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Rapid Communication

A 70 ka record of explosive eruptions from the TALDICE ice core (Talos Dome, East Antarctic plateau)

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ABSTRACT: The new Antarctic TALDICE ice core (72° 49′ S, 159° 11′ E, 1620 m depth), containing abundant primary tephras, provides the opportunity to elucidate the late Quaternary volcanic history of the south polar region, as well as to broaden the East Antarctic tephrostratigraphic framework. Here grain size and glass compositional data for representative tephra layers from the last 70 ka core section are used for source identification. Results point to origin of layers from centres of the Melbourne Volcanic Province (McMurdo Volcanic Group), located ~250 km from the coring site. Occurrence of tephra layers within the ice core record suggests that explosive activity in the identified source was not constant over the considered period, with a minimum of activity between 20 and 35 ka, and increased activity back to 65 ka. In addition to palaeovolcanic implications, the TALDICE tephra layers offer prospects for firm correlations between diverse widely separated palaeoarchives and for accurate dating of the Antarctic climatic record. Copyright © 2010 John Wiley & Sons, Ltd.

KEYWORDS: Eastern Antarctic plateau; major element geochemistry; polar ice cores; tephra layers; volcanic stratigraphy.

Introduction

Ice sequences from polar regions contain evidence of past explosive volcanic events in the form of solid particles and chemical aerosols sourced in volcanic plumes, which fall out onto the ice sheet surface soon after eruptions and are rapidly embedded into the snow/ice deposit (e.g. Zielinski *et al.*, 1997; Castellano *et al.*, 2005). Volcanic ash (tephra) in particular is preserved unaltered in the ice and the glass particles retain their original geochemical compositions that are representative of the parent magma composition. Tephra layers can thus be attributed to their eruption sources and correlated in multiple localities (e.g. Narcisi *et al.*, 2005). Key tephra horizons identified within the ice form time-parallel stratigraphic markers that can be used for dating purposes and for reliable comparison of climatic records over broad areas (e.g. Narcisi *et al.*, 2006; Davies *et al.*, 2008; Hillenbrand *et al.*, 2008). Englacial airfall tephras also provide valuable volcanological information. Distal tephra studies can document style, magnitude and intensity of explosive eruptions, and help detect changes in explosive eruption frequency in the source volcanic centres (e.g. Mortensen *et al.*, 2005). If accurate dating of the englacial volcanic record is accomplished, tephra information can therefore significantly improve the reconstruction of the source volcanic histories and highlight causal links between volcanism and palaeoenvironmental changes (e.g. Zielinski, 2000, and references therein).

Tephra layers, of either local or more distant origin, are common in Quaternary ice sections throughout the Antarctic continent (Smellie, 1999, and references therein). Recent significant investigations of englacial tephras from various locations and settings (e.g. Pallàs *et al.*, 2001; Curzio *et al.*, 2008; Dunbar *et al.*, 2008; Narcisi *et al.*, 2010, and references therein) have demonstrated the potential of Antarctic tephra studies. However, published information on stratigraphically coherent, well-dated ice tephra records is still scarce in comparison with the vastness of Antarctica and with the extent and frequency of the explosive volcanism that occurred in the south polar region over Quaternary times. New tephra inventories from high-resolution ice sequences are needed to extend the tephrostratigraphic framework for the Antarctic region and to increase knowledge of past volcanism.

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In the context of the TALDICE (TALos Dome Ice CorE) European project (www.taldice.org) a ~1620 m deep ice core has recently been drilled at Talos Dome (72° 49′S, 159°11′E, 2315 m), a peripheral dome of the East Antarctic plateau adjacent to northern Victoria Land (Fig. 1). Due to its relatively high accumulation rate (average 80 mm water equivalent a^{-1} over the last eight centuries (Stenni *et al.*, 2002)), this new near-coastal core allows a higher-resolution palaeoclimate study than ice cores taken from the continental interior. Methane and oxygen isotope measurements indicate that the Talos Dome core preserves a continuous undisturbed climatic profile almost analogous to other Antarctic cores and extending back to Marine Isotope Stage (MIS) 7.5, ~250 ka (Stenni *et al.*, 2009; Buiron *et al.*, 2010). The Talos Dome coring site is also located some 200 km from the McMurdo volcanic belt, which is genetically associated to the West Antarctic Rift System and includes several Cenozoic–Recent explosive centres (Wörner, 1999). Previous investigations on a pilot shallow core had already suggested that the Talos Dome ice is an important repository for volcanic aerosols (Narcisi *et al.*, 2001; Stenni *et al.*, 2002). During core inspection of the new TALDICE ice core, more than 100 macroscopic tephra layers were identified, confirming its potential to provide a detailed record of explosive volcanic events.

