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AEOLIAN DIATOMS IN ANTARCTIC ICE CORES:
UNVEILING PAST CLIMATE AND
ENVIRONMENTAL CHANGES

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LIST OF ABBREVIATIONS

LIA: Little Ice Age

LGM: Last Glacial Maximum

SAM: Southern Annular Mode

ENSO: El Niño Southern Oscillation

ASL: Amundsen Sea Low

CC: Coulter Counter

FPP: Fine Particle Percentage

CPP: Coarse Particle Percentage

SPES: Single Particle Extinction and Scattering

OM: Optical microscopy
SEM: Scanning Electron Microscopy
RICE: Roosevelt Island Climate Evolution
MCA: Medieval Climate Anomaly
ERS: Eastern Ross Sea
WRS: Western Ross Sea
RSP: Ross Sea Polynya
HSSW: high salinity shelf water
ABW: Antarctic Bottom Water
WAIS: West Antarctic Ice Sheet
AS: Amundsen Sea
SIC: sea ice concentration
MQ: MilliQ
ABS: Amundsen-Bellingshausen Seas
SSIZ: seasonal sea ice zone
PDO: Pacific Decadal Oscillation
CP: Central Pacific
EP: Eastern Pacific
SOI: Southern Oscillation Index
SWW: Southern Westerly Winds
SHWW: Southern Hemisphere Westerly Winds
ACR: Antarctic Cold Reversal
MIS 2: Marine Isotope Stage 2
MIS 3: Marine Isotope Stage 3
SKT: Skytrain Ice Rise
DB: Dome B

ABSTRACT

Climate change is having a profound impact on our planet, with the polar regions being particularly affected. The interactions between the atmosphere, the ocean, and the cryosphere in these regions have led to the emergence of anomalous conditions. These phenomena are closely linked to major atmospheric circulation patterns, contributing significantly to both local and global climate variations.

As a matter of fact, the polar regions are known to play a critical role in regulating global climate change.

Paleoclimate research is an innovative tool for predicting future climate shifts, offering data about the Earth's climate system.

Ice cores are particularly beneficial for understanding past climates, as they serve as archives of paleoclimate records. These cores not only provide information about historical local climate variations, but reveal also changes at regional, hemispheric, and even global scales, becoming a critical resource for studying rapid climatic impacts.

A novel proxy discovered in ice cores consists of microscopic single-celled algae with silica walls, known as diatoms. These algae are nearly ubiquitous in aquatic environments and have recently been found in ice cores as well. They can be considered aeolian, which means that winds can transport them and, when used as proxies, diatoms can reveal freshwater or marine habitats of origin, source conditions and transport pathways.

This research project is focused on dust and diatoms preserved in Antarctic ice cores, proxies used to investigate the atmospheric and the oceanic environmental patterns that enabled their transport across different regions of the Antarctic continent.

One of the aims is to trace the dust and diatoms' trajectories to determine the original sources of these proxies, with a particular attention on two specific past climatic events: the Little Ice Age and the Last Glacial Maximum. The Little Ice Age was examined using a coastal ice core collected from an island located on the Ross Ice Shelf in the Eastern Ross Sea, while the Last Glacial Maximum is currently under investigation with two other ice cores: one collected from a remote

area in East Antarctica and the other one gathered inland of the Ronne Ice Shelf in the Weddel Sea sector, in West Antarctica.

OVERVIEW

Chapter 1 is the introduction, which is structured with an initial overview of the PhD project followed by a more detailed outline of the research conducted. Topics such as climate change, polar regions, past climate patterns, atmospheric systems and proxies are developed to build the foundation of the thesis. This section establishes the context and the framework for the project's core research.

Chapter 2 is focused on the primary research conducted during this PhD project, study which is centered on the RICE (Roosevelt Island Climate Evolution) ice core. The chapter provides information of the site's location, reviews of previous studies, it discusses the observation, count and identification of aeolian diatom valves, as well as the measurement of mineral dust particles throughout the last 2,000 years of the Holocene, which include the Little Ice Age. Moreover, this chapter includes a section in which the whole Holocene and the total number of diatoms found for the whole period are described, as an integration for future research.

Chapter 3 is structured on the observation, count and identification of aeolian diatoms in the Dome B ice core, which was collected from a remote area in East Antarctica. The chapter includes a description of the site's location during the Last Glacial Maximum and a review of Delmonte et al., 2017, which previously noted the presence of a few diatom valves while conducting dust analyses. In this study, both diatoms and dust were investigated to expand the knowledge on the published datasets edited by Delmonte et al. (2017).

Chapter 4 introduces the Skytrain Ice Rise ice core, collected near the base of the Antarctic Peninsula and adjacent to the Ronne Ice Shelf. This core was examined for diatom valves deposited during the Last Glacial Maximum, to enable a comparison with those observed in the Dome B ice core. The samples were kindly provided by Dieter Tetzner (British Antarctic Survey, Cambridge).

Although diatom valves have been identified, the analysis is still at a preliminary stage, and further research is required to fully interpret the results and assess their significance.

Chapter 5 concludes the thesis by providing a comprehensive summary of the research undertaken throughout this project. It revisits the findings from the study of the RICE, Dome B, and Skytrain Ice Rise ice cores, highlighting the contributions of these data to understand the past climatic changes.

AIMS OF THIS RESEARCH

This PhD research is primarily focused on analysing a new record of dust and diatom valves as proxies from the RICE (Roosevelt Island Climate Evolution) ice core. The study aims to provide information about climatic and atmospheric events observed in the eastern Ross Sea during the last 2,000 years and to assess whether changes driven by these factors have influenced the transport pathways. Moreover, to enhance the PhD project's scope, other two ice cores have been incorporated in this research project: the Dome B and the Skytrain Ice Rise ice cores. For these two ice cores, the aim is to observe the presence of diatom valves during the Last Glacial Maximum.

Research objectives for this PhD research project:

1. To analyse mineral dust and windblown diatom valves from the RICE ice core to reconstruct past climatic and atmospheric conditions on Roosevelt Island over the last 2,000 years.
2. To characterise the climatic and environmental conditions at Roosevelt Island during the last two millennia, with a specific focus on the Little Ice Age (LIA), and to address their regional significance within the broader Ross Sea context.
3. To evaluate the potential of windblown diatoms from the Dome B and Skytrain Ice Rise ice cores as reliable paleoenvironmental proxies for the reconstruction of the atmospheric conditions during the Last Glacial Maximum (LGM).

4. To compare the diatom valves species composition between the Dome B and Skytrain Ice Rise ice cores, checking for similarities and differences in source regions and transport mechanisms.

By exploring these questions, this research aims to contribute with data on past climate variability around Antarctica, improving our understanding of how atmospheric and environmental changes have influenced global climate dynamics over millennia.

1.0 Introduction

1.1 The polar regions

The poles are the most remote, pristine, and extreme regions on Earth, characterised by being the coldest, windiest, driest, and most untouched areas of the planet (Bhardwaj et al., 2018). Both poles are ruled by elements such as ice, snow and water. Antarctica is considered a frozen continent, isolated from the rest of the planet and fringed by the surrounding Southern Ocean and the atmospheric polar vortex. The Arctic region, instead, is a frozen ocean enclosed by continental landmasses and open ocean, strongly influenced by seasonal atmospheric transport and river flows from nearby continents (Anisimov et al., 2007).

The Southern Ocean plays a major role in the global ocean system, primarily through the Antarctic Circumpolar Current (ACC). The ACC, the ocean current transporting the largest volume of water globally (around 140 Sverdrups), is an easterly flow characterised by a complex dynamic involving both wind forcing and geostrophic balance, and it influences climate at both regional and global scales (Rintoul et al., 2010). By facilitating an efficient connection between surface and deep ocean waters, the ACC is involved in air-sea exchanges of heat, fresh water, and atmospheric trace gases. This makes it essential for understanding the evolution of climate, especially in the context of increasing greenhouse gas emissions (Barker and Thomas, 2004, Böning et al., 2008).

In the past few decades, the polar regions' responses to climate change have been observed through interactions between atmosphere, ocean, and cryosphere, and these have led to the formation of anomalous conditions (Turner and Overland, 2009). The Arctic has experienced a significant decline in sea ice extent, reaching a record minimum in 2012 (Stroeve and Notz, 2018), while the Antarctic Peninsula has shown a long term trend of increasing surface temperatures that began well before this period (Vaughan et al., 2003). These atmospheric and oceanic changes in the polar regions are primarily associated with major atmospheric circulations, such as the Southern Annular Mode (SAM) in Antarctica and the Northern Annular Mode (NAM) in the Arctic, both of which contribute significantly to local and global climate variations (Stammerjohn et al., 2008; Turner and Overland, 2009, Jouzel and Masson-Delmotte, 2010).

Consequently, atmospheric and oceanic circulations are considered the main drivers of poleward heat transport. This includes the variation in atmospheric heating between high and low latitudes, as well as the global thermohaline circulation, which governs large-scale oceanic heat redistribution (Turner and Marshall, 2011).

1.2 Ice cores and paleoclimate research

To better understand the climate system and predict future climatic changes, paleoclimate research is considered a crucial tool to assess data on Earth's climate dynamics (Snyder, 2010).

Paleoclimate research traditionally relies on the analysis of physical and chemical properties of climate archives such as ice cores, sediment layers, and tree rings (Jones and Mann, 2004), with an increasing emphasis on learning about biological proxies that contribute to the understanding of past climatic conditions (Mosley-Thompson and Thompson, 2033; Allen et al., 2020).

Among the most valuable archives, cylindrical samples of ice extracted from polar ice sheets and glaciers – known as ice cores (figure 1) – provide critical insights

into past atmospheric composition and climate variability, a potential first recognised between the 1950s and mid-1960s (Salazar, 2018).



Figure 1: ice core drilled from the West Antarctic Ice Sheet Divide (WAIS Divide), containing a dark band of volcanic ash deposited on the ice sheet roughly 21,000 years ago (from <https://nsidc.org/learn/ask-scientist/core-climate-history>)

Much like corals, tree rings and speleothems, ice cores serve as archives of past climatic changes: proxies such as stable water isotopes (e.g., $\delta^{18}\text{O}$ and δD) and annual layer thickness are used to infer temperature and accumulation rates. Other indicators, including dust content, major ion concentrations, and greenhouse gas levels (e.g., CO_2 , CH_4) help assessing the origin of precipitations, atmospheric circulation patterns, and to determine the climate variability on regional to global scales, thus contributing to the understanding of climate change instabilities (Mayewski et al., 2009; Jouzel and Masson-Delmotte, 2010; Rhodes et al., 2012).

Ice preserves a wide range of information related to past climates, stored in annual layers that accumulate atmospheric and environmental data (Brook and Buizert, 2018). One of the main properties of the ice cores is their ability to trap air in bubbles over time, preserving the atmospheric composition from the moment the air was sealed in the ice. These bubbles contain greenhouse gases like carbon dioxide (CO_2) and methane (CH_4), enabling scientists to determine historical levels of greenhouse gases and how this concentration globally influenced the temperature (Brook and Buizert, 2018).

In addition, soluble and insoluble impurities present in the ice, such as aeolian mineral dust, cryptotephra and marine aerosols, are considered important tracers that unveil the origins and transport pathways followed by these particles (Delmonte et al., 2010). These components help researchers understanding past volcanic activity, changes in wind patterns, and shifts in vegetation, supplying grasp of terrestrial and marine environments during glacial and interglacial periods (Legrand and Mayewski, 1997). In particular, explosive eruptions release large quantities of particles and sulphureous compounds into the atmosphere, which are later deposited in glaciers and preserved in the ice. These volcanic layers, easily identifiable, support a precise method for dating ice cores, allowing to link climate changes to specific geological events (Legrand and Mayewski, 1997).

Moreover, one of the most important methods for reconstructing past climates is the analysis of oxygen and hydrogen isotope ratios in the ice. The stable water isotopes ratio of oxygen ($^{18}\text{O}/^{16}\text{O}$) and the stable water isotopes ratio of hydrogen ($^2\text{H}/^1\text{H}$) vary according to the atmospheric temperature when moisture condensates (Dansgaard, 1964). These isotopic variations provide a direct proxy for the temperature at the time when the snow accumulates, allowing scientists to reconstruct regional and global temperature fluctuations over thousands of years (Jouzel et al., 1997).

The use of stable water isotope ratios in Antarctic ice cores, particularly $\delta^{18}\text{O}$ and δD (deuterium), has revealed large-scale climate cycles such as the ~100,000-year glacial–interglacial oscillations. These isotopic proxies reflect past temperatures: lower values generally correspond to colder periods, while higher values indicate warmer intervals. Such cycles are closely linked to variations in Earth's orbital parameters (Milankovitch cycles), which affect the solar insolation. The interplay between the orbital forcing, the changes in atmospheric CO_2 concentrations (measured from gas bubbles trapped in the ice), and the temperature feedback is fundamental in explaining the pacing and magnitude of these climatic shifts (Jouzel and Masson-Delmotte et al., 2010; Brook and Buizert, 2018).

1.3 The Little Ice Age (LIA)

The Little Ice Age (LIA) was a global and significant climatic event, traditionally considered a predominantly Northern Hemisphere phenomenon characterised by colder temperatures and significant glacier advances. However, evidence from the Southern Hemisphere also indicates notable climatic shifts, with glacial expansion occurring in regions such as the southern Andes and the New Zealand Alps, where glaciers reached their maximum Holocene extent in the mid-1800s (Grove, 2019; Broecker, 2000; Rhodes et al., 2012). Similarly, cooling in the Southern Hemisphere during the LIA is evident from temperature reconstructions and glacier advances in Chile and Argentina (Koch and Kilian, 2005; Espizua and Pitte, 2009), as well as from Antarctic ice cores and boreholes (Orsi et al., 2012; Bertler et al., 2011; Rhodes et al., 2012).

The LIA occurred between the Medieval Warm Period (MWP) – a climatic phase marked by relatively warmer temperatures from approximately 950 to 1250 AD (Mann et al., 2009) – and the early 20th-century warming (Grove, 2019). It spanned approximately from 1400 to 1850 AD (Crowley et al., 2008; Rapp, 2008), exhibiting asynchronous cooling patterns between the Northern and Southern Hemispheres (Mayewski and Maasch, 2006). In the Northern Hemisphere, temperature drops were particularly significant in North America (Broecker, 2000), whereas some regions – including parts of the Middle East, central North Atlantic, Africa, areas of the United States, tropical Eurasia, and the extratropical Pacific Ocean – experienced relatively warmer conditions (Mann et al., 2009).

In Antarctica, cooler and stormier conditions influenced the region over the past 5,000 years, with the LIA representing a particularly pronounced period of these climatic changes (Mayewski and Maasch, 2006; Bertler et al., 2011). The persistence of these conditions suggests an intensified meridional atmospheric circulation, potentially linked to strengthened westerly winds and increased cyclonic activity in the Southern Hemisphere (Mayewski et al., 2004; Bertler et al., 2011).

The LIA has been associated with natural climate forcings, including variations in volcanic and solar activity (Crowley et al., 2008; Orsi et al., 2012), as well as disruptions in the thermohaline circulation (THC) (Broecker, 2000). The weakening of the THC has been suggested as a potential driver of the LIA cooling, particularly in the North Atlantic region. This phenomenon may have been triggered by an increase in freshwater inputs from melting glaciers and sea ice, disrupting deep-water formation and slowing down the Atlantic Meridional Overturning Circulation (AMOC) (Broecker, 2000; Rahmstorf, 2002). Proxies obtained from marine sediments (e.g., sortable silt grain size, foraminiferal assemblages) and ice cores (e.g., $\delta^{18}\text{O}$, accumulation rates) indicate that during the LIA, periods of weakened AMOC coincided with colder temperatures and expanded sea ice extent in the North Atlantic (Bond et al., 1997; Lund et al., 2006). In contrast, the cooling observed in Antarctica during the LIA is thought to be a result from the bipolar seesaw mechanism, whereby a slowdown of the AMOC leads to the accumulation of heat in the Southern Hemisphere, followed by delayed oceanic and atmospheric adjustments that, eventually, reduce the Southern Ocean temperatures (Stocker and Johnsen, 2003).

1.4 The Last Glacial Maximum (LGM)

The Last Glacial Maximum (LGM), between 29–19 ka, was the most intense phase of the last ice age, characterised by extensive ice sheets and colder temperatures across the globe, particularly in the polar regions (Hughes, 2022). In the Arctic, the Laurentide Ice Sheet covered much of North America, while the Greenland Ice Sheet extended farther south, dramatically altering regional climate and oceanic circulation patterns (Peltier and Fairbanks, 2006). Cooling in the Arctic was marked by a significant drop in sea surface temperatures and an extensive expansion of sea ice, which in turn modified global atmospheric circulation. The increased sea ice cover strengthened the albedo effect, reducing heat absorption and further reinforcing colder conditions.

In addition, changes in wind patterns and ocean currents sustained climate feedback mechanisms that helped to prolong the LGM cooling phase (Löffverström et al., 2014).

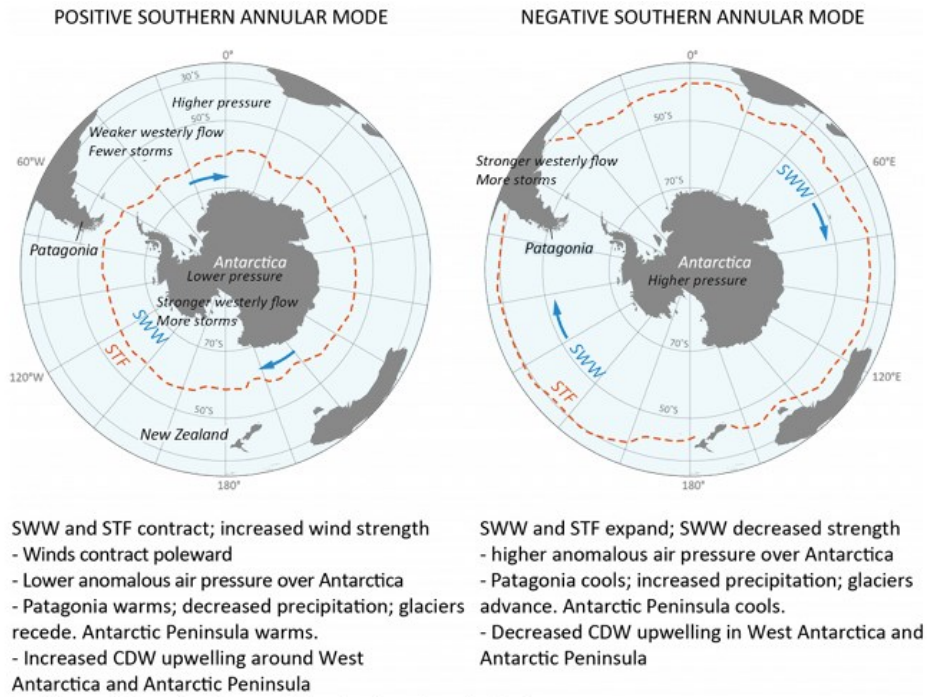
In Antarctica, ice sheets were significantly larger than today, extending onto the continental shelf and contributing to a global sea level drop of around 120 meters (Clark et al., 2009). Ice core data from Antarctica also revealed considerably lower atmospheric carbon dioxide levels during the LGM, which played a critical role in amplifying global cooling (Lüthi et al., 2008).

Although both polar regions were extensively covered by ice during the LGM, regional climate variations were influenced by factors such as ocean currents, atmospheric circulation, and volcanic activity, leading to spatial differences in climate dynamics (Denton et al., 2010). For instance, while Antarctic temperatures were primarily shaped by variations in atmospheric CO₂ and oceanic upwelling, Arctic climate was more sensitive to changes in ice sheet dynamics and shifts in the Atlantic Meridional Overturning Circulation (AMOC). These differences highlight the complex interplay of climate drivers that shaped the glacial conditions across both hemispheres.

1.5 The Southern Annular Mode (SAM)

The Southern Annular Mode (SAM) is the primary mode of atmospheric climate variability in the Southern Hemisphere, characterised by alternating atmospheric pressure patterns between Antarctica and the mid-latitudes (Marshall et al., 2011). When SAM is in a positive phase (+SAM), atmospheric pressure is lower over Antarctica and higher in the mid-latitudes, leading to a poleward shift and strengthening of the westerly winds while the subtropical high-level jet weakens (Abram et al., 2014). In contrast, during a negative phase (-SAM) the opposite occurs, with higher pressure over Antarctica and lower pressure in the mid-latitudes, resulting in equatorward-shifted and weakened westerly winds (Stammerjohn et al., 2008; figure 2).

Moreover, when the subtropical high-level jet strengthens and the westerly winds weaken, becoming more meridionally aligned with the jet and shifting equatorward, the negative phase of SAM occurs (Reboita et al., 2009; Fogt and Marshall, 2020).



*Figure 2: the SAM in its positive and negative phases
(original figure presented by AntarcticGlaciers.org).*

SAM indices reflect the atmospheric variability in sea-level pressure (Bracegirdle et al., 2019) and influence sea ice dynamics across different regions of Antarctica. Normally, a positive SAM phase leads to an increase in sea ice extent in the Ross Sea and other parts of East Antarctica, while contributing to sea ice retreat in the Bellingshausen and Amundsen Seas. When SAM is negative, on the other hand, it often results in decreasing sea ice in the Ross Sea and its increase in the Weddell Sea region, reflecting how complex is the SAM's spatial variability (Bertler et al., 2018; Turner et al., 2017).

Over the past several centuries, the SAM has exhibited its variability with a general trend toward more positive phases since the early 19th century. However, this trend has not been consistent, as SAM experienced periods of negative phases, such as during the mid-20th century, before shifting again to positive values in recent decades (Abram et al., 2014).

These fluctuations have influenced Antarctic climate patterns, with East Antarctica experiencing cooler conditions due to a reduced poleward pressure gradient, which lowered the transport of heat and moisture, as well as reduced katabatic winds (Bertler et al., 2018; Marshall et al., 2013; Marshall and Thompson, 2016). However, during positive SAM phases, an anomalous poleward heat flux carried heat and moisture across the Ross Ice Shelf in the Ross Sea and the Weddell Sea (Bertler et al., 2018; Marshall and Thompson, 2016), contributing to regional warming and to an increase of basal melting of ice shelves over these areas (Nicolas and Bromwich, 2014).

1.6 The El Niño Southern Oscillation (ENSO)

The El Niño Southern Oscillation (ENSO) is a well-documented phenomenon characterised by warm sea surface temperatures (SST) in the tropical Pacific, closely associated to significant atmospheric changes through the Southern Oscillation (SO) (Mayer et al., 2013).

The SO refers to a global-scale seesaw in atmospheric sea-level pressure (Trenberth and Hoar, 1996), measuring air exchanges across the Pacific Ocean, in terms of sea-level pressure differences between Darwin, Australia (western Pacific), and Tahiti (central-eastern Pacific). ENSO, instead, drives seasonal anomalies in temperature and precipitation, and its influence extends to distant regions like Antarctica, far beyond the Pacific basin (Turner et al., 2014).

El Niño is shown in figure 3a.

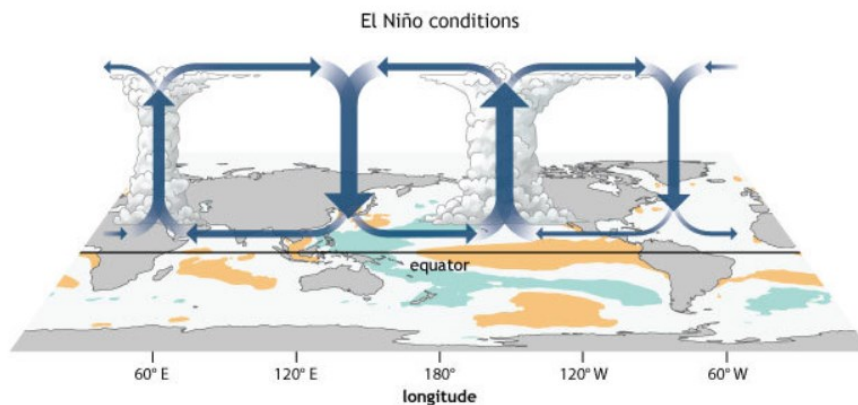


Figure 3a: schematic representation of atmospheric and sea surface temperature conditions during El Niño events (original figure by NOAA Climate.org).

La Niña (figure 3b) is considered the cold phase of the El Niño.

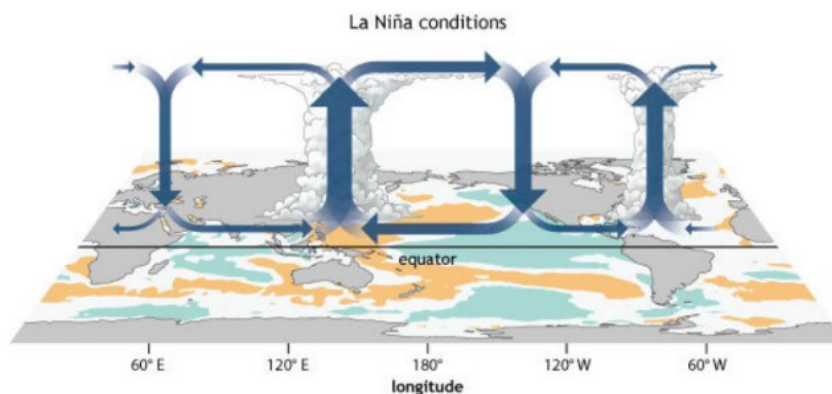


Figure 3b: schematic representation of atmospheric and sea surface temperature conditions during La Niña events (original figure by NOAA Climate.org).

Both oscillations are influenced by the Pacific Ocean's Walker Circulation (Yang et al., 2018). This pattern is known to connect atmospheric circulations and to reflect the SST variations which are driven by ENSO (Bayr et al., 2014). Over Antarctica, ENSO impacts are modulated by changes in the strength and position of the Amundsen Sea Low (Bertler et al., 2006; Turner et al., 2013).

1.7 The Amundsen Sea Low (ASL)

The Amundsen Sea Low (ASL) is a semi-permanent low-pressure system situated between the Ross and Amundsen Seas, particularly north of Marie Byrd Land (figure 4b). The following figure (4 a and b) shows the influence of the ASL over these areas.

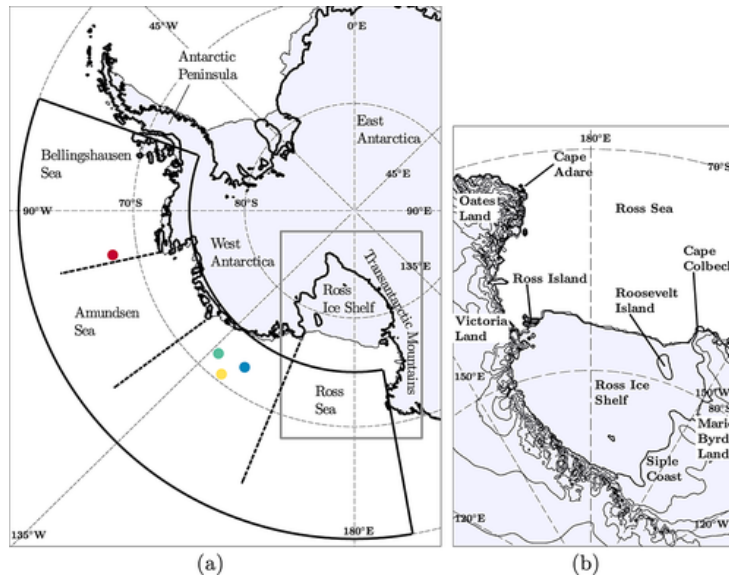


Figure 4a: a map of Antarctica with a black box which outlines the regions influenced by the ASL. The dots in different colours (red, summer; yellow, autumn; blue, winter; and green, spring) represents the mean locations of the ASL. The grey box, instead, is the area extended in figure 4b, which is displaying the Ross Ice Shelf and the Ross Sea region (original figure presented by Coggins et al., 2015).

Its behaviour is highly sensitive to both ENSO and SAM, influencing the climate and the sea ice dynamics in the Ross, Amundsen, and Bellingshausen Seas (Marshall and Thompson, 2016; Turner et al., 2013; Bertler et al., 2004; Bertler et al., 2018).

During ENSO phases, ASL pressure fluctuates, becoming weaker during El Niño events and stronger during La Niña events. When the ASL is in its positive phase (and/or during La Niña events), the ASL typically deepens, while it weakens during a negative SAM phase (and/or El Niño conditions) (Turner et al., 2013; Bertler et al., 2018; Bracegirdle et al., 2019). Although SAM is a circumpolar

mode, the ASL plays a crucial role in modulating the regional expression of SAM-related variability, particularly over West Antarctica. The strength and position of the ASL are further influenced by upper-level atmospheric circulation patterns, especially the subtropical jet (STJ) and the polar front jet (PFJ), which originate over the South Pacific near New Zealand. When the STJ is weak and the PFJ is strong, the enhanced meridional pressure gradient favours the intensification of katabatic winds across the Antarctic interior (Bertler et al., 2006; Turner, 2004). Conversely, a strong STJ and a weak PFJ are associated with a reduced katabatic flow and a more stable tropospheric structure. Variations in the position and intensity of these jets influence the meridional pressure gradient and the strength of the circumpolar westerlies, thereby shaping the phase and impact of SAM (Turner et al., 2013; Bracegirdle et al., 2019).

In addition, the ASL acts as link between the Tropical Pacific and the Amundsen Sea (Bracegirdle et al., 2019) through a pattern of alternating high- and low-pressure anomalies known as the Pacific South American (PSA) pattern. This PSA anomaly contributes to ENSO–Antarctica teleconnections by propagating a Rossby wave train from the Tropical Pacific toward West Antarctica (Karoly, 1989; Bracegirdle et al., 2019).

1.8 Proxies and methodologies used for this PhD research project

The following section of this chapter provides an overview of proxies and methodologies employed and evaluated during this PhD research, offering the reader a general framework before moving on to the more detailed chapters.

1.8.1 Mineral dust

Dust (figure 5) plays a significant role in fluxes changing during glacial and interglacial periods (Fisher et al., 2007), and these variations are influenced by the so-called source ‘intensity’ (Delmonte et al., 2017) which reflects shifts in environmental conditions.

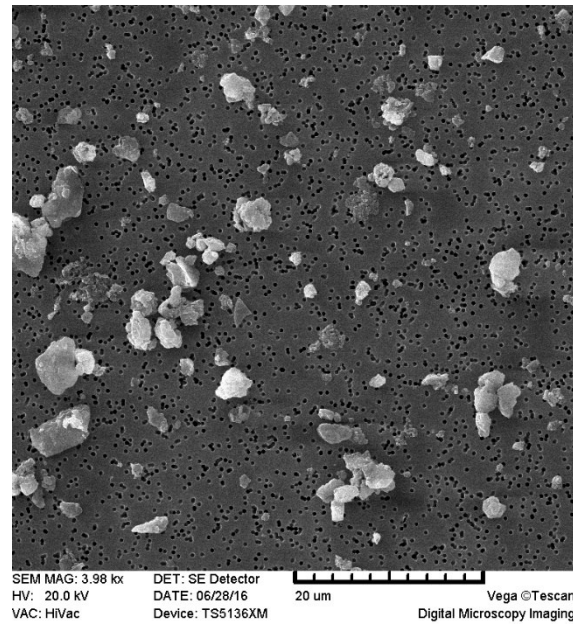
Source and sink areas are investigated using proxies such as the Sr and Nd isotopic composition of dust (Grousset and Biscaye, 2005). These isotopic signatures can be extracted from various locations, allowing the identification of the origin from where the aerosol particles come from (Delmonte et al., 2010).

Dust provenance from high-elevation sites in East Antarctica (Vostok, Dome C, EPICA-DML, Talos Dome) has been traced through different geochemical and mineralogical tracers, especially during glacial periods (Basile et al., 1997; Delmonte et al., 2004, 2008, 2010).

During glacial periods, dust concentrations in Antarctic ice cores increased significantly compared to interglacial periods, often by an order of magnitude (Lambert et al., 2008; Wolff et al., 2010). This marked variability was attributed to heightened aridity and stronger winds in source regions, alongside more efficient atmospheric transport during glacial conditions. In contrast, interglacial periods exhibited lower dust fluxes, reflecting reduced dust mobilisation due to wetter climates and increased vegetation cover in areas of sources (Delmonte et al., 2017).

The variability, in dust fluxes and sources, aligns with global climatic changes, as observed in ice core records from East Antarctica: higher dust concentrations during glacial periods coincide with global cooling, increased aridity, and intensified wind systems, while interglacial phases with warmer and wetter conditions correspond to significantly reduced dust deposition (Lambert et al., 2008; Delmonte et al., 2017).

These patterns enhance the sensitivity of dust cycles to large-scale climatic drivers and underline the importance of dust particles to be used as a proxy for past atmospheric and environmental changes.



*Figure 5: dust particles from a sample of Dome B ice core
(from dataset of Delmonte et al., 2017).*

Dust provenance also reveals notable differences between glacial and interglacial periods. During glacial periods, the primary dust source for high-elevation sites in East Antarctica, such as Dome B and Dome C, has been consistently identified as southern South America, particularly Patagonia, through Sr and Nd isotopic analyses (Basile et al., 1997; Delmonte et al., 2008, 2010). The exposed Patagonian shelf during periods of lowered sea levels further contributed to dust availability. However, isotopic data suggests that during interglacial periods, a more diverse set of sources, including local Antarctic sources and other Southern Hemisphere regions, highlight the reduced dominance of long-range transport pathways (Vallelonga et al., 2010; Delmonte et al., 2017).

During interglacial periods, the reduced dominance of Patagonian sources has been linked to weaker Southern Hemisphere Westerly Winds and higher sea levels, which submerged the Patagonian shelf, limiting the availability of dust. Isotopic analyses suggest contributions from multiple Southern Hemisphere regions, including Southern Africa and Australia, alongside potential local Antarctic inputs (Vallelonga et al., 2010).

Moreover, given the significant role of mineral dust in influencing biogeochemical cycles, particularly through iron deposition, understanding both the changes in dust fluxes and the mineralogical and chemical composition of the dust is essential. In particular, the speciation of iron – whether it is present in readily bioavailable forms such as Fe (II) or bound in less soluble minerals – critically determines its fertilising potential for marine ecosystems. In the Ross Sea, phytoplankton blooms, especially of diatoms, are strongly limited by iron availability. These blooms, often fuelled by inputs of locally sourced iron-rich dust, contribute significantly to the biological carbon pump by sequestering atmospheric CO₂ into the deep ocean (Tagliabue et al., 2017; Arrigo et al., 2003). Furthermore, as climate change alters atmospheric circulation patterns, shifts in both the sources and the geochemical characteristics of transported dust could have profound implications for marine productivity, regional climate feedback, and the global carbon cycle.

1.8.2 Diatoms

Diatoms (figure 6) are the most species-rich group of algae, widely distributed across diverse ecosystems, including freshwater lakes, ponds, streams (Reid et al., 1995; Jones, 1996; Esposito et al., 2008), cryoconite holes (Vinšová et al., 2015), soils (Vijver et al., 2002; Antonelli et al., 2017), mosses (Vijver and Beyens, 1997), sea ice (Arrigo, 2014), benthic sediments (Holland et al., 1974) and oceans (Sarhou et al., 2005). Both freshwater and marine diatom species have a specific role in ecological monitoring, paleoenvironmental reconstructions, stratigraphic correlation, and climate studies (Kellogg and Kellogg, 1996; Mann, 1999; Warnock and Scherer, 2014).

The diatoms' ability to thrive in a wide range of aqueous and subaqueous environments (Thomas et al., 2019) makes them important indicators of nutrient changes driven by climate variation (Bopp et al., 2005). They are commonly used to reconstruct environmental conditions, such as sea ice extent, salinity, pH, and dissolved organic carbon (DOC) (Warnock and Scherer, 2014; Stevenson et al., 1991). Moreover, diatoms play a crucial role in maintaining the balance between the atmosphere and oceans, significantly contributing to global climate stability – a balance now under threat from climate change (Benoiston et al., 2017).



Figure 6: different and coloured diatom valves
(original figure by <https://lifeofplant.blogspot.com/2011/04/diatoms.html>).

Diatoms are microscopic, single-celled algae encased in silica walls also known as frustules (Medlin et al., 1993). They dominate phytoplankton communities when nutrient levels are optimal (Bopp et al., 2005; Kellogg and Kellogg, 1996; Tetzner et al., 2022). Sensitive to oceanographic and environmental changes, diatoms' siliceous cells allow them to be preserved in sediments and, when transported by wind or water, in ice. Diatoms are widely distributed in the Southern Ocean, including regions such as the southern Weddell Sea and the Subtropical Zone, where they are found in open water and sediments, and they have been used for paleoenvironmental reconstructions (Zielinski and Gersonde, 1997). In polar regions, diatoms are observed in association with sea ice at

various depths: on the surface in melt pools, within intermediate layers, and at the bottom of the ice (Palmisano and Sullivan, 1982; Bunt, 1963).

In the Arctic, sea ice diatoms help assessing trends in primary production (Meguro et al., 1967), while in the Antarctic they serve as proxies to reconstruct past sea ice coverage through sedimentary microfossil distributions (Gersonde and Zielinski, 2000). Antarctic sea ice diatom communities have been observed during spring, summer, and fall (Ligowski et al., 1992). When sea ice melts, sea ice diatoms are released into the open ocean (Garrison et al., 1987). While many diatoms eventually sink to the seafloor, some remain near the ocean surface and can be transported into the atmosphere while still viable through wind-driven processes such as bubble-bursting and wave-breaking (Tetzner et al., 2022; King and Tetzner, 2021; Farmer et al., 1993).

Through this process, diatoms can be transported over long distances by winds (Tetzner et al., 2022; McKay et al., 2008), eventually being deposited onto polar ice sheets and buried under snowfall to become part of the ice matrix (Tetzner et al., 2022; Allen et al., 2020).

Once airborne, diatoms can be used as proxies to identify their freshwater or marine habitats of origin, as well as to trace wind transport pathways and source conditions (Allen et al., 2020; Budgeon et al., 2012; Kellogg and Kellogg, 1996). Earlier studies, however, were focused on determining whether marine diatoms found in Antarctic sediments were transported by wind or reworked in situ by glacial processes, a debate known as the "Sirius debate" (Allen et al., 2020; Burckle et al., 1997; Scherer et al., 1998; Burckle et al., 1988).

More recent research on terrestrial ice masses has confirmed that wind transport carries both freshwater and marine diatoms (Budgeon et al., 2012; McKay et al., 2008; Delmonte et al., 2013). For instance, it has been recorded that glacial outwash sediments and diatom valves have been transported over long distances: from Patagonia to Dome B ice core, in East Antarctica (Delmonte et al., 2017).

Moreover, airborne diatoms preserved in ice cores have proven valuable for reconstructing past wind strength and atmospheric circulation patterns, especially

over regions like the Antarctic Peninsula and Ellsworth Land (Tetzner et al., 2022a; Tetzner et al., 2022; Tetzner et al., 2021; Allen et al., 2020).

The Southern Ocean is well documented for its primary productivity, with regions such as the Weddell Sea, Prydz Bay, Bellingshausen Sea, and Ross Sea, showing significant diatom abundance (Cefarelli et al., 2010). As already mentioned, a big portion of this study focuses on the Ross Sea, the most productive of these regions. In the western Ross Sea, diatoms thrive in stratified waters, enhancing ocean productivity (Arrigo et al., 1999). When sea ice and ice edges retreat, sea ice diatoms are released into the water column via meltwater in the upper layers (Leventer and Dunbar, 1996). In the eastern Ross Sea, diatoms play a similar role in enhancing primary productivity, though the dynamics can differ slightly due to variations in oceanographic conditions. While detailed studies on diatoms in the eastern Ross Sea are less extensive compared to the western side, it is known that diatoms in this region are also influenced by sea ice conditions and meltwater processes (Leventer et al., 1998). As sea ice retreats, diatoms associated with the ice are released into the water column, contributing to the nutrient-rich environment that supports marine ecosystems (Leventer and Dunbar, 1996; Arrigo et al., 1999).

1.8.3 Coulter Counter (CC) measurements

The Beckman Coulter Counter Multisizer 4e (figure 7) was used to measure dust particles in RICE and Dome B ice cores. This instrument is a multi-channel system designed for particles (e.g., mineral dust) counting and characterization, consisting of various components that ensure precise and accurate measurements of dust concentration and grain size. The process begins with a sample that is made conductive by the addition of a microfiltered NaCl solution, adjusted to a final concentration of 2% (prepared from a 20% laboratory stock solution composed of pure NaCl, MilliQ water, and formaldehyde).



Figure 7: the Beckmann Coulter Counter Multisizer 4e
(<https://www.beckman.it/cell-counters-and-analyzers/multisizer-4e>).

To maintain the particles in suspension and to prevent their settling, samples are mechanically and continuously stirred until the time of the analysis, so that homogeneity and accuracy in measurements can be ensured.

After these steps, the sample is managed through a glass tube fitted with a carefully calibrated capillary orifice of different sizes, ranging from 10 μm to over 100 μm in nominal diameter. Two platinum electrodes - one located inside the tube and the other outside - generate an electric field. When a particle enters the aperture, it causes a disturbance in the electric field, resulting in a measurable resistance peak. Normally, the increase of resistance corresponds to the particles' volume, allowing the assessment of particle size distribution based on pulse magnitudes.

Each detected particles' volume is subsequently converted to an equivalent spherical diameter. The system offers both particle sizing and counting capabilities within a functional measurement range that spans from 2% to 60% of the capillary orifice's nominal opening.

Data acquisition and processing are carried out using Beckman Digital Signal Processing (DSP), with the results available for extraction and analysis via the proprietary MULTISIZER 4 software.

Coulter Counter measurement results may be affected by various sources of error.

An inevitable presence of unrelated particles in the background can be minimised through rigorous monitoring of laboratory blanks. In this study, periodic blank checks were conducted and considered acceptable if the particle mass concentration remained below 2 ppb.

The calibration of the instrument is vital to ensure accuracy in particles' size and concentration. Indeed, the Beckman Coulter Multisizer 4e was calibrated prior to measurements using a 5-micron nominal latex standard, the concentration assessments were carried out biannually, and no significant changes were detected in either particle concentration or grain size over time.

To avoid the occurrence of multiple particles passing simultaneously through the sensing zone, particles' concentration must be kept sufficiently low. This prevents the so called "coincident passage", where usually the primary coincidence leads to two particles being counted as a single larger particle, thus distorting size distribution. Secondary coincidence arises when two small particles, which would otherwise go undetected individually, are registered as a single larger particle. The Multisizer software applies an automatic correction for primary coincidence up to 10%, using an empirical algorithm based on the sensing zone's effective volume, particle count, and aperture diameter.

Electrical disturbances can contribute to an elevated background count. Any abnormal deviations in the counting process, particularly in the lowest channels, should be promptly identified. To mitigate such interference, the instrument may need to be relocated to an alternative power source or equipped with a voltage stabilizer to minimize electrical noise.

For this study, a 30-micron capillary tube was used to obtain precise measurements of particles with diameters ranging from 0.6 μm to 18 μm . The analytical conditions were set to include a volumetric control mode of 500 μL , a sizing threshold of 1 μm , an aperture current of 600 μA , and a preamplifier gain

of 4. The volume-number-mass size distribution of the samples is presented as a function of particle diameter, categorized into 400 logarithmic scale bins.

