A 10,000 km dust highway between the Taklamakan Desert and Greenland

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Mineralogical, elemental and isotopic measurements point to Eastern Asia as the main source of dust reaching Greenland, both in the present and during the last glacial period. Data suggest that the bulk of the dust derives from the Taklamakan Desert of western China.

Determining the provenance of ice core dust is key to our understanding of the prominent variability in the dust concentration observed in the Greenland and Antarctic ice core records (see also Vallelonga et al. and Gili-Gaiero et al., this issue). Greenland dust provenance was a matter of speculation until the mid 90s. Some studies based on modern aerosol elemental composition suggested the Saharan region as a possible source (Mosher et al. 1993) while back trajectory calculations favored East Asian or North American provenances (Kahl et al. 1997).

The Eastern Asian signature of Greenland ice core dust

A major breakthrough came with the analysis of dust extracted from the Greenland Ice Sheet Project (GISP2) ice core record obtained at Summit in central Greenland. Based mainly on the clay mineralogy of the dust, Biscaye et al. (1997) were able to rule out the Sahara and North American deserts as significant contributors to the dust deposited in Greenland during the Last Glacial Maximum. They showed that instead it closely resembled the fine material deposited in the Chinese Loess Plateau region and must therefore have derived from adjacent deserts. An Eastern Asian provenance was also supported by radiogenic isotope ratios (Sr, Nd and Pb), which were consistent with a Chinese Loess Plateau signature, taking into account the fact that ice core samples unavoidably contain variable amounts of volcanogenic particles mixed with the dust. These findings were confirmed by evidence from rare earth element patterns and extended through several levels of the Greenland Ice Core Project (GRIP) record spanning over 30 ka across MIS-3 and MIS-2 up to the Younger Dryas (Svensson et al. 2000).

