Patagonian glaciers control dust deposited in Antarctica during the last glacial period.

David.E.Sugden,[1] Robert D.McCulloch[2], Aloys J.-M. Bory,[3] Andrew S. Hein[1]

[1] School of GeoSciences, University of Edinburgh, Edinburgh, EH8 9XP, UK
[2] School of Biological and Environmental Science, University of Stirling, Stirling, FK9 4LA, UK
[3] British Antarctic Survey, High Cross, Madingley Road, Cambridge, CB3 0ET, UK. Now at: UMR GEOSYSTEMES, Université des Sciences et Technologies de Lille, Cité Scientifique, 59655 Villeneuve d'Ascq Cedex, France, and Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY 10964, USA.

Dust in the atmosphere plays a role in the transparency of the atmosphere[1], the mineral nourishment of the oceans[2,3] and can be used to constrain global circulation models today and in the past[4]. Antarctic ice cores provide an 800,000 year record of changes in dust flux thought to reflect changes in the vigour of global atmospheric circulation and environmental conditions in source areas[5-8]. Here for the first time we link the source of Last Glacial dust peaks in Antarctica to the gravel outwash plains of Patagonian glaciers in the Magellan area of southernmost South America. We find that there is an on-off switch in that the peaks coincide with episodes when glaciers discharge sediment directly onto outwash plains but not when they terminate in lakes. This finding helps solve several long-standing puzzles, namely: why both dust and fresh water diatom concentrations during glacial maxima are so much higher (x ~20) than at the present day[8,9]; why dust peaks occur only below a certain temperature threshold[10]; and why the decline in dust concentrations at the end of glacial cycles precedes the main phase of warming, the rise in sea level, and the reduction in southern hemisphere sea ice extent[10].

Isotopic tracers (strontium and neodymium isotopic ratios) show that Patagonia rather than Australia or Africa, is the major source of the dust in Antarctic ice cores[11,12]. At present it is not clear, however, what causes the extreme variations in dust flux during glacials. Here we develop a hypothesis concerning the location, nature and dynamics of the source areas in Patagonia. We then show that the isotopic signature of source material matches that of Antarctic dust and compare the record at Dome C over the last 80,000 years[10,13] with an independently dated record of Patagonian glacier fluctuations over the same period[14-16].

Outwash plains have long been recognised as an ideal source for windblown dust. There are two important characteristics. First, the high sediment load delivered by the glacier causes the meltwater river to braid and constantly migrate across its gravel plain. Thus there is an unconsolidated surface devoid of vegetation exposed to the wind. Second, there is marked variability of flow diurnally and seasonally. Diurnal fluctuations mean that sediment is deposited over wide areas at high flows late in the day only to dry out and be available for removal in the following hours. Seasonally, the higher loads of suspended sediment occur as summer melting flushes out the bed of the glacier[17]. An extra factor in the case of Patagonia is that a large area of continental shelf was exposed by lower sea levels during glacial episodes and thus the rivers were longer than those of today.

Dust entrainment depends on several factors and silt and finer particles typically become entrained at wind velocities of 4-8 m/s[18]. Patagonia experiences strong winds. For example, maximum wind velocities at the coastal site of Canal Brecknock (54^{o}29'S; 71^{o}59'W) for every month between April, 2002 and April, 2003 were above 22 m/s, achieving a remarkable 38.8 m/s in March, 2003. In the same period an inland site near Punta Arenas (53^{o}08'S; 70^{o}53'W) experienced monthly maximum wind velocities ranging from 15 to 25 m/s[19]. Such winds are associated with weather systems where cold fronts have the capability of lifting dust high into the atmosphere. During glacial times dust entrainment is likely to have been enhanced by an overall increase in the vigour of atmospheric circulation. Also, the build up of a high and continuous ice sheet upwind would have enhanced the precipitation shadow effect of today and led to drier conditions[20].

The lakes fronting most glaciers on the eastern flank of the maximum Patagonian ice sheet introduce a powerful on-off switch. The outwash plain is supplied with abundant debris when the glacier discharges directly onto it. As soon as the glacier front withdraws slightly, all but the finest material is trapped in the lake and the sediment supply to the outwash plain is cut off, while the water discharge remains constant. Channel gradient is related to sediment load and inversely related to discharge as follows: $S \alpha LD/Q$ where L is sediment load, D is sediment size and Q is discharge[21]. The implication is that a reduction in sediment supply reduces the channel slope and causes the river to incise its channel in the pre-existing outwash plain, leaving elevated terraces. Devoid of disturbance, such terraces become vegetated and thus protected from wind erosion. Thus the effect of a glacier snout withdrawing into its pro-glacial lake is to suddenly reduce both the quantity of sediment available for wind erosion and the size of the outwash contributing area.

