JOURNAL OF QUATERNARY SCIENCE (2010)

Published online in Wiley InterScience
(www.interscience.wiley.com) DOI: 10.1002/jqs.1418

Aeolian dust in the Talos Dome ice core (East Antarctica, Pacific/Ross Sea sector): Victoria Land *versus* remote sources over the last two climate cycles

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Delmonte, B., Baroni, C., Andersson, P. S., Schoberg, H., Hansson, M., Aciego, S., Petit, J-R., Albani, S., Mazzola, C., Maggi, V. and Frezzotti, M. 2010. Aeolian dust in the Talos Dome ice core (East Antarctica, Pacific/Ross Sea sector): Victoria Land *versus* remote sources over the last two climate cycles. *J. Quaternary Sci.*, (2010). ISSN 0267-8179.

Received 14 December 2009; Revised 23 April 2010; Accepted 5 May 2010

ABSTRACT: A new ice core (TALDICE) drilled at Talos Dome (East Antarctica, Ross Sea sector) preserves a ca. 250 ka long record of palaeoclimate and atmospheric history. We investigate dust variability and provenance at the site during glacial periods and the Holocene through the Sr–Nd isotopic composition of ice core dust and potential source areas (PSA). We provide new isotopic data on dust sources from Victoria Land such as regoliths, glacial drifts, aeolian sands and beach deposits. Some of these sources are located at high altitude and are known to have been ice free throughout the Pleistocene. The major features of the TALDICE dust record are very similar to those from central East Antarctica. During glacial times, South America was the dominant dust supplier for Talos Dome as well as for the entire East Antarctic plateau. Conversely, during the Holocene the principal input of mineral dust at Talos Dome probably derives from proximal sources which are the ice-free areas of northern Victoria Land, located at similar altitude with respect to the drilling site. Atmospheric mobilisation of dust from these neighbouring areas and transport inland to Talos Dome can be ultimately associated with advection of maritime air masses from the Pacific/Ross Sea region. Copyright © 2010 John Wiley & Sons, Ltd.

JQS
Journal of Quaternary Science

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KEYWORDS: Aeolian dust; Antarctica; ice cores; paleoclimate.

Introduction

Sr and Nd isotopic systematics are widely applied to studying the geographic provenance of aeolian dust in Antarctica and for the assessment of the palaeo-atmospheric circulation patterns (Grousset and Biscaye, 2005). The rationale consists of comparing the isotopic composition of dust extracted from deep ice cores to that of sediments and soils from target potential source areas (onwards PSA). Indeed, the isotopic composition of the radiogenic isotopes of Sr and Nd vary largely between mantle-derived and crust-derived materials (e.g. Faure, 1986), thus allowing on a broad scale a general distinction between aeolian particles derived from the erosion of young volcanic areas and those deriving from old continental shields (e.g. Grousset *et al.*, 1992). Over the last decade, research strategies have focused both on the isotopic characterisation of central East Antarctic ice core dust itself (e.g. Basile *et al.*, 1997; Delmonte *et al.*, 2004a, 2008; Bory *et al.*, 2010) and on the identification and documentation of present-day and palaeo-dust sources over the continental areas of the Southern Hemisphere (e.g. Smith *et al.*, 2003; Revel-Rolland *et al.*, 2006; Gaiero, 2007; Gaiero *et al.*, 2007). The combined ice core and source data strongly suggest that Patagonia was the most important source for dust in the central part of the East Antarctic ice sheet (EAIS) during Pleistocene glacial ages, the

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westerly circulation providing efficient dust transfer from South America to Antarctica during cold periods over the last 800 ka (Basile *et al.*, 1997; Delmonte *et al.*, 2008).

At present, the isotopic fingerprint of ice core dust is well documented for the central EAIS, especially for dust deposited during Pleistocene glacials (Basile *et al.*, 1997; Delmonte *et al.*, 2004a, 2008), while scarce information exists for interglacials (Delmonte *et al.*, 2007) and limited data are available from sites located on the periphery of the vast ice sheet (Bory *et al.*, 2010; Delmonte *et al.*, 2010). For the Southern Hemisphere continents, consistent efforts aimed at characterising active dust sources inside South America, which already appeared to Grousset *et al.* (1992) as the dominant supplier for glacial dust in central Antarctica. The amount of isotopic information is adequate today for Patagonian and non-Patagonian mineral aerosol exported from southern South America (Gaiero, 2007; Gaiero *et al.*, 2007), although there are still some subregions that are insufficiently documented. In addition to the remote continental landmasses of the Southern Hemisphere, there are several proximal sources for mineral material potentially available for aeolian deflation and transport inland. These are the small ice-free areas located at the present-day margin of the EAIS. Pleistocene glacial deposits could also be important sources for atmospheric dust, as they consist of unconsolidated mineral debris potentially available for aeolian redistribution. These proximal and sometimes highly localised dust sources are poorly documented from the isotopic point of view, but their importance cannot be neglected when dealing with dust extracted from ice cores drilled on the periphery of the EAIS.

Here we document the Sr and Nd isotopic composition of glacial (Marine Isotopic Stage (MIS) 2, 3, 4 and 6) and Holocene aeolian dust extracted from the new deep TALDICE ice core, drilled on the peripheral site of Talos Dome (159° 11′ E, 72° 49′ S; 2315 m above sea level (a.s.l.); Frezzotti *et al.*, 2004) by a consortium of five European nations. Drilling operations started during the 2004–05 field season, and in austral summer 2007 ended with the recovery of a ~1620 m deep ice core. The dome is located in the Ross Sea sector of East Antarctica, on the opposite side with respect to southern South America (Fig. 1). The first ~670 m of the TALDICE ice core include the whole Holocene, while the Middle–Upper Pleistocene boundary is located around ~1420 m depth (B. Stenni, unpublished results). Thus TALDICE offers a rare opportunity to investigate the last climatic cycle in detail, as well as the last ca. 250 ka with reasonable time resolution, within a sector of the EAIS still largely unexplored from the dust and palaeoclimate point of view.

Because of the geographic location of Talos Dome and the proximity of the Transantarctic Mountains, the ice-free terrains from the Victoria Land represent important PSA as they may be today – or may have been in the past – active suppliers for fine-grained mineral material available for wind deflation and inland transport. Therefore, some target PSA samples from northern and southern Victoria Land (NVL and SVL, respectively, Terra Nova Bay representing the limit between these two) were selected in this study (Fig. 1). The selection of PSA samples was based on the knowledge of the glacial history and the landscape evolution of the area during the Quaternary, as deduced from the intensive geological and geomorphological studies carried out over the last decades (e.g. Baroni and Orombelli, 1989, 1991; Orombelli *et al.*, 1991; Baroni *et al.*, 2005a,b, and references therein). Moreover, the combined use of detailed field mapping and information from cosmogenic nuclides (Oberholzer *et al.*, 2003, 2008; Di Nicola *et al.*, 2009; Strasky *et al.*, 2009) allowed dating glacial landforms previously lacking in chronological limits, thus leading to important advances in the understanding of the Quaternary history and dynamics of the EAIS in this area.