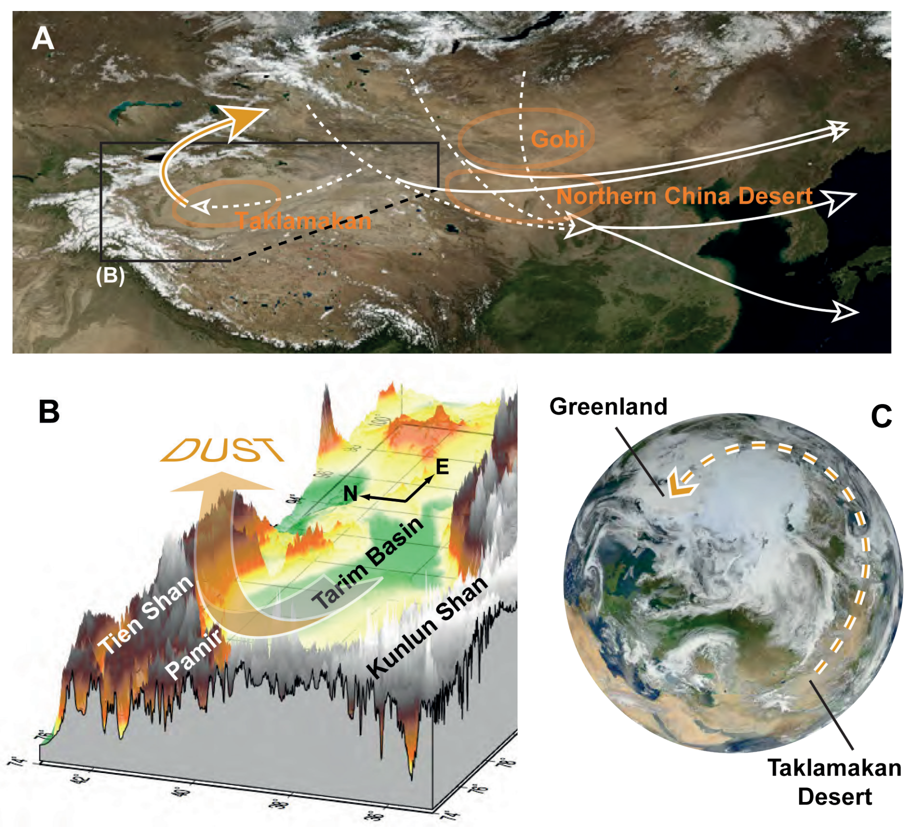

Figure 1: (A) April view of Eastern Asia (Terra MODIS sensor). Locations of the main deserts. Taklamakan and Northern China deserts are indicated together with the main winds (dotted lines) and dust transport pathways (solid lines) in the spring (adapted from Sun et al. 2001). **(B)** 3D-topographic modeling (NASA SRTM30 data) of the Tarim Basin and surrounding mountain chains (5x vertical exaggeration) and schematic illustration the dust's typical pathway in the spring. **(C)** Full disk of the Earth from space, showing both the Taklamakan desert of Western China and the Greenland ice sheet (background images in (A) and (C) courtesy of NASA).

Little change over time

Only minor variability was observed in the mineralogical and isotopic characteristics of these ice core dust samples (Biscaye et al. 1997; Svensson et al. 2000). Slight changes in clay mineralogy, correlated to some degree with the climate $\delta^{18}O$ record, suggested a possible shift in latitude or altitude of the provenance region over time; however, these changes remained small compared with the contrasting mineralogical signatures of the Northern Hemisphere's potential source areas (Bory et al. 2002). Also, the mineralogical and isotopic characteristics of dust extracted from Holocene ice core sections at various elevated sites across central Greenland did not depart significantly from glacial dust signatures (Svensson 1998; Bory et al. 2003a). So, overall, the mineralogical and isotopic signatures of dust in ice-cores all point to Eastern Asia as the overriding supplier of the dust to the top of the Greenland ice cap, both under glacial and inter-glacial climate conditions.

Clues from snow deposits in Greenland

In order to gain further insights into the contributing source region(s), especially in Eastern Asia, the provenance of modern-day Greenland dust was investigated. Large snow pit samples were excavated at the NorthGRIP site, permitting mineralogical and isotopic characterization at a seasonal or even better resolution (Bory et al. 2014). The clay mineralogy of these samples confirmed the eastern Asian source for Greenland dust in the current climate system (Bory et al. 2002), as also observed at Summit by Drab et al. (2002). Furthermore, radiogenic isotopes, Nd in particular, revealed a seasonal shift in provenance within the Eastern Asian region (Bory et al. 2002, 2003b).

Isotopic fingerprints of Eastern Asian deserts

An important effort was thus dedicated to the sampling of Eastern Asian potential source areas and to their mineralogical and isotopic signatures characterization. In order to make source samples comparable with the dust transported to Greenland (whose diameter never exceeds a few micrometers), measurements were carried out on the fine fraction (<5 µm) of the source material, following identical analytical protocols (including carbonate removal) as for Greenland ice-core dust (Biscaye et al. 1997).

These investigations revealed that significant differences exist in fact between the isotopic signatures of the three main source regions in Eastern Asia, i.e. the Mongolian Gobi desert, the deserts of Northern China (e.g. Tengger, Mu Us), and the Taklamakan desert of Western China (Fig. 1A), highlighting the interest of radiogenic isotopes for provenance discrimination in this region (Bory et al. 2003b).

Gobi dust across the Pacific but not in Greenland

One of the most unexpected outcomes was the fact that, although the Gobi area is clearly an active dust source in the region at present (Prospero et al. 2002), no obvious evidence for Gobi dust was found in the Greenland snow pit samples. This was even more surprising since there is indication from satellite data that Gobi dust can be transported across the Pacific Ocean (Husar et al. 2001). Trans-Pacific Gobi dust transport was confirmed using mineralogical and isotopic tracers during one of the most striking Asian dust events ever recorded on satellite images in April 2001, when dust deposited on Mount Logan, the highest mountain in Canada on the Canadian-Alaskan border, revealed a pure Gobi isotopic fingerprint (Zdanovicz et al. 2006). This massive event, however, was not detected in Greenland. The signature of the dust reaching the top of the ice cap during the major spring dust peak in Greenland points instead to the Taklamakan desert as the most important source. Yet, isotopes show that other sources of dust (likely located in Northern China) contribute to the signal, especially during the low dust seasons in Greenland (Bory et al. 2002, 2003b). However,

