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Atmospheric ^{10}Be from Talos Dome (East Antarctic) ice core records geomagnetic dipole intensity from 170 to 270 ka BP

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Abstract. We present high-resolution ^{10}Be concentration and flux records from the Talos Dome ice core (East Antarctica), covering the period from 170 to 270 ka BP, to assess the capacity of Antarctic ice cores to capture the dipole moment reductions triggered by geomagnetic excursions of different amplitudes. Three distinct geomagnetic events are identified in the ^{10}Be flux. The dipole collapse linked to the Iceland Basin Excursion (IBE) is clearly recorded as a ^{10}Be peak flux 1.59 to 2.08 times above background between (192.0 ± 1.4) ka BP and (185.6 ± 1.4) ka BP. A clear asymmetric structure is observed, with a rapid decline of the geomagnetic dipole, followed by a three-step recovery. Two dipole decreases of lower amplitude are also resolved in relation with the Pringle Falls Excursion (PFE), lasting from (218.5 ± 1.90) to (206.0 ± 0.8) ka BP, and the Mamaku Excursion (ME), identified at (242.0 ± 0.3) ka BP, both showing an increase of the ^{10}Be flux by a factor of 1.24 to 1.63. A total of 52 short-term ^{10}Be concentration minima were also identified and are consistently associated with peaks in major ion concentrations, indicating post-depositional effects that affect concentration but not the longer-term flux signal. Comparison with Dome Fuji ice core and oceanic authigenic $^{10}Be/^{9}Be$ records reveals strong agreement in the timing and structure of the dipole moment collapses linked with these excursions. These results further support the use of ^{10}Be for synchronizing ice and marine archives as well as to reconstruct past geomagnetic dipole moment variations and refining age models over the Pleistocene.

1 Introduction

The intensity of the geomagnetic dipole has varied over geological timescales. Among these variations, full geomagnetic reversals as well as incomplete or short-lived reversals, commonly referred to as excursions, are of particular interest for studying the dynamics of the geomagnetic dipole moment (GDM). Recent models suggest that the GDM fluctuations can be explained by stochastic variations in heat transfer between the Earth's core and mantle (e.g. Molina-Cardín et al., 2021).

https://doi.org/10.5194/egusphere-2025-5707
Preprint. Discussion started: 25 November 2025

However, geodynamo may also exhibit deterministic but chaotic behaviour (Gissinger, 2012; Müller et al., 2025; Ryan and Sarson, 2007) – that is, governed by nonlinear physical laws but highly sensitive to initial conditions. Recurrent features observed in paleomagnetic records support this view, implying that the apparent stochasticity of GDM variations may partly emerge from underlying deterministic dynamics. Nevertheless, this stochastic assumption remains a pragmatic first-order approximation due to the complexity of modelling the geodynamo and the sparse, indirect, and occasionally conflicting observational data. Ultimately, progress in understanding the chaotic behaviour of the geodynamo hinges on the availability of reliable, high-resolution, synchronous, and cross-validated records of GDM variations, as this study aims to report between 170 ka BP and 270 ka BP.

Paleomagnetic excursions are the most common manifestations of these large amplitude variations of the GDM. Unlike secular variations – for which the virtual geomagnetic pole (VGP) motion within a cone of 45° around the geographic pole – paleomagnetic excursions consist in large amplitude, though transient, departures of the virtual geomagnetic pole beyond 45° away from the Earth rotation axis. Such events have been reconstructed from paleomagnetic studies of various geological archives such as volcanic sequences (Champion et al., 1988), marine (Valet and Meynadier, 1993) and lacustrine sediments (Oda et al., 2002). In both excursions and full reversals, the intensity decreases (resp. recovery) precede the directional departure (resp. recovery) (ref). When recorded from various and distant sites for the same event, these large amplitude intensity variations express the decrease and the increase of the GDM, concomittent with the VGP migration.

The Iceland Basin Excursion (IBE, naming and dating of the event is discussed in section 2.1), dated to approximately 190 ka BP, is probably the strongest excursion during the Bruhnes chron (< 780 ka BP) (Simon et al., 2016) and has been recorded in the Icelandic basin sediment as a full but transient reversal (Channell et al., 1997). Dipole intensity reduction has been estimated between 70 % (Yamamoto et al., 2010) and 80 % (Simon et al., 2020). Such a significant collapse indeed reaches the threshold of full reversal (Valet et al., 2008), making the IBE ideal to understand GDM variations. Additionally, the intensity and global detectability of IBE make it optimal for archive synchronisation (e.g., Leduc et al., 2006), particularly between sediment and ice core records, where the phase relationship appears minimal (Horiuchi et al., 2016; Simon et al., 2016).

Cosmogenic radionuclides, such as beryllium-10 (^{10}Be), offer a valuable proxy for reconstructing geomagnetic intensity changes. Produced in the atmosphere, particularly in the stratosphere (60 to 66 % (Golubenko et al., 2022; Poluianov et al., 2016; Zheng et al., 2024)), ^{10}Be mainly results from spallation reactions between galactic cosmic rays and atmospheric oxygen and nitrogen atoms (Poluianov et al., 2016). As the flux of highly energetic particles is modulated by GDM strength, ^{10}Be atmospheric production, and subsequent deposition into archives, is correlated with the Virtual Axial Dipole Moment (VADM) intensity (Carcaillet et al., 2004; Simon et al., 2016). The concentration of ^{10}Be in paleoarchives can thus provide records of the dipole moment variations, that can be compared with relative paleointensity studies. While sediment records provide long temporal coverage spanning several Ma (Valet et al., 2025), they may be affected by oceanic circulation (Savranskaia et al., 2024) and sedimentary remobilization (Savranskaia et al., 2021), complicating ^{10}Be-based interpretations. In contrast, ice core

https://doi.org/10.5194/egusphere-2025-5707
Preprint. Discussion started: 25 November 2025

^{10}Be records offer more direct and temporally resolved signals, though they may be altered by snow accumulation variability (e.g., Yiou et al., 1985) and post-depositional processes (e.g., Kappelt et al., 2025; Raisbeck et al., 2006).

As efforts intensify to develop robust dating tools for oldest Antarctic ice (Wolff et al., 2022), potentially extending beyond 1.5 Ma (Chung et al., 2025), cosmogenic nuclide records have gained prominence not only for reconstructing GDM variations, but also for enabling stratigraphic correlations between sediment and ice core archives. To date, few studies have explored geomagnetic excursions in ice cores, and those that do typically focus on high-amplitude events such as the Laschamps (≈41 ka BP (Raisbeck et al., 2017)) and the IBE (Horiuchi et al., 2016). Here, we investigate the capacity of ice cores to capture both high- and low-amplitude excursions, respectively the IBE and the Pringle Falls also named Mamaku or Jamaica, by presenting the longest ^{10}Be record from an ice core currently available. Our ^{10}Be record from Talos Dome (East Antarctica) is compared with the IBE record from Dome Fuji (Horiuchi et al., 2016), as well as with sedimentary records based on authigenic ^{10}Be/^{9}Be. In this context, we assess the fidelity of ice core ^{10}Be as a reliable paleomagnetic proxy and synchronise ocean and ice archives over the 170 ka BP – 270 ka BP interval.

2 Excursions between 170 and 250 ka BP: a review

Between 170 ka BP and 250 ka BP, several geomagnetic excursions have been reported (Figure 1) with different names, sometimes referring to the same event. In order to help the reader understanding this confusing literature, we provide a short overview.

2.1 The 190 ka BP excursion

The geomagnetic excursion dated to ≈190 ka BP, now widely referred to as the Iceland Basin Excursion (IBE), is considered one of the most significant geomagnetic events of the Brunhes Chron (Simon et al., 2016). One of the first attempts to date this excursion with high confidence came from lava flows, notably in the Snake River Plain (Idaho, USA). Champion et al. (1981, 1988) reported transitional paleomagnetic directions in multiple flow units, including Site E in Idaho, and proposed a Potassium-Argon (K-Ar) age of (188 ± 8) ka BP. They named this event the Jamaica excursion, based on terminology used in earlier literature (Ryan, 1972). This naming particularly persisted in the literature related to volcanology.