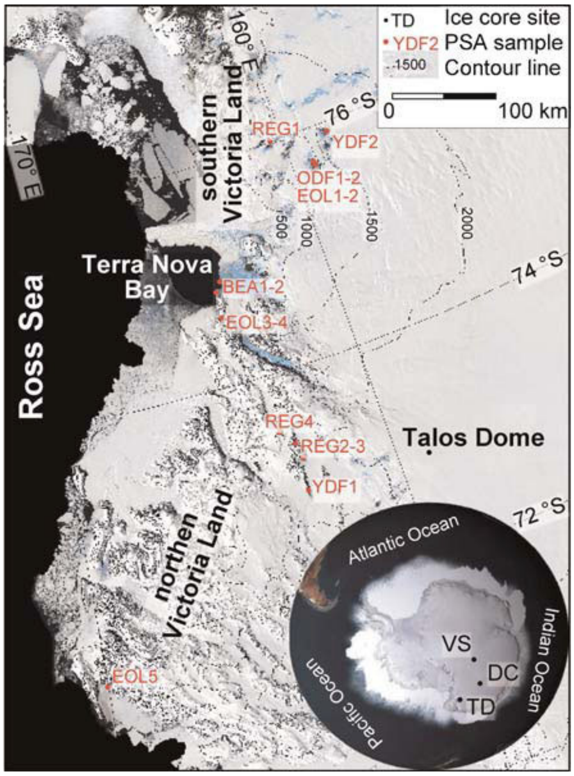

Figure 1 Satellite image (Landsat Image Mosaic of Antarctica Project) of Victoria Land with indication of Talos Dome ice core drilling site and location of PSA samples collection. Insert shows Antarctica and the Southern Hemisphere high latitudes. The Antarctic ice core drilling sites mentioned in the text are reported. TD, Talos Dome; DC, EPICA-Dome C; VS, Vostok. This figure is available in colour online at www.interscience.wiley.com/journals/jqs

We selected four groups of samples that we believe are crucial for atmospheric dust studies and for the investigation of aeolian mobilisation of sediments in this part of Antarctica. These are (1) weathered regoliths, (2) Quaternary glacial deposits dating back to the Last Glacial Maximum (LGM) or the Mid–Early Pleistocene, (3) silt and sand of aeolian origin, and (4) deposits from Holocene raised beaches which have been subjected to wind deflation for several thousand years.

We also present a new, low-resolution record of dust variability through the TALDICE ice core and depict the major features of the record. The first Sr and Nd isotopic data on Talos dome ice core dust are presented for glacial MIS 2, 3, 4 and 6 along with those from the Holocene. Finally, isotopic results from PSA samples are shown and compared with ice core dust. These data, integrated with literature sources, will finally provide a scenario for glacial to interglacial dust provenance in the Pacific sector of the EAIS over the late Quaternary.

Samples and analytical techniques

Dust concentration and size analysis

The analytical procedure adopted for dust concentration and size distribution measurements on TALDICE is identical to that adopted in former studies on Antarctic ice (Delmonte *et al.*, 2004a). A set of ~150 'cut-A' ice core sections (90° core, 20 cm long sections) was selected between 73 and 1617 m depth, decontaminated and analysed in a class 100 clean room at LGGE (Grenoble, France). Dust concentration and grain size (~240 log size bins in the 0.7–20 μm interval) were analysed with a Coulter Counter Multisizer IIe© device. The residual meltwater sample from cut-A sections was kept apart for filtration.

Ice core samples

The very low amount of dust in Antarctic ice makes it necessary to integrate several ice core sections to obtain a few large samples for Sr and Nd isotopic analyses (see supporting information Table S1). We extracted insoluble mineral particles from meltwater samples by filtration on 0.4 μm Nuclepore® polycarbonate track-etched membranes. Two distinct groups of samples were used: 'cut-A' ice pieces allotted for dust studies and 'bag mean' (BM) samples, each 20–30 mL in volume, issued from the laser sensor device after ice core melting and continuous dust analyses. Each BM represents about 1 m ('bag') of core. Prior to filtration, the preliminary sulphate record (E. Castellano, pers. comm.) was checked in order to discard ice sections likely containing volcanic tephra layers. After filtration, the membranes were sonicated in ~5–10 mL of Milli-Q® water and the liquid containing the concentrated dust was evaporated.

Antarctic PSA samples

In an area such as Antarctica the identification of potential dust sources is crucial. For this reason, efforts are made to recognise and select the most important typologies of samples with respect to atmospheric dust studies.

In this work we selected different typologies of PSA samples that can be grouped into four families according to the nature and/or the age of the deposit:

1. Regoliths (REG)
2. Quaternary glacial deposits, namely younger drifts (YDF) and older drifts (ODF)
3. Silt and sand within aeolian sediment traps (EOL)
4. Sands from Holocene raised beaches (BEA)

The geographic location and altitude of sampling sites are reported in supporting information Table S2.

The PSA samples selected and analysed in this work are quite heterogeneous. Some samples (regoliths, for example) derive directly from the mechanical and/or chemical alteration of the parent material and therefore represent 'primary' dust sources *sensu stricto* (Delmonte *et al.*, 2004a). Others are 'secondary' or 'reworked' sources, or a mixture of particles already subjected to a phase of transport (this is the case for glacial drifts, aeolian sand and beach deposits). Moreover, some samples were collected from high-altitude sites at the margin of the EAIS, others from low-elevation sites and even close to sea level. Some samples represent extensive sources (as beaches) while others are highly localised. Finally, some of these PSA are known to have been ice free throughout the Quaternary (Oberholzer *et al.*, 2008; Di Nicola *et al.*, 2009; Strasky *et al.*, 2009), thus representing potential suppliers for fine mineral material both during glacials and during interglacials.

Regoliths

In Antarctica, the combination of very low temperatures and low moisture availability reduces the chemical weathering of rocks. However, regolith can still form there through the combination of physical weathering and mechanical rock disintegration processes. Among these, the action of wind and water in its different physical forms, salt weathering and solar radiation play an important role (Campbell and Claridge, 1987). Although the hyper-arid, cold Antarctic desert is one of the driest environments on Earth, chemical weathering may locally play a more significant role than physical weathering processes. As an example, considering the high heat capacity of dark dolerites, snow melting quickly supplies water suitable for enhancing frost action as well as for driving chemical weathering, particularly effective on frost-shattered blocks and jointed rocks.

The most suitable samples for atmospheric dust studies are represented therefore by weathered regoliths with surface deflation pavement, indicative of a long history of wind erosion.

A set of four regoliths was selected. The southernmost regolith (REG_1) was collected from the northern margin of The Mitten, about 1650 m a.s.l. in the Prince Albert Mountains (David Glacier Basin); this sample derives from *in situ* weathering of Ferrar Dolerites (Jurassic; Carmignani *et al.*, 1989) on a sub-horizontal structural surface (mesa) characterised by ice wedge and contraction polygons, residual Antarctic tors (Selby, 1972) and a well-developed aeolian deflation pavement. Antarctic tors are pitted towers up to a few metres in height, also known as 'Antarctic gargoyles' because they are reminiscent of the statues at waterspouts in medieval architecture (Pocknall *et al.*, 1994; Oberholzer *et al.*, 2008).