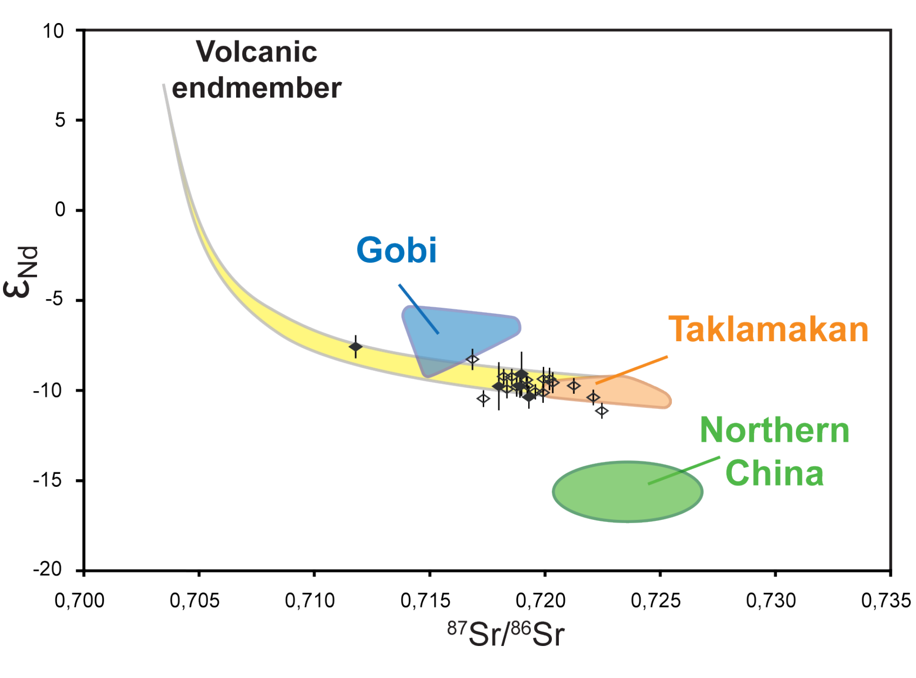

Figure 2: εNd versus $^{87}Sr/^{86}Sr$ signature of Greenland dust extracted from late glacial sections of the GISP2 (closed diamonds) and GRIP (open diamonds) ice core records (Biscaye et al. 1997; Svensson et al. 2000) and of potential source area samples from China and Mongolia (Bory et al. 2003b). The isotopic mixing domain between the Taklamakan desert and a circum-Pacific volcanic end-member is also shown.

considering the weight of the spring peak in the yearly dust deposition flux, all other contributions must clearly be minor compared to those from the Taklamakan.

A perfect launch pad for a 10,000 km flight to Greenland

When ice-core dust is compared to the Eastern Asia potential source areas database, it becomes apparent that almost the entire Greenland Sr and Nd isotopic composition range might actually be accounted for by inputs from the Taklamakan alone, assuming some mixing with minor amounts of volcanogenic material (Fig. 2).

Three main factors may make the Taklamakan so effective at delivering dust to Greenland. (1) The Taklamakan is the major dust source in the region at present and the second most important worldwide after the Sahara (Prospero et al. 2002). (2) The Taklamakan lies within the Tarim Basin, a large topographical depression in Eastern Asia; due to the elevated mountain ranges surrounding the basin, Taklamakan dust is already entrained to elevations >5000 m when it escapes the basin, whereas dust from the Gobi and Northern Chinese deserts are generally transported below 3000 m. (3) Wind systems in the basin often carry Taklamakan dust across the northern hedge of the Tarim, while dust originating from the Gobi and Northern Chinese deserts are initially transported eastward and south-eastward (Sun et al. 2001; Fig. 1b). The higher altitude and latitude at which Taklamakan dust is injected into the Westerlies likely represent a key precondition for long-range transport to Greenland (Fig. 1c). If confirmed (additional data from potential source areas should be generated to complete and refine the fingerprinting of all Asian contributing sources), the fact that most of the dust extracted from Greenland ice originates from a single spot in Western China represents useful clues for our interpretation of the Greenland dust signal and its close correlation to the rapid climate changes identified in the Greenland ice core records (e.g. Steffensen et al. 2008).

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