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Eastern Australia: A possible source of dust in East Antarctica interglacial ice

M. Revel-Rolland [a,b,*], P. De Deckker [c], B. Delmonte [d], P.P. Hesse [e], J.W. Magee [c], I. Basile-Doelsch [f], F. Grousset [g], D. Bosch [h]

[a] Geosciences Azur, Observatoire Océanologique, La Darse, B.P. 48 06235 Villefranche/mer, France
[b] LGCA, Observatoire des Sciences de l'Univers de Grenoble, Université Joseph Fourier, France
[c] Department of Earth and Marine Sciences, The Australian National University, Canberra ACT 0200, Australia
[d] Dipartimento di Scienze dell'Ambiente e del Territorio, Università degli Studi di Milano-Bicocca, Piazza della Scienza, 120126 Milano, Italy
[e] Department of Physical Geography, Macquarie University, Sydney, NSW 2109, Australia
[f] CEREGE Université Aix-Marseille/CNRS/IRD UR161, BP 80, 13545 Aix-en Provence, France
[g] EPOC, Université de Bordeaux I, Avenue des Facultés, 33405 Talence, France
[h] Laboratoire de Tectonophysique, Université de Montpellier II, 34095 Montpellier, France

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Abstract

The Australian continent is characterised by an extremely variable surficial geochemistry, reflecting the varied lithology of Australian basement rocks. Samples representative of Australian aeolian dust have been collected in (1) regions where meteorological records, satellite observation and wind erosion modelling systems have indicated frequent dust activity today (mainly the Lake Eyre Basin), and (2) from deposits of mixed dust materials. The $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ isotopic composition of the fine (<5 μm) fraction of Australian dust samples was measured for comparison with the Sr and Nd isotopic composition of fine aeolian dust that reached the interior of the East Antarctic Plateau. The isotopic field for Australian dust is characterised by $^{87}Sr/^{86}Sr$ ratios ranging from 0.709 to 0.732 and $\varepsilon_{Nd}(0)$ between −3 and −15. The low Sr radiogenic values and $\varepsilon_{Nd}(0)$ of −3 obtained for Lake Eyre samples are explained by the lithology of the Lake Eyre catchment showing a dominance of Tertiary intraplate volcanic material.

These new data show that the dust contribution from Australia could have been dominant during interglacial periods (Holocene and Marine Isotopic Stage 5.5) to Antarctica. During glacial times, studies have shown that the South American dust isotopic signature overlaps the glacial Antarctic dust field suggesting this region as dominant aeolian dust source. However, the Australian Lake Eyre dust isotopic signature partially overlaps with the Antarctic glacial dust signature. We propose that the relatively greater contribution of Australian dust inferred for Antarctic interglacial ice compared with glacial ice is not directly reflective of changes in dust transport pathway, but instead is related to a differential weakening of the South American sources during interglacial time with respect to the Australia sources. Our findings have implications for interglacial versus glacial atmospheric circulation, at least in the Southern Hemisphere.

Keywords: Sr and Nd isotopes; Australian aeolian dust; Lake Eyre Basin; East Antarctica ice core dust

* Corresponding author. Geosciences Azur, Observatoire Océanologique, La Darse, B.P. 48 06235 Villefranche/mer, France. Tel.: +33 493763744; fax: +33 493763766.

E-mail address: mrolland@unice.fr (M. Revel-Rolland).

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1. Introduction

The importance of mineral dust in the atmosphere and its associated impacts have been recognised in (1) the interactions with ocean-carbon dynamics [1], (2) the possible role of dust in glacial cycling [2] and (3) in radiation scattering [3]. A prerequisite for studying the impact of aeolian dust on atmosphere radiation and circulation is to determine adequately the spatial distribution of dust concentration and its temporal variations. Studies [e.g. 4] have highlighted that the concentration of atmospheric dust trapped in polar ice in glacial periods was considerably higher in glacial periods compared to warmer interglacial periods. The average dust flux increase during the Last Glacial Maximum (LGM) with respect to the Holocene indicated by East Antarctic ice cores is about 25 [5]. A comprehensive compilation of worldwide literature data [DIRTMAP database, 5] on dust accumulation rates for the LGM and the Holocene however, points out that the glacial dust increase was neither globally uniform nor ubiquitous.

During glacial times, generally cold and dry conditions prevailed on land, with consequent reduction of the total forested area, expansion of grass-dominated vegetation areas [6], and increase of exposed fine-grained lacustrine material due to lake level decrease. In parallel, the hydrological cycle was reduced [7] and steeper latitudinal thermal gradients led to generally more vigorous atmospheric circulation [5]. All these factors contributed to accentuate the global atmospheric dustiness during glacial times. Understanding the primary causes of these changes is essential for providing a fundamental understanding into the processes controlling the Earth's climate change during the Quaternary.

To gain more insight into the atmospheric dust cycle, it is absolutely necessary to determine the geographical provenance of dust, which can be depicted in different ways [8,9]. For East Antarctica, dust provenance has been investigated using radiogenic isotopes first applied by [10] and largely developed by [11–15]. These studies converge towards the conclusion that the southern part (>32°S) of South America was the main source for dust transported to the Antarctic Plateau in glacial times. Works [11] and [15] also showed that a change of source, or a different source mixing, characterises East Antarctica during interglacial MIS 5.5 and the Holocene, but no conclusion could be drawn about a possible Australian contribution, mainly because of the paucity of Australian samples collected from target source areas.

The objectives of this study are (1) to characterise the $^{87}Sr/^{86}Sr$ versus $^{143}Nd/^{144}Nd$ isotopic composition of dust samples collected from target potential source areas of Australia (palaeolake sediments, sand dunes, loess-like deposits) and (2) to investigate and quantify the possible contribution of Australia as source for mineral dust to East Antarctica.

