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Ice record of a 13th century explosive volcanic eruption in northern Victoria Land, East Antarctica

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Abstract: A volcanic event, represented by both coarse ash and a prominent sulphate peak, has been detected at a depth of 85.82 m in a 90 m ice core drilled at Talos Dome, northern Victoria Land. Accurate dating of the core, based on counting annual sulphate and nitrate fluctuations and on comparison with records of major known volcanic eruptions, indicates that the event occurred in 1254 ± 2 AD. The source volcano is most likely to be located within the Ross Sea region. In particular, the glass shards have a trachytic composition similar to rocks from The Pleiades and Mount Rittmann (Melbourne volcanic province), about 200 km from Talos Dome. Sulphate concentration is comparable with that of violent extra-Antarctic explosive events recorded in the same core, but atmospheric perturbation was short-lived and localized, suggesting a negligible impact on regional climate. It is suggested that this eruption may represent the most important volcanic explosion in the Melbourne province during the last eight centuries; thus this event may also represent a valuable chrono-stratigraphical marker on the East Antarctic plateau and in adjoining areas.

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Key words: ice core, non-sea salt sulphate, northern Victoria Land, Talos Dome, tephra, volcanism

Introduction

Ice offers a unique opportunity to study past volcanism as it is the only medium able to simultaneously preserve dust and gaseous aerosols ejected into the atmosphere during explosive volcanic eruptions. Ice records provide excellent archives of eruptions that enable us to expand our knowledge of volcanic history far beyond the period for which written records exist.

Volcanic aerosols represent a major input to the Antarctic atmosphere because of low crustal and anthropic contributions. Tephra layers, of either local or more distant origin, are common in ice sequences throughout the Antarctic region (Qin 1995, Aristarain & Delmas 1998, Fujii *et al.* 1999, Perchiazzi *et al.* 1999, Smellie 1999 and references therein, Udisti *et al.* 1999). Englacial tephra can be used in a wide range of applications, namely:

a) establishing sound stratigraphical correlations among records over wide areas,

b) contributing to the reconstruction of the source region's volcanic activity, and

c) solving glaciological problems (estimation of ice/snow accumulation rates, dating of glacier oscillations etc).

This paper documents a volcanic event represented by both abundant tephra and sulphate fallout in a 90 m deep ice core from Talos Dome (Fig. 1). Our study uses glaciochemical and particle analysis to show that the eruption occurred in the middle of the 13th century and most probably originated from a volcano in the western Ross Sea region.

Talos Dome ice core

Talos Dome (TD) is one of a few ice domes peripheral to the East Antarctic plateau (159°04'E, 72°46'S; Fig. 1). It is adjacent to the Victoria Land segment of the Transantarctic Mountains, about 300 km from the Pacific Ocean and 250 km from the Ross Sea. On the basis of aeolian surface micro-relief recorded during field work, a katabatic wind-field model (Paris & Bromwich 1991) and annual average winds measured at the Antarctic radiosonde stations closest to TD (Connolley & King 1993), dominant winds at this site show south, south-south-west and east-south-east directions at the surface and south and west at 500 hPa (about 5000 m a.s.l.) and 300 hPa (about 9000 m a.s.l.).

The drilling and research at TD was performed as part of the Italian contribution to the International TransAntarctic Scientific Expedition (ITASE) program (Mayewski & Goodwin 1999), which aims to obtain high-resolution data on climate, atmosphere, and surface conditions over the Antarctic ice sheet during the last millennium. The core, drilled during the 1996–97 Italian Antarctic expedition (Frezzotti *et al.* 1998), was collected at the dome's highest altitude (2316 m), where summer snow melting does not occur (mean annual temperature -41°C). Surface micro-relief and core visible layering surveys have shown no evidence of ice crusts produced by wind exposure during a long hiatus in accumulation. Thus, the TD core can be considered an undisturbed, continuous record of snow accumulation; glaciochemical studies indicate that it spans the period 1217–1996 AD, with a mean snow accumulation rate of 80 kg $m^{-2}a^{-1}$ (B. Stenni personal

