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Scienze della terra, fluidodinamica e matematica. Interazioni e metodiche

Interplay of bottom currents and glacial input on western margin of the Svalbard: evidence from giant piston cores spanning the last 90 ka.

Settore scientifico-disciplinare: GEO/02

DOTTORANDO
Nessim DOUSS

COORDINATORE
PROF. Stefano MASET

SUPERVISORE DI TESI
PROF. Michele Rebesco

Co-SUPERVISORE DI TESI
PROF. Renata Giulia LUCCHI

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ABSTRACT

The present and future climate development is subject to considerable changes due to the increasing human influence on the climate system. The polar regions are particularly affected by this change. However, the extent and speed of this change are controversial. A better assessment requires accurate knowledge of the natural climate variability, i.e. in the periods when human influence did not play a role. This PhD project focuses on the reconstruction of past-climate variability caused by natural forcing and the response of the paleo Svalbard-Barents Sea Ice Sheet using climate signatures preserved in Arctic marine sediments. The geological dataset used for this study derives from two oceanographic cruises under the framework of the Eurofleets2 PREPARED, where core GS191-02PC was recovered from the Isfjorden drift in 1322 m water depth, and from the CAGE19-3KH Calypso piston coring expedition, where core CAGE19-3KH-05GPC was collected from the western termination of Vestnesa Ridge at a water depth of 1321 m bsf and core CAGE19-3KH-15GPC was collected from the Isfjorden Drift at a water depth of 1579 m bsf. The three studied cores were collected employing Calypso Giant Piston corer. The laboratory analyses included: X-Ray radiography and computed tomography (CAT-scan), Core visual description, Multi Sensor Core Logging (MSCL), X-ray fluorescence (XRF) core scan, X-ray diffraction (XRD), Total Organic carbon (TOC) and Total Nitrogen (TN), and grain size analysis. The three cores (spanning from Marine Isotopic Stage-5b to the Marine Isotopic Stage-1) were correlated on the basis of the magnetic susceptibility and identification of marker beds having a regional distribution since the early Weichselian. It was possible to identify and characterize several major climatic events during the last 90 ky such the Meltwater Pulse MWP 1-A (14.6-14.3 ky), (MWP)1-A₀, or MWP-19ky (20.5-20.0 ky), the Heinrich event H2 (23-24 ky), the Heinrich event H4 (38-40 ky), and the Heinrich event H6 (60 ky). These events are characterized by a particular sediment structure that clearly indicates ice melting under warm conditions, and a characteristic mineralogical composition that allows their reliable recognition.

The sedimentological record reveals a highly dynamic ice sheet under variable climatic conditions. The sedimentation in the studied sites is clearly affected by the interplay of down-slope processes mainly occurring during ice sheet waxing and waning and along-slope processes dominated by contour currents during warm conditions when the ice sheet is fairly retreated inland. The interplay between these two main processes causes the depocenters to shift on glacial-interglacial time scales.

Key words: *Paleoclimate, Western Svalbard margin, Clay minerals, Heinrich events, Arctic*

CHAPTER 1: INTRODUCTION

1.1 Why is studying the paleoclimate important ?

The study of past climate is important for several reasons. First, it allows us to understand climate variability by examining past climate records and to quantify natural climate variability, which is useful for distinguishing between natural climate variability and human-induced climate change. Paleoclimate data provide information about the response of Earth's climate system to external forcings such as greenhouse gas concentrations or changes in solar irradiance. This information helps determine the response of the climate system to various factors and provides a basis for understanding and predicting future climate change. In addition, paleoclimatic data serve as an important tool for testing and validating climate models. By comparing model simulations with paleoclimatic data, the ability of models to accurately reproduce past climate conditions can be evaluated. This increases confidence in the performance of the models and improves their reliability for future climate projections. In addition, the paleoclimate record provides valuable information on climatic feedback mechanisms. By examining past climate events and their associated feedback processes, it is possible to quantify how different components of Earth's climate system interact with and amplify changes in climate. This understanding is essential for predicting how feedback may influence future climate scenarios. Paleoclimate records provide a context for interpreting current and projecting future climate trends. By examining past climate changes, patterns and cycles can be identified that can help predict future climate scenarios. This information is important not only to the scientific community, but also to society as a whole, as it is valuable to policy makers, land use planners, and other stakeholders who must make decisions to mitigate climate change and adapt to future climate change. In summary, paleoclimate research contributes to our understanding of Earth's climate system, provides insight into natural climate variability, validates climate models, and helps inform future climate projections. This knowledge is critical for addressing current and future climate challenges and developing effective climate change mitigation and adaptation strategies.

