Antarctic Waters

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Abstract:
Here, we summarise the diatom research topics and applications that have the broadest relevance and importance for Antarctic studies. From the Southern Ocean we focus on biogeography, sea surface temperature (SST) and sea-ice reconstructions (including frontal migrations) and biostratigraphy. We also include the significance of studying laminated diatomaceous sediments and how diatoms are used as bottom water tracers in the global ocean circulation system. Diatoms from Antarctic lake sediments and ice cores are also briefly introduced.

Keywords
Antarctic
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Diatom
Micropaleonotology
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Sea-ice
Sediments
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Transfer Function

Key points/objectives box

- Diatoms are prolific primary producers in the Southern Ocean where they sink to form a circumpolar ring of diatom-rich sediments known as the 'Siliceous Ooze Belt'.
- Southern Ocean diatom communities are sensitive to a range of environmental variables, including sea surface temperatures (SSTs), nutrient availability and the presence of sea-ice; and are valuable proxies for inferring past ocean conditions.
- Diatoms also form important communities in Antarctic freshwaters where they are particularly sensitive to water depths, nutrients and ice cover
- Diatoms from marine and freshwater environments can also be incorporated into Antarctic ice-cores
- Many of the laminated sediments in Antarctica record the seasonal sequence of diatom production
- Climate change is already impacting the distribution, extent and viability of diatom habitats in Antarctica
- Antarctic diatoms contribute many applications for Quaternary paleoenvironmental studies which are discussed in the chapter and include:
  -Biogeography
  -Past sea-surface temperatures and sea-ice patterns
  -Water mass distribution and frontal migrations
  -Tracking Antarctic Bottom Water
  -Biostratigraphy

Glossary:

aerophilic	depending on free oxygen or air
dessication	the process of becoming completely dried
diene	a compound containing two double bonds between carbon atoms
endemic	native and restricted to a certain area or place
eutrophication	excessive loading of nutrients into water bodies
extant	still in existence
phenology	the timing (e.g. seasonal) of life-cycle events in plants and animals
physiology	the way in which a living organism or bodily part functions
siliceous	containing or consisting of silica
sympagic	under sea-ice habitat/ecology
triene	a compound containing three double bonds between carbon atoms
varve	annually laminated sediment

Abbreviations:

AABW	Antarctic Bottom Water
ACC	Antarctic Circumpolar Current
AP	Antarctic Peninsula
BP	before present
^{14}C yr	radiocarbon years
cal ky	calendar years before present
CCD	calcium carbonate compensation depth
CLIMAP	Climate and Environment Monitoring with GPS Atmospheric Profiling
CONOP	Constrained Optimization
DD228/257	Diatom Database 228/257

DSDP	Deep Sea Drilling Project (1966-1983)
FAOD	First Abundant Occurrence Datum
EA	East Antarctica
EPILOG	Environment Processes of the Ice Age: Land, Ocean, Glaciers
GPTS	geomagnetic polarity timescale
HBI	highly branched isoprenoid
HNLC	high-nutrient, low-chlorophyll
IMAGES	International Marine Past Global Changes Study
IODP	International Ocean Discovery Program (2013-present), formerly Integrated Ocean Drilling Program (2003-2013)
IP_{25}	Ice Proxy with 25 carbon bonds
$IPSO_{25}$	Ice Proxy for the Southern Ocean with 25 carbon bonds
ka	thousand years ago
ky	thousand years
LGM	Last Glacial Maximum
LOD	Last Occurrence Data
Ma	million years ago
MIS	Marine Isotope Stage
NADW	North Atlantic Deep Water
ODP	Ocean Drilling Project (1983-2003)
PF	Polar Front
PFZ	Polar Front Zone
POOZ	Permanently Open Ocean Zone
SACCF	Southern ACC Front
SAF	Subantarctic Front
SEM	scanning electron microscope
SHWW	Southern Hemisphere Westerly Wind
SIZ	Sea-Ice Zone
SST	sea surface temperature
SSI	summer sea-ice
STF	Subtropical Front
STZ	Subtropical Zone
WSI	winter sea-ice

Introduction: Antarctic Marine Waters

The southern high latitudes play a critical role in the global climate system. Advances in understanding the paleoceanographic and cryospheric evolution of the Southern Ocean and Antarctica are helping us understand global climate change on a range of timescales. Diatoms are arguably the best fossil group for reconstructing past Antarctic climate change since they are prolific throughout the Southern Ocean (the area between the coast of Antarctica (~70°S) and the Subtropical Front (~40°S) (Fig. 1a), sensitive to environmental conditions, with many species occupying discrete ecological niches.

While it is impractical to detail all diatom-based studies and applications, we summarise those reports which have widespread importance for Antarctic studies and suggest further reading, on these and other topics. From the Southern Ocean we focus on biogeography, sea surface temperature (SST) and sea-ice reconstructions (including frontal migrations), laminated sediments, bottom water tracers and biostratigraphy. Diatoms from lake sediments and ice cores are also briefly introduced.

The Southern Ocean Siliceous Ooze Belt

Diatoms contribute up to 75% of Southern Ocean primary production, despite this being a high-nutrient, low-chlorophyll (HNLC) region. Such abundant diatom growth in surface waters, combined with a high export flux to the seafloor, makes the Southern Ocean the world's main sink for biogenic opal (silica). In particular, the area beneath the Antarctic Circumpolar Current (ACC), a major cog in the global thermohaline circulation, comprises a continuous belt of opal completely encircling Antarctica between ~45° and ~60°S (Fig. 1b). Diatomaceous sediments have accumulated within this belt more or less continuously since at least the Miocene (23.03–5.33 Ma). Today the nutrient-rich Southern Ocean supports a unique flora comprising at least six endemic planktic species according to Zielinski and Gersonde (1997): *Eucampia antarctica*, *Fragilariopsis curta*, *F. kerguelensis*, *F. separanda*, *Shionodiscus gracilis* and *Thalassiosira lentiginosa*. The Polar Frontal Zone acts as a major geographic barrier, separating cooler-water 'Antarctic' species to the south from warmer-water 'Subantarctic' species to the north.

Southern Ocean fossil diatom records spanning the Quaternary are a valuable paleo archive, containing mostly, but not exclusively, extant species in high abundance. For example, Zielinski and Gersonde (1997) report diatom concentrations of 50-200 x 10^6 valves/g surface sediment in the Atlantic sector beneath the ACC. The so-called 'siliceous ooze belt' of well-preserved diatoms, is bound north and south by sediments containing fewer and less well-preserved diatoms; carbonate-rich sediments to the north and silty diatomaceous clay to the south including the Antarctic continental shelf regions (Fig. 1A & B). These boundaries, approximating to the modern Polar Front (north) and the mean position of the winter sea-ice edge (south), have shifted north (south) during past cooler (warmer) periods of climate. High accumulation of biogenic silica also occurred in some localities across the Antarctic continental shelf during the Quaternary, mostly during termination and interglacial intervals. Since these sediments are mostly removed during subsequent glacial periods, these high accumulation records are limited to the last deglaciation and Holocene. Several sites on the Antarctic continental shelf have yielded ultra-high resolution post-glacial records with sediment accumulation rates ranging from 2-16 m per thousand years (ky^{-1}), many of which comprise partially or fully laminated sequences (*see* section on **Antarctic marine diatoms: laminated sediments**).

Applications of Quaternary Antarctic Diatoms

Where well preserved (*see* Jones **'Diatom Introduction and Marine Diatoms'**), diatoms are excellent tools for climate reconstruction because their species composition accurately reflects the environment in which they live and are highly responsive to environmental change. The use of diatoms as a paleoenvironmental tool is especially valuable for marine sediments deposited below the calcium carbonate compensation depth (CCD) and in the high-latitude regions such as the

Southern Ocean. In both environments, siliceous microfossils (diatoms, silicoflagellates, and radiolarians) prevail over calcareous microfossils (nannofossils and planktic foraminifera) because carbonate is not preserved below the CCD (preservational advantage), and reproduction of calcareous-walled microplankton can be severely inhibited in polar waters (environmental advantage). This means that Antarctic marine diatoms are arguably the most reliable microfossil group for reconstructing Southern Ocean environmental parameters. Of critical interest are past fluctuations in SST, circum-Antarctic sea-ice patterns, latitudinal shifts in oceanic fronts and their role in carbon dioxide draw-down. To this end, there has been significant progress in assessing modern diatom species distribution patterns (biogeography) and refining Antarctic diatom-based statistical techniques, developments which have advanced our understanding of the main environmental drivers controlling species abundance and distribution. In this way, Antarctic diatoms are key to elucidating the climatic and oceanographic history of the Southern Ocean. Furthermore, since most Antarctic species found in Quaternary deposits are extant, ecological based applications can be applied to the recent past with confidence. Antarctic marine diatoms are also widely used in biostratigraphy for dating records from both offshore and shelf regions. In the shelf setting, diatoms can also help elucidate sea-level changes, past glacial processes, and ice sheet history. Other interesting applications of diatoms relate to their use as tracers of ocean and atmospheric circulation.

Biogeography, Past Sea-Surface Temperatures and Sea-Ice Patterns
Recent advances have been made in mapping the biogeography of modern marine diatom assemblages deposited in Antarctic seafloor sediments (i.e., core-top sediments representing modern or recent conditions) with respect to environmental controls. This is perhaps one of the most valuable procedures for assessing which hydrographic and cryospheric parameters control the occurrence and abundance of species, since surface sediments contain diatom assemblages that integrate production of the overlying water column over several seasons and years. These modern diatom datasets, or training sets (Fig. 2), have been analyzed by a variety of statistical techniques to create transfer functions. Techniques such as the modern analog technique and the generalized additive model have enabled quantitative reconstructions of SST's and seasonal sea-ice patterns for the Quaternary. These statistical methods are reproducible and follow the assumption that the biogeographic variability of species preserved in the surface sediments reflects the surface water hydrology and, therefore, may be used as a proxy for paleoenvironmental variability. The merits of assessing past SST's and sea-ice patterns are clear; the warming and cooling of the ocean surface is a primary gauge for climate change, while sea-ice (area, duration and concentration) is especially important for climate models because of the many feedback effects and energy exchanges associated with its growth and decay, as well as its impact on the thermohaline circulation. As most diatom flux to the Southern Ocean sediments occurs during the austral summer, relationships between diatom distributions and environmental parameters are best derived with reference to summer conditions. However, reference to winter conditions is equally valid as it provides a means to contrast seasonal extremes as well as factoring in control for particular species distributions.

