Studying Paleoclimate of Southern Ocean using proxy: Diatom

A Dissertation for
GEO 651: Dissertation
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MSc in Applied Geology

by

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DECLARATION BY STUDENT

I hereby declare that the data presented in this Dissertation, "Studying Paleoclimate Of Southern Ocean Using Proxy: Diatom" is based on the results of investigations carried out by me in the MSc Applied Geology at the School of Earth, Ocean and Atmospheric Science, Goa University under the Supervision Dr. POOJA GHADI and the same has not been submitted elsewhere for the award of a degree or diploma by me. Further, I understand that Goa University or its authorities will be not be responsible for the correctness of observations / experimental or other findings given the dissertation.

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CONTENT

FIGURES & TABLE

ABBRIVATION USED

Entity	Abbreviation
Antarctic Circumpolar Current	ACC
Antarctic Medrional Overturning Circulation	AMOC
Antarctic Polar Front	APF
Carbon dioxide	CO_2
Casq	cq
East Wind Drift	EWD
Hydrochloric Acid	HCL
Hydrogen Peroxide	H_2O_2
International Hydrographic Organisation	IHO
Ice Rafted Debris	IRD
Kerguelen Island	KI
Modern Analogue Technique	MAT
Marion Dufresne	MD
Marine Isotopic Stage	MIS
Permanently Open Ocean Zone	POOZ
Polar Front	PF
Sub Antarctic Front	SAF
Sub Antarctic Zone	SAZ
Sea Ice Presence	SIP
Southern Ocean	SO
Southern Origin Bottom Water	SOBW
Sea Surface Temperature	SST
Sub-Tropical Zone	STZ
Winter Sea Ice	WSI
Weddell Sea Bottom Water	WSBW
Weddell Sea Deep Water	WSDW

ABSTRACT

Diatoms are unicellular eukaryotic algae whose cell walls are made up of silica and they form an essential component in the planktic food chain. With their high biological pump efficiency for carbon dioxide (CO_2) exchange, they serve as an important tool for interpreting paleoclimate and paleo oceanographic processes in pristine regions such as the Southern Ocean (SO). The current study focuses on a sediment core MD 12 3401 cq in order to gain a better understanding of climate change and the role of diatoms. The core is collected from latitude 44°40.73 South and longitude 80°23.58 East onboard Marion Dufresne. The study emphasizes on a part of a sediment core from 42 Kyr to 58 Kyr which is characterized by Marine Isotopic Stage 3 (MIS 3). Data shows *F. kergulensis* and *T. lentiginosa* are the most abundant species having relative abundance of 75% and 42 % respectively which dominates in the POOZ diatom group. Based on the diatom abundance sea surface temperature (SST) is quantitatively estimated using a Modern Analogue Technique (MAT) transfer function. The SSTs range between 2 to 10° C at the core site. The SSTs were warmest at the core site between 55 to 52 Kyr and 47.8 to 46 Kyr. However, cooler SSTs of 1°C to 2.5°C were also seen between 45.5 Kyr to 42 Kyr. As a result of which increase in Sea ice was seen at the core location. The warm SSTs between 55 to 52 Kyr and 47.8 to 46 Kyr can be related to the influence of warm surface water from the low latitudes at the core location coming from Kerguelen Island Region.

Key words: Diatoms, Southern Ocean, Marine Isotopic Stage 3, Sea Surface Temperature

CHAPTER 1: Introduction

1.1 **PALEOCLIMATE**

The study of climates without direct observations is known as paleoclimatology. Understanding natural variation and the evolution of the current climate requires reconstructing the historical climate, as observational records cover a very small portion of Earth's history. Paleoclimatology gathers data that was previously stored in rocks, sediments, boreholes, ice sheets, tree rings, corals, shells, and microfossils using a range of proxy techniques from the Earth and life sciences. These paleoclimate records are used in conjunction with proxy dating techniques to reconstruct the historical conditions of Earth's atmosphere. The 20th century saw the maturation of paleoclimatology as a scientific subject. The numerous glaciations the Earth has seen, abrupt cold episodes like the Younger Dryas, and the quick rate of warming during the Palaeocene–Eocene Thermal Maximum are notable eras that palaeoclimatologists study. Research on biodiversity and environmental changes in the past frequently shed light on the current state of affairs, particularly with regard to the influence of climate change on biotic recovery, mass extinctions, and contemporary global warming. A paleothermometer is a technique that uses a proxy from a natural record, such as a sediment, ice core, tree rings, or TEX_{86}, to estimate previous temperatures. Common Paleothermometers are δ18O, Mg/Ca and Sr/Ca, Alkenones, Nearest living relative analogy/coexistence analysis.

For reconstructing ancient climate palaeoclimatologist use a broad range of methods to infer past climates. The methods employed vary according on the characteristic that has to be recreated (temperature, precipitation, or another variable) and the time span during which the climate of interest happened. The majority of isotopic data, for example, comes from the deep marine record, which is only present on oceanic plates that are eventually subducted. The oldest material that is still present is 200 million years old. Furthermore, diagenesis-induced deterioration of older sediments is more common. Over time, resolution and data confidence decline.

1.1.1 PROXY

Physical, chemical, and biological components that have been preserved throughout geologic time (in paleoclimate archives) and may be compared and evaluated with modern-day environmental or climatic factors are known as paleoclimate proxies. In order to extend our knowledge of climate variability to periods when humans started measuring these things, scientists integrate instrumental records (such as thermometer and rain gauge measurements) with proxy-based paleoclimate reconstructions. These historical climatic and environmental reconstructions cover all periods, from yearly fluctuations to those that have place over millions of years. These data aid in our comprehension of the variations in the Earth's climate system before and after land use by humans.

Paleoclimatology uses mountain glaciers and the polar ice caps/ice sheets for a wealth of data. Data from ice-coring studies in the Antarctic and Greenland ice caps date back several hundred thousand years—more than 800,000 years, in the case of the European Project for Ice Coring in Antarctica (EPICA) study. As the snow in the glacier is compacted into ice by the weight of subsequent years' snowfall, air trapped within the accumulated snow forms small bubbles. Since the ice was first formed, the trapped air has proven to be an incredibly useful source for direct measurements of the air's composition. Seasonal breaks in ice accumulation allow for the observation of layering, which can be utilized to create chronology by connecting particular core depths to intervals of time. Variations in the layering thickness can be utilized to ascertain variations in temperature or precipitation. Variations in the quantity of oxygen-18 ($\delta 18O$) in ice layers correspond to variations in the mean surface temperature of the ocean. When compared to water molecules with the typical Oxygen-16 isotope, water molecules containing the heavier ^{18}O evaporate at a greater temperature. As the temperature rises, the ratio of ^{18}O to ^{16}O will increase. It also depends on other elements including the salinity of the water and the amount of water trapped in ice sheets.

There have been shown to be several cycles in those isotope ratios. Plant species present during the formation of the layer can be inferred from pollen observations made in ice cores. Pollen is abundantly generated, and most people are aware of where it is distributed. By counting all of the pollen classified by type (shape) in a carefully chosen sample of a certain layer, one can determine the overall amount of pollen for that layer. Pollen counts in the core can be statistically analysed to illustrate changes in plant frequency over time. Understanding the types of plants that were present can help one understand the temperature, precipitation patterns, and fauna that were present.

For these reasons, the study of pollen is included in palenology. Certain layers include volcanic ash, which can be used to determine when the layer formed. Ash has distinct characteristics that vary depending on the volcanic event (particle shape, colour, and chemical signature). The range of time to associate with the layer of ice will be established by determining the source of the ash. The European Project for Ice Coring in Antarctica (EPICA), a multinational team, has retrieved ice from about 800,000 years ago by drilling an ice core in Dome C on the East Antarctic ice sheet. Under the direction of International Partnerships in Ice Core Sciences (IPICS), the global ice core community has established a priority effort to retrieve the oldest Antarctic ice core record conceivable—one that dates back to or near 1.5 million years ago. Knowing how a proxy relates to a particular feature of climate is necessary in order to utilize it to reconstruct historical climate. Certain atmospheric gases, like carbon dioxide and methane, that are trapped in glacial ice, for instance, can be used

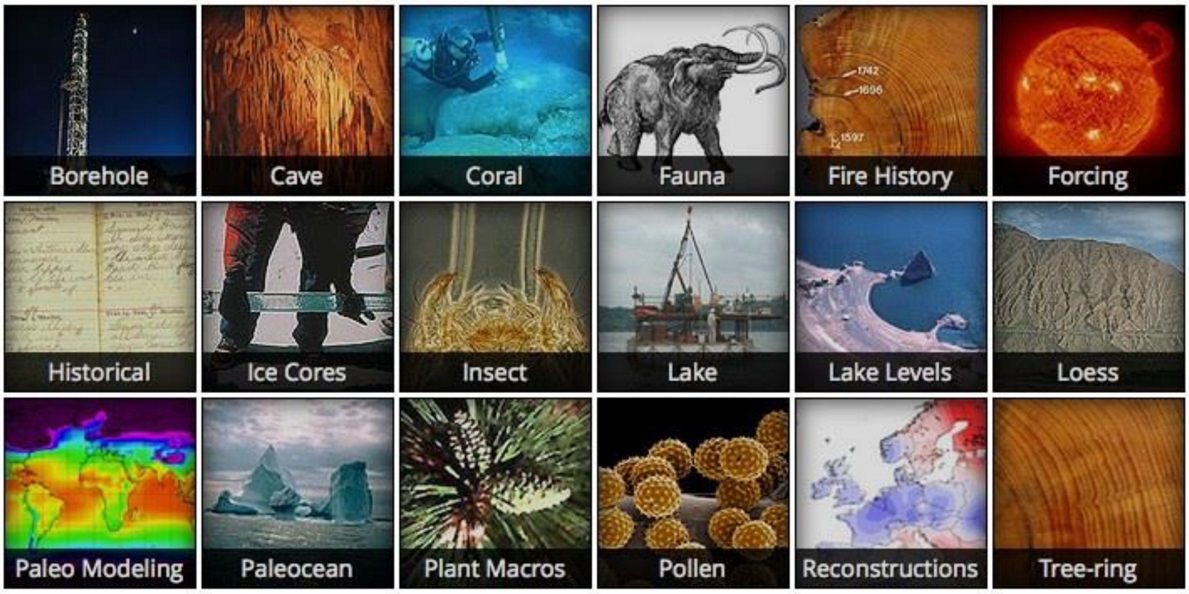

Fig 1.1 Different types of Proxies

as proxies to assess the atmospheric chemistry at the time the ice formed and sealed off from the environment. Some proxies are less direct, including measurements of stable isotopes (like carbon and oxygen) from marine species' shells. To determine the relationship between climate processes and these indirect proxies, calibration experiments in the current system are necessary.

1.2 SOUTHERN OCEAN

Southern Ocean, also known as the Antarctic Ocean comprises the southernmost waters of the world ocean, generally taken to be south of 60° S latitude and encircling Antarctica. With a size of 20,327,000 km2 (7,848,000 sq. mi), it is regarded as the second-smallest of the five principal oceanic divisions: smaller than the Pacific, Atlantic, and Indian oceans but larger than the Arctic Ocean. Early in February 2019, the Five Deeps Expedition conducted a survey to determine the maximum depth of the Southern Ocean, considering the definition that places it south of the 60th parallel.

The deepest point of the trip, at a depth of 7,434 meters (24,390 feet), was located at 60° 28' 46"S, 025° 32' 32"W, according to the multibeam sonar team.

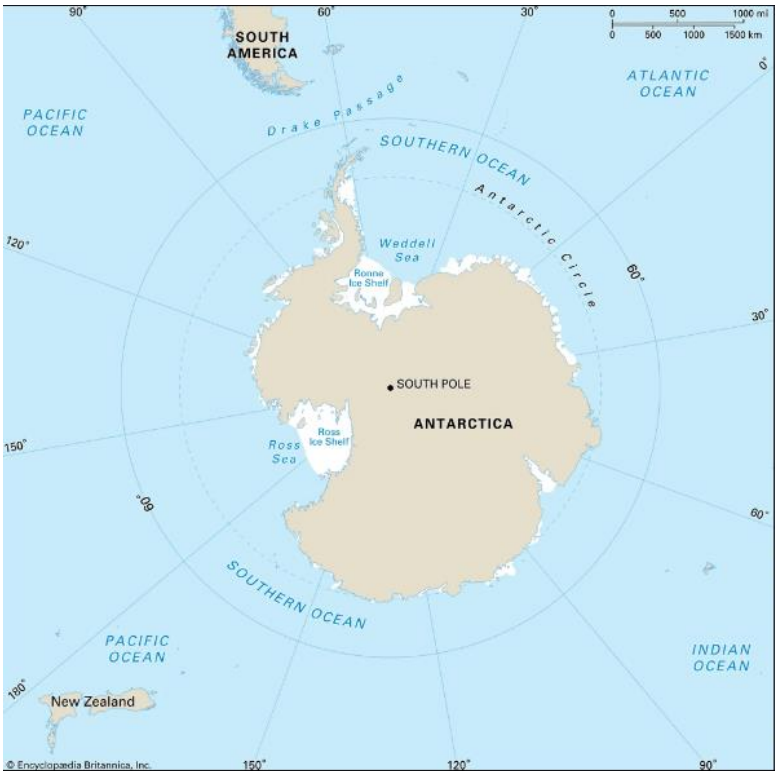

Fig 1.2 Map showing Southern Ocean

This deepest point in the Southern Ocean has been proposed to be called the "Factorion Deep" by expedition leader and chief submersible pilot Victor Vescovo. This idea is based on the name of the crewed submersible DSV Limiting Factor, which visited the bottom for the first time on February 3, 2019. James Cook demonstrated that the world's oceans extended to the southern latitudes during his explorations throughout the 1770s. However, there has been much debate among geographers regarding the definition of the Southern Ocean. Some argue that it should be defined as the body of water bounded by the seasonally varying Antarctic Convergence, an oceanic zone where cold, northward flowing Antarctic waters mix with warmer Subantarctic waters; others disagree, treating its waters as the southern limits of the Pacific, Atlantic, and Indian oceans. Once the significance of the Southern Ocean overturning circulation was fully established, the International Hydrographic Organization (IHO) arbitrated the dispute. As a result, the body of water south of the northern boundary of that circulation is now referred to as the Southern Ocean. The far more well-known Atlantic meridional overturning circulation (AMOC) makes up the other half of the global thermohaline circulation, which is why the Southern Ocean overturning circulation is significant. Similar to AMOC, it has also been significantly impacted by climate change, which has led to a rise in ocean stratification. This may potentially cause the circulation to significantly slow down or possibly beyond a tipping point and collapse completely. The latter would develop over centuries and have detrimental effects on both the global weather system and the health of marine organisms in the Southern Ocean. Furthermore, the Southern Ocean's marine habitats are already shifting as a result of the continuous warming.