2. Australian background

2.1. The Australian continent

Australia is the most arid continent after Antarctica as it consists of approximately 40% of arid zones, largely occupied by dune fields, playa lakes and other desert landforms, including rocky deserts. Two general dust paths in Australia were identified [16], being associated with easterly-moving frontal systems within the zonal westerly winds in the south and the easterly trade winds in the north (Fig. 1A). The northern portion of this continent today records summer monsoonal rain. Present summer precipitation exceeds 1000 mm along the northern coastline and diminishes inland down to <300 mm near Alice Springs. In central Australia, the Lake Eyre Basin (LEB) is the largest internal drainage basin covering an area $>10^6$ km^2 (Fig. 1A). The lowest part in the basin consists of a vast saline playa (9300 km^2). The river tributaries to the lake are mostly fed by sporadic monsoonal summer rains in tropical Queensland and the Northern Territory (Fig. 1A and B). As a result, new sediment loads are regularly supplied to this arid and flat region [17]. The Murray–Darling (MD) Basin covers 10^6 km^2 in southeastern Australia (Fig. 1A) and also plays an important role in providing sediment, which may be vulnerable to aeolian entrainment as dust. Unlike the LEB, the MD system is perennial because the River Murray has its sources mostly in a region of high rainfall principally falling in winter and the Darling River is predominantly fed by summer rains. In summary, the LE and the MD Basins are able to supply vast amounts of fine particles to the surrounding arid lands of central Australia. As a result, deflated aeolian material is common in the southeastern plains and highlands of Australia [17,18]. The existence of the southeast aeolian dust path (Fig. 1A) has been documented at many locations along its course, in soil [18] and on snow [19] in southeastern Australia, in pelagic sediment in the southwest Pacific region [20] and in glaciers in New Zealand [21]. In spite of the omnipresence of aeolian dust in Australia and surrounding oceans, few studies [22–26] have attempted to document the general composition of the aeolian dust and to identify its sources on a continental scale.

2.2. Dust storm in Australia

Dust storms are a common feature in arid inland Australia. In particular, on October 23, 2002, the largest

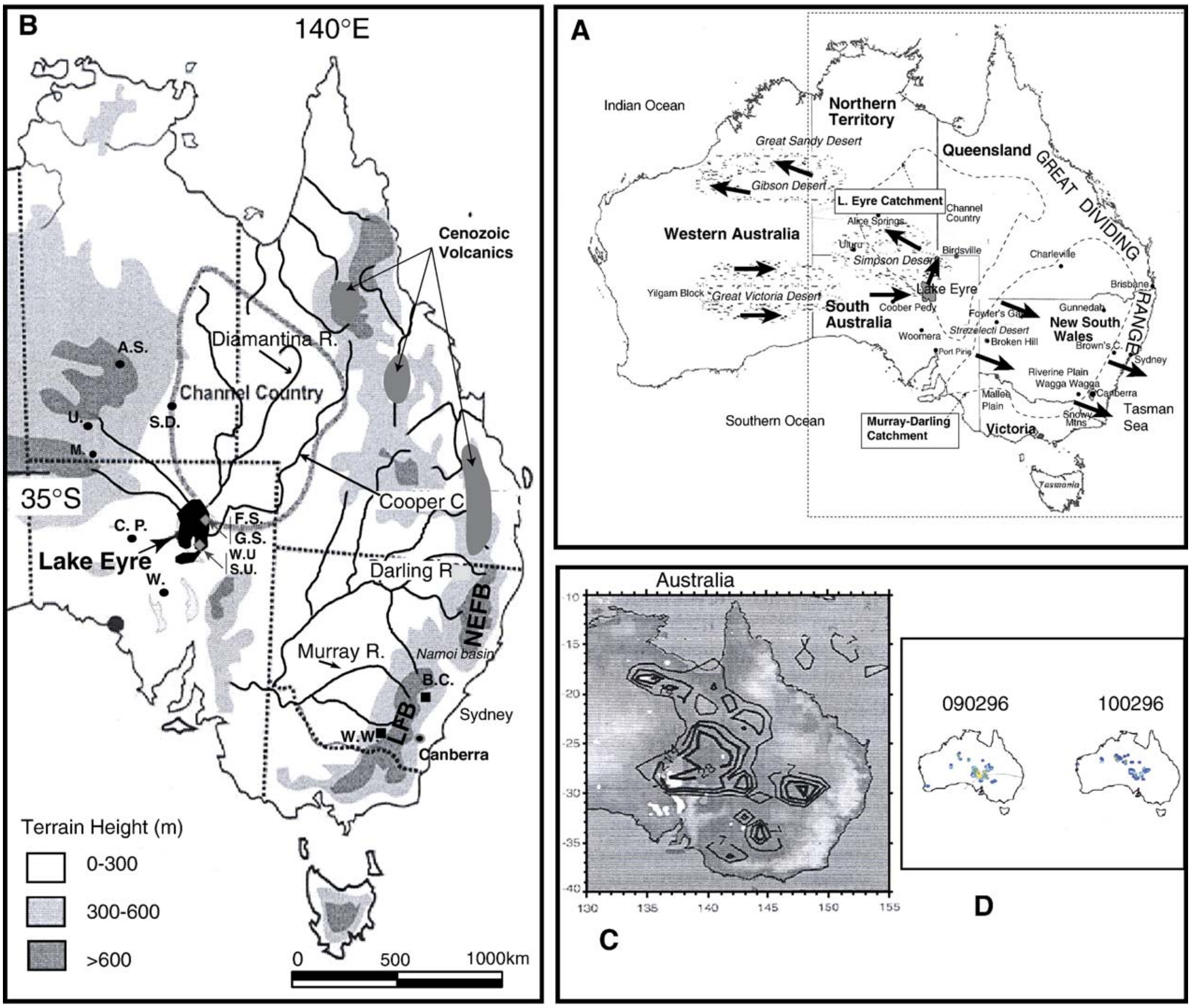

Fig. 1. A) General map of Australia showing the dust paths (indicated by arrows, adapted from [16]). The topography of Eastern Australia is characterised by the Great Dividing Range, which runs in a general N–S direction parallel to the eastern coastline of the continent. This higher-relief mountain range mainly feeds the Cretaceous Great Artesian Basin (equivalent to the east Lake Eyre Catchment) and the Murray–Darling Basin. B) Map of eastern and central Australia showing (i) the locations of Lake Eyre (LE) and Murray–Darling (MD) catchments and respective geologic setting (ii) the sampling location of source samples (diamond for the LE and black circles for sand dunes samples) and loess-like deposit samples (black squares). Adapted from [21]. NEFB: New England Foldbelt, LFB: Lachan Foldbelt. C) Major atmospheric dust source in Australia from TOMS sensor on the Nimbus-7 satellite from [29]. D) Dust emission model results are reported from [30] for the 9 and 10 February 1996. The most severe dust storm for the simulated period occurred between February 8 and 10 in Central Australia. Predicted daily-averaged dust emission patterns are presented with a value of F (in mg m^{-2} s^{-1}) range from 1 to 300 (the highest values are found for the LE region).

