First discovery of meteoritic events in deep Antarctic (EPICA-Dome C) ice cores

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[1] Two distinct dust layers in the EPICA-Dome C ice core (75°06′S, 123°21′E, East Antarctic Plateau) have been shown to relate to individual meteoritic events. Particles forming these layers, investigated by electron microprobe, show peculiar textural, mineralogical and geochemical features and closely resemble extraterrestrial debris in deep-sea sediments and polar caps. Preliminary estimates of cosmic debris input at the studied layers, obtained from Coulter Counter measurements, are 4–5 orders of magnitude greater than the yearly micrometeorite flux in East Antarctic snow and ice. The cosmic events are accurately dated through glaciological models at 434 ± 6 and 481 ± 6 ka, respectively and are located in the core climatic stratigraphy near the "Mid-Brunhes Event". This is the first report of well-dated cosmic horizons in deep Antarctic ice cores. It significantly improves the extraterrestrial record of Antarctica and opens new correlation perspectives between long climatic records of the South polar region. **Citation:** Narcisi, B., J. R. Petit, and C. Engrand (2007), First discovery of meteoritic events in deep Antarctic (EPICA-Dome C) ice cores, *Geophys. Res. Lett.*, *34*, L15502, doi:10.1029/2007GL030801.

1. Introduction

[2] Cosmic particulate matter in the form of interplanetary dust and micrometeorites constantly reaches the Earth surface and is found disseminated in diverse terrestrial deposits [e.g., *Blanchard et al.*, 1980; *Koeberl and Hagen*, 1989]. This material represents the dominant fraction of the present-day extraterrestrial flux [e.g., *Taylor et al.*, 2000] and its study provides information on solar system formation and evolution [*Brownlee*, 1985]. Traces of collisions having regional significance (e.g. impact craters and related ejecta sediments, conspicuous micrometeorite showers caused by passage of large meteoroids or comets) are greatly scattered in the geologic record [e.g., *Grieve*, 1997]. Nonetheless, their detection and study are very important to provide isochronous markers for stratigraphic correlations, and to address issues on future events and related environmental effects [e.g., *Toon et al.*, 1997].

[3] The Antarctic region represents the best site to collect small meteoritic particles because terrestrial input from surrounding deserts is very low [e.g., *Delmonte et al.*, 2002] and extreme environmental conditions prevent chemical weathering. Numerous characterization studies have been carried out on micrometeorites recovered from various Antarctic sites [e.g., *Maurette et al.*, 1991; *Taylor et al.*, 2000]. Recently, a new micrometeorite project has been launched at the permanent French-Italian station of Concordia, on the East Antarctic Plateau, where low accumulation rates allow collection of microparticles from reduced quantities of snow [*Duprat et al.*, 2005]. The bulk of previous and current Antarctic investigations focus on contemporary and recent continuous cosmic dust deliveries, which are incorporated in surface snow/firn layers, or the investigations focus on particle concentrations from blue ice and glacial sediments of unknown age. Little is known about microparticles in old dated Antarctic ice sections, although very valuable documentation on extraterrestrial steady fall and/or individual events is certainly archived in such ancient records [*Harvey et al.*, 1998; *Yada et al.*, 2004].

[4] Deep ice cores from the East Antarctic Plateau offer excellent opportunities to investigate past cosmic dust falls. This is because the recovered ice record (1) is continuous and extends back to several hundreds of thousands of years, (2) is stratigraphically coherent and not affected by ice flow disturbances, and (3) is provided with various paleoclimatic datasets and accurate age scale [e.g., *EPICA Community Members*, 2004], allowing for a reliable reconstruction of past accretion. However, so far, very limited work has been done on cosmic debris in deep East Antarctic cores [e.g., *Yiou et al.*, 1991].

[5] The aim of this paper is to document for the first time two extraterrestrial events from Middle Pleistocene sections of the EPICA-Dome C ice record, East Antarctic Plateau (75°06′S, 123°21′E). We show that these events occur as distinct dust layers consisting of cosmic debris with characteristic features. Since both events are precisely set into the detailed core chronostratigraphic record, we discuss the implications of our findings particularly for linking and dating of southern Hemisphere climatic records.

2. Materials and Methods

[6] The EPICA (European Project for Ice Coring in Antarctica) Dome C ice core, drilled down to 3260 m, has provided a continuous climatic record over the last eight glacial cycles, ca. 800 ka (Figure 1) [e.g., *EPICA Community Members*, 2004].