It partially regulates the distribution of Carbon dioxide (CO_2)between the ocean and atmosphere in addition to exchanging water with other seas. Wind-driven upwelling brings deep ocean waters with high CO_2 and nutrient content to the surface in the contemporary Southern Ocean. On the other hand, phytoplankton development is inhibited by iron shortage (Martin *et al*., 1990; Boyd *et al*., 2000) and Primary macronutrients are reabsorbed into the subsurface prior to their complete consumption. Because of this inadequate nutrient use, deeply stored pCO_2 can leak back into the environment, which raises atmospheric pCO_2 levels (Sigman *et al*., 2010). The Antarctic Circumpolar Current (ACC) is Southern Ocean’s principal oceanographic feature, is the sole global current in the globe. In the winter, around 50% of the Southern Ocean is covered with ice, while in the summer, just 10%. The biota and the climate are both significantly impacted by ice cover (Ainley et al., 2003). So therefore ACC is an essential component of arctic habitats. Algae, crustaceans, worms, prokaryotes, protists (Schnack-Schiel et al., 1998) fish eggs and larvae (Vacchi et al., 2012), birds and seals (Ainley and DeMaster, 1990) live in Antarctic sea ice.

1.2.1 ANTARCTIC CIRCUMPOLAR CURRENT (ACC)

Antarctic Circumpolar Current flows eastward around Antarctica in a closed cycle, unhindered by continents. Since the ACC reduces meridional heat transmission across the Southern Ocean, it is thought to be the primary driver of the formation of Antarctic continental glaciers. The ACC is now the greatest ocean current and the primary method of water exchange between oceans (Kennett, 1977; Barker et al., 2007). The distribution of plankton and the warming of the Southern Ocean are both greatly influenced by the creation of eddies in the Antarctic Circumpolar Current. The Antarctic Coastal Current, also known as East Wind Drift (EWD), flows westward and is driven by wind, just as the ACC. A network of gyres and retroflection's such as those in the Prydz Bay region, the Weddell Sea, and the Bellingshausen Sea—connects these two current systems.

The formation of circumpolar frontal zones linked to this current system is mostly determined by the circumpolarity of the circulation (Orsi et al., 1995). Practically speaking, these fronts' biogeographical significance was understood from the outset of Antarctic exploration (Tate Regan, 1914). The Southern Ocean's northern boundary is commonly understood to be the ACC. The waters transported by the ACC are a mixture of waters of varied global origins since it connects the ocean basins of the Atlantic, Indian, and Pacific oceans. Water moves away from the ACC , both north and south, where it forms the main source of Antarctic Bottom Water. The three oceans in the ACC exchange nutrients, heat, and salt, which is crucial for controlling the global conveyor belt's flow and temperature. The water cools as it travels through the ACC, exchanging carbon dioxide and oxygen with the atmosphere; the resulting thick water sinks and sends heat and gasses into the deep ocean. The water masses in all of the world's seas have various characteristics because of these exchanges, which also produce water masses with distinct distribution patterns.(Turner et al. 2009)

When Antarctica and South America separated, the current features of the region were formed, enabling the ACC to pass through without hindrance (Barker et al., 2007; Turner et al. (eds.), 2009) and the way the Polar Front developed. Although the exact timing of the opening is unknown, it is generally agreed that it happened around the Eocene/Oligocene boundary approximately 34 million years ago (Barker et al., 2007). Since then, the seas south of the Polar Front have been separated from other Southern Hemisphere shelf regions and have been a part of a single system that includes the basins of the Atlantic, Indian, and Pacific seas. Warm water conditions gradually gave way to the current cold-water system in the Antarctic marine environment (from 15◦C to 1.87◦C) (Turner et al. (eds.), 2009). Under these circumstances, evolution gave rise to a highly specialized marine biota with a high degree of Antarctic endemism and a low tolerance for warming (Bilyk and DeVries, 2011).

1.2.2 FRONTS

The fronts are often boundaries of water masses; the underlying Polar Front (PF), which is the source of Antarctic surface water's initial definition and identity, is located where it sinks (Deacon, 1933). Mesoscale eddies and rings that contain them are frequent, especially downstream of topography (e.g., Legeckis, 1977; Gouretski and Danilov, 1994). The fronts meander when there is no restricting seabed topography (e.g., Moore et al., 1999). The fronts' surface expression is often a sharp drop in temperature that moves southward, although in certain locations, especially for the PF, this shallow expression is displaced from the boundary at a depth and moves south across the Kerguelen Plateau close to 70°E. The distinct effects of the fronts on sea-surface height can generally be separated, though in some locations they may combine (Gille, 1994). It is unclear what factors led to the fronts' formation and preservation. While Gille (1994) estimated that 40–70% of ACC transport happened between the PF and SAF, it appears possible that a far larger percentage might be transferred within frontal zones if (Orsi et al.1995) southern ACC front also has transportation from the west to the east.

A discontinuous, wind-driven current that flows westward near the continent and south of the ACC makes up the other major component of the Southern Ocean circulation (Deacon, 1937). Where feasible, this current evolves into clockwise gyres like the Weddell Gyre. A number of ice-related processes, including increased salinity of surface waters due to sea-ice formation and super-cooling via contact, contribute to the production of dense, cold, and salty bottom water in the southern Weddell Sea, which enhances the Weddell Gyre. (e.g., Brennecke, 1921; Foster and Middleton, 1980; Foldvik and Gammelsrod, 1988) with the icy bottom of a floating ice shelf. It is likely that one or both of these processes have altered the water mass ever since the Antarctic glaciers began to recede.

1.2.3 WATER MASSES

Weddell Sea Deep Water (WSDW), which is produced today and lies on top of Weddell Sea Bottom Water (WSBW), which is somewhat warmer and less dense due to mixing. Weddell Sea Deep Water (WSDW) and Weddell Sea Bottom Water (WSBW), which are the names given to the extremely dense bottom water produced today. However, we use the term Southern-Origin Bottom Water (SOBW) in recognition that bottom-water production in the past may not have involved both processes of modification.

WSDW travels northward across the western South Atlantic and beneath the ACC in the eastern Scotia Sea and South Sandwich Trench (e.g., Mantyla and Reid, 1983), mixing along the way with overlaying water masses; SOBW has most likely acted similarly in the past. With the exception of western limits, the flow of northward WSDW transport is continuous and gradual, with a magnitude of less than 5 Sv. Underneath the Antarctic Continental Shelf, similar northward bottom currents flow into the Indian Ocean and SW Pacific. At other places on the Antarctic continental shelf, a smaller water mass modification occurs that is comparable to the creation of WSBW. According to Barker and Burrell (1982), Gamboa et al. (1983), and Barker (1992), the construction of the ACC produced an oceanographic "barrier" that either significantly altered or decreased the northward movement of SOBW. The deep-sea sediments beneath today's WSBW are typically completely barren as even the siliceous bio facies dissolve in it. However, the cool water masses created by mixing further north support the benthic foraminifera, which are utilized in oxygen isotopic studies to look at palaeotemperature and ice volume. Numerous helpful insights have been gained from the modelling. Notably, it has demonstrated that the development of the ACC has most likely had the significant effect of reducing the meridional transport of water and heat, particularly southward surface water. This has resulted in a cooling of water at higher southern latitudes, with temperatures dropping as much as 3 °C (Toggweiler and Bjornsson, 1999; about 1.5 °C—Nong et al., 2000). This suggests that ACC growth plays a part in the beginning or stabilization of Antarctic glacial.

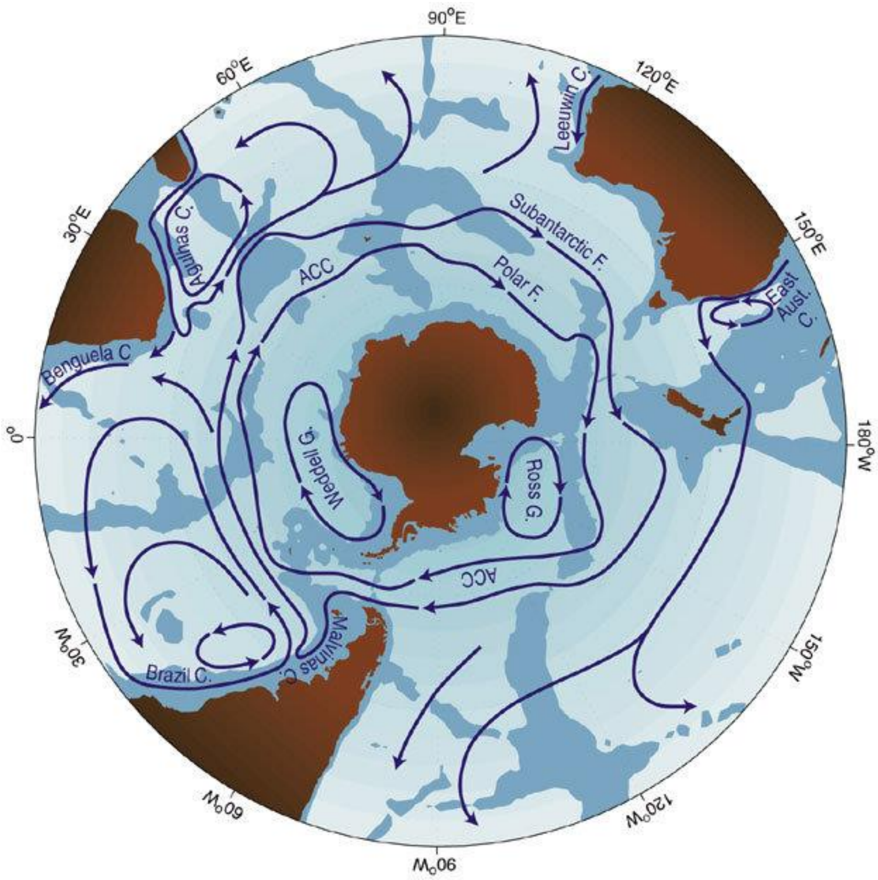

Fig 1.3 :- The Antarctic Circumpolar Current (ACC) is an ocean current that flows clockwise from west to east around Antarctica. It connects the Atlantic, Pacific and Indian Ocean basins, and serves as a principal pathway of exchange between these basins (Alberta, 2004)

1.3 **DIATOMS**

Diatoms are unicellular organisms in which the cell is encapsulated in an amorphous silica box, called the frustule, composed of two intricate valves. Even though they occasionally form colonial aggregations and pseudo filamentous aggregations, diatoms are primarily unicellular creatures. The cell wall is made of silica ($Si0_2$) with an organic covering, with varying degrees of silicification. Cell walls' resistance has proven to be an essential tool for reconstructing the fossil record. Studies of past oceanic circulation and global climatic changes have benefited greatly from the biostratigraphy of fossil diatoms in high latitude waters (Gersonde, 1990). For almost two centuries, the classification of diatoms was based on the structure and ornamentation of the cell walls. The siliceous walls are differently decorated with perforations, ribs, spines, or minute processes (Fryxell & Hasle, 1972a).

Diatoms come in a wide variety of forms and sizes, ranging from 2 to 200 μm. Diatoms are photosynthetic organisms possessing yellow–brown chloroplasts with pigments including chlorophyll a and c, β-carotene, fucoxanthin, diatoxanthin, and diadinoxanthin (Jeffrey, Mantoura, & Wight, 1997). Diatoms can exist in low light environments, such as sea ice, which blocks the majority of solar energy, and can capture a wide variety of wavelengths thanks to their diverse collection of pigments. Chrysolaminarin and oils are the main reserve chemicals in diatoms, which are uninucleate. Only male cells are known to have flagellated cells. Pennate diatoms with raphes may exhibit gliding mobility. Diatoms can make vegetative resting spores and can reproduce vegetatively through binary fission. In general, diatoms divide through vegetative fission 0.1–8 times every day. When the preservation process permits it, this vegetative reproduction enables diatoms to produce a very high biomass, which is the source of diatomite. In the parent diatom's vegetative reproduction, two new hypovalves are formed. Diatom frustule, which gradually shrinks the population's average frustule size. Additionally, they are capable of sexual reproduction, producing gametes, auxospores, and Vegetative cells "typically" form (Hasle & Syvertsen, 1997). The resting spore is another unusual reproductive stage found in some organisms. The diatom may live thanks to the spore, which is generated when unfavourable conditions (such as low light levels and nutrient levels) arise.

Diatoms are of two types: Pennate Shape Diatom & Centric Shape Diatom. Pennate diatoms are divided into two suborders based on the presence or absence of the raphe, which is visible as an elongated fissure or pair of fissures through the valve wall, Centric diatoms are divided into three suborders based on the presence or absence of the marginal ring of processes and the polarity of the symmetry (Anonymous,1975). The level of diversity is unusually great, with 10,000–12,000 recognized species (Norton et al., 1996) and about 285 genera as of 1990 (Round et al., 1990). The 196 diatom species and infraspecific taxa from Antarctic seas and the Southern Ocean are described (115 centric and 81 pennate).

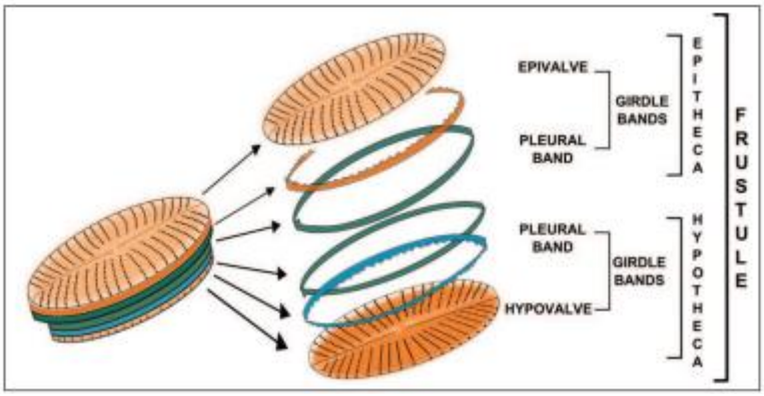

Fig 1.4: Structure of a diatom frustule.

