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Oxygen isotope composition of meteoritic ablation debris from the Transantarctic Mountains: Constraining the parent body and implications for the impact scenario

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Abstract—Microscopic meteoritic ablation spheres recently found on top of the Victoria Land in Transantarctic Mountains, and in the L2 Dome C and DF2691 Dome Fuji ice core layers document a major impact of a 10^8 kg (or larger) cosmic body in the Antarctic region about 480 kyr ago. Although of broadly chondritic composition, the exact nature of the impactor is unknown, and whether the impactor struck the Antarctic ice sheet or exploded in the atmosphere is a matter of debate. Based on oxygen isotope analyses of ablation spheres from the Transantarctic Mountains by means of IR-laser fluorination coupled with mass spectrometry, we suggest that they represent the debris of an atmospheric airburst of a primitive asteroid of CV, CO, or CK composition, or a comet with composition similar to the short-period comet 81P/Wild 2.

INTRODUCTION

Meteoritic ablation spheres are microscopic melt droplets that separate from large meteoroids during atmospheric melting (Harvey et al. 1998). Aggregates of microscopic meteoritic ablation spheres were discovered during the 2006 Programma Nazionale di Ricerche in Antartide (PNRA) expedition in the micrometeorite traps on top of Miller Butte, Victoria Land, Transantarctic Mountains (Figs. 1 and 2). These traps consist of joints and fractures on glacially eroded granitic surfaces filled by local detritus that have been collecting micrometeorites by direct fall over the last approximately 1 Ma (Folco et al. 2008, 2009, 2011; Rochette et al. 2008; Suavet et al. 2011a). Based on a homogeneous chondritic composition, van Ginneken et al. (2010) proposed that the Transantarctic Mountain meteoritic ablation spheres resulted from a single major meteoritic event of ordinary or carbonaceous chondrite parentage. Furthermore, these authors provided petrographic and

geochemical evidence for pairing the Transantarctic Mountain aggregates with the approximately 480 kyr old extraterrestrial dust L2 and DF2691 layers found in the EPICA—Dome C and Dome Fuji ice cores, respectively (Narcisi et al. 2007; Misawa et al. 2010), and concluded that these meteoritic ablation spheres document a continental-scale, Tunguska-like meteorite impact (aerial burst) over Antarctica about 480 kyr ago of a 10^8 kg (or larger) fragment of a stony, primitive asteroid.

Ion microprobe oxygen isotope compositions of the paired L2 particles from EPICA—Dome C ice core presented in abstract form by Engrand et al. (2010), suggested that a CM-CR-CV-like carbonaceous chondrite impacted on the Antarctic ice sheet. However, the large analytical uncertainties and the scatter of the isotope compositions above and below the terrestrial oxygen isotope fractionation line did not allow a definitive conclusion.

Here, we present high-precision oxygen isotope composition of two aggregates of meteoritic ablation

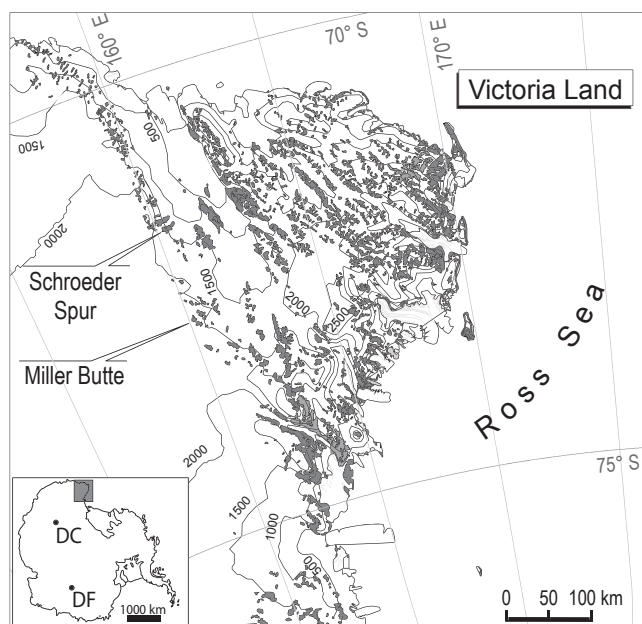


Fig. 1. Map of Victoria Land, Antarctica, showing the location of Miller Butte and Schroeder Spur where aggregates of meteoritic ablation debris were recovered from (#20c.25, #20c.351 and #34.01, respectively). Inset: Sketch map of Antarctica showing the location of Dome C and Dome Fuji where similar spheres were found in ice cores (Narcisi et al. 2007; Misawa et al. 2010) relative to Victoria Land (shaded area).

spheres from the Transantarctic Mountain collection (Fig. 2). Data improve our understanding of the nature of the impactor and of the catastrophic impact scenario that occurred about 480 kyr ago in the Antarctic region.