1.2 Why deciphering the Paleo-Svalbard-Barents Sea Ice Sheet behavior important ?

The Paleo-Svalbard-Barents Sea Ice Sheet Complex (SBSIS) serves as the best analogue of the present-day West Antarctic Ice Sheet, which is a major source of uncertainty in predicting global sea level change. Thus, SBSIS contains a valuable historical reference to better understand and project the future behavior of the present-day West Antarctic Ice Sheet. Paleobathymetric reconstructions of the Barents Sea indicate a similar climate evolution to that of West Antarctica. During the late Pliocene, the Barents Sea was relatively shallow and partially exposed, deepening over time due to glacially induced erosion of the substrate. This resulted in most of the SBSIS becoming a marine ice sheet. Similar to present-day West Antarctica, the SBSIS became more susceptible to intrusion of warm ocean currents, particularly the North Atlantic Current, into the shallow continental shelf. This led to rapid melting and frequent baseline instability, which was exacerbated by concurrent sea level rise. The consequences of such ice sheet destabilization included significant retreat of the inland ice front, substantial ice sheet collapses, and release of the terrigenous material that had been enclosed in the ice.

1.3 Why the Fram Strait?

The Fram Strait is of significant importance due to its role as the primary deep-water gateway connecting the Arctic Ocean to the Norwegian-Greenland Sea. It plays a crucial role in the exchange of water masses, heat, and freshwater between the Arctic and global oceans, making it a key region for understanding and monitoring the Arctic climate system.

The Fram Strait serves as a major pathway for the exchange of warm Atlantic waters and cold Arctic waters. The inflow of warm Atlantic waters into the Arctic through the Fram Strait contributes to the melting of sea ice and influences the Arctic Ocean's temperature and salinity patterns. In addition, it constitutes a major route for the export of sea ice from the Arctic Ocean to the North Atlantic. The melting of sea ice and the discharge of freshwater from Arctic rivers result in the release of freshwater into the Fram Strait. This freshwater discharge influences the density and circulation of surface waters in the North Atlantic, affecting the strength and characteristics of the Atlantic Meridional Overturning Circulation (AMOC), a key component of global ocean circulation.

In summary, the Fram Strait is essential for understanding the dynamics of the Arctic climate system, the exchange of water masses and heat between the Arctic and global oceans, and the

feedback effects on regional and global climate patterns. Its study is vital for understanding the ongoing changes in the Arctic and their potential implications for the Earth's climate system.

1.4 What can clay minerals reveal?

The application of clay mineralogy to reconstruct the origin of sediments has been limited in this area, indicating a knowledge gap that needs to be further explored. This knowledge gap led to the need to investigate this aspect to gain additional insight into the glacial dynamics of the Svalbard-Barents Sea ice sheet. The use of clay mineral stratigraphy in conjunction with other compositional analyses was employed to investigate the potential for identifying minor climate variations since the early Weichselian.

1.5 Objectives

- *To decipher the Late Quaternary palaeoceanographic and palaeoclimatic record of sediment drift located on the Western Svalbard Margin.
- *To reconstruct sediment provenance in relation to the ice stream source areas and their configuration during glacial, deglacial and interglacial intervals.
- *To reconstruct the dense shelf water strength variations and their timings in the different areas of study.