Consistent with previous literature on ice core dust (Delmonte et al., 2002), a standard density of 2.5 g/cm³ was applied for dust mass calculations. This value represents the average density of detrital minerals typically found in ice samples.

$$ppb = \frac{V[\mu m^3] * 2 * 2.5 [g/cm^3]}{1000}$$

The mass concentration of particles is derived from the volume measurements, ensuring accurate estimations of dust load in the analysed samples:

The total particles' volume measured over 500 µL is denoted as V, and to standardise the results to a reference volume of 1 mL, a multiplication factor of 2 is applied. The standard density of 2.5 g/cm³, representing the typical density of eolian minerals, is then used for mass calculations.

To characterise the dust-size distribution, the mode of the volume (mass)-size distribution, obtained through a lognormal fit of the raw data, is used as a key parameter. Another approach in ice core studies is to evaluate the proportion of dust particles within predefined size ranges, which is particularly useful for assessing dust size in low concentration samples and which correlates with the lognormal fit mode (Delmonte et al., 2005).

The two indices frequently applied for this purpose are the Fine Particle Percent (FPP%) and the Coarse Particle Percent (CPP%), which are defined as follows:

$$FPP \% = 100 * \frac{[mass\ 1 - 2\ \mu m]}{[mass\ 0.7 - 5\ \mu m]}$$

$$CPP \% = 100 * \frac{[mass\ 3 - 5\ \mu m]}{[mass\ 0.7 - 5\ \mu m]}$$

1.8.4 Single Particle Extinction and Scattering (SPES) measurements

The EOS CLASSIZER™ ONE (figure 8) was used to measure the particles present in Dome B ice core. This is an advanced optical analysis instrument that utilises the Single Particle Extinction and Scattering (SPES) technique to classify, analyse, and count particles' populations in fluid samples based on their optical properties (e.g., mineral dust).



Figure 8: the EOS SPES Classizer™ One
(<https://www.eosinstruments.com/eos-products/classizer-one/>).

This instrument operates by directing discrete meltwater aliquots, or a continuous sample flow, through a scattering chamber, where a precisely shaped and focused laser beam (wavelength: 640 nm) interacts with suspended particles. As each particle traverses the laser focal point, it generates an interference pattern resulting from the interaction between the transmitted beam and the forward-scattered light. A segmented detector captures this pattern, enabling the measurement of two optical parameters: the extinction cross-section (C_{ext}) and the particle's effective polarizability (α).

To extract these parameters, the system employs Pulse Shape Analysis (PSA) techniques and proprietary algorithms. A built-in validation mechanism ensures that only particles passing through the central region of the beam contribute to the dataset, effectively minimising artifacts. The extinction cross-section (C_{ext}) quantifies the particle's ability to scatter and absorb light, providing a measure of the effective area interacting with radiation (Potenza et al., 2016). Meanwhile, polarizability (α) depends on factors such as particle size, composition, and

shape. The precision of the measurement is further enhanced by the rapid fluid flow, which aligns with the particles' consistently, thereby reducing variability. Similar orientation control has been previously achieved using electromagnetic fields (Lee et al., 2020).

The results of SPES measurements are presented as a two-dimensional histogram, commonly referred to as a “cloud”, generated by the instrument's proprietary software. This cloud visually represents the relative abundance of recorded events across different histogram bins. Each particle's unique microphysical (optical) fingerprint can be extracted, with variations in optical properties forming distinct clusters within the cloud. The colour gradient in these plots typically denotes event density, with warmer colours indicating higher concentrations compared to cooler colours.

The analysis of these distributions enables the extraction of optical properties through theoretical model fitting based on different refractive indices. This process provides information about the composition and structure of the particles, though it may be influenced by particle shape, orientation, internal mixing, and heterogeneous composition (Villa et al., 2016).

In SPES analyses, the fitted refractive index serves as a critical reference for distinguishing particle populations within a sample. To estimate this value, it is required to assume the scattering properties. Specifically, the forward scattering amplitude, a dimensionless measure of the electromagnetic field at a 0-degree scattering angle, establishes the correlation between extinction cross-section (C_{ext}) and polarizability (α). These parameters are linked to the real and to the imaginary components of the scattering amplitude and they are inversely proportional to the wave number.

Refractive index determination, instead, is based on the relative refractive index (m), defined as the ratio between the particle's refractive index (n) in a vacuum and that of the surrounding medium (water): $m = n/w$.

As a result, the particle's refractive index remains the only free parameter in the fitting process, defining it a useful variable in the characterisation of individual particles.

1.8.5 Optical microscopy (OM) analysis

Diatom valves and fragments found in the RICE ice core were observed using an Olympus BX51M optical microscope (figure 9), equipped with reflected light capabilities, which is widely used for micropaleontological studies (Battarbee et al., 2001). This instrument, provided by the EUROCOLD Lab at the University of Milano-Bicocca, enabled detailed observation and taxonomic identification of diatom valves under magnifications of 100x, 500x, and 1000x. At the highest magnification, precise morphological measurements were conducted, as measuring the apical and transapical axes of the valves, using OLYMPUS Stream Essentials software, which offers advanced image analysis and measurement tools designed for microstructures (Olympus, 2015)



Figure 9: the Olympus BX51M optical microscope
(<https://spectraservices.com/product/olympus-bx51m-microscope.html>).

The optical microscope facilitated the identification of diatom genera and, when possible, species-level classification. High-resolution images of individual diatom valves were captured, documenting diagnostic features such as valve shape, symmetry, and structural details (Round et al., 1990). Although the resolution of the optical microscope is lower compared to Scanning Electron Microscopy (SEM), it proves invaluable for rapid screening of large numbers of samples, enabling a classification of the diatom valves and fragments with a high efficiency and reliability (Mackay et al., 2003).

1.8.6 Scanning Electron Microscopy (SEM) analysis

Slides prepared from the filtered aliquots for the Dome B and the Skytrain Ice Rise ice cores (and 10 samples of the Ice Rice ice core) were examined using a Scanning Electron Microscopy (SEM) for the identification and quantification of diatom valves and fragments. The SEM (figure 10) is a powerful analytical tool widely used across various scientific disciplines, including materials science, biology, and environmental research. It provides high-resolution imaging by scanning a focused beam of electrons over the surface of a sample, enabling the detailed examination of morphology, topography, and elemental composition (Goldstein et al., 2003). The SEM observations conducted at the University of Cambridge achieved magnifications ranging from 300,000x to 1,000,000x, allowing for the visualization of fine structural details at the nanometer and micrometer scales with exceptional clarity and precision. This advanced imaging technique facilitates the analysis of both organic and inorganic particles at nanometer and micrometer scales, offering exceptional clarity and precision in distinguishing diatom taxa and identifying surface features such as ornamentation and valve integrity (Mann et al., 1996).



*Figure 10: the SEM at Milan-Bicocca University
(original figure by Brochure-TECLA.pdf of Milan-Bicocca University).*

Additional SEM analyses were performed at the University of Milan-Bicocca (figure 10), further expanding the dataset by providing complementary morphological observations. The integration of multi-institutional SEM analyses enabled a comprehensive investigation of particle characteristics, supporting a more thorough interpretation of the ice core samples.

1.8.7 Diatom valves identification

To identify the diatom valves observed with the Olympus or with the SEM images, I followed a series of systematic steps to achieve species-specific classification whenever possible. However, for most of the microfossils, identification was limited to the genus level.

General features

Valve shape and symmetry: the overall shape of the diatom valve is essential for classification. Diatoms can be centric (radial symmetry) or pennate (bilateral symmetry).

Size: measure the apical axis (longest dimension) and transapical axis (shortest dimension) of the valve. These dimensions are often species-specific.

Striae patterns: when the image quality is sufficient, the arrangement and density of striae (rows of pores or ribs on the valve surface) are examined. Striae density is typically measured within a fixed length, such as 10 μm , as it varies between species. However, this always depends on the resolution of the images.

Specific features of centric diatoms

Radial symmetry: centric diatoms are characterized by radial symmetry, resembling a circular or polygonal pattern when viewed from the valve face.

Central area: the central region of the valve often contains unique structural elements, such as spines, nodules, or areolae.

Marginal features: spines or linking structures may assist in species identification.

Specific features of pennate diatoms

Bilateral symmetry: pennate diatoms exhibit bilateral symmetry along a central longitudinal axis.

Raphe system: many pennate diatoms have a raphe, a slit-like structure on one or both valves that facilitates movement. The presence, absence, or structure of the raphe can be diagnostic.

Shape and ends: the valve ends can be rounded, tapered, or capitate (club-shaped), and this can help differentiate genera.

Striae and areolae: the pattern, the density, and the spacing of the striae and areolae (pores or perforations in the silica cell wall).

Valve surface's details

Texture: the valve surface can be smooth, punctuated with pores, or having intricate patterns.

Spines or other projections: they may be present on centric diatoms, especially on the edges, and can serve as a species-level trait.

Secondary structures: some diatoms exhibit girdle bands or other fine scale features visible under high magnification.

In figure 11, an example of SEM images used for morphological identification is shown. Centric and pennate diatoms can be visually distinguished by their symmetry and specific features.

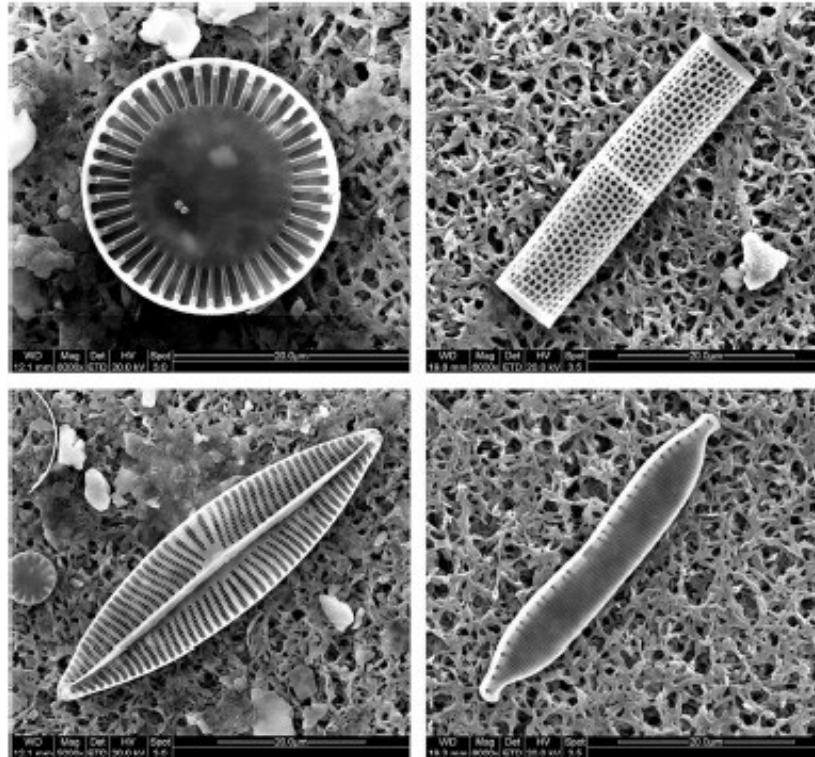


Figure 11: SEM images showing centric diatoms (top row) and pennate diatoms (bottom row). Centric valves display radial symmetry, while pennate valves exhibit bilateral symmetry along the apical axis (original figure presented by Zhang et al., 2020)

Ecological contexts (when assessable)

Marine or freshwater origins: diatoms are categorised as marine, freshwater, brackish or terrestrial, depending on their ecological preference.

Habitat: some species are associated with specific environmental conditions, such as sea ice and benthic zones.

Taxonomic references

Cross-reference observes features with diatom identification keys or taxonomic atlases, such as Hustedt, Round et al. (1990), or more recent guides specific to Antarctic diatoms.

Image annotation and documentation

All observed diatom valves and fragments can be documented through high-resolution imaging. Each valve can be catalogued with corresponding metadata, including sample depth and site location, for later analysis and cross-referencing.

These steps can be used to identify diatom fragments as well; however, fragments must have a good shape and usually be at least 5 microns in apical axis, otherwise the identification would lack in dimension that could help the definition of, at least, the genus. In this research work, fragments are not considered very often, due to the poor quality of the images, the very little sizes of most of them, and therefore the challenging in making a proper identification.

2.0 RICE ice core

2.1 Introduction

2.1.1 The Roosevelt Island Climate Evolution

The Roosevelt Island Climate Evolution (RICE) project is a multinational ice core research initiative aimed at reconstructing past climate variability and understanding the interactions between the atmosphere, the ocean, and the ice in the eastern Ross Sea, Antarctica. More information about the project and its scientific goals is available on the official RICE website: <https://www.rice.aq>.

The main achievement of the project is the extraction and the analysis of a 764-meter ice core that was drilled from Roosevelt Island, a grounded ice rise near the northeastern edge of the Ross Ice Shelf (Bertler et al., 2018). This ice core represents a salient archive of environmental and climatic information, spanning approximately 83,000 years and covering key periods such as the Last Glacial Maximum and the Holocene (Bertler et al., 2011).

Roosevelt Island (figure 12 a and b) is located in the Eastern Ross Sea, and it is a unique geographic feature, measuring 120 km in length and 60 km in width (Bertler et al., 2018). The RICE drill site (79.364° S, 161.706° W) is situated near the island's summit at 550 meters above sea level, with the ice core extending to a depth of 764 meters, reaching 214 meters below sea level (Bertler et al., 2018).

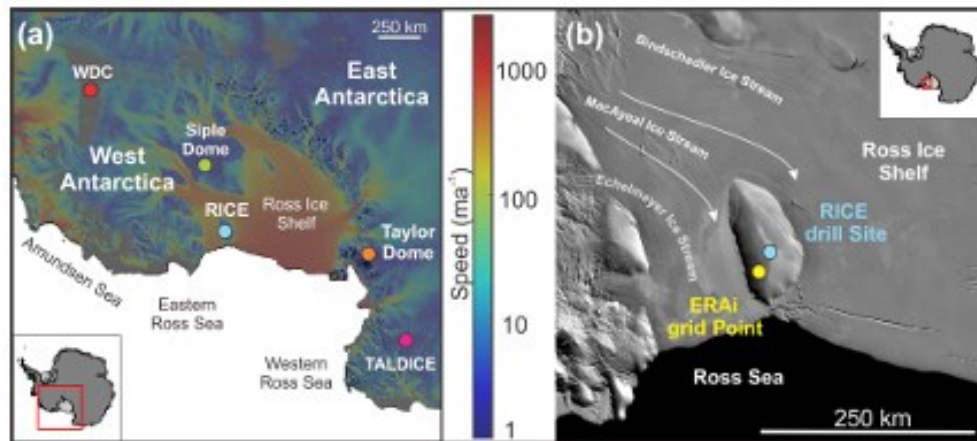


Figure 12a: an overview map of the Ross Sea region and eastern West Antarctica. The coloured dots indicate the locations of ice core drilling sites used in this paper: RICE (blue), West Antarctic Ice Sheet Divide ice core (WDC; red), Siple Dome (green), TALDICE and Talos Dome TD96 (purple), Taylor Dome (orange).

Figure 12b: the location of the RICE drill site (blue) and the nearest ERA-Interim (ERAi) grid point (yellow) (original figure presented by Bertler et al., 2018).

This site is strategically determined for ice core research due to its role as a pinning point for the Ross Ice Shelf, which stabilises the ice sheet and influences ice dynamics (Matsuoka et al., 2015). This steady environment allowed the accumulation of well-preserved ice, enabling the reconstruction of high-resolution records of past climate and atmospheric changes. The ice surrounding Roosevelt Island originates from the West Antarctic Ice Sheet (WAIS), fed by the Bindschadler, MacAyeal, and Echelmeyer ice streams, while it is local the ice accumulation on the rise itself. Marine basins around the island reach depths of 600 meters on the western side and 750 meters on the eastern side, with the Ross Ice Shelf having a thickness of approximately 500 meters (Fretwell et al., 2013).

One of the main aims of the RICE project is to investigate how the Ross Ice Shelf and its surrounding areas have responded to global climate changes over millennial timescales. This includes studying ice dynamics, environmental conditions, and the interactions between the atmosphere, oceans, and ice (Bertler et al., 2018). Notably, past changes in atmospheric circulation – such as

shifts in the Southern Hemisphere westerlies – have significantly influenced the transport of dust and aerosols to the region (Mayewski et al., 2009; Bertler et al., 2011).

The RICE project addresses other scientific objectives such as the study of atmospheric circulation patterns, dust and aerosol deposition, and their relationship to climate variability in the Southern Hemisphere (Delmonte et al., 2004; Lambert et al., 2008). Additionally, the ice core contributes to a better understanding of the stability of the Ross Ice Shelf and its implications for global sea level rise, which is a critical factor for projecting future climate scenarios (Conway et al., 1999; Bertler et al., 2018).

2.1.2 RICE and LIA

The assessment of climatic variability over the Common Era (CE, last 2,000 years; 2 ka BP) is essential for understanding industrial era warming in the context of natural climate fluctuations (IPCC, 2021). Different climatic periods are included in this timeline: the Roman Warm Period (ca. 1-300 CE), Dark Ages Cold Period (ca. 400-765 CE), and the Medieval Warm Period (MWP, 800-1200 CE). The most prominent episode is the Little Ice Age (LIA), marked by global glacial advances, though its timing and magnitude vary regionally. The post-industrial period (1850 CE–present) is recognised as the warmest of the last two millennia, with a pronounced anthropogenic influence (IPCC, 2021).

Earlier climatic changes lacked spatial and temporal coherence, as evidenced by ice cores analyses across Antarctica (Stenni et al., 2017). For example, locations such as WAIS Divide and ice cores from inland East Antarctica denoted cooling before 1900 CE, while coastal sites like Roosevelt Island recorded warming trends (Bertler et al., 2018). Such discrepancies are attributed to the sensitivity of coastal sites to local atmospheric signals modelled by maritime air masses (Nicolas and Bromwich, 2014).

2.1.3 RICE and Eastern Ross Sea (ERS)

The Ross Sea (figure 13), positioned in the Southern Ocean just north of the Ross Ice Shelf (RIS), covers an area of 1.55 million square kilometres. The Ross Ice Shelf, which extends from the southern boundary of the Ross Sea, has an average thickness of 370 meters. The shelf front is located between Cape Adare and Cape Colbeck, while the continental shelf break lies further north (Orsi and Wiederwohl, 2009).

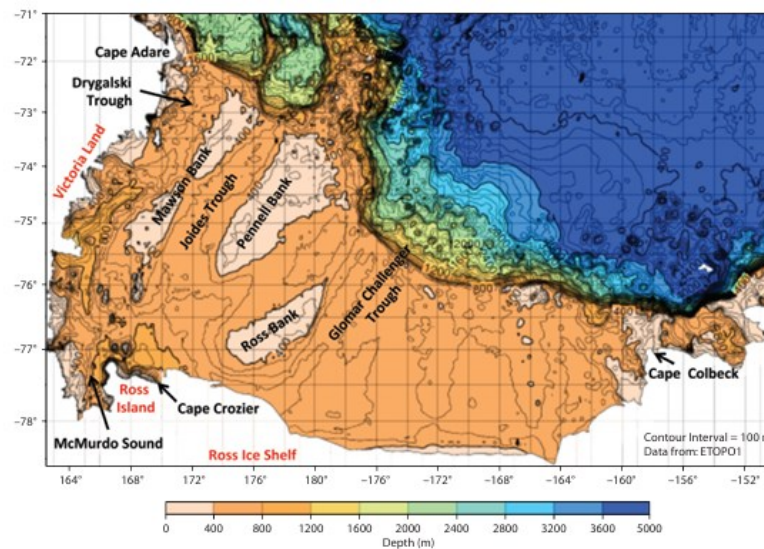


Figure 13: the Ross Sea bathymetry (original figure presented by Smith Jr, Walker O. et al., 2012).

The Eastern Ross Sea (ERS) and Western Ross Sea (WRS) exhibit different geological and environmental characteristics, as the seafloor geology and physiography (Halberstadt et al., 2016), the primary productivity (Cunningham and Leventer, 1998), and the ecosystem dynamics.

Bertler and colleagues (2018) explored regional temperature, snow precipitation and variability at Roosevelt Island during the satellite era. Their findings show that, during the last 2,000 years, the ERS experienced warming, while West Antarctica cooled and the WRS exhibited no significant isotopic enrichment or temperature trends.

This variability mirrors the so-called Ross Sea Dipole, a phenomenon driven by meridional winds and anticyclonic events, which leads to differences in precipitation, sea ice concentrations, and extreme surface air temperatures between the eastern and western Ross Sea (Emanuelsson et al., 2018).

Moreover, although during the last 2,000 years the WRS was generally cooler and the ERS warmer compared to the mean of the past two millennia, it has been observed that during the LIA, the entire Ross Sea experienced a regional warming that exceeded the range of natural variability, with a decrease in snow accumulation in both West Antarctica and the ERS, and an increase in the WRS (Bertler et al., 2011). In addition, the ERS experienced increased intrusions of marine air masses, a weakening of the katabatic winds, and an expansion of the Ross Sea polynya. This is supported by a rise in barium (Ba) concentrations, which serve as a proxy for open water conditions and biological productivity (Kwok et al., 2007).

2.1.4 Ross Sea polynyas

The Ross Sea is recognised for hosting the most productive polynya in the Southern Ocean (Bromwich et al., 1998), and for playing a crucial role in the removal of atmospheric CO₂. It is therefore highlighted the exceptionally high primary productivity of this area (Arrigo et al., 2008; Smith, 2022). Polynyas are known to be large and persistent areas of open water surrounded by thin ice within the pack ice; their formation is influenced by large-scale atmospheric forcing and katabatic winds originating from the Antarctic interior, as well as by local coastal features that inhibit the lateral intrusion of sea ice (Martin et al., 2007).

There are three significant polynyas in the Ross Sea (figure 14). The largest coastal polynya on Earth is the Ross Sea Polynya (RSP), located along the Ross Ice Shelf, east of Ross Island (Arrigo and van Dijken, 2003). The other two, smaller in size, are the Terra Nova Bay (TNB) Polynya, situated just north of the Drygalski Ice Tongue, and the McMurdo Sound (MAC) Polynya, which is the smallest of the three (Bromwich and Kurtz, 1984; Martin et al., 2007; Comiso et al., 2011).

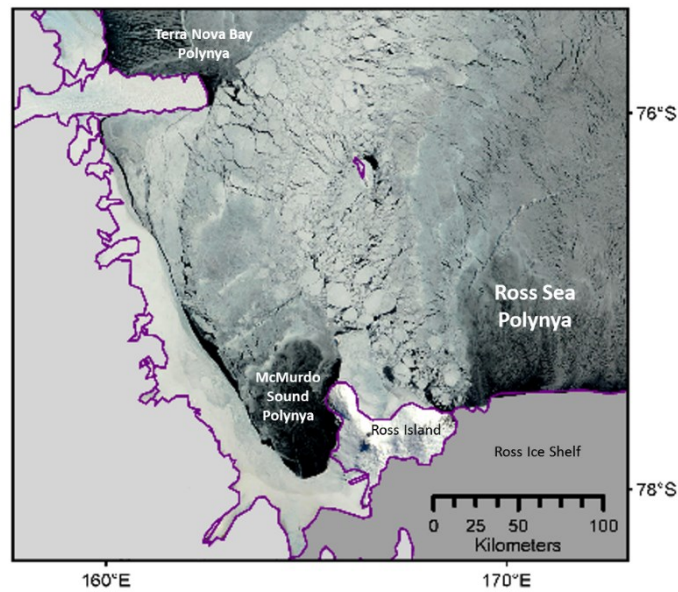


Figure 14: the location of the three known polynyas in the Ross Sea
(from <https://www.antarcticscienceplatform.org.nz>).

These polynyas contribute to the formation of high salinity shelf water (HSSW), which serves as a precursor to Antarctic Bottom Water (AABW) (Comiso et al., 2011). As the salinity of the shelf water increases, it becomes dense enough to sink and, through mixing with Circumpolar Deep Water (CDW), contributes to the formation of AABW, a major driver of global thermohaline circulation (Rhodes et al., 2009).

Overall, polynyas are the precursors of the ocean-atmosphere heat transfer (Reddy et al., 2007), of the ice production and export (Drucker et al., 2011), of the shelf water formation (Orsi and Wiederwohl, 2009), and of the support to the high primary productivity (Bromwich et al., 1998; Arrigo and van Dijken, 2003; Rhodes et al., 2009).

2.1.5 Sea ice and Roosevelt Island

Sea ice is one of the largest ecosystems on Earth, hosting a diverse range of organisms, from microscopic archaea and algae to small crustaceans, fish, and larger invertebrates (Arrigo, 2014). Sea ice has complex optical properties, such as reflection, absorption, and transmission of shortwave radiation (Perovich, 1996), building interesting notions on climate variability.

Sea ice forms in various ways depending on how the ocean surface responds to changes in atmospheric and environmental conditions (Comiso, 2010). The different configurations that represent sea ice are known as: pack ice, which is found offshore; land-fast ice, that forms when seawater reaches its freezing point; snow metamorphosis due to seawater infiltration during flooding events; and platelet ice which develops beneath the sea ice in regions located near floating ice shelves (Arrigo, 2014).

Roosevelt Island lies in a region of the Southern Ocean that experiences pronounced seasonal variability in sea ice extent (figure 15). Unlike other regions of the Southern Ocean, such as the Weddell Sea, where sea ice tends to persist throughout the year, the eastern Ross Sea undergoes complete or near-complete sea ice retreat in summer and re-formation in winter. These variations are strongly influenced by large-scale climate modes such as the SAM and the ENSO, which modulate sea ice extent, atmospheric circulation, and oceanic conditions in the region (Comiso et al., 2011; Bertler et al., 2018).

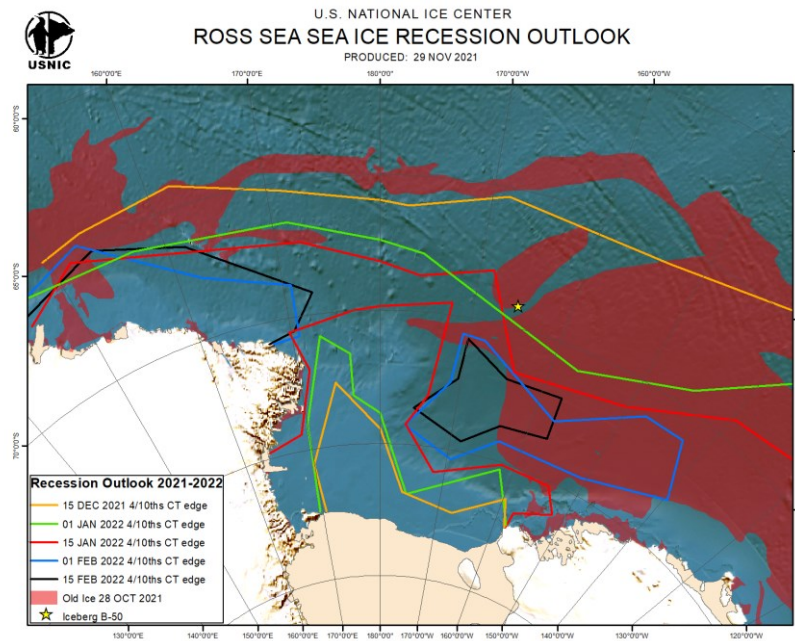


Figure 15: seasonal sea ice recession outlook for the Ross Sea region, highlighting the position of Roosevelt Island. This map illustrates the typical extent and retreat patterns of sea ice during the Antarctic melt season. (from U.S. National Ice Center, 2021).

ENSO, through its phases of El Niño and La Niña, alters the intensity and the direction of wind patterns, sea surface temperatures and precipitations, thus impacting sea ice dynamics in the Ross Sea (Yuan and Martinson, 2000). SAM, instead, reflects the north-south shift in westerly wind patterns encircling Antarctica, and influences the spatial variability of the sea ice. During a positive phase of the SAM, stronger westerly winds can push sea ice away from the Antarctic coast, leading to a reduced sea ice extent in the ERS and, at the same time, promoting the ice formation in the Weddell Sea, due to enhanced cold air advection and sea ice drift patterns. During a negative phase of the SAM, instead, weaker westerly winds contract toward lower latitudes, often resulting in increased sea ice extent in the ERS, due to reduced wind-driven ice export and weaker oceanic mixing. At the same time, sea ice formation in the Weddell Sea may decrease, as the advection of cold air masses and ice drift patterns are less pronounced (Stammerjohn et al., 2008; Turner et al., 2009).

2.1.6 Mineral dust particles in RICE

Mineral dust in the RICE ice core consists of insoluble particles sourced from New Zealand, southern South America, Australia, and ice-free areas of West Antarctica (Neff and Bertler, 2015; Winton et al., 2016).

Seasonal dust patterns align with black carbon peaking slightly in austral summer, though annual dust variability is driven by atmospheric transport, particle availability and depositional regime (Delmonte et al., 2017). Fe and Al typically peak during winter, while Mn peaks in summer, reflecting different intra-annual patterns (Tuohy et al., 2015). Unlike in East Antarctic sites, where dissolved calcium ions indicate terrestrial sources (Wolff et al., 2010), calcium at RICE has a predominantly marine origin during the Holocene. Therefore, in this context crustal elements such as Fe, Al, and Mn are considered more reliable indicators of continental dust inputs (Tuohy et al., 2015; Winstrup et al., 2019).

Higher dust concentrations are linked to storm-related precipitation, with deposition occurring mainly through wet deposition during snowfall (Tuohy et al., 2015). However, a 2-year snowpit (2011-2012 CE) shows episodic dust deposition with spring-summer maxima and winter minima, though winter dust events also occur (Winton et al., 2016b).

This pattern mirrors observations at other Antarctic sites, such as GV7, Berkner Island, and South Pole (Caiazzo et al., 2017; Bory et al., 2010; Legrand and Kirchner, 1988), highlighting the importance of windblown mineral dust, considered the primary insoluble impurity and the major tracer for paleo-atmospheric circulation (Delmonte et al., 2013).

2.1.7 Stable water isotopes and snow accumulation at RICE

Stable water isotopes are variants of water molecules, differing in the number of neutrons in their oxygen or hydrogen atoms, and they are commonly used in ice cores to reconstruct past climate conditions. These isotopes, such as deuterium (δD) provide valuable information about temperature, precipitation, and atmospheric processes (Dansgaard, 1964). At RICE, the deuterium (δD) data shows a positive correlation with surface air temperature, which reflects surface

air temperature variability across the Ross Ice Shelf, the Ross-Amundsen Sea, and Western Marie Byrd Land. Bertler et al. (2018) demonstrated that the Siple Dome site (figure 16) falls within the area of statistically significant temperature correlation with RICE. On the contrary, WAIS Divide doesn't share the same results and therefore this correlation is not available.

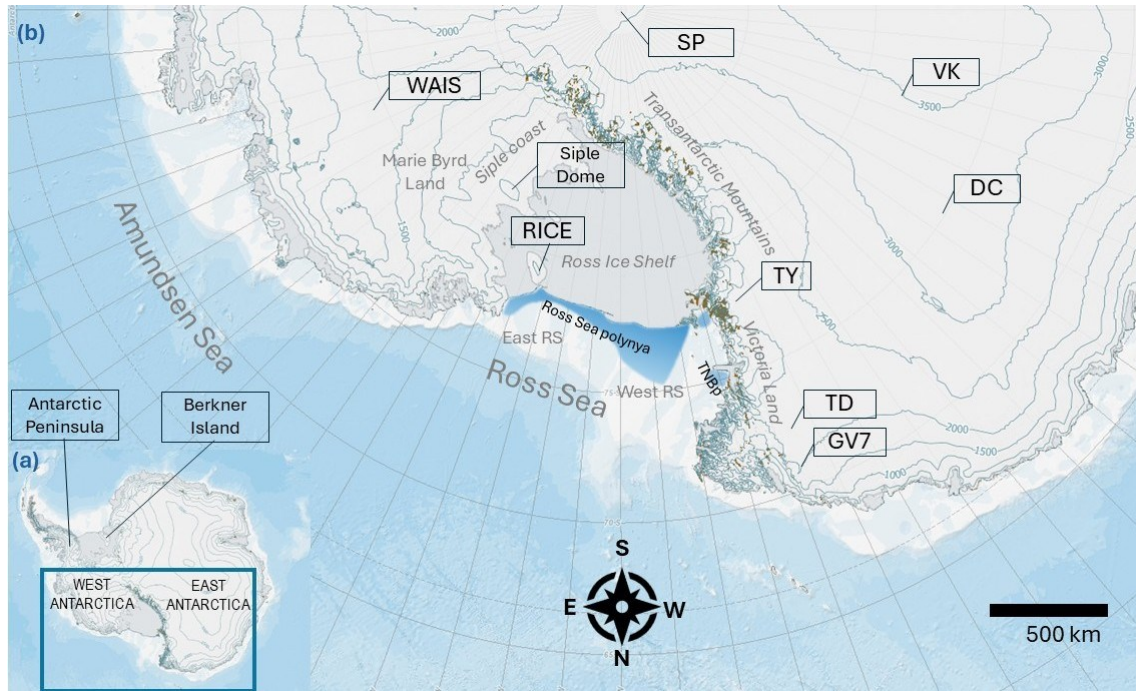


Figure 16: Map of Antarctica with regions and drilling sites cited in the text (source: SCAR Antarctic Digital Database, <https://add.scar.org/>). East RS: Eastern Ross Sea; West RS: Western Ross Sea; SP: South Pole; DC: Dome C; VK: Vostok; TY: Taylor Dome; TD: Talos Dome. Blue shaded area (redrawn from Mezgec et al., 2017) represent the Ross Sea polynya, and the much smaller McMurdo Sound and Terra Nova Bay (TNBP) polynyas. (Lagorio et al., 2024 –accepted for publication).

The δD stable water isotope composition, where δD refers to the ratio of deuterium (2H) to hydrogen (1H) in water, is the main indicator for past temperatures and atmospheric processes. At RICE, the δD composition of snow layers shows a negative correlation with sea-ice concentration (SIC) in the ERS and Northern Amundsen Sea (AS). This correlation suggests that less depleted isotope values occur during periods when air masses and moisture are advected from the nearby Ross Sea region under reduced sea ice conditions

(Emanuelsson, 2016, 2018; Bertler et al., 2018). Contrary, more isotopically depleted precipitations tend to occur during periods of expanded sea ice and/or when air masses travel across West Antarctica, before reaching RICE.

Sea ice in the ERS/Northern AS has also a strong influence on snow accumulation rates at RICE. Periods of reduced SIC are associated with increased snow accumulation and isotopically enriched water vapor, while a higher SIC corresponds with reduced snow accumulation and more isotopically depleted values (Emanuelsson et al., 2023; Bertler et al., 2011). Studying snow accumulation at coastal Antarctic sites such as RICE enables the interpretation of past climatic events, as it reflects both local sea-ice variability and broader atmospheric circulation patterns. Most snow accumulation occurs as snowfall, with clear sky precipitation (diamond dust) contributing only minimally (Sinclair et al., 2010). Intense snow accumulation typically happens when strong meridional (poleward) winds, associated with blocking anticyclones, bring isotopically enriched air masses from the open ocean north of the sea-ice edge to RICE (Emanuelsson et al., 2018, 2023). Modern meteorological data show that these blocking events, while occurring only about 12% of the time (1979-2014 CE), account for approximately 88% of the annual precipitation at the site (Emanuelsson et al., 2016). These events also generate N-NE winds that dominate at Roosevelt Island. Moreover, these large precipitation events are linked to extreme surface air temperature changes and to the formation of the Dipole pattern that is observed between the ERS and the WRS, as well as between the ERS and the Antarctic Peninsula (Lagorio et al., 2024). Blocking anticyclones divert the south-westerly wind flow in the 45°–70°S, 90°–150°W region toward West Antarctica, enhancing meridional wind flow, and interacting with low-pressure systems over the Ross Sea, contributing significantly to the East-West Ross Sea dipole (Emanuelsson et al., 2018).

2.2 Objectives of this study

This study presents new records of aeolian dust and diatoms from the RICE ice core, examining climate and atmospheric conditions in the Eastern Ross Sea over the last 2 ka. The data from the RICE ice core can also be linked to past atmospheric circulation patterns, demonstrating how dust particles and microfossils serve as reliable paleo-proxies for climate reconstructions and future projections (Bracegirdle et al., 2019).

Two main questions are explored:

- (1) What can dust and diatoms, preserved in RICE ice layers, reveal about climatic conditions on the Eastern Ross Sea and on Roosevelt Island?
- (2) How did the LIA manifest locally, and how does it fit within the broader Ross Sea context?

2.3 Methods

The RICE ice core samples were cut for dust and diatom analyses at the New Zealand ice core facility in Wellington. Each sample consisted in dome-shape ca. 15 cm long slices (15x35 mm) from the side of the RICE main core (figure 17, cutting plan: <http://www.rice.aq/core-processing.html>).

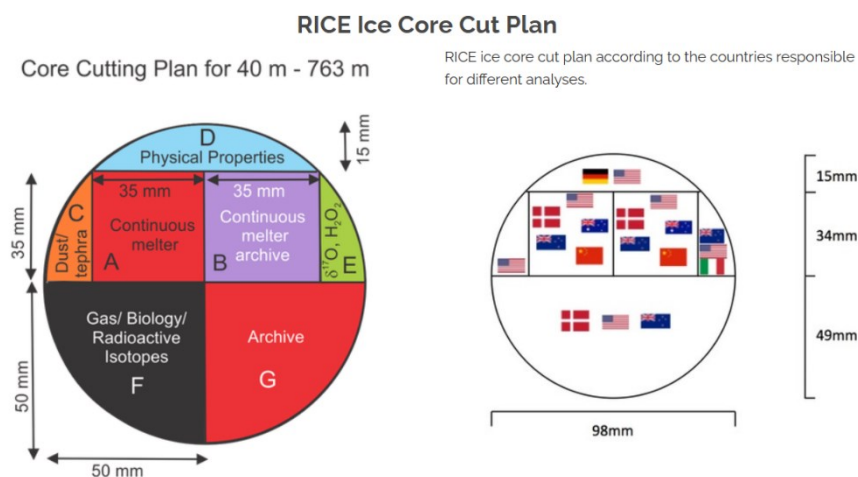


Figure 17: the dome-shaped slice from the RICE ice core that was designated for research and analysis in Italy.

2.3.1 Dust analyses

After shipment to Italy, a set of 412 samples spanning the Holocene climate period was measured for dust concentration and grain size at EUROCOLD Laboratory of Milano-Bicocca University. Dust analyses were performed inside a clean room following standard protocols (Delmonte et al., 2017), using Beckman Coulter Multisizers 4 and 4e, both equipped with orifice tubes having an opening of 30 μm . A rigorous intercalibration between the two instruments was implemented prior to the measurements. This setup allows detection of insoluble impurities with equivalent spherical diameter between 600 nm and 18 μm . Within this interval, from the dust size distribution spectra that are defined over 400 channels (log scale), the size distribution indexes of fine particles percent (FPP%) and coarse particle percent (CPP%) were calculated (Delmonte et al. 2017, 2020). Dust mass was calculated from volume-size distribution spectra assuming an average mineral density of 2.5 g/cm³ (Delmonte et al., 2020).

2.3.2 Diatom analyses

After completion of the dust analyses (~5 mL each aliquot), residual meltwater aliquots of 10 mL each were filtered on polycarbonate track-etched Isopore™ membranes with a porosity of 0.22 μm . These were mounted on glass slides and observed through a reflected light optical microscope (Olympus BX51M, magnification 100x, 500x, 1000x) in search for diatom valves and fragments (table 1). Each valve was identified and counted, then photographed (1000x) and measured for its apical and transapical axis length using the OLYMPUS Stream Essentials software. We note that the optical microscope-based approach used in this study is different from former literature works (Tetzner et al., 2022a, 2022b) where scanning electron microscopy (SEM) imaging was used for diatom counting and identification. Thus, to estimate the potential counting errors, we

compared both methods using a set of 10 samples selected from different depths along the core (from 48 to 625 m depth).

from 48 to 625 m depth	RICE ice core
N° of samples	131
Total diatom counts (n)	1055
Total diatom classified at genus level (n)	1055
Total diatom identified at species level (n)	1041
Total diatom fragments count (n)	323
Total volume filtered (ml)	1310
Mean volume filtered	10

Table 1: counts and basic identification of diatom valves found in the RICE ice core based on the light optical microscopy analysis with Olympus BX51M.

2.4 Results

The stable water isotope and the snow accumulation record from RICE (Bertler et al., 2018) are reported in figure 18a and 18b, respectively, along with the mineral dust size and concentration profile (figure 18c). This latter shows a pronounced variability (CV ~75% on average) during the last 2 kyr, with a mean of about 16.3 ppb (i.e. ngdust/gice). For particles smaller than 5 μm in diameter, concentrations are lower than 30 ppb for 90% of the time over the last 2 kyr. Given an average snow accumulation rate at RICE (Bertler et al., 2018) of about 25 cm w.eq. per year (figure 18b, data from Winstrup et al., 2019), the average dust flux for particles smaller than about 5 μm can be estimated around $4.2 \pm 3.8 \text{ mg m}^{-2} \text{ yr}^{-1}$ (figure 19). This estimate is in line with the flux of ca. $4 \text{ mg m}^{-2} \text{ yr}^{-1}$ calculated for the WAIS ice core site over the last 2.4 kyr (Koffman et al., 2014, figure 19). Such fluxes are about a factor ~2-3 higher than those calculated for peripheral East Antarctic high-elevation sites (e.g. Talos Dome and EPICA-DML). Also, they

exceed by a factor ~ 20 the Holocene dust fluxes calculated for inner East Antarctic plateau sites such as Vostok, Dome C and Dome B (Delmonte et al., 2020). Dust size data from RICE also show a degree of particle sorting that is different from central East Antarctic plateau sites (figure 20). Indeed, the FPP% and CPP% parameters span a much broader range interval at RICE (20-80% and 10-50% respectively) with respect to plateau sites (30-55% and 10-30%, respectively).

The decadal-smoothed profiles of dust size and concentration over the last 2 kyr are reported in figure 18c, along with their long-term smoothing to appreciate variability of the records. Dust concentration is expressed in log-scale, as recommended (Petit and Delmonte, 2009) to appreciate the variability of dust background.