[7] The Dome C ice is generally very clear and the core contains less than twenty visible dust layers. The majority of these layers occur in the uppermost 2200 m and are composed of airborne volcanic ash produced by explosive

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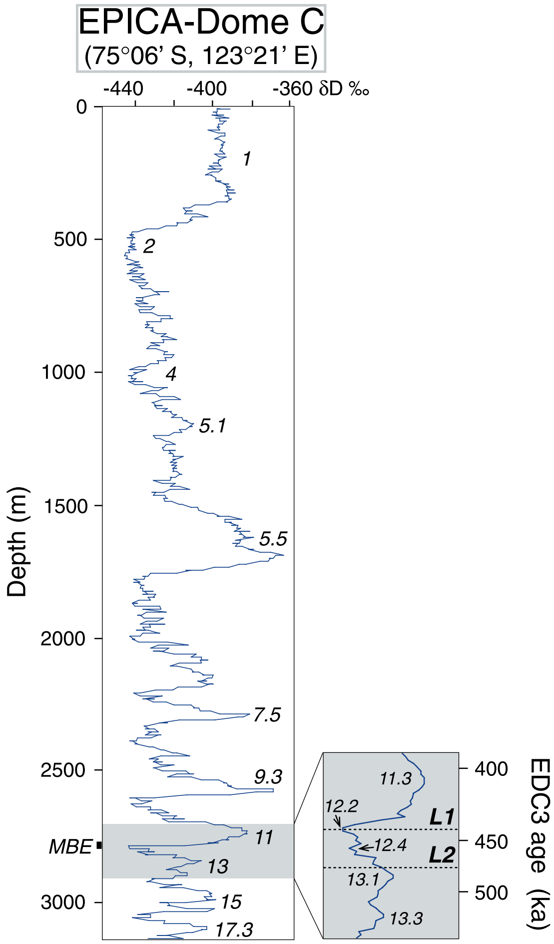

Figure 1. EPICA-Dome C δD record, which is a temperature proxy, with a few marine isotope stage numbers and the position of Mid-Brunhes Event (MBE) indicated [*EPICA Community Members*, 2004]. The box shows the stratigraphic position of studied layers (dashed lines). EDC3 core timescale is from *Parrenin et al.* [2007].

eruptions [*Narcisi et al.*, 2005]. The two discrete dust layers studied here lie at depths of 2788 and 2833 m, respectively (Figure 1). They were identified during core inspection and logging at Dome C and the related ice sections were analyzed in the field for their electrical properties [*Stauffer et al.*, 2004]. Both layers (hereafter L1 and L2) are visually very similar to tephra layers, i.e. they appear as dark, slightly undulated distinct strips with thickness in both cases of a few mm. Fine-scale laminations occurring in both layers could be to due eolian reworking prior to burial or more likely to ice stretching, as is also suggested by anomalies in the thinning function in the bottom 500 m of the core [*Parrenin et al.*, 2007]. The dust layers are precisely framed into the Dome C core chronostratigraphic record (Figure 1). L1 lies at the end of a cold period corresponding to Marine Isotope Stage (MIS) 12; based on the newly developed EDC3 core timescale [*Parrenin et al.*, 2007] its age is 434 ± 6 ka. L2 lies in late part of the interglacial MIS 13 and has an EDC3 age of 481 ± 6 ka.

[8] We have characterized the grain size, morphology, texture and composition of dust particles from both layers in order to assess their origin. The narrow core sections containing the two layers were processed in a class 100 clean room. After decontamination with deionized water and ice melting, grain size measurements were performed using a 256-channel Coulter Counter (for analytical procedures see *Delmonte et al.* [2002]). The particulate matter was recovered by filtration at 8 and 0.4 μm pore size and two or more filters per layer were prepared. Unpolished filters were used for particle external morphology and semi-quantitative major element analysis by scanning electron microscope equipped with an energy dispersive X-ray spectrometer (SEM-EDS). Filters embedded in epoxy resin and polished with microdiamond paste were used for examination of particle interior textures by SEM-EDS and for bulk quantitative elemental analysis by wavelength-dispersive X-ray spectrometry (WDS). For WDS microprobe working conditions see *Narcisi et al.* [2005]. Tens of particles were analyzed from each dust layer (Table 1).