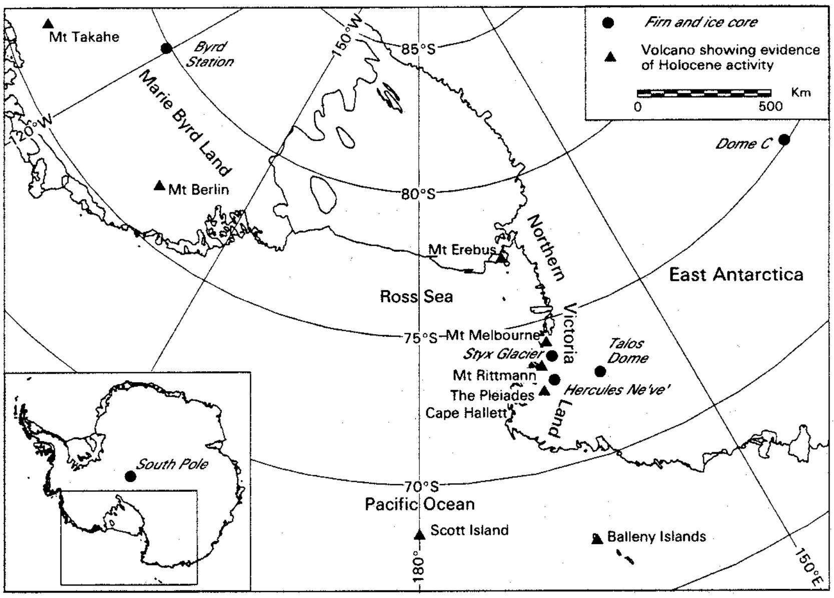

Fig. 1. Location of Talos Dome coring site, and of ice cores and volcanoes referred to in this study.

Table I. Major oxide compositions (recalculated to 100% water free) of the Talos Dome tephra.

Sample	SiO_2	TiO_2	Al_2O_3	Fe_2O_3*	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Total	Na_2O+K_2O	Na_2O/K_2O
1	62.99	0.35	16.50	5.56			0.23	<dl	0.96	9.26	4.14	0.02	100	13.40	2.23
2	62.98	0.36	16.66	5.24			0.27	<dl	0.81	9.60	4.05	0.03	100	13.65	2.37
3	63.83	0.36	15.99	5.81			0.19	0.06	1.28	7.43	5.01	0.03	100	12.45	1.48
4	64.09	0.45	16.38	6.82			0.18	<dl	1.11	6.44	4.48	0.06	100	10.91	1.44
5	64.29	0.36	16.24	6.72			0.27	<dl	1.17	6.46	4.45	0.03	100	10.91	1.45
6	64.14	0.30	16.12	7.00			0.24	<dl	1.15	6.37	4.68	<dl	100	11.05	1.36
7	63.12	0.28	16.01	6.13			0.29	<dl	0.84	8.72	4.60	<dl	100	13.32	1.90
8	63.37	0.38	15.83	7.02			0.23	<dl	1.28	6.92	4.87	0.10	100	11.79	1.42
9	64.60	0.45	16.49	6.19			0.13	<dl	0.97	6.65	4.38	0.15	100	11.03	1.52
10	64.27	0.27	16.15	7.45			0.34	<dl	1.14	5.58	4.79	<dl	100	10.37	1.16
11	61.88	0.30	15.71	6.54			0.20	<dl	1.28	9.51	4.46	0.11	100	13.98	2.13
12	64.51	0.44	16.00	6.93			0.21	<dl	1.18	6.02	4.72	<dl	100	10.74	1.28
13	63.42	0.44	16.13	6.57			0.16	<dl	1.10	7.35	4.78	0.05	100	12.13	1.54
14	63.11	0.21	15.48	5.60			0.24	<dl	1.17	8.80	5.38	0.02	100	14.18	1.64
15	64.50	0.39	16.12	7.12			0.31	<dl	1.16	5.72	4.68	<dl	100	10.40	1.22
16	63.50	0.44	16.01	7.06			0.26	<dl	0.98	7.00	4.73	0.03	100	11.72	1.48
17	64.65	0.44	16.15	6.79			0.28	<dl	1.16	5.80	4.68	0.06	100	10.47	1.24
18	64.99	0.24	16.19	4.58			0.05	<dl	1.18	8.05	4.72	<dl	100	12.77	1.71
19	64.68	0.31	16.46	5.98			0.11	<dl	1.05	7.05	4.30	0.07	100	11.35	1.64
mean	63.84	0.36	16.14	6.37			0.22	0.06	1.10	7.30	4.63	0.05		11.93	1.58
s d	0.80	0.08	0.29	0.75			0.07	–	0.14	1.32	0.31	0.04		1.28	0.34
a	63.84	0.29	16.52		2.00	2.88	0.17	0.14	1.30	7.21	5.32	0.07	99.74	12.53	1.36
b	62.39	0.24	16.56	4.51			0.16	0.25	1.14	7.61	4.96	0.07	97.89	12.57	1.53
c	63.26	0.38	15.77		4.42	2.03	0.22	0.15	1.01	7.19	4.95	0.03	99.40	12.14	1.45
d	62.60	0.43	17.03		1.98	3.22	0.19	0.32	1.09	7.32	5.15	0.07	99.40	12.47	1.42
e	62.19	0.28	16.62		2.73	2.86	0.18	0.19	0.83	8.58	4.48	0.04	98.97	13.06	1.92
f	63.31	0.66	15.71		1.27	5.84	0.19	0.42	2.75	5.36	3.85	0.11	99.47	9.21	1.39
g	64.14	0.58	15.21		1.63	4.66	0.17	0.51	2.00	5.76	4.64	0.07	99.36	10.40	1.24
h	63.60	0.37	15.49		1.42	4.31	0.19	0.10	1.65	6.01	5.20	0.07	98.41	11.21	1.16
i	64.10	0.46	14.62		1.82	5.02	0.23	0.06	2.06	5.54	4.87	0.06	98.84	10.41	1.14