Biogeography
Until the 1990's, understanding of the relationship between the distribution of Antarctic diatoms in core-top sediments to surface water hydrology was limited to a few early reports from the 1960's and 1970's. Although pioneering, these early studies either focussed on only a limited area of the Southern Ocean or covered a wider area in less detail. One of the more useful reports is that by Burckle (1984). He mapped species distributions and preservation from core-tops in all sectors of the Southern Ocean. Although the dataset was relatively small (55 core-tops; nine significant species) and the data points relatively scattered, Burckle produced one of the first diatom biogeographic studies to cover the entire circum-Antarctic, incorporating statistical analysis of the relationship between species distribution and environmental parameters (Fig. 1a). Later, Zielinski and Gersonde

(1997) provided the first truly comprehensive modern species-specific distributional dataset for the Atlantic sector of the Southern Ocean (Fig. 2). They clearly showed that the biogeography and abundance of 35 diatom species in the region are closely related to summer SST and the presence or absence of sea-ice, concluding that diatom species distributional patterns do have paleoenvironmental significance.

A more extensive biogeographical dataset in terms of both spatial coverage and detail is provided in a set of linked research papers by Armand *et al.* (2005), Crosta *et al.* (2005) and Romero *et al.* (2005). Their comprehensive database (termed Diatom Database 228 or DD228) includes sites from the Antarctic coast to Subtropical Zone throughout the Atlantic and Indian sectors of the Southern Ocean (Fig. 2). This dataset gives a much more complete view of the relationships between diatom distribution and environmental parameters. In particular, they broaden the use of the sea-ice control by taking into account its concentration (percentage cover) and duration, not merely its presence or absence. Table 1 presents these sea-ice parameters along with summer (February) SSTs and relative abundance data for each of 14 sea-ice affiliated diatoms. More training sites in the Atlantic and Indian ocean sectors have been added to this (now DD257; Chadwick *et al.*, 2022a) and other biogeographical databases (Fig.2). For the Pacific sector of the Southern Ocean, a suite of core top assemblages has been published by Benz *et al.* 2016.

Affinities for diatom species are defined by their zonal distribution or by statistical groupings to environmental gradients (Fig. 3; Esper and Gersonde, 2014a, b). The correlation of their geographic patterns with sea-surface parameters illustrates the principal environmental control on the occurrence and abundance of each species. For the sea-ice and open-ocean zones, these controls are summer (February) SST and sea-ice cover in terms of (i) concentration during seasonal extremes (summer and winter) (see Table 1, sea-ice diatoms) and (ii) annual duration (months/year). In the Polar Front and Subantarctic Zone the main control on diatom species distribution are warmer, annual SST given the minimal sea-ice influence.

Past Sea-Surface Temperatures and Sea-Ice Patterns

Past SST and sea-ice distribution should be considered together since they are interrelated, albeit not necessarily linearly, over long timescales. For example, Crosta *et al.* (2004) showed in a quantitative diatom study of the Indian sector of the Southern Ocean that during interglacial to glacial transitions, sea-ice expansion lagged the SST decrease by approximately one thousand years (ky), while sea-ice retreat was almost synchronous with the SST increase at glacial terminations.

Sea-ice provides an important and vast habitat for Antarctic diatoms, supporting rich assemblages throughout the growing season. At the height of their growth, populations of sea-ice diatoms can become so dense that they colour the underside of the sea-ice yellowy-brown (Fig. 4B). In the austral winter (September) sea-ice expands to an area of up to approximately 18.5 x 10^6 km^2 (average for 1981-2010; Fig. 1), and although inhibiting diatom production in the surface waters and thus decreasing their flux to the underlying sediments , sea-ice melt stimulates huge blooms of diatoms in the surrounding waters during the austral spring. So-called sea-ice-related taxa, such as the well-known species *Fragilariopsis curta and F. cylindrus* (Fig. 5), have been used to trace winter sea-ice patterns in Quaternary age sediments throughout the Southern Ocean. Chadwick *et al.* (2022b) for example, use *F. curta* + *F. cylindrus* records from eight Southern Ocean sites to compare sea-ice conditions during the last interglacial period with the modern sea-ice setting. Estimations of past summer (February) sea-ice patterns are more problematic since productivity is greatly inhibited and few microfossils are preserved which allow paleoenvironmental reconstructions. However, occurrences of the cold-water (year-round sea-ice) indicator *F. obliquecostata*, along with a decrease in biogenic sedimentation, are used to infer the presence/proximity of summer sea-ice.

Although their dataset was never published in detail, Pichon *et al.* (1992) was one of the first studies to develop a transfer function for reconstructing past SST from diatoms in core-top material from the Atlantic and Indian sectors of the Southern Ocean and which factored in problems caused by dissolution. They applied their transfer function to two cores in the Indian sector of the Southern Ocean to produce SST estimates for the last ~140 ky.

Other studies have focussed on reconstructing conditions at particular time-slices such as the Last Glacial Maximum (LGM). For example, Crosta *et al.* (1998), revising the Pichon *et al.* (1992) dataset, were the first to use the modern analog technique to quantitatively reconstruct circum-Antarctic sea-ice patterns from marine diatoms in terms of months per year (duration) at the LGM. Gersonde *et al.* (2005) applied three statistical methods to 122 published and new marine records, located in all sectors of the Southern Ocean, to quantitatively reconstruct the glacial Southern Ocean at the EPILOG (Environment Processes of the Ice Age: Land, Ocean, Glaciers) time-slice (19.5-16.0 thousand years ago (ka) or 23-19 calendar years before present (cal ky BP). Their results indicate that at the EPILOG LGM the maximum winter sea-ice extent (at a concentration of >15%) reached as far north as nearly 47°S in the Atlantic and Indian sectors, but only to 57°S in the Pacific sector (Fig. 6). This equates to a total, EPILOG LGM circum-Antarctic winter sea-ice expanse of approximately 39 x 10^6 km^2, an areal increase of >100% compared to the 1981-2010 mean extent, agreeing with earlier diatom-based estimations (e.g., CLIMAP (Climate and Environment Monitoring with GPS Atmospheric Profiling)).

In contrast with previous studies, both Crosta *et al.* (1998) and Gersonde *et al.* (2005) suggest an increased seasonality at the LGM based on large differences between the estimated extent of winter and summer sea-ice compared with today. In addition, their estimation of EPILOG LGM summer SST indicates a northward migration of the LGM Polar Front by 4° and 5-10° latitude in the Atlantic and Indian sectors, respectively, with 4-6°C cooling in the modern Subantarctic Zone. Gersonde *et al.* (2005) also infer a similar northward shift in the LGM Subantarctic Front in the Atlantic and Indian sectors but a relatively minimal northward shift of the LGM Subtropical Front leading to compression of the Subantarctic Zone and steepened thermal gradients at the peak of the glacial.

Since 2005, other studies have produced more targeted reconstructions of LGM and late glacial sea-ice extent (Fig. 6). These reconstructions broadly corroborate the LGM position of the winter sea-ice extent by Gersonde *et al.* (2005) and provide evidence that the maximum extent of summer sea-ice occurred between ~30 and ~23 ka and had started to retreat towards its modern position by the LGM, supporting the assertion by Crosta *et al.* (1998) and Gersonde *et al.* (2005) of increased seasonality between winter and summer sea-ice cover at the LGM (Collins *et al*. 2012).

Marine Diatom Biomarker Proxy for Sea-Ice

In 2007, Belt *et al.* introduced the first biomarker proxy for sea-ice - 'IP_{25}' ("Ice Proxy with 25 carbon atoms"). IP_{25} is a mono-unsaturated highly branched isoprenoid (HBI) that is produced by select sea-ice diatoms and found in seafloor sediments beneath seasonal sea-ice throughout the Arctic (*see Belt* **'Structures and applications of biomarkers from Arctic sea-ice diatoms'**). The IP_{25} HBI is not present in Antarctica, instead a close structural analog - a di-unsaturated HBI – was first proposed as a potential sea-ice proxy in Antarctica by Masse *et al.* (2011). Brown *et al.* (2014) established that this 'diene' or 'HBI-II' (termed "$IPSO_{25}$" - Ice Proxy for the Southern Ocean with 25 carbon atoms), is produced by at least one Antarctic sea-ice diatom - *Berkeleya adeliensis* – a sympagic (growing in or under sea-ice) diatom closely affiliated with platelet and land-fast ice. The presence of $IPSO_{25}$ in modern sea-ice, waters and surface sediments is notably skewed towards coastal locations (Fig. 7; Belt *et al.* 2016). This distribution is consistent with *B. adeliensis* as a primary source and suggests that $IPSO_{25}$ may be a better proxy for the *type* of sea-ice rather than the extent, concentration or seasonality of the sea-ice cover.

As with other sea-ice proxies, absence of $IPSO_{25}$ in sediments may result from a permanently open ocean or a persistent ice 'canopy' (ice shelf or perennial/summer sea-ice cover). Unlike other sea-ice proxies, $IPSO_{25}$ may also be missing from sediments beneath the broader sea-ice zone, away from areas of platelet and land-fast ice. Since ice canopies greatly inhibit primary productivity, it is usually straight-forward to identify an open ocean setting based on relatively high organic content of the sediments or the presence of open ocean phytoplankton/proxies. At present, evidence from other

sea-ice indicators/proxies is needed to determine whether sediments devoid of $IPSO_{25}$ are from within the sea-ice zone.
Analyses of older marine sediments show $IPSO_{25}$ is present in Holocene age sediments from sites around the Antarctic continental shelf and in glacial age sediments in the Weddell and Scotia Seas (Fig. 7).

Antarctic Marine Diatoms as a tracer for Antarctic Bottom Water

Marine planktonic diatoms endemic to the Southern Ocean can be transported out of Antarctic waters into the world's oceans via Antarctic Bottom Water (AABW). This is possible where surface-dwelling diatoms are entrained into downwelling AABW during its formation in the Weddell and Ross Seas and on the continental shelf around the Antarctic continent. Entrained diatoms subsequently settling out along the flow path become effective tracers of this deep current. This is clearly demonstrated with diatoms occurring in abyssal surface sediments along the AABW flow path in the southwest and central Pacific and the southwest Atlantic, yet absent in shallower surface sediments bathed by the overlying water mass (e.g., North Atlantic Deep Water (NADW)). Endemic diatoms, particularly heavily silicified frustules such as *F. kerguelensis* (Fig. 8), displaced by AABW have been noted in surface and core sediments as far as 60°N.
Along with the stable isotopic signature of biogenic carbonate, these displaced diatom assemblages help reconstruct past AABW production and export into these oceanic basins. This is of interest since AABW plays a key role in the climate system, being one of the main transporters of heat and salts around the world's oceans. A higher abundance of displaced diatoms may indicate stronger AABW flow. For example, Jones and Johnson (1984) found that for the south-west Atlantic, displaced diatoms are more abundant during interglacials (stronger AABW flow) than glacial maxima (weaker AABW flow). However, unlike stable isotopes, displaced endemic Antarctic diatoms provide an unequivocal tracer for bottom water provenance. Furthermore, in the southwest Pacific, downcore variations in the abundance of displaced open-ocean diatoms (eg. *Fragilariopsis kerguelensis; Thalassiosira lentiginosa*) versus sea-ice related diatoms (eg. *Fragilariopsis curta, F. cylindrus*) may indicate temporal switches in AABW source (open ocean versus continental shelf waters, respectively) through the late Quaternary.