Here we present an overview of the TALDICE tephra record and discuss grain size and geochemical features of representative tephra layers within the ice core section covering the last 70 ka, with the aim of identifying the volcanic sources. We then examine implications of our tephra inventory for reconstruction of past volcanic history in northern Victoria Land, and provide prospects for extensive stratigraphic correlations and refinement to ice-core dating.

Tephra characteristics and inferred source identification

The uppermost 1300 m of the core includes an integral climatic record extending from the present day to MIS 4, with the start of the last deglaciation at about 800 m depth (Fig. 2). A preliminary ice core chronology was obtained by matching the oxygen isotope signals to the Antarctic EPICA-Dome C climatic record (Jouzel *et al.*, 2007) and using CH_4 wiggles (Buiron *et al.*, 2010), with transfer of the related timescale on the studied core. The considered TALDICE core section, spanning the last 70 ka, contains about 60 discrete tephra layers (Fig. 2), with an average tephra frequency of four layers per 5 ka, i.e. one order of magnitude greater than the tephra frequency in deep cores from inland East Antarctic plateau over the last two glacial cycles (Narcisi *et al.*, 2010). The majority of tephra layers are visually prominent and were located and inventoried during core processing (performed in the cold-room facilities of the Alfred Wegener Institute, Bremerhaven). Layers are nearly horizontal and occur as either dark brown/grey distinct strips showing sharp contacts with adjacent ice, or as light grey or milky dusty bands (Fig. 3(A)). Layer thickness ranges from ~1 mm to several centimetres. At times, thick layers appear composed of multiple (up to nine) sub-horizons. A few volcanic layers are faint (<1 mm thick) and were located by grain size analysis and subsequent electron microscope inspection to confirm the presence of tephra.

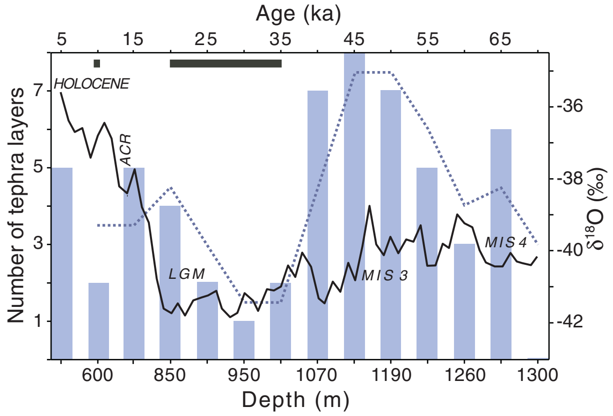

Figure 2 Frequency of occurrence of tephra layers (per 5 ka interval) in the TALDICE core and related running mean (dashed line). Also plotted is the oxygen isotope profile in ice (black line, right axis), with the position of Marine Isotope Stages (MIS), Last Glacial Maximum (LGM), Antarctic Cold Reversal (ACR) and the Holocene period. Increased tephra fallout deposition in the West Antarctic Byrd and Siple Dome ice cores from 35 to 17 ka and at 9 ka (Bay *et al.*, 2004; Gow and Meese, 2007) is shown by a thick black bar on the upper side