dust storm recorded for the last 40 years in Eastern Australia, was characterised by a dust load of about 4 million tonnes [27]. Past observations of dust storms based on meteorological records [18,28] have indicated that there are two majors regions of active wind erosion in Australia (Fig. 1A). These are the Lake Eyre Basin and the western sector of the Murray–Darling Basin. The main dust source areas of the southeastern dust path are the Simpson Desert–Channel Country regions of southwest Queensland, the Strzelecki Desert in South Australia and in western NSW extending south to the Mallee region in Northwest Victoria. The dust source areas of the north-west dust path are less well known, but the Simpson Desert–Channel Country region can also be an origin of this path during post-frontal southerlies [18]. These observations are relatively consistent with satellite imagery ([29] Fig. 1C) and wind erosion models ([30,31] Fig. 1D). An integrated wind erosion modelling system [30] reports that intensive wind erosion was found (Fig. 1D) mainly in the southern part of the Simpson Desert to the North of LEB. In addition, areas of medium dust uplift were identified in the Great Victoria Desert, the Gibson Desert and the west coast of Western Australia. A worldwide geographical mapping of major atmospheric dust sources was recently provided by [29] on the basis of data from the TOMS (Total Ozone Mapping Spectrometer) sensor on the NIMBUS-7 satellite spanning a period of 13 years (1980–1992). Persistent dust activity in Australia (Fig. 1C) was mainly detected in the lower parts of the inland LE and MD drainage basins, where the floodplains of inland-draining river systems and dune fields merge. Surprisingly, the Western Australian deserts, consisting mainly of sand dunes, are not considered to be a major atmospheric source for long transport dust by [29, Fig. 1C]. They have shown that sands and sand dune systems are not good sources for long-range transport of dust in general, since they are devoid of the fine fraction and contain larger particles with very high settling velocity. Also, [18] have indicated that the Gibson Desert in the Western Australia is not a dominant source of dust as this desert is characterised by low dust entrainment, great geomorphic stability and a large extent of stable, indurated surface. Thus, it appears that the present source of dust in Australia corresponds to the two major drainage systems, LE and MD [18], where internal drainage renews supply of fine particles to the arid zones.

3. Methods and results

3.1. The Australian samples

Samples representative of the Australian aeolian dust sources were mainly collected in regions of persistent dust activity (Fig. 1C and D). Both potential dust source areas and aeolian dust deposits (as loess-like deposits) have been selected (Fig. 1B and Table 1). In addition, where possible, we used well-dated samples deposited during glacial periods.

3.1.1. Potential Australian aeolian dust source areas:

- Samples from the Lake Eyre Basin (LEB) are very important since this region is the most active dust supplier today. In addition, it has been demonstrated by [32,33] that between 60 and 50 ka, a major deflation episode excavated the present LE Basin and deposited gypsum-clay-rich material during an aeolian phase (the Williams Point aeolian unit) at a number of sites around the lake. Between 30 ka and 12 ka, LE was drier than it is today and, at many sites around Madigan Gulf, an aeolian unit (the Shelly Island unit) was deposited and formed by material deflated from the playa floor. We have selected two samples representative of the modern-day environment of deposition and two others dated by Optically Stimulated Luminescence (OSL), thermoluminescence and AMS ^{14}C [32,33] at 65 ka (from the Williams Point aeolian unit) and at 25 ka (from the Shelly Island unit) corresponding, respectively, to MIS (Marine Isotopic Stages) 4 and 2.
- Sand dune samples were collected in the vicinity of Alice Springs and the Simpson Desert in the Northern Territory (NT) and in the North of South Australia (SA) respectively. For the Simpson Desert, the presence of red dunes with a dominance of kaolinite-rich clay coatings and pale-coloured dunes with clay pellets were described by [34]. Two samples were obtained from the Simpson Desert and differ in colour (pale and red).

3.1.2. Aeolian dust deposits:

- From the southeastern highlands of NSW, loess-like deposits (parna[1]) were sampled from two different areas identified mainly as aeolian dust deposits. Two loess-like deposits, at Brown's Creek (BC), were chosen because an OSL age indicates that significant aeolian silt deposition started well before the onset of the LGM [36,37]. The BC-1 sample is dated from <8.4 ka, while BC-2 sample dates from the LGM. Four loess-like deposits were sampled in the vicinity of Wagga Wagga (WW) described as a red clay mantle with significant parna deposits [38].
- A suspended dust sample was collected as it fell during the October 23, 2002 dust storm in Canberra (these dust storm characteristics are described in detail in [27]). The grain size distribution profile of this sample reveals a mode around 10 μm with good sorting, which is typical of Australian dust events [39].
- Two marine samples were selected from Tasman Sea gravity core E26.1, described in detail in [20] and further discussed in [39], because the terrigenous fraction of this core is thought to be Australian aeolian in origin and also because the ^{14}C dating permitted selection of one LGM-dated level.

3.2. Sample pre-treatment (<5 μm grain size selection)

During extensive airborne transport, as in the case of dust travelling from the continental areas of the Southern Hemisphere to Antarctica, minerals become sorted around

[1] Butler [35] first used the word parna (aboriginal word for dusty ground) to refer to the aeolian clay deposits in the Riverine Plain.