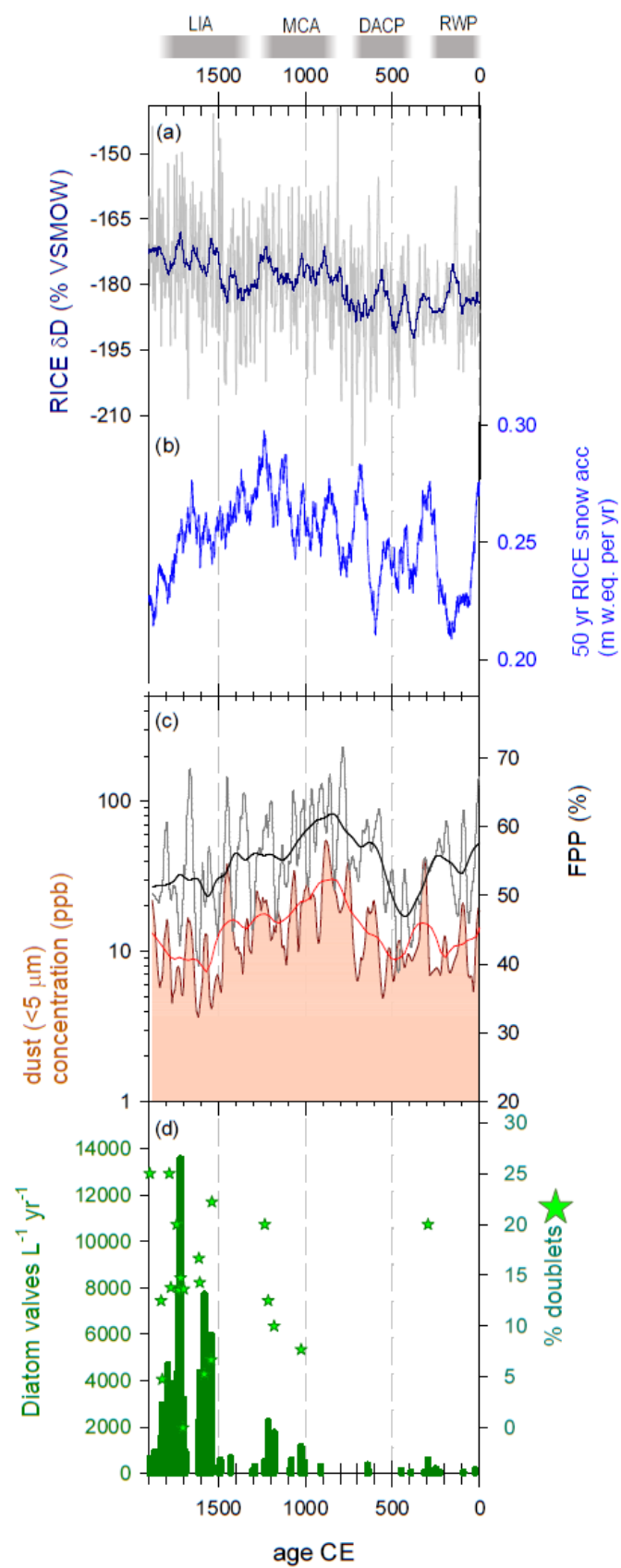


Figure 18: the climate history of RICE over the past ~2,000 years. RWP: Roman Warm Period; DACP: Dark Ages Cold Period; MWP: Medieval Warm Period; LIA: Little Ice Age. (a) RICE water stable isotope record (δD ‰VSMOW; blue line: 50-yr running mean); (b) Snow accumulation at the site (50-yr running mean). (a) and (b) data from Bertler et al., 2018. (c) Dust size index FPP (%) defined as in Delmonte et al. (2017), 20-yr running mean; (d) Concentration (ppb) of dust particles smaller than $5 \mu m$, linear scale; (e) Diatom content of samples, expressed as number of diatom valves per Liter per year. Green stars indicate the percentage of doublets in the samples.

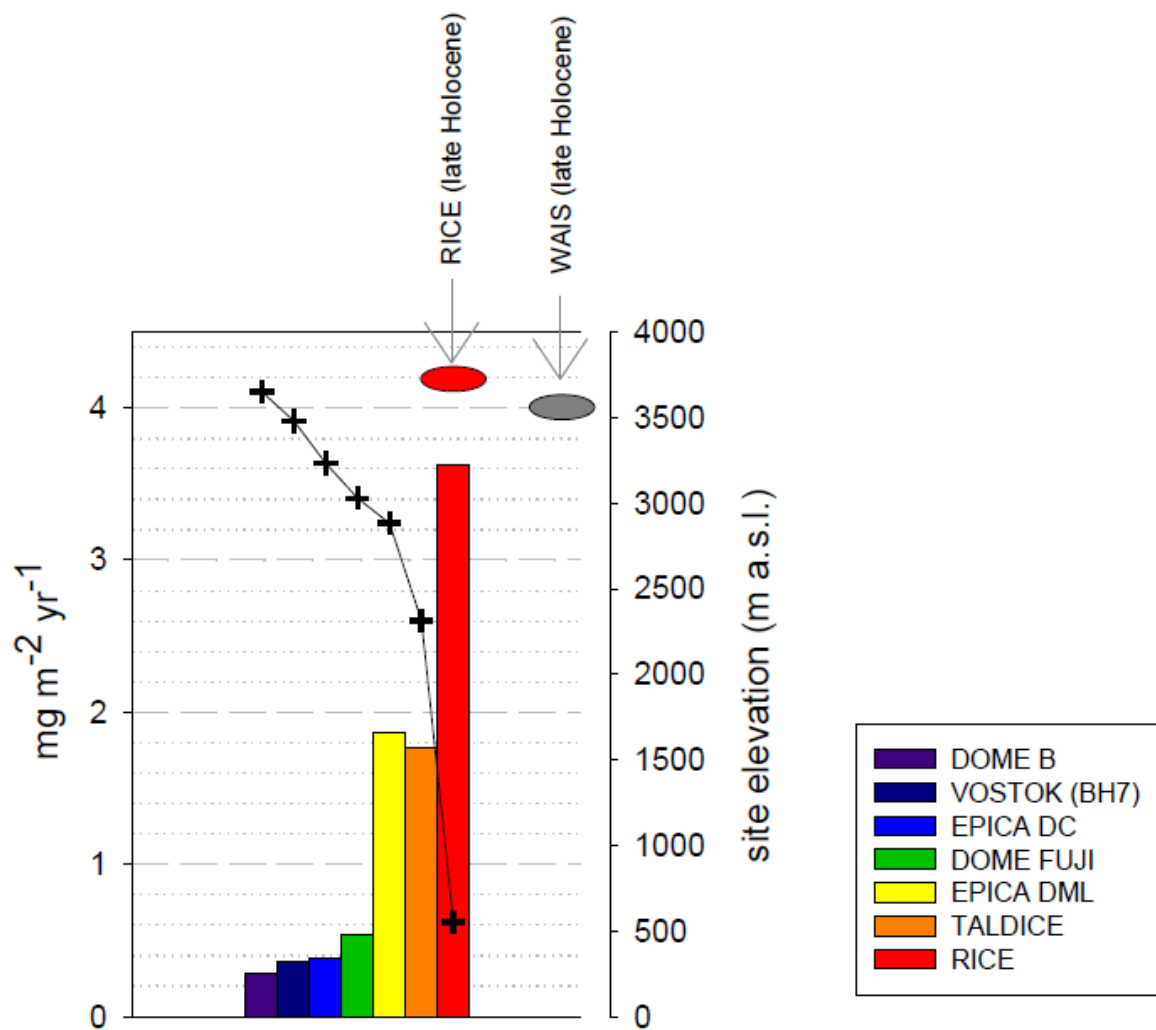


Figure 19: mean dust fluxes at different East Antarctic sites calculated over the entire Holocene (from Delmonte et al., 2020 and references therein), compared to RICE. The altitude of each drilling site is also reported. The Late Holocene dust fluxes for RICE (this work) and WAIS (Koffman et al., 2014) are also reported.

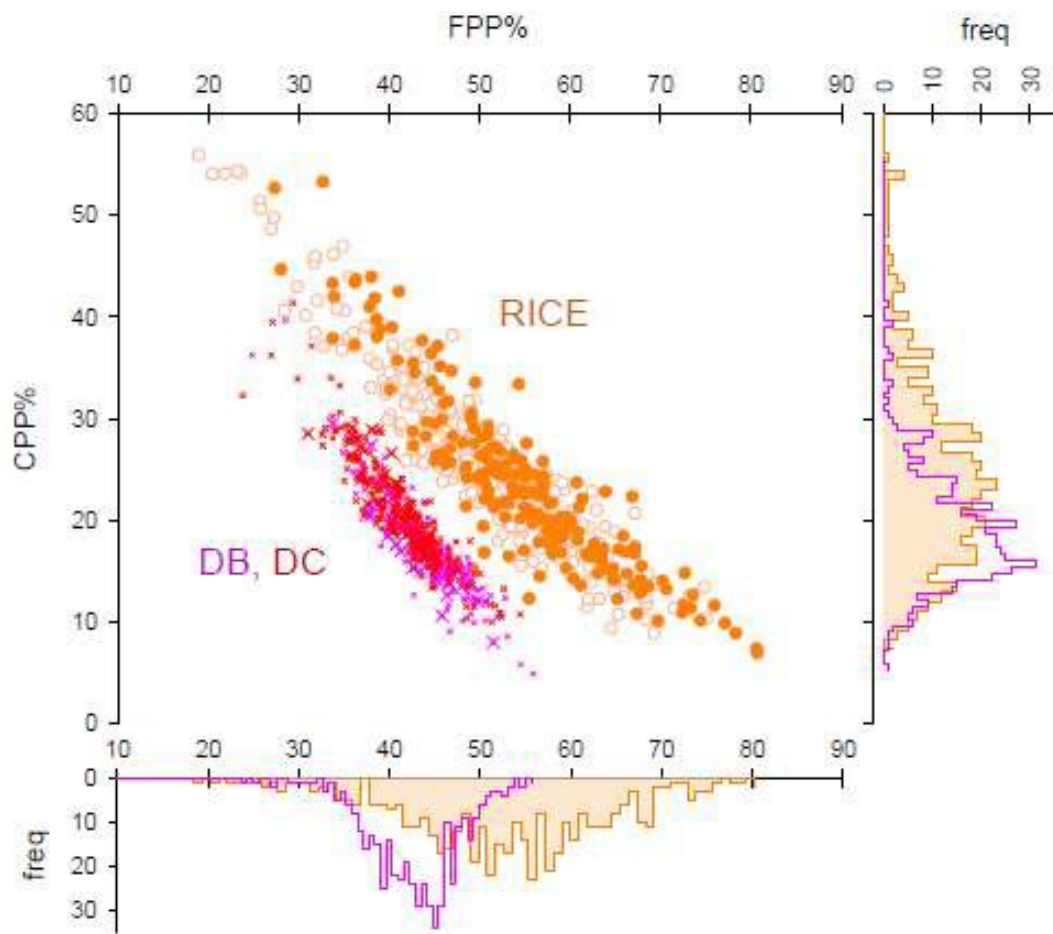
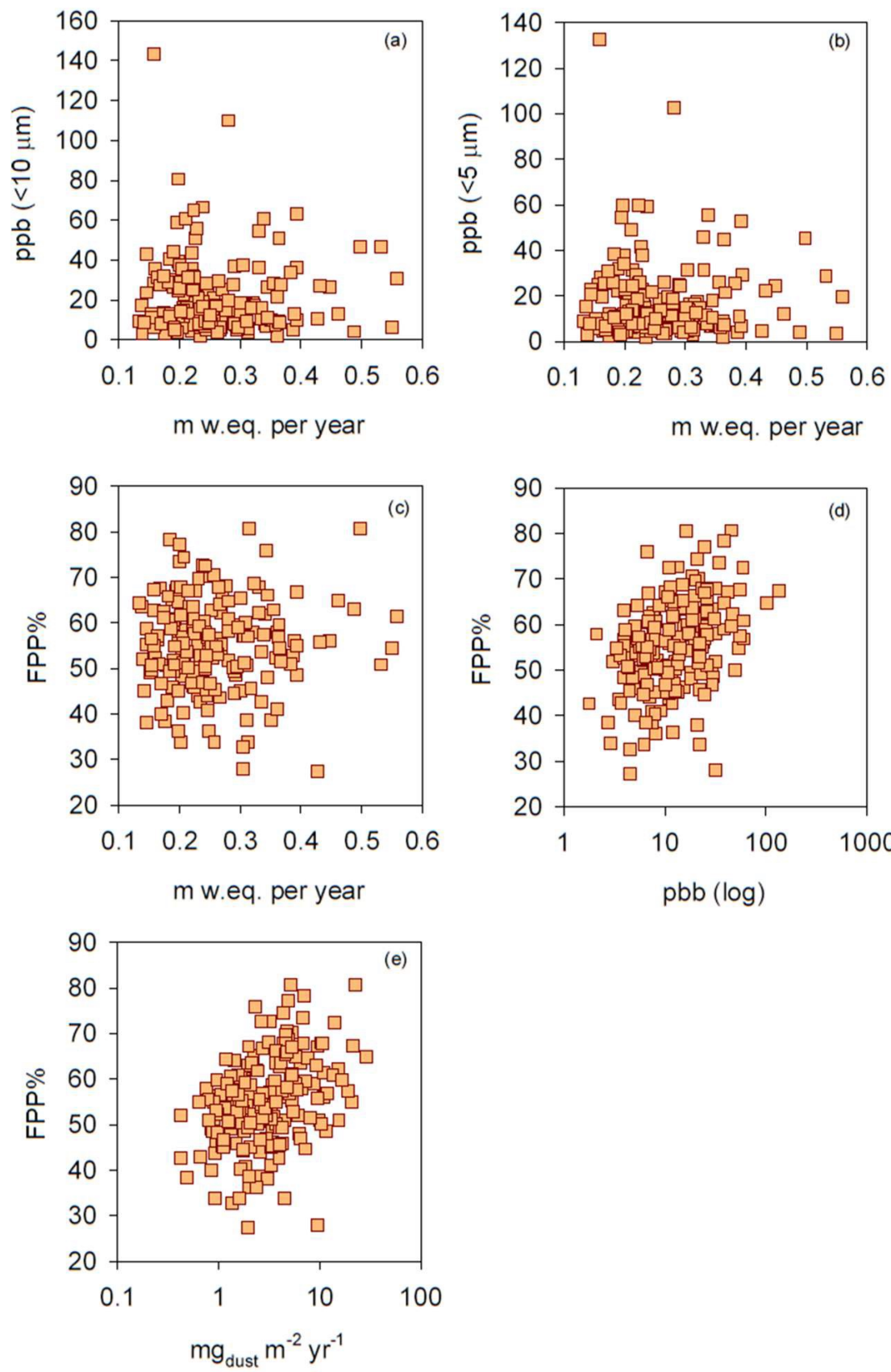


Figure 20: Fine Particle Percent (FPP, %) vs Coarse Particle Percent (CPP, %) calculated according to Delmonte et al., (2005) for East Antarctic plateau sites (Dome B, Dome C) and for RICE. Small 'x' symbols correspond to Holocene data from Dome B (pink) and Dome C (red) while large 'X' symbols correspond to data for the same sites but from the last 2700 years. Similarly, open and filled circles represent RICE data for the Holocene and the last 2,000 years, respectively.

Overall, there is no correlation between snow accumulation and particle concentration neither for particles smaller than 10 μm (figure 21a) nor for those below 5 μm (figure 21b). There is also lack of correlation between snow accumulation and dust grain size (figure 21c). Conversely, good agreement exists between dust concentration (flux) and dust grain size, as confirmed by the Pearson Product Moment Correlation between the variables (figure 21d and e). This means that the major dust inputs are related to fine particle advection.



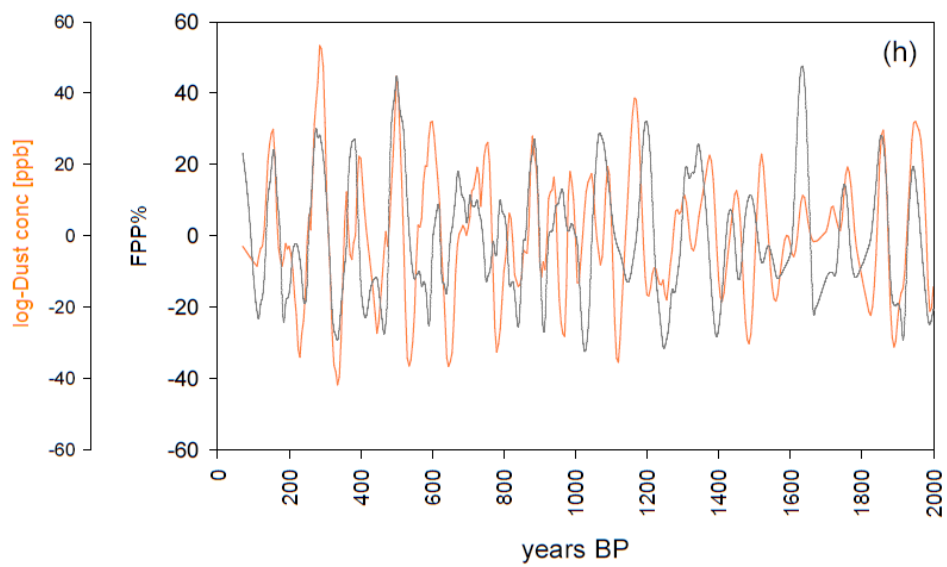
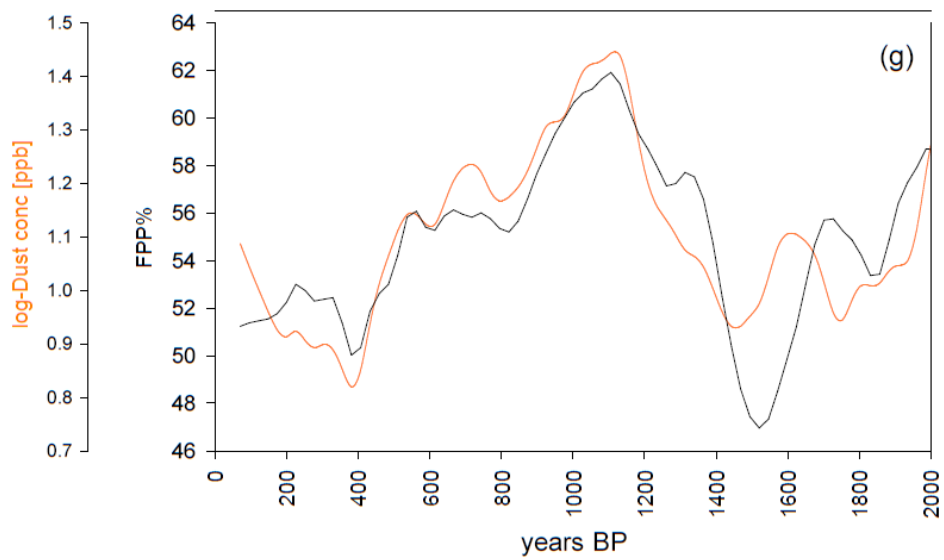
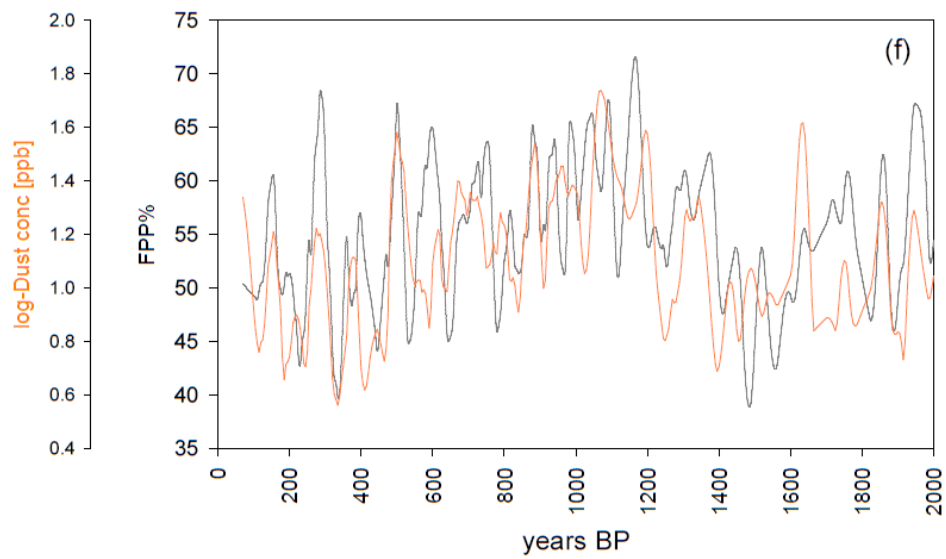
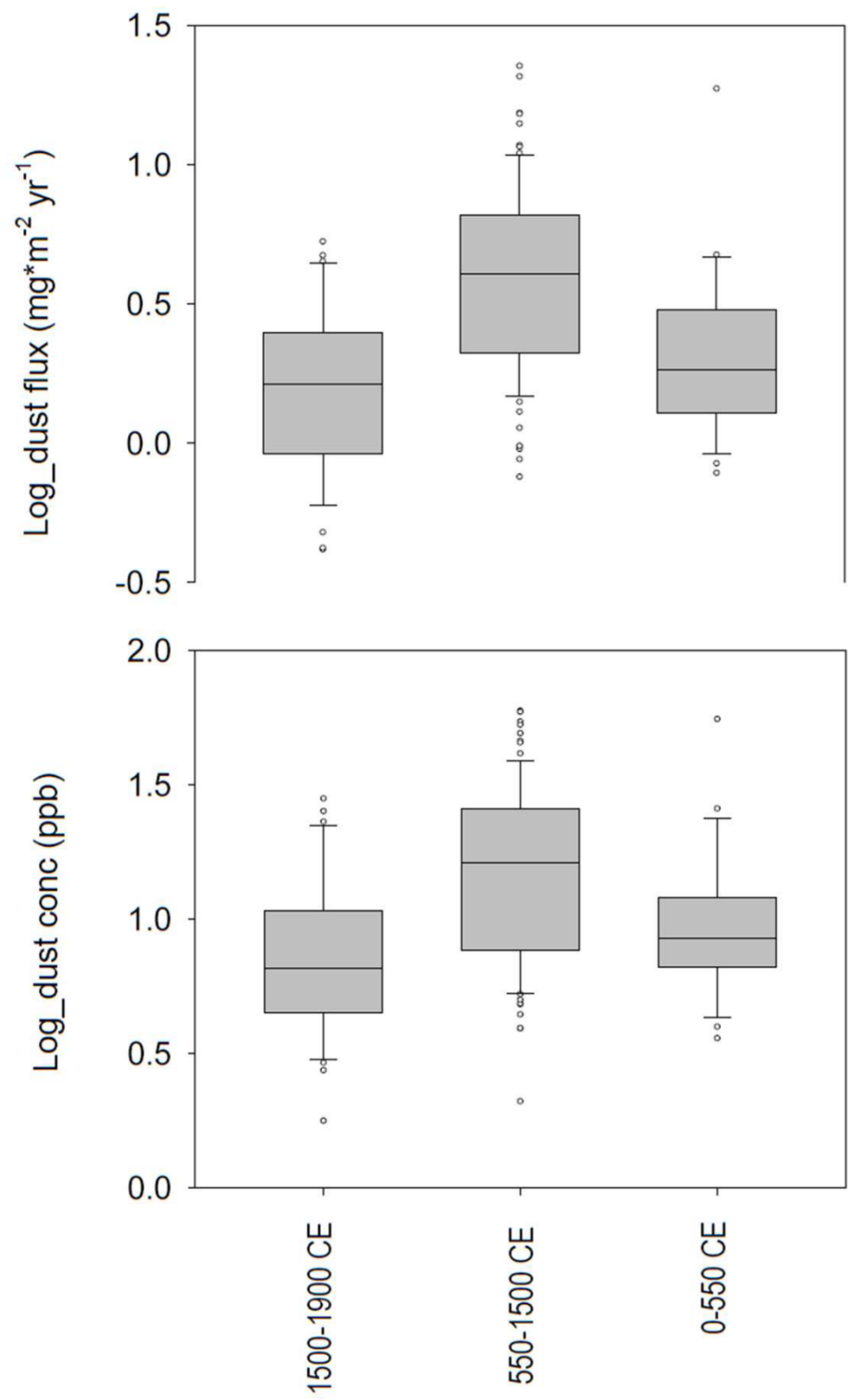


Figure 21: plots (a) and (b) show the lack of correlation between snow accumulation rate and dust concentration. Plot (c) illustrates the lack of correlation between snow accumulation rate and the Fine Particle Percentage (FPP%) while plots (d) and (e) display dust concentration data ($< 5 \mu\text{m}$, ppb, log scale) and flux ($\text{mg m}^{-2} \text{yr}^{-1}$) versus FPP%. The Pearson Product Moment Correlation confirms that the two variables are moderately correlated and tend to increase together (plot d: correlation coefficient 0.335, $P_value=0.00000245$; plot e: correlation coefficient 0.311, $P_value=0.0000129$, $n. \text{ samples}=189$).

Plot (f) displays the stratigraphic profile of dust concentration (log) and dust size (FPP%) vs age as in figure 18 (c) and 18 (d), 20-yr running average. Plot (g) is the Loess local smoothing of original data (polynomial degree 1, sampling proportion 0.1) highlighting the similarities in the long-term trend of the records. Plot (h) shows the log-dust concentration and grain size anomalies normalized (%).

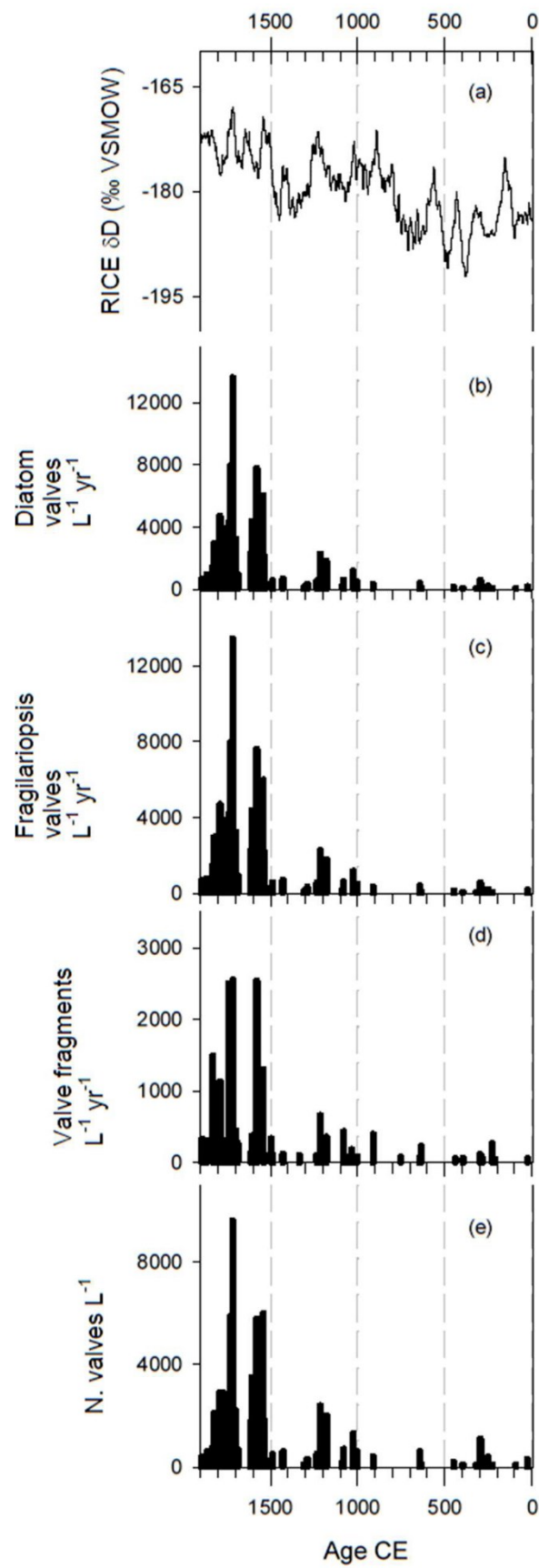
Both the dust size and concentration records highlight a long-standing period of relatively high dust input starting around 550-600 CE and ending around 1470-1500 CE (figure 18c), that was qualitatively deduced based on visual inspection of the record. The beginning and the end of this period broadly coincide with the two-step changes of δD (figure 18a), identified at $580 \text{ CE} \pm 27 \text{ years}$ and $1477 \text{ CE} \pm 10 \text{ years}$ by Bertler et al. (2018) using a minimum threshold parameterisation to achieve a minimised residual error. However, we note that a detailed comparison between dust and stable isotope records in terms of leads and lags of changes is limited by the very different sampling resolution of the two records. In correspondence to the period from about 550 CE to about 1470 CE, when the stable water isotope record shows an increase of 3‰ , the dust record shows concentrations (and fluxes) higher than average for more than 50% of time, while during the following period from 1470 CE to about 1900 CE, when the stable isotope increases again of 5‰ , the dust levels sharply drop to relatively low levels, remaining below average for about 88% of time. The relative difference of dust concentration and fluxes between the three periods 0-550 CE, 550-1500 CE and 1500-1900 CE can be better appreciated from boxplot graphs (figure 22). These two latter periods, that are of particular interest to this study, proved to

have statistically-significant differences in dust concentration and fluxes on the basis of t-test statistics.



*Figure 22: boxplots of the logarithm of dust concentration and flux for the three climatic periods discussed in the text. Statistical t-tests performed on the concentrations (log) and fluxes (log) from the 550-1500 CE and the 1500-1900 CE periods highlighted that differences between these two periods are statistically significant. T-test statistics were performed on dust concentrations (log_ppb) and dust flux (log_mg*m⁻² per yr). Both series passed the normality and the equal variance test. P value <0.001 (t = 5.205 with 122 degrees of freedom) was obtained for Log_ppb. Also, P-value <0.001 (t = 6.103 with 122 degrees of freedom) was obtained for the logarithm of dust flux. This means that the difference in the mean values of the two series between 550-1500 CE and 1500-1900 CE is greater than would be expected by chance, hence there is a statistically significant difference between the two groups.*

The stratigraphic record of aeolian diatoms from the RICE ice core is shown in figure 18d as well as in figure 23 (b to e). Both the absolute value and the valve fragment abundance from this study were normalised considering the time period represented by each sample, spanning ~0.6 to ~2.5 years, in agreement with former studies (Tetzner et al., 2021). The diatom record shows a background influx in the order of 180 valves per Liter per year (valves L⁻¹ yr⁻¹) before about 1500 CE, with two minor increases of up to about 2000 valves L⁻¹ yr⁻¹ around 1200 CE. After the ~1470 CE event of drastic dust decrease and increase in the stable water isotope values, two prominent diatom peaks appear. These peaks exceed 4000 valves L⁻¹ yr⁻¹ and are unprecedented over the last 2 kyr (figures 18d, 23). Diatom peaks are particularly prominent in the periods 1530-1610 CE and 1700-1830 CE for all three indicators - absolute diatom concentration, diatom flux and number of valve fragments detected in the samples (figure 23). As diatom concentration and flux data are not lognormally-distributed, the nonparametric Mann-Whitney Rank Sum Test was used as statistic tool to compare the total valve concentration and flux between 1500-1900 CE and the earlier period (0-1500 CE). Results confirm that the difference in the median values between the two groups is greater than would be expected by chance, i.e. there is a statistically significant difference between the two periods.



*Figure 23: diatom data from RICE. (a) 50-years running average of RICE δD (‰VSMOW), (b) diatom valves (entire) per liter per year, (c) *Fragilariopsis* spp. Valves (entire) per liter per, (d) Valve fragments per liter per year, (e) Valves per liter.*

Regarding diatom analysis, a comparison between optical and electron microscopy revealed that out of a total of 184 valves and 84 fragments, only 2 valves and 16 fragments were missed using the optical method (figure 24). Therefore, we estimate that the optical-based diatom abundances reported in this study may be underestimated by approximately 1% for valves and 19% for fragments compared to the SEM-based analysis. The higher percentage for fragments may be due to their smaller size, which makes them more challenging to identify. Overall, we conclude that the optical-based method used for diatom counting in this study is as reliable as the SEM analysis.

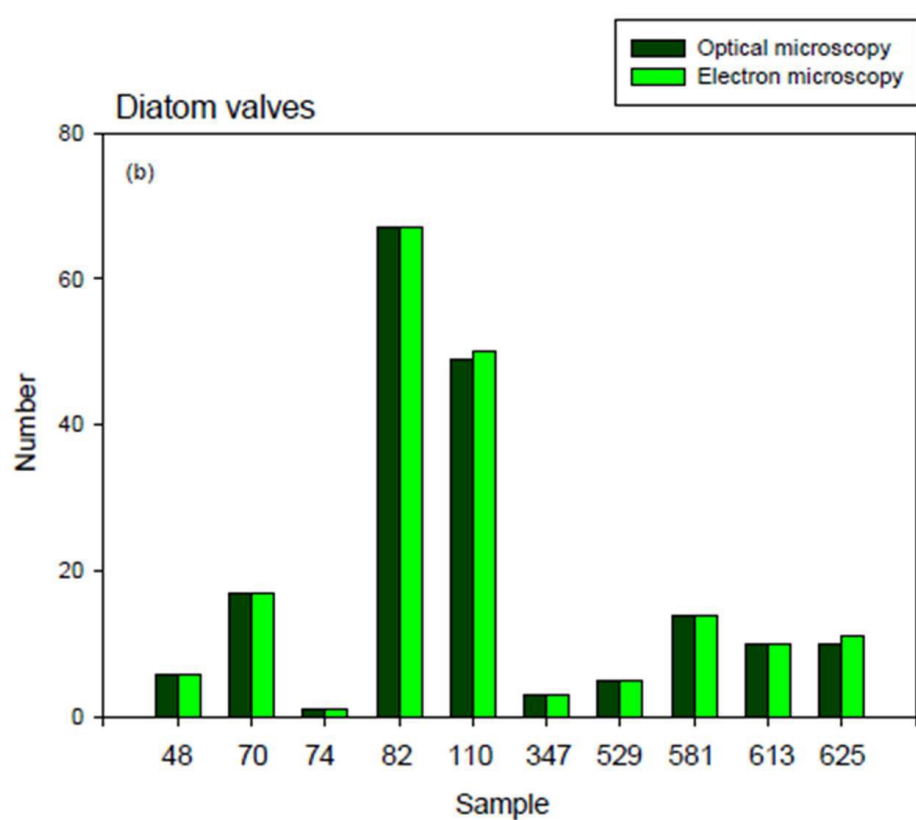
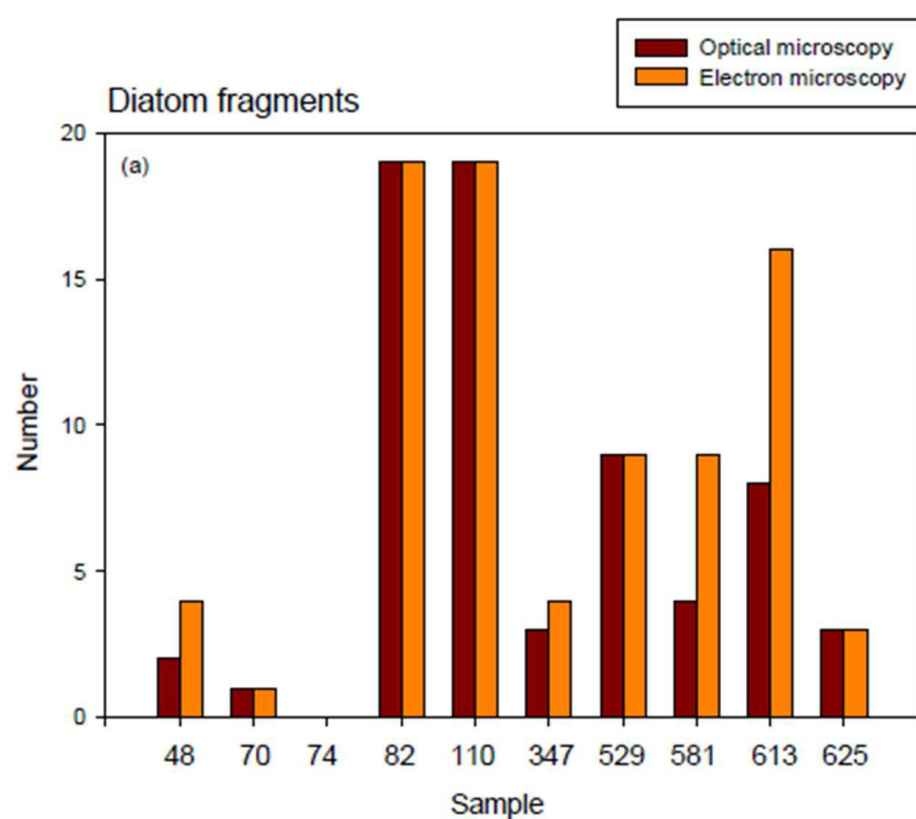


Figure 24: number of diatom fragments (a), and entire diatom valves (b) identified in a set of 10 different samples along the RICE ice core using two independent microscopic techniques: optical microscopy (a: dark orange, b: dark green) and Scanning Electron Microscopy (a: light orange, b: light green). Sample number (x-axis) corresponds to the approximate depth of the sample. For this comparison, the age of samples spans the whole Holocene.

While entire valves could be identified to the species level, this was not the case for most diatom fragments. More than 98.5% of diatom valves were *Fragilariopsis* spp. (figure 25), which we consider as a unique group. We observed *F. nana* and *F. cylindrus*, with occasional presence of *F. curta* (figure 25). Sporadically, doublets of two *F. cylindrus* valves (i.e. pairs of diatom valves attached to one another, forming the simplest colony structure) were detected (figure 25d) in the most recent section of the record (figure 25d). Results from morphometric measurements of entire valves oriented in valve view on the filters (figure 26) show that about 95% of valves display apical axis between 3.4 and 11 μm (mode ~ 5.3 μm) and transapical axis between 1 and 3.5 μm (mode ~ 2.2 μm). These data highlight that most diatoms are small-sized, with dimensions similar to those of *F. nana* and *F. cylindrus*, which are similar to the size of mineral dust at RICE (Winton et al., 2016b). As a result, this dimensional similarity makes it challenging to use filtration techniques to separate dust from diatoms, or to apply deep neural networks for identifying diatoms within the samples (Maffezzoli et al., 2023).

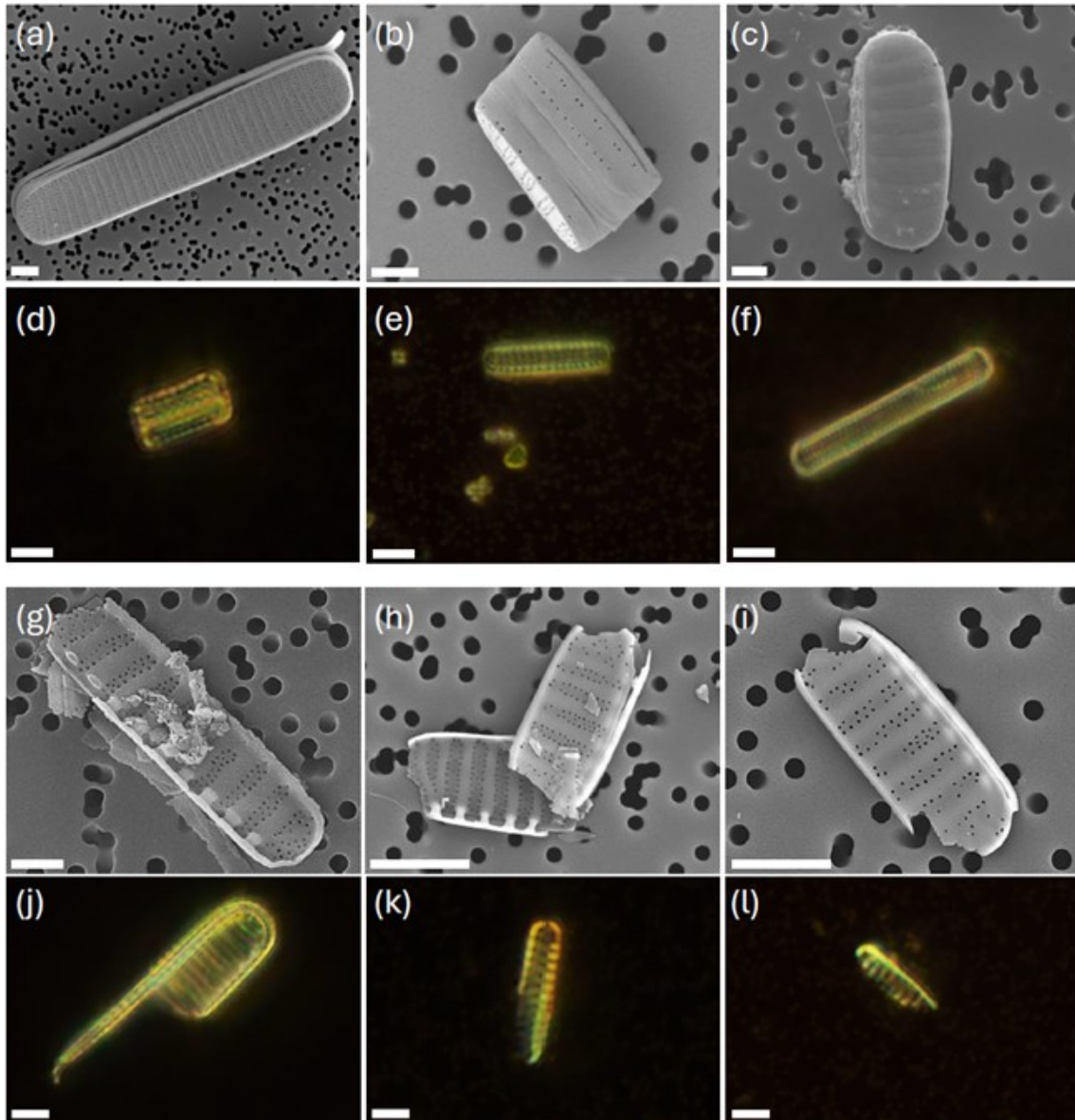


Figure 25: Scanning Electron Microscope (a, b, c, g, h, i) and optical microscope (d, e, f, j, k, l) images of entire diatom valves (a to f) and valve fragments (g to l). Figure a is a *F. curta*, figure b is a *F. cylindrus* in girdle view, figure c is a *F. cylindrus* in valve view, figure d is a doublet of *F. cylindrus*. Fragments: figures g and j are *F. curta*, while figures h, i, k, l are *F. cylindrus*. Scale bar: 1 μm for SEM images and 5 μm for optical images (magnification 1000x).