Three other regolith samples were selected from the Mesa Range area (Fig. 2(a, b), in the Rennick Glacier Basin. One (REG_2) was collected on the Tobin Mesa about 2645 m a.s.l.; another sample (REG_3) was collected on the Pain Mesa at a similar altitude (2650 m a.s.l.). They both derive from the sandy matrix supporting cobbles and pebbles on top of the mesas, and originated from *in situ* weathering of the Ferrar Dolerites (Jurassic; Carmignani *et al.*, 1989). Finally, regolith REG_4 was collected at 2700 m altitude on the Chisholm Hills, a group of small nunataks located on the southern edge of the Mesa Range area, about 90 km from the Ross sea. Sample REG_4 consists of the topmost part of a yellowish sandy layer derived from *in situ* weathering of continental sandstone (Beacon Supergroup, Permian to Late Triassic) and lying below an aeolian deflation pavement. The relict erosional surface sampled at Chisholm Hills shows columns of Ferrar Dolerite weathered to form spectacular Antarctic gargoyles (Fig. 3).

Gargoyles have developed on top of structural and relict erosional surfaces all over Victoria Land. Pithole weathering (1–5 cm) affects the top surface of gargoyles where weathering rind and a shiny desert varnish are common features (Giorgetti and Baroni, 2007). The varnish forms a glassy resistant layer on the rock surface, which is formed by accretion of airborne dust onto the external surface of the rock substrate. Therefore the processes of erosion, chemical weathering and exfoliation were extremely reduced on the column tops (Giorgetti and Baroni, 2007). On the other hand, the surfaces between the tors show effects of strong erosion and excessive exfoliation. In such a cold and arid environment, the varnish can only be mechanically eroded by wind or, in places, by overriding glaciers. The ^{21}Ne surface exposure ages of Antarctic gargoyles at Chisholm Hills (Fig. 3), a few metres apart from our sample REG_4, and on Mt Bowen (in the Prince Albert Mountains, in the vicinity of The Mitten) supplied minimum ages of 2.1–3.5 Ma, not corrected for erosion. Maximum erosion rates, calculated under the assumption of infinite exposure time, are between 17 and 41 cm Ma^{-1} (Oberholzer *et al.*, 2008).

Therefore the EAIS has not attained the elevation of the gargoyle terraces after 3.5 Ma, and since then the summit

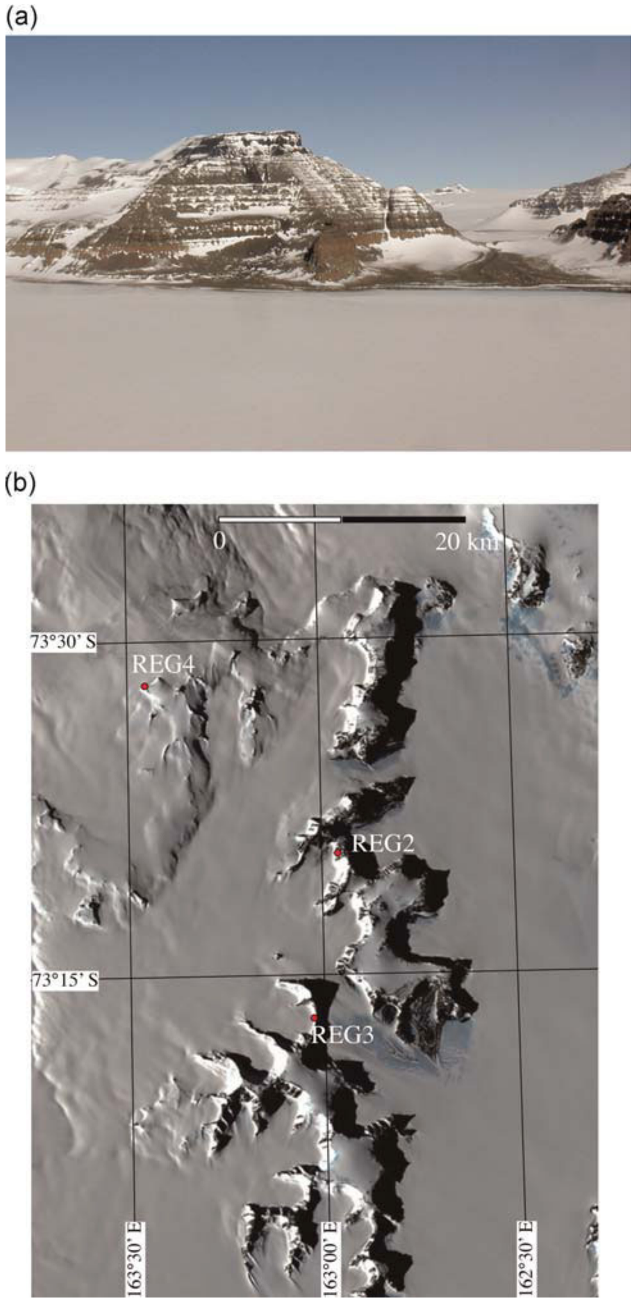

Figure 2 The Mesa Range. (a) Photograph of Mt Frustum (~3400 m a.s.l.), standing at more than 1000 m above the ice surface. (b) Satellite (Landsat 4 TM false colour) composite image of the Mesa Range recorded between November 1989 and January 1990, with scale bar, with indication of sampling sites

surfaces were continuously exposed and well preserved under polar conditions. As a consequence, many nunataks at the margin of the EAIS have been potential dust source areas since at least the Pliocene.

Pleistocene glacial drifts

Quaternary glacial sediments from northern Victoria Land were selected. According to the age of the deposit, they were grouped in Younger drifts (YDF, Late Pleistocene) and Older Drifts (ODF, Early–Middle Pleistocene, Baroni and Orombelli, 1989; Orombelli *et al.*, 1991). Younger drifts are massive, matrix-supported diamicton, ice cored and locally hummocky, grey-brown to olive-grey in colour, and they are dated to the Late Pleistocene (Orombelli *et al.*, 1991; Oberholzer *et al.*, 2003; Strasky *et al.*, 2009).

Figure 3 Antarctic tors or 'gargoyles' on top of a relict glacial erosional surface at Chisholm Hills. Dolerite columns in foreground extend 50–60 cm in height. The ^{21}Ne surface exposure dating of Antarctic tors in Victoria Land (Oberholzer *et al.*, 2003) supplied minimum ages of 2.1–3.5 Ma; thus relict surfaces along the internal margin of the EAIS have potentially been suitable as a PSA since at least the Pliocene (see text)

Older drifts are clast-supported to matrix-supported diamicton with a sandy–silty matrix ranging in colour from dark greyish-brown to olive-grey. Clasts at the surface are deeply weathered and oxidised with yellowish-red or red colour of staining.

For this study, one YDF sample (YDF_1) collected within a glacial cirque in the Mesa Range area about 2120 m a.s.l. was analysed. It represents the matrix of a glacial deposit of probable LGM age, ice cored, and characterised by ice-wedge polygons. A second sample (YDF_2) was collected at Griffin Nunatak about 1700 m a.s.l., from an ice-cored moraine dating back the LGM. In addition, two ODF samples selected for in this work were collected on the Ricker Hills (southern Victoria Land), a small (~70 km^2 wide) group of nunataks close to the present-day margin of the EAIS, ranging in elevation from about 900 to 1830 m a.s.l.. The geology of the area, as well as the related glaciological and geomorphological setting, is summarised by Baroni *et al.* (2008) and Strasky *et al.* (2009). One sample (ODF_1) was collected at 1510 m a.s.l.; it consists of a soil (5–10 cm thick horizon) developed on pre-LGM deposits (RH4 unit, dated with exposure age to Early–Middle Pleistocene; Oberholzer *et al.*, 2008; Strasky *et al.*, 2009). Well-developed ice wedges are typical in the area. Another sample (ODF_2) comes from the eastern side of the Ricker Hills and was collected at ~1300 m a.s.l. It consists of the matrix of glacial deposits. In both cases the sampling area is characterised by aeolian deflation pavement and red-staining of clast surfaces.