SAMPLES AND METHODS

Two samples of the aggregate of meteoritic ablation spheres from micrometeorite trap #20c, Miller Butte, Antarctica ($72^{\circ}42.078' S$, $160^{\circ}14.333' E$; Fig. 1) were selected for the determination of their three oxygen isotope composition: sample #20c.25 of 0.56 mg (Fig. 2A) and sample #20c.351 of 0.3 mg (Fig. 2C). Aggregates were extracted from the host detritus under the stereomicroscope. Information about overall petrography, including size, bulk composition, mineral composition, and degree of weathering, was obtained using a Philips XL30 microanalytical scanning electron microscope (SEM-EDS) at Siena University, Italy. The petrography of an additional particle from micrometeorite trap #34 discovered on the granitic top of Schroeder Spur ($71^{\circ}39.814' S$, $160^{\circ}19.291' E$; Fig. 1) during the 2009 PNRA expedition (namely, sample #34.01) is also reported to document the consistent occurrence of these aggregates in the Victoria Land Transantarctic Mountains. The mineralogy and geochemical composition of an aliquot of

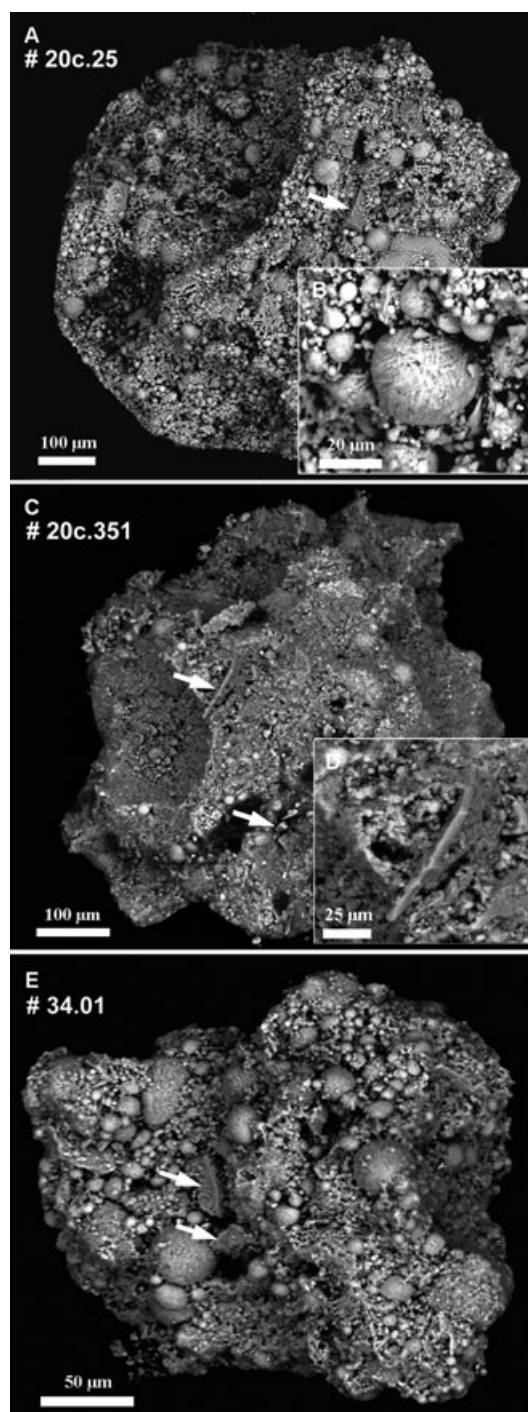


Fig. 2. Backscattered electron images of the aggregates of microscopic meteoritic ablation spheres studied in this work. Obvious bedrock crystals embedded in the aggregates are arrowed. A) Sample #20c.25 from Miller Butte. Note the high abundance of microscopic meteoritic ablation spheres relative to bedrock crystals. B) A close-up view of sample #20c.25. C) Sample #20c.351 from the same micrometeorite trap on the top of Miller Butte. D) A close-up view of sample #20c.351. Note the high abundance of weathering encrustations (mainly jarosite), plus bedrock contaminants. E) Sample #34.01 from Schroeder Spur showing an external surface similar to sample #20c.25.

sample #20c.25 were studied in detail by van Ginneken et al. (2010). As van Ginneken et al. (2010) documented some weathering and bedrock contamination of the aggregates, the oxygen isotope compositions of two samples of the host granitic detritus were also determined to understand the contribution of bedrock contamination and weathering to the oxygen isotopic composition of the aggregates. The sample labeled “host granite” consists of 1.42 mg of unsorted granitic detritus subjected to ultrasonic cleaning in water and sieved in the 200–400 μm size range. This allowed information to be obtained on contamination resulting from inclusion of fresh silicate grains from the bedrock. The sample labeled “host granite <25 μm ” consists of 1.69 mg of granite detritus <25 μm in size. Its mineral composition was determined by X-ray diffraction analysis performed with X’Pert Pro MPD, Panalytical, at CEREGE, France (see Data S1) and it was not treated at all prior to oxygen isotope analysis to obtain information about weathering contamination in the trap.