Table 1
Australian sample locations and Sr and Nd isotopic data

Samples	Name on Fig. 1B	Location (latitude longitude)	Type of deposit	Age	Grain size analysed	$^{87}Sr/^{86}Sr$	(2sig*10^{-6})	$^{143}Nd/^{144}Nd$	(2sig*10^{-6})	ε_{Nd} (0)
New South Wales and ACT										
Canberra, 2002 dust storm	Canberra	Canberra (33°15′S, 148°10′E)	Suspended dust		<5 μm	0.712141	10	0.512286	12	−6.8
Wagga Wagga (1)	W.W.	175 km west of Canberra (35°S, 147° E)	Loess-like deposit		<5 μm	0.716907	11	0.512155	8	−9.4
Wagga Wagga (2)		175 km west of Canberra (35°S, 147° E)	Loess-like deposit		<5 μm	0.717251	14	0.512174	12	−9.0
Wagga Wagga (3)		175 km west of Canberra (35°S, 147° E)	Loess-like deposit		<5 μm	0.719244	8	0.512185	8	−8.8
Wagga Wagga (4)		175 km west of Canberra (35°S, 147° E)	Loess-like deposit		<5 μm	0.718368	15	0.512192	7	−8.7
Brown's Creek (BC-2 0.70 cm)	B.C.	Central Highlands, (~32°S, 149°E)	Loess-like deposit	18.2± 1.8 ka	<5 μm	0.714385	7	0.512226	8	−8.0
Brown's Creek (BC-1 0.15 cm)		Central Highlands, (~32°S, 149°E)	Loess-like deposit	<8.4 ka	<5 μm	0.714161	22	0.512227	9	−8.0
Northern Territory										
Marryat	M.	~26°S, 131°E	Sand dune		<5 μm	0.714550	10	0.512046	9	−11.5
Uluru (Ayers Rocks)	U.	~25 °S 131°E	Sand dune		<5 μm	0.720980	10	0.512074	11	−11.0
Simpson Desert (R8)	S.D.	Rainbow valley (~25°S 133°E)	Sand dune (red colour)		<5 μm	0.719079	10	0.512084	10	−10.8
Simpson Desert (R7)	S.D.	Rainbow valley (~25°S 133°E)	Sand dune (pale colour)		<5 μm	0.732072	13	0.511849	6	−15.4
South Australia										
Lake Eye Basin	F.S.	Franck Site, LE North (~28°S, 137,30′E)	Lacustrine sediment		<5 μm	0.709527	7	0.512489	5	−2.9
Lake Eyre Basin	G.S.	Giffbo, LE North (~28°S, 137,30′°E)	Lacustrine sediment		<5 μm	0.709033	8	0.512469	7	−3.3
Lake Eyre (Shelly Island unit)	S.U.	Jackboot Bay (~29°S, 137°E)	Lacustrine sediment	~25 ka	<5 μm	0.709260	10	0.512472	64	−3
Lake Eyre (Williams Point unit)	W.U.	South Madigan Gulf (~29°S, 137°30′E)	Lacustrine sediment	~65 ka	<5 μm	0.709867	8	0.512444	5	−4
Woomera	W.	Woomera (31°S, 1~36°E)	Sand dune		<5 μm	0.715622	10	0.512299	12	−6.6
Coober Pedy	C.P.	Coober Pedy (29°S, 134°E)	Sand dune		<5 μm	0.711880	8	0.512228	9	−8.0
Eastern Tasman Sea										
Core E26.1 (E1-1 cm)		40°17′S 168°20′E	Marine sed.	~4.5 ka	10 μm	0.711128	118	0.512347	10	−5.6
Core E26.1 (E8-35 cm)		40°17′S 168°20′E	Marine sed.	<18.8 ka	10 μm	0.711945	42	0.512398	42	−4.6

(continued on next page)

Table 1 (*continued*)

Samples	Name on Fig. 1B	Location (latitude longitude)	Type of deposit	Age	Grain size analysed	$^{87}Sr/^{86}Sr$	(2sig*10^{-6})	$^{143}Nd/^{144}Nd$	(2sig*10^{-6})	ε_{Nd} (0)
Data from Grousset et al. [10]	Samples	Lat., long.								
Fowler's Gap	AUE12-M	~31°S, 142°E	Dust		Bulk	0.723238	35	0.512446	31	−3.7
Fowler's Gap	AU-C10	~31°S, 142°E	Dust		Bulk	0.721822	44	0.512037	41	−11.7
Fowler's Gap	AU-C10	~31°S, 142°E	Dust		<5 μm	0.740074	32	0.512128	26	−9.9
Great Sandy Desert	AU4-J	~18°S, 124°E	Loess		Bulk	0.763360	36			
Great Sandy Desert	AUE6-L	~18°S, 124°E	Loess		Bulk	0.732307	23	0.512447	33	−3.7

Details of the Lake Eyre Basin sample and Tasman deep-sea core locations are given in [32] and [20], respectively.

a modal diameter value of 1.8 to 2.5 μm [13]. Significant variations in the Sr isotopic ratios related to grain size have been observed by [40], on suspended mineral in the MD river systems. For example, the size fractions of 1–2 μm, 1 to 25 μm and >25 μm for the Darling River sediments display $^{87}Sr/^{86}Sr$ ratios of 0.709, 0.711 and 0.7114, respectively. In summary, because the Sr and Nd isotopic compositions are strongly dependant on the particle size [40,41], we have carried out Nd and Sr isotopic measurements exclusively on the <5 μm grain