Silt and sand within sediment traps

Silt and sand collected within natural sediment traps (such as rock fractures and sheltered areas below pebbles and blocks) are clearly of aeolian origin, and we shall refer to this group of samples as aeolian sediments. Complementary evidence (not reported in this work) supporting the aeolian origin of these materials consists of the good size-sorting of the sediments, the presence of polished and pitted rounded/subrounded quartz grains and the enrichment in micas.

In this work, aeolian sediments were collected from three different locations. Two samples (EOL_1 and EOL_2) were selected on the margin of the ice sheet, about 1300 m a.s.l. on the Ricker Hills area. Sample EOL_1 consists of sand entrapped within rock fractures, while EOL_2 comes from a buried ice wedge filled by aeolian sand and covered by periglacial stone pavement.

Two additional samples (EOL_3 and EOL_4) were collected on the top of Mt Browning, within the Northern Foothills. Sample EOL_3 was collected around 740 m a.s.l. and consists of fine sand lying below pebbles, while sample EOL_4 was collected around 730 m a.s.l. and consists of fine aeolian sand lying below a quartzite block. Finally, an additional sample (EOL_5) was collected close to Cape Adare on the Duke of York Island, about 105 m a.s.l. The sample consists of aeolian sand on top of Holocene penguin guano lying within a sheltered area.

Holocene raised beaches

Two samples were collected from the Holocene raised beaches of the Terra Nova Bay area, from sites showing surface aeolian deflation pavement (Baroni and Orombelli, 1991; Baroni and Hall, 2004). One sample (BEA_1) was collected on the South Bay of Inexpressible Island about 30 m a.s.l., close to the marine limit, and was dated to 7200 ^{14}C a (Baroni and Hall, 2004). Another sample (BEA_2) was collected on the Cape Russell peninsula (Evans Cove) about 14 m a.s.l. Radiocarbon dating of *Adamussium colbechi* shells provides a Holocene age also for the Cape Russell fossiliferous marine beaches (7505 ± 230 ^{14}C a).

Isotope geochemistry: Sr–Nd

The size fraction smaller than 2 mm in diameter was selected from each Antarctic PSA sample, the only exception being silt and sand from aeolian sediment traps. As these latter were already well sorted in size by natural aeolian processes, the bulk sediment was collected.

The direct comparison of the Sr and Nd isotopic composition of ice core dust and PSA samples can be performed on samples having similar grain size, in order to avoid potential isotopic fractionation related to grain size (Delmonte *et al.*, 2004a; Gaiero, 2007). Therefore, the fraction of particles smaller than 5 μm (diameter) was extracted from all PSA samples, following the procedure adopted in previous studies (Delmonte *et al.*, 2004a). The regoliths and glacial drifts were dissolved and analysed at the Laboratory for Isotope Geology (LIG, Stockholm) together with the ice core samples. The samples of aeolian sands and beach sands were dissolved and analysed at ETH (Zurich).

At LIG a procedure for the chemical dissolution of tiny samples and the subsequent element separation (Rb–Sr, Sm–Nd) using ion-exchange chromatography was developed over recent years and successfully applied to mineral dust in ice cores from East Antarctica and also from Andean ice (Delmonte *et al.*, 2008, 2010). After spiking with a mixed ^{147}Sm/^{150}Nd spike and an ^{84}Sr enriched spike, the samples were

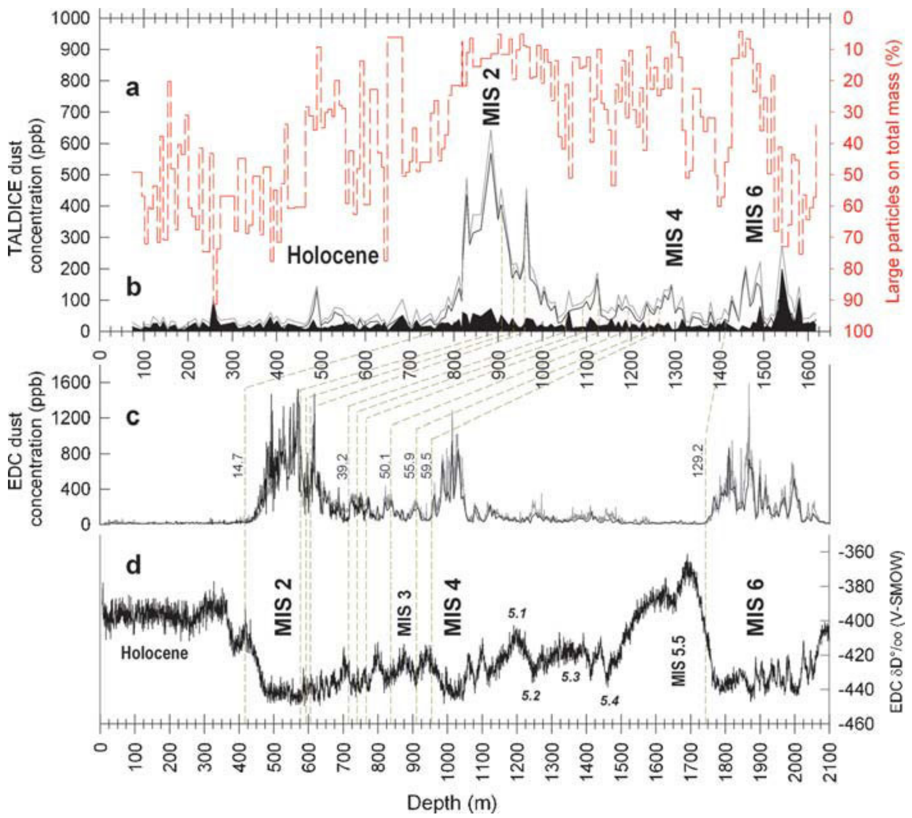

Figure 4 Low-resolution dust concentration profile of TALDICE *versus* depth, and comparison with EPICA-Dome C. (a) Percentage of large-particle (5–20 μm diameter) dust on the total (0.7–20 μm) dust mass. (b) Concentration of insoluble dust particles along the TALDICE core for different size intervals: 0.7–20 μm (total dust mass, grey line); 0.7–5 μm (typical aeolian dust, black line); 5–20 μm (very large particles, black area). (c) EPICA-Dome C (EDC) dust concentration profiles (Lambert *et al.*, 2008; Delmonte *et al.*, 2008) obtained by laser sensor (grey line) and by Coulter counter (black line). (d) EDC stable isotope profile (Jouzel *et al.*, 2007), providing the climate reference. This figure is available in colour online at www.interscience.wiley.com/journals/jqs

digested and purified following the same protocol adopted in earlier studies (see supplementary information in Delmonte *et al.*, 2008). Isolated Nd and Sr fractions were analysed on a thermal ionisation mass spectrometer (TIMS; TRITON©, Thermo Scientific Corp.). Neodymium was mixed with Aquadag© colloidal graphite, loaded on one rhenium filament, and analysed as Nd metal ions in static mode using rotating gain compensation. Strontium was loaded mixed with tantalum as an activator on a single rhenium filament. The total blank for Nd is <10 pg and for Sr <80 pg.