Measurements of $\delta^{18}\text{O}$ and $\delta^{17}\text{O}$ were carried out at the Stable Isotopes Laboratory of CEREGE, France, using the IRMS technique (Alexandre et al. 2006; Crespin et al. 2008) adapted for the measurement of extraterrestrial materials (Suavet et al. 2010). The three oxygen isotopic compositions were measured with a dual-inlet mass spectrometer Delta Plus, Thermo-Finnigan. The gas (O_2) was passed through a -114°C slush to refreeze potential interfering gasses before being sent to the mass spectrometer. To get sufficient 34/32 signal ($m/z = 34$ or $m/z = 32$ or $^{18}\text{O}^{16}\text{O}/^{16}\text{O}_2$) and 33/32 ($m/z = 33$ or $m/z = 32$ or $^{17}\text{O}^{16}\text{O}/^{16}\text{O}_2$) signal (2–3 V), the oxygen from <0.5 mg standards and meteoritic ablation sphere aggregates and sample host granite <25 μm were concentrated in the mass spectrometer in an auto-cooled 800 μL microvolume filled with silica gel and directly connected to the dual-inlet system. $\delta^{18}\text{O}$ and $\delta^{17}\text{O}$ values of the reference gas were fixed through the analysis of NBS28 ($\delta^{18}\text{O} = 9.60\text{‰}$; $\delta^{17}\text{O} = 4.99\text{‰}$). The oxygen isotope results are expressed in ‰ versus V-SMOW. Measured $\delta^{18}\text{O}$ and $\delta^{17}\text{O}$ values of the meteoritic ablation sphere samples were corrected on a daily basis using 1.5 mg NBS28 ($\delta^{18}\text{O} = 9.65 \pm 0.01\text{‰}$, $\delta^{17}\text{O} = 5.02 \pm 0.03\text{‰}$, $N = 2$). During the analyzing period, analyses of UWG-2 (Valley et al. 1995) were made (1.44 mg: $\delta^{18}\text{O} = 6.01 \pm 0.02\text{‰}$, $\delta^{17}\text{O} = 3.13 \pm 0.04\text{‰}$, $\Delta^{17}\text{O} = 0.01 \pm 0.04\text{‰}$, $N = 1$; about 0.35 mg: $\delta^{18}\text{O} = 5.90 \pm 0.06\text{‰}$, $\delta^{17}\text{O} = 3.04 \pm 0.04\text{‰}$, $\Delta^{17}\text{O} = -0.034 \pm 0.04\text{‰}$, $N = 2$). Measurements of small masses samples were corrected for offsets due to the use of the mass spectrometer-cooled microvolume ($+0.60 \pm 0.27\text{‰}$ for $\delta^{18}\text{O}$, $+0.48 \pm 0.13\text{‰}$ for $\delta^{17}\text{O}$, $+0.16 \pm 0.06\text{‰}$ for $\Delta^{17}\text{O}$, based on the measurement of small masses of quartz standard “Boulangé”; Suavet et al. 2010).

Granite samples were measured using the same technique. Measurements were corrected using 1.5 mg NBS28 ($\delta^{18}\text{O} = 8.92 \pm 0.16\text{‰}$ and $\delta^{17}\text{O} = 4.67 \pm 0.08$, $N = 4$). Only the sample host granite <25 μm required the use of the microvolume; in this case, we applied the same correction procedure as for meteoritic ablation sphere samples.

RESULTS

Meteoritic ablation sphere sample #20c.25 from Miller Butte (Fig. 2A) consists of a porous aggregate of a myriad of quench-textured spherules, with individual spherules ranging from <1 to 65 μm in diameter (Fig. 2B). Dominant spherule types include dendritic magnesioferrite spherules plus microporphyritic olivine and magnesioferrite spherules. Sparse bedrock grains of quartz, muscovite, and feldspar are interspersed in the aggregate. Aggregate cavities are partially encrusted by jarosite, a hydrous sulfate of potassium and iron that forms due to terrestrial weathering in the micrometeorite trap. Literature synchrotron X-ray diffraction data (van Ginneken et al. 2010) indicate that the crystalline phases in sample #20c.25 include 7 wt% jarosite and 10 wt% bedrock contamination, in addition to 55 wt% primary magnesioferrite and 25 wt% olivine (Fa_{15}). Sample #20c.351, from the same micrometeorite trap at Miller Butte, shows a larger amount of fine-grained material (mostly jarosite that cements spherules and bedrock grains; Figs. 2C and 2D). Sample #34.01 from Shroeder Spur is rather similar to sample #20c.25 in terms of abundance of quench-textured spherules, spherule types and composition, granitic bedrock inclusions, and sparse encrustations of cementing material (Fig. 2E). X-ray diffraction spectra of “host granite <25 μm ” indicate that the fine-grained detritus in Miller Butte trap contains abundant bedrock minerals like quartz, muscovite, and hornblende; weathering products like gypsum and analcime; as well as amorphous phases, cristobalite and augite (Fig. S1). The latter phases are likely constituents of the volcanic tephra commonly reported in the area (Perchiazzi et al. 1999; Curzio et al. 2008).

