addition to aridity and desert type (*gobi* versus silty/sandy), the interplay of the seasonal variability in regional wind conditions with local topography and large-scale transport pathways in eastern Asia likely accounts for a large part of the variable provenance of mineral dust during the year at NorthGRIP. Besides their significance for atmospheric dust transport model validation, these results will help interpreting the more modest changes in isotopic composition recorded in older, time-averaged ice-cores in terms of possible source and transport-pathway variations, and might thus provide additional clues about what caused the dramatic variations in dust concentration in Greenland over the last climatic cycle.

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