In order to analyse sediment from glacial environments comparable to those prevailing in Patagonia during the high-dust flux peaks in Antarctica, we sampled blue-grey clay/silts dated to the maximum and waning phase of the last glacial period. Such deposits underlie peat bogs and eight sites with basal radiocarbon dates are listed in Table 1 (Fig 1a). In all cases the sediment shows no sign of subaerial weathering and thus accumulated immediately before the growth of the peat bog. The ages of the sediments range from 12,000-20,000 calendar years before present.

To make the comparison possible with dust deposited in Antarctica, we analysed the Sr and Nd isotopic composition of the finest fraction (<5µm) of these sediments using well-established methods [22-24]. There is consistency in the 5 samples from the flanks of the Strait of Magellan with a $^{87}Sr/^{86}Sr$ ratio around 0.711 and mean εNd(0) value of -4.4. The Seno Otway sample in the adjacent valley to the north has a similar $^{87}Sr/^{86}Sr$ ratio of 0.7098 and a differing εNd(0) of -1.8. The North Patagonian Icefield samples are quite distinct with a much more radiogenic $^{87}Sr/^{86}Sr$ (>0,730) and mean εNd(0) of -8.5. The contrast reflects the difference between the Jurassic Andean fold and thrust belt in the south and the presence of pre-Cambrian basement rocks in the vicinity of the North Patagonian Icefield.

The isotopic composition of the last glacial Magellan samples matches that of East Antarctic ice core dust closely (Fig 1b). The match is closer than when Antarctic dust is compared with present day Patagonian eolian dust[25]. The samples near the North Patagonian Icefield have widely dissimilar isotopic signatures. Our results using late-glacial sediments confirm early work pointing to Patagonia as the origin of Antarctic dust; moreover, they point to the Magellan area as one of the possible chief sources.

Comparison of Patagonian glacier history with the dust record in Antarctic ice cores refines the link. During the last glacial cycle an ice sheet 1800 km long built up along the Andes between latitudes 44°S and 55°S. Outlet glaciers expanded eastwards and carved lake basins in the foothills. All meltwater from the ablation zone of the eastern flank of the ice sheet at its maximum drained into the Atlantic Ocean via braided outwash plains (Fig. 2a). Retreat from the maximum position was interrupted by several readvances, commonly exposing a lake at their snouts. The most closely dated sequence, labelled A-E, is in the Strait of Magellan and is based on 84 radiocarbon dates, cosmogenic isotope and amino acid racemization analyses (Fig 2b)[15,16]. Stage A is older than 55 kyr but younger than about 90 kyr. Stages B and C culminate at 23.1 - 25.6 kyr and 20.4-21.7 kyr respectively. During Stages A, B and C the glaciers discharged directly onto outwash plains occupying the dried-out Strait of Magellan. During Stage D, which culminated before 17.7 kyr, glaciers were less extensive than at their maxima and terminated in lakes. Stage E occurred at 11.7 - 15.5 kyr and coincides with the Antarctic Cold Reversal; again glaciers terminated in lakes[26].

In Figure 3 we compare the above glacier reconstructions with the terrestrial Calcium and Deuterium records in the Dome C ice-core. What is significant is that the dust peaks coincide with stages when Patagonian glaciers discharged directly onto outwash plains. Glacier stages that ended in lakes produced no dust peaks. Stages B and C show a good fit with multiple dust peaks. Stage A, which is older than 55 kyr and younger than ~90ky, is likely to correlate with dust peaks at c. 65 kyr. Stages D and E, while comprising extensive glacier advances, produce no discernible dust peaks. This is important when one considers that Stage D coincides with global glacier expansion and Stage E, known to have persisted for several millennia, has left no dust trace.

One apparent anomaly is the dust peak at c.30 kyr that has no apparent correlative in Patagonia. Probably this is a reflection of the difficulty of dating multiple advances that terminate in the same place. Indeed, stratigraphic studies on the coastal cliffs of Stages B and C reveal evidence of multiple glacier advances[27].

The link between dust peaks in Antarctic ice cores and active outwash plains in Patagonia helps explain several puzzles. The shut down of dust early during deglaciation occurs because glaciers retreat into pro-glacial lakes. The correlation only with glacier advances reaching their maximum limits helps explain why the dust peaks in the Dome C ice core occur below a high deuterium threshold[10]. The mechanism also helps explain the high freshwater diatom counts in the ice cores during the Last Glacial Maximum[9]. Perhaps it is simply that the glacier advance displaces diatoms from the lakes and lake sediments onto the outwash plains and exposes them to entrainment by wind.