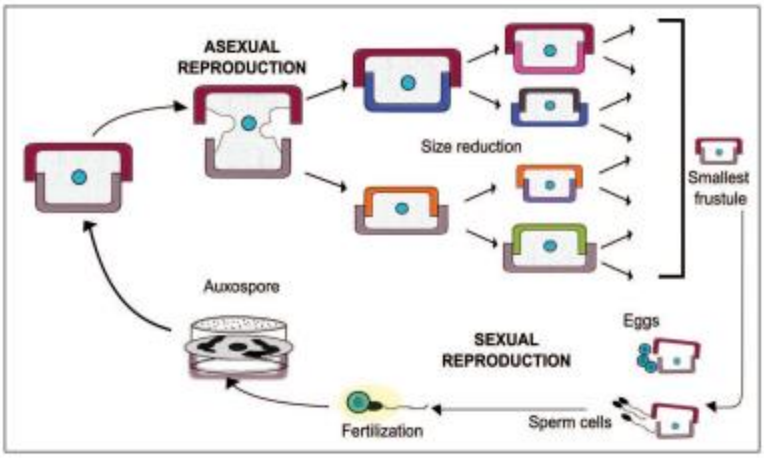

Fig 1.5: Schematic reprepsentation of lifecycle of diatoms with asexual and sexual reproduction

1.4 OBJECTIVES

- To understand Diatom distribution/assemblages in a sediment core
- Quantitative analysis of diatom (To know the Relative & Absolute Abundance over a relative timescale)
- To Understand Past environmental condition

CHAPTER 2: Literature Review

2 LITERATURE REVIEW

The research article on Southern Ocean by Maurizio AZZARO et al.,2016 discusses the Southern Ocean and its main oceanographic feature, the Antarctic Circumpolar Current (ACC), which is the world's only global current flowing eastwards around Antarctica in a closed circulation. The ACC plays a crucial role in the distribution of plankton and observed warming in the Southern Ocean. The formation of eddies in the ACC also significantly impacts the distribution of plankton and warming observed in the Southern Ocean. This paper discusses about various concepts that includes: The Westward-flowing Antarctic Coastal Current here the paper highlights the westward-flowing Antarctic Coastal Current, or East Wind Drift (EWD), which are wind-driven current systems connected by a series of gyres and retroflection. The circumpolarity of the circulation determines the development of circumpolar frontal zones associated with this system of currents. These fronts are recognized as biogeographically important, with polar, subantarctic, and subtropical fronts being the major fronts of the Antarctic Circumpolar Current. The Antarctic sea ice cover, which covers about 50% of the Southern Ocean in winter, has important effects both on climate and on the biota. It provides habitat for a wide variety of organisms including prokaryotes, protists, algae, crustacea, fish eggs, larvae, birds, and seals. The paper also discusses the trends in Antarctic sea-ice cover, indicating an increase in ice cover from 1978 to 2010 but predicts a reduction of 33% by the end of this century. The paper also provides an overview of primary productivity in the Southern Ocean. Research on Antarctic primary productivity, which started around 1840, has evolved over the years with the development and application of new methods to estimate primary productivity. The primary productivity in the Antarctic continental shelf regions ranges from 10 g C m^{-2} to 200 g C m^{-2}, with elevated productivity found in nearly all coastal polynyas. The analysis also includes satellite-based measurements of chlorophyll concentrations in the Southern Ocean, revealing low-mean values, phytoplankton blooms, and highest chlorophyll concentrations located in coastal waters above the continental shelf, the seasonally retreating sea ice, and the vicinity of the major fronts. This paper also talks about the implications of overexploitation in the Southern Ocean, including sealing, whaling, and fishing activities. The reduction of large predators, such as seals and whales, has resulted in a complex ecosystem, affecting species at mid-levels of the food web, including fish and squid. Additionally, the reduction of whaling brought about increased harvesting of fish, leading to rapid reductions in fish stocks, which led to the implementation of the moratorium on bottom fishing for notothenioid. To conclude with this paper it overall provides a comprehensive overview of the Southern Ocean, the ACC, plankton distribution, observed warming, sea ice cover, primary productivity, and the implications of overexploitation activities, shedding light on the complex ecosystem and the challenges it faces. Speaking about Impact of Climate Change The paper discusses the Southern Ocean and the role of the ACC in the distribution of plankton and observed warming in the region. It begins by highlighting the impact of climate change on the Antarctic marine ecosystem, with particular focus on the Southern Ocean, the Antarctic Peninsula, and the ACC. In order to understand more about Fronts we look into M. Civel-Mazens 2020 article focuses on the Antarctic Polar Front migrations in the Kerguelen Plateau region in the Southern Ocean over the past 360,000 years. The Antarctic Polar Front is crucial for nutrient redistribution and biodiversity in the Southern Ocean. The study combines new proxies for subsurface temperature reconstructions and sea-surface temperature reconstructions to refine estimations of the past mean Antarctic Polar Front locations in the Kerguelen Plateau region. Data from sediment cores are used to trace the mean Antarctic Polar Front locations for different climate states, including glacial, peak-interglacial, and mild-interglacial. The study combined a new proxy for subsurface temperature reconstructions based on radiolarian assemblages (sub-ST) with sea-surface temperature reconstructions based on diatom assemblages to refine estimations of the past mean APF locations. Data from sediment cores on a south to north transect were used to trace the mean APF locations for different climate states, including glacial, peak-interglacial, and mild-interglacial. High-resolution temperature records of oceanic sub-surface temperature and sea-surface temperature were generated for the western part of the Kerguelen Plateau, covering the last 360,000 and 150,000 years, respectively. The study suggests that the Antarctic Polar Front (APF) shifted by 6-7 degrees of latitude north of the Kerguelen Plateau during glacial periods in the last 360,000 years. During warmer interglacial periods, the Antarctic Polar Front likely migrated south by ~5 degrees of latitude relative to its modern position, passing through the Fawn Trough. The Antarctic Polar Front migrations and associated changes in the interaction of the Antarctic Circumpolar Current flow with the bathymetric high had important implications for water column structure and regional productivity in the Kerguelen Plateau region. The Antarctic Polar Front shifts affected the water column structure, leading to changes in the interaction of the Antarctic Circumpolar Current flow with the bathymetric high, influencing regional productivity. During glacial periods, the Antarctic Polar Front northward migration resulted in less mixing of the water column over and in the lee of the Kerguelen Plateau, potentially isolating Antarctic surface waters and reducing macro-nutrient supply. In contrast, during warmer interglacial periods, the Antarctic Polar Front southward migration led to a stronger interaction between the ACC, its associated fronts, and topography, resulting in more mixing of the water column over and east of the Kerguelen Plateau.

In the Paper of P.F. Barker et al.,2003 he talks about on Antarctic sea-ice extent and oceanic frontal systems are of primary importance to the marine biota since their marked meridional gradients in physical and chemical properties strongly regulate the phytoplankton contribution to primary productivity. Antarctic sea ice extent along with the Southern Ocean biological productivity varied considerably during glacial-interglacial periods, and both are known to have played a considerable role in regulating atmospheric CO_2 variations in the past. In the present review paper, we seek to understand the past latitudinal variability of the Southern Ocean frontal systems and Antarctic sea-ice extent based on a multi-proxy approach. The first aspect of this paper concentrates on the diatom-based reconstructions of paleo sea-ice and hydrographic changes in the Southern Ocean and its impact on diatom sizes and productivity. Secondly, emphasis would be placed on the studies based on the morphology and isotopic composition of foraminifera and its palaeoceanographic implication. The foraminifera shell preserved in the sediments provide unparalleled archives of morphological change, faunal variations, and habitat characteristics as a result of hydrographic changes. To sum up, the advantage of a multiproxy approach including the magnetic, geochemical and sedimentological parameters have been discussed in understanding the Southern Ocean paleoclimate. So in order to study paleoclimate we go into Southern ocean which is the few pristine area in the world are lesser affected my humans.

In Abhilash Nair 2016 he mentioned about the Southern Ocean which plays crucial part of the climate system, as it exchanges water with other oceans and controls CO_2 partitioning between the ocean and the atmosphere. In the modern Southern Ocean, deep ocean waters with high CO_2 and nutrient content are brought to the surface by wind-driven upwelling. However, the scarcity of iron reduces phytoplankton growth, and major macro nutrients are returned to the sub-surface before they are fully consumed, contributing to raising atmospheric pCO_2 levels.

The CO_2 "leak" occurs mainly in the polar Antarctic zone compared to the Subantarctic zone. Data and models reveal that a combination of biological and physical processes contributed to lowering atmospheric CO_2 during glacial times. Most of the Southern Ocean is a high-nutrient, low-chlorophyll area, with exceptions downstream of some islands. Indian researchers have made several attempts to understand this phenomenon, with recent advances in Southern Ocean palaeoceanography taking us closer to understanding past climate variability at the millennial and glacial-interglacial timescale. This paper discusses the use of various proxies in Southern Ocean palaeoceanography studies, including microfossils, magnets, sedimentological, and geochemical, and highlights the need for a comprehensive perspective on past ocean climatic conditions. Diatoms, unicellular algae with a siliceous skeleton called frustules, contribute over 70% of the primary production in the Southern Ocean and play a major role in global silica and carbon cycling. Diatom cell walls are composed of hydrated silica and are well preserved in sediments. Studies have shown that the spatial distribution of diatoms in surface sediments is well correlated with frontal changes and related nutrient availability in the water column. Larger and heavily silicified diatoms may have effectively contributed to transporting biogenic silica and organic carbon to the sea bed during the last 42 ka BP.

Palaeoceanography is closely linked to the study of planktic foraminifera, which have the highest rate of production and excellent preservation of shells in deep sea sediments. The isotopic composition of foraminifera has been used extensively to infer paleoclimatic and palaeoceanographic variations. Magnetic parameters, along with other paleoenvironmental proxies like ice rafted debris (IRD), calcium carbonate content, and oxygen isotope records, are useful palaeoceanographic indicators in marine sedimentary records.

Speaking about Diatom as proxy and why it is important paper of Tregoe et al.,2022 comes into picture where he briefly mentions about Diatoms which thrive in nutrient-rich surface layers and turbulent conditions, commonly found at high latitudes and in coastal upwelling regions. Large-scale patterns show diatoms are significant in phytoplankton biomass at high latitudes during specific seasons and in equatorial and coastal upwelling regions. Ocean physics, nutrient availability, and interactions with predators, pathogens, and symbionts influence diatom distribution. Molecular biology techniques reveal diatoms may be more relevant in oligotrophic systems than previously thought. Diatoms exhibit diverse traits impacting their fate in the water column and carbon export rates. Diatoms sustain the marine food web and contribute to the export of carbon from the surface ocean to depth. They account for about 40% of marine primary productivity and particulate carbon exported to depth as part of the biological pump. Diatoms have long been known to be abundant in turbulent, nutrient-rich waters, but observations and simulations indicate that they are dominant also in meso- and sub mesoscale structures such as fronts and filaments, and in the deep chlorophyll maximum. In particular, their silica shells provide ballast to marine snow and faecal pellets, and can help transport carbon to both the mesopelagic layer and deep ocean. To conclude with this paper he tells that Diatoms can outcompete other phytoplankton groups, showing strong heterogeneity in distribution at small spatial scales. The distribution of diatoms is tightly coupled with ocean physics, nutrient availability, and interactions with predators, pathogens, and symbionts. Molecular biology techniques reveal diatoms may be more relevant in oligotrophic systems than previously thought. Diatoms play a crucial role in the biological carbon pump by transferring organic carbon to the mesopelagic and CO2 sequestration layers. Their diverse traits directly impact their potential for exporting organic carbon to depth. Diatoms dominate during spring blooms due to their high growth rates and independence from grazers and viruses. Molecular biology techniques reveal diatoms may be more relevant in oligotrophic systems than previously thought.

The paper of Dixit 2005 discusses diatoms as powerful indicators of environmental change. Diatoms are powerful environmental indicators due to their sensitivity to environmental changes, making them valuable tools for assessing water quality and ecological health. Diatoms are sensitive indicators due to their rapid response to environmental changes, reflecting alterations in water quality and ecological conditions. Diatoms reflect environmental changes, serving as powerful indicators of water quality and ecological health.

Now in order to better understand about different diatom species we go into Gersonde et al., 2000 where their paper focuses on reconstructing late Quaternary Antarctic sea-ice distribution using diatoms as a proxy for sea-ice extent**.** Various attempts have been made to reconstruct past sea-ice extents in the Southern Ocean, emphasizing the crucial role of sea-ice in feedback mechanisms and Earth's climate system. The study establishes a proxy for past sea-ice distribution based on diatom records, indicating significant sea-ice variations during specific Marine Isotope Stages in the Antarctic Zone of the Southern Ocean. The distribution of sea-ice indicators like *Fragilariopsis curta* and *Fragilariopsis cylindrus* in surface sediments is closely linked to Antarctic sea-ice distribution, with specific concentrations observed in different regions of the Southern Ocean. *Fragilariopsis curta,* along with *Fragilariopsis cylindrus*, serves as an indicator of sea-ice extent in the Southern Ocean, with specific concentrations observed in different regions, reflecting past variations in sea-ice coverage. High relative amounts of *Fragilariopsis curta* are encountered during periods when the mooring location is covered by sea-ice or when the sea-ice edge straddles the location, showing a close relation to the occurrence of sea-ice. The calculated flux rates of *Fragilariopsis curta* are regionally variable, showing a significant association with the presence of sea-ice over time intervals, rather than just annual sea-ice coverage. Methods used in study includes Diatoms *Fragilariopsis curta* and *Fragilariopsis cylindrus* were utilized as proxies for past variations in sea-ice extent in the Southern Ocean. The study involved the mapping of diatom assemblages from surface sediments and the analysis of sediment cores to define the sea-ice proxy for late Quaternary Antarctic sea-ice distribution. Time-series sediment traps were deployed in different environmental regimes of the Southern Ocean to study annual diatom transfer from the surface to the sea floor, aiding in the establishment of the sea-ice proxy.