Subsequent studies began identifying concomitant excursions in marine sediment cores, particularly in the Pacific. Tauxe & Wu (1990) reported excursion-like signals from two cores on the Ontong Java Plateau (ERDC-89P and ERDC-113P), with age estimates around 190 ka BP. Around the same time, Valet and Meynadier (1993) published data from ODP Sites 848 and 851 showing an excursion between 180 and 200 ka BP, which they tentatively linked to the Jamaica event described by Champion et al. (1981, 1988). Records from the western equatorial Pacific also reported an excursion around that age identified in cores NP5, NP7, NGC16, and NGC29 (Yamazaki and Ioka, 1994), later extended to NP35, NGC36, and NGC38 (Yamazaki et al., 1995).

https://doi.org/10.5194/egusphere-2025-5707
Preprint. Discussion started: 25 November 2025

Highly-resolved analyses of North Atlantic sediment cores confirmed the existence of a short, high-amplitude, and global excursion around 190 ka BP (Weeks et al., 1995), that was associated to the Jamaica event, referring to Champion et al., (Champion et al., 1988). Other sites further supported these conclusions including a suite of eight cores from the Indian and Western Pacific Oceans (Guyodo and Valet, 1996), three cores from the Acores regions (Lehman et al., 1996), and from Northwest Pacific (Roberts et al., 1997). The name Iceland Basin Excursion was formally introduced in 1997 based on high-resolution magnetic studies of sediment core collected from the Iceland Basin, ODP sites 983 and 984 (Channell, 1999; Channell et al., 1997). Both sites of the Iceland Basin revealed a short full reversal event at ≈186–189 ka BP with magnetization components rotating through 180° and back, in coincidence with a relative paleointensity (RPI) low of approximately 3 ka. These records as well as the other studies from that region (listed below), led to widespread adoption of the term Iceland Basin Excursion.

Since 1997, numerous studies have reported the IBE across a wide range of archives and locations. Here, we provide a non-exhaustive list of these observations. IBE has been robustly documented at multiple ODP sites along the Western and Eastern North Atlantic: Sites 1061, 1062, and 1063 (Channell et al., 2012; Christl et al., 2010; Knudsen et al., 2008; Laj et al., 2006; ODP Leg 172 Scientific Party et al., 1998, p.172), as well as at Sites 980, 984, and 919 (Channell, 2006, 1999; Channell and Raymo, 2003). Additional detections were reported from the Labrador basin (Stoner et al., 1998), Western and Equatorial Pacific cores (Gee et al., 2000), Lake Baikal (Demory et al., 2005; Oda et al., 2002), Southern Ocean (Stoner et al., 2003), the Portuguese margin (Thouveny et al., 2004), and the Irminger Basin and on the Eirik Drift (Evans et al., 2007). IBE was first observed with authigenic ^{10}Be measurements from Portuguese margin marine cores MD95-2040 and MD95-2042 (Carcaillet et al., 2004; Knudsen et al., 2008). IBE was reported in a lava flow at Unzen Volcano (Japan) with a K-Ar age of (197 ±17) ka BP (Shibuya et al., 2007). Further establishing its global extent, the GDM low linked to IBE has also been observed in an Antarctic ice core with atmospheric ^{10}Be concentrations from Dome Fuji (Horiuchi et al., 2016). Because of its global characteristics, global stack compilations are representative of the collapse of GDM during IBE (Channell, 2014; Simon et al., 2016; Valet et al., 2020, 2024).

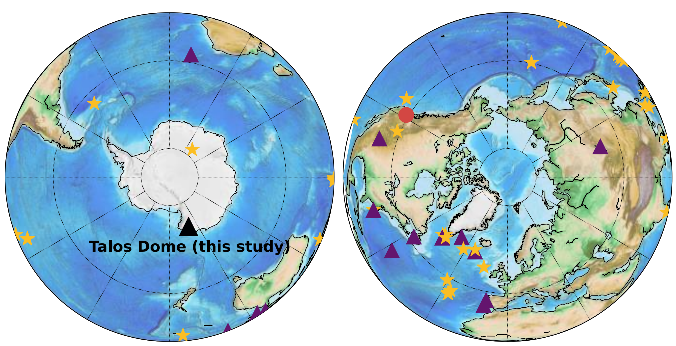

Figure 1: *map of sites recording at least one of the geomagnetic excursions discussed in this paper: the three excursions (triangles), IBE alone (stars), or PFE alone (circle).*

https://doi.org/10.5194/egusphere-2025-5707
Preprint. Discussion started: 25 November 2025

2.2 Excursion(s?) between 205 and 245 ka BP

Several geomagnetic excursions have been identified in the 205–245 ka BP interval, but their amplitude, naming end even number remain debated. Herrero-Bervera et al. (1994) provided one of the most comprehensive syntheses of a RPI low dated to (218 ± 10) ka BP with $^{40}Ar/^{39}Ar$ across multiple western U.S. sites: Pringle Falls – which gave its name to the event – and Summer Lake (Oregon), Mono Lake (Paoha Island), and Benton Crossing (Long Valley, California), although the first observation of a geomagnetic event around that age was probably observed in lava flows from Albuquerque (Geissman et al., 1990). Given dating uncertainties, some studies associated the Pringle Falls excursion to the Jamaica excursion (Langereis et al., 1997). In the Southern hemisphere, a prominent geomagnetic reversal was recorded in the Mamaku ignimbrite, erupted from the Taupo volcanic zone, New Zealand. This event has been dated using $^{40}Ar/^{39}Ar$ methods at (227 ± 8) ka BP (Houghton et al., 1995; Tanaka et al., 1996), with revised estimates at (223 ± 3) ka BP based on improved chronostratigraphy (Mcwilliams, 2001). Updated dating of the excursion recorded in Albuquerque lavas and Pringle Falls ash D – (218 ± 14) ka BP and (211 ± 13) ka BP, respectively – supported that all three sites (Albuquerque, Pringle Falls, Mamaku) likely recorded the same geomagnetic excursion, named Pringle Falls, and dated to (211 ± 13) ka BP (Singer et al., 2008).

However, sediment records complicated this interpretation. For instance, RPI minima were observed around 208 ka BP (Channell, 2006) and 238 ka BP (Channell et al., 2012) in Atlantic sediment cores. Besides, a long minimum is observed in the PISO stack between 208 and 221 ka BP, while a sharp, decoupled minimum is recorded around 238 ka BP (Channell et al., 2009). This led to question the existence of two, instead of a unique, 'Pringle Falls' excursions.

In this sense, the comparison of RPI and cosmogenic nuclide concentrations would solve this ambiguity. Between 200 and 215 ka BP, the RPI low correlates with a cosmogenic nuclide production enhancement (Simon et al., 2016), while a marked RPI low and a minor cosmogenic nuclide production enhancement occurs at ca. 236 ka BP (Simon et al., 2016). However, the latter has also been dated around (230 ± 12) ka BP in Mamaku lavas (Shane et al., 1994). Finally, a small amplitude RPI low has been observed around 250–255 ka BP concomitant with a clear enhancement in authigenic $^{10}Be/^{9}Be$ measured in two West Equatorial Pacific Ocean sediment cores (Simon et al., 2016). This event could correspond to the Calabrian Ridge 0 excursion (Mediterranean Sea, Langereis et al., 1997), the 8α excursion (IODP Leg 172 Sites 1060–1063, Lund et al., 2001), and the Fram strait excursion (Nowaczyk and Frederichs, 1999).

Consequently, a continuous, globally-representative and well-dated record like ice core ^{10}Be from Antarctica would provide valuable information to better understand low-amplitude excursions. However, until now, no study has discussed this double excursion. This literature synthesis supports a cautious approach for dating and identifying the Pringle Falls, Mamaku and Calabrian Ridge 0-like excursion(s?).

To give credit to all these previous studies we will give consensual names to the three excursions we study in this work: the Iceland Basin Excursion (IBE), the Pringle Falls-Excursion (PFE), and the Mamaku Excursion (ME), dated around 190 ka BP, 210 ka BP, and 240 ka BP, respectively.

https://doi.org/10.5194/egusphere-2025-5707
Preprint. Discussion started: 25 November 2025

3 Material and methods

3.1 Talos Dome ice core

Measurements of ^{10}Be have been performed in the Talos Dome ice core (TALDICE). Talos Dome is situated on the East Antarctic plateau (72°48'S, 159°06'E; 2316 m a.s.l., Figure 1), being particularly close to oceans (290 km from the Southern Ocean and 250 km from the Ross Sea) than other drillings like Epica Dome C (EDC) or Dome Fuji (DF) (Frezzotti et al., 2004). The drilling campaign reached 1,620 m, being 175 m above the bedrock (Crotti et al., 2021). It is worthnoting that the drilling was situated in a glacial valley, whose hills reach 1,550 m (Crotti et al., 2021).

The ice core was continuously sampled in sections of 20 cm (when possible) between 1470 m and 1499 m and between 1505 m and 1531 m. The outermost section of the ice core, dedicated to cosmogenic nuclide measurements, had been stored in clean polyethylene bags at -20°C in a cooling facility, close to CEREGE. As part of the LGO2i platform at CEREGE research institute (https://www.cerege.fr/en/equipment/technical-clusters/geochemistry-organic-inorganic-and-isotopic-2/), the ice samples were cut with a saw pre-decontaminated with ultrapure ice and the outermost 1 mm of ice was removed with a ceramic knife. Ice samples were always handled with clean nitrile gloves, and left to melt in glass beakers, covered with plastic film, at room temperature.

In order to compare with ^{10}Be fluxes from Dome C over the last century, 11 samples have been measured from TALDICE firn between 4.5 m and 10 m with a resolution of 50 cm.