The pattern of match and mismatch between glacier extent and the ice-core record is difficult to explain in alternative ways. There is no simple match with climate, as demonstrated by the non-linear relationship between dust and deuterium in the ice cores (Fig. 3). Furthermore, the dust decline in the ice cores precedes both the loss of sea ice in the Southern Ocean[10] and the warming of ocean temperatures around Patagonia[28]. The attribution of dust peaks to sea-level lowering and the exposure of the South American continental shelf is also problematic because the dust decline occurs before sea level rose significantly at the end of the last glacial cycle. Thus we conclude that the dust peaks in the ice cores reflect climatic changes modulated by glaciers that pick out only extreme climatic cooling events in southernmost South America.

The match of dust peaks in Antarctica with outwash activity in southernmost Patagonia raises two interesting possibilities. First, there will be a strong seasonal signal with the dust deposited in Antarctic snow in early summer. Second, the apparent close match of ice-core dust to the Magellan area in southernmost South America is interesting. High-resolution simulations of Last Glacial Maximum climate show intense weather systems being squeezed through Drake Strait between the expanded southern ocean sea-ice limit and the Patagonian ice sheet (Crowley, personal communication, 2008). Cold fronts associated with such storms would bring strong winds to the outwash plains of the dried-out Strait of Magellan.

Methods

The glacial sediments were sampled from beneath peat in kettle holes using a Russian corer. They were sealed and kept in cold storage and AMS ^{14}C dating carried out on mm-thick basal layers in the NERC Radiocarbon Laboratory, East Kilbride[15]. The <5 μm fraction of the sediment was extracted from sediment samples by Stokes-law gravity differential settling, following the removal of possible carbonates and cements of amorphous iron, silica, and alumina, which may carry a different isotopic signature than the aluminosilicate fraction and aggregate particles[22]. After complete acid digestion of the sediment's fine fraction using concentrated HF/HNO3/HClO4 mixture, Sr and Nd were separated using ion exchange resins[24]. Sr and Nd isotopic composition were measured at Lamont-Doherty Earth Observatory of Columbia University, using a Micromass Sector 54-30 thermal ionization mass spectrometer, by dynamic multicollection. Nd was run as NdO^+. Isotopic measurements were corrected for instrumental mass fractionation: $^{87}Sr/^{86}Sr$ ratios were normalized to $^{86}Sr/^{88}Sr=0.1194$, and $^{143}Nd/^{144}Nd$ ratios were normalized to $^{146}Nd/^{144}Nd=0.7219$. Measured NBS987 standard $^{87}Sr/^{86}Sr$ and La Jolla standard $^{143}Nd/^{144}Nd$ yielded 0.710254 (± 17 10^{-6}, 2σ external reproducibility[29], n=26) and 0.511858 (± 24 10^{-6}, 2σ external reproducibility, n=24), and data were normalized with respect to certified values 0.71024 and 0.51186, respectively. Blanks were less than 1 % of Sr and Nd weights, and were considered negligible. For convenience, $^{143}Nd/^{144}Nd$ ratio is expressed as εNd(0), the deviation from the chondritic value ($^{143}Nd/^{144}Nd$ =0.512638) in parts per 10000[30].

References

1. Forster, P., V. and 14 others. Changes in Atmospheric Constituents and in Radiative Forcing. *In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. *et al.,* (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. (2007)

2. Diekmann, B. and 7 others. Terrigenous sediment supply in the Scotia Sea (Southern Ocean): response to Late Quaternary ice dynamics in Patagonia and on the Antarctic Peninsula. *Palaeogeography, Palaeoclimatology, Palaeoecology,* **162**, 357-387 (2000).

3. Winckler,G., Anderson, R.F., Fleisher, M.Q., McGee, D., Mahowald, N., Covariant Glacial-Interglacial dust fluxes in the Equatorial Pacific and Antarctica. *Science,* **320**, 93-96 (2008).

4. Reader, M.C., Fung**,** I., McFarlane, N. The mineral dust aerosol cycle during the Last Glacial Maximum. *J. Geophysical Research,* **104**, 9381-9398 (1999).