At ETH (Zurich), after isotopic enrichment using a ^{150}Nd and ^{84}Sr spike, the samples of aeolian sands and beach deposits were digested. The elements (Sr and Nd) were then purified following the procedure described in Aciego *et al.* (2009). Sr and Nd isotopic ratios were measured on the ETH Thermo Scientific TRITON© TIMS. Neodymium was mixed with H_3PO_4 and loaded onto double rhenium filaments, while Sr was loaded mixed with a $TaCl_5$ activator onto single rhenium filaments. Blanks for Nd were <1 pg and for Sr <20 pg.

In both laboratories, the isotopic ratio data were reduced assuming exponential fractionation. Calculated ^{143}Nd/^{144}Nd ratios were normalised to ^{146}Nd/^{144}Nd = 0.7219. The measured ^{87}Sr intensities were corrected for Rb interference using ^{87}Rb/^{85}Rb = 0.38600 and ratios were reduced using ^{88}Sr/^{86}Sr = 8.375209.

Results

The Talos Dome dust record

Dust measurements on TALDICE 'cut-A' samples provide the first low-resolution profile for the core, which is reported in Fig. 4(b). Dust concentrations are plotted for three different size intervals: (1) 0.7–20 μm, representing the total dust mass analytically detected by Coulter counter; (2) 0.7–5 μm, representing the typical size interval for aeolian dust; (3) 5–20 μm, related to very large dust particles. These latter represent only a very low number of counts, but their contribution becomes important for the dust mass (and volume), where they represent up to 10–50% of the total, as shown in Fig. 4(a).

For the 0.7–5 μm size range, the mass (volume) size distribution of samples shows a lognormal distribution with a variable modal value around ~2 μm (see supporting information Figs S1 and S2). Dust concentration in this size interval definitively controls the first-order variability of the total particle mass and displays the typical climate-related features of central East Antarctic ice cores, where particles larger than about 5 μm are nearly absent.

Actually, despite the different sampling resolution, comparison of the TALDICE record with the EPICA-Dome C dust profile (Fig. 4(c)) shows some similarity. The observation of the most prominent dust features as well as some peculiar dust events allows correlating the two dust profiles as well the EDC stable isotope record (Jouzel *et al.*, 2007; Fig. 4(d)), which provides the climatic reference.

From 73 m (close-off depth) to about 750 m depth, the TALDICE concentration of typical aeolian dust (<5 μm) is very low; this depth interval corresponds to the Holocene and to the Antarctic Cold Reversal (ACR) phase of climate, as one can observe from the stratigraphic correlation with EDC. The Holocene concentration of aeolian dust (<5 μm) is around 20 p.p.b. on average at Talos Dome, corresponding to about 1.3 mg m^{-2} per year in flux (accumulation data from D. Buiron, pers. comm.), while the dust flux at EDC during the same climatic period is about 0.4 mg m^{-2} per year. Between 750 and 1040 m depth the TALDICE core shows well-marked dust pulses corresponding to glacial MIS 2 (~18–30 ka BP). This prominent feature allows the establishment of a preliminary depth-to-depth relationship between the two ice cores. The pleniglacial conditions typical for the LGM can be found in the 820–900 m depth interval at Talos Dome, and in this depth interval the dust concentration is highly variable around a mean value of ~250 p.p.b., corresponding to ~8–9 mg m^{-2} per year in flux. Thus the LGM/Holocene aeolian dust concentration ratio at Talos Dome is ~12, corresponding to a factor of ~6 in fluxes. These values are significantly lower than EDC, where an LGM/Holocene dust ratio of 50 in concentration (and 25 in flux) was calculated (Lambert *et al.*, 2008). The reason for this discrepancy likely lies in the relatively higher Holocene dust flux at Talos Dome compared to EDC.

The comparison of TALDICE and EDC dust records allows extending the stratigraphic correlation throughout MIS 3, where some secondary dust oscillations corresponding to the Antarctic isotopic maxima are visible in both records (Fig. 4), and back to glacial MIS 4 (ca. 60–70 ka BP) and MIS 6 (ca. 135–165 ka BP). At the end of MIS 6, after the sharp dust concentration decrease in correspondence with Termination II (1425–1412 m depth) some typical interglacial values (17 p.p.b. on average in the 1395–1417 m depth interval) can be found in the TALDICE core. This corresponds to the last interglacial, MIS 5.5, which is located around 1550–1750 m in the EDC core. According to B. Stenni (unpublished results), the climatic sequence in the TALDICE core is well preserved until about 1550 m depth, and ice layers at this depth likely date back MIS 7.5 (ca. 250 ka BP).

Isotopic fingerprint of Talos Dome and Victoria Land sources

The Sr and Nd isotopic composition of TALDICE glacial and Holocene dust is reported in supporting information Table S3, and plotted in Fig. 5(a, b) together with literature data from East Antarctic ice cores. Glacial dust (MIS 2, 3, 4 and 6) from Talos Dome (Fig. 5(a)) displays average ^{87}Sr/^{86}Sr ratios of 0.708339 ± 0.000537 ($n = 7$), while $\varepsilon_{Nd}(0)$ is close to CHUR (average $\varepsilon_{Nd}(0) = -0.1 \pm 2.0$; $n = 6$). Overall, the TALDICE glacial isotopic field matches that of coeval (MIS 2–6) and older (MIS 8–20) glacial dust from the interior of the Antarctic plateau (Grousset *et al.*, 1992; Basile *et al.*, 1997; Delmonte *et al.*, 2004a,b, 2008, 2010). The two data points obtained in this work for the Holocene (Fig. 5(b)) are similar to glacial values for TALDICE, and look more radiogenic in Nd with respect to Holocene and interglacial MIS 5.5 values from Dome C and Vostok (Delmonte *et al.*, 2007) despite the large analytical uncertainty (supporting information Table S3) related to the extremely small size of samples. In general, results highlight a similar dust signature for central and peripheral (Talos Dome) East Antarctica during cold periods, but different signatures during the Holocene.

The isotopic composition of the fine fraction (<5 μm in diameter) of Victoria Land PSA samples, i.e. the size fraction typically susceptible to atmospheric transport, is reported in supporting information Tables S4 (LIG data) and S5 (ETH data). Results on PSA are plotted together with TALDICE ice core data in Fig. 6. It can be observed that the isotopic signature of regolith samples from the Victoria Land mesas is close to that of TALDICE ice core dust, in particular for the Pain Mesa and Tobin Mesa samples. Also the younger drift sample collected on the Mesa Range displays an Sr–Nd isotopic signature very close