Diatom Biostratigraphy

Diatoms (and other siliceous microfossils) provide the best biostratigraphic control in offshore Southern Ocean sediments. Planktic marine diatoms make excellent biostratigraphic tools here for several reasons: they are abundant and widespread (now and since the Oligocene ~34 Ma), well-preserved, easily extracted from the sediment and have undergone several relatively rapid, evolutionary events since the late Early Cretaceous (~113 Ma) in this region, driven by climatic and tectonic changes (Scherer *et al.* 2007; Crampton *et al.* 2016). These evolutionary events, which are identified in sedimentary sequences as originations and extinctions of unique taxa, form the basis of a well-developed diatom zonation scheme for the Late Eocene (~36 Ma) to Quaternary by Harwood and Maruyama (1992, and references therein, summarised by Scherer *et al.* 2007). The zonation scheme(s) provide relative and absolute age information and have been developed over many years from mainly offshore cores drilled by the Deep Sea Drilling Project (DSDP), the Ocean Drilling Programme (ODP), and the International Ocean Discovery Program (IODP, formerly the Integrated Ocean Drilling Program). Scherer *et al*. (2007) provide a review of the history of the development of Southern Ocean biostratigraphy and the zonation scheme(s). However, significant recent advancements in Southern Ocean biostratigraphy is presented by Cody *et al.* (2008), which use a computer-based biostratigraphic optimization system (the Constrained Optimization, "CONOP" model) that outputs the most parsimonious sequence of events and absolute ages for over 200 biostratigraphic and paleomagnetic events spread over the past ~20 Ma (most of the Neogene and Quaternary). CONOP is a multi-dimensional graphic correlation system which incorporates comprehensive datasets, minimizing the subjectivity in using traditional zonal methods, eliminating unreliable data and providing a much higher temporal resolution. Importantly, although it is more reliable in offshore areas of the Southern Ocean, it can also be applied to the Antarctic Shelf with improvements made for the Plio-Pleistocene in more near-shore regions (Cody *et al.* 2012).

Antarctic Marine Diatoms: Laminated Sediments

Advances in analytical techniques during the 1990's have realized the potential of laminated, diatom-rich marine sediments to provide seasonal-scale proxy records. Almost surgical precision in sampling has been introduced, including small, discrete samples for quantitative diatom abundance work (Leventer *et al.*, 2002) and scanning electron microscope (SEM) analysis of intact, micron-scale sequences of laminations to investigate diatom species successions through the seasons and relationships between succeeding laminae (Kemp, 1990).

There are two requirements for the formation of laminated diatomaceous sediments in marine sediments: (1) a temporally varying flux of either diatoms or terrigenous grains, or both and (2) a mechanism for preserving the primary sediment fabric. In Antarctic continental shelf sediments, laminations can record the seasonal succession of diatom assemblages with or without a varying flux of terrigenous material from melting glacier ice. Laminae are preserved where bioturbation is inhibited by anoxic seafloor conditions or where the benthos is overwhelmed by the mass flux of diatom material to the sea floor.

Since the recovery of over 40 m of post glacial laminated diatomaceous ooze from Palmer Deep (ODP Site 1098) in 1998, several other high-resolution, late Quaternary laminated units have been collected from basins and troughs around Antarctica, including the Adelie Basin (Wilkes Land margin, EA), Maxwell Bay (South Shetland Islands, AP), the Firth of Tay (Joinville Island, AP), Iceberg Alley (MacRobertson Shelf, EA), Dumont D'Urville Trough (Wilkes Land margin, EA) and Edisto Inlet (Victoria Land, EA) (Fig. 10). The thickness of these laminated units range from tens of centimetres to tens of metres and generally occur as a sequence of discrete diatom layers with no apparent repetition/cyclicity, or as continuous annual 'varved' couplets.

At most of these sites, laminated units are only preserved during the deglacial and early Holocene, reflecting the seasonal succession of intense blooms within calving bays along the retreating ice sheet margin during rapid post-glacial warming (Leventer *et al.*, 2006). Individual lamina typically comprise a layer of exceptionally pure *Hyalochaete Chaetoceros* ooze deposited following the spring bloom, coupled with a layer of mixed diatom assemblages comprising diatoms such as *Corethron pennatum*, *Coscinodiscus bouvet*, *Odontella weissflogii*, *Fragilariopsis* spp. and *Thalassiosira* spp. deposited over the course of the succeeding summer/autumn (Alley *et al*. 2018; Leventer *et al*. 2002; Maddison *et al.* 2006, 2012; Roseby *et al*. 2022). Terrigenous grains originating from meltwater plumes and ice rafted debris, are often present or even abundant within the summer/autumn deposits.

The longest laminated sequence collected so far from the Antarctic continental shelf is the IODP drill site U1357, recovered from the Adelie Basin in 2010. Comprising more than 170 m of seasonally laminated 'varved' sediments, U1357 is one of the world's most expanded Holocene archives and provides a near-annual resolution record of Antarctic glacio-marine/palaeoceanographic conditions since ice retreated from the site ~11,500 cal yr BP (Expedition 318 Scientists, 2011; Fig. 11a & b).

Antarctic Diatoms: Lakes

Less than 1% of the Antarctic continent is ice free and here diatoms can grow in lakes and streams as well as in terrestrial habitats. The majority of the lakes are situated on East Antarctica's coastal oases (e.g., McMurdo Dry Valleys, Vestfold Hills, Gruber Mountains and Schirmacher Oasis), the ice-free areas of the Antarctic Peninsula (e.g., Hope Bay; Sjögren Inlet, Bourgeois Fjord) and the Antarctic Islands (e.g., James Ross Island, Alexander Island, Ross Island, South Orkney Islands, South Shetland Islands). Many Antarctic freshwater diatoms are classed as aerophilic but are also found in aquatic habitats subject to dessication or freezing, others are found in association with terrestrial soils and mosses. Many of the coastal lakes in Antarctica contain diatom records that describe a marine to

fresh-water transition. This ecological shift can be abrupt and be a useful marker for relative sea-level change or release of ice-sheet loading.
An inventory of modern diatom flora from 439 lakes across the Antarctic continent and islands reveals a pattern of increasing endemism and decreasing diversity towards higher latitudes and greater isolation (Verleyen *et al.* 2021). Of all the lacustrine diatom species, 44% are considered endemic to Antarctica, with many specific to one biogeographic area. This high degree of endemism is due to limited dispersal mechanisms and the physical barriers between regions.
Holocene stratigraphic records have accumulated in many Antarctic and Subantarctic lakes. Due to the dearth of other proxies conventionally used in temperate regions (e.g., pollen), diatoms have been extensively used for environmental reconstruction. Hodgson *et al.* (2004) provide a holistic review of Antarctic paleolimnology while Spaulding and McKnight (1999) review the uses of diatoms in lacustrine paleoreconstructions. Diatoms are good indicators of salinity, which in some lakes can be a proxy for climate (eg. changes in meltwater or precipitation inputs versus evaporation or sublimation), while in others it is related to sea level or sea spray. Diatoms have also been used as indicators of the changing extent of glacier/terrestrial ice, lake ice and lake depth.
Transfer functions have been developed for a range of environmental variables, for example, Jones and Juggins (1995) created a transfer function for nutrient availability (evident by high chlorophyll *a* concentrations) based on diatoms assemblages in surface sediments from lakes on Signy and Livingstone Islands. This tool was applied to Holocene records from Signy Island, and together with other proxy data showed a Holocene climatic optimum between 3,800-1,300 ^{14}C yr BP when productivity within the lakes was highest. Changes in the diatom flora related to nutrient enrichment due to local bird and seal populations were also observed.
In the Vestfold and Larsemann Hills, Roberts and McMinn (1996) and Verleyen *et al.* (2003) have developed transfer functions for salinity. The water chemistry of the lakes in these areas respond quickly to changes in local moisture balance, with increasing salinity and decreasing lake-water level during dry periods, with the opposite pattern in wet periods. Roberts *et al.* (2001) used a transfer function approach to obtain a high resolution record of evaporation for the last 650 years from Ace Lake (Vestfold Hills) which was also highly correlated to the seasonal oxygen isotope signal preserved in the Law Dome ice core, suggesting that the diatom-based reconstructions provide a robust paleoclimate signal.
More recently, Saunders *et al.* (2018) and Perren *et al.* (2020) developed diatom-conductivity transfer functions for lakes on the Subantarctic Macquarie and Marion Islands. Lying within the main belt of the Southern Hemisphere Westerly Winds (SHWW), sea salt aerosols produce a strong west-east gradient in the conductivity of water bodies on the islands that is reflected in the diatom assemblage composition. Down core variations in conductivity of the Macquarie Island lake reveal intervals of above average wind strength between 12.1-11.2 ka and after 7 ka. The Marion Island lake record covers the past 700 years and indicates weaker winds between 1450 and 1870 that were associated with a cooler climate and a northward shift in the SHWW belt.
The McMurdo Dry Valleys, located on the western coast of the Ross Sea, are among the coldest and driest places on Earth. Lakes here are some of the harshest aquatic environments in the world. The lakes mostly have perennial ice cover (2.8-6.0 m thick) over liquid water. The volume of these lakes has fluctuated greatly of the last 20,000 years and in recent times lake levels have been rising. Lake Hoare is a perennially ice-covered, closed-basin where diatoms form part of the benthic microbial mats, with characteristic species occurring in shallow-water, mid-depth and deep-water communities. Analysis of the sedimentary diatoms from Lake Hoare indicates that the rapid increase in water level is a recent event.

Antarctic Diatoms: Ice Cores
Diatoms have been found in ice cores throughout Antarctica, even hundreds of kilometres away from potential diatom sources. The first records of diatoms preserved in ice core layers date back to 1983 (Gayley and Ram, 1984) from Dome C and Vostok ice cores. These sites contained small

concentrations of diatoms, with LGM samples being considerably more enriched than Holocene samples. Almost all diatoms found at these sites were non-marine. Later reports from Taylor Dome and South Pole ice cores provided more evidence of non-marine diatoms in ice layers, but also reported the presence of marine diatoms (Kellogg and Kellogg, 1996a, b). At Taylor dome, marine diatoms dominated the assemblage during cold intervals over the last glacial period, while non-marine diatoms dominated the assemblage over the Holocene and warm intervals during the last glacial period (Kellogg and Kellogg, 1996b). While most marine and non-marine diatoms found at these sites are endemic to Antarctica, some species are known to be cosmopolitan.