3.2 Concentration measurements

3.2.1 Concentrations of ^{10}Be

Concentrations of ^{10}Be were obtained following the protocol developed in Raisbeck et al., (Raisbeck et al., 2006) and Baroni et al., (Baroni et al., 2011) and measurements were made on the French Accelerator Mass Spectrometer (AMS) national facility, ASTER (https://www.cerege.fr/en/equipment/laboratoire-national-des-nucleides-cosmogeniques/ams-aster/, Arnold et al., 2010) as part of the LN2C analytical platform.

On average, the 257 samples of approximately 20 cm corresponded to a mean mass of 121 g ($\pm$ 1σ = 10 g). After being cut, the samples were melted at room temperature. A 3 mL aliquot was taken for the measurements of major ions by ion chromatography for future studies on ^{36}Cl. A ^{9}Be carrier solution (10^{-3} g g^{-1} ™Scharlau) was added to each sample with a mean added mass of (0.253 ± 0.001) g, in order to set the $^{10}Be/^{9}Be$ ratio prior to any chemical reaction. Preconcentration and purification of Be samples was performed with cation exchange resins (Dionex AG 50W-X8) and eluted with 12 mL of HNO_3 (3M). Beryllium dihydroxide was subsequently formed adding 1.7 mL of NH_3 (28 %). The precipitate was rinsed twice with 15 mL of a NH_3/H_2O solution (500 mL H_2O/120µL of NH_3 (28%)) prior to be dissolved with 250 µL of HNO_3 (69 %). The beryllium nitrate solution was evaporated at 240°C in crucible. After the final pyrolysis step held at 900°C, the beryllium oxide powder was mixed with niobium powder (in approximately the same mass), and subsequently pressed into a copper cathode. The samples were subsequently measured on the ASTER AMS (Arnold et al., 2010). The $^{10}Be/^{9}Be$ ratio is normalized to the in-house standard that has a $^{10}Be/^{9}Be$ ratio of $(1.191 \pm 0.013) \times 10^{-11}$ at at^{-1} (Braucher et al., 2015) for a ^{10}Be half-life of (1.387 ± 0.012) Ma (Chmeleff et al., 2010; Korschinek et al., 2010).

In addition to the 257 samples, 13 blanks had been measured, made from 100 mL of ultra-pure water (18.2 MΩ cm), with a mean $^{10}Be/^{9}Be$ ratios of $(4.2 \pm 0.3) \times 10^{-15}$ at at^{-1}. In comparison, the $^{10}Be/^{9}Be$ sample ratio mean value is $(8.3 \pm 3.4) \times 10^{-14}$ at at^{-1}. Propagating the counting statistics and all uncertainties related to the chemical preparation and the sample measurements yielded a mean 2σ uncertainty of 6.8 % for the samples. Consequently, the mean ^{10}Be concentration was (2.51 ± 0.08) at g^{-1}.

3.2.2 Major ions

The concentrations of the major ions were measured by classical ion chromatography methods on discrete samples (Morganti et al., 2007). The latter were collected into sample vials using a melting device (Severi et al., 2015) connected to a fraction collector in the cold laboratory of the Alfred Wegner Institute in Bremerhaven. The melter was specifically designed in order to sample just the uncontaminated inner part of each ice core section discarding the possibly contaminated outer layers. The discrete samples were then shared for analysis among four different laboratories: University of Florence (Italy), BAS (Cambridge, United-Kingdom), IGE (ex-LGGE, Grenoble, France), and AWI (Bremerhaven, Germany). The ions measured by each laboratory on the discrete samples were 5 anions (Cl^-, $CH_3SO_3^-$ (MSA), F^-, NO_3^-, and SO_4^{2-}) and 5 cations (Na^+, NH_4^+, K^+, Mg^{2+}, and Ca^{2+}). Measurements were made with a mean resolution of 8 cm (maximum 17 cm). Details about blanks and calibrations are reported in Morganti et al. (2007).

The final dataset, obtained by merging the data from the four laboratories, was finally reprocessed by hand, removing outliers resulting from probable contamination events. In the end, between 1470 and 1531 m, post-processing resulted in the withdrawal of 0 %, 19 %, 3 %, 0 %, 0 %, 2 %, 1 %, 0 %, 0 %, and 0 % of the total sample depths for Na^+, NH_4^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, MSA, F^-, NO_3^-, and SO_4^{2-}, respectively. The acidity profile was reconstructed following an ionic balance ($[H^+] = [NO_3^-] + [SO_4^{2-}] + [Cl^-] + [MSA] + [F^-] – [Ca^{2+}] – [Mg^{2+}] – [K^+] – [Na^+] – [NH_4^+]$ in μEq L^{-1}).

3.3 AICC2023 chronology and ^{10}Be flux

The AICC2023 chronology was used (Bouchet et al., 2023) to date the ice – spanning from (172.3 ± 1.9) ka BP to (275.7 ± 1.8) ka BP – and estimate the annual snow accumulation rate – mean snow accumulation of 5.5 cm a^{-1}. Our record covers several transitions from glacial to interglacial periods, from Marine Isotope Stage (MIS) 6.4 to 8.4 (Railsback et al., 2015), thus resulting in different accumulation rates ranging between (4.3 ± 0.8) cm a^{-1} and (8.1 ± 1.5) cm a^{-1}. On average, the ≈20 cm resolution corresponds to ≈300 years (min = 60 a; max = 1,375 a).

The flux of ^{10}Be was calculated as ^{10}Be concentration × snow accumulation rate × ice density (i.e., 0.917 g cm^{-3}). A half-life corrected flux was also calculated, using the (1.387 ± 0.012) Ma ^{10}Be half-life (Chmeleff et al., 2010; Korschinek et al., 2010). The resulting mean half-life-corrected ^{10}Be flux is $(1.36 \pm 0.26) \times 10^5$ at cm^{-2} a^{-1}, considering uncertainty on ^{10}Be concentration, snow accumulation rate, and ^{10}Be half-life. Although this calculation is numerically valid, it likely overestimates the uncertainty associated with accumulation rate. Indeed, in the AICC2023 chronology, uncertainties on snow accumulation rate

https://doi.org/10.5194/egusphere-2025-5707
Preprint. Discussion started: 25 November 2025

are inherited from the Paleochrono Bayesian framework (Parrenin et al., 2024) and strongly depend on the input uncertainties. During the interval 170–270 ka BP, the relative age uncertainty is only ±1 %, whereas the relative uncertainty in accumulation rates reaches ±20 % (Bouchet et al., 2023). This large value reflects the prior uncertainty (20 %) assigned to accumulation scenarios, which are derived from a poorly constrained empirical relationship between present-day water isotope in the snow and accumulation (Parrenin et al., 2007). In Paleochrono, such prior scenarios are iteratively adjusted within their uncertainty range to fit the dated horizons. In the AICC2023 simulation, posterior age estimates are constrained, but accumulation variations remain loosely constrained. Consequently, the ±20 % snow accumulation rate uncertainty that would arise from directly propagating the AICC2023 accumulation error is likely overestimated and further work is needed to estimate precisely the uncertainty in accumulation scenarios (Bouchet, personal communication).

In order to avoid artificial inflation of the uncertainty associated with ^{10}Be flux variations, we propose a more realistic uncertainty propagation to track relative variations. Rather than applying the full absolute uncertainty of the accumulation rate, we compute the relative uncertainty (% of the accumulation) and apply it to the deviation from the mean accumulation rate (Equation 1). This corrected uncertainty reflects the fact that variability in ^{10}Be flux is primarily driven by changes in accumulation over time rather than by its absolute range of uncertainty. On average, the corrected uncertainty, used when interpreting ^{10}Be flux variations as in Figure 5, is 22 % (min 0.2 %; max 53 %) lower than the raw uncertainty.

$$Corrected\_uncertainty(t)\ (/\%) = \frac{|accumulation(t) - accumulation_{mean\ (170-270\ ka)}| \times 0.2}{accumulation(t)} \qquad \text{Equation 1}$$

The TALDICE ^{10}Be record was compared with ^{10}Be measurements from DF ice core (Horiuchi et al., 2016) and from sediment cores (Simon et al., 2016). The DF record spans a period from 170 ka BP to 205 ka BP. While the record was published using the DFO-2006 chronology (Kawamura et al., 2007) with snow accumulation rate being retrieved from Parrenin et al., (2007), ^{10}Be fluxes were corrected using the most recent DF chronology, DF2021 (Oyabu et al., 2022).

To identify anomalously low ^{10}Be fluxes, which could bias the interpretation of geomagnetic intensity, we applied an objective statistical criterion. These ^{10}Be minima were identified when the concentration fell below the 3 ka rolling average minus the 3 ka rolling average of the standard deviation.