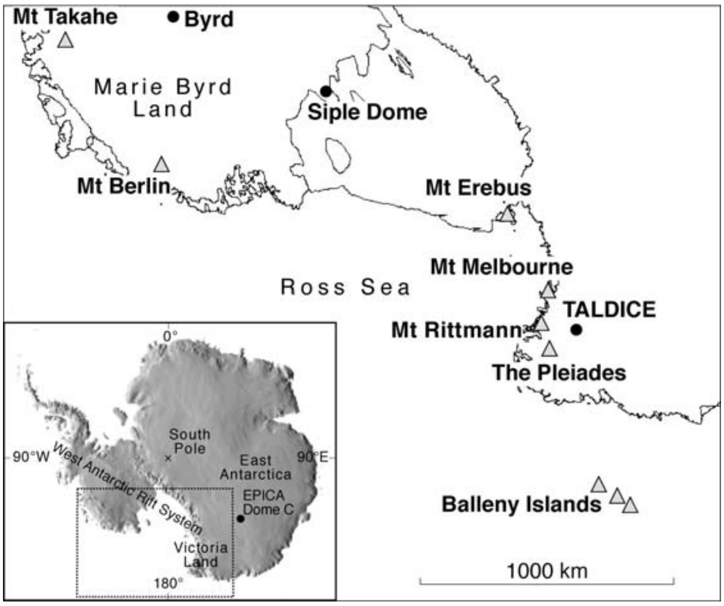

Figure 1 Location of ice core sites (dots) and Quaternary-active volcanoes mentioned in the text. Inset shows the Antarctic continent with the study area (boxed) and other relevant locations

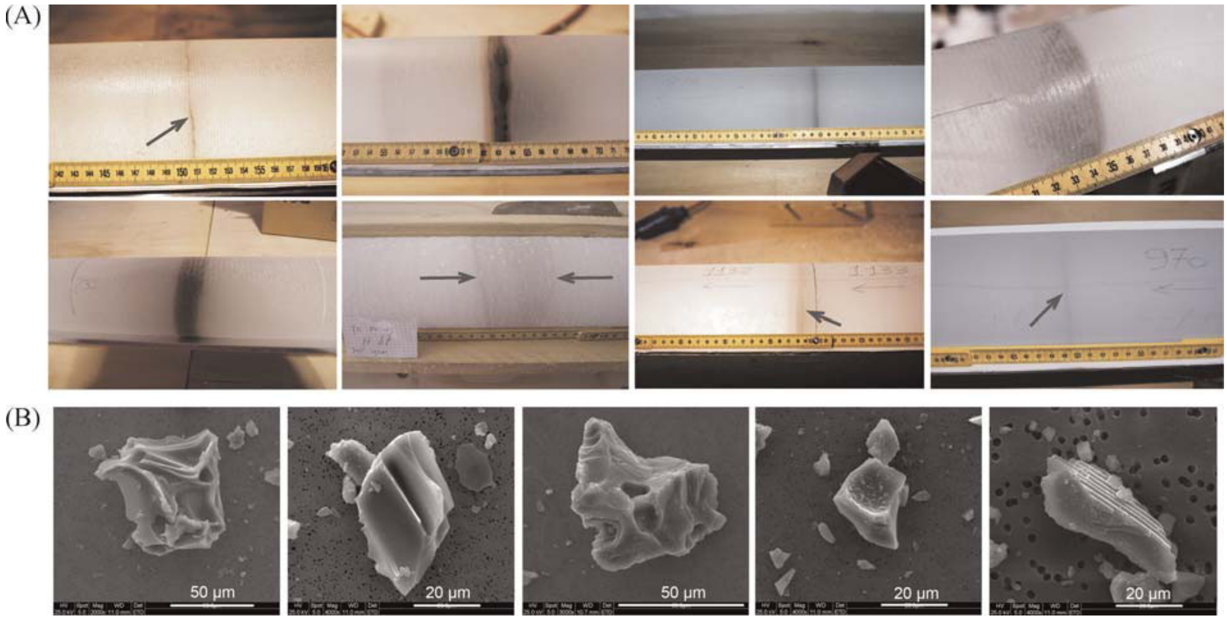

Figure 3 (A) Macroscopic features of tephra layers within the TALDICE ice core. (B) Electron photomicrographs of various tephra (glass and crystal) particles recovered from the studied samples. This figure is available in colour online at www.interscience.wiley.com/journals/jqs