Fe_2O_3* = total Fe expressed as Fe_2O_3; dl = detection limit. Comparative analyses of volcanic rocks from the Melbourne province are also reported.
a. & **b.** Samples 13 and 12 from The Pleiades (Kyle 1990d), **c.**–**e.** samples NN1, NN25 and NN35 from Mount Rittmann, XRF-AAS (Armienti & Tripodo 1991), **f.** & **g.** samples MB14 and MB38 from Mount Melbourne, XRF-AAS (Armienti *et al.* 1991), **h.** & **i.** samples EP14 and SE04 from Mount Melbourne, XRF (Wörner *et al.* 1989).

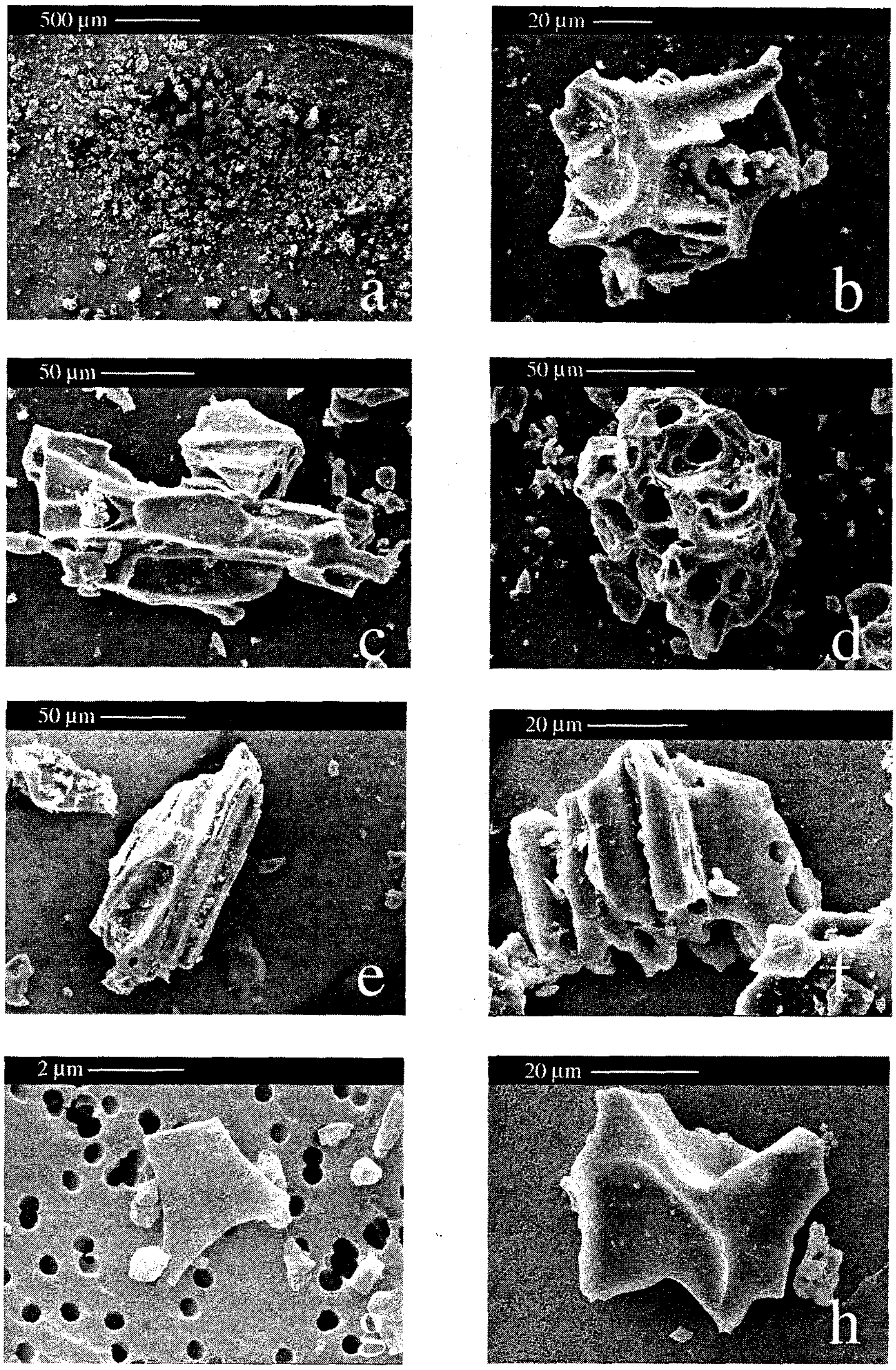

Fig. 2. Scanning electron microscope images of vitric particles. **a.** Overview of the filter at 85.82 m depth showing the abundant pumice and glass shards, **b.** shard with spherical bubbles with fairly thick (7 µm) vesicle walls, **c.** large shard (200 µm long) with elongate vesicles, **d.** highly vesicular pumice with spherical and ovoid vesicles (uncommon), **e.** & **f.** prismatic pumices with parallel tubular vesicles with fairly thick (5 µm) vesicle walls, **g.** tiny plate-like shard, very common in the finer fraction, **h.** Y-shaped fragment from a wall between three vesicles. Note that edges are not abraded.

communication 2000).

Characteristics of the tephra

One coarse tephra is present in TD ice core. The tephra was not evident to the naked eye, and was detected in the laboratory, when a 2.5 cm long ice sample from 85.82 m depth (60.0 m water equivalent) was melted and filtered in a clean room for glaciochemical analysis. The filter was darkened by an abundant insoluble deposit. Microscopic observations revealed that the recovered microparticles were predominantly of volcanic origin (Fig. 2). No significant insoluble deposits were found in the filters contiguous to the one bearing the tephra. No other discrete tephra is present in the TD core.