5. Petit, J-R. et al., Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. *Nature,* **399,** 429-436 (1999).

6. Delmonte, B. et al. Aeolian dust in east Antarctica (EPICA Dome C and Vostok): provenance during glacial ages over the last 800 kyr. *Geophysical Research Letters,* **35**, L07703, doi:10.1029/2008GL033382, (2008).

7. Harrison, S.P., Kohfeld, K.E., Roelandt, C., Claquin, T., The role of dust in climate changes today, at the last glacial maximum and in the future. *Earth-Science Reviews,* **54**, 43-80 (2001).

8. Petit, J-R. et al., Palaeoclimatic implications of the Vostok core dust record. *Nature,* **343**, 56-58, (1990)

9. Burckle, L.H., Gatley, R.I., Ram, M., Petit, J-R. Diatoms in Antarctic ice cores: some implications for the glacial history of Antarctica. *Geology,* **16**, 326-329 (1988)

10. Wolff, E.W., et al. Southern Ocean sea-ice extent, productivity and iron flux over the past eight glacial cycles. *Nature,* **440,** 491-496, doi:10.1038/nature04614 (2006)**.**

11. Grousset et al., Antarctic (Dome C) ice-core dust at 18 k.y.B.P.: Isotopic constraints on origins. *Earth and Planetary science letters,* **111**, 175-182 (1992).

12. Basile, I., et al., Patagonian origin of glacial dust deposited in East Antarctica (Vostok and Dome C) during glacial stages 2, 4 and 6. *Earth and Planetary Science Letters,***146,** 573-589 (1997).

13. Lambert, F., and 9 others. Dust-climate couplings over the past 800,000 years from the EPICA Dome C ice core, *Nature,* **452,** 616-619, doi:10.1038/nature06763,Letter, (2008)

14. Sugden, D.E. et al. late-glacial glacier events in southernmost South America: a blend of ‘northern’ and ‘southern’ hemispheric climate signals. *Geografiska Annaler,* **87A**, 273-288 (2005).

15. McCulloch, R.D. et al., Chronology of the last glaciation in the Strait of Magellan and Bahía Inútil, southernmost South America. *Geografiska Annaler,***87A**, 289-312 (2005a).

16. Kaplan, M.R. and 5 others. Southern Patagonian glacial chronology for the Last Glacial period and implications for Southern Ocean climate. *Quaternary Science Reviews,* **27,** 284-294.

17. Swift, D.A., Nienow, P.W., Hoey, T.B., Mair, D.W.F. Seasonal evolution of runoff fro Haut Glacier d’Arolla, Switzerland and implications for glacial geomorphic processes. *Journal of Hydrology*, **309**, 133-148, doi:10.1016/j.hydrol.2004.11.016 (2005).

18. Summerfield, M.A., *Global Geomorphology.* Longman/Wiley, London/New York, 537 pp.

19. Santana, A., Porter, C., Butorovic, N., Olave, C. Características climáticas del Canal Brecknock el los 54^{0}30’S de latitud, Magallanes, Chile. *Anales Instituto Patagonia (Chile),* **35**, 5-18 (2007).

20. Hulton, N.R.J., Sugden, D.E. 1995 Modelling mass balance on former maritime ice caps: Patagonian example, *Annals of Glaciology,* **21**, 304-310 (1995).

21. Chorley, R.J., Schumm, S.A., Sugden,D.E. *Geomorphology.* Methuen, London and New York, 605 pp. (1984).

22. Biscaye, P. E., Grousset, F.E., Revel, M., Van der Gaast, S., Zielinski, G.A., Vaars, A., Kukla, G. Asian provenance of glacial dust (Stage 2) in the Greenland Ice Sheet Project 2 Ice Core, Summit, Greenland. *Journal of Geophysical Research,* **102**(C12):26, 765-26, 781 (1997).

23. Bory, A. J.-M., Biscaye, P. E., Svensson, A., Grousset, F. E., Seasonal variability in the origin of recent atmospheric mineral dust at NorthGRIP, Greenland. *Earth and Planetary Science Letters,* **196**(3-4): 123-134 (2002).

24. Bory, A. J.-M., Biscaye, P. E., Piotrowski, A. M., Steffensen, J. P., Regional variability of ice core dust composition and provenance in Greenland. *Geochemistry Geophysics Geosystems,* **4**(12): 1107, doi:10.1029/2003GC000627 (2003).

25. Gaiero, D.M., Dust provenance in Antarctic ice during glacial periods; from where in South America? *Geophysical Research Letters*, **34**, L17707, doi:10.1029/2007GL030520, (2007)

26. McCulloch,R.D., Bentley, M.J., Tipping, R.M., Clapperton, C.M., Evidence for late-glacial ice-dammed lakes in the central Strait of Magellan and Bahía Inútil, southernmost South America. *Geografiska Annaler,* **87A**, 335-362 (2005b).