All identified tephra layers were processed following the same protocol adopted in former ice core tephra studies (e.g. Narcisi *et al.*, 2005). Briefly, the particulate matter was separated from the melted ice by filtration performed in ultra-clean facilities, and at least two particle-bearing filters per sample were routinely prepared. Unpolished filters were used to determine the morphology and maximum size of the particles using a scanning electron microscope. The other filters were embedded in epoxy resin and polished using diamond pastes and individual glass shards were geochemically characterised using an electron microprobe (see Table 1 for analytical conditions). An ash aliquot of each sample was dedicated to grain size measurements that were performed using a Coulter Counter, according to the procedure presented by Delmonte *et al*. (2002). A catalogue including macroscopic, micromorphological, granulometric and geochemical details of all identified tephra beds is in preparation and will be presented in detail elsewhere.

The representative ash layers considered in this work come from various core depths and exhibit different characteristics. The grain size modes range from 5 to 20 μm, while aeolian continental dust typically shows a mode of 2 μm, with particles larger than 5 μm practically absent (Fig. 4(A)). Under the microscope, the samples are predominantly made up of unabraded volcanic glass particles with varying proportions of mineral crystals (Fig. 3(B)). The grains generally show a maximal size of a few tens of microns. The angular morphology of the shards indicates that the samples were not significantly reworked by wind after their deposition. In addition, the volcanic glass does not appear altered and/or corroded and therefore its geochemical composition can provide reliable source information.

Results of electron probe microanalysis of single shards (Table 1 and Fig. 4(B)) indicate that the glass composition within single samples either forms a tight cluster (e.g. TD 822) or has a wide compositional range (e.g. TD 1191), the latter probably being related to zoned magma bodies. Altogether, a wide range of compositions, including basic, intermediate and acid rock types, is represented in the studied core. However, all samples display an alkaline character and form a coherent

Table 1 Major element composition of volcanic glass from TALDICE tephra samples[a]

Sample	*n*	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O
TD 681	17	50.53 (0.89)	2.72 (0.14)	16.85 (0.50)	10.49 (0.47)	0.24 (0.02)	3.51 (0.44)	7.26 (0.33)	5.56 (0.70)	2.84 (0.24)
TD 779	21	62.36 (0.55)	0.47 (0.02)	17.98 (0.30)	4.96 (0.16)	0.18 (0.03)	0.29 (0.04)	1.21 (0.11)	7.29 (0.48)	5.27 (0.20)
TD 822	12	59.74 (0.32)	0.79 (0.06)	18.32 (0.20)	5.97 (0.45)	0.19 (0.02)	0.93 (0.09)	2.70 (0.17)	6.45 (0.35)	4.91 (0.21)
TD 970	23	67.55 (0.45)	0.30 (0.02)	16.17 (0.30)	4.19 (0.13)	0.13 (0.02)	0.08 (0.03)	1.45 (0.05)	4.87 (0.33)	5.26 (0.18)
TD 1105D	19	47.43 (0.80)	3.48 (0.55)	16.06 (0.46)	11.22 (0.66)	0.19 (0.02)	5.36 (0.91)	10.36 (1.14)	4.14 (0.49)	1.77 (0.26)
TD 1183	13	65.95 (0.64)	0.31 (0.04)	15.34 (0.50)	5.76 (0.28)	0.19 (0.02)	0.01 (0.01)	1.04 (0.15)	6.48 (0.59)	4.93 (0.26)
TD 1189	9	46.38 (0.35)	4.25 (0.22)	14.94 (0.47)	13.52 (0.42)	0.22 (0.04)	5.38 (0.30)	11.31 (0.26)	3.04 (0.40)	0.97 (0.15)
TD 1191	12	54.37 (1.23)	2.42 (0.32)	16.69 (0.58)	8.58 (0.92)	0.22 (0.03)	2.35 (0.41)	5.43 (0.95)	5.92 (0.77)	4.02 (0.88)