Scanning electron microscopy was used to examine the glass shards in detail. Particles range in size from a few µm to about 200 µm (Fig. 2). The larger glass particles are represented by subequant or slightly elongate shards with spherical and ovoid vesicles and fairly thick vesicle walls (Fig. 2b–d) and by prismatic pumices with parallel tubular vesicles (Fig. 2e & f).

The fine ash fraction is made up of dense curved, plate-like and cuspate vitric pyroclasts formed by the fragmentation of large vesicle walls (Fig. 2g & h). Lack of abrasion indicates that the tephra has a fallout origin and has not been reworked. Occurrence of both vesicular pumiceous and vesicle-wall fragments suggests formation during a magmatic explosive eruption (Heiken 1974, Heiken & Wohletz 1985).

Assessment of major element composition of the tephra was made after taping the filter bearing the tephra to an aluminium stub and coating it with a carbon film. Single glass shards were analysed with a SEM/EDS system (Cambridge Stereoscan 360 equipment), using synthetic compounds for calibration and applying the ZAF correction method. Working conditions were the following: accelerating voltage 20 kV, probe current 0.14 nA (LaB_6 filament), counting time 50 s. According to the scheme proposed by Le Bas *et al.* (1986), analyses indicate a trachytic composition (Table I and Fig. 3). Variations in Na_2O contents, and related spread in total alkali, might be due to sodium loss during microprobe analysis (Keller 1981, Hunt & Hill 1993). The chemical similarity of coarse pumices and fine-grained shards indicates that the whole tephra was produced during the same volcanic event. XRD analysis of the filter indicates the presence of alkali feldspar, probably sanidine.