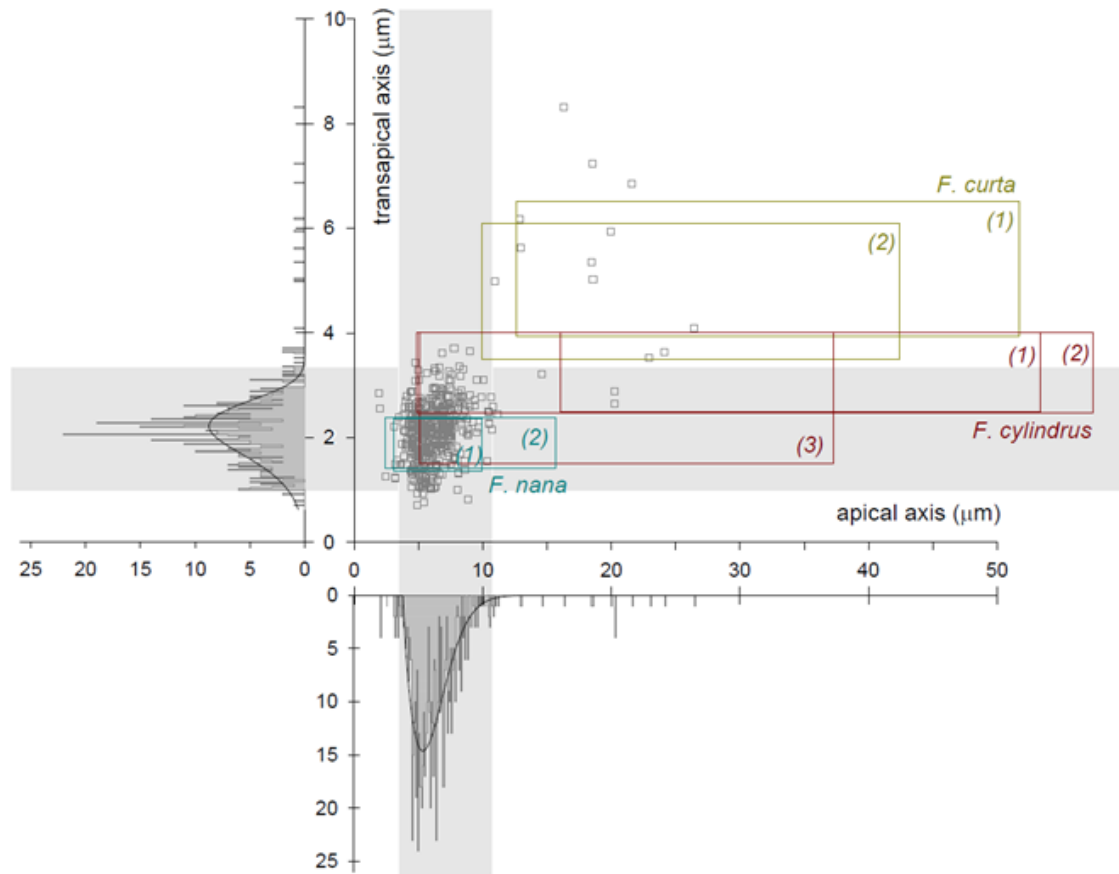


Figure 26: morphometric data of entire valves from the RICE ice core. Apical axis (μm) vs transapical axis (μm). Frequency histograms (bottom and left) are also reported. Grey bands indicate the interval where 95% of specimens are included. Boxes with n.1 refer to morphometric data for *F. cylindrus*, *F. nana*, *F. curta* from Cefarelli et al., 2010; boxes marked with n.2 refer to earlier literature morphometric data collected and listed in Cefarelli et al., 2010. Box with n. 3 refers to data from Lundholm and Hasle (2008) for *F. cylindrus*.

Fragilariopsis Hustedt is a genus of marine diatoms that includes many planktonic species, a few benthic species, and several species associated with sea ice (Round et al., 1990; Cefarelli et al., 2010). Spatially, *Fragilariopsis* spp. has been observed in a variety of habitats: within sea ice and ice melt zones (Aslam et al., 2018; Leventer, 1998), at ice edges (Kang and Fryxell, 1992), in sediments (Gersonde and Zielinski, 2000), and only rarely in open waters (Lundholm and Hasle, 2008).

In girdle view, their frustules appear rectangular or elliptical-linear-lanceolate, while in valve view those can be either isopolar or heteropolar (Round et al., 1990). When present, the canal raphe is distinctly eccentric, lies flat with the valve, and lacks poroids on the outer wall (Round et al., 1990). The valve striae are separated by prominent interstriae and typically contain two rows of poroids. The striae are generally parallel, except near the poles (Round et al., 1990). The valve mantle may either lack pores or display striae with one or more rows of poroids. Girdle bands, composed of a series of siliceous hoops (Medlin et al., 1993), resemble the mantle and can be unperforated or feature one or more rows of poroids. Like other photosynthetic algae, *Fragilariopsis* diatoms have two chloroplasts, located on either side of the median transapical plane (Von Quillfeldt, 2001). *Fragilariopsis* species typically form flat, ribbon-like colonies, where most or all the valve face is joined (Round et al., 1990; Cefarelli et al., 2010).

In this study, *Fragilariopsis cylindrus* diatoms were observed as solitary cells or as doublets, consistent with the description provided by Cefarelli et al. (2010). This species typically does not form planktonic algal communities after the ice melts (Leventer, 1998).

The valve shape is linear and isopolar, with broadly rounded ends. Cefarelli and colleagues (2010) reported that *F. cylindrus* has an apical axis length of 15.5–55.0 μm and a transapical axis of 2.4–4.0 μm , with 10–16 transapical striae in 10 μm . The striae are straight, typically perforated by two rows of poroids, though rarely three. Toward the valve ends, the striae become nearly parallel to the apical axis (Cefarelli et al., 2010).

Frenguelli (1958) revisited the length and width measurements of *F. cylindrus*, finding a valve length of 5–37 μm , a valve width of 1.6–4.0 μm , and 14–16 striae in 10 μm . These dimensions correspond to both *F. cylindrus* and *F. nana*, which are morphologically similar. However, in 2008, Lundholm and Hasle distinguished the two species based on valve width and the number of poroid rows per stria: *F. cylindrus* has a width of 2.4–4.0 μm and 40–60 poroids, while *F. nana* has a width of 1.4–2.4 μm and 60–80 poroids. In this study, all observations were classified under the name of the species *F. cylindrus*.

F. cylindrus is a marine planktonic and ice-dwelling diatom species found in both polar regions (Lundholm and Hasle, 2008). It is commonly used as a proxy to track sea ice distribution over time, as its presence is influenced by sea ice extent and retreat in response to climatic events (Von Quillfeldt, 2004; Gersonde and Zielinski, 2000). In the Weddell Sea, *F. cylindrus* has been reported as abundant in the pack ice and in the water column near the ice edge (Kang and Fryxell, 1993).

Fragilariopsis nana typically exists as a solitary cell, though it can occasionally form doublets (Cefarelli et al., 2010). The valve shape is linear and isopolar, with broadly rounded ends. The apical axis ranges from 3 to 10 μm , while the transapical axis is 1.5 to 2.2 μm . The transapical striae number 14–20 in 10 μm . The striae are straight and perforated by two or three rows of poroids, with the rows becoming radiate or nearly parallel to the apical axis toward the valve ends (Cefarelli et al., 2010).

This species is marine planktonic and ice-dwelling, found in both polar regions (Lundholm and Hasle, 2008).

Fragilariopsis curta exhibits a linear, heteropolar valve shape, with one end wider than the other, and both ends rounded. The apical axis typically ranges from 12.5 to 54.5 μm , while the transapical axis is between 4.0 and 6.5 μm . The transapical striae number 10–14 in 10 μm and are generally straight to slightly oblique, curving near the ends. Each stria is usually perforated by two rows of poroids, though occasionally there may be three. Toward the ends of the valve, the rows of poroids become more radiate or perpendicular (Cefarelli et al., 2010).

F. curta is a marine diatom commonly found in cold southern regions, inhabiting both plankton and ice environments, as well as oceanic and neritic waters. It is one of the most prevalent species in the Weddell Sea (Kang and Fryxell, 1993; Hegseth and Von Quillfeldt, 2002; Cefarelli et al., 2010). Initially identified as *F. cylindrus* due to its similar length, *F. curta* was later distinguished by its heteropolar valve shape, in contrast to the isopolar shape of *F. cylindrus*, providing a basis for recognizing them as separate species.

2.5 Discussion

2.5.1 Transport of dust and diatoms to RICE

The influx of mineral dust aerosols onto the Antarctic ice sheet shows significant variation across space and altitude, as highlighted by the pronounced dust flux gradients in both East and West Antarctica (figure 19). The central East Antarctic plateau is mainly impacted by well-sorted dust of remote origin, characterized by low flux values and small dust grains. In contrast, West Antarctica (Koffman et al., 2014) and peripheral Antarctic ice sheet sites (Delmonte et al., 2013; Bory et al., 2010) experience a mix of local and remote dust sources, with a different atmospheric transport regime than plateau sites (Petit & Delmonte, 2009). In this respect, our new dust data from RICE offers an important addition to the understanding of the dust cycle in coastal, low-elevation sites. The paleoclimatic significance of aeolian dust and diatoms transported to RICE is closely tied to its geographic and glaciological setting. Roosevelt Island is a grounded coastal ice rise at the northeastern margin of the Ross Ice Shelf, deeply influenced by its proximity to the open ocean and its neighbouring sea ice zone. Hence, the transport of terrestrial and marine aerosols to the site is very complex. Back trajectory analyses (5 days) of seasonal airmasses for the period 2006-2012 CE (Tuohy et al., 2015) revealed that austral summer trajectories are dominated by three clusters: one is related to local short-range transport, two others represent long-range transport. One of these long-range clusters consists of the distal oceanic component, driven by low-pressure systems moving across the Southern Ocean. This cluster is responsible for the transport of marine aerosols to the RICE site (Tuohy et al., 2015). The second long-range cluster involves air masses that travel over long distances, passing over the South Pacific landmasses before reaching RICE through the West Antarctic/Amundsen-Bellingshausen Seas (ABS, Tuohy et al., 2015). Since these latter pathways are linked to the significant transport of heavy metals and dust to RICE, Tuohy et al. (2015) concluded that the transport of mineral dust is closely tied to large-scale atmospheric circulation patterns in the South Pacific sector of the Southern Ocean.

Among atmospheric forcing factors responsible for the modulation of long-range transport of dust, we mention the state of the Amundsen Sea Low (ASL), a climatological low pressure centre in the ABS and Eastern Ross Sea area, which is in turn strongly affected by large-scale atmospheric circulation modes of variability such as the Southern Annular Mode (SAM) and the El Niño-Southern Oscillation (ENSO, Emanuelsson et al., 2023).

The aeolian transport of diatoms at RICE follows instead a different atmospheric pattern. Most diatom species are marine planktonic and sea ice-related, supporting a proximal marine origin of diatom-transporting air masses. This hypothesis is corroborated by the evidence of an exceptionally high degree of valve preservation, sometimes being present as doublets in our record. These fresh-looking aspects of diatoms suggest a rapid transport of the cells directly from the proximal marine source to the RICE ice core site and support the hypothesis that the main diatom source at the site is represented by the nearby Ross Sea waters.

Previous studies (Allen et al., 2020; Tetzner et al., 2021, 2022a, 2022b) on West Antarctica and the Antarctic Peninsula have shown that diatom species and their seasonal variability can differ between coastal, low-elevation sites and continental, high-elevation sites. Coastal areas exhibit a distinct seasonal signal, dominated by species such as *F. cylindrus* and *F. curta*, which are typically sourced from the seasonal sea ice zone (SSIZ). In contrast, continental sites at higher elevations are enriched with open ocean diatoms from distal sources (Tetzner et al., 2022b). Additionally, the seasonal signal at these higher elevation sites is less pronounced.

In this sense, RICE mostly resembles coastal sites of the Peninsula, where local diatom transport is predominantly related to local oceanic air mass transport. The stratigraphic records of aeolian dust and diatoms at RICE, therefore, are highly complementary since they are related to different types of atmospheric transport. As discussed below, these new records open new perspectives on the interpretation of the paleoclimatic signals from the core.

2.5.2 Environmental changes at RICE in the context of the Ross Sea region: the period from 0 CE to 1470 CE

The reconstruction of dust and diatom variability at RICE offers a valuable opportunity to explore the influence of key drivers of regional climate conditions over the past two millennia, as well as the major atmospheric and oceanic changes in the Eastern Ross Sea area. Throughout the dust record, we observe that periods of elevated dust concentration and flux are generally associated with finer particles. This suggests that the most significant dust transport events at RICE are linked to the advection of remotely-sourced particles, rather than local transport. Although no statistically significant relationship is found at finer time scales, periods of increased dust input at RICE, including the extended period from 550-1470 CE, which encompasses the Medieval Climate Anomaly (MCA), appear to coincide with higher snow accumulation rates and more enriched stable water isotope values, at least until around 1250-1300 CE. Bertler et al. (2018) found that stable isotopes exhibit a statistically significant negative correlation with sea-ice extent in the South Pacific (AS/ERS). Therefore, periods of increased dust input generally align with periods of reduced sea-ice extent in the ERS sector of the Southern Ocean, as indicated by higher snow accumulation rates and more enriched stable water isotopes. We conclude that increases in dust, stable isotopes and snow accumulation are associated with reduced sea-ice extent in the ERS and more effective penetration of long-range northerly air masses to the RICE site. Since dust-rich air masses typically travel above the marine boundary layer (Petit & Delmonte, 2009), we do not expect to observe significant input of open ocean marine diatoms together with mineral dust. Indeed, our data indicates that during periods of increased dust content, only background levels of aeolian diatom influx are detected at the site. (figure 18, figure 23).

To put our climate reconstruction at RICE into the broader context of the Ross Sea region, we compare our data with TALDICE ice core records from Talos Dome. This site is located on the periphery of the East Antarctic plateau facing the Ross Sea and the South Pacific (figure 16). The sea-salt sodium (ssNa) record from the site has been interpreted as related to the extent of newly-formed

pack ice in the Western part of the Ross Sea. We observe therefore (figure 27b) that around 800-1000 CE the extent of pack-ice neoformation in the WRS was very low (Mezgec et al., 2017), while it increased from ~1000 CE to 1300 CE. In parallel, we observe that between ~800 and 1000 CE, the Ross Sea “polynya efficiency” index was indeed also quite low, while it increased from about 1000 CE. This polynya-related parameter was introduced by Mezgec et al. (2017) and since it is derived from a stacked marine record of *F. curta* from the coastal sea ice zone of the WRS and from the ssNa record from Taylor Dome, it is mainly linked to the activity of the Ross Sea polynya on its westernmost side.

Interestingly, around 1200-1300 CE, when the RICE snow accumulation reaches its maximum and dust influx remains high (suggesting an efficient marine air mass penetration to the site), the sea ice in the ERS and Amundsen Sea was likely minimum while, conversely, pack-ice extent in the WRS was at its maximum extent. We deduce that the period around 1200-1300 CE was the time when the Ross Sea experienced a strong sea ice dipole between its eastern and western parts (figure 27b-c). This time period coincides with maximum expression of the Ross Sea temperature dipole observed from the comparison of stable water isotope records of RICE and TALDICE (Bertler et al., 2018).

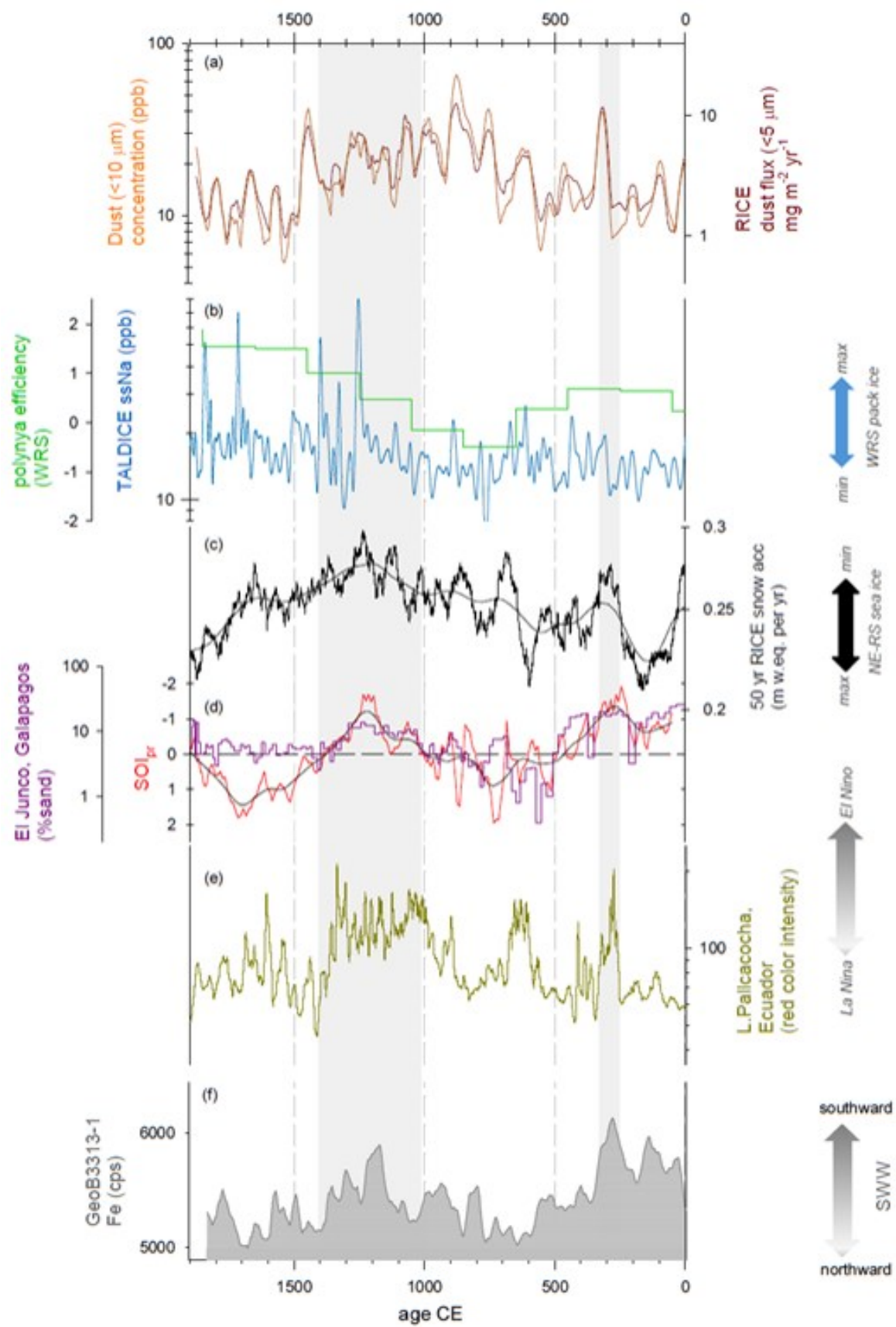


Figure 27: comparison of ice core and climate records from the Southern Hemisphere over the last 2,000 years. (a) Concentration of dust particles smaller than 10 μm (ppb), and flux ($\text{mg m}^{-2} \text{ year}^{-1}$) of particles smaller than 5 μm . (b) Sea salt Sodium (ssNa) concentration at TALDICE and polynya efficiency (Mezgec et al., 2017). (c) RICE snow accumulation rate, as in fig. 2b. (d) Red line: Southern Oscillation Index (SOI_{pr}) record (with Loess smooth superposed, black line) from Yan et al., 2011.

This index was calculated as the difference between the reconstructed precipitation records from Indonesia and the Galapagos. Purple line: rainfall history of the Galapagos, used in the reconstruction of SOI_{pr} , but extending on a longer period.

This series is derived from a lake level reconstruction based on grain size data from Lago El Junco sediment core. (e) Laguna Pallcacocha, Ecuador red colour intensity record of sediments from Moy et al., 2022. El Niño-related high precipitation events are related to greater colour intensities. (f) Iron content from GeoB3313-1 core (Lamy et al., 2001); higher Fe concentrations indicate a poleward position of the southern westerly winds (SWW) and vice versa.

2.5.3 The dipole pattern and climate drivers

To accurately interpret our 2 kyr record, it is crucial to consider current meteorological patterns in the Ross Sea as well as the meteorological effects of El Niño and La Niña. The establishment of a “dipole-like” pattern in air temperature and sea-ice concentrations between the ERS and WRS is often associated with formation of near-stationary anticyclones (Emanuelsson, 2018). These impede the progression of the westerly circulation and induce a significant meridional transport to RICE from N-NE (Turner et al. 2016), that is responsible for humidity advection to the site. Indeed, several research studies highlight the importance of the Amundsen Sea Low (ASL) on the climate of the Amundsen–Bellingshausen Sea (ABS)/ERS region, and hence the climate at Roosevelt Island. The ASL is an area of climatologically low atmospheric pressure characterized by a large geopotential height variability, associated with both depressions and blocking high pressure ridges. When these near-stationary anticyclones form, they impede the progression of the westerly circulation and associated storm tracks. It has been observed (Turner et al., 2013; O’Connor et al., 2021; Raphael et al., 2019; Yiu and Maycock, 2019) that the ASL depth and location, both latitude and longitude, vary in relation to other climate drivers, including El Niño Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO) and the Southern Annular Mode (SAM). In particular, the frequency of blocking

events in the southern high latitudes increases significantly during ENSO warm phases (El Niño), particularly over the southeast Pacific during the austral spring and summer (Renwick, 1998). Observational data provides evidence that El Niño climate conditions induce anomalous northerly wind flow along the western side of the blocking ridge in the Amundsen/ERS. This pattern favours poleward movement of sea ice and net sea ice loss with advection of warm and moist air masses towards the RICE site (Zhang et al., 2021). In addition, reanalysis-forced regional climate model outputs indicate that central Pacific El Niño results in a significant increase in snow accumulation in the western Ross Sea sector, while causing a notable decrease in the Amundsen Sea sector, while an eastern Pacific El Niño is associated with similar, albeit weaker, patterns (Macha et al., 2024).

However, the response to El Niño forcing in the Ross Sea is double-sided: while the eastern part of the Ross Sea displays a statistically-significant negative correlation between the Southern Oscillation Index (SOI) and temperature, with warmer temperatures during El Niño events, the coastal WRS areas of Victoria Land show positive or non-significant correlation with SOI, with generally colder temperatures during El Niño events, southerly winds, surface temperature cooling and lengthening of the sea-ice season (Li et al., 2021). No significant relationship between pack ice in the western part of the Ross Sea and ENSO emerges from modern data, while in the Amundsen and ERS the sea ice decreases by 10-20% during El Niño events and increases in the Eastern Amundsen and Bellingshausen Sea as well as in the Weddell Sea. This pattern is known as the Antarctic sea ice dipole, representing the leading mode of ENSO-related Antarctic Sea ice variability (Li et al., 2021). The reason for the tight coupling between El Niño and atmospheric circulation in the area of RICE and more generally in the Ross Sea (Bertler et al. 2004) relies on changes of the split jet in the proximity of New Zealand. This induces a subsequent weakening of the polar front jet during El Niño, an eastward shift and weakening of ASL, reduced cyclone density in the ERS and more frequent blocking, with associated thermal and mechanical forcing (Bertler et al. 2011).

On longer (climatological) timescales, these considerations suggest a possible relationship between dust input to RICE, local snow accumulation, stable water isotopes, sea ice in the WRS and ENSO. Since ENSO is a complex climate pattern that involves interactions between the ocean and the atmosphere, relying on a single proxy for paleo-ENSO may oversimplify the underlying dynamics, which cannot be fully captured by a single proxy alone. For this reason, in this study we use two widely-recognised and well-established paleo-records to investigate ENSO behaviour over the past 2 kyr. These are the SOI-precipitation (SOIpr) index from the tropical Pacific (Yan et al., 2011, figure 27d) and the red colour intensity record from Laguna Pallcacocha in southern Ecuador (Moy et al., 2002, figure 27e). The SOIpr index is calculated as the difference between normalized annual rainfall data from the tropical western Pacific and the equatorial eastern and central Pacific (Yan et al., 2011), with negative values of the index indicating El Niño-dominated conditions. For the past two millennia, precipitation records from Indonesia and the Galápagos Islands were selected for the calculation of the index. Specifically, historic rainfall data for Indonesia were derived from salinity reconstructions based on planktonic foraminifera oxygen isotopes and Mg/Ca ratios, while rainfall history in the Galápagos was reconstructed using lake level data from El Junco (Yan et al., 2011). Indeed, the grain size of sediments in El Junco lake (figure 27d) is highly sensitive to precipitation changes associated with the Pacific Walker Circulation and El Niño events. The second ENSO proxy we refer to in this study is based on the colour and composition of sediment layers at the bottom of Laguna Pallcacocha (Ecuador). This is linked to intense El Niño events, since increased convective precipitation driven by anomalously high sea surface temperatures in the Pacific leads to higher stream discharge and increased terrestrial material input into the lake. This detrital input includes iron-rich minerals, typically reddish in colour. As a result, periods of increased or decreased runoff can be detected by analysing the red intensity record of sediment layers, from which a time series of moderate-to-strong El Niño events have been constructed (Moy et al., 2002). Because these two series capture the regional impacts of ENSO events and are based on different proxies, they exhibit both similarities and differences; however, some

time intervals where both paleo-ENSO records exhibit dominant El Niño-like conditions over the last 2 kyr can be identified. Considering periods when SOIpr index is negative and at the same time the red colour intensity record is above the 75th percentile, as example, some intervals dominated by El Niño-like conditions can be identified. The longest of these is the ~400 years long period from 1000 CE to about 1400 CE, followed by a ca. 80-year long period from ~255 to 335 CE (figure 27, grey bars). During both these periods, we observe an increase in snow accumulation at RICE, as well as relatively high or increasing dust levels, consistent with the scenario described above of preferential advection of warm and moist air masses to RICE site. On the other hand, the stable isotope signal appears more complex. While it shows an increase in tandem with the dust record as previously discussed, it does not show a discernible peak around 300 CE interval (figure 18). This is likely because the earliest part of the RICE record represents a period of dynamic changes in the Ross Ice Shelf, with the calving line either terminating or having just completed its last phase of retreat (Yokoyama et al., 2016). Under these conditions, it can be hypothesized that the surface waters of the Eastern Ross Sea were much cooler, leading to a different response in stable isotopes. We conclude that the variability of snow accumulation and dust flux/concentration align with the relationship expected between El Niño and atmospheric circulation anomalies in the Ross Sea region inferred from present-day meteorological data.

The El Niño-related weakening of the zonal westerly winds in the region between 45°–70°S, 90°–150°W with consequent increase of air mass advection from the N-NE to the RICE site seem to be related to the enhanced meridional flow to the WAIS divide observed by Koffman et al. (2014). By analysing mineral dust size in the WAIS ice core, Koffman et al. (2014) observed a southward shift of the Southern Westerly Winds and increased meridional dust transport to WAIS during El Niño events. Indeed, this can result from blocking events in the Eastern Ross Sea (Emanuelsson, 2018), and in this sense, the coherency between our observations and conclusions from Koffman et al. (2014) for WAIS divide can be justified.

Similarly, the shift southwards of south Westerlies in association with El Niño is also imprinted in the marine sediment record GeoB3313-1 from the Chilean continental slope (41°S, 74°27'W). This record is tightly related to the rainfall history of the western side of the Chilean Andes and suggests enhanced aridity around 1110–1395 CE (figure 27f) in Southern Chile. As noted by Koffman et al. (2014), this feature is also in agreement with a southern shift of the South Westerly Winds. Interestingly, such a feature is also notable around 300 CE, where El Niño-like conditions are observed, supporting the possible relationship observed in the most recent part of the record.

2.5.4 The period 1470-1900 CE

After about 1470 CE, the RICE record is characterized by a sudden drop in dust concentration and flux, accompanied by a more gradual snow accumulation decrease suggesting increased pack ice in the ERS/Amundsen Sea. In parallel, the stable water isotope composition at RICE increases abruptly, in apparent contradiction to the general relationship between snow accumulation/sea ice and stable water isotopes observed in the earlier part of the record. Bertler et al. (2018) hypothesised that a novel source for isotopically-enriched vapor could justify this sudden stable water isotope increase. Interestingly, such isotope enrichment during the LIA time frame coincides with the appearance of unprecedented peaks in the concentration of sea ice-related and marine planktonic diatoms (figures 18, 28, 22). These are predominantly observed between ~1500 CE and 1850 CE as two separate peaks around 1530-1610 CE and 1700-1830 CE.

Diatom peaks occur concurrently with stable water isotope enrichments and decreased snow accumulation. This means they correspond to a period of intense influence of local low-elevation marine air masses originating from the marine boundary layer. This is also suggested by the significant increase of marine species (Na^+ , Ca^{2+} , K^+ , Mg^{2+} , SO_4^{2-}) in the RICE ice core (figure 28, data from Brightley, 2017) in correspondence to diatom peaks, with respect to the period 1200-1400 CE. Comparable values of aeolian diatom fluxes have never been observed along the RICE record and point towards the presence of newly-exposed oceanic water masses in proximity of the site. We note that the position of the calving line remained almost the same during that period (Yokoyama et al., 2016); therefore, we believe the diatom peaks can be related to a new phase of expansion of the Ross Sea polynya during the sea ice formation season. In particular, we suggest an enlargement of the Ross Sea polynya along the central and eastern portion of the Ross Ice Shelf front, which may imply the opening of the Roosevelt Island Polynya, considered as the eastern extension of the significantly larger Ross Sea polynya. This development could have exerted a considerable influence on a regional scale.

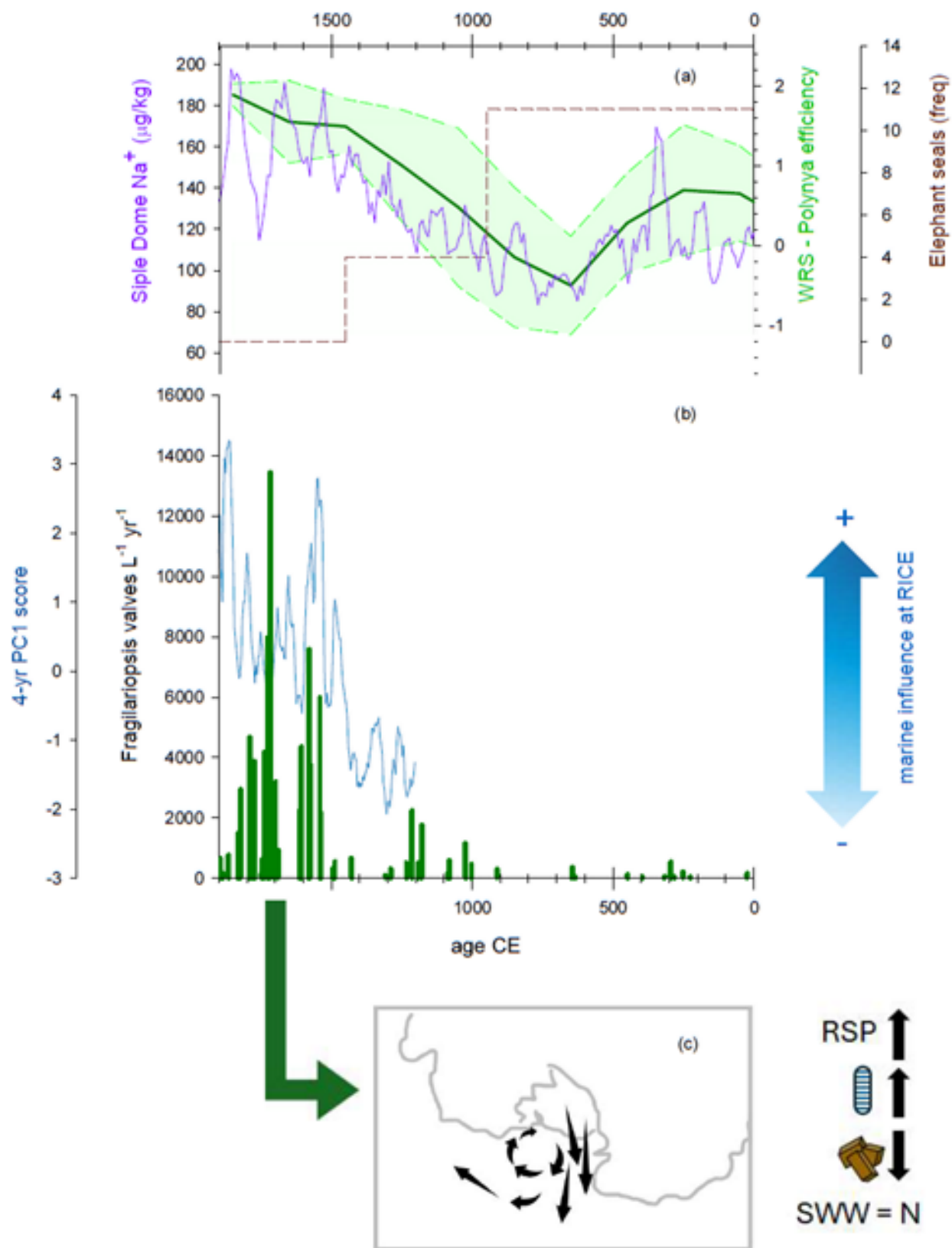


Figure 28: (a) the polynya efficiency (Mezgec et al., 2017) with standard deviation values, derived from a stacked record of *F. curta* from the coastal sea ice zone of the Western Ross Sea and ssNa record from Taylor Dome (see Mezgec et al., 2017 for details). Elephant seal frequency data from Hall et al., 2006 (as reported in Mezgec et al., 2017). Sodium data from Siple Dome are also reported (Kreutz et al., 1997) (b) First principal component obtained from the 4 year-resolved ICP-MS data series (Brightley, 2017) spanning the period 1204-1992 CE; PC1 explains 62% of the variance and is related to marine-sourced winds (see text). Green histograms refer to the number of entire *Fragilariopsis* spp. valves per Liter per year (same as in figure 23c). (c) Qualitative sketch of the atmospheric circulation pattern leading to expansion of the Ross Sea Polynya and diatom transport to RICE. Arrows on the right show expansion of the RSP, increase in aeolian diatom content, decrease in dust influx and northward shift of the SWW.

2.5.5 Ross Sea polynya formation and associated meteorological patterns

Diatoms windblown to the RICE site likely underwent a very short transport directly from the adjacent sea, as revealed mainly by their excellent degree of preservation. Specimens consist almost exclusively of marine planktonic and sea ice-related species, that we believe to be entrained by winds during the early austral spring, at the time of the rapid increase of the polynya areal extent. The Ross Sea Polynya is considered to be primarily a wind-driven polynya (Zwally et al., 1985) although it may be in part thermally-driven (Jacobs and Comiso, 1989). The enlargement of the polynya, mostly occurring west of the date line, is mainly related to enhanced katabatic drainage from Byrd, Skelton, and Mulock glaciers, from barrier winds along the Transantarctic Mountains and from katabatic surges originating from the Siple Coast of West Antarctica propagating horizontally across the Ross Ice Shelf to its northern edge (Bromwich et al., 1998, Morales Maqueda et al., 2004). Ice production and drift from the Antarctic Ross Sea polynya is also modulated by a semipermanent low-pressure system located to the east (Bromwich et al., 1998; Drucker et al., 2011). In the Ross Sea, in particular, this low-pressure system produces strong southerly winds off the western Ross Ice Shelf and a return air flow towards Roosevelt Island (Drucker et al., 2011). This return flow is particularly relevant as the potential driver for the atmospheric transport of diatom and marine aerosol to the RICE site from the nearby sea surface waters.

The Holocene history of the Ross Sea polynya activity documented by Mezgec et al. (2017) is mainly based on marine sediment and ice core data from the WRS and from East Antarctica. Thus, it represents a comprehensive picture of the W-NW Ross Sea polynya, where the major enlargement typically occurs, but it is not possible to exclude that the development of the polynya in the central part of the ice shelf front and towards the much smaller Roosevelt Island polynya might have had a slightly different evolution. Present-day data (Wang et al., 2022; Wang et al., 2023) highlight that the eastward expansion of the polynya is generally correlated to the integrated areal expansion of the polynya itself. This evidence could account for the agreement between the diatom peaks in the RICE records during the LIA and the increase in the “polynya efficiency” index (Mezgec et al., 2017). Bromwich et al. (1993) observed that the speed of katabatic surges from the Siple Coast plays a key role in modulating the opening of the polynya in the central part of the Ross Ice Shelf front. It is therefore plausible that the intensity of katabatic surges from the Siple Coast increased during the Little Ice Age (LIA), contributing to a significant expansion of the polynya along the central and eastern parts of the Ross Ice Shelf front. In the context of the present-day climate, enhanced southerly winds off the central Ross Ice Shelf are likely associated with a deeper low-pressure system centred approximately north of RICE. Therefore, this cyclonic circulation system may drive the advection of marine aerosol-rich air masses towards our drilling site.

Meteorological observations highlight that katabatic surges typically promote the establishment and development of mesoscale cyclones inside the Ross Sea. After their formation, they then move north-eastwards, ultimately bringing maritime air masses to the site (Carrasco et al., 2003). Numerical simulations by Heinemann and Klein (2003) show that the topography of Antarctica plays an essential role in mesocyclone formation where the convergence of katabatic airflow provides cyclonic shear for the initial formation of the cyclone. Therefore, katabatic winds are the primary factor driving the opening and development of coastal polynyas. These polynyas, in turn, create an area of open water near the coast, which serves as a source for sensible and latent heat fluxes. This promotes low-level baroclinicity between the open water and the continent, leading to

further warming and moistening of the atmosphere over the polynya, which contributes to mesocyclogenesis (Klein and Heinemann, 2001). We propose that there may be a positive feedback between katabatic winds, polynya formation, and the development of mesoscale cyclones. After the initial development, the evolution of mesocyclones requires upper-level synoptic-scale support to form a synoptic or sub-synoptic system (Heinemann and Klein, 2003; Carrasco et al., 2003).

2.5.6 Atmospheric conditions leading to enhanced diatom transport during the LIA

Given the above-mentioned meteorological evidence for present-day climate, we hypothesize that during the LIA the local maritime air mass advection towards the RICE site, responsible for diatom and marine aerosol transport to the site, might have been related to increased katabatic winds over the central and Western part of the Ross Ice Shelf with maximum polynya development and enhanced atmospheric return flow of local maritime air masses to RICE (figure 28c). We believe that these maritime, diatom-rich air masses derive from low-elevation atmospheric layers. In fact, the dynamical and thermodynamical interactions between atmosphere and ocean are strongly influenced by the presence of the polynya, that modifies the vertical structure of the atmosphere promoting the development of a relatively thicker and well-mixed convective boundary layer (Fusco et al., 2009). We also note that the opening of the Roosevelt Island polynya had influence on local scale, since the sodium record from Siple Dome, located some hundreds of kilometres on the Siple Coast of West Antarctica (Kreutz et al., 1997) mimics the expansion of the whole Ross Sea polynya (figure 28a). The hypothesis of a significant enlargement of the Ross Sea polynya during the LIA is also supported by data from the western side of the Ross Sea, pointing towards prolonged cold climate conditions with significant increase of katabatic winds and polynya areal extent between the 16th century and the beginning of the 19th century. The TALDICE ice core shows the most negative stable water isotope values of the last 2000 years (Stenni et al., 2011) and an 11% decrease in snow accumulation compared to the preceding period, indicating colder and windier conditions at that time. Indeed, cooling in East Antarctic and the Ross

Sea could lead to stronger katabatic flow, in turn leading to an increased polynya efficiency and more sea-ice production (Mezgec et al. 2017). The Taylor Dome record shows prolonged cold stable water isotope temperature anomalies (Steig et al., 2000), and the stable water isotope and geochemical records from Mt. Erebus Saddle (Rhodes et al., 2012) highlight that the region experienced colder than average temperatures prior to 1850 CE and strong katabatic winds between 1500 and 1800 AD. According to Rhodes et al. (2012), prior to 1875 CE the biological productivity in the Ross Sea polynya was ~80% higher than any subsequent time. Bertler et al. (2011) also report colder temperatures and more extensive sea ice, as well as decreased snow accumulation in the WRS at the time of the LIA. The increased efficiency of the Ross Sea polynya over the last ~500-600 years is also reflected in significant ecological changes in Victoria Land (figure 28). Hall et al. (2006, 2023) observed the near-complete disappearance of elephant seal (*Mirounga leonina*) colonies in Victoria Land, which they linked to the increased persistence of landfast sea ice. We note that a key factor for the reproductive success of elephant seals is the proximity of open water to their nursery sites. Thus, the disappearance of elephant seal colonies in Victoria Land during the LIA can be interpreted as being related to a significant increase in landfast sea ice. This hypothesis is also supported by independent marine data, such as those from Edisto Inlet in the north-western Ross Sea (Tesi et al., 2020), where persistent summer fast ice has been observed over the last 700 years.

Given that the formation, persistence, and variability of Antarctic polynyas are known to be influenced by landfast sea ice (Fraser et al., 2019; Mezgec et al., 2017), we hypothesize that our data (figure 28) support the connection between the permanent abandonment of the elephant seal population along the Victoria Land coast during the LIA and the expanded extent and occurrence of the Ross Sea polynya. This relationship was previously proposed by Mezgec et al. (2017) for the Holocene period.

Between about 1470 CE and 1900 CE, a time for which we infer the expansion and development of the Roosevelt Island polynya, predominance of positive SOIpr and enhanced Pacific Walker circulation (Yan et al., 2011) suggest a more

La Niña-like mean state. We note that here we use the recent SOIpr hydrological reconstruction that includes records from the Indo-Pacific, from the central tropical Pacific and from the eastern equatorial Pacific and which is an atmospheric/hydrological record in agreement with other hydrological records (Rein et al., 2005) indicating a more La Niña-like mean state during the LIA. However, this series conflicts with sea surface temperature reconstructions that suggested the LIA was characterized by a more El Niño-like state, as discussed in detail by Yan et al. (2011). Under La Niña-like conditions, the polar front jet (Turner, 2013) and the ASL became more intense (deeper ASL), while the low-level easterly jet along with the katabatic flow from the Antarctic are enhanced (Bertler et al., 2006). As a result, a deeper ASL often coincides with a larger Ross Sea polynya, as also revealed (Wang et al., 2022) by modern satellite data.

2.6 Conclusions

The influx of aeolian dust and diatoms at RICE are related, respectively, to large-scale atmospheric circulation patterns in the ERS/Amundsen Sea and to the local oceanic influence of air masses from the marine boundary layer. The combination of these proxies improves the understanding of the climatic and atmospheric changes experienced by Roosevelt Island over the past 2 kys, that are related to a number of forcing factors such as ENSO. During the 550-1470 CE period, when higher/less depleted stable water isotope values are observed, the increased importance of blocking ridges in the Amundsen Sea and a weakened ASL promoted dust-rich air mass advection to RICE. This pattern was accompanied by an increasing trend in snow accumulation and reduced sea ice in the ERS/Amundsen Sea. Comparison with WRS data suggest an opposite behaviour on the two sides of the Ross Sea around 1200-1300 CE, with enhanced katabatic outflow in the WRS, reactivation of the Ross Sea polynya, and maximum extent of pack ice. Interestingly, sustained multi-decadal El Niño dominating conditions coincide with periods of enhanced northerly air mass advection to RICE and with the southward shift of the South Westerly Winds hypothesized on the basis of data from West Antarctica and South America.

After 1470 CE, the RICE site was subject to a rapid atmospheric circulation reorganization in response to the development of the Roosevelt Island Polynya, leading to an unprecedented input of marine planktonic and sea ice-related diatoms at RICE and low dust influx, in tandem with decreased snow accumulation and increased sea-ice extent in the ERS/Amundsen Sea. We propose that the increased efficiency of the polynya during the period covering the Little Ice Age is related to the eastward expansion of the Ross Sea Polynya and Roosevelt Island polynya formation, which extends as a protrusion of the much larger Ross Sea polynya, but with a significant regional impact in the Ross Sea area.

2.7 RICE – the entire Holocene

The next graphs (figure 29 a and b) represent the raw diatom counts, as a direct visualization of their absolute abundance throughout the Holocene, as well as the diatom valves flux expressed as the number of diatom valves per liter per year).