Now to better understand about Antarctic sea ice & its importance along with different diatom groups we look into Ghadi et al., 2020 paper where author tells us that Antarctic sea ice is crucial for global climate, impacting ocean circulation, biological productivity, and CO_2 partitioning. However, little is known about its past history, particularly in the southwestern Indian sector of the Southern Ocean. New quantitative records of winter sea-ice concentration, sea-surface temperatures, and productivity in sediment core SK 200/33 from the Permanently Open Ocean Zone over the last 156,000 years reveal that hydrological structures migrated northward during all glacial periods, with the Southern Antarctic Circumpolar Current Front reaching the core site, the Antarctic Polar Front at ~46°S, and the winter sea ice (WSI) likely extending to ~49°S. Hydrological fronts and WSI edge migrated poleward during the early Holocene and last interglacial. The Atlantic sector showed higher amplitude variations in WSI over the last glacial-interglacial cycle, possibly due to the presence of the Weddell Gyre transporting sea ice from the Weddell Sea. Methods used in this paper are Diatom assemblages were analysed to infer past oceanographic conditions such as sea-surface temperature and winter sea-ice concentration and duration .Quantitative estimates of sea-surface temperature and winter sea-ice parameters were provided using the Modern Analogue Technique. Biogenic silica was extracted from sediment samples using specific procedures for opal-rich sediments. To conclude results got were Down-core variations in diatom assemblages showed fluctuations in sea-ice diatom group, water stratification group, POOZ diatom group, and SAZ diatom group over the last 156,000 years. The highest occurrences of the sea-ice diatom group were observed during glacial stages, while the POOZ group dominated the diatom assemblages throughout the core's history. Total diatom abundance was highest during interglacial periods and deglaciations, with lower values observed during glacial periods. The core site is located in the Permanently Open Ocean Zone, bound by the Antarctic Polar Front and Southern ACC Front, providing insights into past sea-ice conditions and oceanographic changes.

In order to understand about warm temperature we look into M. Civel-Mazens et al., 2021 Wherein he tells that the oceanography of the western Indian sector of the Southern Ocean is complex due to the presence of subantarctic islands and plateaus altering the zonal flow of the Antarctic Circumpolar Current. The Agulhas Return

Current plays a crucial role in transporting warm surface waters from low latitudes to the Subantarctic Zone east of the Kerguelen Islands.

Western boundary currents like the Agulhas Current are vital for redistributing equatorial heat excess to mid- and high latitudes, influencing the Earth's climate system. This study focuses on reconstructing past oceanographic changes in the Kerguelen Plateau region over the last 40,000 years using sea-surface and sub-surface temperature data based on diatom and radiolarian census counts. Methodology in the study involves species identification was based on taxonomic concepts used in previously published studies, assigning specimens to over 190 taxa. Radiolarian census data from two cores were used to reconstruct sub-surface temperatures, with samples prepared and identified using specific laboratory protocols. Diatom and radiolarian census counts were utilized to infer past oceanographic changes in the Kerguelen Plateau region over the last 40,000 years. The Modern Analog Technique was applied to fossil diatom assemblages to reconstruct past summer sea surface temperatures. And results got were Sea-surface and sub-surface temperatures in the Kerguelen Plateau region over the last 40,000 years showed expected glacial-interglacial patterns, with significant temperature differences between surface and sub-surface waters during specific periods. The injection of warm surface waters from Indian low latitudes, transported by a strengthened Agulhas Return Current during the glacial period, influenced the temperature differences observed in the region. The study suggests that the surface conditions in the Subantarctic Zone of the Kerguelen Islands are shaped by the interplay between Southern Ocean hydrological fronts and the Agulhas Return Current, both influenced by climate variations.

CHAPTER 3: Materials and Methodology

3.1 STUDY AREA

The sediment core collected at Station 10 is designated as CAROTTE MD 12-3401 cq(Casq) and has a length of 8.21 m. The position of the station where sediment core was collected Latitude 44°40.73 South and Longitude 80°23.58 East onboard Marion Dufresne.. The sediment core was collected from the eastern side of the East Kerguelen Island of station 10 in the Southern Ocean which is at South of Indian Ocean on 16 February 2012. The Kerguelen Island is located in the subantarctic zone. The core was collected from the depth of 3445 m and wind speed of 23 knots were recorded during the time of collection.

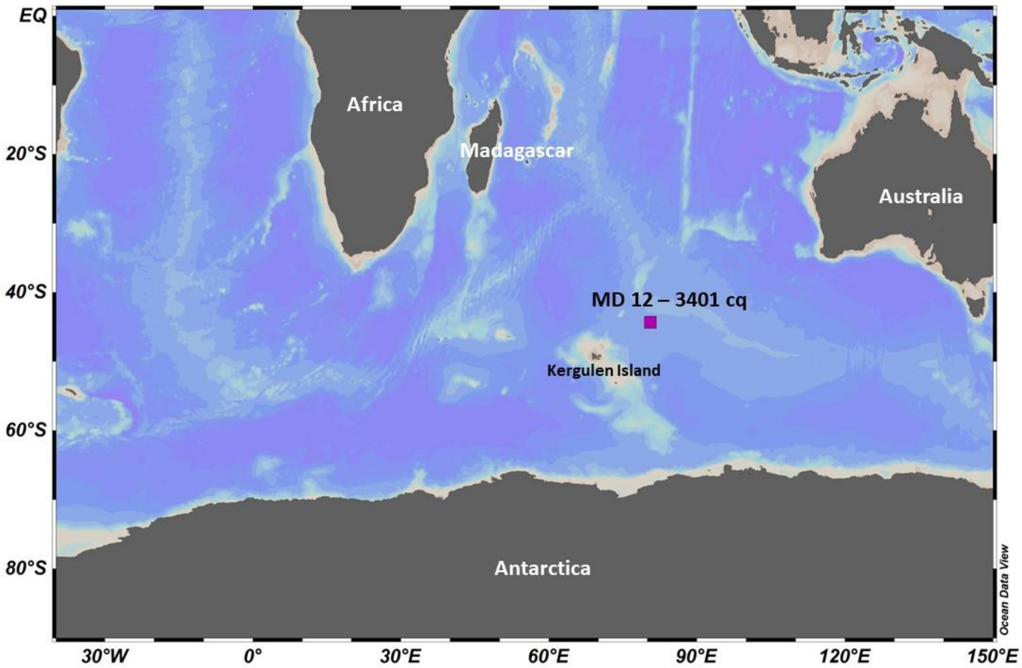

Fig 3.1: Study area showing the location of the present sediment core site MD 12 3401 cq

3.2 METHODOLOGY

3.2.1 Sample preparation for diatom analysis

The present study uses Casq sediment core MD 12-3401 cq which was collected In this study the section from length of 600 cm to 821 cm has been analysed. The core is subsampled at every 4 cm.

Following are the detailed steps followed while extracting diatoms from the sediment.

3.2.2 Slide Preparation

1. In a clean labelled 250 ml beaker around 0.3 g of the dried sample was taken.
2. To remove organic matter from the sediment, 15 ml of hydrogen peroxide (H_2O_2), was added to the beaker. The beaker was then covered with foil and left for 24 hours to react.
3. Using distilled water the sample was washed by decantation method. This was performed four times.
4. To remove any calcareous material from the sample, same was treated with 15ml Hydrochloric acid (HCL)
5. The sample was kept to react for 24 hours after which step 3 was repeated.
6. After cleaning, the sample-containing beaker was agitated and transferred into a 50 ml red-capped container archive. Any leftover diatom material was sprayed out of the beaker and labelled with the sample depth.
7. After agitating the archives until the diatom material became suspended, the sample was transferred to beakers, and any leftover material was sprayed away using milliQ water.
8. In the next step, 30 ml of MilliQ water were placed in a petri plate with clean coverslips inserted. { Note: coverslip should not float }

9. After carefully swirling the mixture, 150 µl of a homogenous sample was suspended from the centre on coverslips.
10. A Petri dish was filled with 10 ml of MilliQ water and left undisturbed for the following 24 hours. The water was decanted the following day using tissue paper, and once the petri dish had completely dried, it was placed on a hot plate set at 70°C until all of the moisture had been extracted from the sample.
11. A slide was then put on the coverslip after 4 to 5 drops of the mounting medium (Canada balsam)were poured using a glass rod or dropper. { Note: wait until all air bubbles disappear }
12. All essential initials were accurately labelled on the slides.

3.2.3 Diatom Counting

For each 4 cm depth 350 diatoms were counted with 175 diatoms on each slide of each depth at the 100 X magnification on Zeiss Microscope.

Later diatoms were grouped based on their environmental conditions (Ghadi et al., 2020). The diatom groups include:

Table 3.2.3: Diatom groups after Ghadi et al., 2020.

Sea Ice Group	POOZ group	Water Stratification Group	SAZ group
Actinocyclus actinochilus, F.curta, *F. cylindrus,* *F. obliquecostata,* *F. ritscheri,* *F. sublinearis*	*F. kerguelensis,* *F. rhombica,* *F. separanda,* *Rhizosolenia styliformis gp,* *Thalassionema nitzschioides,* *Thalassiosira gracilis,* *T. lentiginosa,* *T. oliverana,* *Thalassiothrix sp.,* *Trichotoxon reinboldi*	*Chaetoceros resting spores,* *Rhizosolenia antennata,* *Thalassiosira antarctica*	*Azpetia tabularis sp.,* *Hemidiscus cuneiformis,* *Thalassionema nitzchoides var. lanceolata,* *T. eccentrica, T. oestrupi gp*

The Sea Ice Diatom Group:- represented by the species thriving in SST range of -1 to 1°C and sea ice duration of 8-11 months/ year

The Water Stratification Diatom Group:- mainly composed of chaetoceros spp. Resting spores that flourish in an SST range of 0 to 2°C and sea ice cover of 5-9 months/year.

The POOZ Diatom Group:- characterised by open ocean diatoms. They are found abundant within SST range of 2 to 10° C and sea ice cover of 1 to 7 months/ year.

The Sub Antarctic Zone Diatom (SAZ) Group:- composed of species that are abundant in warm waters where SST ranges between 11 and 14°C and are absent in sea ice regions.

Fig 3.2: Sediment samples treated using H_2O_2 and HCL to remove any organic matter and Calcium Carbonate

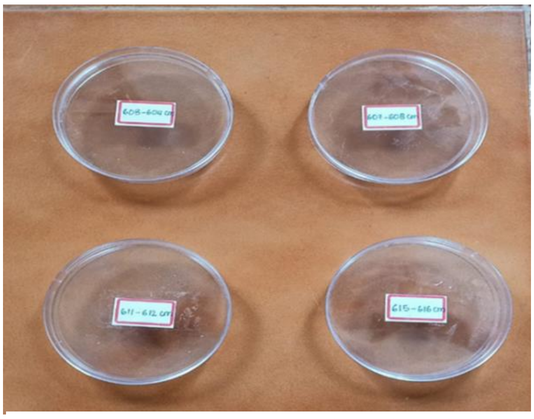

Fig 3.3: Cover slip was placed at the center of the clean labelled petri dish followed by adding 30 ml of distilled water

Fig 3.4: 150 µl of sediment sample was added on the coverslip and later 10 ml of distilled water was added. Kept untouched for next 24 hours.

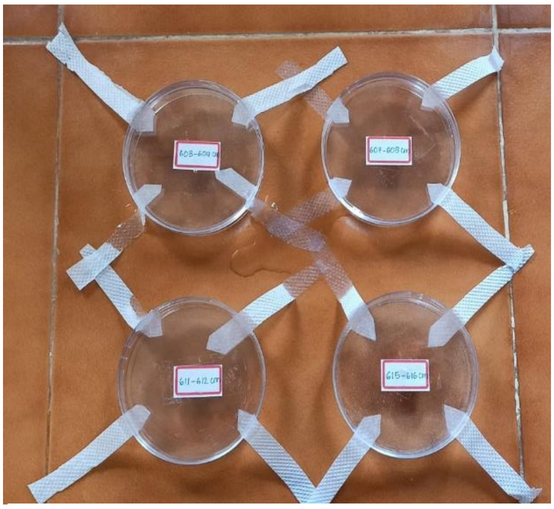

Fig 3.5: Water is decanted from petri dish and allowed the petri dish & coverslip to get dry completely.

Fig 3.6: Cover slips were used to prepare slides using Canada Balsam as Mounting Medium

Fig 3.7: Diatoms counting was done under 100X magnification.

CHAPTER 4: Results

4 RESULTS

The core of interest for this study is from 600 cm (42 Kyr) to 821 cm (58kyr) of sediment core MD 12-3401 cq which falls within the Quaternary Period of Geological Time Scale. This core of interest represents the warm interglacial period i.e. Marine Isotope Stage 3 that range from 24,000 years to 60,000 years before present. *Fragilariopsis kerguelensis* and *Thalassiosira lentiginosa* are the most abundant diatom species found in the sediment core**.**

Following are different types of diatoms encountered in the core MD 12 3401 cq

Fragilariopsis kerguelensis **(Fig 4.1 a)**

In girdle view, the valve face is slightly curved towards the ends, and in valve view, the cells are elliptical. The cells are either solitary or form ribbon-shaped colonies that are joined by the valve surfaces. Transapical striae are generally straight and coarse, with a small curve around the valve sides. Two rows of alternate areolae punctate the intertrial membranes.

F. kerguelensis are found in the Southern Ocean near sea ice close to Davis Station and offshore Wilkes Land (Archer et al, 1996) as well as on the surface of the water between the Kerguelen and Heard Islands (O'Meara, 1877). "The most abundant diatom in Antarctic Seas" is how this species has been characterized (Hart, 1942).

Azpeitia tabularis **(Fig 4.1 b)**

The cells are discoid and solitary. Valves have a flat, round shape. The areolae have a slight fasciculation. A marginal ring with a shortened neck and laterally expanded appearance is the result of labiate processes. On the periphery of the central annulus, the massive, single labiate process is found. There is no pseudodulus.

Azpeitia tabularis are found in Coastal waters near Davis Station, East, Arctic Ocean (Grunow, 1884),Prydz Bay, East Antarctica (Ligowski, 1983), Ross Sea (Watanabe, 1982), Kerguelen sector of the Southern Ocean (Hustedt, 1958).