CHAPTER 2: OCEANOGRAPHIC AND GEOLOGICAL SETTINGS OF THE STUDY AREA

2.1 Presentation of the Arctic ocean

The Arctic Ocean covers approximately 14,055,000 km² and includes various seas such as the Greenland Sea, White Sea, Barents Sea, Kara Sea, Laptev Sea, East Siberian Sea, Chukchi Sea, Beaufort Sea, and Baffin Bay. (**Fig. 2-1**) Understanding the tectonic evolution of the Arctic region since the breakup of Pangea is challenging due to limited data and the complex Phanerozoic history characterized by compression, extension, plate boundary changes, and reactivation events ([Shepard et al., 2013](#)).

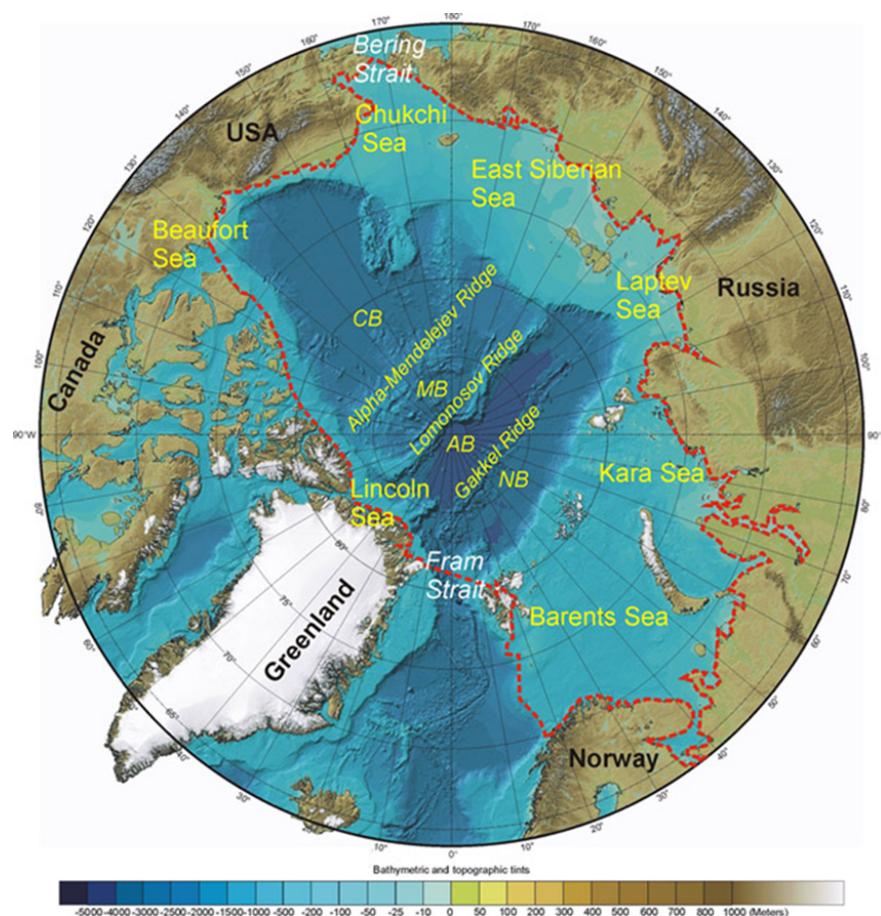


Figure.2-1: Maps of the arctic ocean and its different constituents (seas, main tectonic structures, and main basins). Red dotted line indicates the limit of the arctic ocean, Bathymetry map From the international bathymetric charts of the arctic ocean IBCAO, Jacobsson et al, 2012. From Coastal wiki.