4 Results

Between 170 ka BP and 270 ka BP, TALDICE ^{10}Be concentrations vary between $(0.25 \pm 0.03) \times 10^4$ at g^{-1} and $(7.1 \pm 0.2) \times 10^4$ at g^{-1}, with mean concentration and uncertainty values of 2.5×10^4 at g^{-1} and 0.08×10^4 at g^{-1}, respectively (Figure 2A). This period spans MIS 8 to 6, including Termination III and the MIS 7, a time marked by pronounced climatic fluctuations (Railsback et al., 2015). After accounting for variations in snow accumulation rates using the AICC2023 chronology (Bouchet et al., 2023), ^{10}Be fluxes show values between $(1.9 \pm 0.4) \times 10^4$ at $cm^{-2}\ a^{-1}$ and $(31.0 \pm 6.1) \times 10^4$ at $cm^{-2}\ a^{-1}$ (Figure 2B). These flux variations highlight notable production changes independent of deposition variations. Concurrently, VADM values fluctuated indicating intervals of geomagnetic instability (Channell et al., 2009; Simon et al., 2016). In particular, 4

https://doi.org/10.5194/egusphere-2025-5707
Preprint. Discussion started: 25 November 2025

geomagnetic excursions are reported with little to strong depletions of the VADM, around 190 ka BP, 215 ka BP, 240 ka BP, and 258 ka BP (Figure 2E). An increase in the ^{10}Be flux related to a background production is expected during such minima due to reduced geomagnetic shielding, discussed in Section 5.2 and 5.3. One geomagnetic excursion is already clearly recorded in TALDICE: a pronounced ^{10}Be flux peak associated with the IBE excursion around 190 ka BP. Another event, previously identified in two sediment cores from the South-West Pacific (Simon et al., 2016), likely occurred around 258 ka BP but is not recorded in TALDICE due to the absence of measurements caused by a missing section of the ice core.

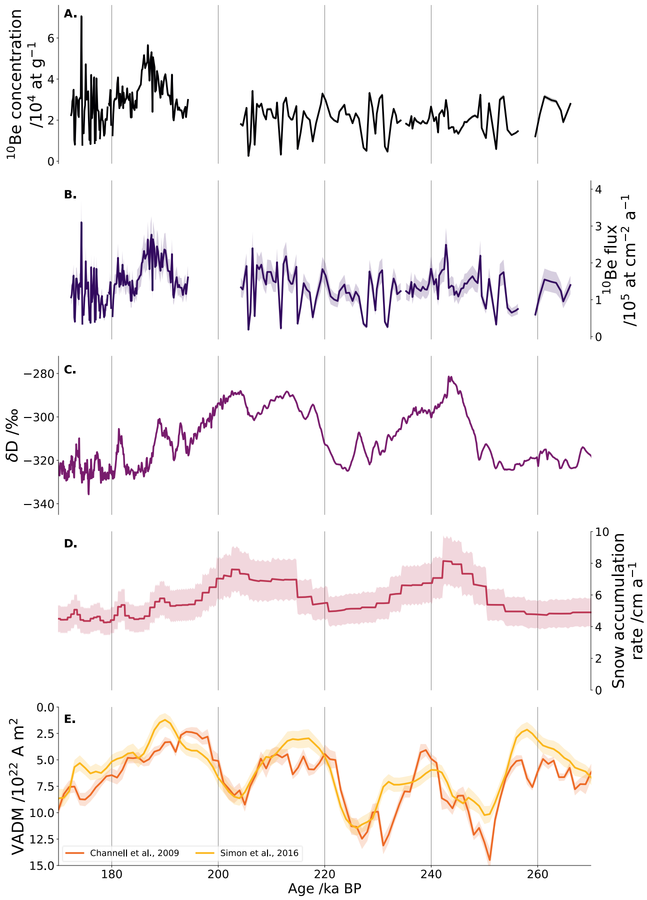

Figure 2: *TALDICE ^{10}Be concentration (10^4 at g^{-1}; A) and flux (10^5 at cm^{-2} a^{-1}; B). The uncertainties (shaded in black and purple) accounts for the concentration uncertainty and, in the case of flux, the variation of the accumulation (see section 4). Climate variations are recorded in TALDICE with δD (‰; C; Stenni et al., 2011). Snow accumulation rate (cm a^{-1}; D) is retrieved from the AICC2023 chronology (Bouchet et al., 2023). Virtual Axial Dipole Moment (VADM, A m^2) is estimated from Relative Paleointensity (Channell et al., 2009) (orange) or from authigenic $^{10}Be/^9Be$ (Simon et al., 2016). Note that the axis is reversed.*

A total of 52 minima in ^{10}Be concentration were identified across the TALDICE record studied in this work, which appear to coincide with maxima in the concentrations of major ions (Figure 3). This association is statistically significant (permutation test's p-value = 0.0001), though no direct quantitative relationship can be established. The major ions involved originate from a variety of sources, including oceanic sea spray (Na^+, Cl^-, Mg^{2+}, MSA, SO_4^{2-}), crustal dust (Ca^{2+}, Mg^{2+}), and volcanic (SO_4^{2-}) sources. In addition to ion concentration peaks, many of the ^{10}Be minima are also associated with decreases in the Cl^-/Na^+ ratio which is typically used to study changes in the relative contributions of marine aerosols or alterations in transport processes (Legrand et al., 2017).

To test whether the identified ^{10}Be concentration minima preferentially occur under particular conditions, we compared their distribution against δD and [Ca^{2+}]. Of the 47 minima identified (only considering the depth below 1570 m after which the δD is deteriorated), 36 occurred during glacial intervals (δD < -300 ‰), which is proportional to the fraction of the record spent in glacial conditions (76 %). A χ^2 test confirms no significant increase in the number of minima during glacials (p = 0.72), and δD values at ^{10}Be minima are statistically indistinguishable from non-minima levels (Mann-Whitney U test, p = 0.58). In contrast, [Ca^{2+}] concentrations are systematically higher at ^{10}Be minima. While median [Ca^{2+}] is only slightly elevated at minima compared to the background (Mann–Whitney U p = 0.06), contingency tests using thresholds show strong enrichment: for example, 17 % of ^{10}Be minima exceed 15 ppb Ca^{2+} compared to 11 % of the background (χ^2 = 9.3, p = 0.002), and 8 ^{10}Be minima exceed 30 ppb compared to only 8 out of 252 non-minima samples (Fisher's exact test, p < 0.001). This suggests that short-lived ^{10}Be minima preferentially coincide with dust-rich conditions.

After removing the 52 identified ^{10}Be minima, rolling averages can be calculated to smooth the record and obtain the first-order variations, which are likely to result. Test 1 ka, 3ka and 5 ka rolling averages (Figure S1) illustrate the trade-off between noise reduction and signal preservation. Given the mean resolution of our record (300 a) we selected a 3 ka rolling average as a practical compromise. This choice provides stable background trends while preserving the amplitude of GDM-related variations. The resulting 3-ka averaged ^{10}Be flux record can be compared to geomagnetic reconstructions, including the Dome Fuji ice core data (Figure 4, Horiuchi et al., 2016), authigenic $^{10}Be/^9Be$ records from marine sediment cores (Figure 5, Simon et al., 2016) and ^{10}Be production (Figure 5, Poluianov et al., 2016) calculated from RPI-based VADM (Channell et al., 2009). Flux enhancement during geomagnetic excursions or events depends strongly on the choice of background taken as reference. Here, we consider either the full 170–270 ka BP interval ^{10}Be flux mean average ((1.36 ± 0.26) × 10^5 at cm^{-2} a^{-1}) or a fixed baseline of 1.1 × 10^5 at cm^{-2} a^{-1} as reference values. The latter could be considered as representative of the long-term background ^{10}Be flux, which is close to the minimum values the 3 ka rolling average around 178 ka BP and 223 ka BP. Depending on the chosen baseline, the flux enhancement factors during specific events are as follows: for the 190 ka BP event (IBE), the ^{10}Be flux is 1.59 or 2.08 times the background; for the 205–215 ka BP event (PFE), the increase is 1.24 or 1.62 on average; and for the 240 ka BP event (ME), the peak flux reaches 1.25 or 1.63 times the reference value.