3. Results and Interpretation

[9] Grain size measurements, and optical and electron microscope observations revealed that both layers consist of

Table 1. Major Oxide Composition of Particles in the EPICA-Dome C Dust Layers[a]

	Layer L1			Layer L2		
n	WDS Interior 22	EDS Surface 82	EDS Interior 25	WDS Interior 25	EDS Surface 46	EDS Interior 24
SiO_2	35.77 ± 2.24	1.8–56.8	9.9–42.3	31.40 ± 6.19	11.6–47.6	11.4–52.3
TiO_2	0.04 ± 0.02	bdl-1.7	bdl-0.5	0.10 ± 0.05	bdl-0.4	bdl-0.6
Al_2O_3	1.06 ± 0.87	bdl-8.4	bdl-7.4	1.89 ± 1.25	0.4–7.5	bdl-8.8
Cr_2O_3	0.38 ± 0.21	na	bdl-4.1	0.45 ± 0.22	na	bdl-4.1
FeO	27.94 ± 6.10	14.1–94.7	12.6–76.2	28.55 ± 9.50	16.4–74.6	6.8–70.0
MnO	0.35 ± 0.07	bdl-1.3	0.1–1.1	0.26 ± 0.06	bdl-1.0	bdl-0.4
MgO	29.95 ± 6.83	bdl-43.2	3.1–43.6	24.01 ± 8.82	4.3–39.6	4.4–43.9
CaO	0.81 ± 0.65	bdl-10.6	0.2–3.3	1.52 ± 1.09	0.2–6.8	0.2–5.5
Na_2O	0.25 ± 0.15	bdl-3.0	bdl-1.8	1.36 ± 1.33	bdl-4.6	bdl-6.1
K_2O	0.03 ± 0.02	bdl-0.9	bdl-0.3	0.06 ± 0.04	bdl-1.5	bdl-0.4
NiO	1.45 ± 0.66	bdl-10.5	0.3–3.3	1.82 ± 0.65	bdl-7.3	0.3–3.7
SO_3	0.38 ± 0.25	na	bdl-2.2	0.15 ± 0.10	na	bdl-2.0
Total	98.40 ± 2.32	100	100	91.58 ± 10.53	100	100

[a]Composition by either WDS (broad-beam analysis) or EDS (point analysis) microprobe is given as wt%, where *n* is the number of analyses from different particles. WDS data are presented as mean and standard deviation. EDS data are presented as range and are normalized to 100%. Total iron reported as FeO. bdl: below detection limit; na: not analyzed.

dark brown/black angular and rounded grains of large size (see auxiliary material).[1] SEM observations on the coarser particles indicate that sample L1 shows maximal grain size of ca. 100 μm. It is mostly composed of angular compact olivine particles, showing at times tiny metal inclusions. This sample also contains a minor proportion of spherical and angular particles, which are ca. 10 μm in size or larger and show internal porphyritic texture. Sample L2 has a modal value of the volume-size distribution of ca. 7–12 μm (Figure 2). Under the microscope, the coarser fractions consist mostly of spherical particles up to 25 μm in size, which are mostly glassy with magnetite dendrites (see auxiliary material). A minor grain population consists of olivine and pyroxene crystals with metal inclusions. They have angular shapes and sizes larger than the spheres (typically 30–40 μm, up to ca. 60 μm). Angular grains in layer L2 also include fragments of spheroidal particles with pronounced dendritic textures. Typical eolian dust (feldspars, quartz) in both samples is negligible and confined in the 2–3 μm size fraction.

[10] Microprobe analyses indicate that L1 and L2 are geochemically comparable to each other (Table 1 and Figure 3), suggesting a similar origin. Defocused beam WDS elemental composition of particle interiors from both layers is dominated by O, Si, Mg and Fe, with low contents of Al and Ca, and very low proportions of K and Ti and Ni and Cr commonly observable. EDS microprobe data on both particle surfaces and interiors display wide variations because they include point analyses from various mineral components and from glass, however they are broadly consistent with WDS values.

[11] The obtained results strongly suggest that the particles forming both studied layers have an extraterrestrial origin. The observed "coarse" grain size is not coherent with eolian deposition, since mineral aerosol input in East Antarctic ice is typically around 2 μm [*Delmonte et al.*, 2002] (Figure 2). Such grain size is in the range of airborne volcanic ash reaching the Antarctic interior [*Narcisi et al.*, 2005] (Figure 2), however neither shapes or geochemistry of the studied particles match features of Antarctic tephra layers (Figure 3). Spherical shapes are suggestive of melting processes during atmospheric entry and internal textures of the studied spheres, characterized by magnetite networks enclosing silicate glass, are a distinctive feature of cosmic spherules from various sites [e.g., *Blanchard et al.*, 1980; *Koeberl and Hagen*, 1989]. Porphyritic textures and mineral assemblages of the angular particles are consistent with unmelted and partially-melted micrometeorites at various terrestrial locations [e.g., *Beckerling and Bischoff*, 1995]. A volcanic origin can be excluded because englacial tephra layers in distal East Antarctic sites are almost devoid of phenocrysts [*Narcisi et al.*, 2005]. Therefore, the observed mafic crystals with tiny metal inclusions are relicts of the precursor body that were not completely melted during passage through Earth's atmosphere. Finally, the obtained "chondritic" elemental composition is well comparable with various collections of cosmic particles and rule out either a volcanic or a continental nature of the studied grains (Figure 3). The elemental abundances do not fit those of microtektites (Figure 3), indicating that the L1 and L2 Dome C particles are truly cosmic debris produced from meteoroid entry into the atmosphere, and not impact ejecta.