The bulk composition of the surfaces of samples #20c.25, #20c.351, and #34.01, along with the bulk composition of the spherules from a sectioned aliquot of sample #20c.25 from van Ginneken et al. (2010), is reported in Table 1 and are plotted in Fig. 3. Figure 3 shows similar compositional patterns for the external surfaces of particles #20c.35, #20c.351, and #34.01. Enrichments in S, K, and Fe and depletions in Mg and Ni relative to the chondritic bulk spherule composition are likely due to the presence of jarosite of weathering origin. Also, Cr, Ti, and Mn can be accommodated by jarosite. The high Al and Na are likely due to bedrock

Table 1. Bulk composition of aggregates of meteoritic ablation spheres from the Transantarctic Mountains obtained by averaging multiple SEM-EDS raster ($20 \mu\text{m}^2$) analyses of their external surface. These particles are contaminated with bedrock crystals and weathering products (mainly jarosite and analcime). The bulk composition of the meteoritic ablation spheres obtained through EPMA of a sectioned aliquot of aggregate #20c.25 is reported for comparison.

Sampling site	Miller Butte	Miller Butte	Schroeder Spur	Miller Butte
Particle name	20c.25	20c.351	34.01	20c.25
Method	SEM-EDS	SEM-EDS	SEM-EDS	EPMA
	external surface	external surface	external surface	bulk spherule composition
Reference	This study	This study	This study	van Ginneken et al. (2010)
Na ₂ O	2.6	1.4	1.9	1.27
MgO	4.2	2.1	3.4	24.5
Al ₂ O ₃	10.5	6.8	10.0	2.5
SiO ₂	38.9	27.0	31.2	35.7
P ₂ O ₅	0.9	0.7	1.2	0.24
SO ₃	6.8	10.6	11.0	0.14
Cl	bdl	bdl	–	bdl
K ₂ O	3.2	4.5	3.7	0.10
CaO	1.5	1.2	1.4	2.04
TiO ₂	0.8	0.5	0.6	0.12
Cr ₂ O ₃	0.9	1.3	0.7	0.60
MnO	0.6	0.8	0.5	0.29
FeO	28.0	41.6	33.5	29.1
NiO	1.1	1.4	1.1	1.70
Total	100.0	100.0	100.0	98.3

bdl = below detection limit.

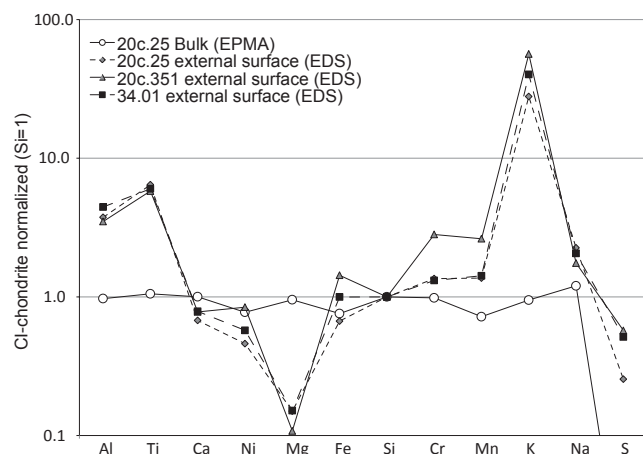


Fig. 3. Spider diagram showing CI-normalized (McDonough and Sun 1995) major element compositions (EDS analyses) of the external surfaces of particles #20c.25 and #20c.351 from Miller Butte, and #34.01 from Schroeder Spur. Literature EPMA bulk meteoritic ablation sphere composition of #20c.25 is reported for comparison (van Ginneken et al. 2010).

contamination: fresh alkali feldspars when coupled with high SiO₂ (i.e., particle #20c.25), or their alteration products, like analcime and/or alunite, when coupled with lower SiO₂ (i.e., particle #20c.351). Furthermore, X-ray diffraction spectra of samples #34.01 and #20c.25 (van Ginneken et al. 2010) show nearly identical patterns (in terms of peak positions and intensities) indicating identical

mineral composition and relative mineral abundances (see Data S1, Fig. S2). Petrographic and mineralogical data thus suggest that the three particles #20c.25, #20c.351, and #34.01 are paired, thus documenting their systematic occurrence on a regional scale in Victoria Land, Antarctica. Furthermore, data suggest that the meteoritic ablation spheres underwent similar style of weathering and bedrock contamination and that particle #20c.25 and #20c.351 are the least and the most altered due to weathering and bedrock contamination, respectively.

The three-oxygen isotope compositions of the meteoritic ablation sphere aggregates are $\delta^{18}\text{O} = 2.98 \pm 0.27\text{‰}$, $\delta^{17}\text{O} = -1.70 \pm 0.14\text{‰}$, $\Delta^{17}\text{O} = -3.26 \pm 0.07\text{‰}$ for sample #20c.25, and $\delta^{18}\text{O} = 6.50 \pm 0.27\text{‰}$, $\delta^{17}\text{O} = 2.85 \pm 0.14\text{‰}$, $\Delta^{17}\text{O} = -0.54 \pm 0.08\text{‰}$ for sample #20c.351 (Table 2). The three-oxygen isotope compositions of the host granitic detritus are $\delta^{18}\text{O} = 13.65 \pm 0.17\text{‰}$, $\delta^{17}\text{O} = 7.12 \pm 0.09\text{‰}$, $\Delta^{17}\text{O} = 0.03 \pm 0.12\text{‰}$ for “host granite,” and $\delta^{18}\text{O} = 4.97 \pm 0.32\text{‰}$, $\delta^{17}\text{O} = 2.68 \pm 0.16\text{‰}$, $\Delta^{17}\text{O} = 0.09 \pm 0.14\text{‰}$ for “host granite < 25 μm ” (Table 2).