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Preprint. Discussion started: 25 November 2025

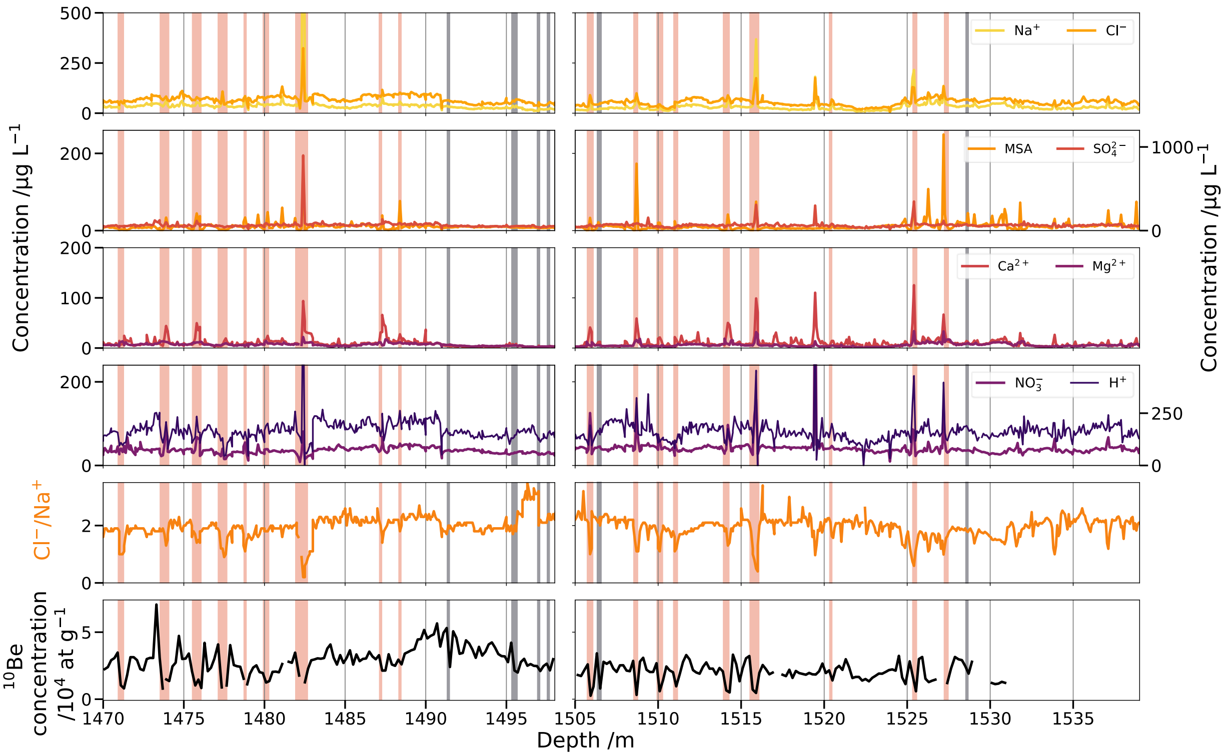

__Figure 3__: minima in ^{10}Be concentration (black) are highlighted in shaded orange and grey if there are or are not concomitant with maxima in major ion concentrations, respectively. The resolutions are the measurement resolution, i.e. ≈20 cm for ^{10}Be but 10 cm for major ions. The major ion concentration profiles are in high resolution (8 cm). Acidity profile (H^+) is calculated from an ionic balance (see section 3.2.2).

5 Discussion

5.1 ^{10}Be abrupt minima

Post-depositional artifacts in the geomagnetically-induced ^{10}Be signal in ice cores have been widely discussed, particularly in Greenland, where dust contributions have been shown to significantly affect the total ^{10}Be budget especially during glacial periods during which the dust level are higher than during interglacials (Baumgartner et al., 1997). Among known confounding factors, snow accumulation plays a central role: when poorly constrained, ^{10}Be concentrations tend to mirror accumulation variability (Yiou et al., 1985), complicating interpretations in terms of solar or geomagnetic modulation (Delaygue and Bard, 2011). Additional pre-depositional processes – such as stratospheric transport, volcanic injections (Baroni et al., 2011), wind-induced grain metamorphism (Lal et al., 2001), and general atmospheric aerosol dynamics (Zheng et al., 2024) – can all influence the ^{10}Be deposition. However, in the case presented here, we report distinct ^{10}Be minima that cannot be explained by variations in accumulation, deposition processes, or atmospheric circulation.

https://doi.org/10.5194/egusphere-2025-5707
Preprint. Discussion started: 25 November 2025

These ^{10}Be minima co-occur with sharp maxima in major ion concentrations (e.g., Na^+, Cl^-, Ca^{2+}), yet the ions originate from diverse sources. This rules out scenarios similar to single-source volcanic fallout (Baroni et al., 2011), terrestrial dust input (Baumgartner et al., 1997), or irregular snow redistribution (Poizat et al., 2024) and extreme atmospheric events such as atmospheric rivers (Wille et al., 2021). Instead, the inverse relationship between ^{10}Be and major ions suggests a post-depositional control. Spikes in the concentration of major ions have been observed in the deep section of EDC that had been linked to impurities migration in the ice crystal boundaries (Traversi et al., 2009). Thus, in-ice migration or redistribution of ^{10}Be at depth could also explain the ^{10}Be minima. For example, Raisbeck et al. (2006) reported ^{10}Be anomalies in the deepest parts of the EDC core (>700 ka; >3,100 m). Unlike reported here in TALDICE, maxima were observed in EDC. As reported in Kappelt et al. (2025), horizontal migration of Be was proposed to explain these maxima, as "smoothing over several thousands of years does not yield a distribution resembling the expected production signal smoothed by a vertical migration" (Kappelt et al., 2025). However, it is worth noting that some of the EDC ^{10}Be maxima were also concomitant with spikes in other species, including dust (Raisbeck et al., 2006). Similarly, major ion spikes in EDC were associated with low acidity (Raisbeck et al., 2006), which is different from the high acidity observed in TALDICE. Baumgartner et al. (1997) proposed another mechanism to explain the covariations between ^{10}Be and dust. Indeed, in the deepest and warmest ice of the GRIP core (Greenland), up to 40–50 % of ^{10}Be become dust-bound – higher than the <5 % seen in Holocene ice – due to ice metamorphism. The migration of ^{10}Be and dusts at the ice grain boundaries would result in higher local concentrations and thus favour the adsorption of ^{10}Be onto dust particles. Although such effects are expected to be less pronounced in low-dust Antarctic settings, deeper sections of ice cores, where ice crystals are large, may promote localized enrichment of major ions and ^{10}Be adsorption onto grain-boundary dust, muting the dissolved-phase signal. This mechanism is also in agreement with higher relocations and reactions of dusts in deep TALDICE (Baccolo et al., 2021). The significant connection between ^{10}Be minima occurrence and elevated Ca^{2+} concentrations, particularly above 30 ppb, suggests that extreme, non-atmospheric conditions are the main drivers of these ^{10}Be minima. The absence of a significant relationship with the glacial/interglacial state, as defined by δD, reinforces the idea that these anomalies are not controlled by large-scale atmospheric changes in production or transport, but instead reflect in-ice processes. In this way, although future studies should continue to investigate this question, ion remobilisation associated with ice grain metamorphism could lead to ^{10}Be incorporation into larger mineral aggregates that are not released by our extraction protocol.

These short-scale ^{10}Be minima are typically confined to one or two consecutive samples representing 20 to 40 cm in depth, with only two events exceeding 60 cm. Their limited extent implies that the broader ^{10}Be flux record remains intact, preserving the long-term geomagnetic signal. In the TALDICE core, once these short-lived minima are accounted for and removed, the ^{10}Be record robustly mirror geomagnetic variability. Past studies had suggested to account for these outliers calculating a rolling median (Raisbeck et al., 2006). However, during glacial periods, the median method results in similar ^{10}Be fluxes than based on a rolling mean average (Figure S2). On average, the method based on minima identification results in +10 % ^{10}Be flux compared to the median method (Figure S2).

https://doi.org/10.5194/egusphere-2025-5707
Preprint. Discussion started: 25 November 2025

5.2 ^{10}Be ice core fluxes

Reconstructing ^{10}Be flux requires reliable estimates of both concentration and snow accumulation rate, as both parameters can vary by up to a factor of two during geomagnetic excursions or between glacial/interglacial variations, respectively. In particular, assessing snow accumulation rates across Termination III and MIS 7 is challenging, as this interval is marked by rapid and complex climatic variability (e.g., Caillon et al., 2003; Pérez-Mejías et al., 2017). This makes it essential to confirm the accuracy and precision of the accumulation reconstruction.

For the period 170–270 ka BP, the mean 3ka rolling ^{10}Be flux in TALDICE is 1.44 × 10^5 at cm^{-2} a^{-1}, which slightly increases to 1.56 × 10^5 at cm^{-2} a^{-1} when the identified ^{10}Be minima are excluded. For the overlapping period 170–190 ka BP, the TALDICE ^{10}Be flux relative variations are in good agreement with the Dome Fuji record (Horiuchi et al., 2016) (Figure 4). This coherence not only highlights the homogeneous ^{10}Be deposition over East Antarctica, but also indicates that accumulation changes are well captured in both age models (AICC2023 for TALDICE (Bouchet et al., 2023) and the Dome Fuji DFO-2006 chronology (Kawamura et al., 2007)). This agreement is further improved when the recent Dome Fuji chronology from Oyabu et al. (2022) is applied (R^2 = 0.50, with DF values calculated on TALDICE timestep), compared to the older DFO-2006 chronology (R^2 = 0.39). The consistent temporal evolution of ^{10}Be fluxes across these independent ice cores supports the reliability of these datasets for investigating variations in the GDM.