[1]Auxiliary materials are available in the HTML. doi:10.1029/2007GL030801.

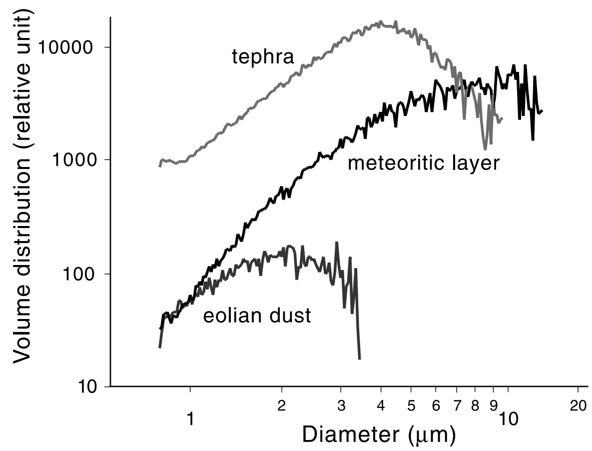

Figure 2. Volume-size distribution of meteoritic layer L2 compared to typical tephra and eolian dust samples from the EPICA-Dome C core. In the meteoritic layer, 19,822 particles with diameter larger than 0.7 μm were counted. 1700 particles have a diameter larger than 5 μm, and 398 larger than 8 μm. Less than 3 particles were counted for sizes larger than 13 μm.

[12] From particle concentration obtained by Coulter Counter measurements of the 0.7–13 μm fraction, we estimate a micrometeorite input at the event forming L2 of ca. 0.3 g m^{-2}. A similar value can be expected also for the other studied event, since the two layers show comparable thickness and granulometry. This debris amount is 4 orders of magnitude greater than the yearly contemporary micrometeorite flux recorded at Dome C for particles larger than 30 μm (ca. 0.01 mg m^{-2}) [*Duprat et al.*, 2006] and 4–5 orders of magnitude greater than the annual cosmic particle input in East Antarctic ice during the last 200 ka (from ca. 0.003 to ca. 0.05 mg m^{-2}) [*Yiou et al.*, 1991; *Yada et al.*, 2004].

4. Discussion and Conclusion

[13] Cosmic dust allows the deduction of the composition of primitive solar system material, estimate the accretion rates of extraterrestrial matter, and establish stratigraphic correlations. The latter purpose can be achieved if particles are related to single depositional events. In this respect, the copiousness of cosmic debris, which is confined within the studied layers and is not mixed with significant extraneous (i.e. terrestrial) matter, already suggests relation to individual meteoritic falls rather than to steady input. Our findings are clearly different from previous micrometeorite records in Antarctic cores, which were related to a few cosmic microparticles from large ice sections [*Yiou et al.*, 1991]. In addition, the ice core stratigraphy is continuous and undisturbed [*EPICA Community Members*, 2004], leading to exclude selective secondary concentration of cosmic particles of normal continuous fall from surrounding ice. Surface phenomena at the EPICA site can influence the ice record only at a year timescale [*Barnes et al.*, 2006]. Therefore, the possibility of a hiatus of snow accumulation