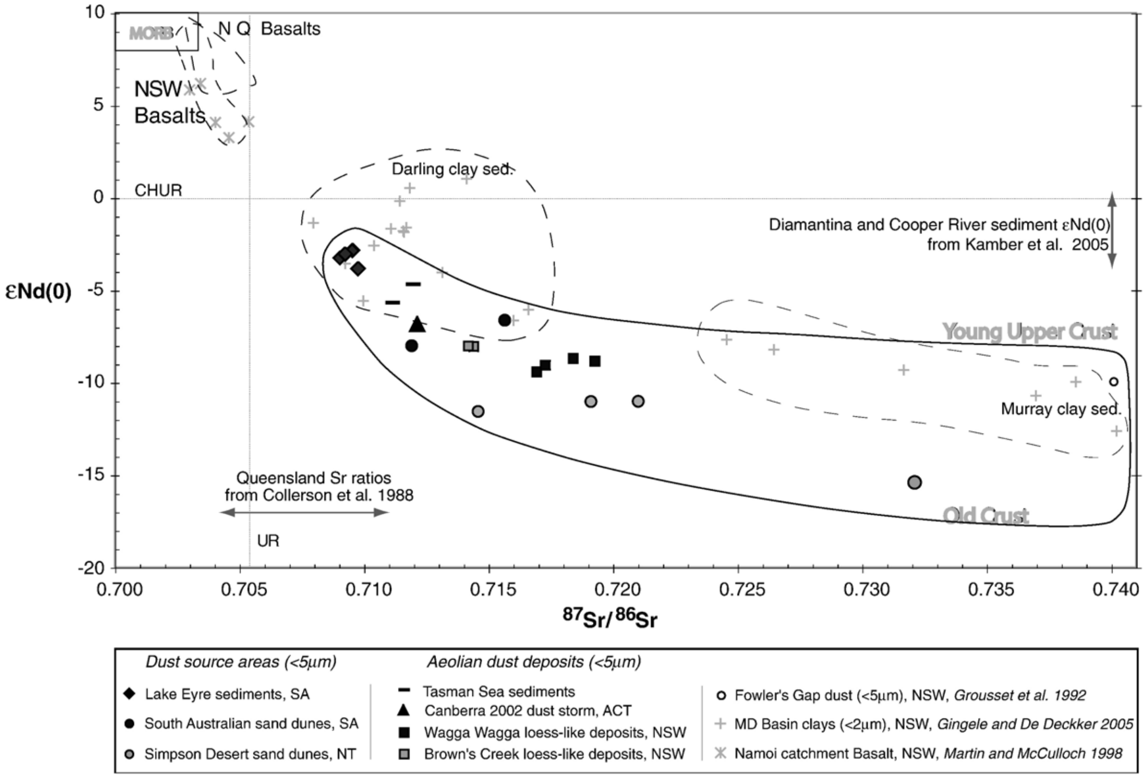

Fig. 2. $^{87}Sr/^{86}Sr$ versus $\varepsilon_{Nd}(0)$ isotopic signature (Table 1) for the carbonate-free, and strictly <5 μm fraction, of the Eastern Australian dust samples (dark outlined field). Dotted outlined fields and the arrows correspond to the Sr and Nd isotopic compositions reported from the literature: 1) the Namoi catchment basalt (grey crosses) [52] and the basalts province from Eastern Australia–NSW and North Queensland (NQ) Basalts [49–51]; 2) the carbonate-free clays (<2 μm) fraction of Murray–Darling River sediments [54] 3) The $\varepsilon_{Nd}(0)$ values comprise between 0.48 and −3.57 from four alluvial sediment samples collected in the Diamantina River (over a length of 450 km) and Cooper Creek after the summer floods of 2002 and 2003 [55] 4) the Sr isotopic composition of the Queensland groundwaters showing $^{87}Sr/^{86}Sr$ ratios between 0.7045 to 0.7118 [56]. Only the <5 μm Australian sample isotopic composition from [10] is reported in this figure whereas the bulk Australian isotopic values are reported in the Table 1.

size fraction of all Australian samples, corresponding to the size of aeolian dust in Antarctic ice cores. Observations from different authors suggest that carbonates are almost absent in East Antarctic ice cores [13,42,43]. Calcite present originally at the source might have been dissolved during atmospheric transport through reactions with acid aerosols.

By means of a simple preliminary test with cold HCl, we analysed samples tested negative for carbonate for Sr–Nd analyses. The mineralogy has also been analysed by X-ray diffraction for the most important Australian samples in order to better control their mineralogical nature and to confirm the absence of carbonate (Revel et al. in prep).

The acid leaching (with acetic acid buffered at pH = 5) of samples with carbonates as well as the size separations for all the Australian samples have been performed following the same laboratory procedures as [13]. The size of the particles analysed was carefully checked with a Laser Particle Counter (Coulter Multisizer IIe), and only samples presenting at least 95% of the total mass finer than 5 μm have been accepted.

3.3. Sr and Nd isotopic composition measurements

Sr and Nd chemical extraction was carried out at the Laboratory of Tectonophysics of Montpellier. A 25 mg aliquot, considered to be representative of each sample, was taken for analysis of Sr and Nd isotope ratios. Samples were dissolved into Savillex beakers in a [$HF + HClO_4 + HNO_3$] mixture. Chemical extractions of Sr and Nd were carried out following the analytical procedures of [44,45].

The isotopic measurements were made at the University of Paul Sabatier in Toulouse, using a multi-collector mass spectrometer Finnigan MAT 261.

The measured $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios have been corrected for mass fractionation by normalizing to $^{86}Sr/^{88}Sr = 0.1194$ and $^{146}Nd/^{144}Nd = 0.7219$,