The presence of diatoms over the Antarctic ice sheet can be explained by winds. Winds can entrain diatoms from a wide range of sources, from dried lake beds and exposed sediments to the sea and sea-ice surfaces. Over the ocean, winds create waves and induce the formation of micrometre-sized droplets of seawater which can transfer organic material (including diatoms) from the sea-surface microlayer into the atmosphere. Once in the atmosphere, diatoms can be transported by winds over long, intercontinental distances (>1000 km) and at high elevations (~3000 m a.s.l.). When airborne diatoms reach the polar ice sheets, they are deposited and then buried under subsequent snowfall events to finally become part of the ice matrix. The distance and elevation between diatom sources and the ice core sites supports aeolian transport as the primary mode of transfer. However, the nature and specific controls determining the entrainment, transport and deposition of diatoms are not fully understood.

Budgeon *et al*. (2012), Allen *et al*. (2020) and Tetzner *et al*. (2022a) have analysed the diatom assemblages in several Antarctic ice cores over the satellite-era (1979-present) to discover that most of the diatoms preserved in Antarctic coastal sites are marine taxa and endemic to the Southern Ocean, supporting a wind-mediated transfer of diatoms. Subsequently, Tetzner *et al*. (2022b) demonstrated that there is a strong correlation between the number of diatoms preserved in Antarctic Peninsula ice core annual layers and annual mean wind strength at the core of the SHWW belt. These recent findings highlight that diatom records preserved in Antarctic ice core layers can be used as a novel proxy for past wind variability, with the potential to contribute to the understanding of past changes in atmospheric circulation, primary productivity, sea-ice and polynya formation.

Antarctic Diatoms: Impacts of Climate Change

Parts of Antarctica have been warming up to three times faster than the global average over the past 50 years. In just the last few years, Antarctica has experienced record sea-ice minima, extreme heat and accelerated loss of land-ice. The rates and scale of environmental change are having, and will continue to have, a profound impact on both marine and terrestrial ecosystems.

In the oceans, sea surface warming, acidification, reduced sea-ice cover and increased meltwater are changing the physical and biogeochemical properties of Antarctic waters. There is already good evidence that diatom blooms on the west Antarctic Peninsula continental shelf have shifted southwards in response to the warming and decline in sea-ice cover during the 1980's and 90's (Montes-Hugo *et al.* 2009). Whilst continued warming over the coming decades is predicted to increase diatom productivity over the Southern Ocean, there are large uncertainties concerning how the size, physiology (e.g., nutrient uptake, photosynthetic efficiency, growth rates) and phenology (e.g., growth cycles, seasonal cycles) of individual diatom species respond to environmental stresses (e.g., lower pH; reduced stratification; nutrient supply; grazing pressures; phytoplankton competition, microbial activity) as well as how these responses affect overall diatom productivity, distribution, consumption and export.

On land, the impacts of regional warming over recent decades are most pronounced in the Antarctic Peninsula, West Antarctica and coastal areas of the East Antarctic Margin where ice thinning and melt rates are highest (Smith *et al.*, 2020). Continued expansion and consolidation of ice-free coastal and inland areas will provide new habitats for diatoms and other organisms, especially where melt water creates ponds, streams and lakes. Existing lakes will also be affected by nutrient export from

increasingly productive catchments as vegetation and fauna expand with warming, probably causing eutrophication to which diatoms will respond.
Whilst the direct impacts of ongoing climate change will affect the physical and biogeochemical conditions of Antarctic diatom habitats, the less predictable ecosystem responses (e.g. competition, consumption) are also likely to exert pressures on the diversity and distribution of Antarctic diatoms over the coming decades.

Conclusion

In this article we demonstrate how diatoms are a powerful paleoclimate tool in both marine and fresh-water systems using fossil record examples from Antarctic waters. The nutrient-rich Southern Ocean is the world's richest source of marine biogenic opal, resulting in a circum-Antarctic 'siliceous ooze belt'. We summarise the latest information on diatom biogeography in surface sediments used to reconstruct past sea-surface temperatures (SST's) and sea-ice patterns. We also discuss their use as bottom water tracers and for biostratigraphy. Records of freshwater diatoms have been found in lakes on ice-free areas of the continent and on sub Antarctic islands, providing valuable archives from rare and remote settings. Finally, we reflect on the likely impacts of recent and future climate change on Antarctic waters and consider the potential impacts on diatom ecology.

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Revised Figure 1: A) Southern Hemisphere map showing main oceanographic features, including: region of the Antarctic Circumpolar Current (ACC) (blue shading based on Gille *et al*., 2016); positions of Southern Ocean fronts (Southern ACC Front, Antarctic Polar Front, Subantarctic Front, SubTropical Front); average summer sea-ice extent; average winter sea-ice extent and oceanographic zones (Sea-ice Zone, Permanentaly Open Ocean Zone, Polar Front Zone, SubAntarctic Zone). B) distribution of siliceous muds and oozes comprising the Southern Ocean opal belt based on Burckle (1984) & Dutkiewicz *et al*. (2016). Topographic data from the SCAR Antarctic Digital Database, 2023. Sea-ice data extracted from ‘Fetterer, F., K. Knowles, W. N. Meier, M. Savoie, and A. K. Windnagel. Sea Ice Index, Version 3. 2017, Distributed by National Snow and Ice Data Center. https://doi.org/10.7265/N5K072F8. Date Accessed 11-30-2023’. Polar fronts taken from South Georgia GIS, 2023. Subtropical Front extracted from ‘Orsi, AH., Harris, U. (2019) Fronts of the Antarctic Circumpolar Current - GIS data, Ver. 1, *Australian Antarctic Data Centre* - https://data.aad.gov.au/metadata/records/antarctic_circumpolar_current_fronts, Accessed: 2023-02-14’. Sediment lithology from digital data (http://portal.gplates.org/cesium/?view=seabed) presented in Dutkiewicz *et al*. (2016).

Revised Figure 2: Surface sediment sample sites used in studies of diatom biogeographic distribution. Symbols show locations of surface sediment samples used as reference sites in studies to determine diatom biogeographical distribution. Produced by the Mapping and Geographic Information Centre, © British Antarctic Survey, UK Research and Innovation, 2023. Topographic data from the SCAR Antarctic Digital Database, 2023. Sea-ice data extracted from ‘Fetterer, F., K. Knowles, W. N. Meier, M. Savoie, and A. K. Windnagel. Sea Ice Index, Version 3. 2017, Distributed by National Snow and Ice Data Center. https://doi.org/10.7265/N5K072F8. Date Accessed 11-30-2023’. Polar fronts taken from South Georgia GIS, 2023. Subtropical Front extracted from ‘Orsi, AH., Harris, U. (2019) Fronts of the Antarctic Circumpolar Current - GIS data, Ver. 1, *Australian Antarctic Data Centre* - https://data.aad.gov.au/metadata/records/antarctic_circumpolar_current_fronts, Accessed: 2023-02-14’

Revised Figure 3: Spatial distribution of the three sea-ice related diatom taxa *Fragilariopsis curta* group (combined *F. curta* and *F. cylindrus*), *F. obliquecostata* and *F. sublinearis* in relation to winter (WSI) and summer (SSI) sea-ice extent (black lines indicate 15% concentration of each). **Figure 7 from Esper & Gersonde (2014b)**

Revised Figure 4: Pack ice in Pacific sector of Southern Ocean during *RRS* James Clark Ross Cruise (JR179) in 2008: A) view astern towards the Filchner Ice Shelf and Birkner Island; B) upturned ice alongside ship. (Photographs by C.S. Allen).

Revised Figure 5: Secondary electron-scanning microscope images of A) the bipolar diatom *Fragilariopsis cylindrus* and B) the endemic Antarctic diatom *F. curta*, used to trace past winter sea-ice patterns in the circum-Antarctic. (Images provided courtesy of J. Pike.)

Revised Figure 6: Sea-ice distribution at the EPILOG LGM timeslice compared to modern conditions. EPILOG LGM-WSI, maximum extent of winter sea-ice at the LGM (September, concentration >15%); M-WSI, maximum extent of modern winter sea-ice (September, concentration >15%); and M-SSI, maximum extent of modern summer sea-ice. Values indicate estimated winter (September) sea-ice concentration in percent derived with the modern analog technique and the generalized additive model. Large dots, concomitant occurrence of cold-water indicator *Fragilariopsis obliquecostata* (>1% of diatom assemblage) and summer sea-ice (February, concentration > 0%) interpreted to represent sporadic occurrence of EPILOG LGM-SSI (maximum extent of summer sea-ice at the LGM); medium dots, presence of winter sea-ice (September, concentration >15%, diatom winter sea-ice indicators >1%); small dots, no winter sea-ice (September, concentration <15%, diatom winter sea-ice indicators <1%). Modified from Gersonde *et al*. (2005) *Quaternary Science Reviews* 24: 869-896, with permission from Elsevier BV. Original image amended with other LGM sea-ice limits from Allen *et al.* (2011); Collins *et al.* (2012); Ferry *et al.* (2015); Xiao *et al.* (2016); Benz *et al.* (2016); Ghadi *et al.* (2020); Torricella *et al.* (2021) & Jones *et al.* (2022).

Revised Figure 7: Distribution of *Berkeleya adeliensis* and $IPSO_{25}$ in previous studies. Summary map of Antarctica showing locations where *Berkeleya adeliensis* and HBI diene II ($IPSO_{25}$) have been identified in sea-ice, surface sediments and palaeo records (note: B. spp designates studies where diatom identification was not conducted beyond the genus level). The black and white stippled lines refer to the median winter and summer sea-ice margins for the interval 1979–2010, respectively. Abbreviated location names are as follows: AP, Antarctic Peninsula; BS, Bellingshausen Sea; AS, Amundsen Sea; AL, Adélie Land; WI, Windmill Islands; PB/EF, Prydz Bay/Ellis Fjord; LB, Lützow-Holm Bay. The structure of the di-unsaturated HBI lipid biomarker diene II (IPSO25) is also shown. Sea-ice data extracted from ‘Fetterer, F., K. Knowles, W. N. Meier, M. Savoie, and A. K. Windnagel. Sea Ice Index, Version 3.

2017, Distributed by National Snow and Ice Data Center. https://doi.org/10.7265/N5K072F8. Date Accessed 11-30-2023'. Reproduced from Belt *et al.* (2016) *Nature Communications* 7:12655 doi: 10.1038/ncomms12655.