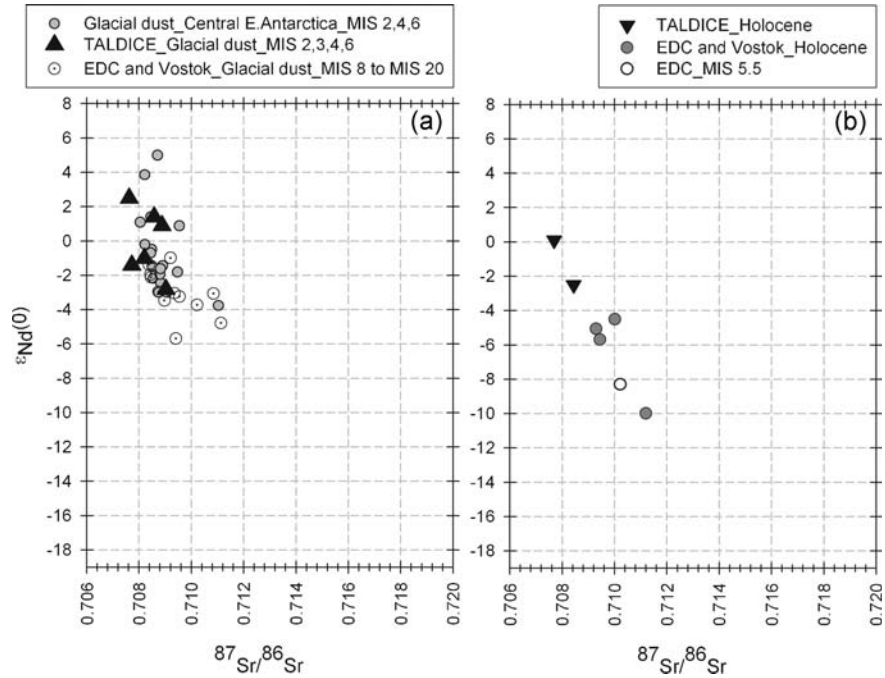

Figure 5 Sr–Nd isotopic composition of TALDICE and central East Antarctic ice core dust. (a) $^{87}Sr/^{86}Sr$ *versus* $\varepsilon_{Nd}(0)$ composition of TALDICE glacial dust from MIS 2, 3, 4 and 6 (this work) and comparison with coeval (MIS 2, 4, 6) and older (MIS 8–20) glacial extracted from central Antarctic ice cores (EDC and the *old* Dome C core, Vostok, Dome B, Komsomolskaia). Data sources: Grousset *et al.*, 1992; Basile *et al.*, 1997; Delmonte *et al.*, 2004a,b, 2008, 2010. (b) Isotopic composition of Holocene dust from TALDICE and comparison with available data from EDC and Vostok ice cores (Delmonte *et al.*, 2007) for the Holocene and for the previous interglacial (MIS 5.5). Sr and Nd isotopic ratios from TALDICE, along with associated errors, are reported in supporting information Table S3

to regoliths from that area, in agreement with the common lithology of the materials. The Southern Victoria land sample of the Griffin Nunatak moraine, conversely, displays an isotopic signature different from TALDICE dust, more radiogenic in Sr than the ice core samples.

The two ODF samples from the Ricker Hills display a crustal-like (e.g. Zindler and Hart, 1986) signature with higher $^{87}Sr/^{86}Sr$ and a lower $\varepsilon_{Nd}(0)$ compared to the bulk earth, which makes them very different from typical ice core dust. These characteristics are probably related to the local lithology of materials, as corroborated by the signature of aeolian sands collected in from the same area. Indeed, aeolian samples from the Northern Foothills and from Duke of York Island also display more negative $\varepsilon_{Nd}(0)$ values compared to TALDICE dust. Finally, the two samples from Holocene emerged beach deposits display very unradiogenic $\varepsilon_{Nd}(0)$ values, and are also markedly different from TALDICE Holocene ice core dust.

Discussion

The first, low-resolution, dust concentration record from TALDICE shows that the variability of total dust mass is dominated by typical aeolian particles, smaller than 5 μm in diameter and showing modal values around 2 μm. At first order, the Talos Dome stratigraphic dust record mimics that from the EPICA-Dome C (Lambert *et al.*, 2008) and Vostok (Petit *et al.*, 1999) ice cores that are representative of central East Antarctica. In addition, TALDICE shows the presence of large (5–20 μm in diameter) particles throughout the core; this was not the case for central Antarctica (e.g. Delmonte *et al.*, 2004b), where dust is typically smaller than 5 μm. In terms of concentration (Fig. 4b) the profile of large particles at Talos Dome displays, over and above the natural variability of the data, only limited or negligible changes, apparently climate-independent. In relative (%) terms, conversely, particles larger than 5 μm represent a negligible part of total dust mass during glacials (~10% on average), but an important contribution to the total dust mass during the Holocene (~50% on average).

Windborne dust to Antarctica from remote continental sources is typically included in the <5 μm size range, and therefore the presence of larger particles with high settling velocity provides an indication of a contribution from proximal sources. This local contribution obviously includes all size bins, but while large particles are exclusively related to atmospheric transport from areas close to the drilling site, particles smaller than 5 μm may be a mixture of remote and proximal sources. The quantitative assessment of the local *versus* remote input is not straightforward. Hypothesising a general uniformity of dust flux over Antarctica with respect to remote sources, the comparison of the average Holocene dust flux in central Antarctica (~0.4 mg m^{-2} per year, related exclusively to dust from remote sources) with average Holocene flux of particles smaller than 5 μm at Talos Dome (~1.3 mg m^{-2} per year) suggest that the 0.9 mg m^{-2} per year excess of dust flux at Talos Dome (i.e. 70–80% of the total dust mass, all sizes included) may be due to the contribution from local sources.

Victoria Land dust sources

Regoliths are of first-order importance as they are enriched in fine-grained particles derived from *in situ* alteration of the parent material and potentially available for aeolian deflation and transport inland. Weathered regoliths with surface aeolian deflation pavement are particularly interesting for dust studies as they provide an indication for a long history of wind erosion. Glacial drifts are also important for atmospheric dust studies as they consist of fresh, unconsolidated debris immediately available for wind mobilisation and transport, in particular after glacial maxima. The YDF samples collected and analysed in this work formed during the LGM and likely represented important dust sources during and after the last deglaciation.

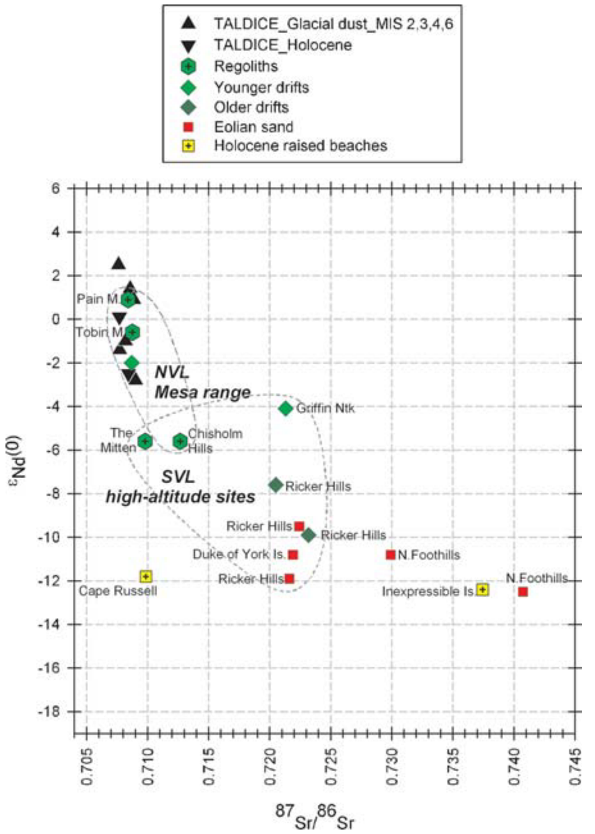

Figure 6 Talos Dome dust and Victoria Land sources. Comparison of TALDICE glacial and Holocene dust with Victoria Land PSA samples analysed in this work. Each symbol refers to one family of PSA, as described in the text. The dashed lines define an arbitrary isotopic field for high-altitude samples collected in Southern Victoria Land (SVL) and Northern Victoria Land (NVL). This figure is available in colour online at www.interscience.wiley.com/journals/jqs