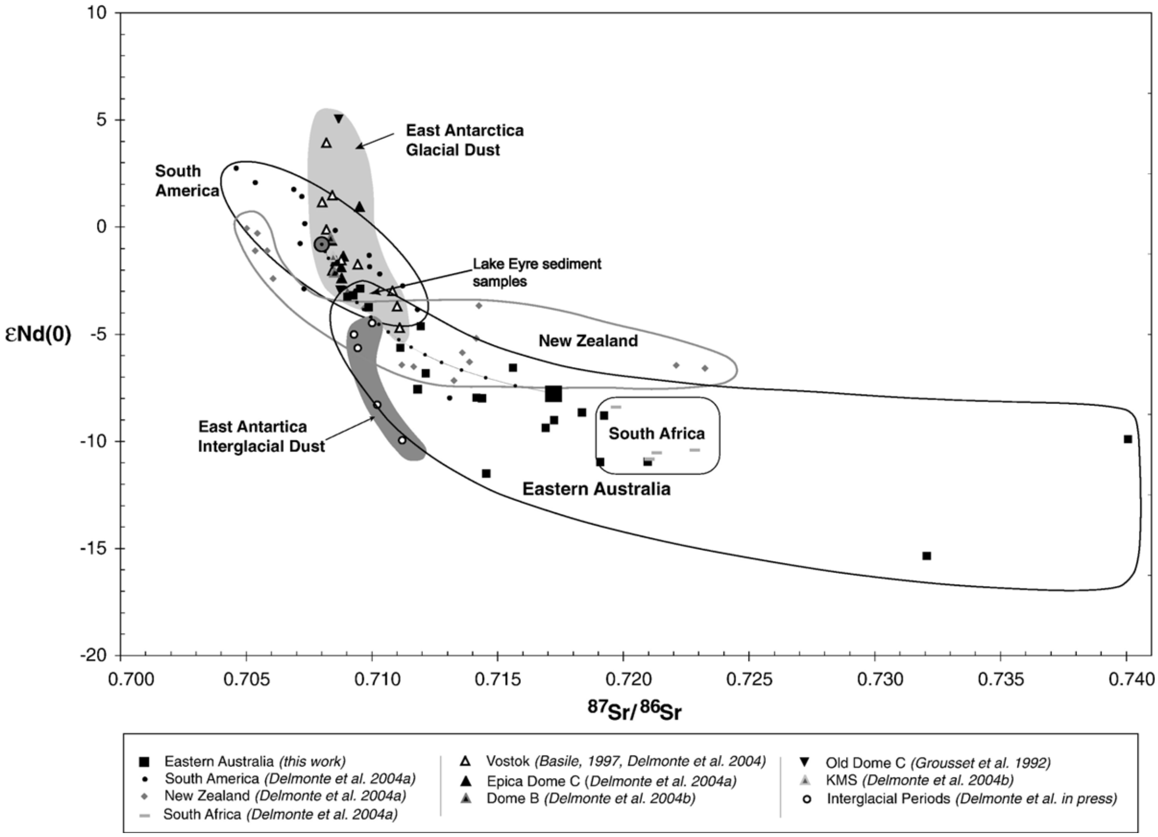

Fig. 3. $^{87}Sr/^{86}Sr$ versus $\varepsilon_{Nd}(0)$ isotopic signature of East Antarctic ice core dust from interglacial (Holocene and isotopic stage 5.5 in Epica Dome C and Vostok from [11,15]) and from glacial (Dome B MIS 2; Old Dome C; KMS Termination I; Vostok MIS 4 to 12; Epica Dome C MIS 2, 4 and 6, from [10–13]) and comparison with the samples from Eastern Australia (this work), New Zealand [13], South America and South Africa [10–13]. All the data presented in this figure are from the <5 μm size fraction. Isotopic fields were defined by free form outlined from the available points. Theoretical mixing hyperbolae (using the mixing equation of [66]) between South American and Australian end-members are plotted (dotted line) to calculate the mixing proportion between these two potential sources of the glacial ice dusts.

respectively. Strontium standard STD NBS 987 was measured with an average $^{87}Sr/^{86}Sr = 0.710256$ versus the certified value of 0.710250. Neodymium standard (STD Rennes) was analysed with an average of $^{143}Nd/^{144}Nd = 0.511965$ versus the certificate value of 0.511962. Results are expressed as: $\varepsilon_{Nd}(0) = [[^{143}Nd/^{144}Nd\ (meas.)/\ ^{143}Nd/^{144}Nd\ (CHUR)] - 1]*10^4$. The CHUR (Chondritic Uniform Reservoir) value is 0.512638 [46]. Blanks averaged 0.1 ng and were negligible in all cases.

3.4. The Australian source dust Sr–Nd isotopic signatures

The Sr and Nd isotopic compositions of the Australian samples are listed in Table 1, and are plotted in Fig. 2.

Whatever the type of samples, all Sr and Nd isotopic values are aligned along a hyperbolic mixing curve linking a depleted mantle-derived (NQ and NSW Basalts) end-member and the main continental crust end-member, with $^{87}Sr/^{86}Sr$ ratios ranging from 0.709 to 0.732 and $\varepsilon_{Nd}(0)$ between −3 and −15. Sr and Nd isotopic ratios of the NSW loess-like deposits and the NT/SA sand dune samples (except for the Simpson R7 sample) display a similar, and relatively narrow, range of values ($0.712 < {}^{87}Sr/^{86}Sr < 0.721$) and $\varepsilon_{Nd}(0)$ between −7 and −12. The LEB samples display lower $^{87}Sr/^{86}Sr$ ratio values and higher $\varepsilon_{Nd}(0)$ of about −3. The Canberra dust and the Tasman Sea sediment samples display similar values, being intermediate between the LEB and loess-like deposit/sand dune values.

There are no differences between glacial periods and Holocene isotopic values for the LEB sediment samples, for the BC loess-like deposit in NSW and small differences between those ages in Tasman Sea core E26.1 sediment. The pale-colour Simpson Desert (R7, Table 1) sample records a high radiogenic Sr ratio of 0.732. The mineralogy of the bulk fraction of pale-colour Simpson Desert sample (Revel et al., in prep) is different from the other (R8) with a high quartz content (98.5%) and low clay (<1%). This result could be explained by the concept developed by [29] that fine particles have already been advected from this sand dune region.

4. Discussion

4.1. The isotopic signature of Australian aeolian dust

The Australian continent geology is extremely varied [47]. Central and Western Australia are well known for consisting mostly of an old cratonic basement dated at 3–1.5 Ga. For example, Achaean rocks [48] of the Western Australian Yilgarn Block (Fig. 1A) are characterised by high $^{87}Sr/^{86}Sr$ (0.86–0.96) and sand dune samples in the Great Sandy Desert [10] by high $^{87}Sr/^{86}Sr$ (0.732–0.763, Table 1). Eastern Australian surface rocks, on the other hand, consist mostly of post-Palaeozoic sediments and a recent volcanic province over a large area on the coastal fringe, deposited over a Paleozoic basement [49]. For example, rocks of the New England Fold Belt (NEFB, Fig. 1B) consist mainly of Tertiary basalts with $^{87}Sr/^{86}Sr$ ratios of 0.703–0.705 and positive $\varepsilon_{Nd}(0)$ and Permian granites with $^{87}Sr/^{86}Sr$ ratios of ~0.7127 and $\varepsilon_{Nd}(0)$ about −5 [50–52]. The geology of the northwestern part of the Great Dividing Range, which supplies material to the LEB, is characterised by basaltic rocks of Palaeozoic, Cretaceous and Cenozoic age [53]. This varied lithology of Australian basement plus sediment rocks is well reflected in the Sr and Nd isotopic composition of river sediments from the MD [54] and LE [55] basins. These compositions are reported in Fig. 2. The MD Rivers clay sediments have scattered ranges of $^{87}Sr/^{86}Sr$ (0.708 to 0.755) and $\varepsilon_{Nd}(0)$ (1.4 to −12), due to differences in the composition and age of rocks in their respective catchments [52,54]. Sediment samples collected in the Diamantina River and Cooper Creek display $\varepsilon_{Nd}(0)$ values between 0.48 and −3.57 (Fig. 2), implying that the basalt-dominated soils represent a major erosion source for the Diamantina River and the Cooper Creek [55]. Unfortunately, no Sr isotopic ratios were obtained for these samples. However, [56] reported groundwater isotopic compositions from the same Queensland area, and their results show relatively unradiogenic $^{87}Sr/^{86}Sr$ ratios (0.7045 to 0.7118, Fig. 2). These “juvenile” strontium isotopic signatures most likely reflect an interaction with Cenozoic mafic igneous rocks, which occur on the eastern side of the Basin.