Figure 8: Light microscope image (plane-polarized light) of the endemic diatom *Fragilariopsis kerguelensis*, one of the main contributors to biogenic opal in Southern Ocean sediments. Image taken from late Quaternary laminated sediments of the East Antarctic Margin. The lower specimen is 50 mm long. (Image provided courtesy of E.J. Maddison). **NB. Figure 3 in previous edition of this chapter.**

Figure 9: Compilation and correlation of the Plio-Pleisotcene diatom zonation for the northern and southern part of the Southern Ocean. Both absolute and relative age information is provided: ages in (Ma); chronostratigraphy (epochs); and the geomagnetic polarity timescale (GPTS, polarity, and chrons). Reproduced from Zielinski & Gersonde (2002) *Marine Micropaleontology* 45: 225-268, with permission from Elsevier BV. **NB. Figure 8 in previous edition of this chapter.**

Revised Figure 10: Map showing sites of published core records including laminated diatomaceous sediments. Abbreviated location names are as follows: AP, Antarctic Peninsula; AL, Adélie Land; PB, Prydz Bay; SG, South Georgia.

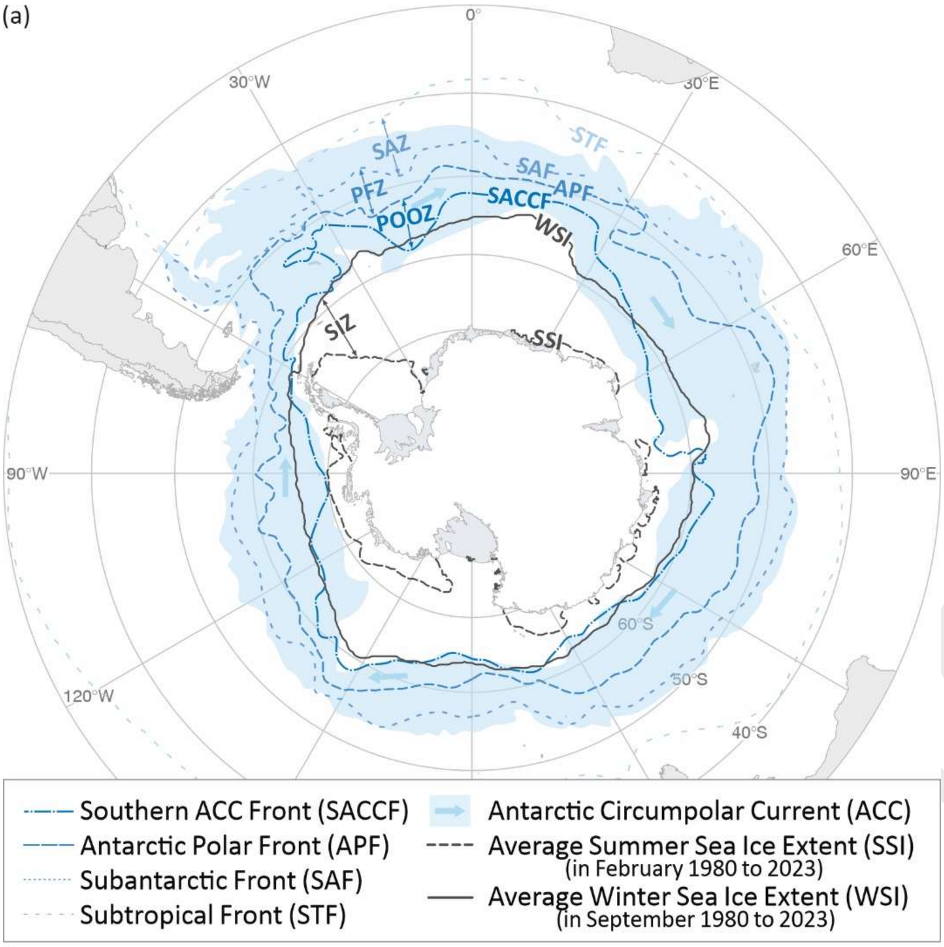
Revised Figure 11: A. Core image of typical laminations observed at the base of lithostratigraphic Unit I, Hole U1357A (interval 318-U1357A-18H-7, 35–59 cm). Dark–light couplet represents annual sedimentation, the accumulation rates are slightly higher than 2 cm yr^{-1}. **B-F.** Photomicrographs of representative fields of view from millimeter- to centimeter-scale laminations, Hole U1357A. Biosiliceous-rich laminations; (B) gray fibrous lamina with large centric diatom *Thalassiosira lentiginosa,* a number of *Fragilariopsis* (pennate) species, and *Chaetoceros* resting spores (Sample 318-U1357A-19H-4, 147 cm; 147.00 mbsf); (C) orange lamina with multiple specimens of the silicoflagellate *Distephanus speculum speculum* (hexagonal structures) and numerous *Chaetoceros* resting spores (small dark shapes) (Sample 318-U1357A-19H-1, 86 cm; 169.96 mbsf); (D) white lamina with needle-shaped pennate diatoms *Thalassiothrix antarctica* (narrower pennate) and *Trichotoxon reinboldii* (wider pennate) (Sample 318-U1357A-19H-2, 19 cm; 170.78 mbsf). **E.** Olive-green siliciclastic lamina with several species of *Thalassiosira* (centric diatoms), fragmented pennate diatoms, and *Chaetoceros* resting spores (Sample 318-U1357A-19H-2, 80 cm; 171.39 mbsf). **F.** Black siliciclastic lamina with siliciclastic components and several fragmented pennates (Sample 318-U1357A-19H-6, 45 cm; 177.04 mbsf).

All images reproduced from Expedition 318 Scientist (2011) *Proceedings of the Integrated Ocean Drilling Program*, 318. doi:10.2204/iodp.proc.318.105.2011.

Table 1: Temperature and sea-ice parameter ranges and maximum relative abundances of the 14 sea-ice species and groups in DD228 (adapted from Armand *et al*. (2005) *Palaeogeography Palaeoclimatology Palaeoecology* 223: 93-126, with permission from Elsevier BV).

Figure 1.

(a)


0°
30°W
30°E
60°E
90°W
90°E
120°W
60°S
50°S
40°S
STF
SAZ
SAF
APF
PFZ
SACCF
POOZ
WSI
SIZ
SSI
Southern ACC Front (SACCF)
Antarctic Polar Front (APF)
Subantarctic Front (SAF)
Subtropical Front (STF)
Antarctic Circumpolar Current (ACC)
Average Summer Sea Ice Extent (SSI)
(in February 1980 to 2023)
Average Winter Sea Ice Extent (WSI)
(in September 1980 to 2023)

(b)

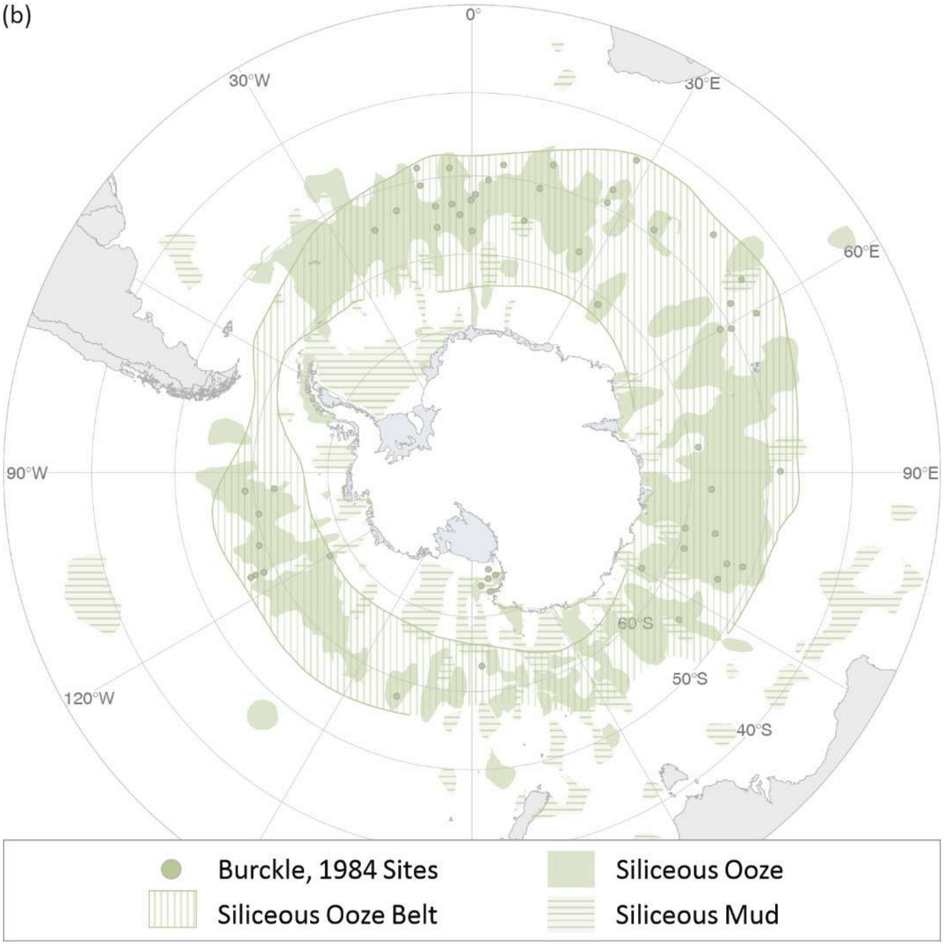

0°
30°W
30°E
60°E
90°W
90°E
120°W
60°S
50°S
40°S
Burckle, 1984 Sites
Siliceous Ooze Belt
Siliceous Ooze
Siliceous Mud

Figure 2.