These deposits were originally correlated to the 'Ross Sea I' glaciation (Baroni and Orombelli, 1989) and were referred to as 'Terra Nova Drift' by Orombelli *et al.* (1991). The ODF date back the Early to Mid Pleistocene, and consist of thin and discontinuous deeply weathered glacial deposits lacking constructional form. The ODF samples selected in this work come from the Ricker Hills and they are comparable to those described by Orombelli *et al.* (1991) in the Terra Nova bay area (Terra Nova II and III). Surface exposure dating by *in situ* produced cosmogenic nuclides revealed that our sampling site for ODF samples was not overidden by the EAIS during the Middle and Late Pleistocene, while the low erosion rates indicate that the modern climate conditions in the area have persisted since at least the Early Pleistocene (Strasky *et al.*, 2009). Therefore, these potential sources were active over the whole time period spanned by the Talos Dome ice core record. We note that the Nd isotopic signature of SVL Quaternary glacial deposits reported in this study is very similar to that reported by Farmer *et al.* (2006) on the $<63\ \mu m$ size fraction of onshore Quaternary glacial tills from the Allan Hills area.

Aeolian materials were selected for atmospheric dust studies as they provide a natural sample of mineral aerosol already subjected to a first phase of deflation, atmospheric selection, transport and deposition (natural capture into sediment traps). Finally, emerged beach deposits were also considered in this work. Although beaches represent low-elevation sources, they cover extensive areas in coastal Victoria Land. Moreover, they often display clear geomorphological evidence for a long history of wind deflation and particle mobilisation. The two beach samples analysed in this work were collected from raised beach deposits that are known to have been deflated by wind since at least the Middle Holocene (Baroni and Orombelli, 1991; Baroni and Hall, 2004).

A comparison of isotopic data from the Victoria Land PSA samples and the TALDICE ice core dust signature (Fig. 6) shows that the low-altitude sources, such as the Holocene emerged beaches from the Terra Nova Bay area, Duke of York Island and the Northern Foothills, can be reasonably excluded as major sources for dust at Talos Dome. When mid- to-high-altitude sites are considered, a further subdivision based on geographic criteria can be made between northern and southern Victoria Land sources (Figs 1 and 6). These latter show a crustal-like signature that is coherent with literature data (Farmer *et al.*, 2006) and that is markedly different from the TALDICE ice core dust. On the other hand, samples (regoliths and younger drifts) collected at high altitude in NVL (Mesa Range) match very well the Talos Dome ice core dust signature. Therefore, the Mesa Range area (Fig. 2(b)), located along the internal border of the Transantarctic Mountains, appears as the most probable Antarctic dust source for the nearby sector of the EAIS, where the Talos Dome is located. Regoliths from that area are known to have been active ice free (active) dust sources throughout the Pleistocene, while the moraines dating back to the LGM represent accumulations of unconsolidated and unsorted material available for wind mobilisation and transport, particularly during and after the last deglaciation.

Dust sources for TALDICE and central Antarctic sites during glacial and interglacial periods

During Pleistocene glacial periods the similar dust isotopic fingerprint for Talos Dome and central Antarctic ice cores, as well as the comparable dust flux and grain size, this latter almost totally represented by $<5\ \mu m$ particles, suggest that the whole East Antarctic plateau received a major dust input from a common and remote source.

In this respect, the Southern Hemisphere PSAs were intensively studied over the last decade in order to define dust provenance at Dome C, Vostok and central East Antarctica (Basile *et al.*, 1997; Delmonte *et al.*, 2004a; Revel-Rolland *et al.*, 2006; Gaiero *et al.*, 2007; Sugden *et al.*, 2009). Gaiero (2007) pointed to Patagonia as primary source for dust exported long range from South America to Antarctica in glacial times, and to a lesser extent to the high-altitude Altiplano-Puna plateau; the mixing between these two subregions being almost identical to Argentinean loess that is composed of the same primary materials with respect to the isotopic compositions. Our results show that the isotopic composition of East Antarctic glacial dust, including Talos Dome, matches well with Patagonian and Argentinean materials (Fig. 7). Although the overlap of isotopic fields from South America and NVL (Fig. 7) does not allow excluding a contribution from local sources at Talos Dome during glacials, the small grain size of dust and the comparable flux at Talos Dome and EDC during MIS 2 suggest that a local contribution, if present, was almost certainly overridden by the important dust advection from remote areas.

Interestingly, East Australian dust sources such as palaeolake sediments, sand dunes and loess-like deposits (Revel-Rolland *et al.*, 2006) show an isotopic signature markedly different from TALDICE glacial dust (Fig. 7). This evidence excludes Australia as dominant dust supplier to Talos Dome during cold times, and corroborates the hypothesis of a uniform South American origin of dust over the entire East Antarctic plateau, from the South

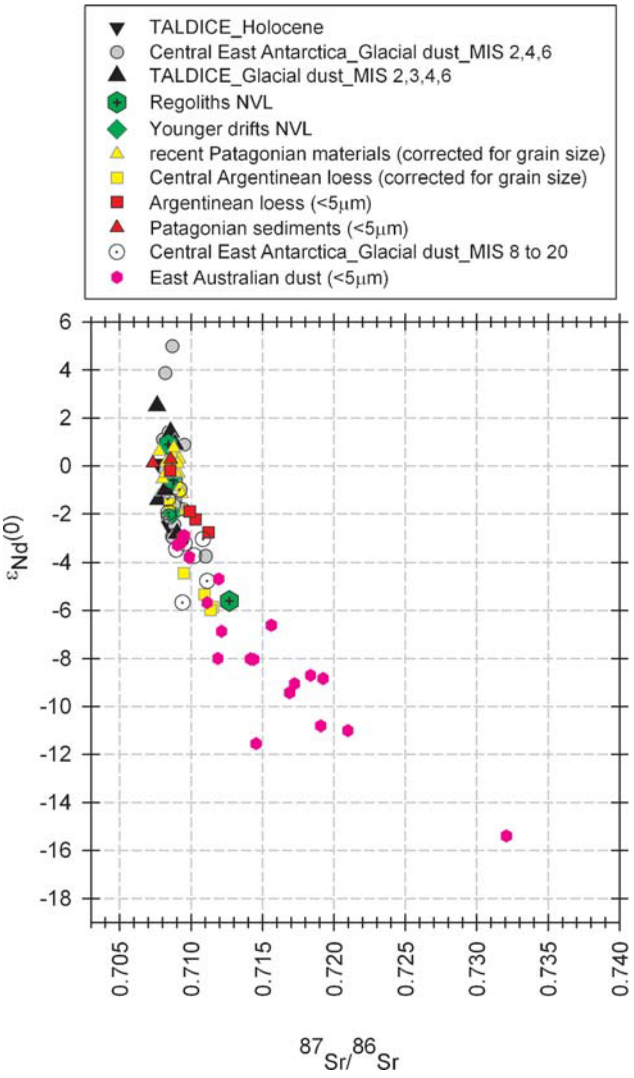

Figure 7 TALDICE and central Antarctic ice core dust, Antarctic *versus* remote sources. The isotopic composition of TALDICE glacial and Holocene dust and central Antarctic glacial dust (data as in Fig. 5(a)) is compared with regolith and glacial drifts from NVL analysed in this work and with literature data from remote source regions for dust in Antarctica. For South America, the isotopic composition of Patagonian materials and Argentinean loess (Gaiero, 2007; Gaiero *et al.*, 2007; Delmonte *et al.*, 2004a) is reported. When the data are available for the $<63\,\mu m$ size fraction, the $^{87}Sr/^{86}Sr$ isotopic correction for size fractionation (0.0028 units) was applied, as suggested by Gaiero (2007). For Australia, the Sr–Nd isotopic composition of the fine ($<5\,\mu m$) fraction of target potential source regions of east Australia (palaeolake sediments, sand dunes, loess-like deposits) is reported (Revel-Rolland *et al.*, 2006). This figure is available in colour online at www.interscience.wiley.com/journals/jqs