DISCUSSION

Oxygen Composition of the Parent Material

Three oxygen isotope analysis is a powerful tool to classify meteoritic materials, as their compositions vary

Table 2. Three oxygen isotope composition (in ‰ versus V-SMOW) of aggregates of meteoritic ablation spheres from Miller Butte (particles #20c.25, #20.351 and ablation sphere bulk composition) and samples of the host granite (see text for details).

Sample	$\delta^{18}\text{O}$	$\delta^{17}\text{O}$	$\Delta^{17}\text{O}$
20c.25	2.98 ± 0.27	1.70 ± 0.14	-3.26 ± 0.07
20c.351	6.50 ± 0.27	2.85 ± 0.14	-0.54 ± 0.08
Ablation spheres*	≈ 1.73	≈ -2.96	≈ -3.86
Host granite	13.65 ± 0.17	7.12 ± 0.09	0.03 ± 0.12
Host granite < 25 μm	4.97 ± 0.32	2.68 ± 0.16	0.09 ± 0.14

*Bulk oxygen isotope composition corrected for bedrock contamination and weathering.

widely between different meteorite groups (Fig. 4) (Clayton et al. 1991; Clayton and Mayeda 1999). Recent studies showed that the oxygen isotope composition of cosmic spherules, which are completely melted during atmospheric entry, can be used to identify their parent material, provided that the physical-chemical processes that occur during the atmospheric entry and that affect their oxygen isotope composition are well understood (Cordier et al. 2011, 2012; Suavet et al. 2011b). These processes include evaporation, which is a mass-dependent fractionation, and direct mixing with atmospheric oxygen, which is a mass-independent fractionation. These two processes occur also in the fusion crusts of macroscopic meteorites, i.e., their outermost part, which is subject to melting and evaporation during atmospheric entry heating (Clayton et al. 1986). On a $\Delta^{17}\text{O}$ versus $\delta^{18}\text{O}$ diagram (e.g., Fig. 4), evaporation will shift values horizontally toward heavier oxygen isotope composition (i.e., high $\delta^{18}\text{O}$) along lines parallel to the terrestrial fractionation line (TFL). In turn direct mixing with Earth's atmosphere will shift oxygen isotope compositions linearly toward the composition of atmospheric oxygen. Terrestrial weathering may also influence the isotopic signature of extraterrestrial material that stayed on Earth's surface for long periods of time and may pull their oxygen isotope values toward the TFL.

The oxygen isotope compositions of the two aggregates of meteoritic ablation spheres from the Transantarctic Mountains, samples #20c.25 and #20c.351, are plotted in a $\Delta^{17}\text{O}$ versus $\delta^{18}\text{O}$ diagram (Fig. 4) along with the composition of the host detritus (this work), and of atmospheric oxygen and Antarctic ice from the literature to study the fractionation and contamination processes that affected the isotopic composition of the spherules during their formation in the atmosphere and storage in the micrometeorite trap.

The light-isotope enrichment (i.e., lower $\delta^{18}\text{O}$) of "host granite < 25 μm " (representative of the weathered bedrock material in the trap) compared to "host granite" (representing fresh bedrock detritus in the trap) likely due to the occurrence of weathering products like jarosite, gypsum, analcime, and alunite, is commonly

observed in the Transantarctic Mountain micrometeorite traps (Rochette et al. 2008; see the Results section). These hydrous minerals form by aqueous alteration from saline waters produced occasionally by the melting of snow and tend to shift compositions toward the oxygen isotope composition of the Antarctic ice. Fig. 3 and Table 1 show that the bulk composition of #20c.351 contains higher content of S, K, Fe, Cr, and Mn compared with #20c.25. Petrographic observation suggests that this is the result of the higher content of weathering products, mainly jarosite encrustations, in particle #20c.351 (Fig. 2). Thus the higher $\Delta^{17}\text{O}$ value of sample #20c.351 relative to #20c.25 observed in Fig. 4 indicates a higher degree of weathering and probably bedrock contamination. Increasing alteration in the trap thus broadly follows the line joining sample #20c.25 to sample #20c.351, with maximum alteration on the TFL (green arrow in Fig. 4). We therefore conclude that the least weathered and contaminated sample #20c.25 represents the best experimental approximation to the pristine bulk isotopic composition of the meteoritic ablation spheres. The latter should lay along the dashed segment of the green alteration line in Fig. 4, i.e., with $\Delta^{17}\text{O}$ values lower than that of sample #20c.25 ($\Delta^{17}\text{O} < -3.26\text{‰}$). Based on relative mineral abundances from synchrotron XRD analyses in the literature (van Ginneken et al. 2010) we calculate approximately 20 wt% contamination of terrestrial oxygen due to the occurrence of weathering products and bedrock crystals in the #20c.25 aggregate. This constrains the pristine bulk composition of the meteoritic ablation spheres to a $\Delta^{17}\text{O} \approx -3.9\text{‰}$ value as shown in Fig. 4. Based on this model of increasing alteration, the closer vicinity to the TFL of sample #20c.351 may account for a mixing with terrestrial bedrock and weathering products of about 85%, which is consistent with the observed larger proportion of weathering products compared with other samples (Fig. 2C) and to its bulk composition more contaminated by elements present in weathering products (Fig. 3; Table 1).