***Asteromphalus hookeri* (Fig 4.1 c)**

Cells are discoid and can exist alone or in short chains of two or three. The centre hyaline portion of the valves, which makes about 33-50% of the valve diameter, is somewhat convex. There are Six to nine hyaline rays, one noticeably smaller than the others, stretch from the centre nearly to the valve's borders before coming to a stop in a tubular process that protrudes. Larger cells have more rays overall. Within the core region, the dividing lines are straight. Sectors in the outermost regions appear solitary. *Ast. hookeri* are found in

Prydz Bay, East Antarctica which has wide distribution in temperate and subpolar seas (Hendey, 1937),South Georgia (Hendey, 1937). These are also common throughout Antarctic oceanic areas (Hargraves, 1968), Indian sector of the Antarctic (Kozlova, 1962) and Weddell-Scotia Sea (Garrisons a/., 1987).

***Chaetoceros* resting spores (Fig 4.1 d)**

Chaetoceros. Gran (1897) is distinguished by two subgenera: Hyalochaetae, which is tiny and fragile, often having one or a few plate-like chloroplasts and thin setae, and Phaeoceros, which is massive and robust in forms with many, small chloroplasts and thick setae armed. *Chaetoceros* resting spores are found in southern ocean.

***Eucampia antarctica* (Fig 4.1 e)**

Cells can be seen alone in spiral chains or doublets. The spiralling process is caused by the valve and girdle bands growing asymmetrically, either as vegetative cells or as highly silicified "winter" resting spores. Broad, flattened, ocellate, or tapering horns can be seen. The valves are elliptical. The labiate process is marginal and isolated.

E. antarctica are found in Prydz Bay, East Antarctica, Weddell Sea (Buck & Garrison, 1983; Fryxell, 1989), Heard Island, (Manguin, 1954), Wilkes Land, Antarctica (Bunt & Wood, 1963),Indian Ocean sector of the Antarctic (Kopczyhska et al., 1986), Weddell-Scotia Sea (Garrison et al., 1987), coastal waters off Syowa Station, East Antarctica (Ishikawa et al., 2001).

Fragilariopsis ritscheri **(Fig 4.1 f)**

Cells can be found alone or in groups. In a valve view, big cells are linear to lanceolate and wider at one pole, whereas small cells are linear to elliptical. Transapical striae are curled close to the valve poles and go straight through the centre of the cell. Striae are more oblique at the poles and approximately wide at the poles. Poroids, which typically alternate in two or three rows, puncture interstitial membranes. The number of striae is equal to the number of bent fibulae. No pseudodulus is present. There is canal raphe, though it's not always evident.

F. ritscheri are found in Southern Ocean, coastal Antarctica and south of Australia; Southern Ocean, offshore Wilkes Land, offshore Wilhelm II Land, sub-Antarctic and Antarctic (Hustedt, 1958; Kozlova, 1962; Hasle, 1965), Weddell-Scotia Confluence (Garrison et al., 1987), Liitzow-Holm Bay (Tanimura et al, 1990).

Fragilariopsis curta **(Fig 4.1 g)**

The valve surfaces hold the single or chain-forming cells together. In a valve view, cells are linear and feature rounded poles, one of which is wider than the other. While striae close to the valve poles are curved, transapical striae are straight. There are one or three rows of areolae that puncture the interstitial membrane. Fibulae are quite wide and arranged irregularly, and they are found in significantly less quantities than striae.

No pseudodulus is present. There is no proof of terminal nodules. This species as being 1937 characteristic of the coastal diatom flora of land masses within the Polar Front (Hendey).

F. curta are found within the Antarctic zone (Manguin 1960) and in greatest numbers near the coast (Kozlova 1962).

***Fragilariopsis doliolus* (Fig 4.1 h)**

Fragilariopsis doliolus, which has the unusual ability to produce barrel-shaped chains, is related to seven distinct tintinnid genera, five of which have not yet been identified. The Atlantic and Pacific Ocean basins were the typical locations that brought the organisms together.

***Fragilariopsis doliolus* (Fig 4.1 h)**

Fragilariopsis doliolus, which has the unusual ability to produce barrel-shaped chains, is related to seven distinct tintinnid genera, five of which have not yet been identified. The Atlantic and Pacific Ocean basins were the typical locations that brought the organisms together.

***Rhizosolenia crassa* (Fig 4.2 b)**

Cells exist alone, in pairs, or in short chains. Short, bilaterally symmetrical valves can have a conical shape. Areolae function properly. There is Otaria. Otaria has a concave distal border. Claspers are prevalent. Two and four delicately areolate dorsiventral columns are seen in intercalary girdle bands. Small and abundant are chloroplasts.

R. crassa are found in Southern cold-water regions (Hasle & Syvertsen, 1997), Weddell Sea, Wilkes Coast (Wood, 1960), Antarctic Permanent Open-Ocean Zone to Sea-Ice Zone (Armand & Zielinski, 2001).

***Thalassiosira lentiginosa* (Fig 4.2 c)**

In girdle view, the cells are narrowly rectangular, discoid, and solitary. Valves have a round, flat shape. Areolation is usually fasciculate. The valve face is covered in uniformly sized strutted processes that lack both internal and exterior tubes and resemble tiny areolae. The labiate process is single, and the outer border has a radially oriented slit-like opening. Chloroplasts are abundant and tiny.

T. lentiginosa are found in Coastal waters off Davis Station, East Antarctica, Indian, Atlantic and Pacific sectors of the Antarctic (Johansen & Fryxell, 1985), Ross Sea (Watanabe 1982), Weddell-Scotia Confluence (Garrison et al., 1987south of Australia (Wood, 1960); Prydz Bay, SIBEX (Boden, 1985).

***Thalassiothrix antarctica* (Fig 4.2 d)**

In the girdle view, the cells are needle-shaped, straight, slightly curved, or sigmoidal, and they form radiating colonies. The head poles are separated from the foot poles. The heads and foot poles have rounded apexes with two projecting spines each. In one marginal row, areolation is seen. Along the frustule, there is a row of fine spines pointing in the direction of the head pole; these spines are more numerous in this direction. The valve surface has tiny foramina. Every apex exhibits the labiate process. Chloroplasts are spherical and abundant.

Thalassiothrix antarctica is found in Heard Island, Southern Ocean (Kopczyhska et al, 1998); Southern cold-water region (Hasle & Syvertsen, 1997). Their wide distribution is also seen in South Atlantic, Pacific and Indian Oceans (Hendey, 1937).

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Fragilariopsis rhombica **(Fig 4.2 f)**

Cells are oriented toward the poles and range in form from circular to elliptical. Transapical striae are internally somewhat thicker and have a straight centre that curves toward the poles. membranes between striae made up of one or two rows of poroid areolae. There is no central nodule.

F. rhombica are found in Coastal waters near Davis Station, offshore of Wilkes Land, Weddell-Scotia Confluence (Garrison et al, 1987), Heard Island. (Manguin, 1954). These species are also found in Indian Ocean sector of the Antarctic (Jouse et al., 1962; Kozlova, 1962), Bellingshausen Sea and South Orkneys (Frenguelli & Orlando, 1958).

Thalassiosira antarctica **(Fig 4.2 g)**

Chitinous threads that emerge from a central cluster of strutting processes hold the chain of cells together as they develop. Typically, the distance between cells is two to three times greater than the average cell size. Less silicification occurs in larger cells. Valves are round at first, but as they become smaller, they become noticeably convex. Radial areolation is bifurcate to fasciculate and loculate. One can see strutted processes. The labiate process is a big, sessile, single process that is found in the outer ring of valves with one marginal ring and between rings in valves with two or three marginal rings of strutting processes. The exterior opening of the labiate process is extended and oriented identically, whereas the internal opening is aligned with the valve's radius.

T. antarctica are found in South Atlantic, Southern Ocean and sub-Antarctic (Fryxell et al., 1981), Heard Island (Manguin, 1954), Weddell-Scotia Confluence (Garrison et al., 1987).

***Actinocyclus actinochilus* (Fig 4.2 h)**

Single, cylindrical to discoid cells are seen. Valves have a diameter of 20–112 µm and are flat with rounded edges. Areolae are varied in size, ranging from 5 to 11 µm in 10 µm, and they are loculate, with an inner foramen surrounded by a thickened rim. They are arranged in solitary radial rows that can occasionally be curved or incomplete. The distance between the marginal labiate processes, which are laterally enlarged. There are occasionally non-perforated pseudodonodulus near the point where the flat portion of the valve face and mantle meet. The valve mantle has 13–21 striae per 10 µm. Chloroplasts are discoid and abundant.

A. actinochilus are found in Coastal waters near Davis Station, East Antarctica (Everitt & Thomas, 1986); Weddell Sea (Moisan & Fryxell, 1993); Weddell-Scotia Sea (Garrison et al, 1987); Indian Ocean sector of the Antarctic (Kopczyhska et al., 1986)

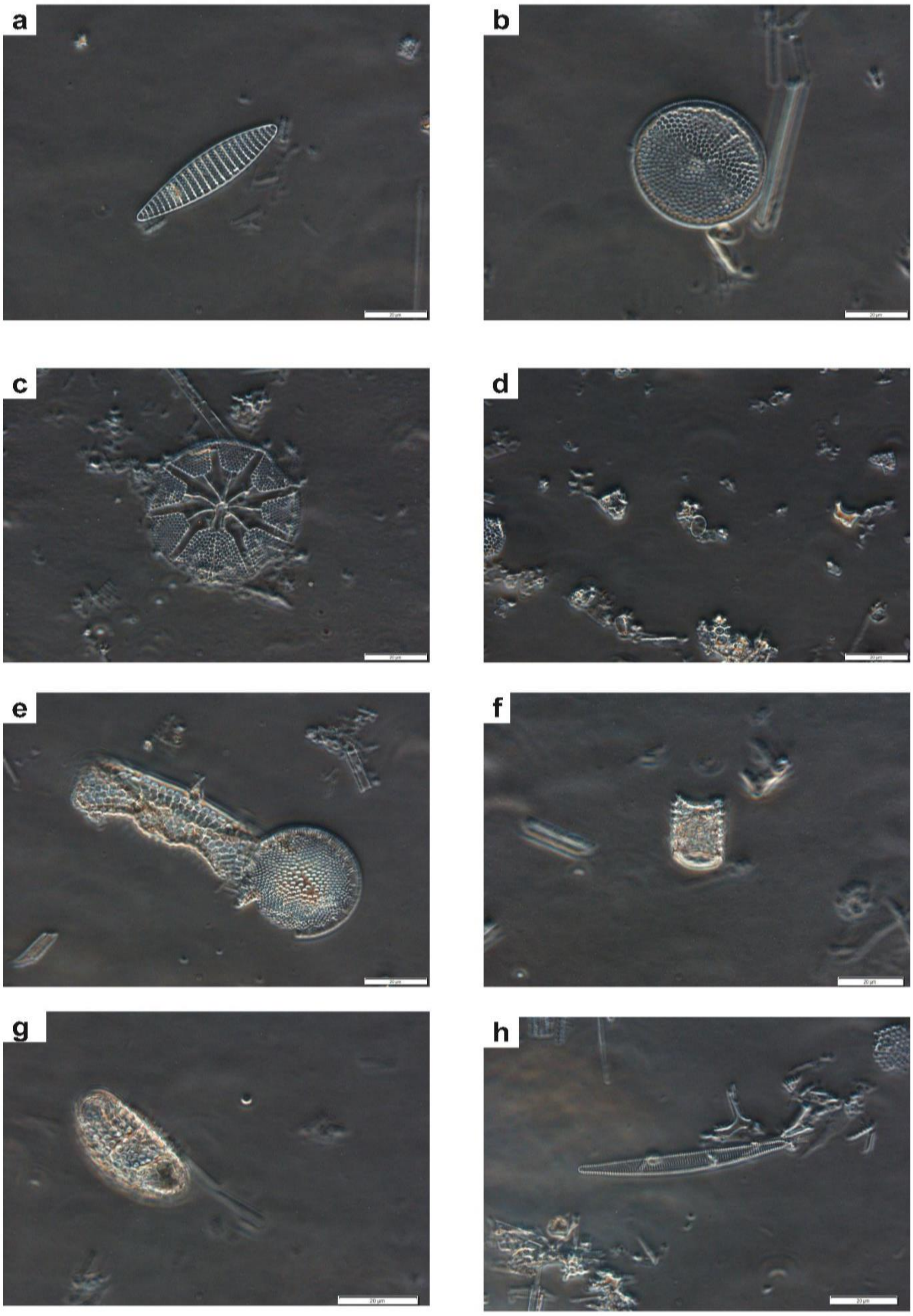

Fig 4.1: Different types of diatoms encountered in the core MD 12 3401 CQ. These are a) *F. kerguelensis, b) Azpeitia tabularis, c.) Asteromphalus hookeri, d)Chaetoceros* resting spores, e) *E. antarctica var. antarctica*, f) *E. antarctica* (Intercalary valve, cingular view), g) *E. antarctica* (Intercalary valve, valve view), h) *F. doliolus*