Atlantic sector to the south Pacific/Ross Sea sector during the LGM, thus providing constraints for atmospheric GCM simulations of glacial climate.

Because of the drastic decrease of mineral dust input from remote sources during the deglaciation and the extremely low dust input from distant sources during the Holocene, the relative contribution of dust from local sources became important at Talos Dome after the LGM. This is not the case for central Antarctica, and for this reason some important Sr–Nd isotopic differences between inland sites and Talos Dome arise during the Holocene (Fig. 5(b)).

For central East Antarctic ice cores, a change in the dust source terrains was suggested on the basis of isotopic data (Delmonte *et al.*, 2007). This hypothesis was also supported by complementary evidence: the elemental composition (Marino *et al.*, 2008; Gabrielli *et al.*, 2010) as well as the magnetic properties (Lanci *et al.*, 2008) of mineral particles are variable. However, despite the clear evidence for a change in dust characteristics and provenance with climate, there is still no consensus on the assessment of dust origin in central Antarctica during the Holocene. In this respect, an important contribution from eastern Australia during the Holocene and during present-day climate was suggested by isotopic composition data (Revel-Rolland *et al.*, 2006), providing a scenario supported by results of modelling studies (e.g. Li *et al.*, 2008). Further studies are needed, however, to determine the contribution from sub-regions that are yet isotopically undocumented (Delmonte *et al.*, 2007).

Implications for regional and large-scale atmospheric circulation

Talos Dome is located in an area where katabatic winds (very cold air masses blowing from the Antarctic inland) and milder maritime air masses from lower latitudes converge (Frezzotti *et al.*, 2007; Parish and Bromwich, 1987). Earlier work (e.g. Stenni *et al.*, 2002) suggested that intrusions of maritime air masses played an important role over the last 800 a, while present-day meteorological data (Scarchilli, 2007) show that ~50% of air masses travelling about 1 km above Talos Dome originate from the Antarctic interior, whereas ~30% come from the Ross Sea. The importance of strong maritime air mass incursions in the Talos Dome area at the present day can also be deduced from meteorological data obtained over the last ~20 a from automatic weather stations located in NVL (data available at www.climantartide.it). Wind direction and intensity data actually show that the NVL area is under the influence of non-katabatic winds (potentially representing maritime air mass incursion in the area) with surface wind speed suitable for aeolian dust mobilisation and transport ($>8\,m\,s^{-1}$; Berthier *et al.*, 2006) for ~5–10% of the year.

Our findings highlight that Antarctic ice-free areas are important sources for dust windblown to the periphery of the EAIS during the Holocene. For Talos Dome one possible source area is the Mesa Range, located at similar altitude about 150 km away in an E–SE direction. Under these conditions, strong convective uplift is not necessary for dust in order to reach the EAIS, but only air mass circulation is important. We hypothesise that aeolian mobilisation of mineral particles from the Mesa Range (and likely from other high-altitude ice-free areas of NVL) and transport inland are favoured during penetration of maritime air masses onto the plateau. Therefore, we believe the Holocene dust flux record from TALDICE may bring some hints to the variability of the atmospheric circulation in the South Pacific/Ross sea periphery of the East Antarctic plateau. For the last glacial period, both the dust flux and the isotope signature suggest a common dust source for Talos Dome and for sites located over the EAIS. If confirmed, our results can provide important constraints for AGCM, including the dust cycle for glacial climatic conditions.

Conclusions and further perspectives

We presented a preliminary dust record from Talos Dome, which is located on the Ross Sea sector of the EAIS on the opposite side with respect to South America. The record spans ca. 250 ka and shows a first-order glacial/interglacial variability that is very similar to central Antarctic ice cores. However, the relatively higher Holocene dust fluxes compared with central Antarctic ice cores make the LGM/Holocene dust flux ratio significantly lower at Talos Dome with respect to EDC and Vostok sites, likely due a contribution from local dust sources.

The new data on the Sr and Nd isotopic fingerprint of TALDICE ice core dust and Victoria Land PSA allow a preliminary assessment of the remote *versus* local dust input at the site of Talos Dome. Isotopic data are interpreted along with results on dust concentration and size, and integrated with literature data from Southern Hemisphere dust sources and from central East Antarctic ice cores. During glacial periods dust originated from South America, while local sources prevail during the Holocene.

With a glacial dust signature comparable to that from the East Antarctic plateau, the Talos Dome ice core will provide strong constraints for AGCM simulating glacial climatic conditions.

For the Holocene, the analysis of several PSA samples suggests that the high-altitude ice-free areas of Victoria Land were the most probable proximal dust sources for Talos Dome. Within these areas, glacial deposits and regoliths represent important sources for fine mineral debris available for aeolian mobilisation. Because of the geographic setting of the area, dust transport inland is favoured during penetration of maritime air masses onto the EAIS. For this reason, the Holocene record of dust in the Talos Dome ice core has some potential for depicting the variability of atmospheric circulation at a regional scale.

To date, further investigations to characterise better the contribution of local emissions to the site would be of interest to confirm our results. We mention also that the isotopic similarity between South American and local sources leave open the possibility that the South American contribution remains significant for Talos Dome during the Holocene. In this respect, it would be of interest to identify better the large particles found in TALDICE samples by microscope, microprobe and rare earth element analysis to differentiate from the long-range dust reaching the Antarctic plateau, as well as to characterise the dust properties from ice cores drilled close to the expected source. Microscope investigations are in course in order to validate the size distribution provided by the Coulter counter. Finally, in the field, measurements and monitoring of the level of short-lived radioisotopes (e.g. ^{222}Rn) emitted by rocks and soils would also help to better estimate the regional influence of bare area to the atmosphere in the Talos dome area, and would be of interest for a deeper understanding of regional atmospheric circulation patterns.

Acknowledgements This work was carried out at the Swedish Museum of Natural History and was supported by SYNTHESYS funding (project SE-TAF-4807) made available by the European Community – Research Infrastructure Action under the FP6 ‘Structuring the European Research Area’ Programme. The Talos Dome Ice core Project (TALDICE), a joint European programme, is funded by national contributions from Italy, France, Germany, Switzerland and the UK. Main logistical support was provided by PNRA. This is TALDICE publication no. 6. This work is a contribution to the PolarCLIMATE Project HOLOCLIP.

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