Characteristics of the tephra-bearing ice

A sharp and prominent sulphate peak is associated with the deposition of volcanic particles. Non-sea salt sulphate ($nssSO_4^{2-}$) concentration of the ice sample (2.5 cm long) containing the tephra is 5.09 µeqL^{-1} (Fig. 4), about five times the background value (0.98 ± 0.47 µeqL^{-1}). The ice samples immediately above and below the tephra show $nssSO_4^{2-}$ concentrations in the range of background levels. On the basis of the snow accumulation rate, obtained by ice density and time scales, the ice sample containing both volcanic particles and sulphate aerosol corresponds to 0.25 year of accumulation; thus the volcanic fallout was very rapid.

Dating of the core and age of the eruption

A multi-parameter approach including tritium, $nssSO_4^{2-}$ and NO_3^- was used to date the TD core. The core was analysed continuously by sampling 3000 ice slices from 3.5 cm (upper part of the core) to 2.5 cm (lower part) in length. This corresponds to 3–8 samples per year of accumulation. Concentration of anions were determined using ion chromatography, according to the procedures described in Gragnani *et al.* (1998). As it was found that the Cl^-/Na^+ ratio (1.12 µeqL^{-1}) is similar to that of bulk seawater, namely 1.18 µeqL^{-1}, $nssSO_4^{2-}$ concentrations were calculated by subtracting the sea-salt surface contribution using Cl^- as a conservative tracer, as performed also by Cole-Dai *et al.* (1997).

Preliminary dating of the core was carried out by counting fluctuations of $nssSO_4^{2-}$ and NO_3^-. Both parameters show seasonal cyclicity in polar ice cores (Mosley-Thompson *et al.* 1993, Langway *et al.* 1994, Stenni *et al.* 1999) and are widely used to establish accurate depth–age relationships (e.g. Cole-Dai *et al.* 1997). Dating was fine-tuned using the increase in tritium related to thermonuclear atmospheric bomb tests in the 1960s (Jouzel *et al.* 1979) and volcanic peaks of $nssSO_4^{2-}$ as time markers. Oxidation of SO_2 to H_2SO_4 occurs within one month following an eruption (Coffey 1996). If the SO_2 is injected into the stratosphere, it can remain there as H_2SO_4 for several years and may reach the polar regions, where it is scavenged by snowfall. An increase of H_2SO_4 or $nssSO_4^{-2}$ concentrations in polar snow has been observed up to three years after a major eruption (Clausen *et al.* 1997, Cole-Dai & Mosley-Thompson 1999). At TD, numerous $nssSO_4^{2-}$ peaks are superimposed on background levels (Fig. 4). All the peaks (except that associated with the tephra under observation

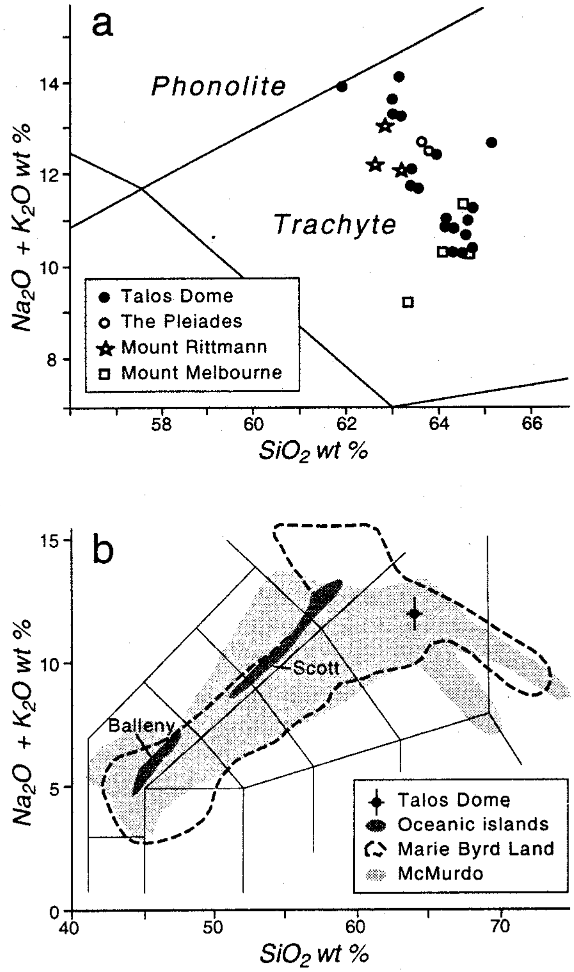

Fig. 3. Total alkali–silica diagram (Le Bas *et al.* 1986). **a.** Results of glass analysis on Talos Dome tephra and comparative analyses (normalised to 100% water free) of volcanic rocks from the Melbourne province (see also Table I), **b.** average value (*n* = 19 shards) of the Talos Dome tephra and compositional fields for volcanic provinces located within 2000 km from Talos Dome (from LeMasurier 1990b).