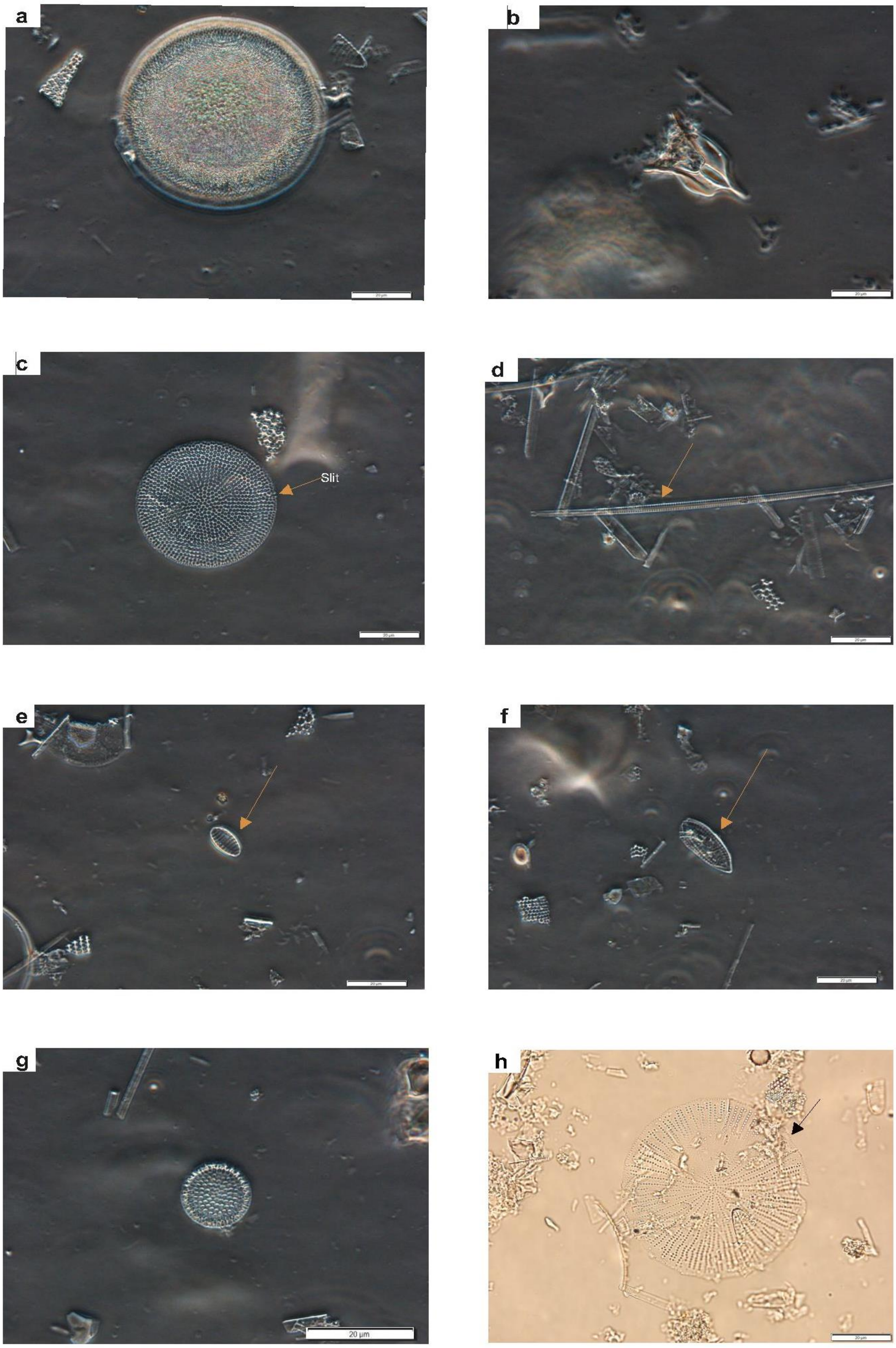

Fig 4.2: Different types of diatoms encountered in the core MD 12 3401 CQ.
These are: a) *Thalassiosira oliverana* , *b) Rhizosolenia crassa, c) T. lentiginosa, d) Thalassiothrix antarctica*, e)*Fragilariopsis seperanda*, f) *F. rhombica,* g) *T. antarctica sp*, h) *Actinocyclus actinochilus*

Relative Abundances of *Fragilariopsis kerguelensis, Thalassiosira lentiginosa, Thalassiothrix antarctica, Chaetoceros resting spores, Actinocyclus actinochilus, Thalassiosira oliveriana, Thalassiosira antarctica, Fragilariopsis rhombica, Fragilariopsis separanda, Fragilariopsis curta, Fragilariopsis ritscheri, Azpeitia tabularis* are 75%, 42%, 5%, 24%, 1.1%, 1.1%, 1.1%, 0.9%, 0.9%, 1.1%, 1.5%, 0.9% respectively.

When comparing Relative Abundance of different Diatom species with Age. It was observed that *F. kerguelensis* (Refer fig 4.3 g and fig 4.6 c), *T. lentiginosa* (Refer fig 4.3 f and fig 4.5 d) *and Chaetoceros* resting spores (Refer fig 4.3 d and fig 4.6 d) were found throughout the age from 58 Kyr (817cm) to 42 Kyr (588.5cm). While *Act. actinochilus* were more in abundance during 48 Kyr (682cm) to 42 Kyr (588.5cm) and later decreased to 0.3% (Refer fig 4.3 c and fig 4.6 a) *T. oliveriana* were in abundance throughout except during 51 Kyr (723cm) to 53 Kyr (748cm) where no traces of this specie were found (Refer fig 4.3 b and fig 4.5 b). *T. antarctica* were abundant during 54 Kyr (760.5cm) to 57.8 Kyr (814cm) and Relative Abundance was seen between 1.2% to 4.3% (Refer fig 4.3 a and fig 4.6 f). *F. rhombica* were more abundant during 50Kyr (710.5 cm) to 42Kyr (588.5cm) and 55Kyr (772.5cm) to 53 Kyr (748cm) where Relative Abundance was ranging between 0.3% to 0.9% and 0.3% to 0.5% respectively (Refer fig 4.4 f and fig 4.6 b). For *F. separanda* Relative Abundances were seen 0.3%, 0.6% and 0.9% during 57.5 Kyr (809cm) to 48 Kyr (682cm), 54 Kyr (760.5cm) to 52.5 Kyr (741.5cm) and 44.8 Kyr (630cm) to 43.8 Kyr (615cm) respectively (Refer fig 4.4 e and fig 4.5 f). For *F. curta* relative abundance during 51.7 Kyr (731.5cm) to 48 Kyr (682cm) was ranging between 1.8 to 2.5% (Refer fig 4.4 d and fig 4.5 c). Relative Abundance for *F. ritscheri* was seen 0.5% whereas during 49.5 Kyr (704cm) to 42 Kyr (588.5cm) Relative Abundance for the same were seen ranging between 0.3% to 1.4 % (Refer fig 4.4 b and fig 4.5 a). *Azpeitia tabularis* had 0.9% Relative Abundance during 45Kyr (632.5cm) to 44 Kyr (618cm), 0.3% to 0.6% during 56 Kyr (785.5cm) to 51.7 Kyr (731.5cm) and few traces were also seen during 44 Kyr (618cm) to 43 Kyr (603.5cm) that is 0.3% (Refer fig 4.4 a and fig 4.6 g). *F. obliquecostata* had Relative Abundance ranging between 0.3% to 0.85% and was present only during Age 57 Kyr - 56 Kyr (801cm-785.5), 55 Kyr - 54.2 Kyr (772.5cm-762.5cm) and 45.8Kyr to 45.4 Kyr (644.5cm-638.5cm) (Refer fig 4.4 c and fig 4.5 e). *Trix antarctica* was found in abundance during 52Kyr (735.5cm) that 5.1% where as it was negligible during57.8 Kyr (814cm), 56 Kyr to 55.7 Kyr (785.5cm-7812.5cm), 53 Kyr (748cm) and 44 Kyr (618cm) (Refer fig 4.3 e and fig 4.6 e).

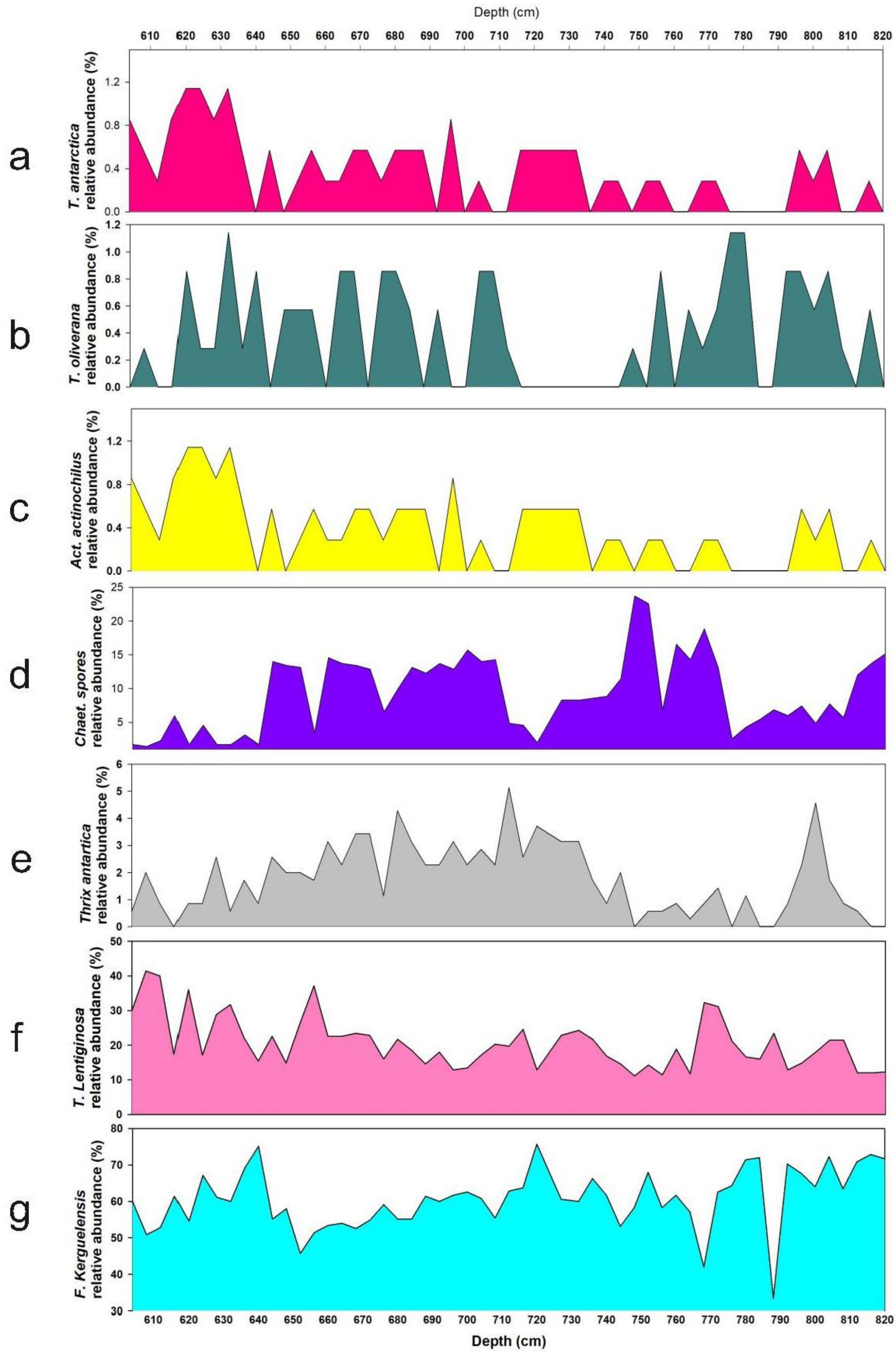

Fig 4.3: Relative Abundance (%) of different diatom species with respect to Depth (cm) from core MD 12-3401 cq

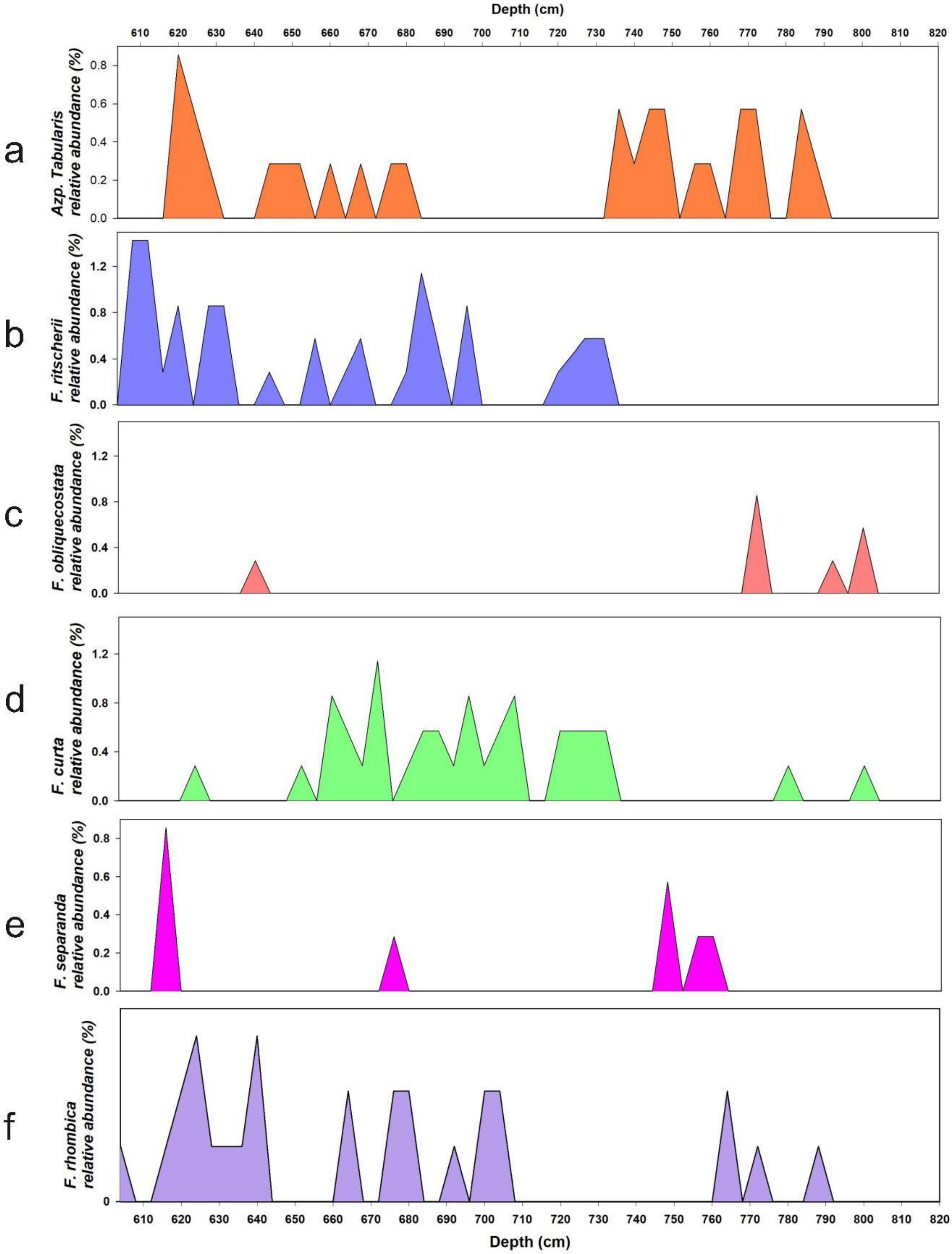

Fig 4.4: Relative Abundance (%) of different diatom species with respect to Depth (cm) from core MD 12-3401 cq