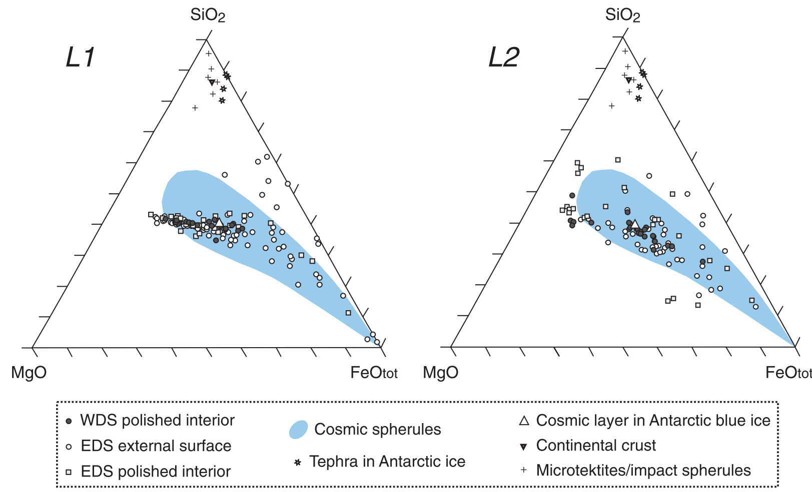

Figure 3. Comparison of grain-specific chemical analyses from this study with Greenland/deep sea cosmic spheres [*Maurette et al.*, 1986], tephra layers in Antarctic ice [*Narcisi et al.*, 2005], cosmic layer detected in Victoria Land blue ice [*Harvey et al.*, 1998], average composition of the continental crust [*Wedepohl*, 1995], and Australasian microtektites/impact spherules [*Glass et al.*, 2004].

for a time interval sufficient to concentrate the constant micrometeorite deposition in a discrete layer (using the above input estimate this interval would be at least a few thousands of years) is ruled out. We therefore conclude that both layers represent individual meteoritic events. In both cases, the debris produced by meteoroid disruption fell out onto the Dome C surface and then became part of the ice record with no significant stratigraphic displacement.

[14] Considering that micrometeoritic fallout in ancient Antarctic ice is largely undocumented, and that fall events are uncommon phenomena in the Earth record, our detection of two distinct Middle Pleistocene events at one site and within a short geological time interval (ca. 50 ka) is an outstanding finding. Our unexpected discovery provides the first evidence of meteoritic events in Antarctic ice cores and represents a major step towards reconstruction of extraterrestrial stratigraphic record of the Antarctic continent, which is to date largely unknown.

[15] Astrophysical implications of our findings will be discussed elsewhere. Here we focus mainly on potential implications for correlation purposes. The two meteoritic horizons show distinctive particle features and lie in precise chronostratigraphic positions within the core climatic record (Figure 1). Therefore, similarly to airborne volcanic ash layers, they form valuable marker beds for independent link and dating of stratigraphies from different sites. Depending on the scale of the identified events (local meteorite showers or large events of regional scale), our discovery can enhance correlation perspectives between long Antarctic ice climatic records and even circumpolar sequences. In this respect, note that the Dome C events are stratigraphically located in the vicinity of the so-called Mid-Brunhes Event (MBE), roughly corresponding to the transition between MIS 12 and MIS 11 (Figure 1), which marks a notable amplitude and duration change of climate cycles with respect to the previous periods [e.g., *EPICA Community Members*, 2004]. The cosmic horizons could be used to unambiguously compare South polar climatic archives from different realms across this peculiar transition [e.g., *Hodell et al.*, 2003], and therefore help clarify the causes of the Event. The occurrence of micrometeorite horizons close to this distinct climate change may also renew the debate on a possible relationship between climate and extraterrestrial dust accretion [*Muller and MacDonald*, 1997], although the presented data certainly are not sufficient to draw any conclusion. Lastly, meteoritic debris is suitable for radioisotope dating [*Nishiizumi et al.*, 1989], however the high uncertainties on cosmogenic terrestrial ages of Middle Pleistocene material (typically several tens of thousands of years) limit interest in the application of such dating methods to the studied layers.

[16] From preliminary examination of known extraterrestrial events in the southern Hemisphere, there are no suitable counterparts of the Dome C events. The Eltanin impact (ca. 2.15 Ma) [*Gersonde et al.*, 1997], the event responsible for the Australasian microtektite layer (ca. 0.8 Ma) [e.g., *Glass et al.*, 2004], and the 2.3–2.7 Ma meteoritic event recorded in Victoria Land blue ice [*Harvey et al.*, 1998] are too old to be related. Impact events in Australia and South Africa do not show matching ages [*Haines*, 2005; *Reimold et al.*, 1998] and the 445-ka Argentinean event [*Schultz et al.*, 2004] most likely was not large enough for connection with Dome C layers.

[17] In conclusion, although magnitude and geographic extent of detected events are not known, the new EPICA-Dome C findings significantly increase knowledge on Antarctic meteoritic events in geological times and provide unique time-synchronous markers for potential stratigraphic correlations in the South polar region. More generally, the long Antarctic ice records are mines of detailed geological information and our discovery confirms their extraordinary capacity to archive environmental facts of the various types.

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