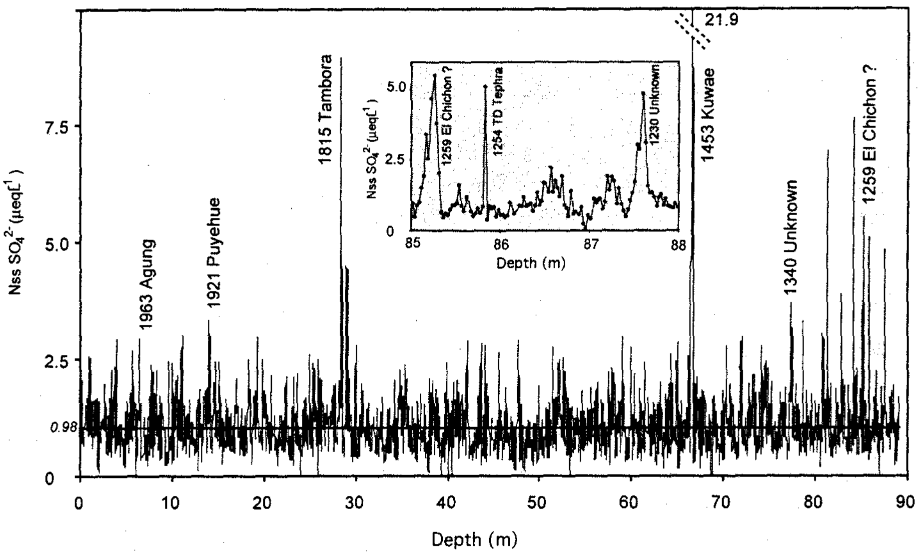

Fig. 4. Non-sea salt sulphate ($nssSO_4^{2-}$) concentration versus depth in the Talos Dome core. The shaded area includes $nssSO_4^{2-}$ signals of the 1259, 1254 and 1230 eruptions and is shown enlarged in the insert.

here) are well-known markers in polar regions and correspond to fallout of extra-Antarctic explosive volcanic eruptions. The main volcanic signal (21.9 μeqL^{-1}) occurs between 66.46 and 66.72 m and according to the counting of annual fluctuations is dated at around 1450 AD. It is correlated with the 1453 AD Kuwae eruption (Cole-Dai *et al.* 1997 and references therein, Zielinski 2000). Between 81.35 and 85.26 m four strong acid peaks are present. By comparison with Byrd Station and South Pole ice records (Langway *et al.* 1995), they can be dated at 1285–87, 1277–78, 1269–70 and 1259 respectively. This peak series has been found in several Antarctic ice cores (see also Cole-Dai *et al.* 2000, Udisti *et al.* 2000) and represents an excellent chronological marker. Other prominent spikes are assigned to the eruptions of 1963 (Agung), 1921 (Puyehue), 1815 (Tambora), and 1340 (unknown). Sulphate signals of the identified extra-Antarctic explosive eruptions last up to three years, in agreement with evidence at South Pole (Delmas *et al.* 1992, Cole-Dai & Mosley-Thompson 1999) where accumulation rates are similar to TD.

The volcanic event recorded at 85.82 m depth by ash and sulphate fallout is dated at 1254 ± 2 AD. The $nssSO_4^{2-}$ peaks at 85.37 m and 87.80 m, respectively (Fig. 4), represent the closest chronological constraints. As already mentioned, the younger peak can be linked to the 1259 eruption which, according to Palais *et al.* (1992), may be related to the El Chichon volcano. The older peak (87.80 m) can be assigned to Unknown 1230. Signals of both 1259 and 1230 eruptions occur in Greenland and Antarctica cores (Palais *et al.* 1992, Langway *et al.* 1995).