2.2 Oceanographic context: Main circulation system

The Arctic Ocean plays a dual role in the global circulation of the oceans. It facilitates the transfer of Pacific waters into the Atlantic Ocean through the Bering Strait, progressively reaching the Canadian Archipelago and Greenland. Additionally, it contributes to the uptake, modification, and return of Atlantic water to the Atlantic Ocean, playing a crucial role in heat-salt exchange in the Northern Hemisphere, as discussed by Rudels et al., 1999. The eastern side of the Fram Strait serves as a significant pathway for the transportation of warm water from the middle latitudes to the Arctic Ocean, as indicated by Schauer et al., 2004.

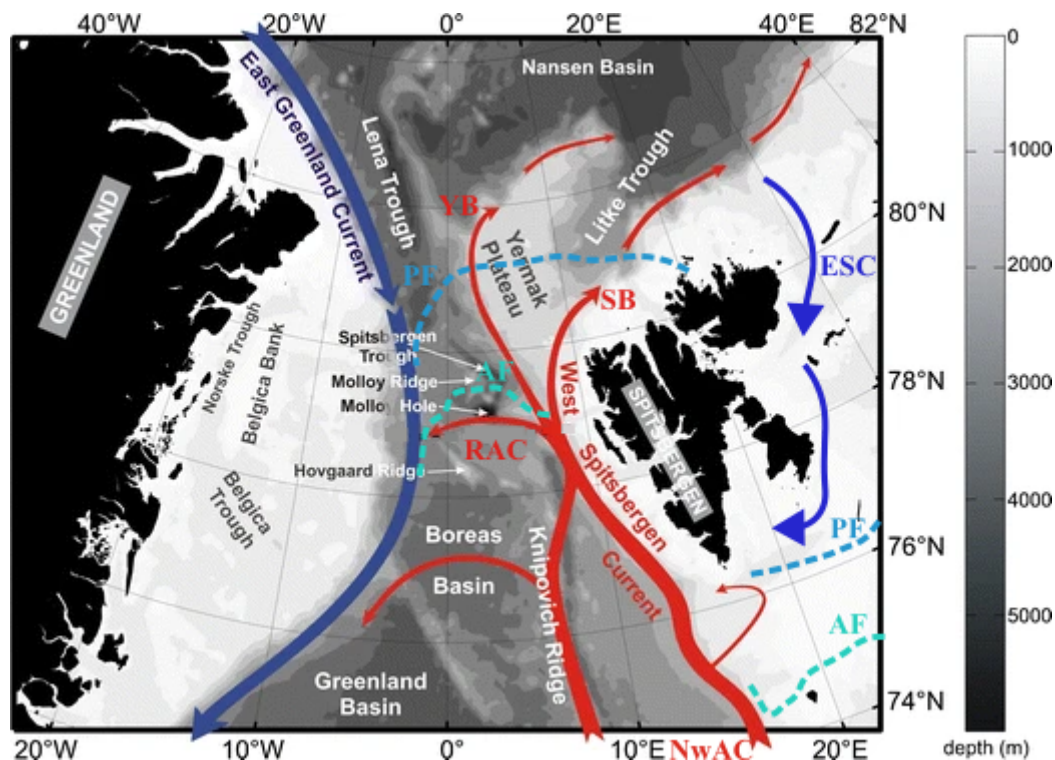


Figure.2-2: Ocean circulation on the Fram Strait based on the bathymetry from the international bathymetric chart (Jakobsson et al., 2008). PF: Polar Front; AF: Arctic Front, ESC: East Spitsbergen Current, SB: Svalbard Branch; YB: Yermak Branch; and RAC: Return Atlantic Current, Modified from Rebesco et al, 2013