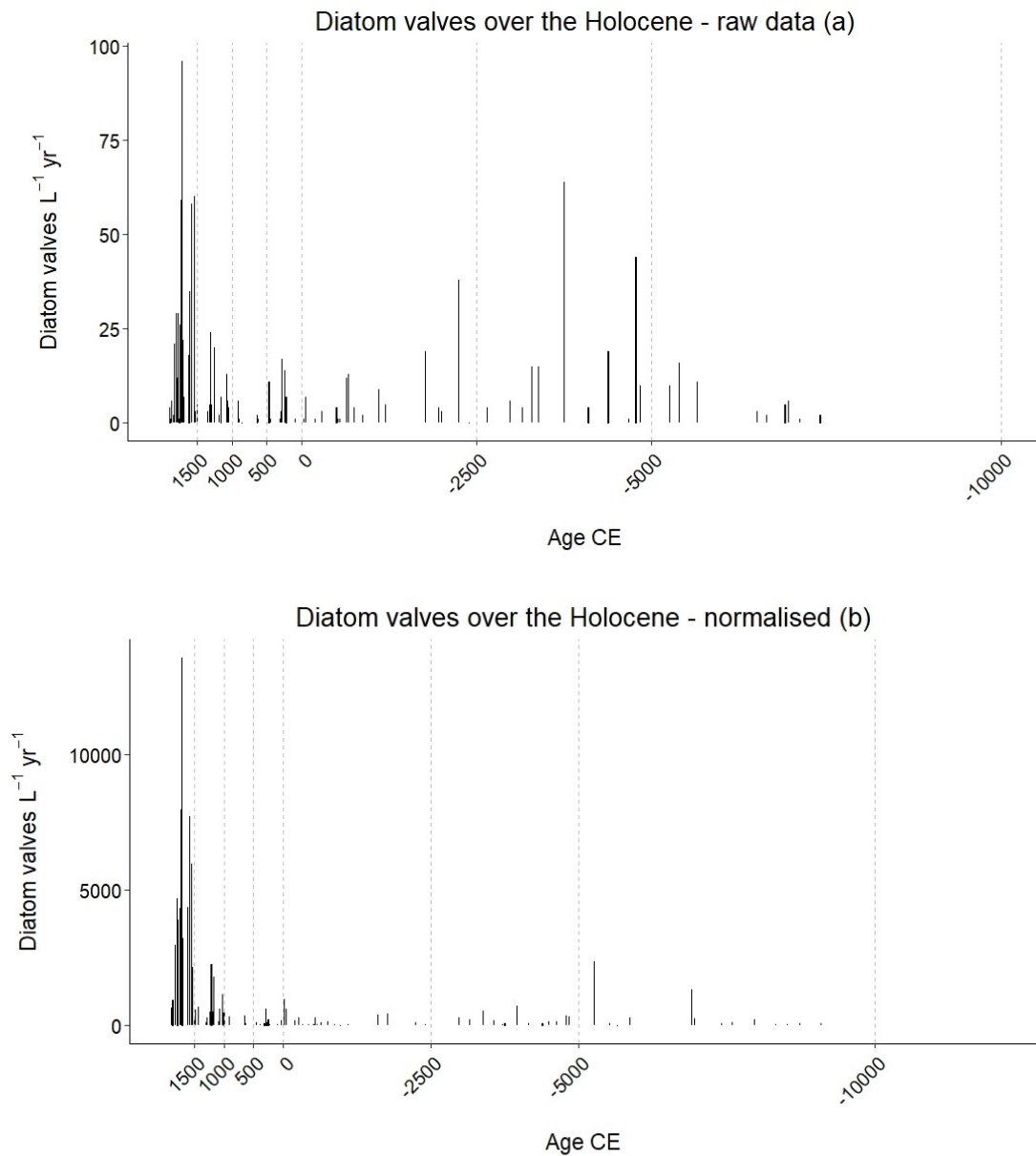


Figure 29 (a) and (b) show the diatom valve record from the Holocene.

Figure 29a presents the raw data, while figure 29b shows the normalised flux of diatom valves ($L^{-1} yr^{-1}$).

From figure 29a, it is visible that at the beginning of the Holocene, the diatom valve abundance is relatively low with sporadic occurrences recorded.

Compared to the LIA, none of the Holocene peaks indicate a significant increase in diatom valves deposition. Throughout the early and mid-Holocene, the diatom valves presence remains irregular, with an unstable trend and intermittent fluctuations always at low values. Thus, the diatom valves inputs reflect a continuous, albeit very limited, deposition over time.

Figure 29b, instead, shows that the data is normalised with respect to the period that each sample represents. This is done to allow a better appreciation of the very low diatom deposition flux, with this fluctuating and irregular but consistently low “background” of diatom valves inputs.

Regarding the diatom valves genus composition, the assemblage is overwhelmingly dominated by *Fragilariopsis* spp., which accounts for 98,87% of the total valves observed in this interval (945 out of 954 valves). Freshwater diatoms are nearly negligible, comprising only 1,13% of the assemblage (9 valves, 4 of them are illustrated in figure 30). Among the freshwater diatom valves, all belong to the genus *Luticola* spp., except for three valves of *Pinnularia* spp., whose freshwater or brackish origin remains uncertain.

Lastly, table 2 summarises all diatom counts performed along the RICE ice core, including the samples from the LGM interval. For the LGM, only two freshwater diatom valves were observed; therefore, this interval was not included in any corresponding plot.

from 48 to 757 m depth	RICE ice core
N° of samples	149
Total diatom counts (n)	1070
Total diatom classified at genus level (n)	1490
Total diatom identified at species level (n)	1041
Total diatom fragments count (n)	345
Total volume filtered (ml)	1490
Mean volume filtered	10

Table 2: counts and basic identification of diatom valves found in the RICE ice core (Holocene + LGM) based on the light optical microscopy analysis with Olympus BX51M.

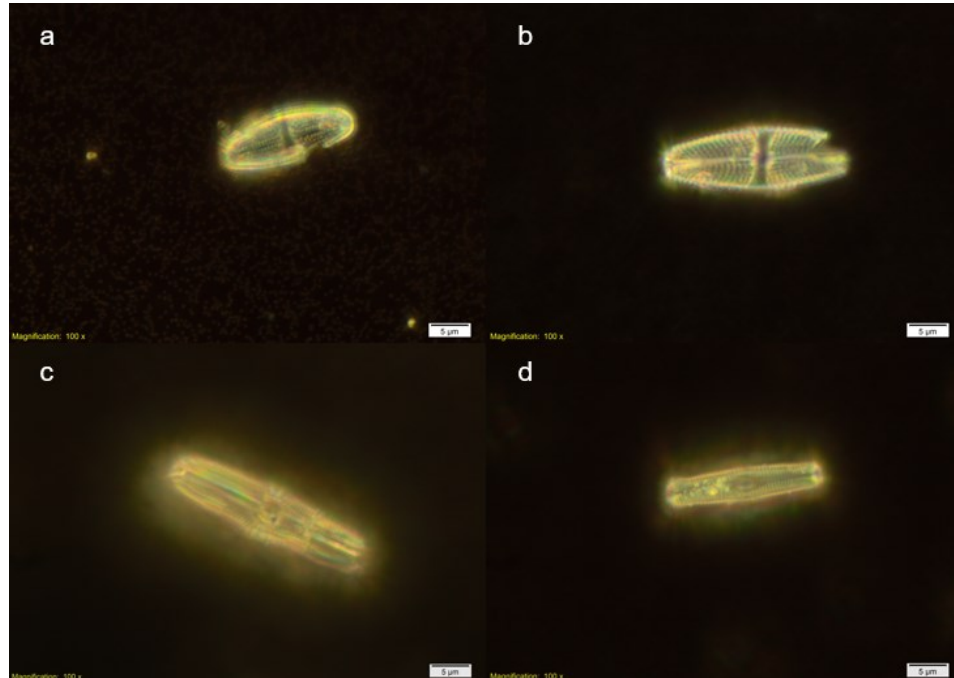


Figure 30 represents two valves of Luticola spp. (a and b) and two valves of Pinnularia spp. (c and d). Scale bar: 5 µm for optical images (magnification 1000x).

The comparison between the two graphs highlights complementary perspectives on diatom valves deposition in the RICE ice core during the Holocene. The raw data graph (figure 29a) illustrates the absolute abundance of diatom valves, revealing their sporadic but persistent presence throughout the epoch, particularly during the later Holocene, where it is notable that diatom valves peaks occur during the LIA. In contrast, the diatom valves flux graph (figure 29b) normalises these occurrences, offering a clearer view of the deposition intensity over time. Together, these representations (figure 29 a and b) show that the diatom valves deposition is consistently low at the beginning of the Holocene, characterised by fluctuating trends and intermittent increases, until becoming more pronounced during the most recent 2,000 years. However, the exact mechanisms driving these trends remain uncertain, reflecting a combination of transport pathways and depositional processes that needs more research to be done.

Despite the clear dominance of marine diatoms in the assemblage, the early and mid-Holocene do not show strong evidence of sustained marine input before the late-Holocene increase. The overall diatom valves flux remains low, suggesting that either the transport efficiency was low, and maybe the depositional conditions were unfavourable, or that marine diatom productivity in the source region did not provide a significant input to Roosevelt Island during that time. These suggestions would strengthen the hypothesis that the Roosevelt Island Polynya was not well developed during the early Holocene (Lagorio et al., 2024, accepted for publication). These observations align with previous reconstructions of the Ross Ice Shelf dynamics, which indicate that a significant portion of the ice shelf retreat, potentially enhancing the diatom valves transport, occurred mainly after ~5,000 years ago (Yokoyama et al., 2016). At the beginning of the Holocene, when the calving line of the Ross Ice Shelf was more advanced, diatom valves deposition in figure 29 a and b appears limited, reflecting a possible reduction of environmental inputs/aeolian transports. This suggests that as the ice shelf retreated during the mid to late Holocene, the diatom valves flux increased with peaks culminating in the last 2,000 years. While these observations might look ideal, the exact relationship between these factors remains speculative. Other

parameters, such as atmospheric circulation, wind intensity, and diatom productivity in source regions, may have also played significant roles, and therefore further research is necessary.

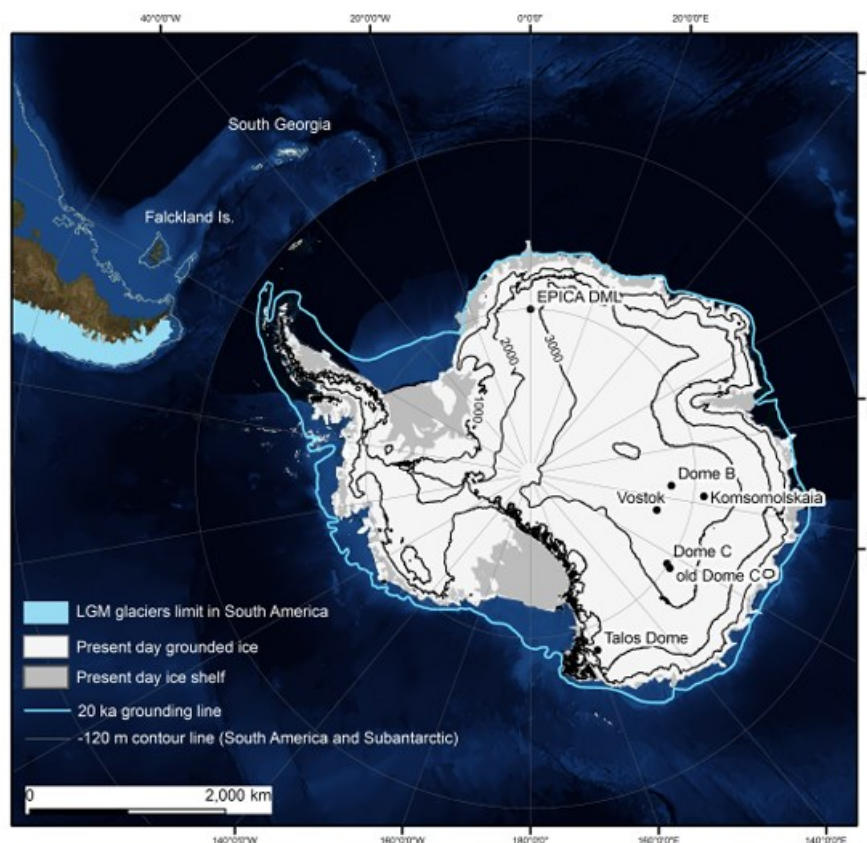
To contextualise this topic, it is important to recall that the Roosevelt Island Climate Evolution ice core was drilled at the summit of Roosevelt Island, a prominent ice dome located within the Ross Ice Shelf in West Antarctica. Throughout the Holocene, the Ross Ice Shelf underwent significant changes, including episodes of retreat and re-advance, driven by atmospheric and oceanic warming. These movements are hypothesised to have influenced the diatom valves deposition patterns in the RICE ice core by altering atmospheric transport pathways and depositional environments. Geological evidence, as described by Yokoyama et al. (2016), identifies two major episodes of ice-shelf retreat, with the most extensive collapse occurring between ~5,000 and 1,500 years ago. This retreat facilitated a transition from sub-ice shelf conditions to open marine environments, potentially enhancing the transport of diatoms into the region.

This paragraph highlights the need and the importance to do more research on the Holocene, at the beginning of this epoch, and from different points of view: it would be ideal, as few diatoms have been noted during that time, to understand why this input is low, and which factors build this situation. RICE ice core is definitely a very good archive for past climatic changes and, for the last 2,000 years, this ice core gives to research very important, interesting and innovative results, allowing to keep building up on further projects that hopefully will make a good impact in learning about past, present and future global climate.

3.0 DOME B ice core

3.1 Dome B and LGM

The Dome B ice core, extracted from a high-altitude site in East Antarctica at approximately 3650 meters above sea level (figure 31, 77°05'S, 94°55'E; Jouzel et al., 1995; Delmonte et al, 2017), is a very important archive for reconstructing past climate and atmospheric conditions.



*Figure 31: the Dome B location, in East Antarctica
(original picture presented in Delmonte et al., 2017).*

This remote region is characterised by extremely cold temperatures, often reaching annual averages below -50°C , and low precipitation rates, making it one of the driest areas on Earth. Indeed, snow accumulation in East Antarctica is estimated at approximately $30\text{--}40\text{ kg m}^{-2}\text{ yr}^{-1}$ during the Holocene, reflecting no major changes in climate, while during the Last Glacial Maximum, these rates

dropped significantly to around $10\text{--}20 \text{ kg m}^{-2} \text{ yr}^{-1}$, because of colder global temperatures and reduced atmospheric moisture availability (Jouzel et al., 1987; Delmonte et al., 2017).

Therefore, the Dome B site, remote and with complete absence of surface melting, ensures the preservation of pristine climatic and environmental records. The ice layers of Dome B capture variations in isotopic composition, greenhouse gas concentrations, and mineral dust fluxes which are essential in reconstructing temperature, precipitation, and atmospheric circulation patterns over the last climatic cycles (Jouzel et al., 1995).

The LGM and deglaciation sections of the core have been particularly important, as they give access to the last pleniglacial phase (28–13 kyr). Moreover, they contributed to the understanding of the Antarctic Cold Reversal (ACR), a climatic event previously documented in other ice cores, such as Byrd (1968) (Blunier et al., 1997; Jouzel et al., 1995). The ACR, a period of Antarctic cooling during the broader global deglaciation (14.5–12.8 ka), was previously unknown. This finding demonstrated that the Antarctic temperature evolution during the last deglaciation was not linear but included a significant intermediate cooling phase, reshaping our understanding of glacial-interglacial transitions.

This unique combination of cold temperatures, low precipitation, and continuous accumulation makes Dome B a benchmark location for understanding paleoenvironmental changes. However, much of the research at Dome B has focused on the last climatic cycle, approximately the past ~35,000 years, including glacial-interglacial transitions and associated atmospheric and environmental changes.

Stable isotope analyses, particularly of deuterium (δD), have been used in reconstructing past temperature variations. Foundational work by Jouzel et al. (1987, 1995) established the direct relationship between the isotopic ratios and the sea-level changes (figure 32).

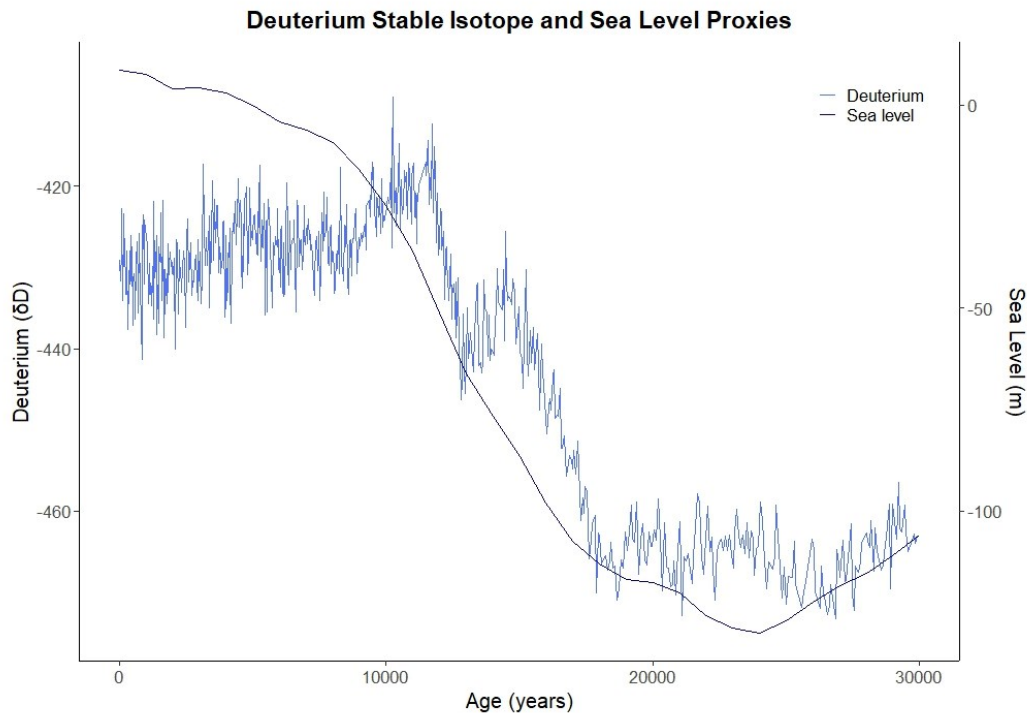


Figure 32: the deuterium stable isotope (δD) (data from Jouzel et al., 2005) and the sea level (data from Spratt and Lisiecki, 2016) over the LGM.

Deuterium (δD), a stable isotope of hydrogen, is a widely used proxy for reconstructing past temperatures in ice core studies (Stenni et al., 2010). The δD isotope is controlled by the temperature at which precipitation condenses.

As air masses cool while travelling towards Antarctica, heavier isotopes preferentially condense and precipitate first, leaving the remaining moisture increasingly depleted in heavy isotopes. This process, known as Rayleigh distillation, results in a strong correlation between δD values and past temperatures (Jouzel et al., 1997).

During glacial periods, colder conditions led to stronger isotopic fractionation, causing δD values to be significantly lower compared to interglacial periods. The extensive expansion of ice sheets and glaciers during the LGM further amplified this effect by reducing atmospheric moisture availability, leading to even greater

depletion in deuterium (δD) recorded in Antarctic ice cores (Jouzel et al., 1995; Stenni et al., 2010).

In contrast, during warmer interglacial phases, δD values increased, as higher temperatures reduced isotopic fractionation and enhanced the proportion of heavier isotopes in precipitation.

By analysing δD in ice cores, such as those from Dome B, Dome C, or Vostok, scientists can trace temperature variations associated with glacial and interglacial cycles (Jouzel et al., 1987; Jouzel et al., 1995). These temperature changes drive the growth and melting of ice masses, illustrating the close relationship between δD records and sea level fluctuations over time (figure 32).

During the last glacial period, around 33 ka, Antarctic deuterium (δD) records indicate cold conditions associated with substantial glacial expansion. This timeframe corresponds to Marine Isotope Stage 3 (MIS 3), characterised by intermediate glacial conditions and significant climatic variability. Antarctic δD values are notably reduced during this period, suggesting a phase of sustained cooling that supported ice sheet growth (Jouzel et al., 2001).

Although these conditions were not as extreme as those observed during the LGM – when sea levels dropped by ~120–130 meters – they still contributed to a marked global sea level decline, as ice mass accumulated across Antarctica. Sea level reconstructions for the LGM, such as those by Spratt and Lisiecki (2016), indicate that sea levels were significantly lower than today, reinforcing the close relationship between ice volume and δD signals.

Moreover, deuterium (δD) records reflect not only temperature changes but describe also shifts in atmospheric and oceanic circulation patterns, defining the transitions between the last glaciation and the Holocene (Jouzel et al., 2001).

During Marine Isotope Stage 2 (MIS 2), culminating in the LGM, the information about dust particle dynamics and atmospheric transport pathways are obtained by analysing the Dome B ice core. Indeed, it is known that larger dust particles are typically associated with low-altitude lateral advection, likely driven by cyclonic systems penetrating the Antarctic interior, whereas smaller particles were transported by high-altitude tropospheric currents and deposited through

subsidence (Lambert et al., 2008; Delmonte et al., 2004). As a result, dust particle size serves as a proxy for identifying the typology of atmospheric transport, with coarse particles reflecting regional or low-level input, and fine particles indicating long-range, high-altitude transport mechanisms.

Dust particles reaching Dome B site during this period originated primarily from Patagonia and Tierra del Fuego in South America. These regions are well known as major dust sources during glacial periods, with the SWW being the transport of mineral dust across continents (Delmonte et al., 2010; Lambert et al., 2008).

Moreover, during the LGM, global sea levels were significantly lower by approximately 120 – 130 meters, exposing vast portions of the continental shelf surrounding Patagonia and Tierra del Fuego (Sugden et al., 2009; Kohfeld and Harrison, 2001). These newly exposed shelf areas likely served as additional dust source regions, contributing with large amounts of unconsolidated sediments highly susceptible to wind erosion. Indeed, the Patagonian Ice Sheet expanded extensively, covering most of southern Chile and Argentina and reaching its maximum extent before starting to retreat at ~19 ka (Glasser et al., 2008). Similarly, WAIS was significantly more extensive than today, with its grounding line reaching far onto the continental shelf (Bentley et al., 2010).

This process contributed to the increased availability of fine mineral particles, which were entrained and transported toward Antarctica by the prevailing westerlies. In parallel, the expansion of glacial outwash plains and the aridification of continental regions further enhanced dust mobilisation and long-range transport, ultimately amplifying atmospheric dust fluxes to central East Antarctica. These processes occurred within a broader climatic framework defined by the extreme conditions of the LGM, known to represent one of the most extreme climatic phases of the late Pleistocene, and to alter significantly global and regional environmental conditions.

At its peak, around 26,000 – 19,000 years BP, global temperatures were estimated to be approximately 6 – 7°C lower than pre-industrial levels, with regional variations (Shakun et al., 2012). In Antarctica, temperatures at Dome B and other East Antarctic sites were likely 8 – 10°C lower than present, intensifying

atmospheric aridity and reducing precipitation rates to nearly half of Holocene values (Stenni et al., 2004).

The atmospheric circulation was also markedly different during the LGM. The SWW were displaced northward and intensified, strengthening the transport of dust and other aerosols across the Southern Ocean and into Antarctica (Kohfeld et al., 2013). Precipitation patterns shifted accordingly, with drier conditions dominating many mid-latitude regions, further promoting dust deflation and transport. Additionally, sea ice extent in the Southern Ocean expanded significantly, with winter sea ice extending 2 – 5° further equatorward than present-day conditions (Gersonde et al., 2005). This vast expansion of sea ice likely altered ocean-atmosphere interactions, influencing regional climate patterns and potentially modifying the transport pathways of airborne particles, including diatoms and mineral dust.

These extreme conditions contribute to the environmental framework within which the diatoms preserved in the Dome B ice core were entrained and deposited. The exposure of Patagonian shelf sediments due to lower sea levels, combined with intensified wind patterns, created ideal conditions for the mobilisation and long-range transport of both mineral dust and diatom valves and fragments, shaping the diatom record observed in this ice core.

3.2 Objectives of this study

This study presents new records of aeolian dust and diatoms from the Dome B ice core, located in East Antarctica, spanning the Last Glacial Maximum (LGM), approximately 24,000 to 33,000 years before present (BP). Mineral dust particles were analysed using the Single Particle Extinction and Scattering (SPES) instrument and the Beckman Coulter Multisizer 4/4e (CC), while diatom valves and fragments were observed, measured, and identified using images captured by the Scanning Electron Microscopy (SEM) at the University of Cambridge.

Two questions are addressed for this research study:

(1) How do the new diatoms observed during 2024 expand upon the existent record for the Dome B ice core?

(2) Can the new aeolian diatom findings from the Dome B ice core provide further information about the paleoenvironmental conditions and the transport pathways experienced during the LGM?

3.3 Methods

Dust analyses and diatom filtration were conducted in a clean room environment to ensure analytical reliability and prevent contamination (total volume filtered is reported in 3.4 Results – table 4). Each sample, measuring 15 mm in length and representing lateral sections from the edge of the ice core, was cleaned in three pre-cleaned beakers filled with Milli-Q (MQ) water. The MQ water was refreshed for each sample to ensure that the melting process involved only clean, uncontaminated water. Although the cleaning step reduced the sample volume by approximately 50%, it ensured the removal of surface contaminants, in accordance with the established protocol (Delmonte et al., 2002). The outer layer of each sample was discarded, while the inner portion was carefully cleaned, divided into two aliquots, and left to melt in Corning containers.

Once fully melted, a 10 mL aliquot was transferred into an accuvette and analysed using the Coulter Counter (CC), followed by the Single Particle Extinction and Scattering (SPES) instrument. In total, 18 samples were analysed, covering four-time intervals of the LGM: approximately 24, 26, 29, and 33 thousand years ago. These time periods correspond to ice core depths of 631, 660, 720, and 780 meters. Accordingly, the samples are labelled DB631, DB660, DB720, and DB780, based on their respective depths and associated ages.

Following dust analyses, the remaining aliquot of meltwater was filtered using polycarbonate track-etched Isopore™ membranes with 0.4 µm porosity. The membranes were mounted on glass slides, and in total 28 samples were prepared and analysed: observed initially under optical microscopy before detailed analysis with scanning electron microscopy at the University of Cambridge. SEM images were acquired automatically from pre-established areas, following the methodology in Tetzner et al. (2021, 2022a, 2022b). The SEM, capable of magnifications between 300,000x and 1,000,000x, provided

high-resolution imaging for accurate identification of diatom valves and fragments.

The analysis followed established protocols (Tetzner et al., 2021, 2022a, 2022b), involving the systematic review of approximately 50,000 SEM images, of which ~28,000 were examined in detail (table 3, supplementary S1). Over several months, I performed a two-step identification: a preliminary screening to detect diatom valves and fragments, followed by a more detailed classification phase. Each object was categorised as a definitive diatom valve, a fragment, or a non-diatom particle. This meticulous process ensured consistency and accuracy in the final dataset.

Dome B ice core - BAG (depth)	tot pics observed
631	15648
660	4000
720	4000
780	4000

Table 3: number of images observed for each bag of Dome B ice core.

These four time periods refer to ice core depths 631, 660, 720 and 780 meters. Therefore, the samples are named DB631, DB660, DB720 and DB780 as the depth and referring to the ~24, ~26, ~29 and ~33 ka.

Additionally, I reviewed both published and unpublished images from the previous study conducted in 2017 on the same core (Delmonte et al., 2017; personal communication), obtained with the Olympus BX51M optical microscope. I compiled a secondary dataset of previously identified diatoms, aligning the observations with the classification criteria used in this study to ensure consistency.

The 2017 dataset includes samples from bags DB631 and DB660, allowing a qualitative comparison with the 2024 dataset. However, it is important to note that

the 2017 study was not conducted in a systematic way, as it primarily focused on the presence and the identification of diatom valves rather than on the application of a comprehensive and quantitative analysis. In contrast, bags DB720 and DB780 were analysed exclusively in 2024, thus providing new data points and expanding the temporal coverage of the diatom record in the Dome B ice core.

The identification process focused primarily on diatom valves, as diatom fragments are often too small and lack diagnostic features for reliable classification. Valves, on the other hand, offer morphological characteristics that allow for more accurate identification and ecological interpretation.

In both datasets, the term “unidentifiable” was used when it was not possible to determine whether a valve was pennate, centric, or in girdle view. In many cases, such as the quality of the image, the presence of an organic matter, or valve orientation obscured key features, the classification was not possible. These limitations were carefully documented to maintain transparency in the dataset.

3.4 Results

The resulting datasets are summarised in the following tables (4 and 5), which include all the identified genera (when classification to the genus level was not reachable), as well as the categorised 'girdle view' and 'unidentified.'

DOME B ice core	DB631 ~24 ka	DB660 ~26 ka	DB631 ~24 ka	DB660 ~26 ka
Dataset	2024	2024	2017	2017
N° of samples	5	4	11	4
Total diatom counts (n)	11	10	11	6
Total diatom classified at genus level (n)	9	7	8	5
Total diatom identified at species level (n)	3	0	2	2
Girdle view - unclassifiable (n)	2	1	1	0
Total volume filtered (ml)	110	49	110	40
Mean volume filtered	22	12	10	10

Table 4: counts and basic identification of diatom valves found in the Dome B ice core based on SEM images analyses conducted in 2023/2024.

The number of samples for DB631-2024 (n=5) differs from DB631-2017 (n=11) because the 2024 samples were prepared prior to reviewing the 2017 dataset.

DOME B ice core - genus %	DB631 ~24 ka	DB660 ~26 ka	DB631 ~24 ka	DB660 ~26 ka
Dataset	2024	2024	2017	2017
<i>Navicula</i> spp.	36%	20%	27%	50%
<i>Nitzschia</i> spp.	9%	20%	-	17%
<i>Luticola</i> spp.	27%	10%	-	17%
<i>Staurosirella</i> spp.	9%	10%	-	-
<i>Placoneis</i> spp.	-	-	9%	-
<i>Amphora</i> spp.	-	-	9%	-
<i>Planothidium</i> spp.	-	-	9%	-
<i>Diploneis</i> spp.	-	-	18%	-
<i>Ciclotella</i> spp.	-	10%	-	-

Table 5: detailed categorisation of diatom genera identified in the Dome B ice core, based on analyses performed in 2023/2024.

From table 4, we can observe that in 2024 the total diatom counts for DB631 and DB660 are 11 and 10, respectively. These numbers closely match the 2017 dataset for DB631 (11 diatoms), but they are higher for DB660 (6 diatoms in 2017).

The 2024 dataset demonstrates a stronger ability to classify diatoms at the genus level: in fact, 9 diatom valves classified in DB631 (2024) versus 8 in DB631 (2017) and 7 diatom valves classified in DB660 (2024) versus 5 diatom valves classified in DB660 (2017).

However, species-level identification remains challenging, with DB631 (2024) achieving 3 species-level identifications and DB660 none. This is in alignment with 2017 dataset.

The number of diatoms categorised as "girdle view-unidentifiable" is equal to 3 in the DB2024 dataset and 1 in the DB2017 dataset.

The average volume filtered in 2024 (22 mL for DB631 and 12 mL for DB660) exceeds that of 2017 (10 mL for both). This likely contributes to the higher total diatom counts in the 2024 dataset, especially for DB660. This data is later normalised when comparing the two site locations, Dome B and Skytrain Ice Rise, to guarantee consistency.

In table 5, instead, the different genera observed in the two dataset and their percentage represents their abundance are illustrated. It is evident that *Navicula* spp. is the most abundant genus in both datasets, followed by *Nitzschia* spp., *Luticola* spp and *Staurosirella*.spp.

3.4.1 Main genera present in Dome B 2024 dataset

Navicula spp. is predominant across all periods, with the highest abundance at the ~24 ka interval. This cosmopolitan genus includes marine, freshwater, and brackish species, reflecting diverse environmental conditions. Members of this genus are known for their adaptability to various ecological conditions, from nutrient-rich to oligotrophic waters, and these diatoms can be part of benthic, planktonic, and epiphytic communities. *Navicula* spp. is particularly prevalent in polar and subpolar regions, where its presence often reflects local environmental conditions and sediment transport pathways. (Round et al., 1990; Spaulding et

al., 2010). Furthermore, the genus includes species associated with ice-related habitats and coastal regions, underscoring its ecological versatility (Witkowski, 2000).

Luticola spp. is found across multiple periods, with a higher abundance at the ~24 ka interval. It is mainly associated with freshwater and terrestrial habitats, although some species are found in brackish environments. This genus is widely distributed across polar regions, particularly in Antarctica where it grows in extreme conditions, such as cryoconite holes, meltwater streams, and terrestrial soils. *Luticola* spp. is notable for its tolerance to desiccation and salinity fluctuations, as well as its ability to colonize nutrient-poor environments. The genus is often used as an indicator of local environmental conditions, including glacial melt and sediment deflation processes (Van de Vijver and Mataloni, 2008). Its ecological significance has been further highlighted in studies focusing on diatoms in Antarctic and Subantarctic regions, which documented its role in shaping local benthic communities (Levkov et al., 2013).

Cyclotella spp. is notably abundant at the ~33 ka interval, but it is also present at the ~26 interval. It mainly prospers in freshwater habitats, particularly in oligotrophic and mesotrophic lakes with low to moderate nutrient levels. This genus is often associated with stratified water columns where light availability is high, making it well-suited to stable aquatic environments during periods of thermal stratification. Certain species of *Cyclotella* group also exhibit adaptability to brackish and marine environments, including coastal and estuarine regions, due to their tolerance for variable salinity conditions (Round et al., 1990; Kilham et al., 1996; Spaulding et al., 2010).

Nitzschia spp. is present at ~24 ka and ~26 ka intervals, with two valves at ~24 ka. This is a highly diverse genus of diatoms with a global distribution across marine, freshwater, and brackish environments. Members of this genus are often associated with coastal regions, sea ice, and nutrient-enriched habitats, reflecting their ecological flexibility (Round et al., 1990; Hasle and Syvertsen, 1997). In polar regions, species of *Nitzschia* are frequently observed in fast ice and

meltwater pools, where they contribute to primary productivity and play a critical role in the food web (Medlin and Hasle, 1990).

Staurosirella spp. is observed at ~24 and ~26 ka intervals. Predominantly associated with freshwater environments, particularly in oligotrophic to mesotrophic lakes, rivers, and streams where nutrient levels range from low to moderate. This genus develops in benthic and epiphytic habitats, often attaching to substrates like rocks, sediments, or aquatic plants (Round et al., 1990).

3.4.2 Girdle view – unidentifiable category

The identification is challenging when valves are observed in girdle view, a common limitation in both OM and SEM image analyses.

The 'girdle view – unidentifiable' category includes diatom valves that could not be classified due to insufficient detail in SEM images or because of their valve's fragmentation, as well as their possible visualisation in girdle view, preventing the further identification.

3.4.3 Apical length of the common diatom genera in Dome B 2024 dataset

Figure 33 presents the apical lengths (μm) of the diatom valves genera mostly found in the Dome B ice core: *Nitzschia* spp., *Cyclotella* spp., *Luticola* spp. and *Navicula* spp., with their respective ranges of apical lengths.

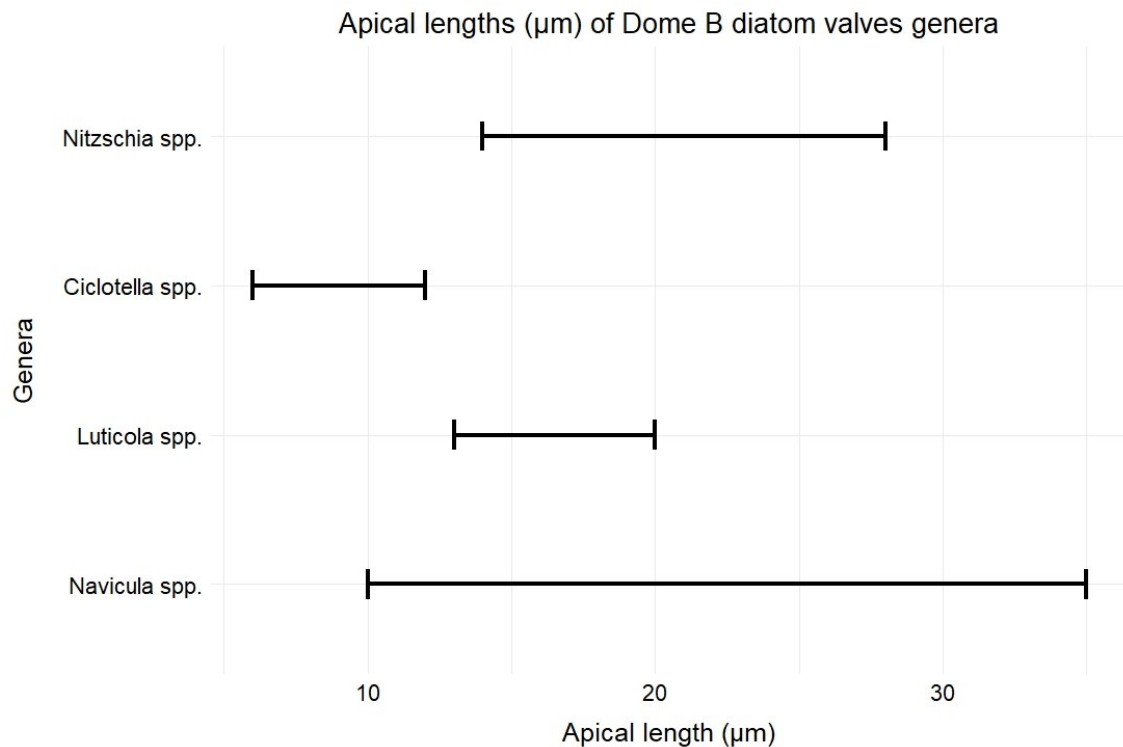


Figure 33: apical lengths (μm) of the most prevalent genera in the record.

From this graph, we can observe that *Nitzschia* spp. exhibits the broadest range of apical lengths, extending between approximately 14 μm and 28 μm , highlighting its morphological variability; *Cyclotella* spp. shows a moderate range, with apical lengths varying between 6 μm and 12 μm , suggesting a more compact and less variable morphology compared to *Nitzschia* spp; *Luticola* spp. displays a narrower range, spanning approximately 13 μm to 20 μm , indicative of consistent morphology within this genus; *Navicula* spp. demonstrates a wide range of apical lengths, between roughly 10 μm and 35 μm , emphasizing its high diversity in form.

3.4.4 Images of the main diatom genera in Dome B 2024 dataset

Following, figure A1-A2, figure B1-B2, figure C1-C2-C3-C4 and figure D1-D2-D3-D4 present examples of the main genera found in 2024 Dome B samples.

Nitzschia genera

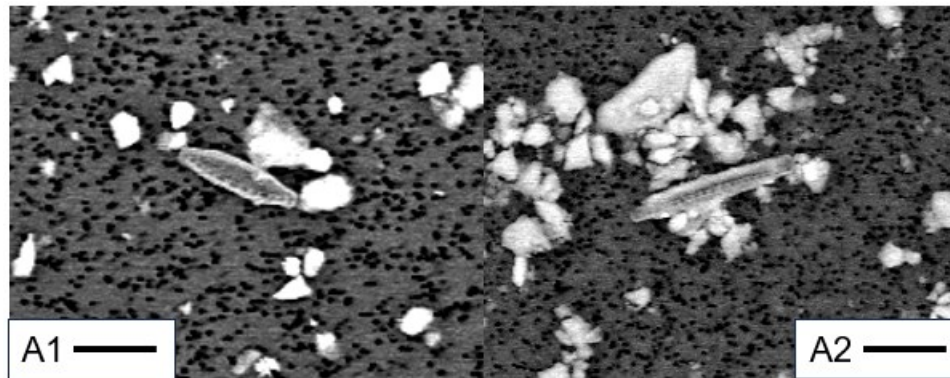


Figure A1-A2: two individuals of the Nitzschia genera, found in bags DB631 and DB660.

Scale bar: 10 μ m for SEM images.

Cyclotella genera

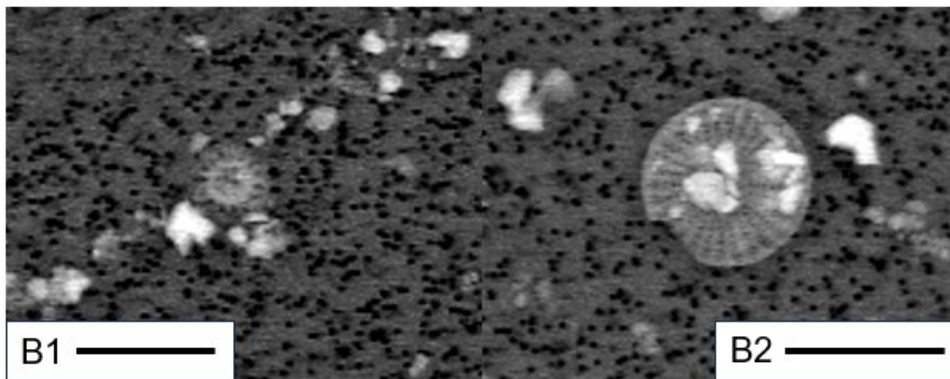


Figure B1-B2: two individuals of the Cyclotella genera, observed in bag DB780.

Scale bar: 10 μ m for SEM images.

Luticola genera

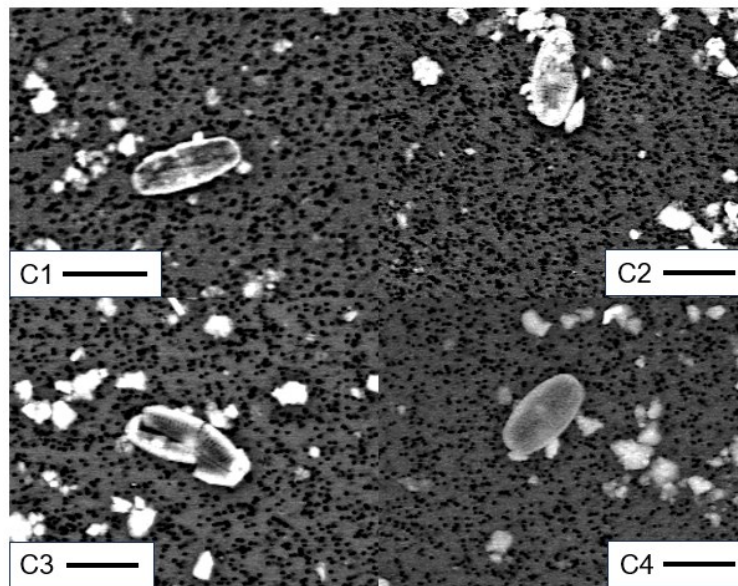


Figure C1-C2-C3-C4: individuals of the *Luticola* genera, found in bags DB631, DB660 and DB780. Scale bar: 10 μ m for SEM images.