[a] TD sample label refers to the bottom depth of the 1 m long core increment containing the tephra. Geochemical data are expressed as oxide values (wt% recalculated to 100%, volatile-free) and reported as mean and standard deviation (in parentheses) of *n* analyses. Total Fe as FeO. Analyses were carried out on different glass shards with a CAMECA SX-50 wavelength dispersive electron microprobe (accelerating voltage 20 kV, beam diameter 1 μm). Measuring conditions were adjusted to minimize Na migration under the electron beam (e.g. Morgan and London, 2005). Peak counting times and beam current were 10 s and 2 nA, respectively for Na, K, Al and Si, and 20 s and 20 nA, respectively, for the remaining elements, backgrounds counted for half of the peak-count time. A set of natural and synthetic standards were used for primary calibration and reference materials (including glass samples characterised by Morgan and London, 2005) were routinely analysed to check precision and accuracy of geochemical results. Analyses yielding total oxide sums <95% or showing obvious microlite contamination were not included in the dataset. Analytical error is estimated to be 1% relative for SiO_2, 1–2% relative for Al_2O_3 and 3–5% relative for the other element oxides.

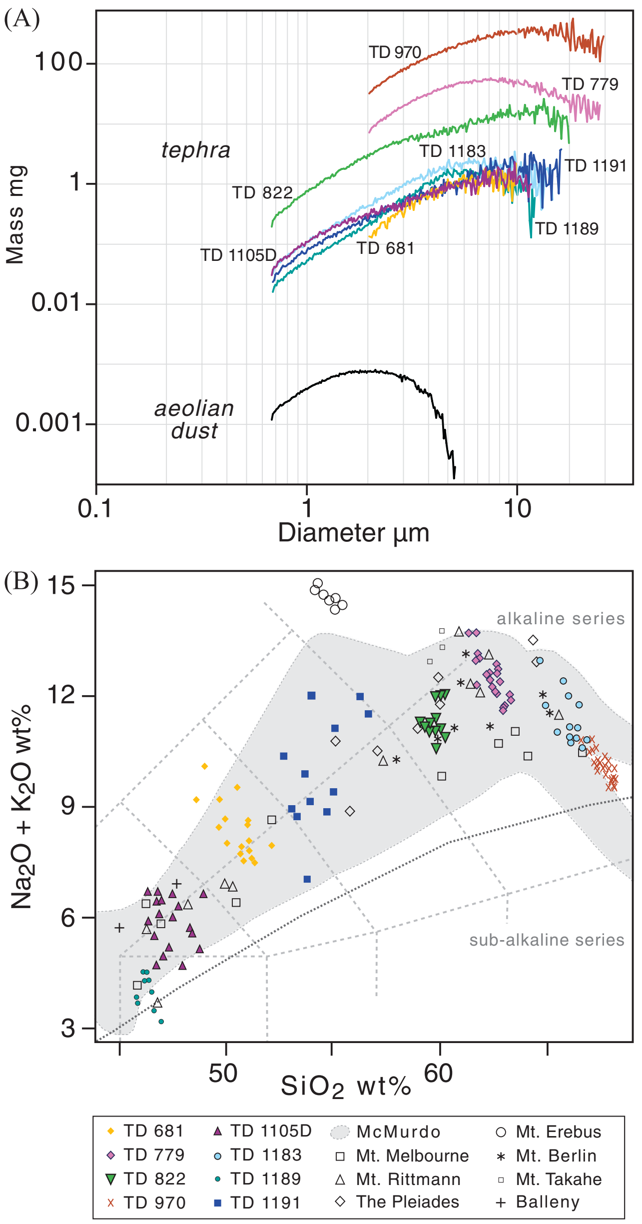

Figure 4 Granulometric and geochemical characteristics of TALDICE tephra layers. TD sample label refers to the bottom depth of the 1 m long increment containing the tephra. (A) Mass–size distributions compared to a typical ice core sample of aeolian continental dust. (B) Composition of individual glass shards. Classification scheme and discrimination line between rocks of the alkaline and sub-alkaline series from Rickwood (1989, and references therein). Compositional field for McMurdo Volcanic Group (excluding the extinct Hallett volcanoes) from LeMasurier (1990), and representative geochemical data for products from Mt Melbourne (Wörner *et al.*, 1989), Mt Rittmann (Armienti and Tripodo, 1991), The Pleiades (Kyle, 1982), Mt Erebus (Harpel *et al.*, 2008), Mt Berlin (Dunbar *et al.*, 2008), Mt Takahe (Wilch *et al.*, 1999) and Balleny volcanoes (Wright and Kyle, 1990) are plotted for comparison. This figure is available in colour online at www.interscience.wiley.com/journals/jqs