In the studied region, the oceanographic circulation is predominantly influenced by the Western Spitsbergen Current (WSC) (**Fig. 2-2**), a warm and saline current that has exerted significant control over sedimentation in the Fram Strait since the late Miocene, as observed by Eiken et al., 1993. Changes in this current are generally detectable in the sediment record. The warm WSC facilitates ice-free conditions in the western and northern parts of Svalbard during winter and plays a crucial role in monitoring the Arctic climate, as emphasized by the IPCC (2019). The WSC originates from the Norwegian Atlantic Current (NwAC) (**Fig. 2-2**), which is a combination of waters from the Nordic Seas and the Atlantic. At 69°N, the NwAC splits into two

major branches: the North Cape Current (NCC), which flows along the Scandinavian continental slope, and the WSC, which moves northward. The WSC manifests as three branches in the surrounding area of the eastern Fram Strait: the Yermak Branch (YB), which flows into the Arctic Ocean; the Svalbard Branch (SB), which follows the northern edge of Svalbard; and the Return Atlantic Current (RAC), as identified by [Nilsen et al., 2016](#) (**Fig. 2-2**). The SB current associated with the Arctic water transforms to East Spitsbergen Current (ESC), characterized by a cold surface flow that contributes to the formation of the polar front. The Spitsbergen Trough Current (STC) is a local current that represent longer and slower route of Atlantic water, guided by the topography of the western Spitsbergen shelf, circulating within the troughs (e.g., Bellsund, Isfjorden, Kongsfjorden). On the western side of the Fram Strait, the cold Arctic waters descend, giving rise to the formation of the East Greenland Current (EGC) (**Fig. 2-2**). This oceanic current plays a crucial role in sustaining the Greenland ice cap, as documented by [Hopkins et al., 1991](#) and [Aagaard et al., 1987](#).

2.3 Paleoclimatic context of the study area since the Weichselian

As the studied sediment cores reach the early Weichselian the paleoclimatic context will be focused only on that interval.

2.3.1 Marine Isotope Stages and factors influenced changes in glacial conditions

Marine isotope stages (MIS), also known as marine oxygen-isotope stages or oxygen isotope stages, are cycles of warm and cold periods in the Earth's paleoclimate. These stages are determined based on oxygen isotope data, which reflects temperature changes derived from various sources such as ice cores or marine deep-sea cores ([Lowe et al., 1997](#)).

The current period is referred to as MIS 1, and as we move backward in time, even-numbered stages represent colder glacial periods with higher oxygen-18 (^{18}O) values. On the other hand, odd-numbered stages indicate interglacial periods with lower ^{18}O values. The data used to determine these values are collected through proxies such as pollen, foraminifera, and other indicators. Approximately 6 million years of paleoclimate history have been identified, encompassing over 100 stages. Some of these stages are further divided into substages, such as MIS 5 where the letters a, c, and e denote warmer periods, while b and d represent colder intervals (**Fig. 2-3**).

The fluctuations of glaciers result from a complex interplay of various factors, including climate, insolation, precipitation, ocean currents, and other processes. When glaciers grow, it is primarily due to accumulations of precipitation, while a decrease in melting and calving (ablation) also contributes to their growth. A colder climate generally results in lower moisture levels, leading to limited annual precipitation in the area. This limitation has long been considered a key factor in restricting the growth of ice sheets in the Arctic region (Boulton, 1979). During extended periods of the Weichselian glaciation, the cold climate caused precipitation to occur as snow even during the summer months (Mangerud & Svendsen, 1992). As a result, the land surface became covered with snow, while the submerged equilibrium line beneath the sea allowed for further ice accumulation as the sea regressed during heavy glaciations (Denton & Hughes, 1981).