Source of the eruption

Much evidence indicates that the 1254 AD volcanic event recorded at TD originated in Antarctica. The abundance of volcanic particles and their coarse size (up to 200 μm) is consistent with a local source. Extra-Antarctic tephras found in south polar ice and snow are represented by isolated, fine-grained (< 10 μm) shards (de Angelis *et al.* 1985, Palais *et al.* 1990). Additionally, the $nssSO_4^{2-}$ deposition associated with the 1254 AD volcanic eruption forms a sharply defined feature involving only one ice sample (0.25 year of accumulation), and differs significantly from the volcanic signals recorded at TD relating to eruptions from extra-Antarctic regions (Fig. 4). The atmospheric residence time of soluble aerosols produced by volcanic eruptions may depend on several factors (Palais & Kyle 1988); however it has been generally observed that violent extra-Antarctic explosive events produce broad signals in the ice lasting a few years, while local non-stratospheric eruptions, whose aerosol fallout is much quicker, are often associated with sharp spikes (Moore *et al.* 1991). Finally, a $nssSO_4^{2-}$ signal for the 1254 AD eruption is absent in the EPICA (European Project for Ice Coring in Antarctica) record at Dome C (cf. Udisti *et al.* 2000, fig. 6) and has not been identified in South Pole and Byrd Station ice cores (Delmas *et al.* 1992, Langway *et al.* 1994, Langway *et al.* 1995; Fig. 1). Nearby shallow cores at Styx Glacier (230 km east-south-east of TD) and Hercules Névé (180 km east of TD; Fig. 1) do not go back far enough in time (Stenni *et al.* 1999, Udisti *et al.* 1999) to record the 1254 AD event. The lack of matching signals for the 1254 AD event in Antarctic records indicates a proximal source, probably in the Ross Sea region.

Comparison of chemical composition of the TD tephra with rocks erupted by Antarctic volcanoes contribute to source identification. This comparison is made difficult by the different analytical methods used for Antarctic rocks (XRF on bulk rock samples) and the TD tephra (SEM/EDS on single glass shards). Specifically, data from bulk analysis may be affected by the presence of inclusions, microlites, and weathering products on the surface of samples (Westgate & Gorton 1981). This contamination is avoided by grain-discrete analysis (e.g. Smith & Westgate 1969).

If we restrict our search to within a radius of about 2000 km from TD, the following provinces can be considered as possible candidates (Fig. 1): Balleny Islands and Scott Island, which are oceanic islands on the Antarctic Plate; Marie Byrd Land; and the Hallett, Erebus and Melbourne volcanic provinces of the McMurdo Volcanic Group. All of these volcanoes are located to the north and east of TD.

The Balleny Islands and Scott Island volcanoes are excluded as a possible source because their products show basanitic and phonotephritic to phonolitic compositions respectively (Fig. 3b).

Trachytic products are known from the Marie Byrd Land volcanoes (Fig. 3b), amongst which Mount Takahe and Mount Berlin show evidence of Holocene activity (LeMasurier 1990a). Moreover, field observations at these volcanoes and the presence of distal tephra in the ice cores and marine sediments up to 3000 km from the inferred source (Kyle *et al.* 1981, Palais *et al.* 1988, Shane & Froggatt 1992, McIntosh & Wilch 1995, Wilch *et al.* 1999) indicate that remarkable explosive eruptions occurred there, although they were not climatically significant at a continental scale (Palais & Kyle 1988). However, trachytes from both Mount Takahe and Mount Berlin show a remarkable peralkaline character (Fig. 5). This, together with the lack of a 1254 AD sulphate peak in the Byrd station ice core, rules out these volcanoes as a possible source of the TD tephra.

In the McMurdo Volcanic Group, provenance from the Hallett volcanic province is excluded because radiometric dating indicates Miocene activity (McIntosh & Kyle 1990). In the Erebus province, Mount Erebus is known to have been active since one million years ago (Kyle 1990a), with persistent strombolian activity in recent decades (Kyle 1994, Rowe *et al.* 2000). However the products of this volcano are predominantly phonolitic (Kyle 1990b); trachytes are volumetrically insignificant and related to lavas and endogenous domes (Moore & Kyle 1990, Kyle *et al.* 1992), excluding it as a source of the TD tephra.