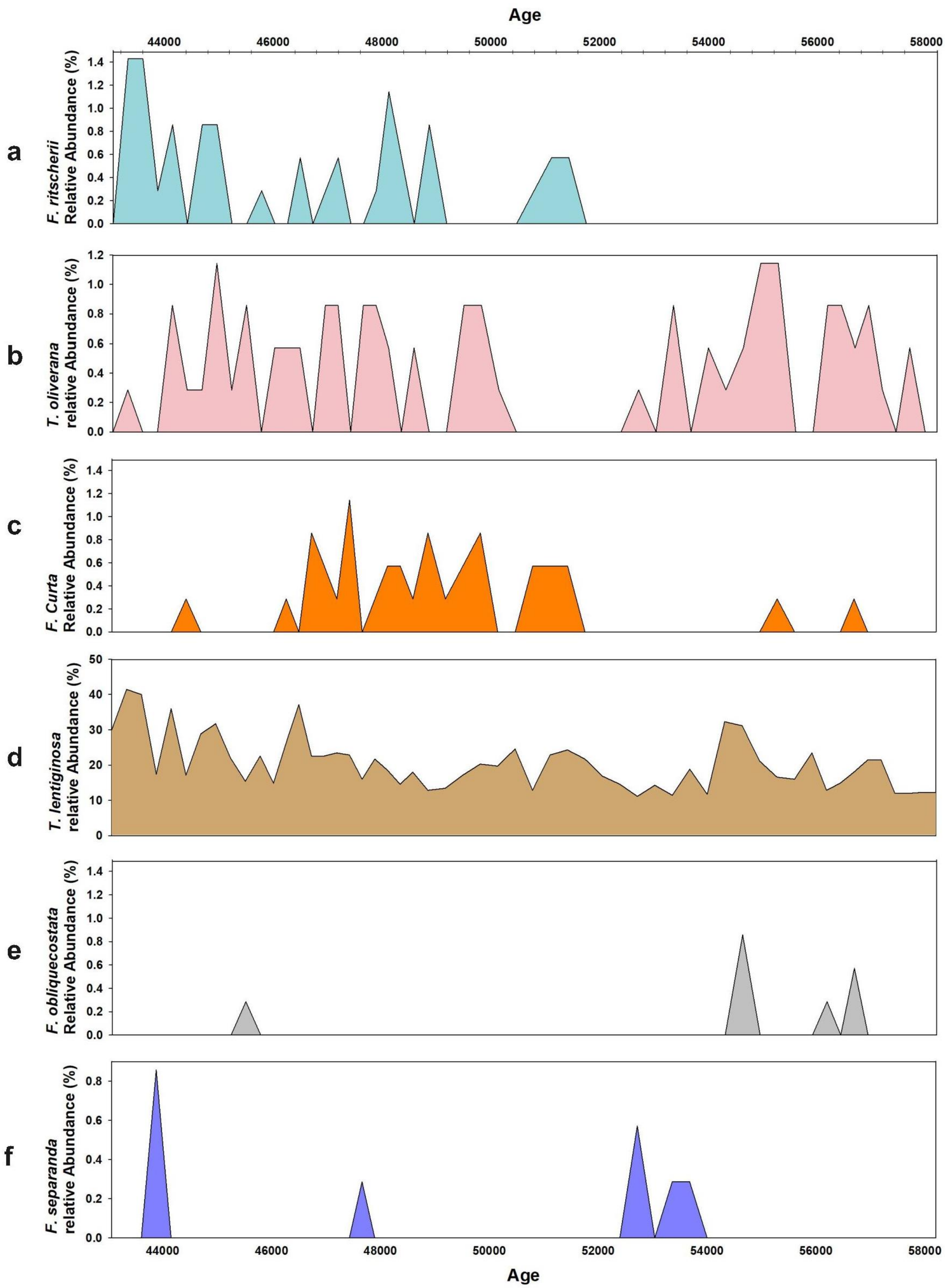

Fig 4.5: Relative Abundance (%) of different diatom species with respect to Age from core MD 12-3401 cq

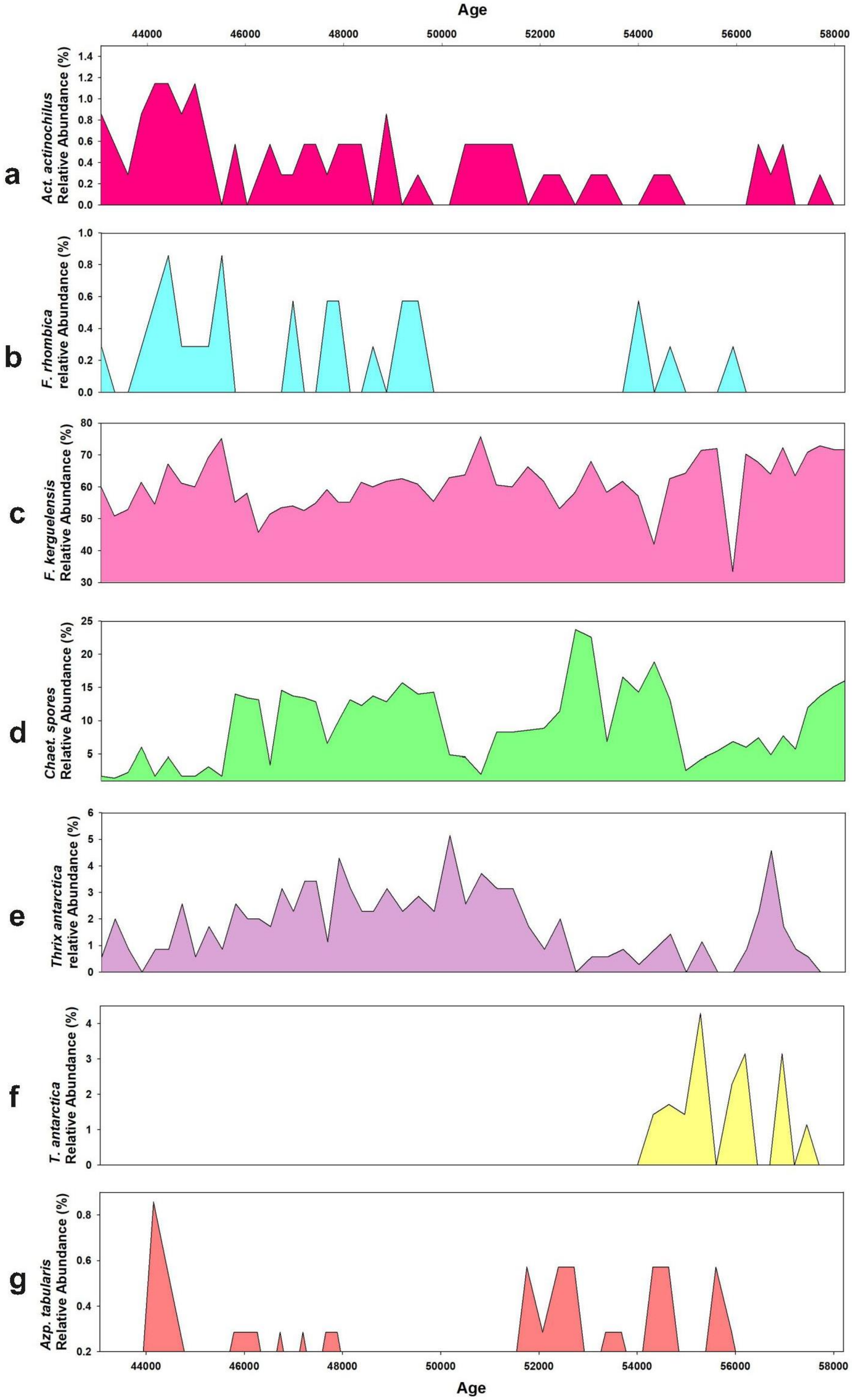

Fig 4.6: Relative Abundance (%) of different diatom species with respect to Age from core MD 12-3401 cq

The SEA ICE group abundance ranges between 0 to 4%. Diatom assemblage shows all time high during 44.5 Kyr (625.5cm) that is 4%. During 43.9 (616.5cm) Kyr diatom assemblage is 3.3% which is little higher than the moderate. The Sea Ice group is all time lowest during 58 Kyr (817cm), 57. – 57.2 (809cm-804.5cm) Kyr, 56-55.6 Kyr (785.5cm-780cm), 54-53.7Kyr (760.5cm-756.5cm) which is 0% and during rest of the ages the Sea Ice group fluctuate from 0.2% to 3.8% which is lower than the moderate. (Refer fig 4.7 d)

The POOZ group shows higher abundance of diatom assemblage. The Relative Abundance varies between 57% to 94% where highest is seen at age 57.2 Kyr (804.5cm), 54.9 Kyr (771.5cm), 50.8 Kyr (710.5cm), 47.7 Kyr (677cm), 45 Kyr (632.5cm), 43.3 Kyr (607.5cm) that is 94 %,94 %,92 %.91 %,92 %.94 % respectively and lowest at 56.4 Kyr (791.5cm) which is 57%. During 56.8 Kyr (798cm), 55.9 Kyr (784cm), 52 Kyr (735.5cm) diatom assemblage was seen 80.6%, 80.8% , 80.9% which was little higher than the moderate. Rest of the POOZ group fluctuate from 75 % to 80.2 % which is lower than the moderate. (Refer fig 4.7 b)

The WATER STRATIFICATION group shows Relative Abundance ranging between 1.5 % to 24%. During 50.8 Kyr (720.5cm), 43.9 Kyr (616.5cm), 43 Kyr (603.5cm) were seen 1.5% lowest whereas highest during 52.7 Kyr (744cm) which was 24%. During 58.2 Kyr (698cm), 56.4 Kyr (791.5cm), 53.5 Kyr (754cm), 49 Kyr (698cm) Relative Abundance were seen 15.2 %, 21 %, 15.2 %, 15.1% which is higher than the moderate and rest of the group fluctuate from 3% to 14.9% which is lower than the moderate. (Refer fig 4.7 c)

The SAZ group shows Relative Abundance 0% to 3.4%. Where in highest is seen during 53.7 Kyr (756.5cm) which is 3.4%. During 56.8 Kyr (798cm) and 52.7 Kyr

(744cm) abundance is 15% which is higher than the moderate whereas during 48.2 Kyr (685.5cm) to 45.7 Kyr (685.5cm) is seen 0.2% and during 44.2 Kyr (621cm) is 0.9% which little lower than moderate. And at rest of the ages Relative Abundance seen as negligible that is 0%. (Refer fig 4.7 a)

While comparing Sea Surface Temperature (SST) during 60 to 52 Kyr SST in the sediment core MD 12 3401 cq was average between 3° to 9°C. Here warming event can be seen when SST reached almost 9°C. During 50 to 48 Kyr SST was average between 0.5°C to 6°C. There was presence of very prominent cooling event when temperature decreased to 0.5°C at 51 Kyr. During 48 to 40 Kyr SST average between 1°C to 9°C. Here warming event was seen where SST reached 7°C and 9°C. Warm SST originates from the Indian Sub Antarctic Zone (SAZ) and Sub-Tropical Zone (STZ) west of the Kerguelen Island (KI), transporting warm surface waters from low latitudes into the Indian SAZ during MIS 3. (Refer fig 4.7 e)

When comparing Sea Ice Presence (SIP) was averaging between 0.3 to 5.1 months/years. During 58.3 Kyr to 54.7 Kyr was averaging between 1 to 3.9 months/years. From 52.4 Kyr to 46.3 Kyr SIP was averaging between 0.3 to 5.1 months/years. 45.8 Kyr to 43 Kyr SIP was ranging between 2 to 4 months/years. (Refer fig 4.7 f)

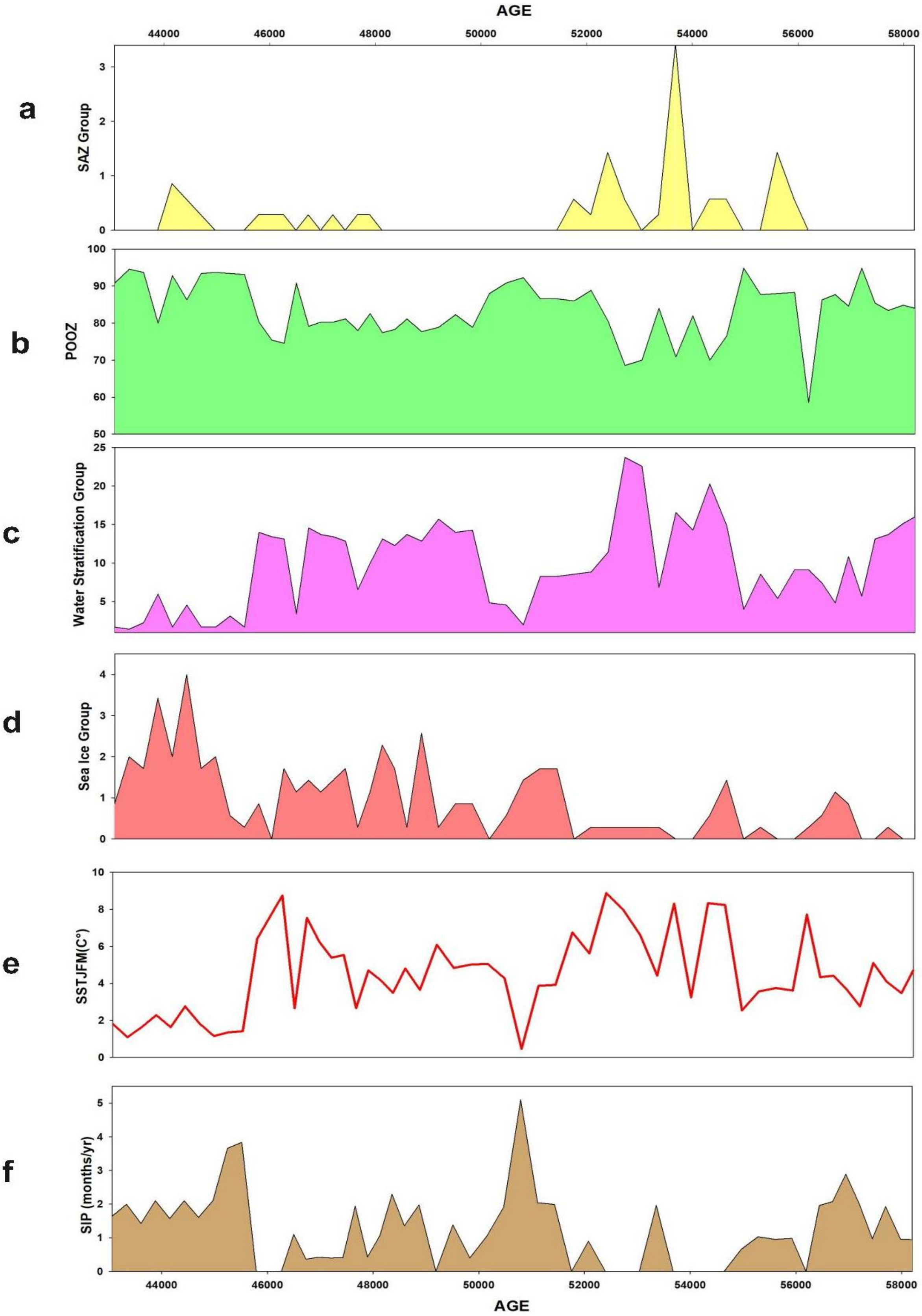

FIG 4.7: Plots from **a** to **d** represents Diatom Groups with respect to Age, Plot **e** represents Sea Surface Temperature with respect to Age, Plot **f** represents Sea Ice Pressure with respect to Age