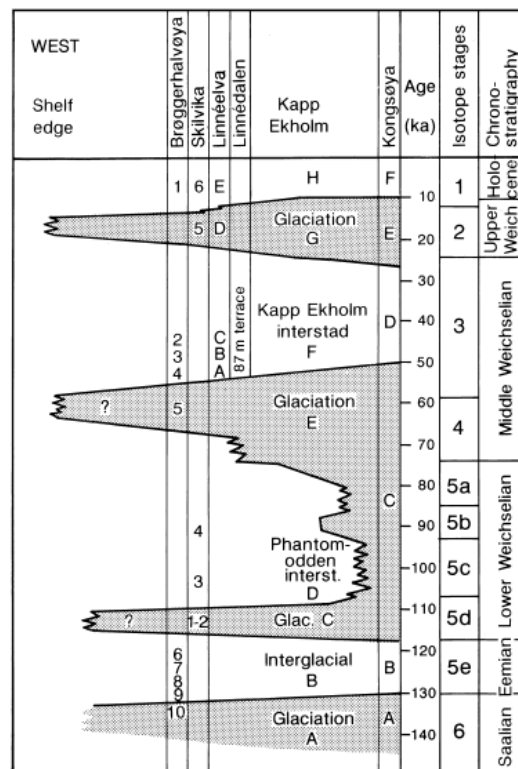


Figure.2-3: A glacialiation curve for the Northern Barents Sea and Svalbard, From Mangerud et al, 1998.

2.3.2 Glaciation history and sedimentary processes

Over the past 117 ky, three glacial maximums of the Eurasian ice cover have been identified. The first is the Early Weichselian, which occurred approximately between 117- 74 ky during Marine Isotope Stage 5d (MIS 5d). This phase was characterized by a dominant eastern ice sheet in the Kara Sea, accompanied by a smaller ice cover in Scandinavia, representing the glacial maximum in the eastern region (Svendsen et al., 2004).

During the Mid-Weichselian period (MIS-4), two significant advances of the ice sheet occurred, as identified by [Larsen et al., 2006](#). The first advance took place from approximately 74- 59 ky, during which the Barents Sea Ice Sheet was connected to the Scandinavian Ice Sheet. The second advance is dated to the period between 55-45 ky.

The Last Glacial Maximum, 20 ky (MIS-2) witnessed the ice reaching its maximum extent over Scandinavia and the Barents Sea ([Siebert et al., 2001](#)).

During full glacial periods, substantial amounts of sediment are deposited on the outer shelf and upper slope of the western Barents Sea. This deposition led to the westward progradation of the Barents Sea continental margin ([Vorren et al., 1989](#)). The margin underwent repeated truncation, indicating erosion caused by grounded ice and subsequent redeposition further westward. This suggests that the ice must have reached the shelf in multiple re-advances. Due to the instability of the large sediment accumulations, several mass wasting events are inferred to have occurred, resulting in the formation of glacigenic debris flows. These debris flows are believed to have contributed to the formation of the glacial debris lobes observed on the TME.