geochemical array suggesting an origin from volcanic centres in a single common source region.

The results obtained provide clues for tephra source identification. The fairly large layer thickness and mass along with coarse grain size exclude an origin of the studied samples from extra-Antarctic volcanic regions and are more consistent with a local source(s). The major element composition of the glass phase further constrains ash provenance, with indication of the source tectonic setting. The invariably alkaline signature of the Talos Dome samples clearly indicates a connection with extension-related magmatism. This eliminates volcanic sources related to other tectonic settings, such as South American, Antarctic Peninsula, and South Sandwich Islands volcanoes, which instead represent significant volcanic ash contributors in inland East Antarctic ice cores (Smellie, 1999; Narcisi *et al.*, 2010). The studied layers are most probably related to volcanism within the West Antarctic Rift System, which is the site of widespread and abundant alkaline magmatism from several Cenozoic volcanoes (e.g. LeMasurier, 1990). In particular, our geochemical results compare well with published compositional data of volcanic products from Mt Melbourne, Mt Rittmann, and The Pleiades (Fig. 4(B)), belonging to the Melbourne Volcanic Province (McMurdo Volcanic Group) and located within a radius of ~250 km from Talos Dome (Fig. 1). These volcanoes display evidence for explosive activity during Quaternary times (e.g. Wörner *et al.*, 1989, and references therein; Armienti and Tripodo, 1991), further corroborating the conclusion that they are the most likely sources of the TALDICE layers. Other Antarctic volcanoes can be ruled out. Mt Erebus has produced numerous tephra deposits in the last tens of thousands of years (Harpel *et al.*, 2008) but is discounted because of its inconsistent composition (Fig. 4(B)). Also Mt Takahe and Mt Berlin volcanoes in Marie Byrd Land (Fig. 1) can be excluded because their recent tephras are geochemically different with respect to Al_2O_3 and FeO contents from the TALDICE more evolved products (cf. Wilch *et al.*, 1999; Dunbar *et al.*, 2008). Lastly, eruptions from the mafic Balleny volcanoes (Fig. 1) would probably have been too weak and too distant to have produced the coarse thick mafic layers in the TALDICE core.

Palaeovolcanic implications

The above considerations on tephra source can be extended to the other prominent ice core tephra layers, confirming the excellent geographic and glaciological characteristics of the Talos Dome ice archive for recording fallout from explosive eruptions sourced in the nearby Melbourne Volcanic Province (Narcisi *et al.*, 2001). Considering that the regional atmospheric circulation pattern has not changed significantly during the Late Pleistocene (e.g. Delmonte *et al.*, 2010), our tephra record can provide a detailed documentation of the regional explosive volcanic activity that can fruitfully be used to integrate other published local stratigraphies. Indeed, knowledge of Antarctic volcanism is hampered by the remote and inaccessible location of volcanic edifices and by the thick snow/ice cover on their flanks that limit field studies and preclude detailed reconstruction of past histories of individual volcanoes – even direct recognition of vents that might have been recently active (e.g. Corr and Vaughan, 2008). This applies also to the Melbourne Volcanic Province centres, the most likely source for the studied tephras, as their Late Pleistocene–recent pyroclastic stratigraphy is somewhat limited and poorly dated (e.g. Kyle, 1982; Armienti and Tripodo, 1991).