Navicula genera

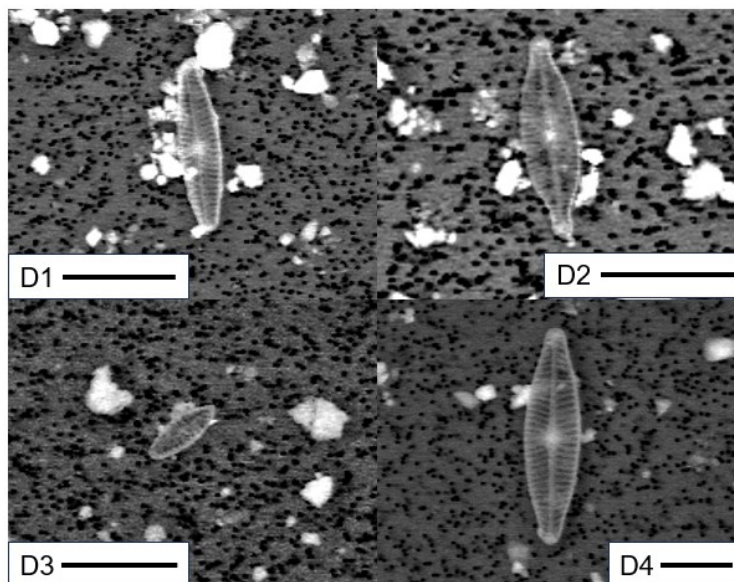


Figure D1-D2-D3-D4: individuals of the *Navicula* genera, observed in bags DB631 and DB780. Scale bar: 10 μ m for SEM images.

3.4.5 Comparison of habitat distribution – 2024 versus 2017

The figure 34 illustrates the distribution of diatom habitat types across the bags 631 and 660 from the Dome B ice core analyses conducted in 2017 and 2024.

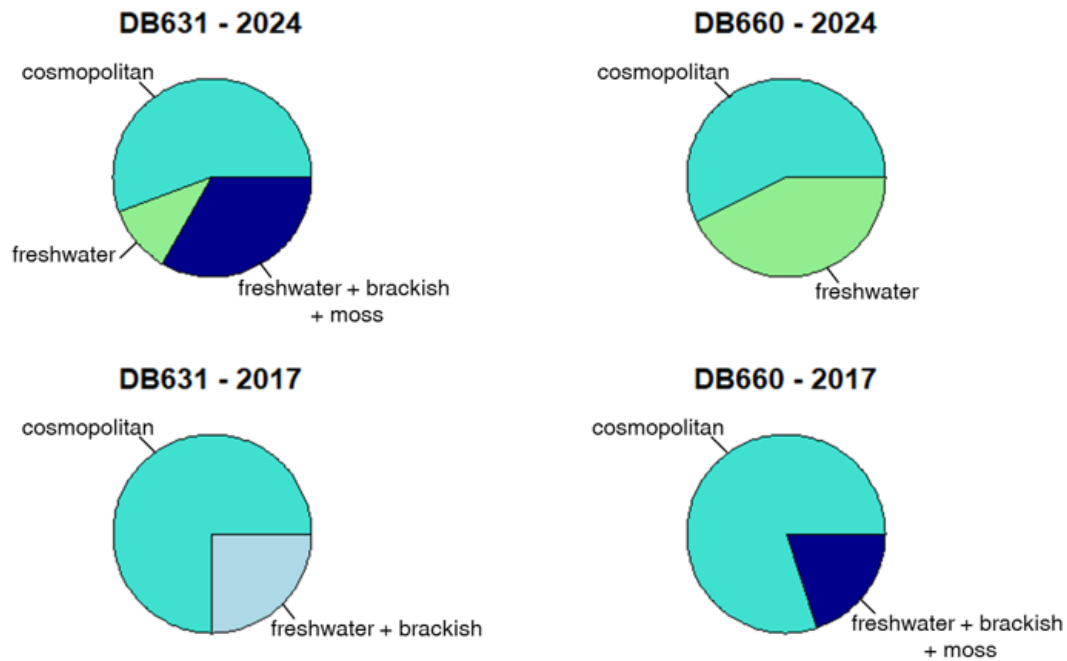


Figure 34: habitat distribution of diatom valves in the Dome B ice core samples 631 and 660 for both datasets (2024 and 2017).

The habitat types are categorised as cosmopolitan, freshwater, freshwater + brackish + moss, and freshwater + brackish. Girdle view diatoms were not included in the pie chart as they were not identifiable due to the lack of details that could be observed.

3.4.6 Comparison of diatom genera– 2024 versus 2017

Figure 35 compares the genera composition of diatom valves across the bags 631 and 660 from the Dome B ice core analyses conducted in 2017 and 2024.

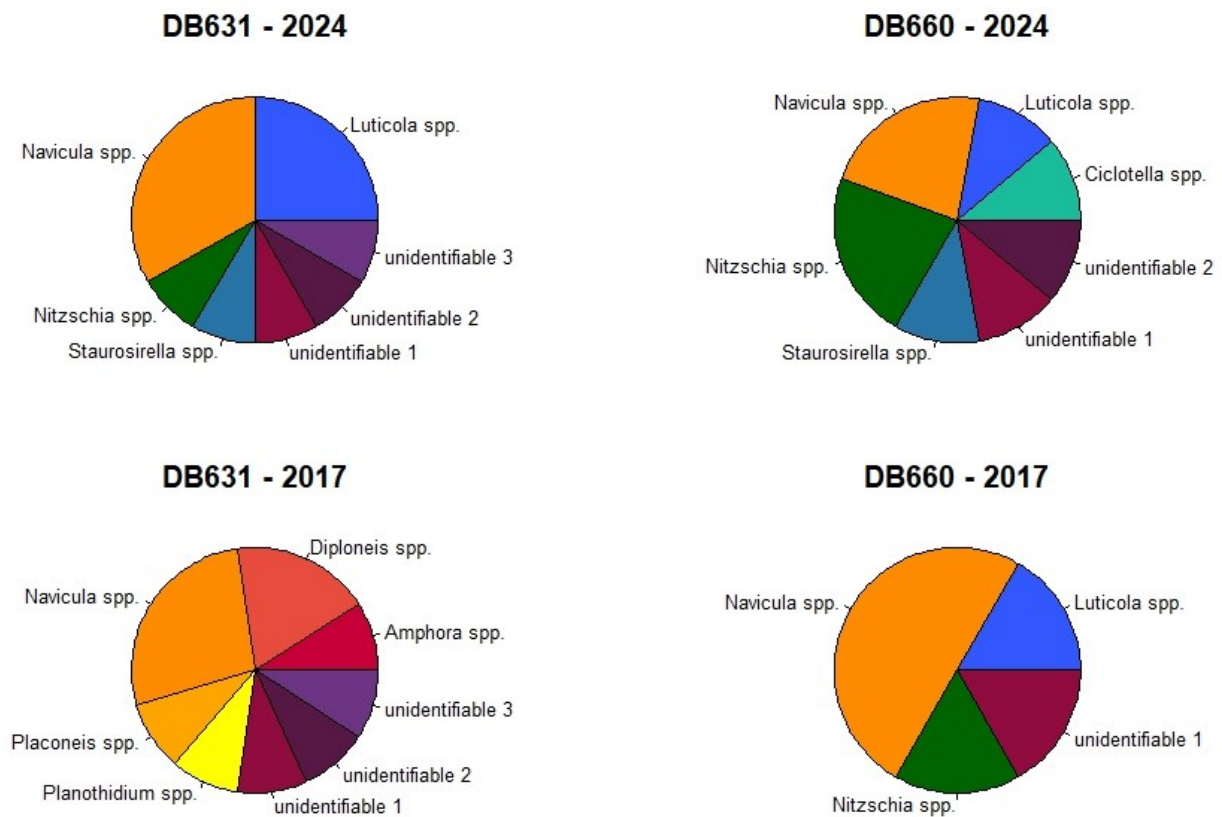


Figure 35: different diatom valves genera observed in the Dome B ice core samples 631 and 660 for both datasets (2024 and 2017).

The genera identified in the Dome B samples 631 and 660 for both datasets (2024 and 2017) suggest a deeper knowledge of diatom abundance and diversity

3.4.7 Distribution of the diatom genera over the LGM in 2024 dataset

Figure 36 illustrates the distribution of the diatom genera identified in the Dome B ice core dataset 2024, and it shows the number of diatom valves identified for each period.

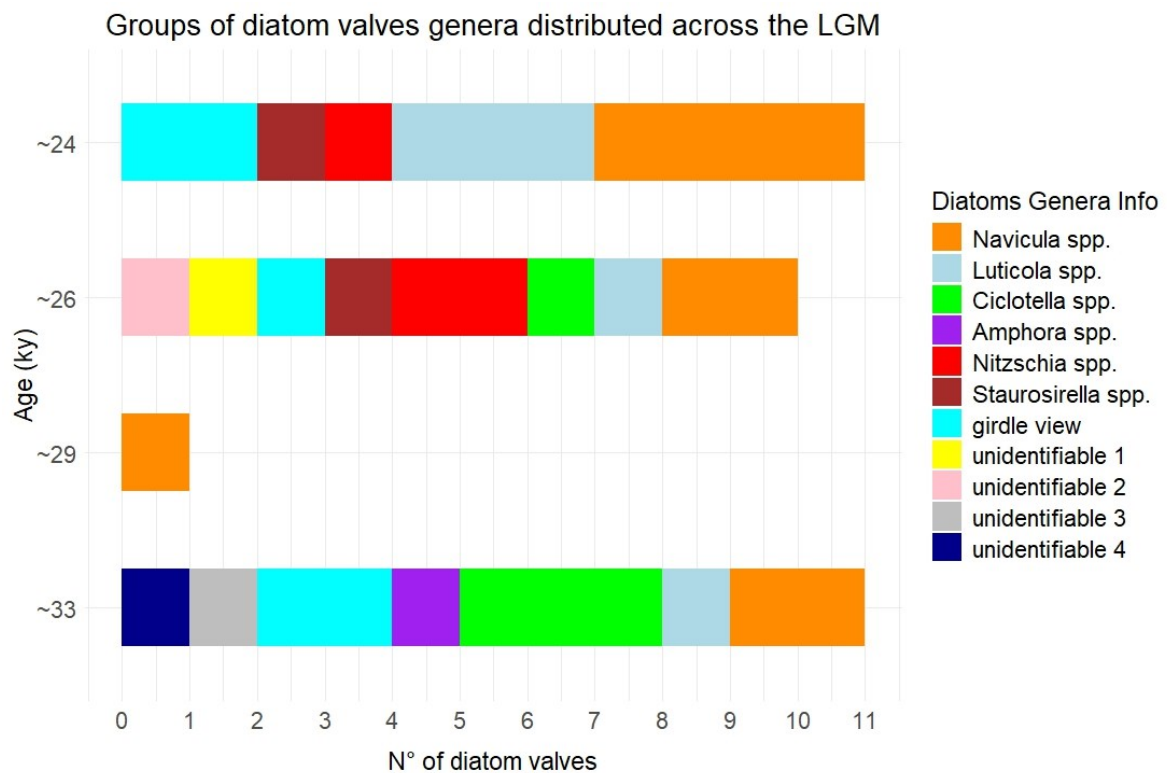


Figure 36: distribution of the main diatom valves genera identified in the Dome B ice core during the LGM (~24, ~26, ~29, and ~33 ka).

The data reveal remarkable variability in the abundance and diversity of genera across different periods, with a higher diversity observed at ~24, ~26 and ~33 ka.

3.4.8 Diatom valves and fragments distribution over the LGM in 2024 dataset

Figure 37 presents the distribution of diatom valve and fragment concentrations during the four different periods of the LGM.

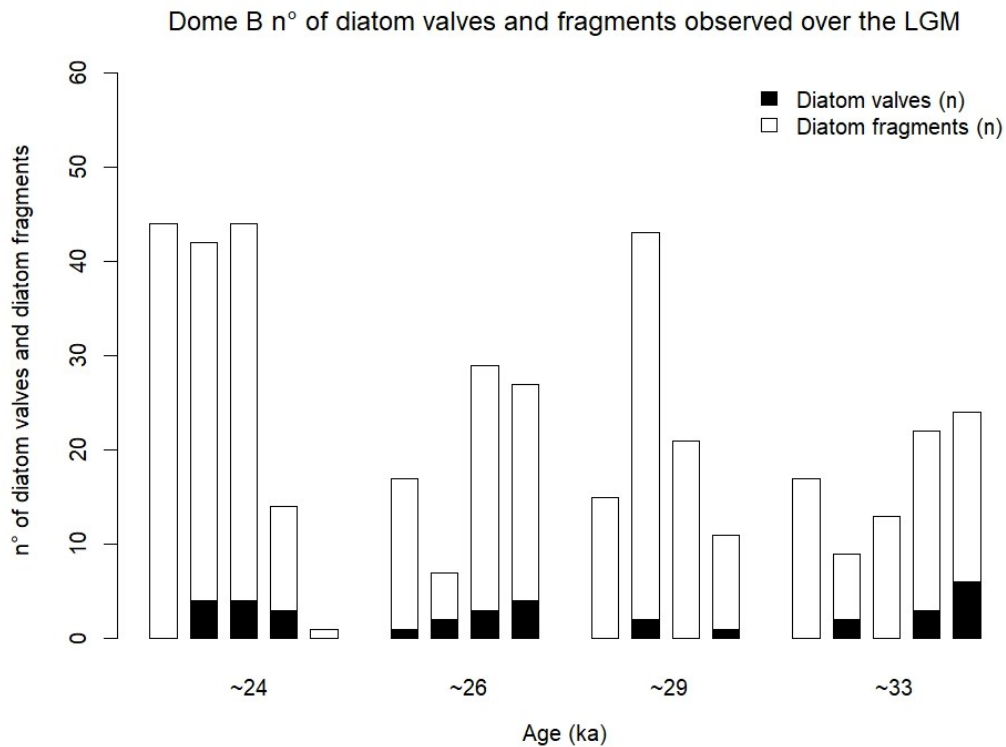


Figure 37: n° of Dome B diatom valves and fragments during the LGM.

Diatom valves are represented in black, showing a relatively stable distribution across the periods. The contribution of valves is relatively stable in periods ~24 and ~26 ka, while there is a decline in ~29 ka interval, followed by an increase during period ~33 ka.

Diatom fragments are represented in white bars, and they account for most of the total number in every period. The highest contribution of fragments is observed during the ~24 and the ~26 ka intervals. A gradual decrease in number is evident across subsequent periods, with the lowest counts recorded in the ~26 and ~33 ka intervals.

3.5 Discussion

From table 4, it is evident that the DB631 2024 and DB631 2017 datasets report the same number of diatom's counts (n). However, DB660 2024 appears to have a higher number of observed diatoms compared to DB660 2017. Given that the 2017 dataset was not collected systematically, this difference should be interpreted with caution, as a direct quantitative comparison between the two datasets is not appropriate.

A possible explanation for this discrepancy could be the methodological improvements introduced in the 2024 SEM analysis, which likely enabled the detection of smaller diatoms that might have been overlooked in 2017, when observations were conducted using the optical microscope. Therefore, rather than a direct numerical comparison, the results should be considered qualitative, highlighting the broader trends in diatom preservation, detection, and methodological advancements over time.

This table also shows that for all samples, more than 50% of the total diatoms were classified at the genus level (n), which provides information about the habitats and the potential origins of these diatoms. However, at the species level, only three specimens have been identified, resulting in notably low classification numbers. For example, no diatoms in DB660 2024 were identified to the species level, while the numbers remain minimal for other samples. This confirms that while SEM can provide high-resolution details necessary for species identification, the magnification used for this study is still insufficient in many cases due to the morphological similarities between certain diatoms and the challenges in the proper identification.

Additionally, a small number of valves were categorized as "unidentifiable," due to their orientation in girdle view: this orientation makes it challenging to distinguish whether the valve is pennate or centric.

Overall, table 4 confirms the presence of diatoms in the Dome B ice core with the new dataset, but it also highlights the inherent difficulties in diatom identification.

Table 5 provides an overview of the genus composition for each sample, expressed in percentages. *Navicula* spp. is the only genus consistently present

across all four samples, while *Nitzschia* spp. and *Luticola* spp. are absent only in DB631 2017. This finding suggests that a more extensive examination of DB631 2024 enabled the discovery of greater variability in diatom genera around ~24 ka. Other genera, such as *Staurosirella* spp., are present in small numbers, with only two valves recorded in DB631 2024. Rare occurrences of *Placoneis* spp., *Amphora* spp., *Planothidium* spp., *Diploneis* spp., and *Cyclotella* spp. have also been observed. These genera, although infrequent, further enhance the understanding of diatom diversity in the Dome B ice core.

In conclusion, table 5 highlights the differences between the two datasets. The increased diversity observed in the 2024 dataset enriches the knowledge of diatom genera present in Dome B, emphasising the importance of detailed and comprehensive analyses to capture the full variability of diatom assemblages over time.

Moreover, the pie chart in figure 34 represents the relative habitat distribution of the diatom genera observed in Dome B samples 631 and 660 for both datasets, 2024 and 2017.

In the 2024 dataset, the assemblage is dominated by cosmopolitan genera, which represent more than half of the total genera observed. In addition, a substantial portion of the assemblage corresponds to freshwater, brackish, and moss-associated taxa, suggesting a combination of aquatic and terrestrial environmental contributions. A smaller fraction is composed of strictly freshwater genera, indicating the presence of taxa adapted exclusively to non-saline environments.

In contrast, the 2017 dataset for DB631 shows a dominance of cosmopolitan genera, but with an even greater proportion compared to 2024. Interestingly, the freshwater + brackish category is more prominent in the 2017 dataset than in 2024, suggesting a slightly different ecological signature between the two records.

The comparison of habitat distribution in sample DB660 between 2024 and 2017 highlights similar trends. In the 2024 dataset, cosmopolitan genera once again dominate the assemblage, indicating the prevalence of broadly adaptable taxa. However, freshwater genera contribute a more significant portion of the

assemblage in DB660 compared to DB631, suggesting a stronger freshwater influence in this interval. The 2017 dataset of DB660 also shows a higher concentration of cosmopolitan genera relative to 2024, resembling the pattern seen in DB631 2017. Furthermore, the presence of freshwater + brackish + moss-associated taxa in DB660 2017 aligns more closely with the composition observed in DB631 2024, potentially reflecting similarities in depositional or source conditions.

Overall, across both time periods and samples, cosmopolitan genera consistently dominate the diatom assemblages, underscoring their ecological plasticity and resilience in diverse environmental conditions. The freshwater category remains a constant contributor only in the DB631 datasets from both 2017 and 2024, indicating potential freshwater influences. The freshwater + brackish + moss category is observed in both time periods and across different samples, suggesting either changes in minor contributors over time or shifts in environmental inputs affecting diatom source assemblages.

Few diatoms were identified at specie-level during ~24 ka interval: *Navicula* spp. emerges as the dominant taxonomic group across all analysed intervals, reaffirming its widespread occurrence in Antarctic ice records. Within this group, two specific species were identified: *Navicula gelida* (2 specimens) and *Navicula perminuta* (n° of valve identified =1).

Navicula gelida (figure 38) presents a lanceolate morphology with slightly rounded ends and bilateral symmetry along its longitudinal axis, a characteristic feature of pennate diatoms (Van de Vijver et al., 2002; Medlin and Priddle, 1990). The valves range in length from 10 to 30 µm and in width from 4 to 6 µm (Medlin and Priddle, 1990; Witkowski, 2000). The striae are parallel to slightly radiate, with a density of 12–16 striae per 10 µm. Due to the presence of fine areolae within the striae, the observation under the SEM is often required for accurate resolution (Medlin and Priddle, 1990; Witkowski, 2000). The raphe (figure 39 and figure 40) is straight and centrally located, with indistinct terminal fissures, while the valve surface exhibits fine areolae that may not always be fully discernible

under optical microscopy but are clearly visible in the SEM images (Witkowski, 2000).

Navicula gelida is a marine benthic diatom predominantly found in polar and subpolar regions, including the Antarctic coastline and nearby continental shelves. Its occurrence has been well-documented in Antarctic marine environments, particularly in coastal areas and shallow waters. Medlin and Priddle (1990) describe its widespread distribution in Antarctic waters, emphasizing its adaptation to cold marine conditions. Van de Vijver et al. (2002) highlight its association with sediment-rich habitats, such as those along the Antarctic continental margin, where it thrives in benthic environments. These studies confirm its presence in marine ecosystems influenced by coastal and ice-associated processes.

The next figure presents a *Navicula gelida* captured with the SEM at Milan-Bicocca University.

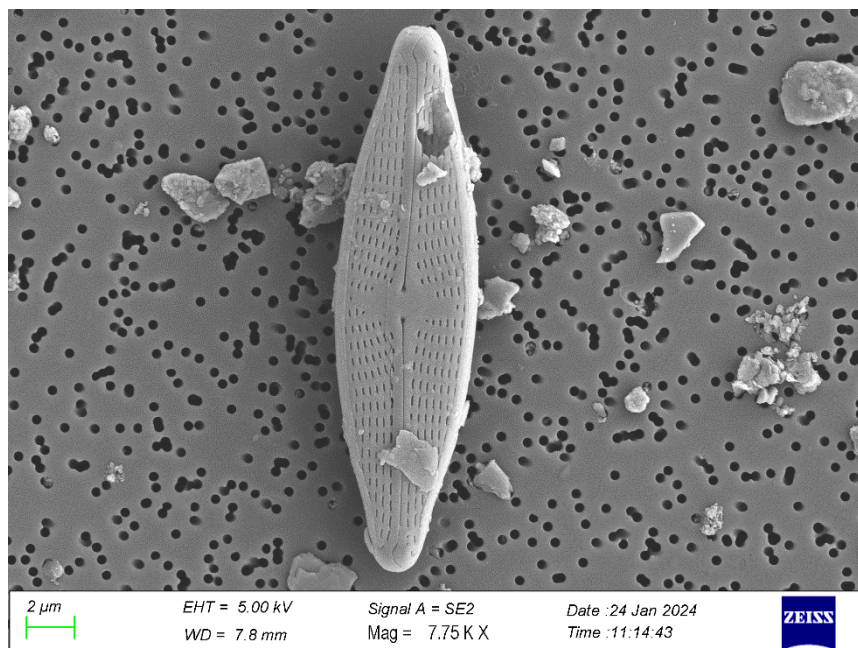


Figure 38: a *Navicula gelida* (SEM image).

The following figures (39-40) highlight details of this diatom species.

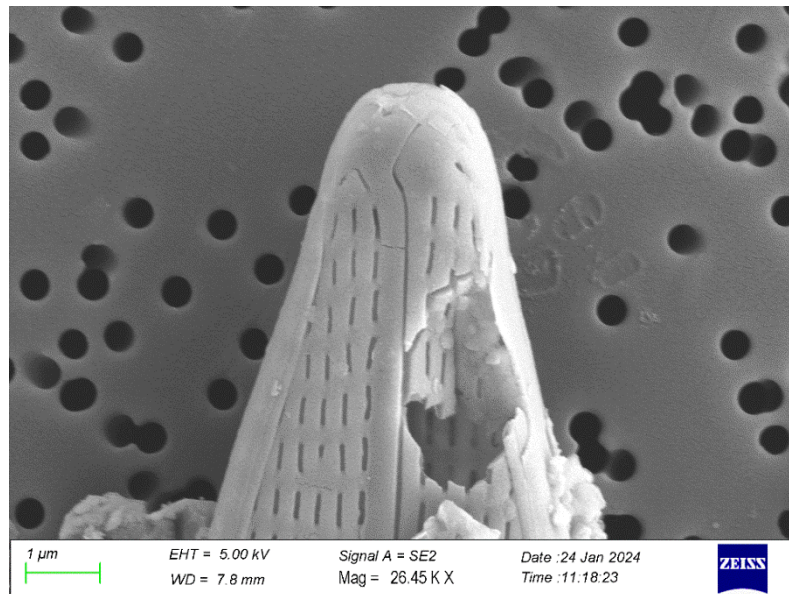


Figure 39: one end of the Navicula gelida and it is visible its raphe curving towards the tip, considered one of the key features of this species.

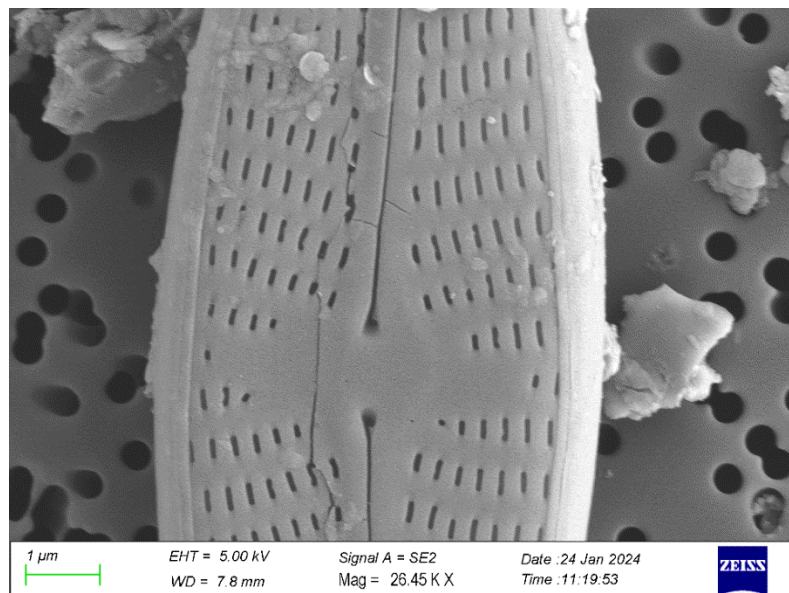


Figure 40: the raphe of the Navicula gelida that splits towards the center and the longitudinal pores distributed across the entire surface of the valve.

Navicula perminuta in figure 41, instead, is characterised by an elliptical-lanceolate valve shape with slightly rostrate apices, distinguishing it morphologically from *N. gelida* (Round et al., 1990). Like other species of the genus, it exhibits bilateral symmetry along the longitudinal axis, typical of pennate diatoms.

The valves range from 8 to 20 μm in length and approximately 3 to 5 μm in width (Round et al., 1990; Witkowski, 2000). The striae are more densely packed than in *N. gelida*, with a density of 16–22 striae per 10 μm . The striae are arranged in a parallel to slightly radiate pattern and often require the SEM imaging for accurate resolution, due to the fineness of the ultrastructure (Round et al., 1990). The raphe system (figure 42 and figure 43) is well-defined and slightly deflected near the apices, a morphological feature that aids in distinguishing *Navicula perminuta* from other *Navicula* species (Round et al., 1990). The surface of the valves displays regular areolae, which are easier to be observed under the SEM (Witkowski, 2000).

Navicula perminuta is considered cosmopolitan, found in marine, freshwater, and brackish environments. It has been recorded in a variety of ecological settings, reflecting its broad adaptability (Round et al., 1990; Witkowski, 2000).

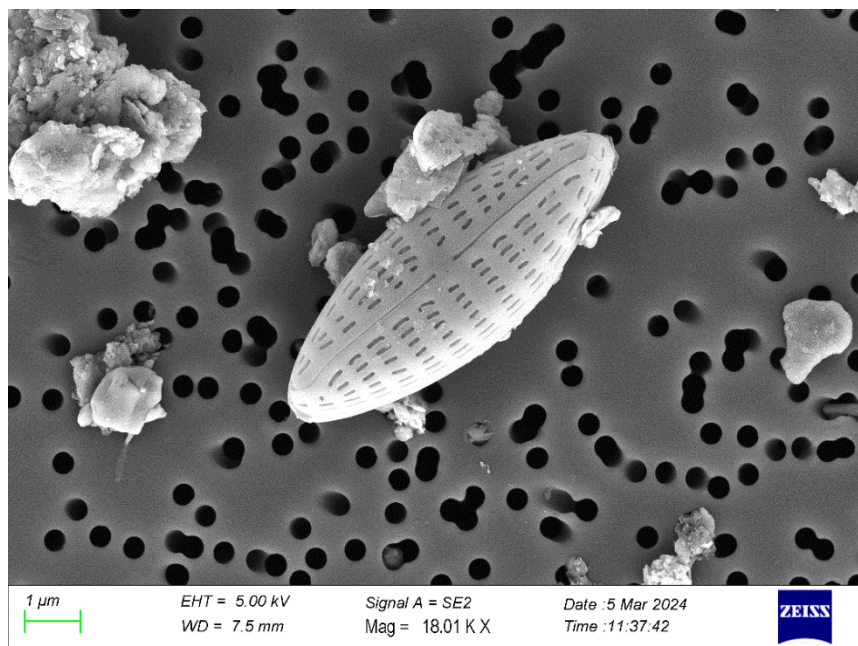


Figure 41: a *Navicula perminuta* (SEM image).

The following figures, 42 and 43, highlight details of this diatom.

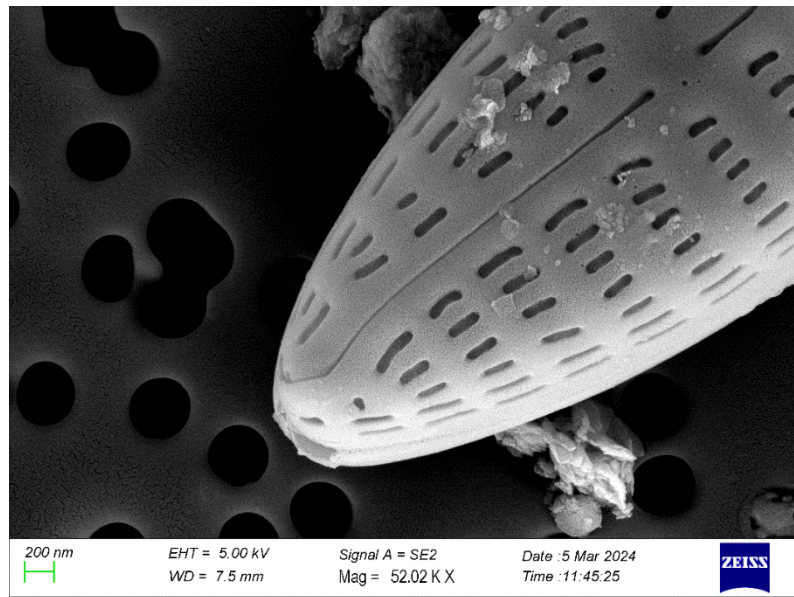


Figure 42: one end of the *Navicula perminuta* and it is visible its raphe curving towards the tip, similar to *N. gelida*.

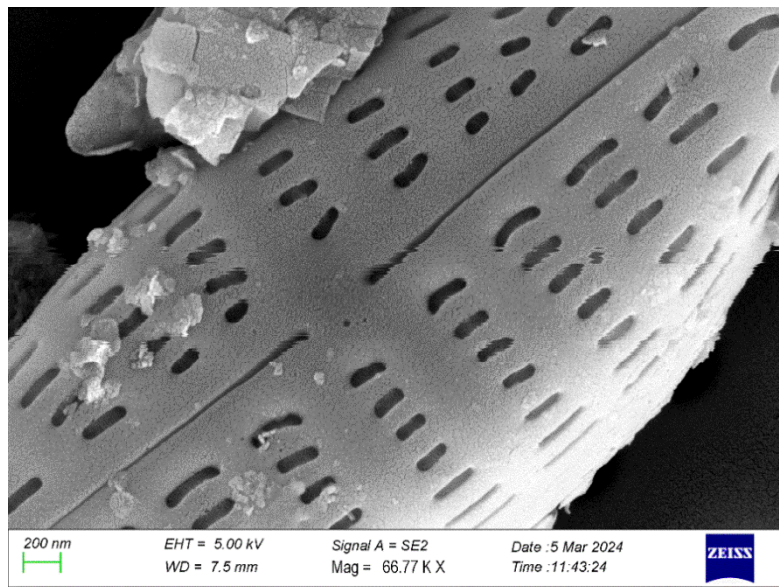


Figure 43: the raphe of the *Navicula perminuta* that splits towards the center and the longitudinal pores distributed across the entire surface of the valve.

Scanning Electron Microscope (SEM) images were collected at the University of Milan-Bicocca by Paolo Gentile.

Navicula gelida and *Navicula perminuta* have been reported to frequently co-occur in polar diatom assemblages, particularly in marine or sea ice habitats, highlighting shared ecological niches and similar transport pathways (Zidarova et al., 2022; Kellogg and Kellogg, 1987; Medlin, 1990).

Figure 36 provides an overview of the distribution of diatom genera across different layers of the Dome B ice core, representing time intervals of ~24 ka, ~26 ka, ~29 ka, and ~33 ka. This temporal distribution highlights the variability in diatom genera and their abundance during the LGM.

The samples reveal a notable diversity of diatom genera, including *Navicula* spp., *Luticola* spp., *Cyclotella* spp., *Amphora* spp., and *Nitzschia* spp., alongside several "unidentifiable" categories.

At ~24 ka interval, *Navicula* spp. and *Luticola* spp. dominate the assemblage, with contributions from other genera such as *Nitzschia* spp. and *Amphora* spp. This diversity suggests a depositional environment influenced predominantly by freshwater sources, with the possibility of occasional brackish or marine inputs reflected in *Amphora* spp. and in two identified species from *Navicula* spp.

The ~26 ka interval presents a shift with the appearance of *Cyclotella* spp. and a rare occurrence of *Amphora* spp., while alongside the presence of *Navicula* spp. and *Luticola* spp. continues. *Cyclotella*'s association with freshwater lakes highlights stable freshwater inputs, while *Amphora*'s presence hints at a potential, though minor, marine or brackish influence.

At ~29 ka interval, the diversity observed is reduced, with *Navicula* spp. being the only identified genus. This decline could indicate harsher environmental conditions during this period, limiting both diatom transport and deposition. The dominant freshwater genus suggests minimal to no marine influence.

At ~33 ka, diatom diversity resurges, with the observation of *Luticola* spp., *Cyclotella* spp., *Nitzschia* spp. and *Navicula* spp.

Overall, the dominance of freshwater-associated genera such as *Navicula*, *Luticola*, and *Cyclotella* suggests the predominance of freshwater origins. However, the occasional presence of genera such as *Amphora* and *Nitzschia*,

which are known to thrive in marine or brackish environments, along with the occurrence of *Navicula gelida* and *Navicula perminuta*, suggest the possibility of episodic marine inputs.

The identification of *Navicula gelida* and *Navicula perminuta* in the ~24 ka interval provides a small yet direct piece of evidence of a marine contribution to the Dome B diatom record. This specific finding is particularly relevant as it aligns with the peak of LGM. Their presence in the Dome B ice core at ~24 ka supports the hypothesis proposed by Delmonte et al. (2017), suggesting that the exposed Patagonian continental shelf, which emerged due to lowered sea levels during the LGM, served as a significant source of marine benthic diatoms. The expansion of these deflation areas likely provided a suitable habitat for *Navicula gelida*, which could have subsequently been entrained and transported to the East Antarctic plateau by the SHWW. Similarly, the occurrence of *Navicula perminuta*, known for its adaptability to a range of environmental conditions and to be able to grow in marine, freshwater, and brackish environments, suggests that its transport to Antarctica could have been originated from both marine and terrestrial sources. The presence of *Navicula perminuta* further supports the notion of mixed aquatic influences, reflecting the interplay between different atmospheric transport mechanisms and depositional environments (Sims et al., 2006; Zidarova et al., 2022).

To analyse the diatom valves and fragments flux preserved over time, figure 37 illustrates their presence across the LGM. The data reveals a significant decrease in diatom abundance at ~33 ka interval, when compared to ~24, ~26, and ~29 ka. This variability reflects shifts in environmental changes, such as sea level fluctuations, wind transport dynamics and ice sheet extent variations.

The reduced abundance of diatom valves and fragments at ~33 ka could be associated to relatively higher sea levels compared to subsequent LGM stages. During this time, coastal and shelf environments in South America may have still been partially submerged, limiting the availability of exposed sediments that later became dust sources as sea levels dropped further into the LGM. Consequently, the supply of diatoms from deflation areas such as the Patagonian continental

shelf may have been more restricted at ~33 ka interval compared to later periods, influencing the flux of diatom deposition in the Dome B ice core.

However, it is important to acknowledge the limitations of interpreting depositional trends based on a restricted number of identified diatoms. While the presence of *Navicula gelida* and *Navicula perminuta* add information, however it is important to notice that the low number of identified specimens necessitates caution in drawing definitive conclusions. Similarly, the identification of *Cyclotella* spp., although suggests a possible transport from lacustrine or proglacial environments, again the specimens observed are few.

To better understand the origin of the diatom assemblages observed in the Dome B ice core, it is essential to consider the mechanisms of dust particle transport. The aeolian dust measured in the Dome B ice core during the LGM originated primarily from South America, Patagonia and Tierra del Fuego, and these areas are known to be the major dust sources for central Antarctica. The extensive influence of SHWW facilitated the long-range transport of mineral dust across continents, as demonstrated by previous studies (Delmonte et al., 2010; Lambert et al., 2008).

Patagonia and Tierra del Fuego were extensively glaciated during the LGM, with ice sheets reaching their maximum extent between ~26 and ~19 ka, covering vast areas and extending onto the continental shelf (Glasser et al., 2008; Sugden et al., 1995). As the ice sheets retreated in response to climate warming, previously glaciated landscapes became exposed, providing substantial sources of fine-grained sediments for aeolian transport (Kaplan et al., 2008). Moreover, the Patagonian continental shelf, exposed to lower sea levels, further contributed to the availability of sediments mobilised by strong westerly winds (Peltier, 2004). These intensified winds transported mineral dust across the Southern Ocean into East Antarctica, as evidenced by dust records from Dome B, Dome C, and Vostok ice cores (McCulloch et al., 2000).

In addition, sea level reconstructions indicate that during the earlier phase of the LGM, at ~33 ka interval, sea levels were relatively higher compared to the glacial sea level minimum around ~26–19 ka (Lambeck et al., 2014). Higher sea levels at ~33 ka would have resulted in reduced exposure of dust and diatom source

areas, such as the Patagonian continental shelf, which harboured benthic marine diatoms including *Navicula gelida* and *Navicula perminuta* (identified in this study), as well as *Diploneis* spp., *Luticola* cf. *cohnii*, and *Amphora* spp., as reported by Delmonte et al. (2017). One diatom valve of the genus *Amphora* was also found in bag DB780 from the 2024 Dome B dataset. However, since the comparison between the 2017 and 2024 datasets was conducted only on bags DB631 and DB660, this *Amphora* spp. identification had not been previously highlighted.

Conversely, the periods around ~24, ~26, and ~29 ka were characterized by lower sea levels, leading to a more extensive exposure of the continental shelf, thus enhancing the contribution of marine-derived diatoms to the Dome B record. According to Lambeck et al. (2014) and Kaiser and Lamy (2010), global mean sea levels varied significantly throughout the Late Glacial period, with important implications for the exposure of potential dust and diatom sources such as the Patagonian continental shelf. Around ~33 ka, sea levels were approximately 60–70 meters lower than present, meaning that a considerable portion of the Patagonian shelf remained submerged and less available for sediment deflation. By ~29 ka, sea levels had dropped further to approximately 80–90 meters below present, resulting in the exposure of a larger section of the continental shelf. This trend continued, reaching one of the lowest sea levels during the LGM around ~26 ka, with estimates ranging from 100 to 120 meters below present. At this point, sediment deflation areas would have been at their maximum extent. Sea levels remained similarly low around ~24 ka, maintaining broad exposure of dust and diatom source regions and sustaining aeolian transport potential toward Antarctica.

As illustrated in figure 37, the decline in diatom valves and fragments at ~33 ka interval aligns with the hypothesis that higher sea levels (figure 32) reduced the exposure of crucial sediment sources such as the Patagonian continental shelf (figure 44).

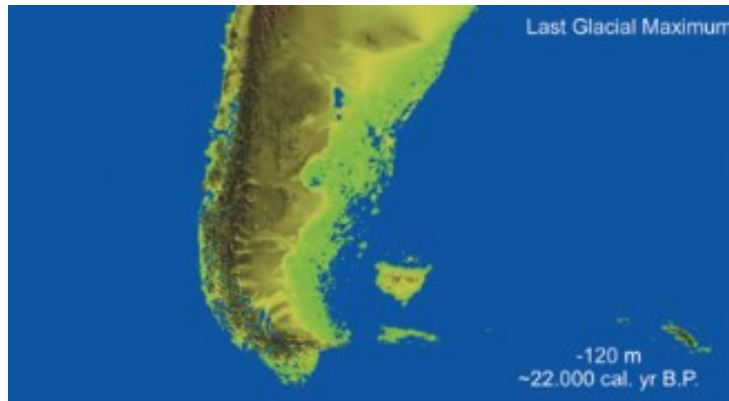


Figure 44: palaeogeographical evolutionary model of Pampa and Patagonia during the LGM (original figure presented by Ponte et al., 2011).

However, it is also important to consider the potential contribution of local Antarctic sources. Previous studies have documented the presence of freshwater diatoms in meltwater streams, subglacial lakes, and terrestrial ice-free areas, such as the McMurdo Dry Valleys and coastal regions (Hodgson et al., 2004; Sabbe et al., 2004). Possible inputs could include meltwater outflows from proglacial lakes or subglacial hydrological activity, which – although still poorly constrained for this period – have been reported in specific Antarctic regions (Weber et al., 2014; Obryk et al., 2017). These environments, which contain diatom assemblages adapted to extreme polar conditions, could have contributed to the diatom populations observed in the ice core through local deflation and redeposition processes. Although katabatic winds may have facilitated the mobilisation of diatom-bearing sediments from exposed Antarctic landscapes, it is unlikely that this kind of transport reaches the high-elevation sites of central East Antarctica supplementing long-range transport from South America. In fact, katabatic flow typically blows towards the sea, and a high-altitude return air flow would imply strong convective activity for diatom uplift, while that is not the case for Antarctica and in general cold climates (Parish and Bromwich, 2007).

Nevertheless, the contribution of such sources to the Dome B record during the LGM must be considered with caution. The Antarctic ice sheets were significantly more extensive, and the climate was considerably colder than today (Anderson

et al., 2002), likely reducing or eliminating many of the potential ice-free habitats known in the current Antarctic landscape.

Thus, while the possibility of local Antarctic sources cannot be entirely excluded, long-range transport from lower-latitude regions – particularly South America – remains the most plausible explanation for the diatom assemblages observed in the Dome B ice core during the LGM.

3.6 Conclusions

To summaries, these findings not only build upon previous interpretations that identified Patagonian sources as main contributors to the Dome B dust record but also emphasised the value of integrating biological proxies, such as diatom valves, into the reconstructions for past environmental conditions. By combining diatom and dust analyses, this study offers a more comprehensive understanding of the interplay between sea-level changes, ocean-atmosphere dynamics, and aeolian transport mechanisms during the LGM.

The observed variability in dust deposition patterns at Dome B aligns with the dynamic interplay of atmospheric circulation patterns and evolving source region conditions. The influence of glacial-interglacial cycles on the availability and transport of dust highlights the complexity of reconstructing past atmospheric processes and underscores the importance of high-resolution ice core records in capturing these intricate interactions.

Building on these observations, the following analysis explores the variability of diatom assemblages and their environmental implications across the LGM layers. The distribution of diatom valves and fragments provides critical insights into atmospheric transport dynamics and depositional environments. *Navicula* spp., cosmopolitan, dominates the record with the identification of *Navicula gelida* and *Navicula perminuta*, emphasising the role of marine benthic sources. These species likely originated from the exposed Patagonian continental shelf during the LGM, supporting the conclusions of Delmonte et al. (2017), while also indicating a small but significant oceanic contribution to the Dome B diatom record, complementing the predominantly freshwater sources previously identified.