27. Benn, D.I. and Clapperton, C.M. Pleistocene glacitectonic landforms and sediments around central Magellan Strait, southernmost Chile. *Quaternary Science Reviews,* **19,** 591-612 (2000).

28. Lamy, F., et al. Antarctic timing of surface water changes off Chile and Patagonian ice sheet response. *Science,* **304**, 1959-1962 (2005).

29. Goldstein, S. L., Deines, P., Oelkers, E. H., Rudnick, R. L., Walter, L. M., Standards for publication of isotopic ratio and chemical data in *Chemical Geology*. *Chemical Geology,* **202**: 1-4 (2003).

30. Wasserburg, G. J., Jacobsen, S. B., DePaolo, D. J., McCulloch, M. T., Wen, T., Precise determination of Sm/Nd ratios, Sm and Nd isotopic abundances in standard solutions. *Geochimica et Cosmochimica Acta,* **45**: 2311-2323 (1981).

Acknowledgements

We thank the following for financial support: NERC, Royal Society, Carnegie Trust for the Universities of Scotland, British Antarctic Survey, FONDECYT 1060020, EU Marie Curie Fellowship; and the following for laboratory support: Charlotte Bryant and NERC Radiocarbon Laboratory, East Kilbride, Adele Hanley (Lamont-Doherty Earth Observatory, Columbia University), Mervyn Greaves (Cambridge University). Pierre Biscaye, Tom Crowley, Barbara Delmonte, Harry Elderfield, Ross Purves and Eric Wolff were encouraging and insightful.

Table 1. Location, minimum age and isotopic signature of last glacial Patagonian clay/silts

Location and No.	$^{87}Sr/^{86}Sr$	+/-	$^{143}Nd/^{144}Nd$	+/-	εNd(0)	+/-	^{14}C	+/-(1 σ)	Cal. yr at 1σ
1. Isla Dawson, Magellan St. (53^{0}34'S, 70^{0}30W)	0.711691	0.000010	0.512412	0.000013	-4.40	0.26	10314	80	11773-12578
2. Guayrabo, Magellan St. (53^{0}36'S, 70^{0}58'W)	0.710961	0.000010	0.512431	0.000013	-4.04	0.26	13186	78	15561-16140
3. Amarillo, Magellan St. (53^{0}25'S, 70^{0}59'W)	0.710945	0.000010	0.512409	0.000013	-4.46	0.26	13849	81	16367-16864
5. Otway, Magellan (52^{0}48'S, 71^{0}05'W	0.709765	0.000020	0.512548	0.000017	-1.76	0.34	12638	60	14348-15507
6. Cerro Ataud, N.P.I., (47^0 17'S, 72^{0}39'W)	0.730747	0.000020	0.512218	0.000020	-8.19	0.40	13550	95	16030-16520
7. Esmeralda, N.P.I., (47^{0}17'S, 72^{0}33'W)	0.738596	0.000013	0.512191	0.000015	-8.72	0.30	10975	80	12890-13130
9. P. Hambre, Magellan St. (53^{0}36'S, 70^{0}57'W)	0.711718	0.000020	0.512407	0.000015	-4.50	0.30	14470	50	17078-17583
10. St. Maria, Magellan St. (53^{0}18'S, 70^{0}58'W)	0.710073	0.000017	0.512405	0.000012	-4.55	0.24	16530	120	19547-19807

Figure captions

Fig 1. (a) Location of the late-glacial sample sites in relation to the present day ice masses in Patagonia.

(b) Sr and Nd isotopic composition of Patagonian glacial sediments compared to that of ice-core dust from East Antarctica[6] and to that of present-day Patagonian aeolian dust[25]. Error bars on North Patagonian sediments εNd(0) and $^{87}Sr/^{86}Sr$ are smaller than symbols.

Fig.2. (a) Geomorphological map showing moraine limits and associated outwash plains formed by the Lago Cochrane/Pueyrredon glacier at the Last Glacial Maximum and during more extensive earlier glaciations. Such outwash plains, up to10 km across, were common in southernmost Patagonia and extended ~ 500 km to beyond the present Atlantic coast. The pro-glacial lake which formed during retreat from the Last Glacial Maximum is typical of many Patagonian glaciers.