The TALDICE tephra temporal sequence (Fig. 2) suggests that the Melbourne Volcanic Province was persistently active over the last 70 ka. In addition, noticeable changes in the tephra frequency suggest fluctuations in the numbers of explosive eruptions. Specifically, after a period with significant tephra deposition started at ~65 ka, a decrease in the number of tephra layers is recorded from about 35 to 20 ka. The West Antarctic tephra records from Byrd and Siple Dome ice cores (Fig. 1) are both largely influenced by local (Marie Byrd Land) volcanoes and include the period investigated. They show coherent patterns with sustained tephra deposition between 35 and 17 ka, peaking at about 19.5 ka (Gow and Meese, 2007). Using an optical borehole logging technique, a prominent volcanic peak at about 9 ka was detected at Siple Dome (Bay *et al.*, 2004). Assuming that the considered tephra records are complete and unaffected by artefacts, we note contrasting temporal trends as lower tephra frequency at Talos Dome during the last glacial period corresponds to increased volcanic dust input in the two West Antarctic cores (Fig. 2). The link between glaciation and volcanism has been discussed in several studies (Huybers and Langmuir, 2009, and references therein). As for volcanic records obtained from tephra layers in Antarctic ice cores, Bay *et al.* (2004) observed a close temporal association between periods of increased ash deposition at Siple Dome and cold stages at a Greenland ice core throughout the last glacial period, suggesting a bipolar causal connection between volcanism and climate. Increased ice thickening causing crustal stress was suggested to explain the high amount of tephras produced by Marie Byrd Land volcanoes in the late glacial and entrapped in West Antarctic ice cores (Kyle *et al.*, 1981). Assuming that the temporal patterns of ice core tephra deposition (Fig. 2) reliably refer to volcanic periodicity, the different timing for local volcanism in West and East Antarctica might be the response of diachronous ice sheet variations (Anderson *et al.*, 2002), or be related to more complex mechanisms, featuring an interplay of climate-related, tectonic and magmatic factors. Huybers and Langmuir (2009) recently suggested that the unclear Antarctic ice core volcanic signal with respect to climate changes might reflect the fact that there are few subaerial volcanoes in southern high-latitude regions. Indeed, some Antarctic volcanoes have large portions of their volcanic edifices and magma chambers much beneath the ice sheet (e.g. LeMasurier, 1990) and therefore might be poorly sensitive to changing glacial conditions. The available data are insufficient to draw any firm conclusion. Future comparison between ice core tephra and sulphate stratigraphies will be useful in differentiating local and distant volcanic signals and help in understanding underlying mechanisms for Antarctic volcanic temporal variations.

Future prospects

By combining particle size and glass geochemical characteristics of representative samples, we have identified the likely main source region for TALDICE tephra layers related to the last 65 ka, which was the Melbourne Volcanic Province. The new Talos Dome core, containing abundant primary tephra layers of local derivation, can be regarded as an important sequence for reconstructing an improved history of explosive eruptions in Antarctica, supplementing the stratigraphic record obtained by outcrop studies and documenting previously unknown temporal trends and specific episodes.

Aside from palaeovolcanic implications, our record widens the existing East Antarctic tephrostratigraphic framework to the Victoria Land region, and provides potential tools for tephra correlation with ice cores from the inland plateau of East Antarctica (Narcisi *et al.*, 2010, and references therein) and the West Antarctic ice sheet (Kurbatov *et al.*, 2006), and possibly with marine sediment sequences from the Ross Sea (e.g. Licht *et al.*, 1999), all of which contain Quaternary volcanic layers that originated in the Melbourne Volcanic Province. Such climate-independent stratigraphic correlations are critical to reliably compare diverse widely spaced records and detect synchronicity or lead/lags of climatic and environmental signals (e.g. Davies *et al.*, 2008). A further attractive prospect concerns the improvement of the ice core timescale through attribution of tephras to their radiometrically dated proximal counterparts (e.g. Narcisi *et al.*, 2006) and direct dating of ice core tephra layers by radioisotope methods. In this respect, ongoing analyses are testing the ^{40}Ar/^{39}Ar dating feasibility of TALDICE samples containing coarse feldspar grains (Fig. 3(B)). This dating essay could help in obtaining a more accurate chronology of the palaeoclimatic events recorded in the studied core.

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