3.7 SPES and CC measurements

3.7.1 Introduction to SPES and CC

In this section, diatom and mineral dust concentration and size from Dome B samples are obtained using the SPES and the Coulter Counter measurements. Specifically, outputs from SPES measurements include the extinction cross-section (Cext), the particle concentration expressed and the number concentration as a function of the particle diameter, obtained from Cext. For the CC, we consider particle concentration measured in units of ppb or ng of dust per mL of meltwater sample, and the CPP% parameter calculated in the 2.5-5 μm size range (expressed as equivalent spherical diameter; Delmonte et al., 2002). Additionally, diatom fragments identified through high-resolution SEM imaging were examined to assess whether their presence is related to the transport of dust particles measured by SPES and CC. Diatom valves, although analysed through SEM images, were excluded from this discussion due to their negligible concentration, limiting their statistical significance and contribution to the analysis. The higher abundance of fragments compared to whole valves suggests that focusing on fragments may provide more representative information about particle transport and deposition.

3.7.2 Results of SPES and CC measurements

Figure 45 illustrates the age-depth relationship of the Dome B ice core. The curve represents the age (in ka BP) at various depths of the ice core, reflecting the timeline reconstructed from ice core dating methods (Delmonte et al., 2017). The four highlighted points correspond to specific depths where samples DB631, DB660, DB720 and DB780 were extracted for analyses using different techniques, such as SPES and CC for this research section.

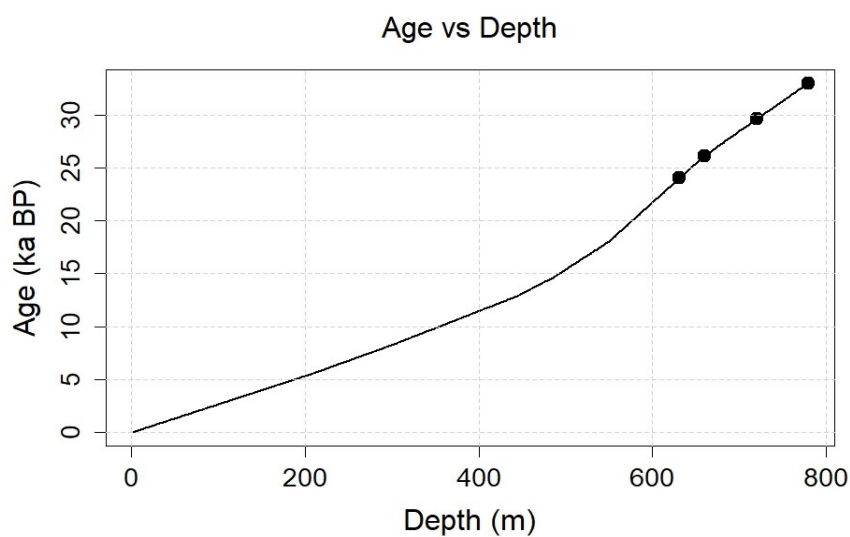


Figure 45: plot of Dome B age (transferred onto the AICC2012 timescale) against depth. The points, from left to right, correspond to the ages of ~24, ~26, ~29 and ~33 ka.

Figure 46 shows the relationship between particles' concentration measured using the SPES instrument (x-axis) and the CC (y-axis). Each data point represents the particles concentration for a specific sample.

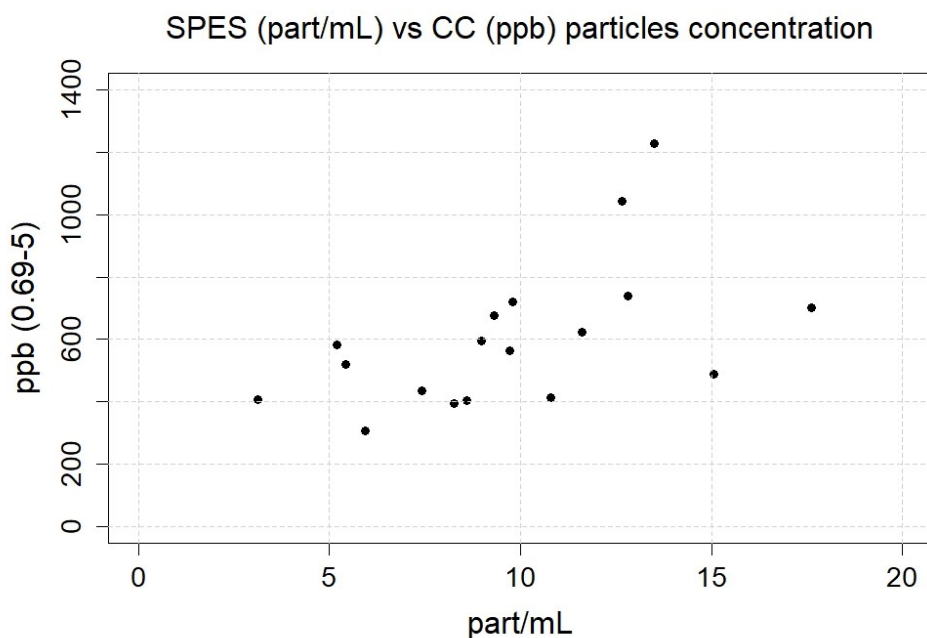


Figure 46: scatter plot of dust particle concentrations measured using SPES (particles/mL) and CC (ppb), showing no significant correlation between the two datasets.

The plot in figure 46 clearly represents a missing correlation caused by, and at the same time indicating, the difference in the size range and the physical parameters accessed by the two methods.

Following, figure 47 demonstrates the CPP2.5-5 over time, spanning from ~24 ka to ~33 ka. The values appear relatively stable, oscillating between 25 and 40% across the examined interval, with minimal fluctuations. A slight decline is observed towards older ice sections, though the overall variation is minimal.

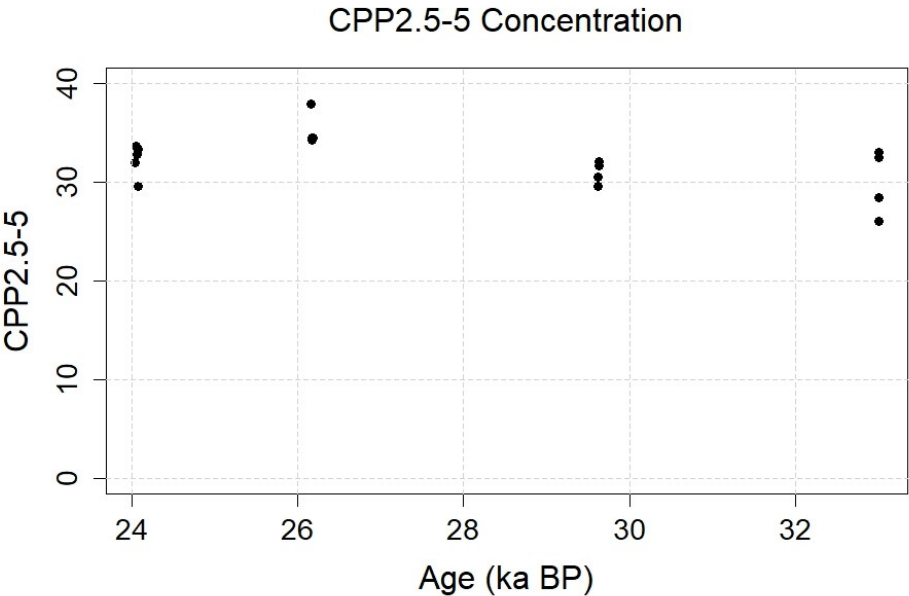


Figure 47: relationship between diatom fragment counts (n) and the CPP2.5–5 particles' concentration index over the LGM.

Figure 47 represents the relationship between diatom fragment counts (n) and the CPP2.5–5 particles' concentration index obtained from the Coulter Counter (CC). The y-axis shows the number of diatom fragments, while the x-axis represents the CPP2.5–5.

Figure 48, instead, demonstrates that the number of diatom fragments changes appreciably irrespectively of the CPP2.5-5 index.

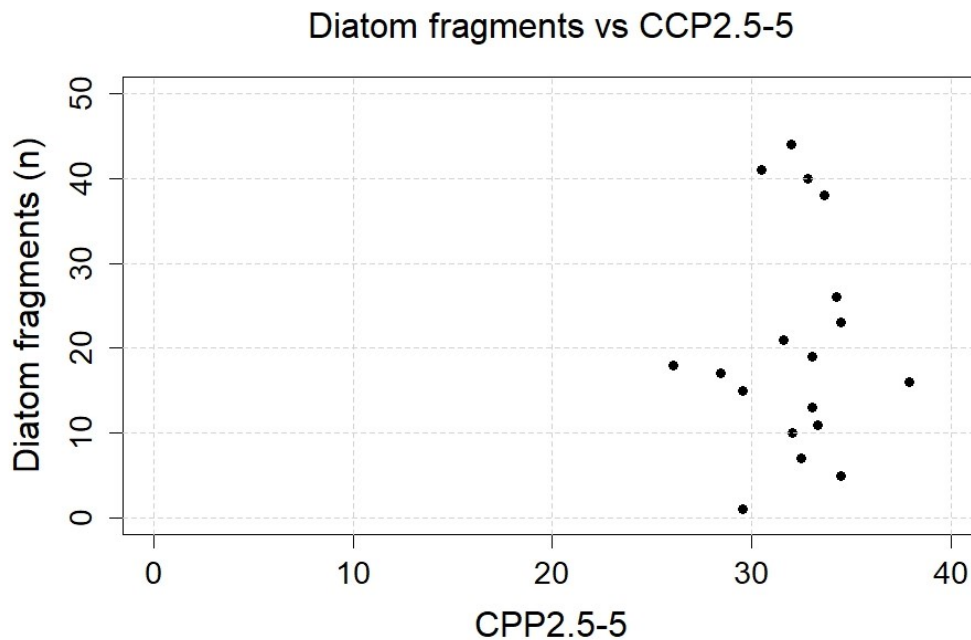


Fig. 48: scatter plot illustrating the distinct nature and apportionment of CPP2.5–5 particles and diatom fragments.

This plot indicates the different nature and apportionment of the two species. While there are instances where high CPP2.5–5 concentrations coincide with moderate diatom fragment counts, the overall distribution of points suggests variability in the relationship, without a consistent trend.

The next figure, 49, highlights the extinction cross-section (Cext) values over the Last Glacial Maximum (LGM) interval as a function of age (ka).

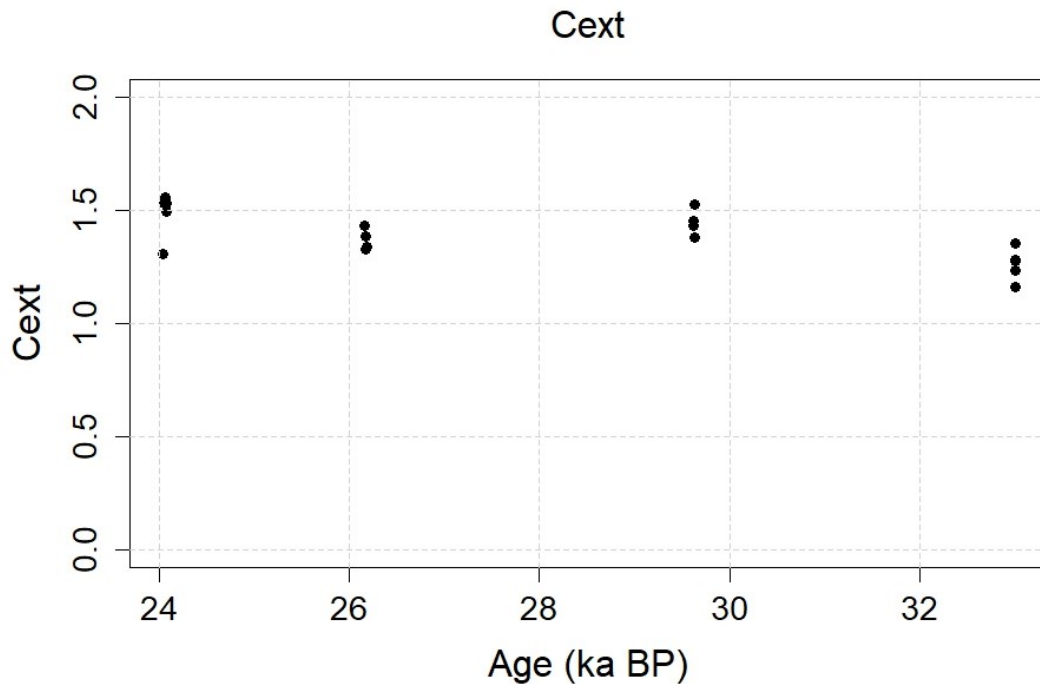


Figure 49: the extinction cross-section (Cext) values over the Last Glacial Maximum (LGM) interval as a function of age (ka).

While the data indicates a slight downward trend from ~24 ka to ~33 ka, the overall variability in Cext values remains relatively low, suggesting consistent optical properties for most of the particle population across the studied interval. Noticeable, in figure 49, is that the behaviour is roughly in agreement with that shown in figure 47 for the CPP2.5-5. This correlation could be due to the major effect in Cext caused by the largest-size fraction of the population, that clearly shifts to upper values the average Cext.

After, figure 50 is a scatter plot that demonstrates the relationship between the extinction cross-section (Cext) measured by the SPES instrument and the

number of diatom fragments observed. The y-axis represents the number of diatom fragments, while the x-axis indicates the Cext.

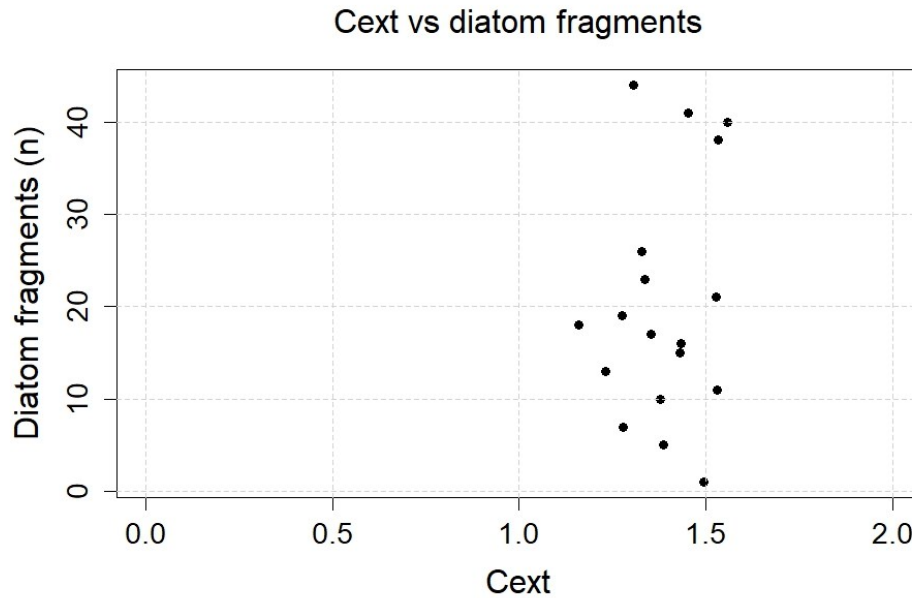


Figure 50: scatter plot showing the relationship between extinction cross-section (Cext), as measured by the SPES instrument, and the number of diatom fragments observed.

In figure 50 is evident that there is not a clear correlation as the data points are scattered without forming a linear or discernible trend, indicating no significant relationship between the Cext values and the number of diatom fragments (n). Certain Cext values correspond to a wide range of diatom fragment counts, while others correspond to very few fragments. This variability suggests that the parameters are not linked directly. This is accordance with the missing correlation observed for the CPP2.5-5, still suggesting the different apportionment and features of dust and diatoms fragments. It is important to observe that this assumption is true although no strong correlation exists between SPES and CC measurements, as reported in figure 27.

Figure 51 illustrates the variation in diatom fragment concentration (n) across the different time intervals during the Last Glacial Maximum (LGM). The y-axis represents the number of diatom fragments, while the x-axis indicates the approximate age of the samples in thousands of years (ka).

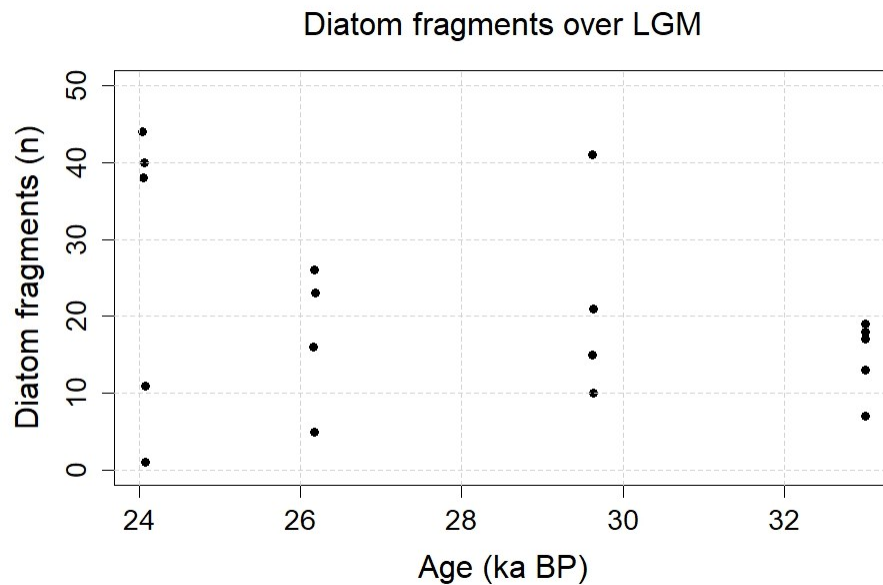


Figure 51: the variation in diatom fragment concentration (n) across the over the LGM.

Again, figure 51 represents the number of diatom fragments shows relevant fluctuations over limited time intervals, suggesting an appreciable non-regular apportionment.

3.7.3 Discussion of SPES and CC measurements

The results reported in figure 46 demonstrate that both instruments provide consistent data, with the points aligning along a horizontal trend, particularly at higher concentration ranges. This consistency underscores the reliability of SPES measurements in detecting particles at mL comparable to ppb (0.69-5 μm) measured by the CC.

The results reveal that SPES and CC provide complementary data, with SPES measuring a broader range of particle sizes and concentrations compared to the CC. Specifically, SPES captures three orders of magnitude in particle concentration (part/mL) that are not detected by the CC. This discrepancy arises from the fundamental difference in measurement principles: SPES measures every individual particle in the sample, providing an absolute concentration for all particle sizes, while the CC reports the percentage of particles within specific size ranges (e.g., 0.69–5 μm for this study). This methodological difference explains why SPES captures a broader overall concentration, as it considers every particle in the sample, whereas the CC focuses on proportional representation within pre-defined size categories.

The observed discrepancies may stem from the unique sensitivity of SPES, which not only measures particle size and concentration but also captures additional optical properties such as extinction and scattering. These properties provide an added layer of particle characterization, and such differences underscore the complementary nature of these two methods, with SPES introducing new dimensions to the analysis of particle characteristics.

In figure 47, the observed variability in CPP at the Dome B site is approximately 15%, aligning with findings from Delmonte et al. (2020), which reported natural CPP variations ranging from 10% to 20% at high-elevation plateau sites in Antarctica, such as Dome C and Vostok. These fluctuations are indicative of consistent atmospheric transport mechanisms and the dynamic interplay between remote and proximal dust sources. The CPP variations occur throughout the Holocene, with periodic oscillations on secular timescales, primarily in the 330–380 years to ~120 years range, with a common significant frequency band

around 200 years at both Dome C and Vostok, suggesting a recurrent pattern in dust transport dynamics (Delmonte et al., 2020).

The dominant source of aeolian dust in East Antarctica during glacial periods, particularly at plateau sites like Dome B, Dome C, and Vostok, has been identified as South America, specifically Patagonia and Tierra del Fuego (Delmonte et al., 2008). Long-range transport pathways, primarily governed by SHWW, facilitate the deposition of mineral dust from these regions, reflecting the extensive influence of these atmospheric systems on Antarctic dust records (Delmonte et al., 2020).

Additionally, studies on Victoria Land, East Antarctica, particularly at Talos Dome, offer insights into regional dust contributions and their variability. Delmonte et al. (2013) highlighted that Talos Dome, situated closer to ice-free areas in Northern Victoria Land, receives a significant input of dust from local sources. These proximal contributions are strongly influenced by regional atmospheric circulation patterns, including katabatic winds and cyclonic activity, as well as seasonal variations in dust deflation. The interplay between local and remote sources creates a more variable dust record at Talos Dome compared to plateau sites like Dome B. or Dome C. This variability underscores the importance of site-specific dynamics, with Talos Dome serving as a valuable reference for understanding the influence of local sources on dust deposition in East Antarctica. For instance, Delmonte et al., (2013) highlight the higher variability in dust deposition compared to plateau sites, driven by the interplay of local and remote sources. This variability underscores the importance of considering site-specific dynamics when interpreting dust deposition patterns in East Antarctica.

The slight decline in CPP2.5–5 around ~33 ka observed in figure 47 may reflect subtle shifts in these transport and depositional dynamics. Such changes could result from reduced coarse particle availability in source regions, potentially due to variations in sediment moisture levels or seasonal exposure, or from alterations in atmospheric circulation patterns, including shifts in the strength or position of Southern Hemisphere westerly winds. Transport efficiency, influenced by changes in wind intensity or circulation pathways, could have also played a role in this observed trend.

These findings emphasize the critical role of atmospheric processes in shaping dust deposition patterns during the LGM. The observed CPP variability at Dome B aligns with the natural fluctuations documented at plateau sites such as Dome C and Vostok, while comparisons with Talos Dome highlight the distinct influence of local versus remote dust sources on East Antarctic dust records.

In figure 48, diatom fragments remain a minor component of the particle population. These fragments do not exhibit any discernible correlation with either CPP_{2.5–5} or SPES measurements across the ~24 to ~33 ka period. The dominance of mineral dust particles within the overall assemblage likely overshadows the contributions of biological particles, such as diatom fragments. The lack of correlation between diatom fragments and other particle parameters highlights the distinct processes influencing these components. While mineral dust reflects steady atmospheric transport and source dynamics, diatom fragments are likely tied to episodic events or variability in source region productivity and deflation.

In figure 49, the Cext values exhibit limited variability, suggesting stable particle sizes, composition, and optical properties throughout the observed time span. This stability may indicate that particles originated from similar sources and were transported via consistent pathways during the LGM. This uniformity suggests persistent atmospheric circulation patterns and steady dust source activity over the studied time interval. Such stability in particle characteristics underscores a relatively constant influence from the primary dust sources and transport mechanisms throughout this period.

A slight decline in Cext near ~33 ka, although small but consistent with the CC measurements, could hint at a reduction in the presence of larger or more optically active particles. This change may reflect minor shifts in atmospheric transport dynamics or depositional processes at this earlier stage of the LGM. Factors such as reduced particle size availability at the source regions or variability in atmospheric circulation intensity could contribute to these observations.

The low variability in Cext also aligns with the minimal biological contribution to the particle assemblage, as observed in the limited abundance of diatom

fragments. Biological particles, such as diatoms, often introduce greater variability in optical measurements due to their distinct properties. The absence of significant contributions from such particles further supports the interpretation of a predominantly mineral-dust-dominated record during this period, making it particularly challenging to detect the very few diatoms' fragments present.

The lack of correlation between Cext values and diatom fragment counts shown in figure 50 is a meaningful result that underscores the distinct nature of these two particle types.

While mineral dust dominates the SPES measurements due to its overwhelming abundance compared to diatom fragments, the goal of this analysis was just to explore potential links between transport or deposition mechanisms of dust particles and diatom fragments.

If correlation was observed, it could have suggested shared atmospheric transport pathways or depositional conditions influencing both particle types.

For example, similar trends might have indicated that diatom fragments were entrained and transported with dust particles under specific climatic or environmental conditions. However, the absence of correlation instead denotes that the deposition of diatom fragments is influenced by distinct events compared to the continuous atmospheric processes governing mineral dust transport.

Additionally, the morphology of diatom fragments may play a role in the lack of correlation. Unlike spherical or regular-shaped mineral dust particles, diatom fragments have irregular, diverse and unique shapes that can affect how they interact with the SPES laser beam. The beam's interaction depends on factors like shape, orientation, and composition, which might result in a weak or non-detectable signal for these biological particles.

This finding aligns with the hypothesis that diatom fragments originate from specific source regions or events, such as deflation from coastal sediments or meltwater streams, rather than being uniformly distributed across the particle assemblage. While the exposed Patagonian continental shelf during glacial periods, as highlighted by Delmonte et al. (2017), remains a significant dust

source for central Antarctica, it is not the sole explanation for the presence of diatom fragments. Other potential sources, such as local Antarctic coastal regions or sediment transport via meltwater streams, may also contribute to the observed variability. This underscores the complexity of the processes governing the transport and deposition of biological particles in polar environments, requiring a multi-faceted approach to fully understand their origins.

Last, figure 51 represents that diatom fragment concentrations remain relatively stable between ~24 and ~33 ka, indicating a consistent influx of biological material transported through aeolian mechanisms during this period. This stability reflects persistent environmental and atmospheric conditions, characteristic of the Last Glacial Maximum. Key observations include the overall stability of fragment counts during the LGM, suggesting steady source productivity and consistent transport conditions. The slight decline in concentrations near ~33 ka could point to reduced diatom productivity in source regions, possibly driven by environmental shifts such as changes in sea levels or climatic conditions. Alternatively, the decrease may result from variability in sediment deflation rates or atmospheric transport efficiency, including potential shifts in the intensity or positioning of the SHWW (Menviel et al., 2008). These findings underline the role of diatom fragments as indicators of source region activity.

3.7.4 Conclusion SPES and CC measurement

The analysis of Dome B aliquots using SPES and CC has provided valuable insights into the particle dynamics and transport mechanisms during the LGM. However, the results underscore a lack of correlation between diatom fragments and other measured parameters, such as SPES and CC data, suggesting distinct processes influencing these particles' transports.

The strong alignment between SPES and CC data, particularly at higher concentration ranges, highlights the reliability and complementary nature of these instruments for studying submicron and micron-sized particles. Despite minor deviations, the overall consistency of results underscores their combined utility in analysing mineral dust dynamics.

The limited variability in Cext and CPP2.5–5 values suggest stable atmospheric circulation and persistent dust source activity during the LGM. This stability is likely linked to the dominance of mineral dust sources, such as the exposed Patagonian continental shelf, mobilised by consistent wind dynamics. A subtle decline near ~33 ka may hint at minor environmental changes, but overall, the record reflects a predominantly mineral-dust-dominated particle assemblage.

Diatom fragments remain a minor component of the particle population, with concentrations showing relative stability across the ~24 to ~33 ka interval. However, they exhibit no discernible correlation with SPES extinction cross-section (Cext) or CC-derived CPP2.5–5 indices. This disconnect indicates that mineral dust particles dominate these parameters, overshadowing the optical and size-based contributions of rarer biological particles.

The lack of correlation between diatom fragments and mineral dust parameters emphasizes their distinct origins and transport mechanisms. While mineral dust reflects steady atmospheric transport and source activity, diatom fragments are likely tied to episodic transport events or variability in biological productivity and sediment deflation. This highlights the complexity of mixed particle assemblages in ice core records and their respectively aeolian transports.

The stable concentrations of diatom fragments suggest persistent source region productivity and consistent aeolian transport conditions during the LGM. The slight decrease in fragment counts near ~33 ka may reflect environmental shifts, such as reduced biological productivity, changes in sediment deflation rates, or variability in transport efficiency. These findings underline the role of diatom fragments as indicators of biological activity and atmospheric circulation dynamics during glacial periods.

While SPES and CC measurements show strong correlations for mineral dust, their lack of alignment with diatom fragment data reinforces the conclusion that diatom fragments do not correlate with dust particles and that their transport must be different.

4.0 Skytrain Ice Rise ice core

4.1 Introduction to Skytrain Ice Rise

Skytrain Ice Rise (figures 52 and 53) is an independent ice dome located at latitude $79^{\circ}44.46'$ S and longitude $78^{\circ}32.69'$ W, positioned at the boundary between the WAIS and the Ronne Ice Shelf (Hoffmann et al., 2022; Mulvaney et al., 2021, 2022; Wolff et al., 2025). It features a circular shape with a diameter of approximately 80 km and an elevation of 784 meters above sea level (Mulvaney et al., 2021, 2022, 2023). The ice thickness reaches 651 meters, resting on a relatively flat basal topography approximately 168 meters above sea level (Hoffmann et al., 2022; Mulvaney et al., 2022). The mean annual temperature at the site is -25.9°C , with a basal temperature of -14.9°C (Mulvaney et al., 2021; Hoffmann et al., 2022).

The ice rise sits on a bed that is above sea level but is almost surrounded by ice shelves, which rest on seabed exceeding 1000 meters in depth (Hoffmann et al., 2022; Mulvaney et al., 2022). On the WAIS side, the ice rise is shielded by the Ellsworth Mountains, ensuring it has remained an isolated flow center, unaffected by inland ice intrusion (Mulvaney et al., 2021, 2022, 2023).



Figure 52: a map of West Antarctica, the Ronne Ice Shelf and the drilling site (red arrow) of the ice core (original figure presented by Hoffmann et al., 2022).

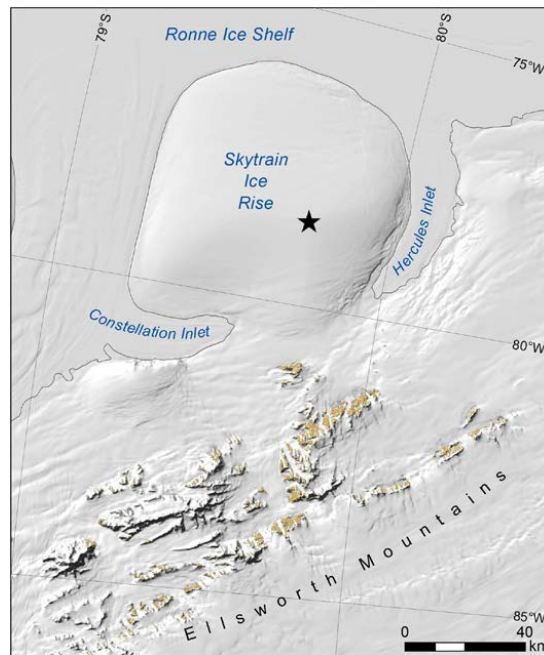


Figure 53: the Skytrain Ice Rise from where the Skytrain Ice Rise ice core was drilled (original figure presented by Mulvaney et al., 2021).

The Skytrain Ice Rise ice core offers a valuable record for reconstructing past climatic and environmental conditions (Mulvaney et al., 2021; Hoffmann et al., 2022). Through the analysis of this core, researchers can gain insights into the sensitivity of the WAIS to past temperature fluctuations and its response to interglacial periods (Hoffmann et al., 2022). Changes in the extent and altitude of the WAIS have profound implications on the surrounding ice shelves, influencing their stability and interaction with ocean currents (Mulvaney et al., 2021). Additionally, the core allows for the study of long-range atmospheric dust transport and deposition, offering a deeper understanding of the climatic and environmental processes that have shaped Antarctica over millennia (Hoffmann et al., 2022; Mulvaney et al., 2021). Furthermore, it helps to elucidate the complex interactions between regional and global climate systems, shedding light on how Antarctic ice dynamics respond to broader climate forcings (Hoffmann et al., 2022).

Drilled to bedrock in the 2018/19 field season, the Skytrain Ice Rise core is part of the WACSWAIN (WArm Climate Stability of the West Antarctic ice sheet in the last INterglacial) project (Mulvaney et al., 2021). This initiative aims to investigate the stability of the WAIS during the Last Interglacial, approximately 120,000 years ago, a period characterized by global temperatures comparable to present-day conditions (Hoffmann et al., 2022). Data from the core will contribute to improving our understanding of ice sheet behaviour and its potential contributions to future sea-level rise (Mulvaney et al., 2021).

Pre-drilling radar surveys indicated well-preserved stratigraphy with minimal disruption, confirming the site as an optimal location for obtaining a high-resolution climate record (Mulvaney et al., 2021, 2022, 2023; Hoffmann et al., 2022). The upper 2,000 years of the core were dated using annual layer counting, while deeper sections were aligned to established age models such as AICC2012, utilizing tie points including methane and $\delta^{18}\text{O}$ measurements (Mulvaney et al., 2021). This ice core serves as a solid chronological framework that enhances our understanding of WAIS stability and provides critical data to refine future climate models (Wolff et al., 2025).

4.2 Objectives of this study

This research study presents new records of diatom valves from the Skytrain Ice Rise ice core during the LGM, covering approximately 24,000 – 29,000 years BP. The decision to focus on the same period of time as the Dome B ice core was driven by the desire to gain a deeper understanding of the LGM in an important area for stability and climate change impacts.

The research questions addressed in this study are:

- 1) Is it possible to obtain paleoenvironmental and paleoclimatic information from LGM the diatom valve record obtained from Skytrain Ice Rise ice core?
- 2) How do this compare to the LGM diatom record of Dome B?

4.3 Methods

The samples were prepared by Dieter Tetzner at the British Antarctic Survey (BAS), Cambridge, using the same methodology applied on the RICE and the Dome B ice cores. Each sample, measuring approximately 15 mm in length and representing lateral dust sections, was cleaned by submersion in three pre-cleaned beakers filled with Milli-Q (MQ) water. To ensure contamination-free processing, the MQ water was replaced for each sample, allowing the melting process to occur in clean, uncontaminated water. This decontamination step resulted in a 50% reduction in sample volume but proved highly effective in eliminating surface contaminants.

Each meltwater aliquot was adjusted to match the volume of the Dome B samples as closely as possible. Since the objective of this study was to investigate the LGM, the Skytrain Ice Rise samples were prepared to represent the same time window as the corresponding Dome B ice core samples.

The aliquots of the Skytrain Ice Rise samples were filtered using polycarbonate track-etched Isopore™ membranes with a 1.0 µm pore size. These membranes were subsequently mounted on aluminium stubs.

A total of 12 samples were prepared, covering three time intervals of the LGM: approximately 24, 26, and 29 thousand years ago. These time periods correspond to ice core depths of 597, 601, and 608 meters. Accordingly, the samples are labelled SKT597, SKT601, and SKT608, based on their respective depths and associated ages. These depths are equivalent to those of the DB631, DB660, and DB720 samples from the Dome B ice core.

These 12 samples were scanned using a Scanning Electron Microscopy (SEM) at the University of Cambridge by Dieter Tetzner. The analysis was performed using an automatic stage, with the instrument capturing approximately 7,000 images of pre-defined areas, following the procedure described by Tetzner et al. (2022a, 2022b, 2021). The SEM images were subsequently shared with me for the identification of diatom valves and fragments (table 6, supplementary S2).

Skytrain Ice Rise ice core - BAG (depth)	pics observed
595	1785
601	2295
608	2340

Table 6: number of images observed for each bag of the Skytrain Ice Rise ice core.

Table 7, instead, shows the correspondence between sample bags from the Skytrain Ice Rise (SKT) and Dome B (DB) ice cores, with their respective estimated ages (ka). It is noticeable that no SKT sample is currently available for the ~33 ka time interval.

Ka	SKT bag n°	DB bag n°
~24	597	631
~26	601	660
~29	608	720
~33	-	780

Table 7: samples for Dome B and Skytrain Ice Rise ice cores.

After acquiring the images, Dieter forwarded them to me for microfossil analysis. I screened the material and recorded any microfossils observed during the examination.

4.4 Results

From the approximately 7,000 SEM images analysed, a total of 9 diatom valves were identified. While a few additional potential diatoms were observed, they were excluded due to insufficient image resolution and quality to confirm their identification with confidence. Additionally, 80 diatom valve fragments were recorded. These numbers are relatively low; however, given the conditions during the LGM, a low abundance of diatoms is not unexpected.

The following table 8 presents the findings derived from the analysis of the 9 identified diatom valves. Diatom fragments have been excluded from consideration due to their insufficient identification, which limits the available information.

Skytrain Ice Rise ice core	STK597 ~24 ka	STK601 ~26 ka	STK608 ~29 ka
N° of samples	4	4	4
Total diatom counts (n)	3	4	2
Total diatom classified at genus level (n)	2	2	0
Total diatom identified at species level (n)	0	0	0
Girdle view - unclassifiable (n)	0	1	0
Total volume filtered (ml)	66	70	87
Mean volume filtered (ml)	17	17	22

Table 8: counts and basic identification of diatom valves found in the Skytrain Ice Rise ice core based on SEM images analyses conducted in 2024.

Among the diatoms classified at the genus level in the Skytrain Ice Rise ice core, three distinct genera were identified:

Diploneis spp.: one valve of *Diploneis* was observed. This genus has previously been reported by Delmonte et al. (2017) in the Dome B ice core. Diploneis diatoms are typically characterized by their elongated, symmetrical valves with distinct striae and central raphe systems. They are usually found in freshwater and brackish environments.

Luticola spp.: one valve of *Luticola* was identified, consistent with findings in both the 2017 and 2024 records of the Dome B ice core. Luticola is known for its high

tolerance to desiccation and salinity fluctuations, as well as its ability to thrive in nutrient-poor environments. These diatoms are typically associated with freshwater and terrestrial habitats, though some species can also be found in brackish environments.

Cyclotella spp.: two valves of *Cyclotella* were found, mirroring observations in the 2024 Dome B ice core record (because they are observed in the same time interval for both sites). *Cyclotella* diatoms are planktonic and primarily thrive in freshwater habitats, particularly in oligotrophic and mesotrophic lakes with low to moderate nutrient levels. However, some species have adapted to brackish and marine environments.

Now the next figures display, respectively, a *Diploneis* spp. (figure E) and a *Luticola* spp. (figure F)

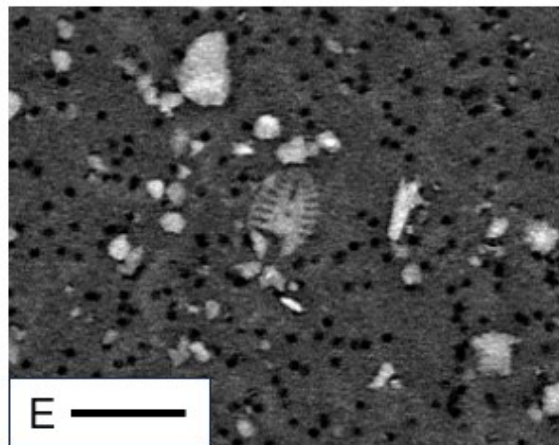


Figure E: a *Diploneis* spp. diatom valve.

Scale bar: 10 μm for SEM images.

The *Diploneis* spp. specimen exhibits well-defined characteristics, including its elongated, symmetrical valve structure with distinct striae and a prominent raphe system.

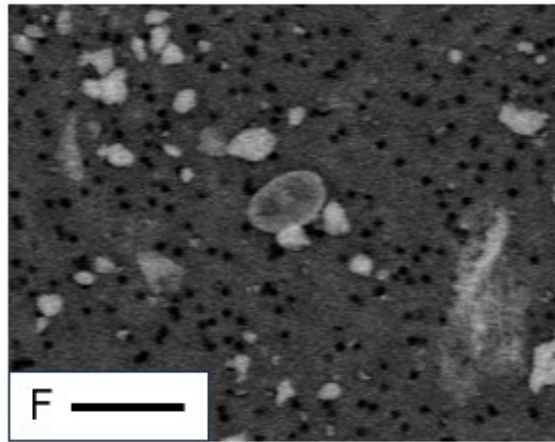


Figure F: a *Luticola* spp. diatom valve.
Scale bar: 10 μm for SEM images.

Figure F shows the diatom valve of a *Luticola* spp., a bit grainy; however, diagnostic features such as its elliptical shape and the central nodule are still distinguishable, allowing a tentative classification.

The next figure (G1-G2) shows two diatom valves of *Cyclotella* spp.

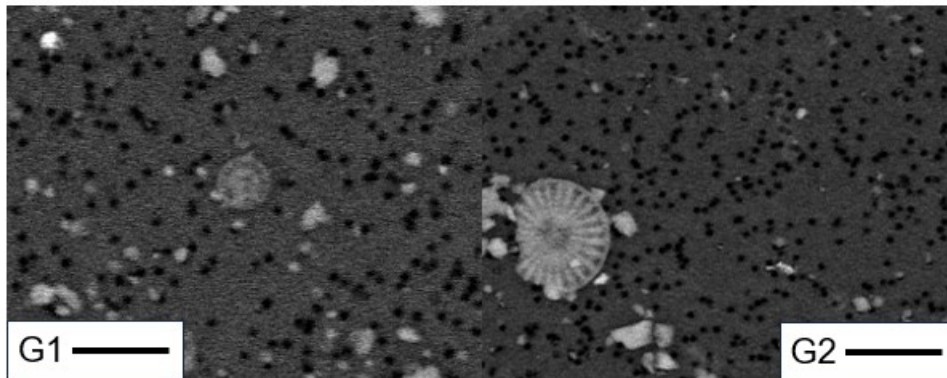
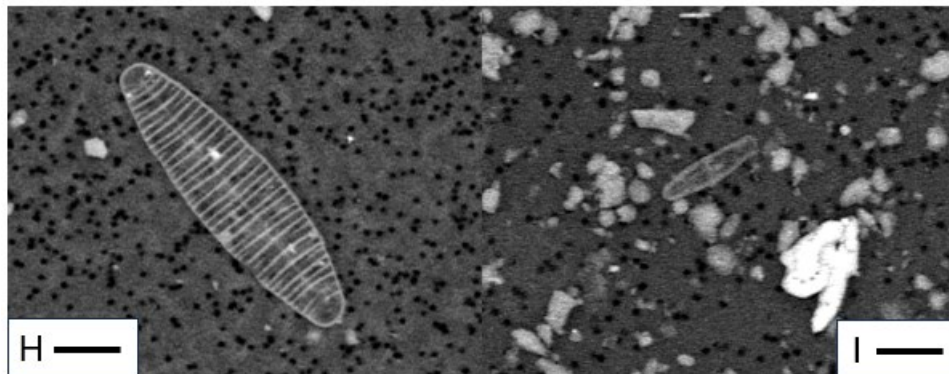


Figure G1-G2: two *Cyclotella* spp. diatom valves.
Scale bar: 10 μm for SEM images.

Figure G1 highlights a diatom valve with less clarity and lower image quality, making detailed observation more challenging. However, the characteristics such as the circular shape, the radial striae pattern, and the central shadow support

the tentative identification as a *Cyclotella* spp. diatom. In contrast, figure G2 displays a larger and more clearly visible centric diatom, allowing for better identification.

A few images (figures H-I, L-M, N) of unidentified diatom valves are presented; however, they present the raphe system, suggesting they belong to the benthic species. At this stage, further taxonomic classification is not possible due to the limited resolution and available morphological details. However, these findings open the way for future research, as a more detailed analysis using advanced imaging techniques and taxonomic studies could provide valuable information for this research purpose. In fact, understanding the presence of benthic diatoms in the Skytrain Ice Rise ice core may contribute to identifying potential source regions and transport mechanisms happened during the LGM, as it has been done for the Dome B ice core.