(b) The limits of ice advances in the Strait of Magellan region, constrained by field mapping and many dates[15]. During Stages A-C, the glaciers terminated directly onto outwash plains flowing along the dry Strait of Magellan. During Stages D and E the glaciers terminated in pro-glacial lakes. A = > 55 kyr and < ~90 kyr; B = 23.1 - 25.6 kyr; C = 20.4 – 21.7 kyr; D = <17.7 kyr; E = 11.7 – 15.5 kyr).

Fig. 3. Glacier reconstructions during Stages A-E compared with non-sea-salt Calcium (a proxy for dust) and Deuterium records in the Dome C ice core (EPICA Dome C time scale). SRTM 30plus data was used to create the topographic maps and the approximate position of the coast line during periods of lower global sea level is indicated for each Stage. The grey-shaded bars indicate the age constraints on each Stage. During Stages A-C glaciers ended directly on outwash plains, permitting high dust yields. During stages D and E glaciers ended in lakes, suppressing dust volumes.

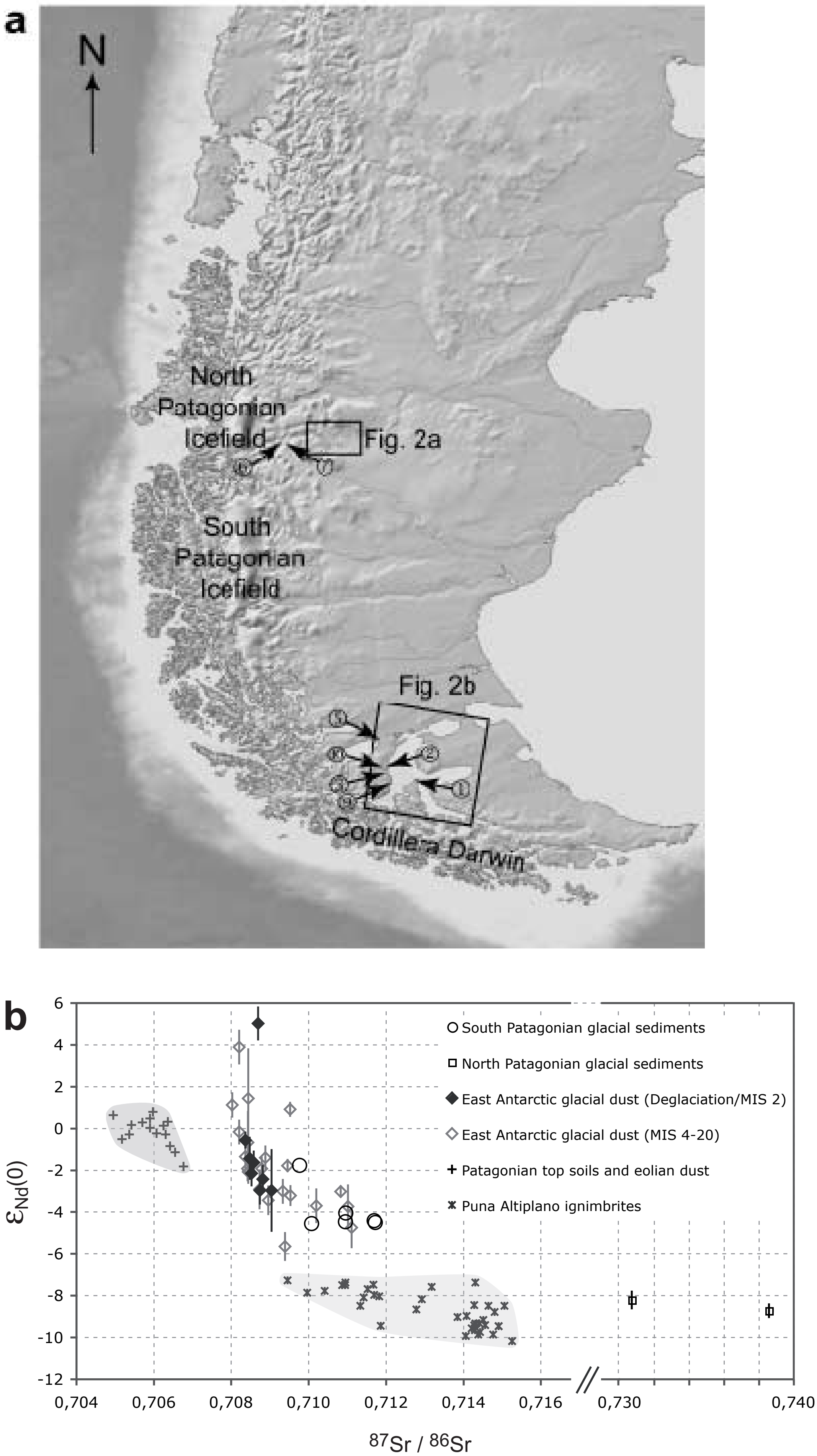
a
N
North Patagonian Icefield
Fig. 2a
South Patagonian Icefield
Fig. 2b
Cordillera Darwin
b
South Patagonian glacial sediments
North Patagonian glacial sediments
East Antarctic glacial dust (Deglaciation/MIS 2)
East Antarctic glacial dust (MIS 4-20)
Patagonian top soils and eolian dust
Puna Altiplano ignimbrites
$\varepsilon_{Nd}(0)$
6
4
2
0
-2
-4
-6
-8
-10
-12
0,704
0,706
0,708
0,710
0,712
0,714
0,716
0,730
0,740
^{87}Sr / ^{86}Sr