However, a notable difference is observed between ^{10}Be fluxes measured in the TALDICE and Dome Fuji (DF) ice cores (Figure 4). While the mean ^{10}Be flux in TALDICE over this period is 1.56 × 10^5 at cm^{-2} a^{-1} (accounting for the minima), the DF ice core shows significantly higher values, reaching 2.85 × 10^5 at cm^{-2} a^{-1} (Horiuchi et al., 2016), or 2.76 × 10^5 at cm^{-2} a^{-1} when recalculated with the revised Dome Fuji chronology (Oyabu et al., 2022). The TALDICE values, however, are consistent with those from other Antarctic sites, such as EDC, which reports mean fluxes of approximately 1.44 × 10^5 at cm^{-2} a^{-1} for the period 200–300 ka BP (Cauquoin, 2013). This pattern persists over the last millennium Between 1000 and 1885 a CE, the mean ^{10}Be flux was 1.58 × 10^5 at cm^{-2} a^{-1} at Dome C (Baroni et al., 2019), and approximately twice as high at Dome Fuji (3.08 × 10^5 at cm^{-2} a^{-1}, Horiuchi et al., 2008). Although no ^{10}Be measurements are available for the last millennium at Talos Dome, comparison of recent century data shows similar mean fluxes between Talos Dome (1.49 × 10^5 at cm^{-2} a^{-1} (Supplementary Table 1)) and Dome C (1.39 × 10^5 at cm^{-2} a^{-1} (Baroni et al., 2019)). These lower fluxes relative to the last millennium are consistent with the occurrence of solar minima during this interval. Overall, the persistent factor-of-two difference between Dome Fuji and the two other East Antarctic sites (TALDICE and Dome C) indicates that the systematic offset between records extends into recent times. At present, there is no line of evidence indicating that this offset reflects large-scale atmospheric transport differences across East Antarctica. Global models such as ECHAM, GEOS-Chem or SOCOL (Golubenko et al., 2024; Zheng et al., 2024) have insufficient spatial resolution and poorly constrained deposition schemes across glacial-interglacial periods to test such regional gradients. On the other hand, the "polar bias" can hardly explain this observation as it concerns hemispheric-scale mixing differences between polar and low latitudes and is specific to glacial periods (Adolphi et

https://doi.org/10.5194/egusphere-2025-5707
Preprint. Discussion started: 25 November 2025

al., 2023). Although the origin of this persistent twofold offset remains unresolved, it has no impact on the interpretation of GDM variations, which solely rely on relative variations of ^{10}Be flux.

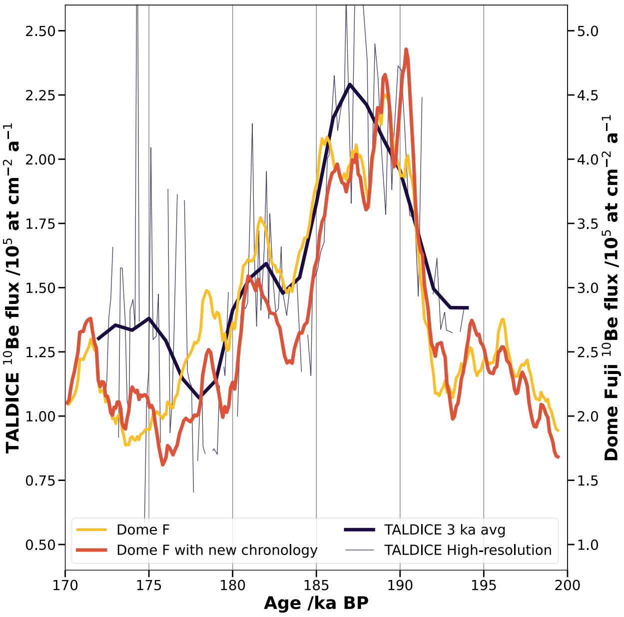

Figure 4: *comparison of Dome Fuji (yellow, Horiuchi et al., 2016) and TALDICE (purple, this study) ^{10}Be flux records for IBE. The revised Dome Fuji record is also presented based on chronology revision, which modifies snow accumulation rate (orange, Oyabu et al., 2022).*

5.3 Geomagnetic excursions between 170 ka BP and 270 ka BP

5.3.1 The low geomagnetic intensity during the Iceland Basin Excursion

The Iceland Basin Excursion (IBE), around 190 ka BP, stands out as one of the most prominent geomagnetic events recorded in an Antarctic ice core. Based on the TALDICE ^{10}Be flux data, a flux enhancement factor of 1.59 to 2.08 is observed, depending on the reference background (see section 4. Results). Such enhancement factors place IBE among the strongest known geomagnetic excursions of the last 1 Ma, comparable to or slightly higher than the Laschamps event as measured in East Antarctic cores (Raisbeck et al., 2017) or oceanic cores (Simon et al., 2020), with no equivalent recorded between 200 and 800 ka BP (Cauquoin, 2013), and approaching the amplitude of the Bruhnes–Matuyama transition (Raisbeck et al., 2006; Simon et al., 2020). Assuming a constant solar modulation potential of 650 MV, ^{10}Be production scenarios can be calculated (Poluianov et al., 2016) from the VADM reconstructions from RPI data (Channell et al., 2009) (Figure 5). For IBE peak, ^{10}Be production is expected to be 1.97 times higher than the 200 ka BP minimum ^{10}Be production according to the RPI-based VADM reconstruction (Channell et al., 2009), which is smaller than the observed 2.15 increase in the authigenic ^{10}Be/^{9}Be record (Figure 5, Simon et al., 2016).

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Preprint. Discussion started: 25 November 2025

Global transport models consistently indicate that polar ^{10}Be deposition originates from low-latitude production. GEOS-Chem simulations explicitly estimate deposition fluxes, indicating that about 52 % of ^{10}Be deposited between 60°S and 90°S is produced at lower latitudes (Zheng et al., 2024). As a result, a "polar bias" may affect ^{10}Be signals in Antarctic ice cores, as polar sites do not record solely polar atmospheric production but rather a mix between the ^{10}Be produced from low to high latitudes (Adolphi et al., 2023; Field et al., 2006). Model results suggest that geomagnetic field disturbances may be attenuated by 20 % to 37 % due to this bias under glacial conditions, but may not be attenuated during interglacial periods (Adolphi et al., 2023). Given that the IBE occurred during the interglacial MIS 7.1, the TALDICE ^{10}Be flux can be considered reliable for estimating enhancement factors. Accordingly, the observed twofold (2.08) flux increase at TALDICE would imply a complete depletion of the geomagnetic dipole moment, consistent with VADM reconstructions. Conversely, the lower factor of 1.59 would suggest either a smaller GDM reduction or a modest polar bias associated with the cooler conditions of MIS 7.1. This range reflects uncertainties in defining the background reference level, emphasizing the importance of background assumptions when quantifying excursion intensities from ^{10}Be flux records.

The structure of the ^{10}Be flux anomaly during IBE is also noteworthy: it features a rapid onset of the ^{10}Be signal associated with the dipole collapse, followed by a slow and three-step dipole moment recovery (Figures 2, 4 and 5). Variations in ^{10}Be fluxes obtained for the Laschamps excursion from ice cores (Muscheler et al., 2005; Raisbeck et al., 2017) and sediment cores (Ménabréaz et al., 2012; Simon et al., 2016, 2020) already revealed such a dynamics. Interestingly, this asymmetric pattern mirrors the observed pattern for polarity reversals (e.g., Valet and Meynadier, 1993; Valet et al., 2005): a slow decrease of the dipole moment in the initial polarity followed by an abrupt recovery of the dipole moment in the new opposite polarity. After long and intensive debates (Kok and Tauxe, 1996; Mazaud, 1996; Meynadier et al., 1998; Meynadier and Valet, 1996), the hypothesis was recently tested on authigenic $^{10}Be/^{9}Be$ records reconstructed from sediment cores (Simon et al., 2018; Valet et al., 2024, 2025) which suggested that the asymmetric patterns were not convincingly reproduced for any of the reversals of the last 4 Ma. However, the consistent asymmetry of the dipole moment collapse and recovery observed for Iceland Basin and Laschamps excursions might reveal a fundamental difference between the dynamics of excursions and reversals, and should be carefully considered in future geodynamo modeling efforts.

Regarding the timing, the IBE flux maximum forms a plateau between (192.07 ± 1.41) ka BP and (185.56 ± 1.44) ka BP, suggesting a ≈7 ka interval of extremely low magnetic field strength. This age is in general agreement with previous estimates from sedimentary and volcanic archives. For instance, the age aligns well with the K–Ar dating of transitional lava flows from the Snake River Plain at (188 ± 8) ka BP (Champion et al., 1988), and with excursion ages inferred from high-resolution marine sediment cores in the Ontong Java Plateau (≈190 ka BP; Tauxe and Wu, 1990) and the eastern equatorial Pacific (Valet and Meynadier, 1993). It is also consistent with authigenic $^{10}Be/^{9}Be$ records from Portuguese margin cores (Carcaillet et al., 2004). Slightly older ages, such as the (197 ± 17) ka BP have been reported though for the Unzen lava flow in Japan (Shibuya et al., 2007). These variations are likely due, at least in part, to the prolonged duration of the event, as indicated by the ≈7 ka plateau in ^{10}Be flux, which complicates the definition of a single "event age" and may account for the spread in reported timings.

Furthermore, fine-scale features in the IBE record, such as a short-lived recovery at 182 ka BP following a minimum at 183 ka BP, and a subsequent flux minimum around 178 ka BP with recovery by 174 ka BP, are visible in both TALDICE and DF cores as well as in oceanic cores (Figure 4). These well-resolved features are also mirrored in ocean sediment records (Black 430 stars in Figure 5) and could serve as valuable tie points for synchronizing paleoclimate archives across different media.