Based on a study of oxygen isotopic signatures of meteorite fusion crusts (i.e., close analogs to meteorites' ablation sphere), Clayton et al. (1986) suggested that the

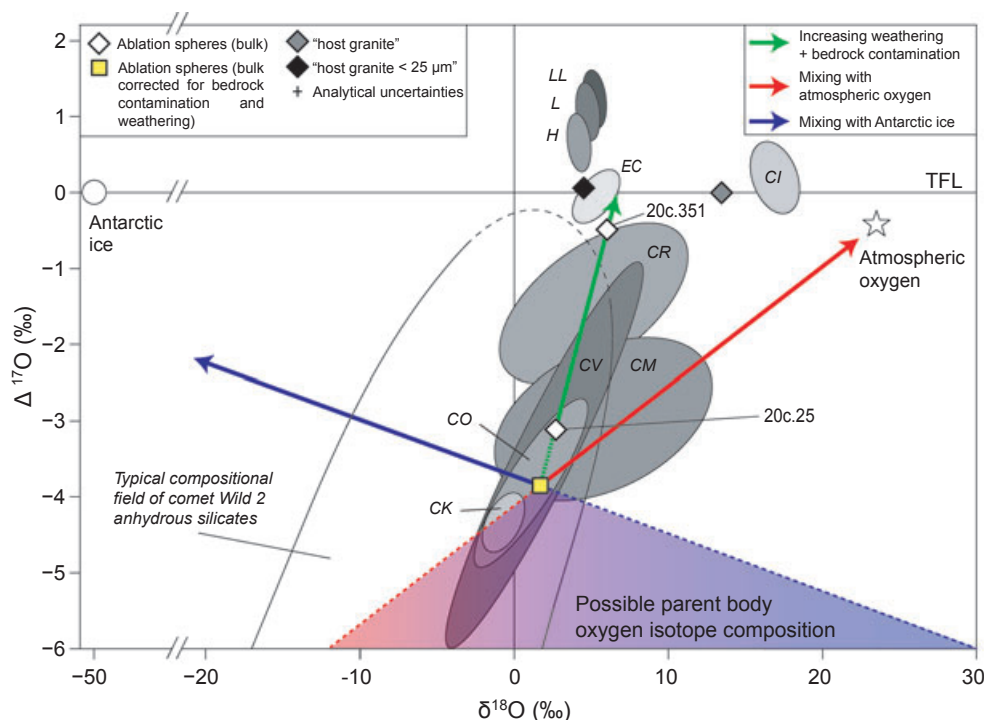


Fig. 4. $\Delta^{17}\text{O}$ versus $\delta^{18}\text{O}$ diagram (values in ‰ versus V-SMOW) for aggregates of meteoritic ablation spheres from the Transantarctic Mountains and of the host granite measured by IRMS (analytical uncertainties are $\pm 0.27\text{‰}$ for $\delta^{18}\text{O}$, $\pm 0.07\text{‰}$ for $\Delta^{17}\text{O}$; error bars are included in the diamond symbols). The solid green arrow joins the least (#20c.25) and the most weathered (#20c.351) samples of meteoritic ablation sphere aggregates and shows the compositional effects of increasing terrestrial weathering plus bedrock contamination during storage in the micrometeorite trap. The model bulk composition of the meteoritic ablation spheres corrected for weathering and bedrock contamination is shown at one end of the dashed green line (yellow square). The oxygen isotope composition of their precursor material lies in the red and blue shaded field, corresponding to compositions corrected for mixing with atmospheric oxygen (red arrow) and mixing with oxygen from Antarctic ice (blue arrow); namely dominant red and blue areas indicate prevalent mixing with atmospheric oxygen and prevalent mixing with Antarctic ice, respectively. The isotopic composition of atmospheric oxygen is $\delta^{18}\text{O} = 23.5\text{‰}$, $\Delta^{17}\text{O} = -0.4\text{‰}$ (Thiemens et al. 1995), that of Antarctic inland ice is $\delta^{18}\text{O} \approx -5\text{‰}$ (Jouzel et al. 2007). Bulk isotopic compositions of meteorites including CO, CV, CM, CR, and CI carbonaceous chondrites, H, L, and LL ordinary chondrites, and enstatite chondrites (EC) are shown for comparison (Clayton et al. 1991; Clayton and Mayeda 1999; Newton et al. 2000). The isotopic compositional field of anhydrous silicates from short-period comet 81P/Wild 2 is also displayed (McKeegan et al. 2008; Nakamura et al. 2008).