Figure 1

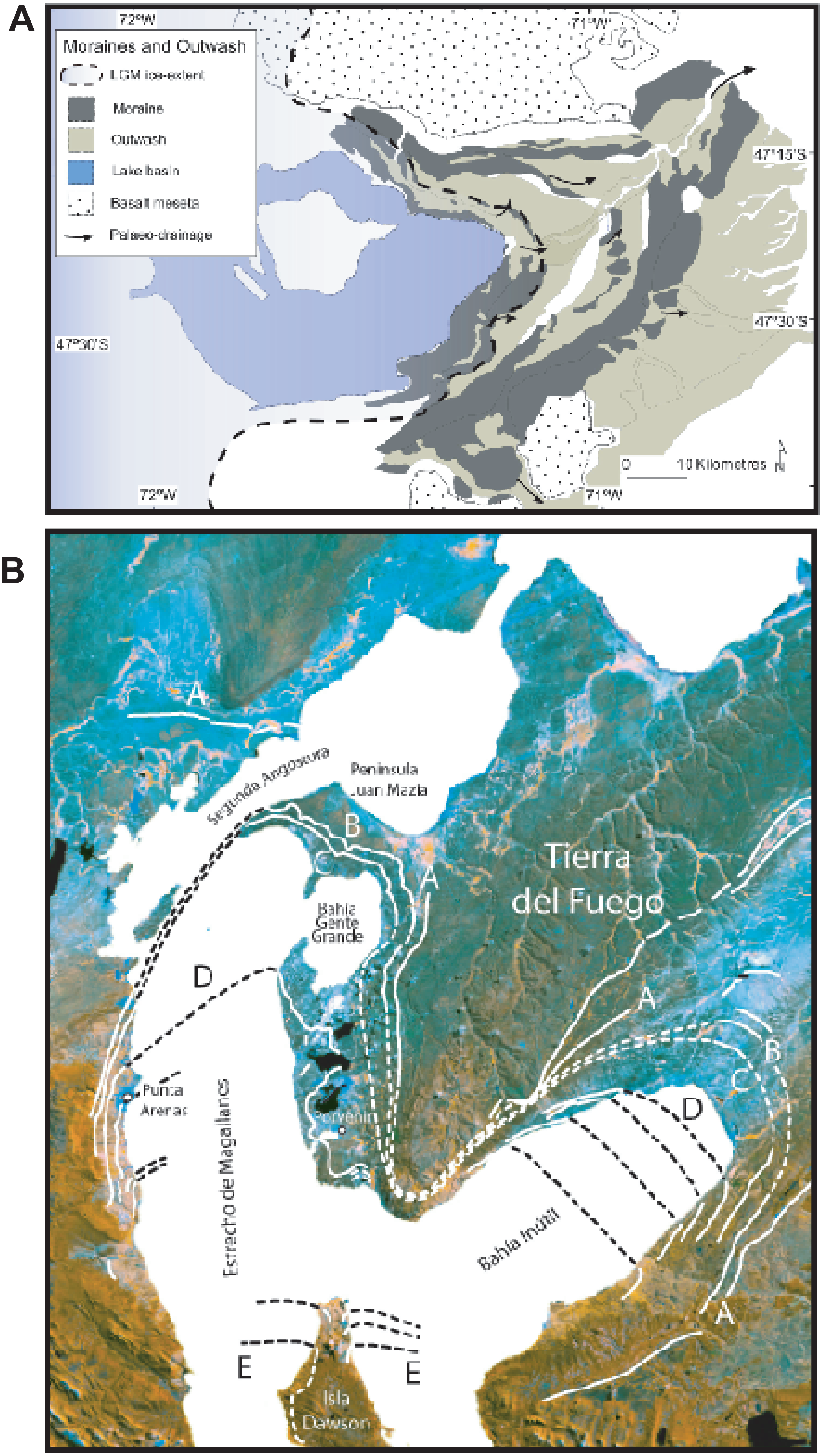
A
Moraines and Outwash
LGM ice-extent
Moraine
Outwash
Lake basin
Basalt meseta
Palaeo-drainage
72°W
71°W
47°15'S
47°30'S
0
10 Kilometres
N
B
Segunda Angostura
Peninsula
Juan Mazla
Bahia
Gente
Grande
Tierra
del Fuego
Punta
Arenas
Porvenir
Estrecho de Magallanes
Bahia Inutil
Isla
Dawson
A
B
C
D
E