*Figure H-I: two benthic diatom valves.
Scale bar: 10 μ m for SEM images.*

The raphe is very visible in the valve of figure H, while in figure I it is a bit more challenging to be seen.

Figure L-M show two diatom valves unidentifiable.

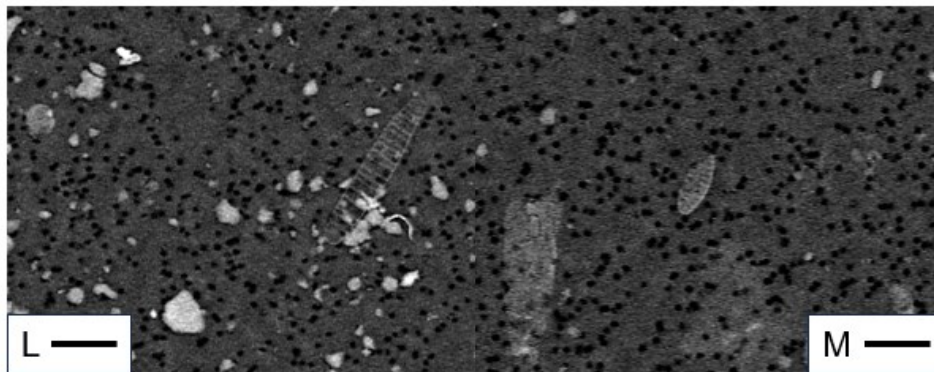


Figure L-M: two diatom valves unidentifiable.

Scale bar: 10 μ m for SEM images.

The image quality for figures L and M is suboptimal, and both valves exhibit minor missing fragments. Additionally, it is unclear whether they possess a raphe, making it impossible to determine if they are benthic diatoms.

The next figure, N, show a diatom in girdle view.

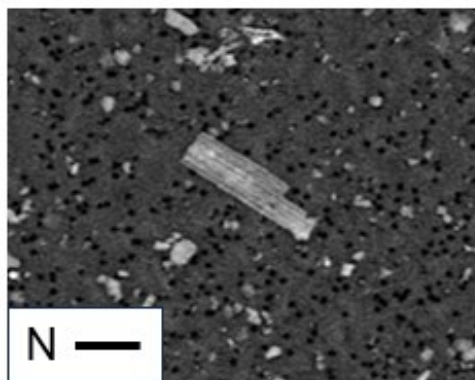


Figure N: a diatom valve in girdle view.

Scale bar: 10 μ m for SEM images.

Figure N displays a diatom in girdle view, with a small missing section. As stated throughout this PhD thesis, diatom valves observed in girdle view prevent a good and possible identification.

4.4.1 Skytrain diatom valve and fragments distribution across the LGM

The next figure illustrates the distribution of diatom valves and fragments in the Skytrain Ice Rise ice core across three time periods during the LGM: ~24 ka, ~26 ka, and ~29 ka. The total number of diatom valves is represented by black bars, while the total number of diatom fragments is shown by white bars

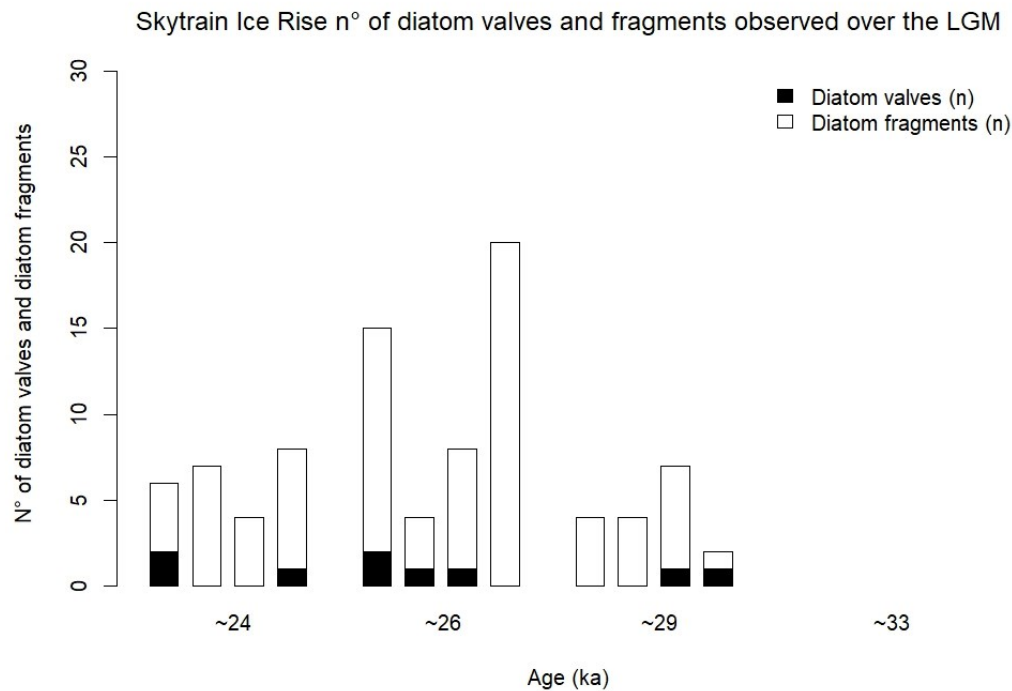


Figure 54: the number of Skytrain Ice Rise diatom valves and fragments during the LGM.

The figure 54 shows the variation in abundance (n) of diatom valves (black bars) and diatom fragments (white bars with black outline) for the ~24 ka, ~26 ka, and ~29 ka time intervals. The figure highlights that diatom fragments are more abundant than valves across all samples and that the total diatom content (valves + fragments) varies through time, with the highest flux observed at ~26 ka and a clear decrease at ~29 ka. Diatom fragments are more abundant during ~26 ka, followed by ~24 ka and ~29 ka. Diatom valves, instead, have similar results in ~24 ka and ~26 ka, while they are lower as the diatom fragments during ~29 ka.

4.4.2 Comparison between Dome B and Skytrain Ice Rise ice cores

It is important to highlight that in this study, approximately 7,000 images were analysed, whereas around 28,000 images were examined in the Dome B ice core study. As a result, additional calculations are necessary to enable a meaningful comparison of diatom abundances by normalising to the total number of images and the corresponding sample volumes (in mL) for each core. Such an approach will provide a more accurate assessment of whether a decreasing trend in diatom valve presence is consistently observed across both sites. The comparison is done over the overlapping periods ~24, ~26 and ~29 ka.

4.4.3 Pennate and centric diatom valves for DB and SKT ice cores

Figure 55 a and b presents the distribution of pennate and centric diatom valves in the Dome B ice core during the LGM. The graph suggests that pennate diatoms are always dominant and that are more abundant in the 24 ka for both sites, while centric diatoms are present at ~26 ka in both and at ~33 ka in Dome B ice core only as in Skytrain Ice Rise ice the period ~33 ka is not observed.

The differences observed between Dome B and Skytrain Ice Rise locations suggest that we could consider that, while both sites experienced similar atmospheric transport processes, local depositional factors or preservation conditions or differences in source regions may have influenced the observed diatom assemblages.

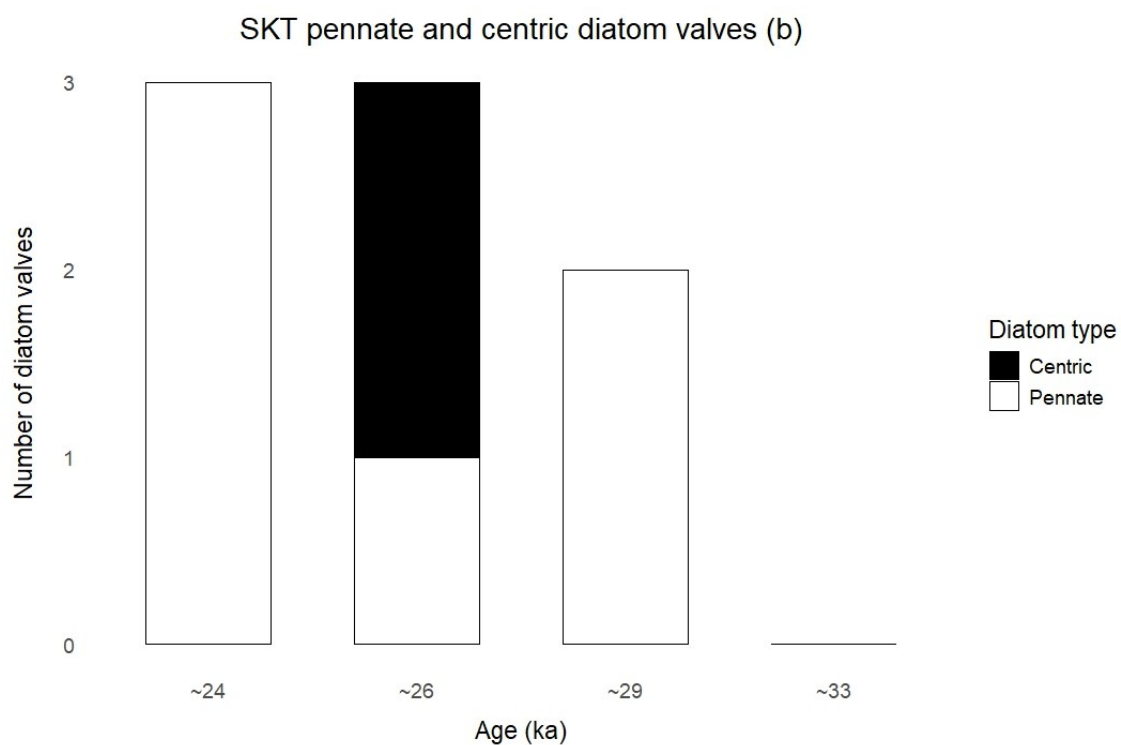
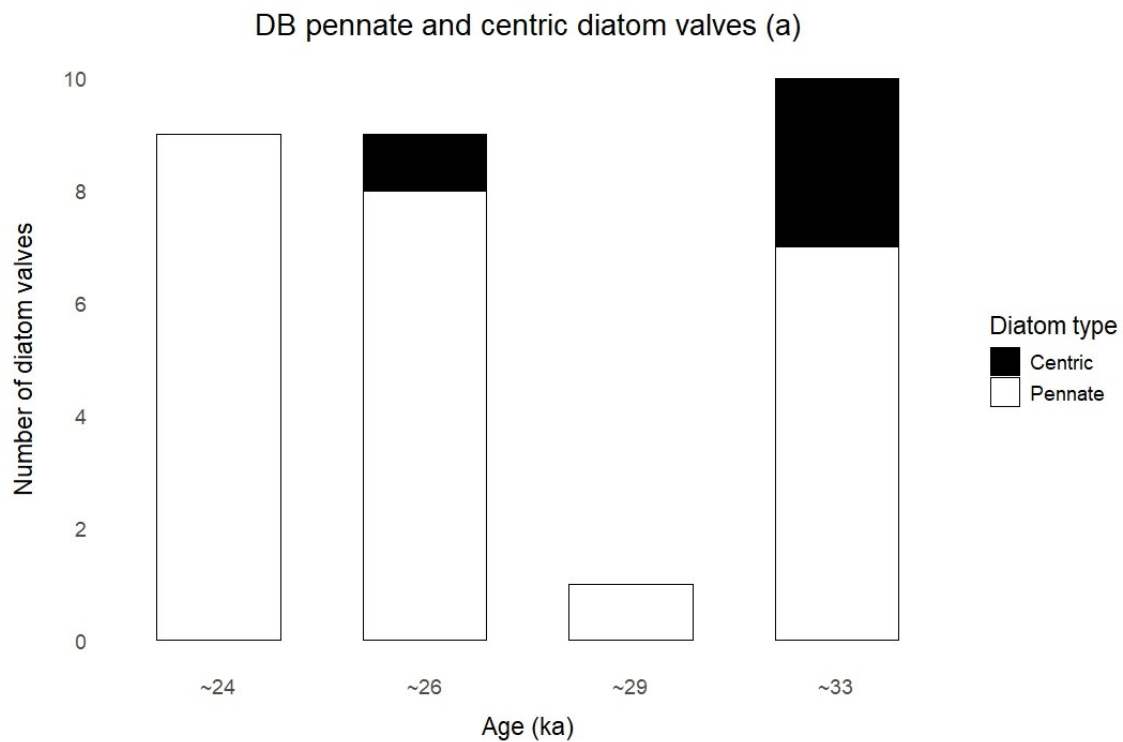


Figure 55a: pennate and centric diatom valves in the Dome B ice core across the LGM.

Figure 55b: pennate and centric diatom valves in the Skytrain Ice Rise ice core across the LGM.

4.4.4 Estimation of diatom valves and fragment for full filter coverage

The estimation of the total number of diatom valves and fragments, that could have been reached if the entire filter had been analysed, was obtained to get a more comprehensive evaluation of diatom valves and fragments abundance.

In figure 56 a and b, the estimated diatom valve and fragment counts for the Dome B and the Skytrain Ice Rise ice cores and for the full filter coverage is shown.

These trends present similar results to the data shown in figures 37 and 54, where the number of diatom valves and fragments is related to the portion of filter analysed. For the full coverage of the filter, there are no differences in terms of diatom valves and/or fragments proportions.

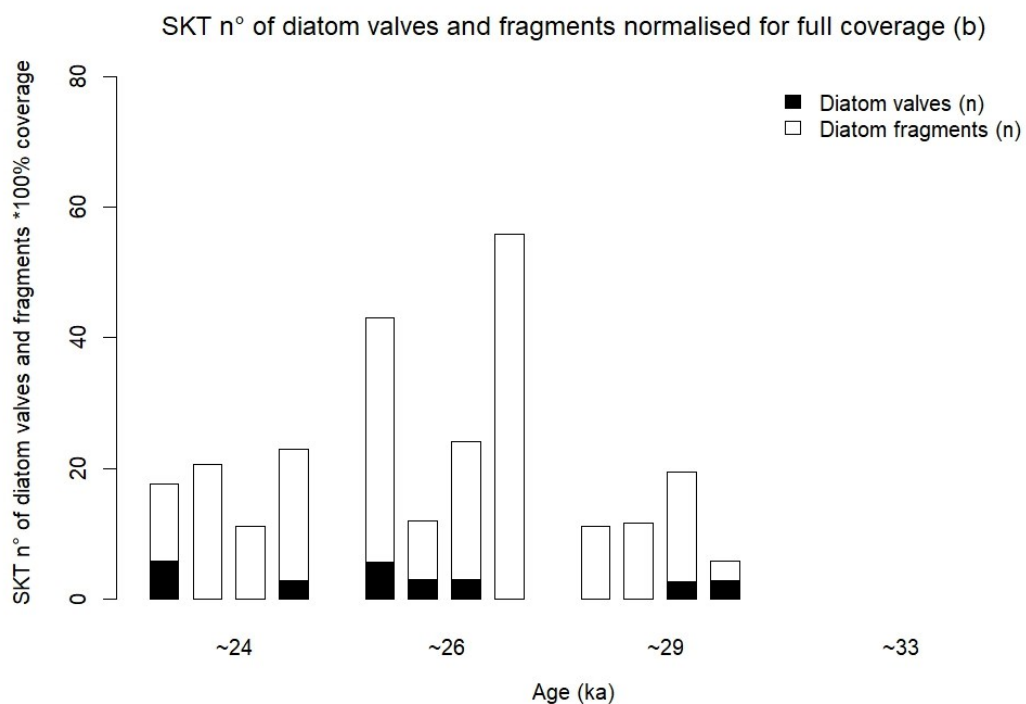
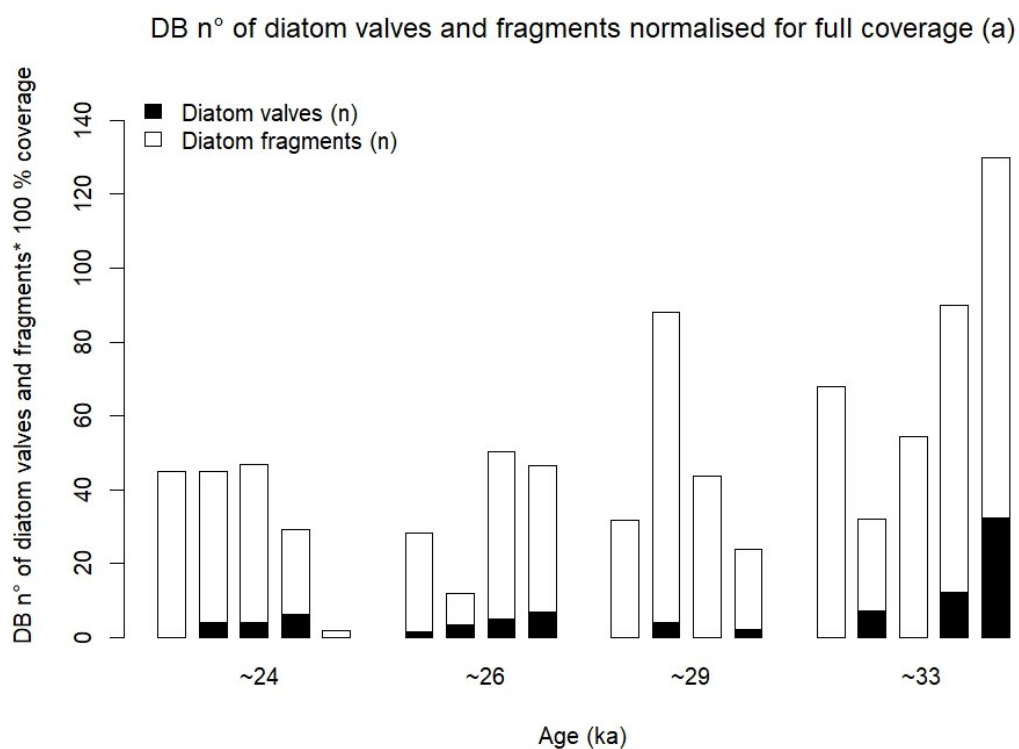


Figure 56 a and b: estimation of the diatom valves and fragments from the Dome B and the Skytrain Ice Rise ice cores for full coverage.

4.4.5 Normalised diatom valves and fragments for full filter coverage

Figure 57 a and b present the normalised diatom valves and fragments for the Dome B and Skytrain Ice Rise ice cores, respectively, expressed as a flux (valves and fragments per liter -and not per mL- per year) and for the full coverage, to check whether the number of these specimens would change, or not.

Figure 57a shows an increase in the number of diatom valves and fragments across the different time periods when compared to figure 56a. This suggests that normalisation, expressed as number of valves per litre per year over the entire temporal coverage, offers a clearer framework for interpretation and reinforces the assumptions made.

A similar, though more subtle, trend can be observed in figure 57b, when compared to figure 56b.

It is important to note that this apparent increase mainly applies to the Dome B ice core, for which only half of the available SEM images were analysed. In contrast, all SEM images from the Skytrain Ice Rise ice core were examined, which explains the minimal differences between the trends shown in figure 56b and 57b.

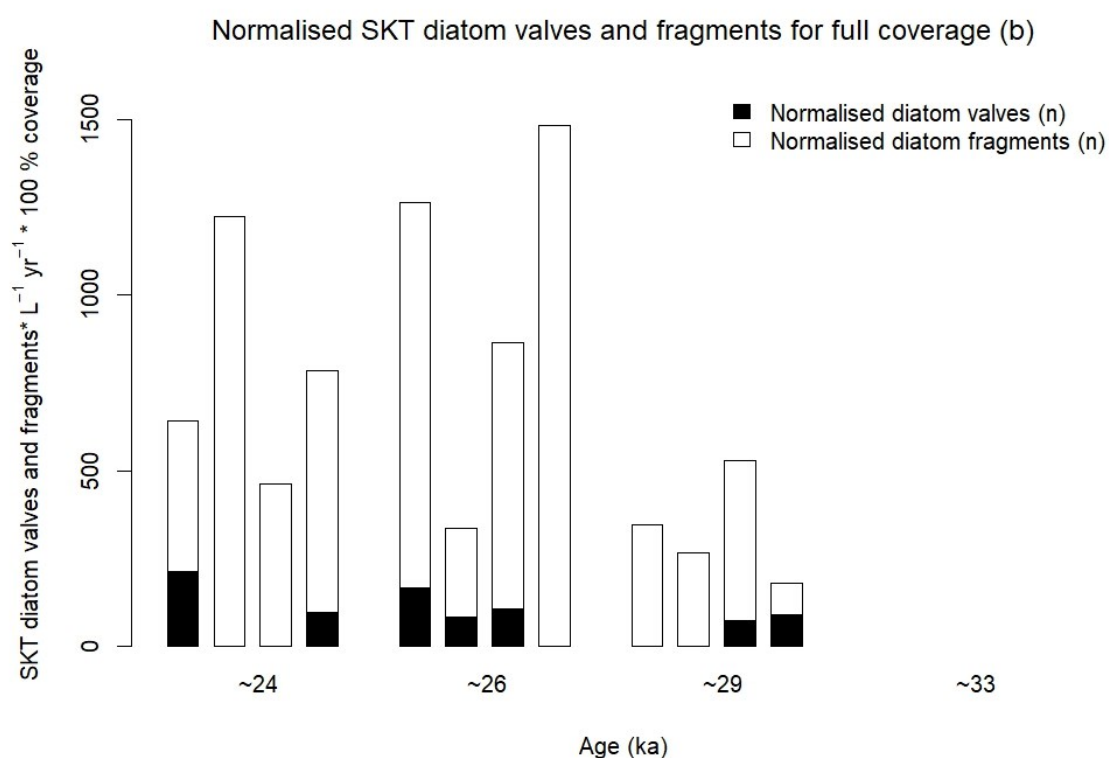
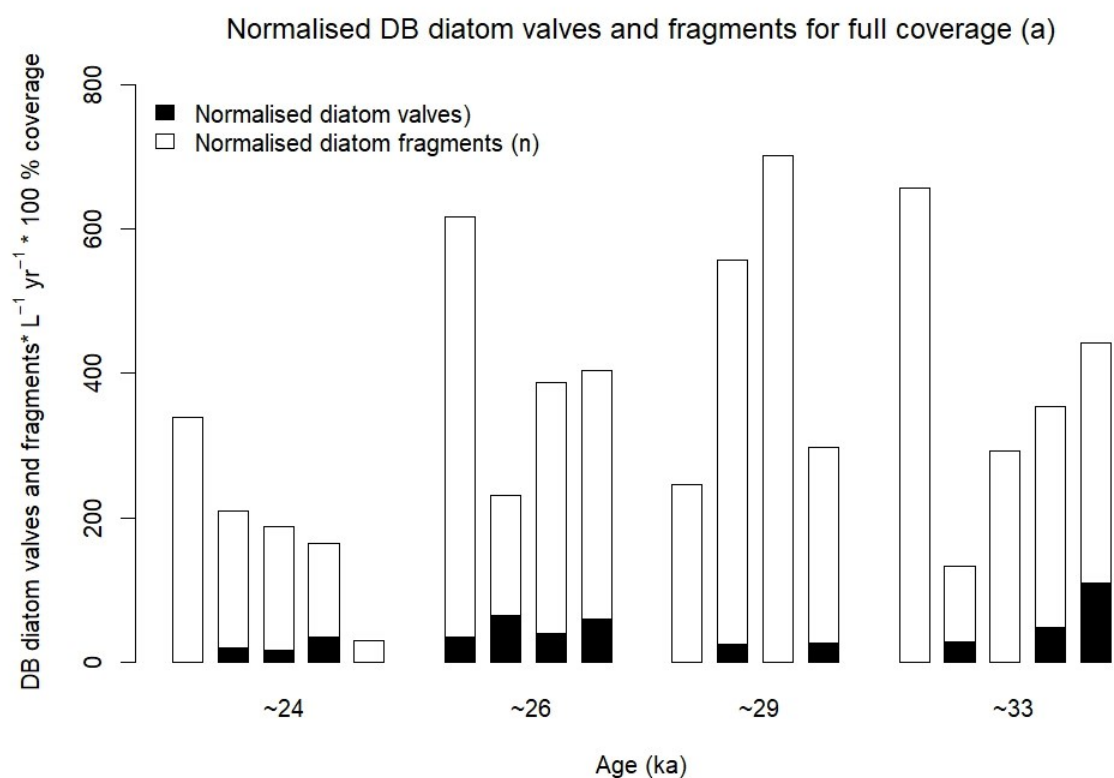


Figure 57 a and b: normalised diatom valves and fragments flux from the Dome B and the Skytrain Ice Rise ice cores for full coverage.

4.5 Discussion

The preliminary results from the analysis of the Skytrain Ice Rise ice core reveal the presence of a limited number of diatom genera, with a predominance of freshwater species. Among the identified genera, *Diploneis spp.*, *Luticola spp.*, and *Cyclotella spp.* were observed, consistent with previous findings from the Dome B ice core. The presence of predominantly freshwater diatoms suggests similar atmospheric transport mechanisms affecting both sites during the LGM.

One main difference between the Dome B and Skytrain Ice Rise ice cores is the absence of marine benthic diatoms in Skytrain Ice Rise, whereas at Dome B, these species were identified in both the 2017 and 2024 datasets. This discrepancy raises important questions regarding transport pathways, depositional environments, and preservation conditions at the two sites. Further investigation is needed to better describe the potential transport mechanisms responsible for these differences.

A possible explanation lies in differences in atmospheric circulation patterns or localised wind dynamics, which could have influenced the transport efficiency of marine-derived particles (Tetzner et al., 2022). Given that Skytrain Ice Rise is located at a lower elevation compared to Dome B, differences in altitude could have played a role in influencing the atmospheric circulation and the depositional processes, potentially affecting the transport of marine benthic diatoms.

However, it is also important to consider these methodological limitations: at Skytrain Ice Rise, some diatoms with raphe were observed, but due to the limited resolution of the SEM images, their species- or genus-level identification was not possible. This means that some marine benthic diatoms could potentially be present at Skytrain Ice Rise, but they are unrecognised.

Thus, while the current dataset suggests an absence of marine benthic diatoms at Skytrain Ice Rise, this may be partly due to the limitations in identification rather than a true absence in the ice core. Further analyses with higher-resolution imaging and expanded sample coverage would help confirm whether marine benthic species are present but have gone undetected.

Regarding the freshwater diatoms, their origin remains a crucial aspect to explore. Given their ecological preferences, these diatoms likely derived from glacial lakes, meltwater streams, and exposed glacial outwash plains in the Southern Hemisphere mid-latitudes, particularly South America. During the LGM, extensive glaciation in Patagonia led to the formation of proglacial lakes, which acted as reservoirs for freshwater diatoms (McConnell et al., 2008). These diatoms could have been entrained and transported by the SHWW and deposited in Antarctic ice through long-range atmospheric processes (Tetzner et al., 2022; Lichti-Federovich, 1984).

A particularly interesting finding in the Skytrain Ice Rise ice core is the presence of centric diatoms (*Cyclotella spp.*) at ~26 ka, mirroring the same observations made for the Dome B site.

This suggests that the atmospheric transport processes during this period may have favoured the deposition of centric diatoms at both sites. The reason why centric diatoms are observed only at the ~26 ka interval in both cores remains unclear, but this raises several hypotheses, including changes in source region availability, wind strength, or climatic fluctuations affecting atmospheric transport efficiency (Tetzner et al., 2022; Delmonte et al., 2004). Indeed, a potential explanation for the ~26 ka interval is that it represents a phase of intensified dust and particle transport, leading to the increased deposition of these centric diatoms (Kohfeld et al., 2013), whereas at other time intervals, weaker atmospheric circulation patterns may have reduced their entrainment into the atmosphere.

Moreover, the combined number of pennate and centric diatoms exhibits a decreasing trend over time at both sites (figure 55 a and b), indicating potential shifts in atmospheric transport dynamics and source availability during the LGM. Notably, the Skytrain Ice Rise samples currently lack representation for the ~33 ka interval, during which centric diatoms were observed at Dome B. Additional sampling from this period would be crucial to determine whether similar depositional trends occurred at Skytrain Ice Rise.

As observed in the Dome B core, the overall number of diatom valves in Skytrain Ice Rise is low, which aligns with expectations for the LGM: the low diatom counts suggest that long-range atmospheric transport, potentially driven by glacial winds and specific climatic events, played a crucial role in their deposition.

In addition, several unidentified diatom valves were observed, some of which might potentially be benthic species. The fact that very few marine and benthic diatom valves were identified at Dome B (both in the 2017 and 2024 datasets), but none at Skytrain Ice Rise so far, may support the hypothesis that different atmospheric transport processes or depositional environments influenced their presence at each site.

Therefore, in terms of the relative presence of centric and pennate diatoms, it is not possible to define significant differences between the two cores. Both forms have been observed at Dome B and Skytrain Ice Rise, but the total diatom counts remain low at both sites, likely reflecting the limited deposition during the LGM. This scarcity of valves limits any robust comparison of centric versus pennate abundance across the two locations.

To further improve the comparison between Dome B and Skytrain Ice Rise, we estimated how the number of diatom valves and fragments would have changed if full filter coverage had been achieved, rather than considering only the observed images. Two approaches were applied: the first to assess whether the abundance of diatom valves and fragments would change when scaled to the full filter coverage; the second to calculate diatom valves and fragments fluxes, therefore normalising the data per volume and time, and evaluating whether the trends would differ under full filter coverage conditions.

For the Skytrain Ice Rise ice core, no significant changes are observed in the trends of diatom valves and fragments across the different normalizations. In contrast, the Dome B ice core shows noticeable variations in abundance trends and fluctuations. As mentioned, this difference is primarily due to the number of SEM images analysed. This highlights that normalization and the calculation of full coverage help provide a better estimate of the overall trend, as it would appear if the complete image set and entire filter had been included.

4.6 Conclusions

The observed discrepancies between Dome B and Skytrain Ice Rise highlight fundamental differences in both image availability and aeolian transport dynamics, underscoring the need for tailored normalisation techniques when comparing diatom records from different ice cores. These methodological disparities emphasise the importance of considering the extent of image coverage when interpreting abundance trends, as incomplete sampling may lead to underestimations of diatom deposition during specific periods.

While the current dataset provides information about these two sites as past archives, further research is essential to refine our understanding of atmospheric transport mechanisms and their influence on diatom distribution in Antarctic ice cores. Future studies should aim to expand the number of analysed SEM images, enhance imaging resolution, and incorporate complementary analytical approaches—such as geochemical fingerprinting or detailed paleoenvironmental reconstructions—to better constrain diatom provenance and transport pathways.

In addition, integrating these findings with broader climate models and ice core datasets from other Antarctic regions would enhance our capacity to distinguish regional signals from larger-scale climatic patterns. Addressing these gaps will contribute to improving reconstructions of past atmospheric circulation and strengthen the role of diatoms as reliable climate proxies in Antarctic paleoenvironmental research.

5.0 Conclusion

This doctoral research has contributed to advancing scientific innovation by demonstrating the potential of diatoms as valuable proxies for paleoclimate and paleoenvironmental reconstructions. Their application is increasingly recognised as a promising tool to expand future research in this field.

By integrating multiple records from the RICE, Dome B, and Skytrain Ice Rise ice cores, this study has explored the complexity of atmospheric and oceanographic processes over both the Holocene and the Last Glacial Maximum. The results obtained throughout this thesis have enhanced our understanding of how dust and aeolian diatoms are entrained, transported, and deposited in Antarctic ice cores, and how these particles and microfossils can be used to reconstruct past climate variability with a resolution and taxonomic specificity that opens new interpretative pathways

The RICE ice core offered the opportunity to investigate the most recent 2,000 years, including a climatically relevant period such as the Little Ice Age. The combined analysis of dust concentration and diatoms' observation and identification enabled the reconstruction of atmospheric circulation patterns and depositional processes responsible for the transport and archiving of dust and aeolian diatoms in the RICE ice core. Notably, the diatom record provides new evidence for the eastward extension of the Ross Sea Polynya during the Little Ice Age, leading to the development of the Roosevelt Island Polynya, an innovative research discovery that allow to broader understand the Ross Sea Polynya dynamics during the Holocene.

In addition, on the most recent 2,000 years, this research has also explored the diatoms' observation and identification throughout the entire Holocene, highlighting their sporadic but persistent presence in the RICE ice core. While the early and mid-Holocene are characterised by low diatom abundance, the late Holocene shows the increasing peaks described in the last 2,000 years, during the Little Ice Age. These findings suggest that the climatic and environmental conditions evolved significantly over the Holocene epoch, possibly influenced by changes in ice shelf dynamics, atmospheric circulation patterns and source

regions productivity. Although the mechanisms behind these trends remain partially unresolved for the early Holocene, this work underscores the importance of continuing to research on the variability of diatom abundance from different perspectives.

The Dome B and Skytrain Ice Rise ice cores allowed a deeper exploration of diatoms' observation and identification during the Last Glacial Maximum.

The Dome B ice core revealed a clear predominance of freshwater diatoms, along with the presence of a few marine benthic taxa. These findings support the hypothesis proposed by Delmonte et al. (2017), which suggested that the exposure of the Patagonian continental shelf during low sea levels enabled the marine benthic diatoms to be entrained by wind and transported over long distances.

This interpretation is consistent with previous studies that documented similar mechanisms of aeolian diatoms transport from South America to Antarctica during glacial periods (Burckle et al., 1988; Kellogg & Kellogg, 1996; Petit et al., 1981). For instance, Kellogg & Kellogg (1996) identified marine diatoms in South Pole ice core and interpreted their presence as evidence of long-range atmospheric transport. Similarly, Burckle et al. (1988) found marine diatoms embedded in East Antarctic ice cores, highlighting the role of strong glacial westerlies in lifting and transporting microfossil-rich dust across the Southern Ocean.

In this context, the occurrence of marine benthic taxa at Dome B can be interpreted as further confirmation of this transport pathway, reinforcing the idea that the aeolian input reaching the East Antarctic Plateau during the LGM included sediment and microfossils originating from continental shelf areas along the South American margin. The simultaneous presence of freshwater diatoms suggests a mixed signal, reflecting both distal transport and potential reworking from freshwater and/or brackish environments.

For the Dome B ice core, dust measurements were carried out using two instruments: the Single Particle Extinction and Scattering and the Coulter Counter. These analyses highlighted both correlations and discrepancies

between the two methods in detecting particles, and this comparison was also extended to the number of diatom fragments observed through the SEM images.

The Skytrain Ice Rise core, as well as the Dome B ice core, showed the presence of freshwater diatoms. However, for some specimens, identification to the genus level was not possible due to limitations in imaging quality, which prevented the recognition of fine morphological details required for more accurate classification. However, the diatoms observed suggest a contribution from multiple habitat sources. Nevertheless, their low abundance makes it difficult to draw definitive conclusions. The Skytrain Ice Rise ice core shows potential for further investigation, as the presence of diatoms indicates that they could serve as paleoenvironmental proxies at this site as well.

Acquiring additional data would help clarify the dominant transport mechanisms and pathways affecting Antarctica and determine whether similar patterns are shared between Skytrain and Dome B, or if distinct regional dynamics are at play. Further diatom-focused analyses on the Skytrain Ice Rise core are needed to fully explore this potential.

This thesis demonstrates that diatom records provide a unique and underutilised proxy for reconstructing past climate in Antarctic ice cores. The ecological specificity of diatom taxa, combined with their sensitivity to transport dynamics, allows for the identification of likely source regions and helps to elucidate on the variability in atmospheric and oceanic circulation patterns that govern their deposition. These findings highlight the potential of diatom-based reconstructions to complement traditional proxies and refine our understanding of regional climate evolution.

While this research represents a significant contribution to Antarctic paleoenvironmental reconstruction, it also opens new paths for future investigations. Expanding the temporal and spatial coverage of diatom records, improving analytical resolution through advanced imaging, and integrating complementary techniques, such as geochemical fingerprinting or molecular analysis, could be crucial to further trace the provenance and transport pathways of these materials. Moreover, linking these records to broader Antarctic and

Southern Hemisphere datasets, and embedding them into climate modelling frameworks, will strengthen our ability to interpret both regional and global climatic dynamics in the context of ongoing environmental changes.

Ultimately, this thesis demonstrates that combining multiple proxies through a multi-site and a multi-temporal approach significantly enhances our capacity to interpret environmental signals archived in Antarctic ice cores. Diatoms have proven to be a powerful and informative component of the cryosphere's natural archive. By contributing new data and perspectives, this work helps consolidate their role as meaningful climate proxies and sets the stage for more comprehensive reconstructions of past climate variability in the Southern Hemisphere.

Through this journey across millennia of climatic history, this thesis has sought to give voice to the smallest of the witnesses, the beautiful and unique diatoms, whose silent presence in the ice offers a deep knowledge on what shapes our planet. In a world where climate signals grow ever more urgent, unlocking the secrets held in Arctic and Antarctic ice not only enriches scientific understanding, but also deepens our responsibility to protect these archives and the planet they reflect.

6.0 References

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7.0 Supplementary

BAG 631	pics observed	BAG 660	pics observed	BAG 720	pics observed	BAG 780	pics observed
Subsample	n°	Subsample	n°	Subsample	n°	Subsample	n°
DB631_0-9A_N	420 of 420	DB660_0-10_N	546 of 924	DB720_0-15_N	394 of 840	DB780_12-24_N	210 of 760
DB631_0-9A_NC	750 of 750	DB660_0-10_S	546 of 924	DB720_0-15_S	394 of 840	DB780_12-24_S	210 of 760
DB631_0-9A_S	420 of 420						
DB631_0-9A_SC	750 of 750	DB660_10-20_N	485 of 840	DB720_15-26A_N	424 of 903	DB780_24-35A_N	250 of 840
		DB660_10-20_S	485 of 840	DB720_15-26A_S	424 of 903	DB780_24-35A_S	250 of 840
DB631_0-9B_N	420 of 420						
DB631_0-9B_NC	765 of 765	DB660_20-31_N	484 of 800	DB720_15-26B_N	394 of 840	DB780_24-35B_N	220 of 820
DB631_0-9B_S	420 of 420	DB660_20-31_S	484 of 800	DB720_15-26B_S	394 of 840	DB780_24-35B_S	220 of 820
DB631_0-9B_SC	765 of 765						
		DB660_31-42_N	485 of 840	DB720_26-35_N	404 of 860	DB780_35-47A_N	200 of 800
DB631_9-21A_N	420 of 420	DB660_31-42_S	485 of 840	DB720_26-35_S	404 of 860	DB780_35-47A_S	200 of 800
DB631_9-21A_NC	750 of 750						
DB631_9-21A_S	420 of 420			DB720_35-45_N	384 of 820	DB780_35-47B_N	200 of 800
DB631_9-21A_SC	750 of 750			DB720_35-45_S	384 of 820	DB780_35-47B_S	200 of 800
DB631_9-21_B_N	400 of 800					DB780_47-60A_N	200 of 800
DB631_9-21_B_S	400 of 800					DB780_47-60A_S	200 of 800
DB631_21-33A_N	574 of 574					DB780_47-60B_N	210 of 760
DB631_21-33A_NC	450 of 450					DB780_47-60B_S	210 of 760
DB631_21-33A_S	492 of 492						
DB631_21-33A_SC	450 of 450					DB780_60-75A_N	310 of 940
						DB780_60-75A_S	310 of 940
DB631_21-33B_NC	279 of 279						
DB631_21-33B_S	493 of 493					DB780_60-75B_N	200 of 800
DB631_21-33B_SC	420 of 420					DB780_60-75B_S	200 of 800
DB631_33-45A_N	400 of 800						
DB631_33-45A_S	400 of 800						
DB631_33-45B_N	400 of 800						
DB631_33-45B_S	400 of 800						
DB631_45-50A_N	462 of 924						
DB631_45-50A_S	462 of 924						
DB631_45-50B_N	462 of 924						
DB631_45-50B_S	462 of 924						

Table S1 : all the SEM images observed for the Dome B ice core.

BAG 597	pics observed	BAG 601	pic observed	BAG 608	pic observed
Subsample	n°	Subsample	n°	Subsample	n°
SKT597_0-5	570 of 570	SKT601_68-72	585 of 585	SKT608_0-5	600 of 600
SKT597_5-10	570 of 570	SKT601_72-76	555 of 555	SKT608_5-10	570 of 570
SKT597_10-15	600 of 600	SKT601_76-80	555 of 555	SKT608_10-15	600 of 600
SKT597_15-20	585 of 585	SKT601_80-84	600 of 600	SKT608_15-20	570 of 570

Table S2 : all the SEM images observed for the Skytrain Ice Rise ice core.

Estratto per riassunto della tesi di dottorato

L'estratto (max. 1000 battute) deve essere redatto sia in lingua italiana che in lingua inglese e nella lingua straniera eventualmente indicata dal Collegio dei docenti.

L'estratto va firmato e rilegato come ultimo foglio della tesi.

Studente: Serena Lagorio

matricola: 956566

Dottorato: Scienze Polari

Ciclo: 36°

Titolo della tesi¹ :

Aeolian diatoms in Antarctic ice cores: unveiling past climate and environmental changes

Abstract:

This thesis presents a study on aeolian diatoms from three Antarctic ice cores: RICE, Dome B, and Skytrain Ice Rise. The RICE ice core, spanning up to 83,000 years, focuses on the last 2,000 years and highlights how diatoms, used as proxies, describe the atmospheric circulation patterns that contributed to the eastward extension of the Ross Sea Polynya and the development of the Roosevelt Island Polynya. Dome B and Skytrain Ice Rise ice cores investigated the Last Glacial Maximum (~33,000–24,000 years ago), assessing diatom presence and provenance. Previous studies identified few marine benthic diatoms in Dome B, suggesting a possible origin from the Patagonian shelf. These findings served as a reference to detect potential similarities and to better understand past atmospheric and oceanic dynamics. Overall, this research demonstrates the value of diatoms as climate proxies and contributes to advancing multi-proxy approaches for paleoenvironmental reconstructions in Antarctica.

Titolo della tesi² :

Diatomee eoliche nelle carote di ghiaccio antartiche: rivelare i cambiamenti climatici e ambientali del passato

Questa tesi presenta uno studio sulle diatomee eoliche provenienti da tre carote di ghiaccio antartiche: RICE, Dome B e Skytrain Ice Rise. La carota RICE, che copre fino a 83,000 anni, si concentra sugli ultimi 2,000 anni e mette in evidenza come le diatomee, utilizzate come proxy, descrivano i pattern di circolazione atmosferica che hanno contribuito all'estensione verso est della

¹ Il titolo deve essere quello definitivo, uguale a quello che risulta stampato sulla copertina dell'elaborato consegnato.

² Il titolo deve essere quello definitivo, uguale a quello che risulta stampato sulla copertina dell'elaborato consegnato.

Ross Sea Polynya e allo sviluppo della Roosevelt Island Polynya. Le carote Dome B e Skytrain Ice Rise hanno indagato l'ultimo massimo glaciale (~33,000–24,000 anni fa), valutando la presenza e la provenienza delle diatomee. Studi precedenti hanno identificato alcune diatomee bentoniche marine in Dome B, suggerendo una possibile origine dalla piattaforma continentale della Patagonia. Questi risultati sono serviti come riferimento per individuare potenziali analogie e comprendere le dinamiche atmosferiche e oceaniche del passato. Questa ricerca dimostra il valore delle diatomee come proxy paleo climatici.

Firma dello studente

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