In summary, the Australian continent is characterised by extremely variable Sr and Nd isotopic compositions (contrary to the South America continent), but what is the contribution of each of these areas in the aeolian dust composition? [18,28,29] have shown, by satellite and meteorological observations, respectively, that active dust storm regions are located in Central–Eastern Australia. Consequently, in order to characterise the Australian aeolian dust isotopic signature (end of §1), we carefully selected samples mainly from Central–Eastern Australia.

In Fig. 2, the isotopic results from our size selected (“aeolian dust-like”) samples are characterised by $^{87}Sr/^{86}Sr$ ratios ranging from 0.709 to 0.732 and $\varepsilon_{Nd}(0)$ from −3 to −15. The loess-like deposit samples from southeastern Australia and sand dune samples display relatively similar isotopic compositions. This is consistent with the clay mineralogy data of Eastern Australia of [23]. These authors have compared the clay mineral composition of suspended dusts, soils and sand dune sediments of southern Queensland and NSW and have concluded that dune sediment and soils do not significantly differ from each other. This similarity suggests that the Brown's Creek and Wagga Wagga loess-like deposits in eastern NSW have received dust from sand dunes and dry lake beds deflated from the semi-arid region of the LEB and MD Basin, in agreement with observations from [25].

The Tasman Sea core samples are characterised by isotopic compositions similar to the Canberra dust sample with $^{87}Sr/^{86}Sr$ being around 0.711, suggesting that the dominant source of these marine sediments is the Australian aeolian dust as was already postulated by [20]. However, the Sr and Nd isotopic composition pattern for New Zealand (see Fig. 3) overlaps the Tasman Sea sediment value, suggesting that a New Zealand contribution cannot be discounted for core E26.1 located west of New Zealand.

Significant results are those obtained from the LEB, which is an important area of fine-grained dust supply at the present time. The four samples show fairly low radiogenic Sr values and $\varepsilon_{Nd}(0)$ of −3 to −4. Given that the lithology of LE catchments (see above) shows a dominance of Tertiary intraplate volcanic material in the headwater [55,57], these values are easily explained.

Another significant result is from the suspended dust sample collected during the Canberra dust storm. As [58] showed that, during a dust storm, several potential sources can contribute to a dust plume (as wind direction can change from northerly pre-frontal to a westerly winds within minutes during the same storm), we consider that these kinds of suspended dust samples adequately represent the Australian aeolian sources. Indeed, these suspended dust samples (and at a lesser degree also the loess-like deposits) are probably the result of a mixing of dusts from several sources with distinct isotopic compositions. Unfortunately, no Sr and Nd analysis has been undertaken thus far on suspended dust material in Australia for comparison. The clay mineralogy of suspended dust carried out by [23] collected during dust storm events (monitoring stations at Charleville, Fowlers Gap and Gunnedah) have shown that the mineralogy varies between events and regions (e.g. kaolinite/illite ratios of 2–2.8; 0.8–1; 1.2–4, respectively).

Interestingly, using three different kinds of sediment (lacustrine, marine and loess-like deposits) in the Australasian region, we have been able to compare the isotopic signature of present (interglacial) and glacial dust deposits and observe no clear change in the isotopic signature. Therefore, we suggest that the "fingerprints" of the potential source area of dust in Australia did not change over the last ~65,000 years. For example, if the sources of dust during the last glacial periods have changed towards an increase of dust contribution from Western Australia, we should have obtained an isotopic composition with higher $^{87}Sr/^{86}Sr$ ratios as Western Australia is characterised by Archean rocks (§4.1).

In summary, to proceed further on this question of sources in Australia, more geochemical data, in particular, from suspended dust collected during dust storms, are required to better document the nature of aeolian dust emanating from this continent.

4.2. Australian aeolian dust as a source in Antarctica ice cores

The Sr and Nd isotopic composition of East Antarctic ice core dust [10–15] from five drilling sites of the inner Plateau (Vostok, Epica Dome C and the old Dome C drilling site, Dome B and Komsomolskaya) and both for glacial and interglacial times is reported in Fig. 3. The isotopic signature of fine-grained dust from potential source areas (South America, South Africa, New Zealand and Eastern Australia) is reported for comparison.

4.2.1. Interglacial periods

The interglacial 5.5 and the Holocene dusts of the East Antarctic [12,15] are characterised by Sr ratio values around 0.710 and quite negative $\varepsilon_{Nd}(0)$ ranging from −4.5 to −10. This gives an overall isotopic signature for interglacial dust significantly less radiogenic in Nd than for glacial times. As observed by [15], the southern South American dust isotopic field (constructed on the basis of samples collected at latitudes >32°S) is definitely outside the interglacial dust values, and this clearly suggests a change in the source mixing between glacial and interglacial times. However, in their study [15], the Australian isotopic field was insufficiently documented. Data from this work are fundamental in this respect. Indeed, it can be observed that Nd isotopic values for interglacial Antarctic dust span the same interval as the Australian dust samples, but the latter display a shift towards more radiogenic Sr values. Overall, the Eastern Australian and East Antarctic interglacial dust isotopic fields are very close, suggesting Australia as a possible dust source to the East Antarctic Plateau during interglacial times.

The shift in Sr ratios cannot be explained by a difference in particle size. The mean size of Australian samples studied here is 4 μm whereas dust ice cores have a modal value of 2 μm [13]. Thus, if the Sr and Nd measurements of Australian samples had been strictly done on the <2 μm size, the Sr ratio should be higher [41].

A possible explanation could be the presence of very low amounts of gypsum or carbonates in the Antarctic interglacial samples. It has been mentioned earlier that there are almost no carbonates in East Antarctic ice, at least during glacial times. However, interglacial ice has not been examined mineralogically [8]. Moreover, gypsum can be present in the samples with important effects on the Sr isotopic budget. A better understanding of the dust mineralogy in Antarctica would help solve this question.

Another explanation could be that the interglacial Antarctic dust consists of a mixture of more than two sources: either a South America source plus a mixture one based on negative $\varepsilon_{Nd}(0)$ sources (possibly Western Australia; South Africa e.g. Kalahari Desert; and/or Antarctica e.g. Terre Adélie), or a mixture between the Lake Eyre sources and negative $\varepsilon_{Nd}(0)$ value sources such as Western Australia, South Africa or Antarctica.