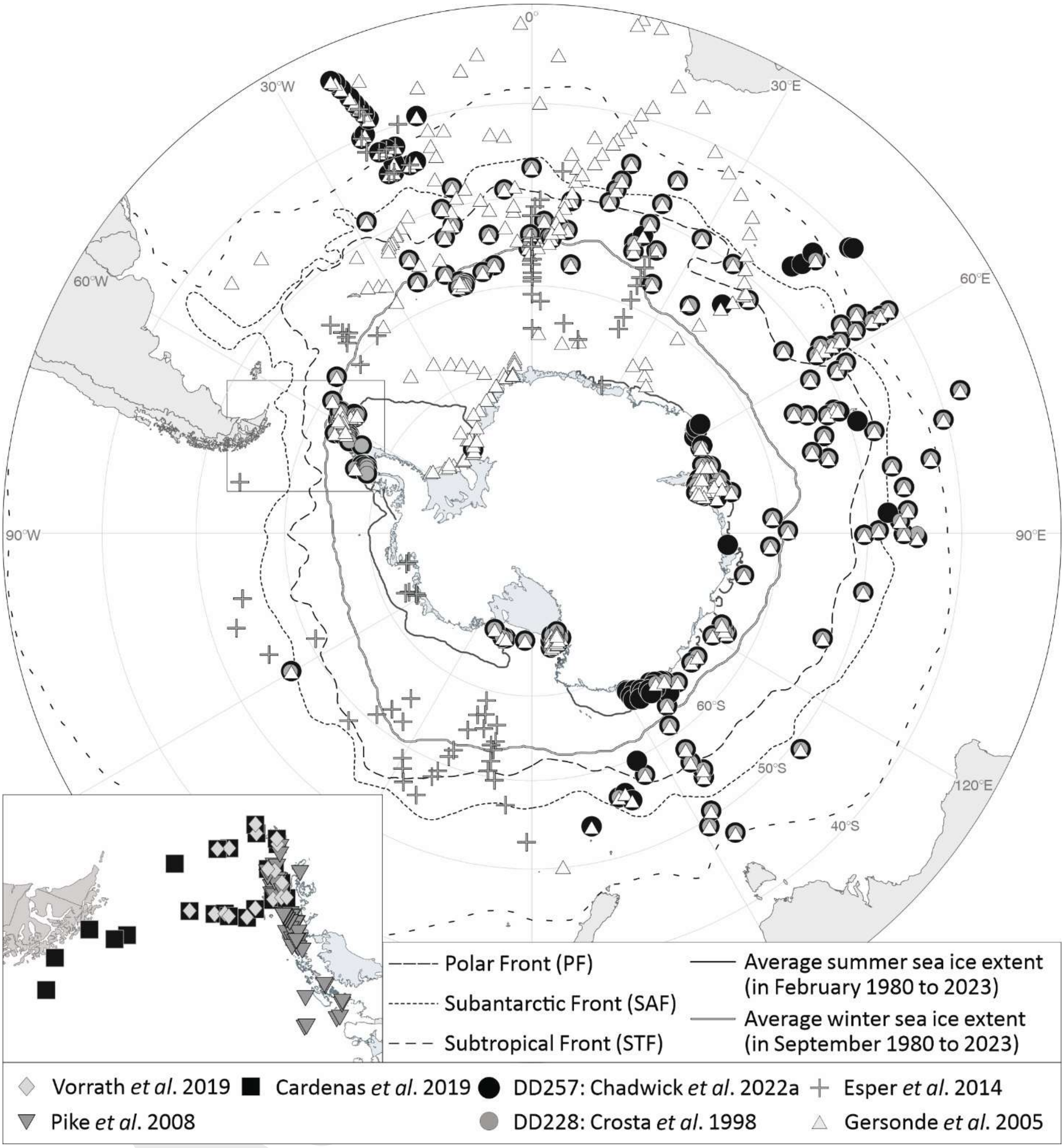
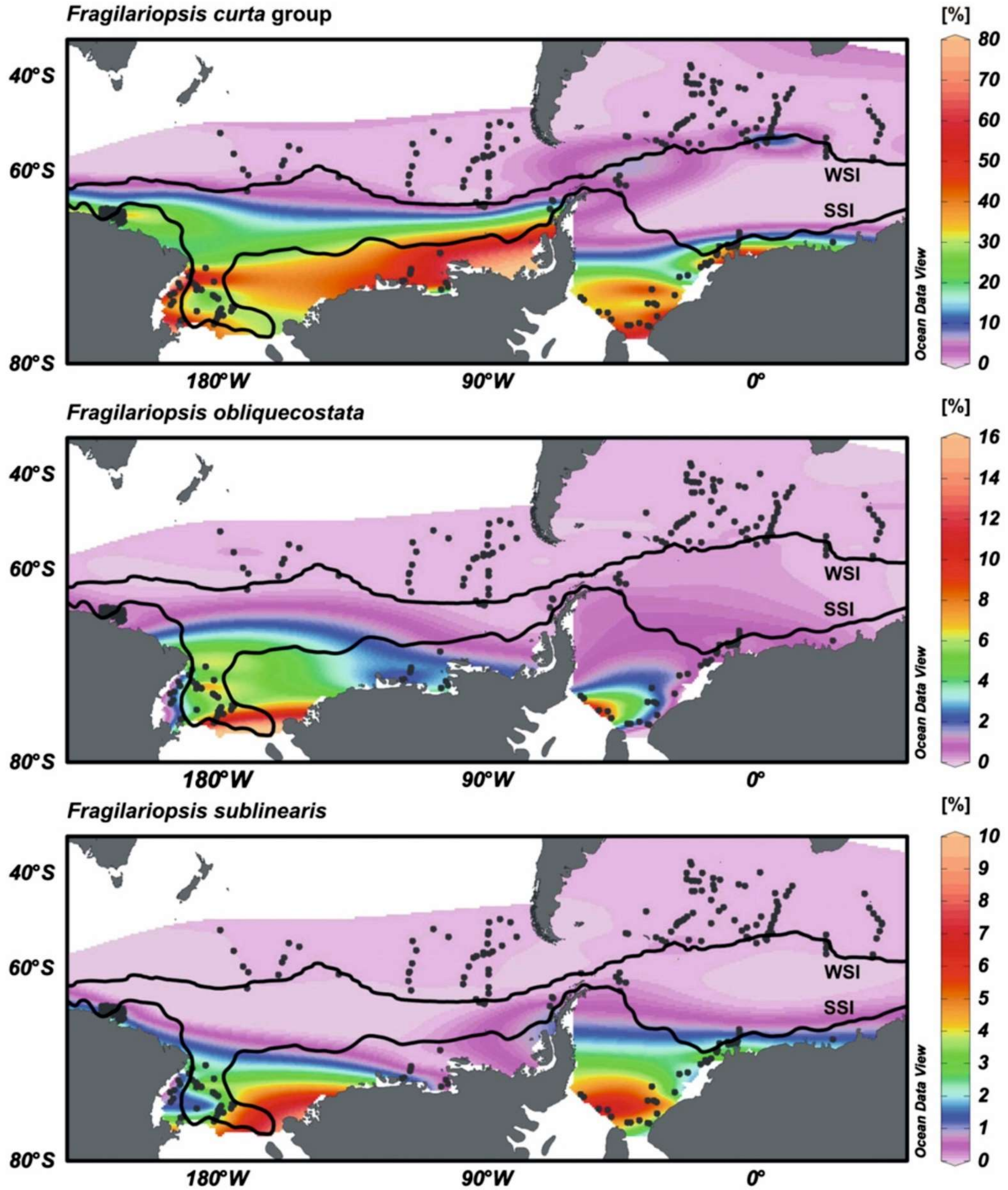

0°
30°W
30°E
60°W
60°E
90°W
90°E
60°S
50°S
40°S
120°E
Polar Front (PF)
Subantarctic Front (SAF)
Subtropical Front (STF)
Average summer sea ice extent (in February 1980 to 2023)
Average winter sea ice extent (in September 1980 to 2023)
Vorrath et al. 2019
Cardenas et al. 2019
DD257: Chadwick et al. 2022a
Esper et al. 2014
Pike et al. 2008
DD228: Crosta et al. 1998
Gersonde et al. 2005

Figure 3.



Fragilariopsis curta group
[%]
80
70
60
50
40
30
20
10
0
Ocean Data View
40°S
60°S
80°S
180°W
90°W
0°
WSI
SSI
Fragilariopsis obliquecostata
[%]
16
14
12
10
8
6
4
2
0
Ocean Data View
40°S
60°S
80°S
180°W
90°W
0°
WSI
SSI
Fragilariopsis sublinearis
[%]
10
9
8
7
6
5
4
3
2
1
0
Ocean Data View
40°S
60°S
80°S
180°W
90°W
0°
WSI
SSI

Figure 4.

(a)
(b)

Figure 5.

(a)
(b)

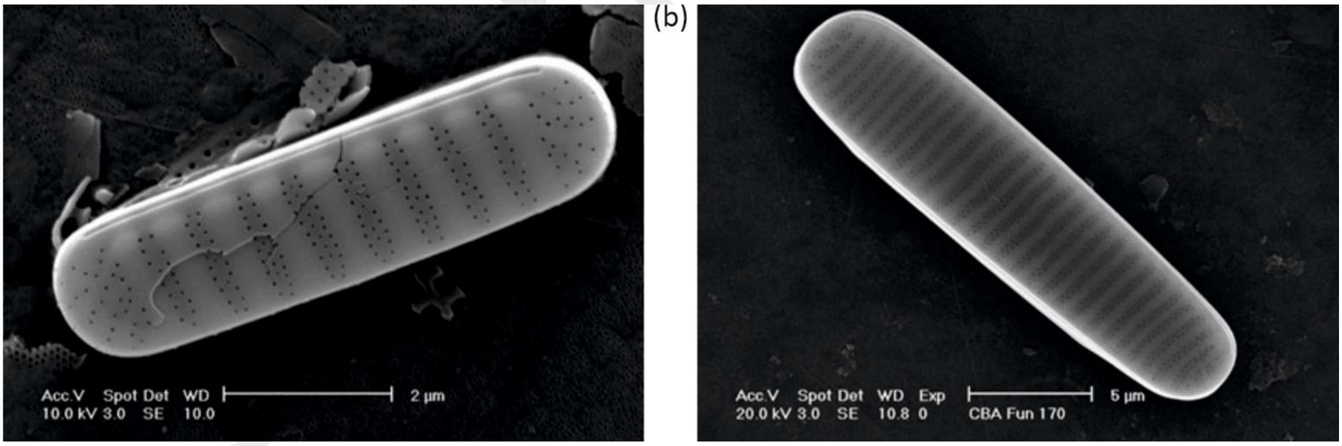
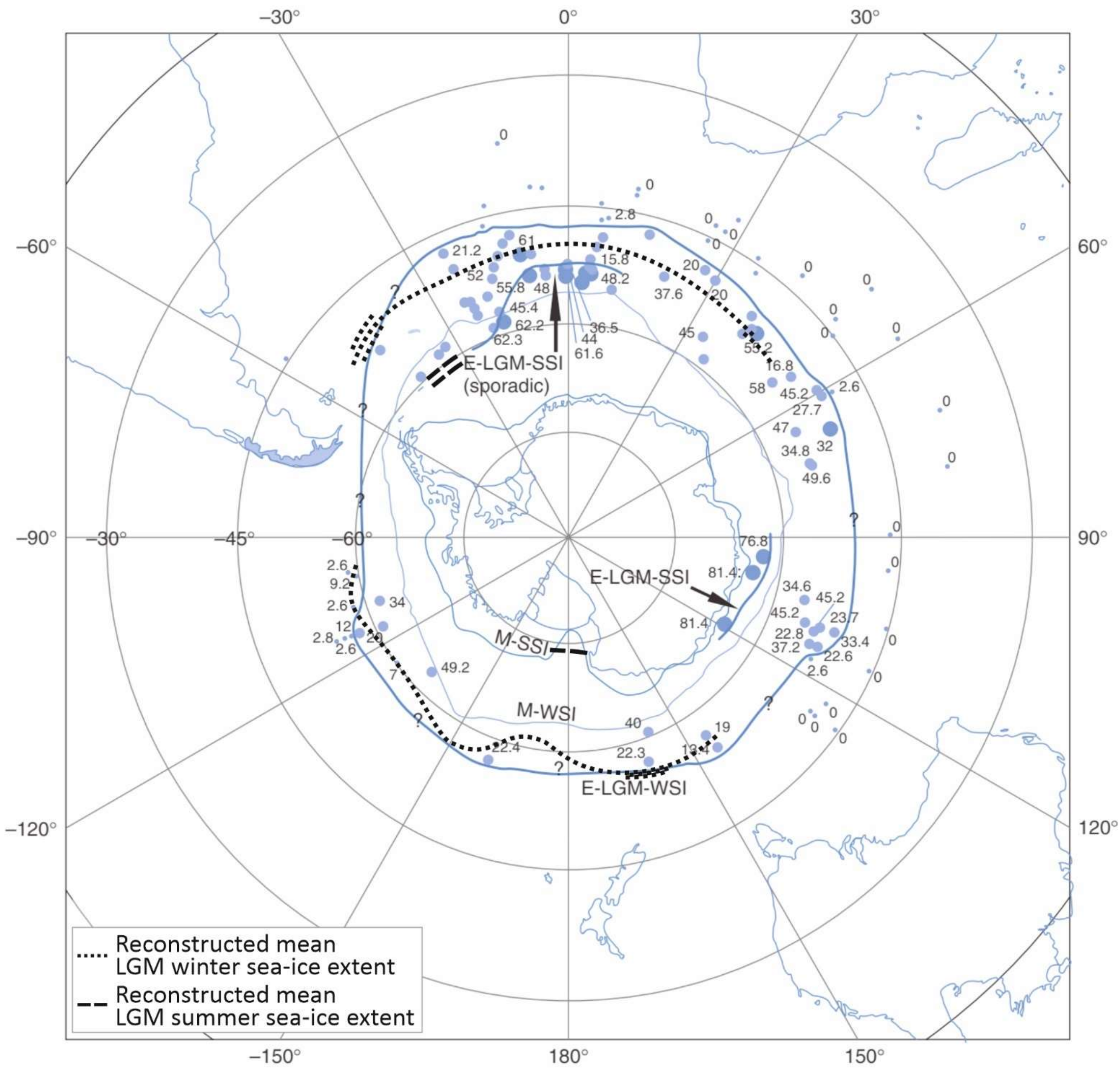