main process affecting the oxygen isotope composition of fusion crusts of stony meteorites during their formation is a direct mixing between extraterrestrial and atmospheric oxygen (Fig. 5). Furthermore, meteorite ablation spheres from the Transantarctic Mountains have chondritic Na_2O contents (from 0.39 wt% to 1.46 wt%; van Ginneken et al. 2010), similar to chondritic fusion crusts (Genge and Grady 1999). This suggests that evaporation and related mass-dependent isotopic fractionation during atmospheric entry should be negligible. The oxygen isotope composition of the precursor of the meteoritic ablation spheres is therefore mainly modified by mixing with terrestrial oxygen during melting in the atmosphere. In the present case, mixing can be discussed within the context of two plausible endmember impact scenarios (Engrand et al. 2010; Misawa et al. 2010; van Ginneken et al. 2010): mid-air explosion of the impactor (airburst) and direct impact

onto the Antarctic ice sheet, which was already in place at the time of the impact.

In the first case, ablation spheres would have formed within an impact plume dominated by atmospheric oxygen, in the second case in a plume of hot water vapor dominated by Antarctic ice oxygen. A plume of intermediate composition is also plausible if the shock wave produced by the airburst blasted and melted the surface of the Antarctic ice sheet. The oxygen isotope compositional field of precursor material of the Transantarctic Mountain ablation spheres therefore extends below $\Delta^{17}\text{O} < -3.9\text{‰}$ between the mixing lines with atmospheric oxygen and Antarctic ice as shown in Fig. 4.

Parent Body and Impact Scenario

Figure 4 shows the model isotope composition of the precursor material of the Transantarctic Mountain

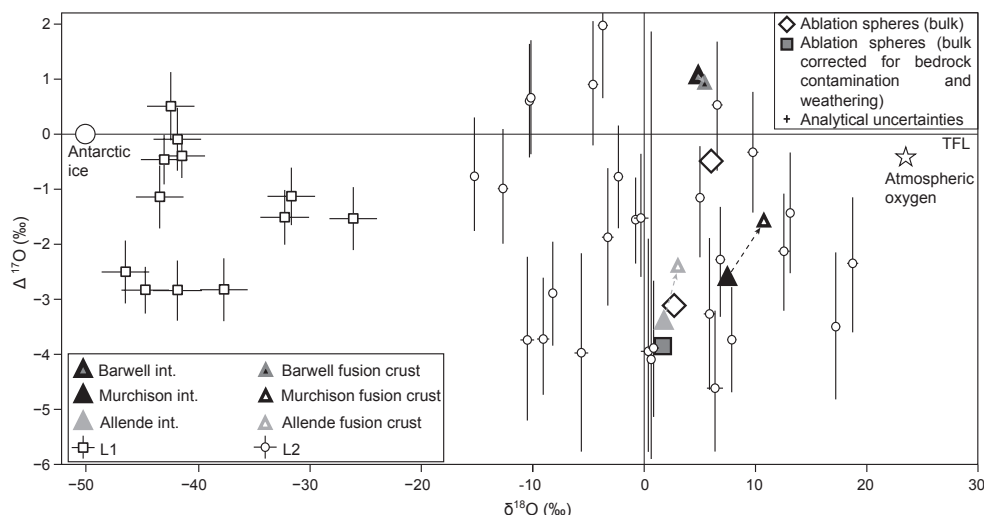


Fig. 5. $\Delta^{17}\text{O}$ versus $\delta^{18}\text{O}$ values (in ‰ versus V-SMOW) of individual meteoritic ablation debris particles from extraterrestrial dust layers DF2641, L1, and L2 from the Dome Fuji and EPICA-Dome C ice cores, respectively (data from Misawa et al. [2010] and Engrand et al. [2010], respectively; data for L2 have been graphically derived from Figs. 2 and 3 of Engrand et al. 2010); and from interiors and fusion crusts of chondrites Barwell (L6), Murchison (CM2), and Allende (CV3) (data from Clayton et al. 1986).

meteoritic ablation spheres along with known solar system objects of similar chondritic bulk composition. The model composition plots well below the TFL and partially overlaps the composition of the CV, CO, and CK carbonaceous chondrites (Clayton et al. 1991; Clayton and Mayeda 1999; Newton et al. 2000), as well as that of the anhydrous silicate fraction of short-period comet 81P/Wild 2 (McKeegan et al. 2008; Nakamura et al. 2008). This observation indicates that ordinary chondrite, enstatite chondrite, CR and CI carbonaceous chondrite parentages can be ruled out. It further suggests that the parent body of meteoritic ablation spheres was most likely a fragment of an asteroid of CV, CO, or CK carbonaceous chondritic composition, or a body similar to the short-period comet 81P/Wild 2 (Flynn et al. 2006), within a context of a dominant mixing with atmospheric oxygen. The fact that the model composition of the ablation spheres plots at the low $\Delta^{17}\text{O}$ extreme of the CM compositional field makes this parentage unlikely. Note that atmospheric exchange and kinetic isotope effects in the atmosphere may account for an approximately 8‰ variation in the $\delta^{18}\text{O}$ of fusion crusts of meteorites (Clayton et al. 1986). This may represent a possible shift for the Transantarctic Mountain meteoritic ablation spheres, which are close analogs to the fusion crusts of stony meteorites (van Ginneken et al. 2010).