The possibility of a Western Australian and/or South African contribution to Antarctica cannot be excluded, but the South African and Western Australian dust isotopic field [10–13] is still insufficiently documented for targeted, fine fraction sampling.

4.2.2. Glacial periods

Most East Antarctic dust samples from the glacial periods are restricted to the range of $^{87}Sr/^{86}Sr$: 0.708 to 0.710 and $\varepsilon_{Nd}(0)$: −3 to 4 with only exceptions for the Vostok MIS 6, 8 and 12. This clearly suggests a dominant southern South American contribution in glacial times [10–13]. The New Zealand dust isotopic field is also close to the Antarctic dust field but the possible New Zealand contribution has been estimated to be negligible on the basis of a variety of arguments (developed in [13,59]), among which is the absence of any tephra layers in the Vostok ice core from the active Taupo volcanic zone.

The Australian dust isotopic signature from the LEB samples partially overlaps with the glacial dust signature, suggesting that the Australian contribution in Antarctica may not be excluded during glacial periods. In particular, three samples from Vostok MIS 6, 8 and 12 indicate values tending towards the Australian dust field.

If you hypothesise that Antarctic dusts consist of a mixture of mainly two end-members during the glacial periods: South America and Australia, we can broadly quantify the Australian contribution. Theoretical mixing hyperbolae (Fig. 3) have been constructed between (1) a South American end-member [characterised by the values of the Puerto Madryn sample ($^{87}Sr/^{86}Sr$:0. 70732 and ε_{Nd} (0): 0.12)] selected as it is the only sample located in an area with persistent dust activity [29], and (2) an Australian end-member characterised by the mean of all available <5 μm size Australian samples (see Table 1). The mixing hyperbolae line on Fig. 3 reveals a contribution from South America ranging from 90 to 80% and an Australian contribution from 10 to 20%, in Antarctic samples. This is consistent with the quantification already mentioned by [12] for hypothesis 3 (85–90% of Patagonian dust; ~10–15% of Australian or Africa dust). However, in three cases, for samples corresponding to the Vostok MIS 6, 8 and 12, we can estimate a contribution of 50% for both end-members. As many samples have isotopic compositions that do not fall onto the mixing line, further isotopic data from more target samples such as suspended dust storm or lake samples from Australia and South Africa are needed in order to reliably quantify the end-members and (as mentioned in §4.1) to progress with a firm identification of sources.

Results from isotopic dust fingerprinting are in accordance with the mineralogical study of [60,61], which observed lower kaolinite abundance under glacial climatic conditions with respect to interglacials, and suggested a possible dust transport to East Antarctica from Australia under present and mid-Holocene conditions. Indeed, kaolinite and illite are the dominant clay minerals in Australia [62].

During the Quaternary, there is clear evidence of colder and drier condition during glacial periods in contrast with interglacial periods in Australia (e.g. [16]). In particular, the LE level record used as proxy for the Australian monsoon [63] shows playa floor deflation events (indicative of aridity) during the glacial periods with an increase of exposure of fine-grained material, and therefore, the lake would have become a significant provider of long transport dust. A higher contribution of aeolian dust to the southwestern Pacific Ocean during the LGM (and previous glacial intervals back to MIS 10), compared to the Holocene, is discussed in [20] and [18]. Climate and environmental changes linked to glacial/interglacial transitions generally weakened the strength (or activity) of all dust sources in extratropical southern latitudes. However, the change of East Antarctic dust origin between glacials and interglacials could reflect either (1) a change in atmospheric circulation patterns and/or (2) a change in atmospheric moisture content and/or (3) a differential weakening of one source with respect to the other(s).

We propose that the relatively greater proportion of Australian dust inferred for Antarctic interglacial ice compared with glacial ice may therefore, not be directly reflective of changes in dust transport from Australia. Instead, the much greater (two orders of magnitude) concentration of dust in glacial periods may well include a greater rate of deposition of Australian dust as is seen in the marine sediments. The primary cause of the variation in dust geochemistry is the sensitive response of South American, and New Zealand, dust production to the glacial cycles. In both cases, dust is overwhelmingly derived from glacial outwash and, possibly, deflation of exposed continental shelves. Both these sources were most active during glacial phases and nearly shut off in interglacial ones [64,65]. As a result, South America, and possibly New Zealand, quantitatively dominate the flux of dust to Antarctica during glacials, but make almost less contribution in the interglacial dust, which, as a consequence, is dominated by the lower flux of Australian dust.

5. Conclusion

The Sr and Nd isotopic composition analyses of Australian aeolian dust reveal that Australia was a possible source for East Antarctic dust during interglacial periods. For the purpose of obtaining samples representative of the Australian aeolian dust sources, samples were carefully collected in regions (mainly the Lake Eyre Basin) where meteorological records, satellite observation and integrated wind erosion modelling systems, have indicated frequent dust uplift. The isotopic field for Australian dust (<5 μm fraction) is characterised by $^{87}Sr/^{86}Sr$ ratios ranging from 0.709 to 0.732 and $\varepsilon_{Nd}(0)$ between −3 and −15.

The Sr and Nd isotopic composition of East Antarctica ice core dusts [10–15] has been compared with the isotopic composition of potential sources such as South America, South Africa, Eastern Australia and New Zealand. This comparison reveals that, during the interglacial periods (Holocene and 5.5 periods are characterised by Sr ratio values around 0.710 and $\varepsilon_{Nd}(0)$ values from −4.5 to −10 [15]), Australia was possibly the dominant source of dust to Antarctica. South Africa and local Antarctic sources are also not excluded as potential sources but insufficient data do not permit such a conclusion. During glacial periods, the South American dust isotopic field overlaps with the glacial Antarctic dust field, suggesting that South American dust was the dominant source in all the sites in East Antarctica as already contemplated by [10–15]. However, the Australian dust isotopic signature (in particular, the Lake Eyre dust samples) partially overlaps with the Antarctica glacial dust signature suggesting that the Australian contribution in Antarctica may not be negligible in glacial periods. These results suggest that the relatively greater contribution of Australian dust inferred for Antarctic interglacial ice compared with glacial ice is not directly reflective of changes in dust transport, but instead it could be related to a differential weakening of South American and New Zealand sources during interglacial time with respect to the Australian (and also South Africa) sources.

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