Figure 6.



Reconstructed mean LGM winter sea-ice extent
Reconstructed mean LGM summer sea-ice extent
E-LGM-SSI (sporadic)
E-LGM-SSI
M-SSI
M-WSI
E-LGM-WSI

Figure 7.

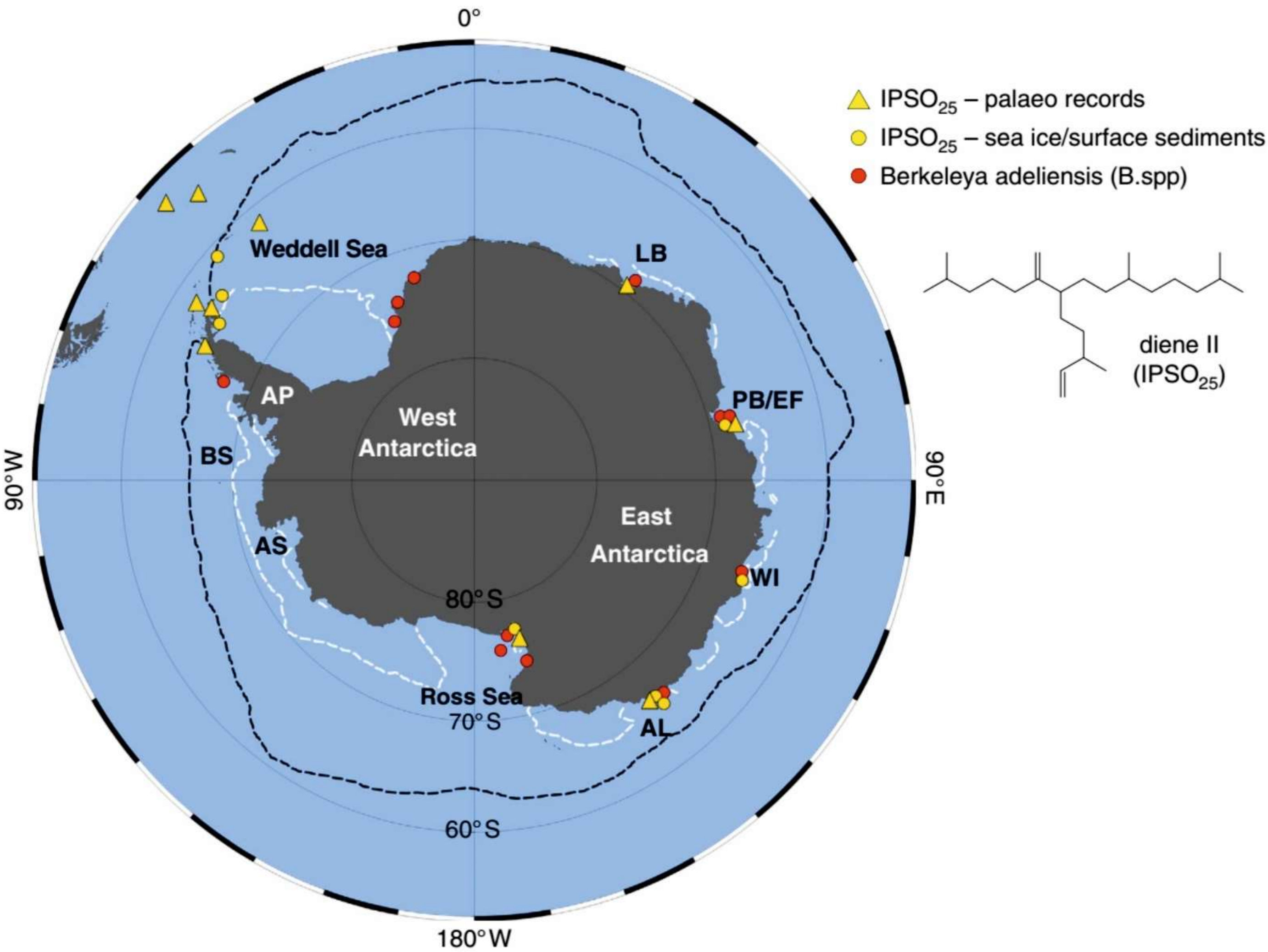


Figure 8.

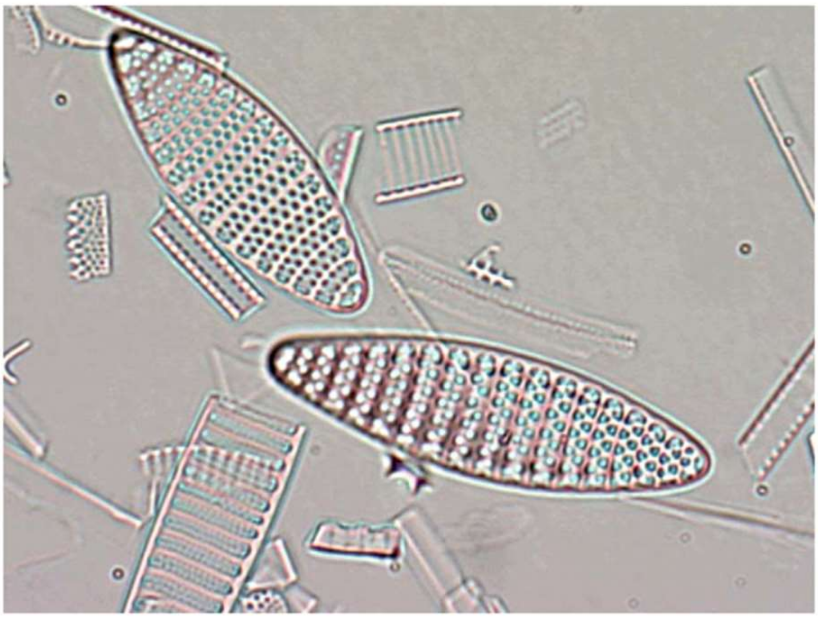


Figure 9.

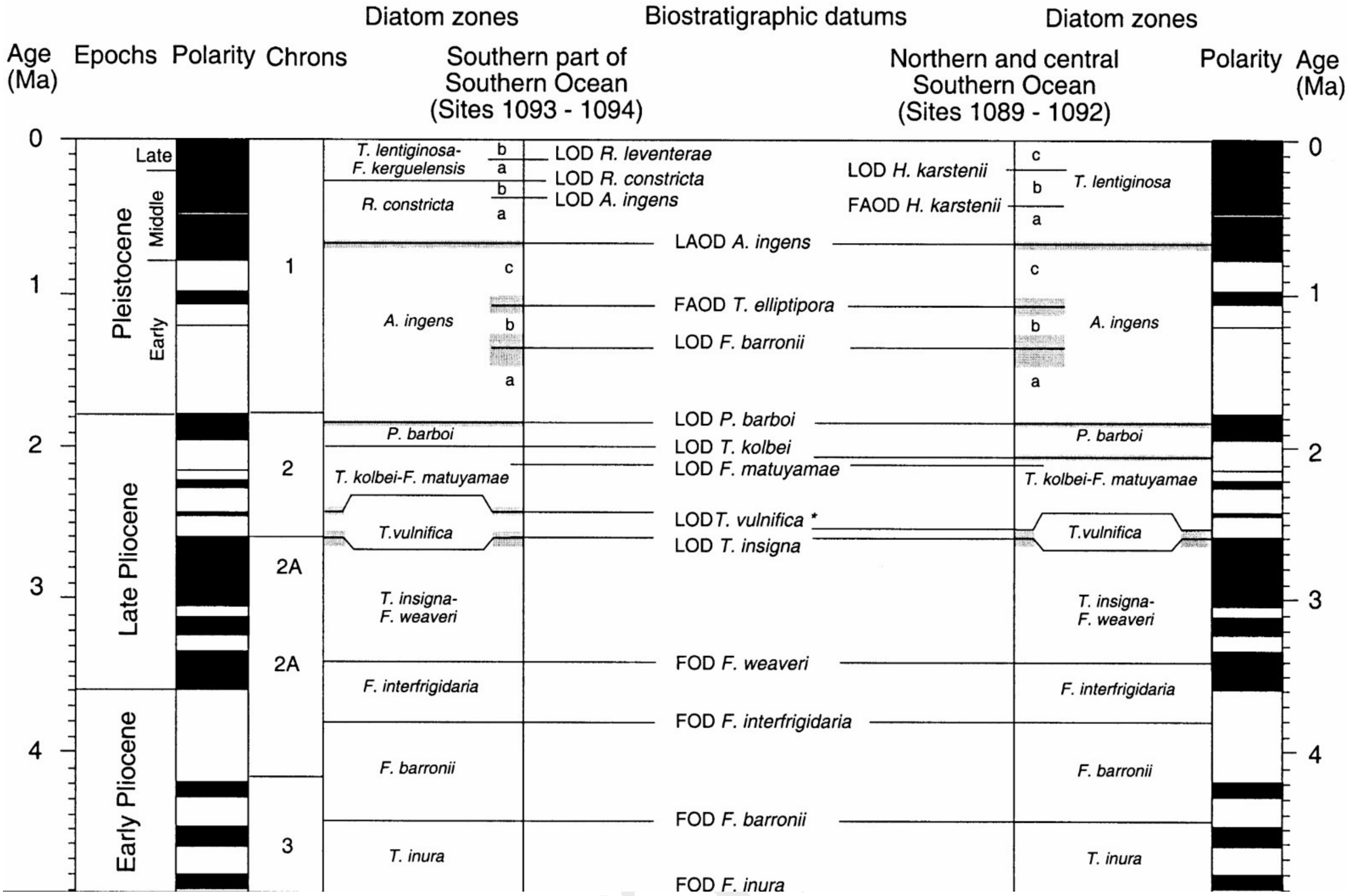


Figure 10.