Figure 5 shows that the oxygen isotopic composition of 17 individual dust particles from the EPICA-Dome C L2 layer vary widely with values ranging from $\delta^{18}\text{O} = -17.5\text{‰}$, $\delta^{17}\text{O} = -9.8\text{‰}$ to $\delta^{18}\text{O} = 20.1\text{‰}$, $\delta^{17}\text{O} = 8.2\text{‰}$ (Engrand et al. 2010). Based on this dataset, Engrand

et al. (2010) suggested a parent material of CM-CR-CV chondritic or cometary composition. The large scattering of $\delta^{18}\text{O}$ values was interpreted by both exchange with Antarctic ice (for low $\delta^{18}\text{O}$ values) and evaporation and/or mixing with this atmosphere (for high $\delta^{18}\text{O}$ values). Although the uncertainties on $\Delta^{17}\text{O}$ for L2 particles are important, the oxygen isotope composition of individual particles from L2 determined by Engrand et al. (2010) appear consistent with the bulk oxygen isotopic composition of the Transantarctic Mountain ablation spheres determined in this work. This evidence suggests pairing and strengthen previous hypothesis of a continental-scale distribution of the ablation debris of a major meteoritic event over Antarctica (Engrand et al. 2010; Misawa et al. 2010; van Ginneken et al. 2010). The oxygen isotope composition of the aggregates from the Transantarctic Mountains determined in this work can be considered the best experimental approximation to the bulk composition of the parent body of this major meteoritic event, as it is the average of a myriad of spherules. In turn, the wide compositional scatter of L2 particles, with positive and negative $\delta^{18}\text{O}$ values, suggests that individual particles formed within a heterogeneous and turbulent plume characterized by variable contents—in space and time—of atmospheric and Antarctic ice oxygen.

An important exchange with Antarctic ice oxygen suggestive of a major meteoritic impact on the Antarctic ice sheet is possibly recorded in the dust particles of the L1 EPICA-Dome C and DF2641 ice core layers and is associated with a more recent meteoritic event occurring approximately 430 kyr ago: $\delta^{18}\text{O}$ values in the L1 particles

are systematically depleted in heavy oxygen isotopes and do not vary widely (Fig. 5; Misawa et al. 2010). This is not the case for L2 particles. Furthermore, if L2 particles and the Transantarctic Mountains meteoritic ablation spheres resulted from a direct impact on the ice sheet, thus showing an important depletion in heavy oxygen isotopes of similar amplitude as for L1 particles, the parent body should have an oxygen isotope composition that is not observed among known objects in the solar system (Fig. 4). The direct impact on the Antarctic ice sheet seems an unlikely scenario for the formation of the paired Transantarctic Mountain and L2 ablation spheres, thus favoring an airburst similar to the 1908 impact over Tunguska, Siberia. Also, as previously suggested by van Ginneken et al. (2010), an atmospheric airburst would better explain the continental distribution of the impactor debris.

Models of meteoritic impact in the Earth's atmosphere suggest that a 10^8 kg carbonaceous chondrite (i.e., minimal mass of the impactor responsible for the meteoritic ablation spheres estimated by van Ginneken et al. 2010) would produce an airburst at an altitude of about 15 km (Bland and Artemieva 2006) and short-period comets with a mass of the same order would produce an airburst at an altitude of about 25 km (Chyba et al. 1993). At these altitudes, models show that an airburst produces a plume of extraterrestrial debris that stops before reaching the ground and is ejected into the upper atmosphere along a rarefied entry column. The plume subsequently expands laterally at an altitude of about 100 km over an area of thousands of kilometers and then falls out due to gravitational drag (Boslough and Crawford 1997; Shuvalov and Artemieva 2002).

CONCLUSION

Combining high-precision IRMS oxygen isotope study and literature data, we conclude that the meteoritic ablation spheres found in the Transantarctic Mountains and in the L2 Dome C and DF2691 Dome Fuji ice core layers are the microscopic debris of a high-altitude (> 15 km) atmospheric airburst of a cosmic body several tens of meters in size or larger (i.e., at least 10^8 kg), which impacted Earth's atmosphere over Antarctica approximately 480 kyr ago. The impactor was most likely an asteroid of CV, CO, or CK composition or a comet with composition similar to that of the short-period comet 81P/Wild 2.

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article

Data S1: X-ray diffraction (XRD) patterns for samples “host granite <25 μm ” and #34.01.

Fig. S1: X-ray diffraction (XRD) of the sample “host granite <25 μm .”

Fig. S2: X-ray diffraction patterns (background subtracted) for the meteoritic ablation sphere aggregates

#34.01(red) and #20c.25 (blue; van Ginneken et al. 2010). As discussed in the text, the similar patterns and major peaks, intensity suggest, apart for the terrestrial jarosite, similar mineralogy and relative mineral abundances.

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