Figure 2

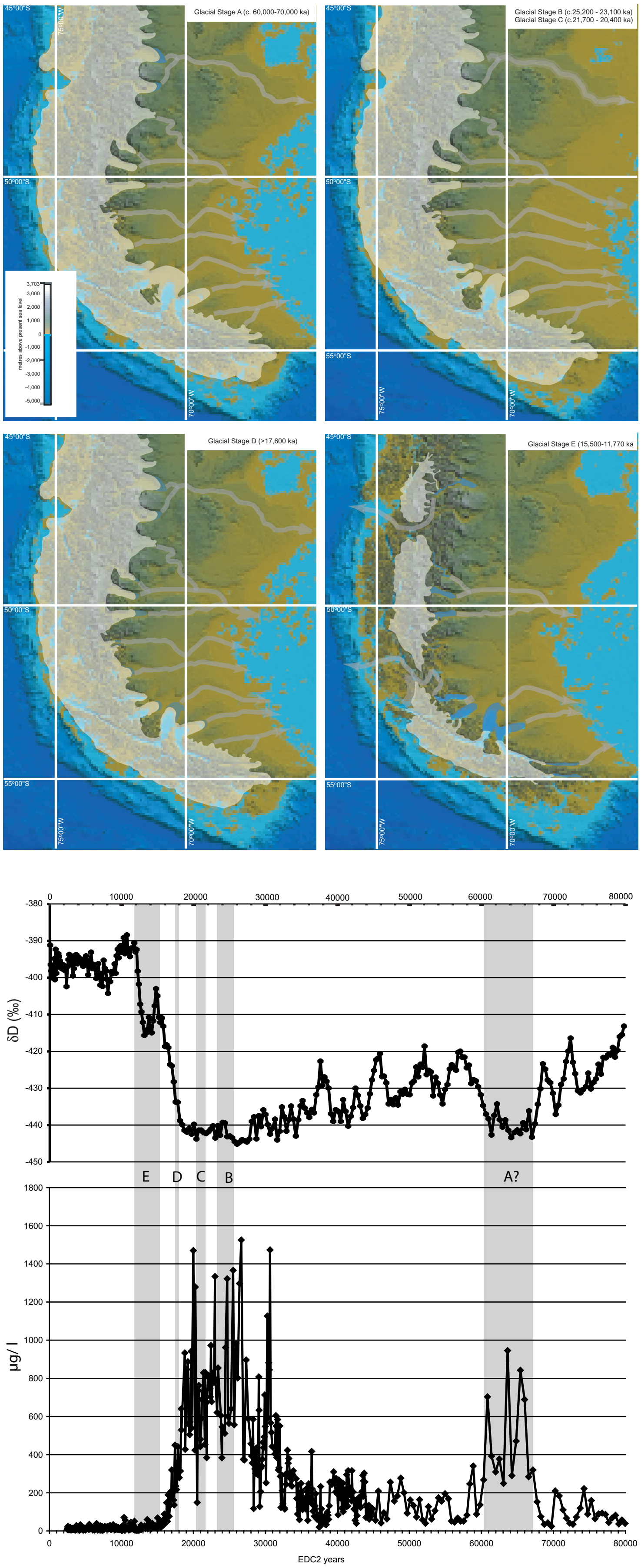
Glacial Stage A (c. 60,000-70,000 ka)
Glacial Stage B (c.25,200 - 23,100 ka)
Glacial Stage C (c.21,700 - 20,400 ka)
Glacial Stage D (>17,600 ka)
Glacial Stage E (15,500-11,770 ka
45°00'S
50°00'S
55°00'S
75°00'W
70°00'W
metres above present sea level
δD (‰)
E
D
C
B
A?
µg/ l
EDC2 years

Figure 3