When comparing Absolute Abundance of diatom at various ages it depicts that during 42 kyr abundance was seen at peak that is 120x 10^6 valves/g during 48 Kyr this could be because of nutrient content, high diatom productivity and preseravtion. . Also between 56kyr to 54 kyr abundance was seen in mild peak which was 90 x 10^6 valves/g. Lower abundance was seen at around two places. During 58kyr to 57 kyr the abundance was negligible to around 0.1x 10^6 valves/g to 0.2x 10^6 valves/g. and other was during 50kyr to 48kyr which was seen 10x 10^6 valves/g. During 54 kyr to 50kyr abundance was ranging between 30x 10^6 valves/g to 60x 10^6 valves/g. Also during 48kyr to 42kyr abundance was ranging between 52x 10^6 valves/g to 58x 10^6 valves/g. (Refer fig 4.8)

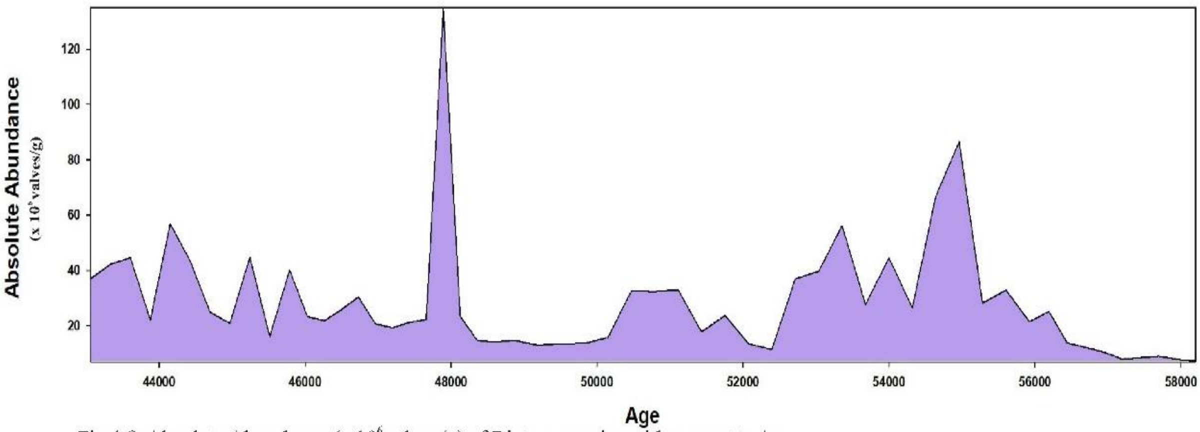

Fig 4.8: Absolute Abundance (x 10^6 valves/g) of Diatom species with respect to Age

CHAPTER 5: Discussion

5: DISCUSSION

In this study, the records are presented for sediment core MD 12 – 3401 cq from length 600 cm to 821 cm. Their relative abundance has been calculated and plotted against the Age. (Fig. 4.5 & 4.6). The sea Ice diatoms varies between 0 % to 4 %. The core site shows presences of diatom throughout the core. The Water Stratification group shows diatom abundance record throughout the core which vary from 1.4 % to 24 %. The POOZ group abundance varying from 57% to 94% where *F. kerguelensis* and *T. lentiginosa* being the most abundant diatom species throughout the sediment core. Diatom abundance record of SAZ group was lowest than other three groups where relative abundance ranged from 0 to 3.4% . The overall diatom abundance varies between 0.1-120 x 10^6 valves/g of sediments. Sharp decrease in total abundance was noted during 58 to 57 Kyr with the lowest abundance of 0.1-0.2 x 10^6 valves/g. The gradual increase is seen 48 Kyr also in 48 to 42 Kyr.

Diatom based MD 12 3401 cq records from the southern ocean shows warming SSTs during 58.2 Kyr to 42.7 Kyr. The temperature here varies from 3° to 9°C. During 48 to 40 Kyr SST average between 1°C to 9°C. Here warming event was seen where SST reached 7°C and 9°C.

The MD 12 - 3401 cq. Sea Surface Temperature (SST) data was compared with SK 200/ 27 and SK 200/ 33 which is located in western side of MD 12 M402 cq. As seen from Fig 4.1 is evident that the SSTs recorded in SK 200 – 27 were ranging between 1.2°C to 4.2 °C and in SK 200 – 33 were ranging between 1.3°C to 2.8°C. This warming event seen because of sediment core lies in region where Dynamical Subtropical Front (DSTF) merges with SAF thus bringing the warmth from lower latitudes of the Indian Ocean. The interplay between the Agulhas Return Currents (RC) intensity and modification in the Southern Ocean fronts has been suggested as a possible reason in delivering the warm water at the core site (Thesis Pooja Ghadi 2023).

Comparing Sea Surface Temperature Data of SK 200 - 27 and SK 200 – 33 with MD 12-3401 cq

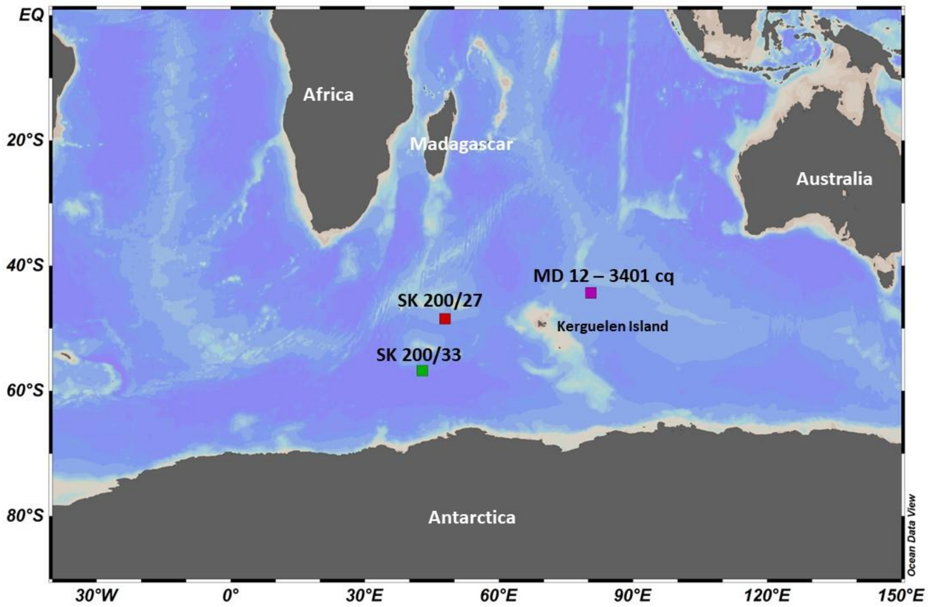

Fig 5.1: Study area showing the location of the core SK 200/27 (red square) and SK 200/33 (green square) which is located at the western side of the present study sediment core site MD 12 3401 cq (purple square)

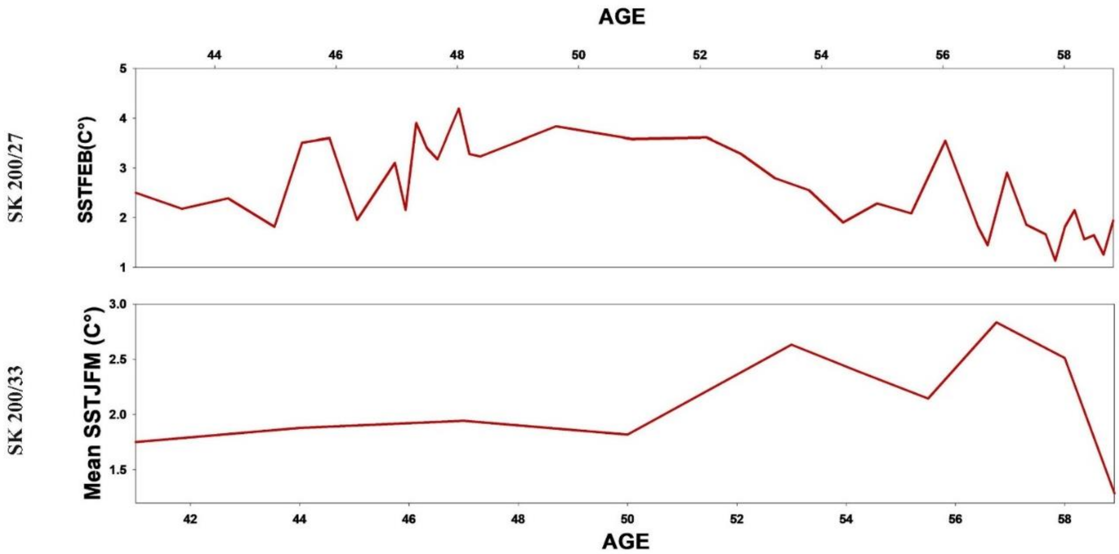

Fig 5.2: Sea Surface Temperature (SSTs) data of Core SK 200/27 and SK 200/33 with respect to Age

SK 200 – 27

While comparing Sea Surface Temperature (SST) with Age, SST were ranging between 1.2°C to 4.2 °C. From 58 to 54.3 Kyr the temperature was ranging between 1.2 to 3.5°C. As we move from 54.3 to 48.1 Kyr temperature was uniformly increasing from 1.9°C to 3.9°C and then later sudden decrease in temperature of around 3.2°C. From 48.1 to 45 Kyr SSTs were fluctuating between 3.1°C to 4.2°C and from 45 to 41 Kyr temperature decreased to 1.7°C to 2.5°C. (Refer fig 4.1)

SK 200 – 33

While comparing Sea Surface Temperature (SST) with Age, SST were ranging between 1.3°C to 2.8°C. During 58 Kyr temperature was 2.5°C which later decreased to 1.3°C. During 58 Kyr to 50Kyr temperature was averaging between 1.8°C to 2.5°C. From 50 Kyr to 43 Kyr temperature was same that is 1.9°C with fluctuation of 0.1°C (Refer fig 4.1)

As I compare my data with SK 200 – 27 and SK 200 – 33, I can conclude that in MD 12 – 3401 cq there is comparatively prominent warming can be seen when temperature reached almost 9°C. Hence I can say that my study area is dominated by POOZ diatom group.

CHAPTER 6: Conclusion

6: CONCLUSION

The present research uses diatoms as a proxy to study the paleoclimate of the southern ocean. The study of climate without direct observation is known as paleoclimatology, and it involves reconstructing past climates from data found in rocks, sediments, and other materials. Therefore, the Southern Ocean is one of the few prime locations in the globe where human influence is minimal, making it an ideal spot to research paleoclimate and climate change. Southern Ocean is southernmost points of the Indian, Pacific, and Atlantic oceans—which stretch south to the Antarctic continent. ACC is its principal oceanographic feature. Because ACC reduces meridional heat transport, Antarctic glaciers are formed as a result of their actions.Through the use of diatom proxies, research on the temperature, salinity, and sea-ice dynamics of the Southern Ocean helps to improve the accuracy of climate models and offers insights into long-term climate change. As the predominant marine primary producers, diatoms are crucial to the modern ocean's carbon, silica, and nutrient budgets. Through the analysis of diatom species distribution and abundance, paleoclimatic conditions can be inferred. The current study makes use of sediment core MD 12 3401 cq length, which ranges from 600 cm to 821 cm and falls within the Quaternary epoch of the Geological Time scale (MIS 3; 60,000 to 24,000 years ago). Data shows *F. kergulensis* and *T. lentiginosa* are the most abundant species having relative abundance of 75% and 42 % respectively which dominates in the POOZ diatom group. Diatom at various ages it depicts that during 42 kyr abundance was seen at peak that is 120x 10^6 valves/g during 48 Kyr. A Modern Analogue Technique (MAT) transfer function is used to quantitatively determine sea surface temperature (SST) based on the diatom abundance. SSTs revealed a warming event of nearly nine degrees Celsius in temperature. The Indian Sub Antarctic Zone (SAZ) and Sub-

Tropical Zone (STZ), located west of Kerguelen Island (KI), are the source of these warm SST. During MIS 3, warm surface waters from low latitudes were transported into the Indian SAZ. There was an average of 0.3 to 5.1 months/year of sea ice presence (SIP). High-resolution data on the palaeoceanography is provided by the diatom record from the Kerguelen region in the Indian sector of the Southern Ocean. Comparing the core with the surrounding region's core reveals the Agulhas current and its retroflection over the expected sea surface temperatures. The Agulhas current regulates surface currents. To properly describe the local phenomena, more data recordings from the Kerguelen Region are needed.

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