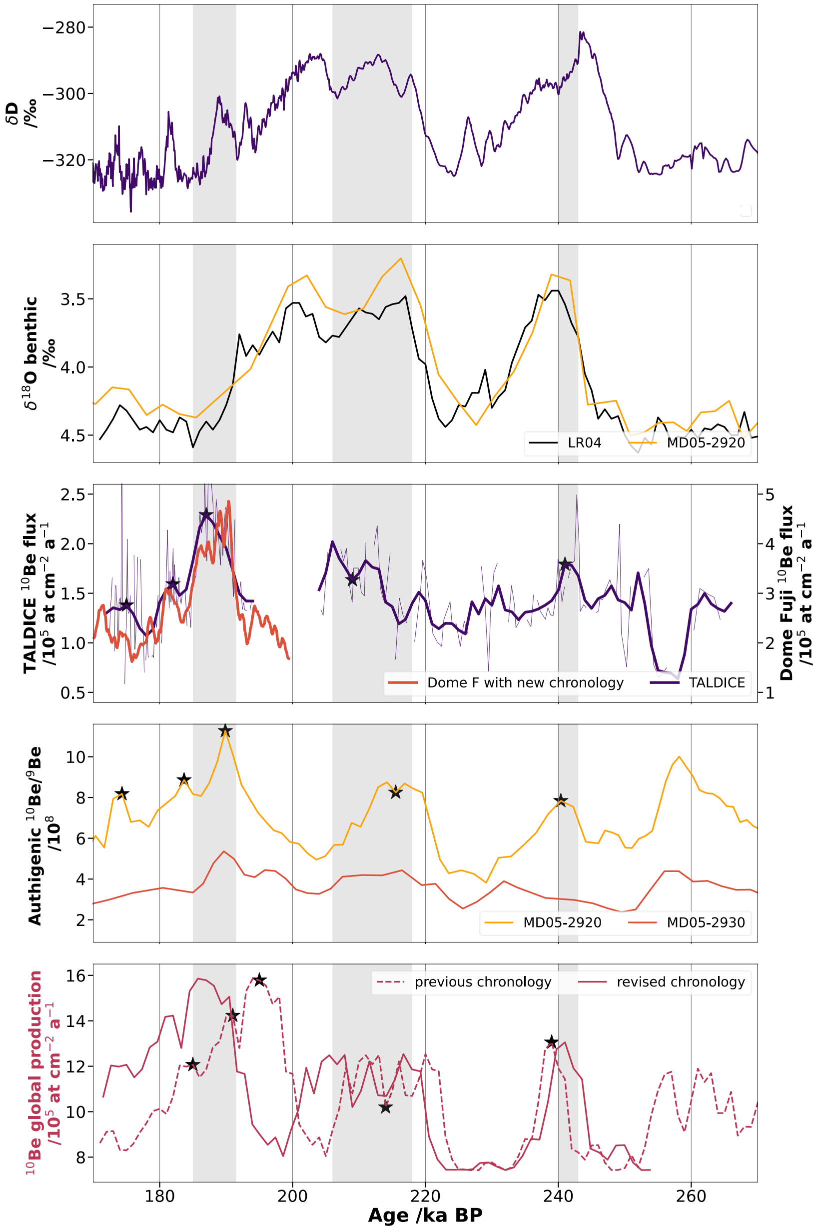

Figure 5*: Comparison of ^{10}Be and climate records from ice cores and marine sediments over 170–270 ka BP with, in order: TALDICE δD (/‰), benthic δ^{18}O (/‰) from LR04 stack (Lisiecki and Raymo, 2005) and MD05-2920 (Tachikawa et al., 2014),*

https://doi.org/10.5194/egusphere-2025-5707
Preprint. Discussion started: 25 November 2025

TALDICE and Dome Fuji ^{10}Be (in purple and red respectively, /at cm^{-2} a^{-1}), authigenic $^{10}Be/^{9}Be$ from MD05-2920 (yellow) and MD05-2930 (orange) (Simon et al., 2016), and the ^{10}Be global production (/at cm^{-2} a^{-1}; Poluianov et al., 2016) calculated from RPI-based VADM (Channell et al., 2009). Grey bars highlight the main geomagnetic excursions discussed in the text (IBE, PFE, ME). Timing of identifiable geomagnetic features (black stars in TALDICE, MD05-2920, and RPI-based VADM) is used to obtain a revised chronology of RPI-based VADM used for calculating the ^{10}Be production.

5.3.2 The lower amplitude Pringle Falls and Mamaku Excursions

In addition to the IBE, the TALDICE ^{10}Be record supports the existence of two distinct geomagnetic events for the period 205-270 ka BP (Figure 5). The identification of lower-amplitude geomagnetic excursions in this interval requires a cautious approach (see section 2.2 and Channell et al., 2020). Unlike more prominent events, these excursions often lack clear and well-dated signatures. The first event, occurring between (206.0 ± 0.8) ka BP and (218.5 ± 1.9) ka BP, shows a flux enhancement factor of 1.24 or 1.62, depending on the background reference, and is here associated with the Pringle Falls Excursion (PFE). The second, centred at (242.0 ± 0.3) ka BP, shows a peak enhancement factor of 1.25 or 1.63, and is tentatively identified as the Mamaku Excursion (ME). To the best of our knowledge, it is the first discussion of these events in an ice core. Compared with the authigenic $^{10}Be/^{9}Be$ record (Simon et al., 2016), TALDICE ^{10}Be flux suggests that the PFE and ME are of similar moderate amplitude but differing in duration: the PFE is characterized by a prolonged period (≈8 ka) of reduced field intensity, while the ME presents a brief minimum lasting only 2–3 ka, in agreement with RPI profile (Channell et al., 2009). However, it is important to note that unlike IBE, these events are not clearly expressed in ^{10}Be concentrations, and only emerge in the ^{10}Be flux (i.e., once considering snow accumulation rate variations and considering ^{10}Be minima). This raises the possibility of accumulation-related artifacts. Nevertheless, both events occur during interstadial periods (MIS 7.3 for PFE and MIS 7.5 for ME) marked by elevated accumulation rates, approximately 8 cm a^{-1} (Figure 2), thus supporting the consideration of snow accumulation rate variations. This is further corroborated by the correlation between the concentrations of Na^+ and ^{10}Be (R^2 = 0.23, after the removal of the minima, Figure S3) which indicates that about 23 % of ^{10}Be concentration is explained by climate-driven variations in ^{10}Be deposition. Moreover, the robustness of the AICC2023 chronology over this interval, supported by a dense network of stratigraphic tie-points and chronostratigraphic markers (Bouchet et al., 2023), strengthens the reliability of the flux signals. While confirmation from additional ice cores is required, the present evidence supports the occurrence of two distinct moderate geomagnetic excursions (PFE and ME), enriching the geomagnetic field history during MIS 7.

The relatively modest amplitude of the Pringle Falls and Mamaku excursions raises the question of whether their visibility in the TALDICE ^{10}Be record could be enhanced by climatic conditions, beyond a bias resulting from snow accumulation reconstruction. In particular, the occurrence of the three excursions during interstadial stages of MIS 7 (7.1 for IBE, 7.3 for PFE, and 7.5 for ME) raises the question of a climate-dependent polar bias. Model studies suggest that polar ^{10}Be records are less sensitive to geomagnetic field variations under glacial conditions, when atmospheric mixing is reduced, and more responsive under interglacial climates (Adolphi et al., 2023). In this view, excursions expressed during interglacials may partly reflect enhanced transmission of the global ^{10}Be production signal to polar deposition, while equivalent geomagnetic variations during glacial periods would appear more attenuated. However, the polar bias affects amplitude rather than timing: it cannot generate spurious excursions, but may modulate their visibility in ice core records. The consistent expression of IBE, PFE, and ME in both ice and marine archives, including RPI, indicates that these events correspond to genuine geomagnetic disturbances, albeit potentially amplified by more efficient atmospheric mixing during interglacials.

A further event around 258–262 ka BP has been reported in marine records, including a pronounced ^{10}Be/^{9}Be peak in equatorial Pacific sediments (Simon et al., 2016) and RPI lows in Atlantic and Mediterranean archives (Langereis et al., 1997; Lund et al., 2001; Nowaczyk and Frederichs, 1999). This excursion, sometimes termed the Calabrian Ridge 0, 8α, or Fram Strait event, is not expressed in TALDICE (Figure 5). Its absence can be explained by the fact that this interval coincides with long-lasting ^{10}Be low values, which cannot be identified as minima by our statistical filtering procedure, preventing detection of a robust flux signal. Additional high-resolution ice core data will be required to evaluate whether this excursion can be identified in Antarctic records.