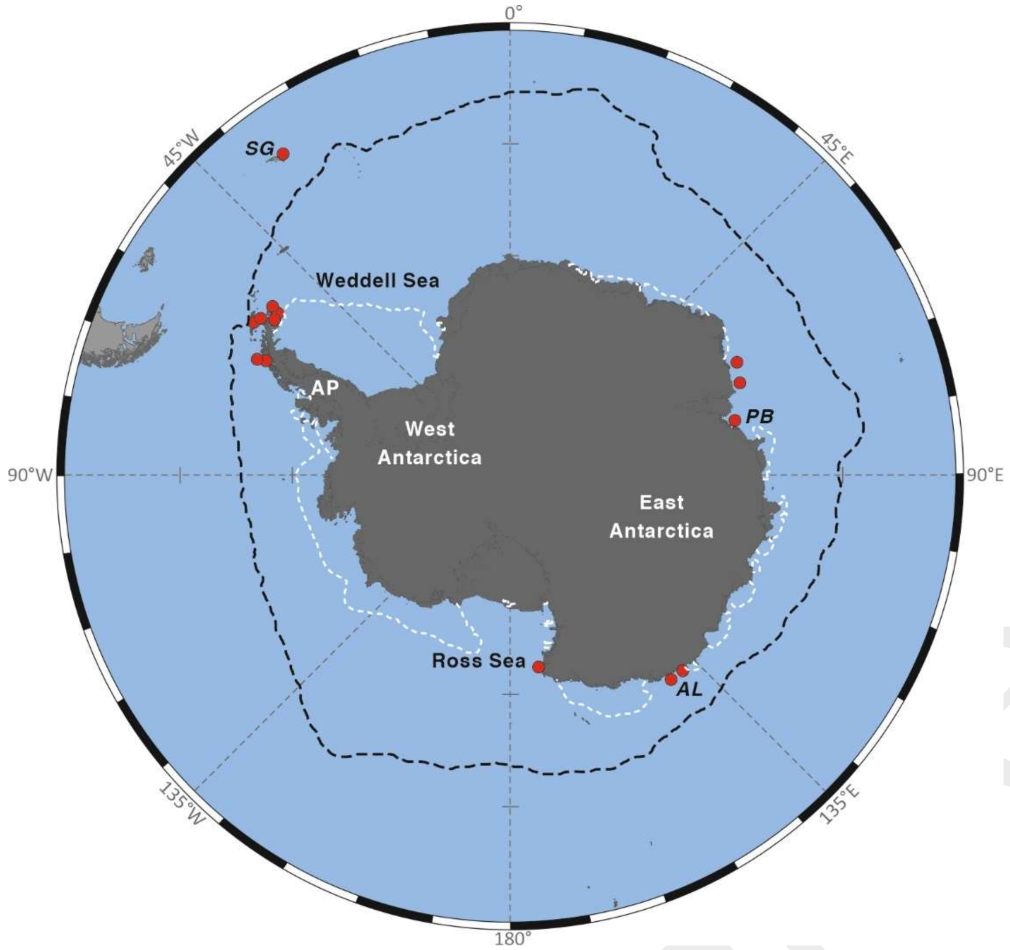

0°
45°W
45°E
90°W
90°E
135°W
135°E
180°
SG
Weddell Sea
AP
West
Antarctica
East
Antarctica
PB
Ross Sea
AL

Figure 11.

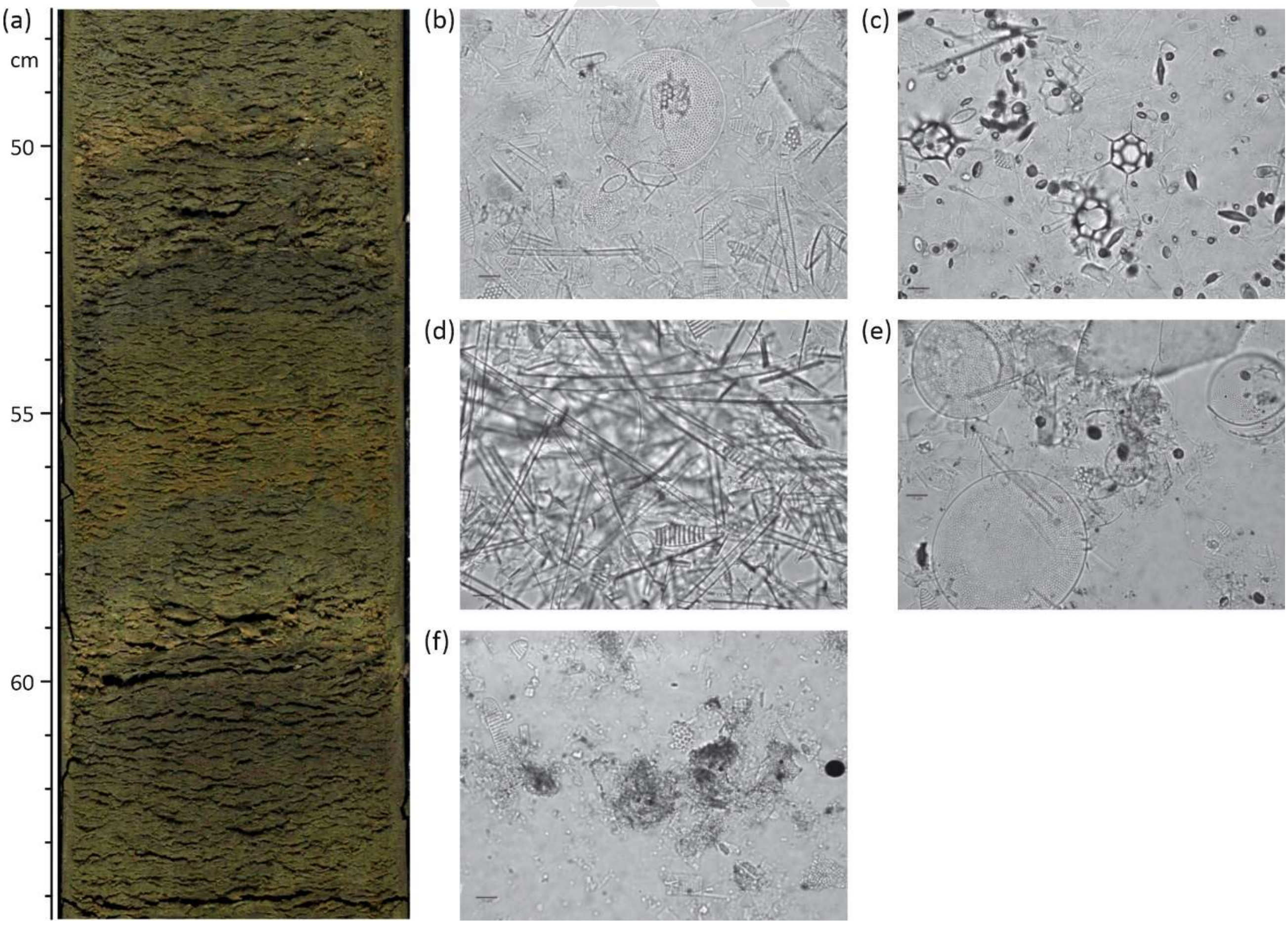

(a)
cm
50
55
60
(b)
(c)
(d)
(e)
(f)

Table 1.

Sea-ice diatoms (data from Table 1, Armand *et al*., 2005)	*Max. relative abundance (MRA) (%)*	*Feb. SST at MRA* (°C)	*Feb. SST range* (°C)	*Max. sea ice duration at MRA (months/yr)*	*Max. summer (Feb.) sea-ice concentration at MRA (%)*	*Max. winter (Sept.) sea-ice concentration at MRA (%)*
Actinocyclus actinochilus	2.9	0 to 1	−1.3 to 9	9	2	82
Chaetoceros resting spores	91.8	−0.5 to 1.5	−1.3 to 3.5	7	43	62
Fragilariopsis curta	64.6	0.5 to 1	−1.3 to 2.5	10	20	83
Fragilariopsis cylindrus	2.9	0.5 to 1	−1.3 to 3	8.5	0	87
Fragilariopsis obliquecostata	10.2	−1 to 0	−1.3 to 2	8.5	0	90
Fragilariopsis rhombica	3.8	0.5 to 1	−1.3 to 11.5	9	1	93
Fragilariopsis ritscheri	2.9	0 to 3	−1.3 to 7.5	0 or 9	0 or 28	0 or 72
Fragilariopsis separanda	6.9	−0.5 to 1.5	−1.3 to 1.8	8.5	0	90
Fragilariopsis sublinearis	6.1	0 to 1	−1.3 to 2.5	7.5	24	61
Porosira glacialis	6.4	0 to 0.5	−1.3 to 2	8	0	90
Porosira pseudodenticulata	2.2	0 to 0.5	−1.3 to 2	9.5	28	81
Stellarima microtrias	3.2	−0.5 to 0.5	−1.3 to 3.5	8.5	0	88
Thalassiosira antarctica group	31.8	0 to 0.5	−1.3 to 3.5	8.5	3	92
Thalassiosira tumida	2	−0.5 to 0.5	−1.3 to 7	8.5	0	90