Trachytic rocks are common in the Melbourne volcanic province (Fig. 3). Among the volcanoes in this province, Malta Plateau and Mount Overlord have been excluded, because according to the available radiometric dating, they were active during the Miocene (Kyle 1990c). Mount Melbourne shows evidence of Pleistocene to recent activity (Kyle 1990c). The most recent eruptions were explosive and produced widespread pumice deposits; in particular a significant pumice eruption tentatively dated at 200 years ago is documented by a major tephra at various sites on the eastern side of Mount Melbourne (Keys *et al.* 1983, Lyon 1986, Wörner & Viereck 1989, Wörner *et al.* 1989, Armienti *et al.* 1991). However, provenance from this volcanic field is excluded because its trachytic products generally show Na_2O contents below 6% (Wörner *et al.* 1989, table 2, Wörner & Viereck 1990, fig. A.10.7), and also differ from the TD tephra with regard to their Al_2O_3 and CaO contents (cf. Table I, samples from f to i). Volcanoes of The Pleiades may have been the source of the TD tephra, as they are considered dormant on the basis of young radiometric dating and evidence of hydrothermal alteration (Kyle 1990d). Moreover, pyroclastic rocks indicating explosive activity are noted amongst their products and the rocks are geochemically similar to the TD tephra (cf. Table I, samples a and b; Fig. 3a). Geochemical similarities are found also with Mount Rittmann rocks (cf. Table I, samples c to e; Fig. 3a), the volcano recently discovered in Victoria Land (Armienti & Tripodo 1991). On the basis of its fumarolic activity, it is considered active (Bonaccorso *et al.* 1991) and thus it may have been responsible for eruption of the tephra recovered at TD. Both The Pleiades and Mount Rittmann are located about 220 km east of TD.

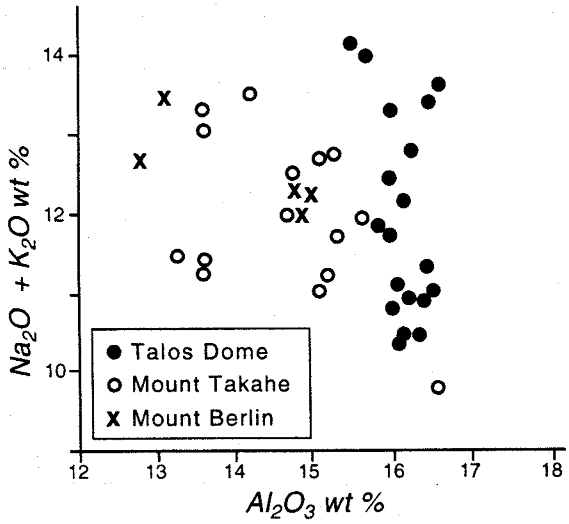

Fig. 5. Total alkali against Al_2O_3 diagram of the Talos Dome tephra and of trachytic samples from Mount Takahe and Mount Berlin volcanoes, Marie Byrd Land (Palais *et al.* 1988, LeMasurier & Kawachi 1990, LeMasurier & Rex 1990, 1991).

Significance of the eruption

Considering the dominant winds in the Victoria Land region and adjacent plateau, and assuming that prevalent wind direction patterns have not changed in the last millennium, TD lies in a favourable location for recording fallout of historical eruptions from volcanoes in the Ross Sea region. As no local eruptions except the 1254 AD event have been recorded in the TD ice core, either as tephra or as a prominent sulphate peak, this event could represent the most important volcanic explosion of the Melbourne province over the time span contained in the TD core, i.e. the last eight centuries. Sulphate concentration is comparable with that of the violent extra-Antarctic explosive events recorded within the same core (Fig. 4), but atmospheric perturbation was very short-lived and localized, suggesting a negligible impact on regional climate.

Conclusions

The explosive volcanic event that was identified in the lower part of TD core by both abundant air-borne particulate matter and prominent sulphate fallout has been characterized by chemical analysis on tephra and related ice. Accurate assessment of chronology indicates that this eruption occurred in 1254 ± 2 AD. The source volcano is most likely The Pleiades or Mount Rittmann volcanoes in the Melbourne province (which lie about 200–250 km from Talos Dome). This relation is based on geochemical similarities, and chronological (evidence of activity in historical times) and volcanological (evidence of explosive activity) consistencies. The assertions made about the origin of the tephra are tentative and might be reviewed in the light of new data on stratigraphy, chronology and geochemistry of Victoria Land's volcanism.

This eruption may represent the most important volcanic explosion of the Melbourne province in the last eight centuries. Given its precise age and the well-constrained characteristics of the erupted products, this event can be regarded as a valuable chrono-stratigraphic marker in Victoria Land region and adjacent East Antarctic plateau and Ross Sea.

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