5.4 Consistency of ice core and oceanic ^{10}Be records

The comparison between atmospheric ^{10}Be fluxes from ice cores and authigenic ^{10}Be/^{9}Be ratios from marine sediments reveals overall agreement (Figure S4.A), supporting the reliability of both archives in recording geomagnetic events. Previous studies have highlighted the close correspondence between atmospheric and authigenic ^{10}Be records (e.g., Czymzik et al., 2020). For IBE, high-resolution alignment is observed between ice cores (TALDICE and Dome Fuji, see section 5.3.1) and marine sediment cores (Figure 5). In particular, MD05-2920 captures the same three ^{10}Be peaks at 174, 182, and 187 ka BP. PFE is also identified in both MD05-2920 and MD05-2930, while ME is not detected in MD05-2930, likely due to the core's lower temporal resolution (ca. 4 ka around 240 ka BP), which may not resolve the short 2–3 ka duration of the event.

A systematic time offset between the oceanic and the ice core records is observed (Figures 5, S4.A). When comparing authigenic ^{10}Be/^{9}Be from core MD05-2920 to the TALDICE ^{10}Be flux, the best correlation is obtained when the oceanic record is shifted 3 ka younger ($R^2 = 0.37$, Figure S4), which remains within the uncertainties of the marine core age model (Tachikawa et al., 2014). Nevertheless, does this 3 ka offset result from age model uncertainties or reflect a physical lag in the system, thereby limiting the possibility to use paleomagnetic events as chronostratigraphic horizons?

A phase shift linked to mixing processes would result in a delayed and attenuated ^{10}Be signal. Although excursion amplitudes are consistent between the two archives (Figure 5), this depends on complex processes that can be involved such as polar bias linked to incomplete atmospheric mixing (Adolphi et al., 2023), oceanic circulation and transport (Jeromson et al., 2025; Savranskaia et al., 2021) and bioturbation in sediments (Raisbeck et al., 1985). Nevertheless, if a physical phase shift occurred, we would expect the ice core signal to lead the oceanic record due to various oceanic mixing effects, thereby resulting in a delayed (and attenuated) marine authigenic ^{10}Be/^{9}Be signal. To investigate the delay, we can examine the cross-correlation between the ^{10}Be/^{9}Be from core MD05-2920 and the ^{10}Be flux from TALDICE. Such analysis (Figure S4.B) shows the highest correlation when MD05-2920 is shifted by 3 to 3.7 ka earlier. Another approach consists in examining the evolution of the

https://doi.org/10.5194/egusphere-2025-5707
Preprint. Discussion started: 25 November 2025

delay between well-defined paleomagnetic events identified in both records (marked with stars in Figure 5). If major changes in oceanic circulation influenced the sedimentation of oceanic ^{10}Be, the lag would vary between glacial and interglacial periods (Savranskaia et al., 2024). However, we observe no variation in the lag across glacial–interglacial variations (Figure S4.C), indicating a consistent phase relationship between atmospheric and authigenic ^{10}Be signals. This approach yields a mean offset of 2.3 ka (Figure S4.C). Taken together, these results suggest that the observed delay is the result of age model uncertainty in the marine core, and that ^{10}Be production events are likely recorded synchronously in both oceanic and ice core archives. This conclusion is consistent with previous findings that suggest a limited reservoir effect and minimal climatic bias in ^{10}Be-based chronologies (Ménabréaz et al., 2012). These findings reinforce the value of ^{10}Be as a reliable synchronizing tool across sediment and ice archives. In the context of the Beyond EPICA project, they emphasize the role of ^{10}Be in refining chronologies and investigating climatic transitions, particularly across complex intervals such as the Mid-Pleistocene Transition.

Because of this broad agreement, a comparison of ^{10}Be production calculated from RPI-based VADM and authigenic ^{10}Be/^{9}Be with ice core ^{10}Be fluxes is possible. Using the VADM reconstruction from RPI (Channell et al., 2009) and assuming a constant solar modulation potential of 650 MV, ^{10}Be production was calculated following Poluianov et al. (2016). Between 170 and 270 ka BP, ^{10}Be production was at a mean of 10.5×10^5 at cm^{-2} a^{-1} (min = 7.4 ; max = 15.9). Compared with the 1.56×10^5 at cm^{-2} a^{-1} mean flux in TALDICE (removing ^{10}Be minima), this reveals a mean scaling factor of 6.7 (min = 4.8; max = 10.2). This scaling factor reflects the combined influence of geographic production patterns, including hemispheric asymmetries in production (Panovska et al., 2023) and atmospheric transport and deposition (Delaygue and Bard, 2011; Golubenko et al., 2024; Heikkilä et al., 2009). Consequently, quantitative interpretation of these ratios remains difficult, which highlights the need for continued model/data integration to constrain transport and deposition processes.

6 Synthesis and conclusion

This study presents a high-resolution ^{10}Be flux record from the East Antarctic TALDICE ice core, covering the interval from 170 to 270 ka BP, and evaluates the reliability of ^{10}Be as a paleomagnetic proxy. Three main conclusions emerge:

1. **Identification of ^{10}Be minima**

Within our record, 52 ^{10}Be minima restricted to single or double sample layers have been identified, most coinciding with maxima in major ion concentrations. Such observation indicate that these minima are likely the result of post-depositional processes within the ice rather than changes in atmospheric production. Although the precise mechanism remains unresolved, these minima were identified, and, once corrected for, did not compromise the reliability of the geomagnetic signal. Future high-resolution analytical approaches, such as laser ablation, may help quantify the redistribution of impurities in old ice crystals, thereby enabling the mechanisms of ^{10}Be redistribution to be identified. In the quest of old ice samples, such investigations will be particularly important for interpreting highly-rearranged ice layers in deep or blue ice records, and call for improved extraction protocols that take in-ice remobilization into account.

2. **Recording the geomagnetic dipole moment variations**

The TALDICE record demonstrates clear preservation of high-amplitude geomagnetic excursions, but also smaller ones, first identified in an ice core. The Iceland Basin Excursion (IBE) is well recorded, with a flux enhancement factor of 1.59–2.08 and a clearly defined low-dipole field interval between (192.0 ± 1.4) ka BP and (185.6 ± 1.4) ka BP. The structure of this event is notably asymmetrical, with a rapid decline in dipole intensity followed by a more gradual, three-step recovery, and may highlight fundamental differences between excursion and reversal dynamics, with implications for geodynamo modeling.

In addition to the geodynamo physics, the IBE is a valuable analogue of the Laschamps excursion , providing an opportunity to reassess the proposed modifications in atmospheric processes suggested for the Laschamps event. For instance, the prolonged low dipole field and its potential impact on atmospheric chemistry and biological systems (e.g., Cooper et al., 2021; Dasari et al., 2022) make it a prime target for future interdisciplinary investigations.

In addition, the TALDICE ^{10}Be record captures two lower-amplitude geomagnetic excursions: a long-lasting Pringle Falls Excursion (PFE), from (218.5 ± 1.9) to (206.0 ± 0.8) ka BP, and a brief Mamaku Excursion (ME) at (242.0 ± 0.3) ka BP, both associated with flux enhancement factors of 1.24 to 1.63. However, the 258–262 ka BP excursion is not observed in TALDICE due to prolonged ^{10}Be minima values and a gap in the dataset. Nevertheless, the observation of small amplitude features in the records, including the three step IBE recovery and the PFE and ME, offer great possibility for cross-checks between the chronologies of different archives.

3. Agreement between oceanic and ice core records

The strong agreement between TALDICE and marine authigenic ^{10}Be/^{9}Be records reinforces the potential of ^{10}Be as a robust tool for synchronizing marine and ice core archives.

Our results reveal that the oceanic records (MD05-2920 and MD05-2930) precede the ice core by ca. 3 ka, a discrepancy attributable to uncertainties in the age model rather than a genuine phase shift. Crucially, no systematic differences were observed between glacial and interglacial intervals, which further validates the limited oceanic-atmospheric differences. This multi-archive consistency not only strengthens the fidelity of reconstructions of past geomagnetic dipole moment variations, but also offers a promising avenue for refining chronologies and exploring climate-magnetic field interactions during critical intervals such as the Mid-Pleistocene Transition.

Data disponibility

A Zenodo repository is available with the following dataset (Lamothe et al., 2025):

Sheet 1: Depth top, depth bottom, Age top from AICC2023, age bottom, age uncertainty, accumulation, accumulation uncertainty, Be concentration, Be concentration uncertainty, Be flux, Be flux uncertainty

Sheet 2: Depth, concentration of major ions (Cl^-, $CH_3SO_3^-$ (MSA), F^-, NO_3^-, SO_4^{2-}, Na^+, NH_4^+, K^+, Mg^{2+}, and Ca^{2+}).

Author contributions

AL and MB conceptualized the study. Formal analysis was performed by AL, EA, MS, RT, MA, FW, RM, KK, GA, and FZ. Investigation and validation was done by AL, EB, NT, and MB. MB managed the project and aquired the funding. AL was supervised by MB and EB. AL undertook data curation, visualization, and writing of the first draft, with contributions from all co-authors.

Conflict of interests

The authors have no conflicts of interest to declare.

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