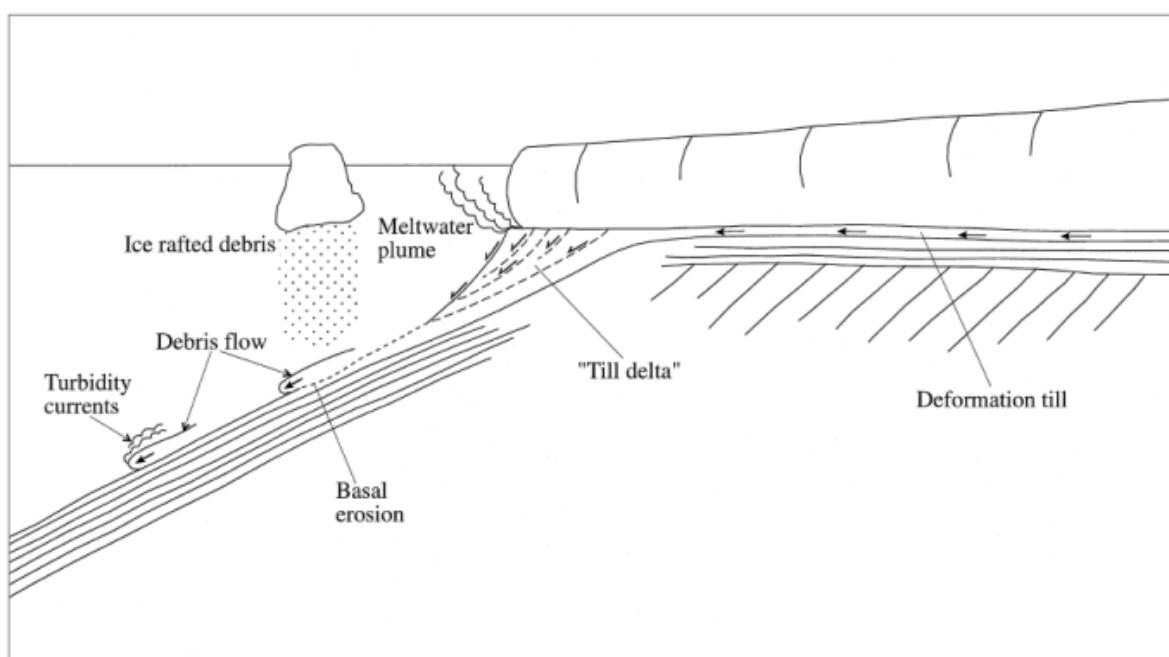


Figure.2-4: A sketch of sedimentary process during glacial interval, From Vorren et al., 1997

2.3.3 Deglaciation history and sedimentary processes

The deglaciation of the northwestern Barents Sea continental margin is a topic of ongoing research, and multiple studies have been conducted to investigate its timing and processes. (Elverhøi et al., 1995; Rebesco et al., 2011, 2013a; and Rütther et al., 2012). Although there are

different interpretations, there is general consensus among scientists that the retreat of glaciers began in the deeper troughs, driven by ocean warming and rising sea levels.

The deglaciation process in the Barents Sea has been divided into five steps, representing the last glacial maximum and the subsequent thawing of the ice (Winsborrow et al., 2010).

The first step corresponds to the Late Weichselian glacial maximum, during which the ice sheet extended across the entire Barents Sea Shelf. (Andreassen & Winsborrow, 2009; Winsborrow et al., 2010). The initial stage of deglaciation commenced approximately 17,5 ky according to Vorren and Laberg (1996). During this phase, there was a notable retreat of the ice margin in the western Barents Sea, followed by a subsequent re-advance within the Bear Island Ice Stream. The ice stream received contributions from tributaries originating from the land (Winsborrow et al., 2010). Later, a significant change in the ice dynamics of the ice sheet occurred. The focal point of the maximum ice volume shifted towards a more eastern location, resulting in the majority of Tromsøflaket and the Bear Island Trough becoming free of ice (Winsborrow et al., 2010). However, the Djuprenna Through Ice Stream and the Nordkappbanken-east, which received ice from the north flowing from the Kola Peninsula, remained active and experienced a readvance (Winsborrow et al., 2010). This stage is estimated to have occurred around 16ky (Winsborrow et al., 2010). The next step, which is estimated to have occurred around 15 ky (Winsborrow et al., 2010), was characterized by glaciomarine conditions north of the Kola Peninsula. During this stage, the southern Barents Sea became free of ice, and the ice margin shifted to the outer-fjord areas in northern Norway. During the last step of deglaciation, there was a notable westward retreat of ice on the Kola Peninsula, while the ice margin continued its southward movement in northern Norway. This stage is estimated to have occurred around 12,5 ky. The beginning of the deglaciation is always marked by a meltwater plume sedimentation which implies a significant discharge of sediment-rich water from the ice streams at the shelf edge in the form of plumites (Hesse et al., 1997). They are represented as laminated deposits characterized by alternating layers of fine sandy silt or coarse silt with clayey silt or silty clay, typically in 1 or 2 cm thickness. These layers, or laminae, are usually planar, occasionally deformed by the presence of dropstones, and the fine sandy silt lamina grades upward into a mud lamina (Dowdeswell, 2001)

2.3.4 Sedimentary process during interglacial periods

The majority of the material deposited in the marine environment has a hemipelagic origin. This material originates from nearby continental areas and is primarily transported into the sea

through aeolian activity and ocean currents (Nichols, 2009). Only a small fraction of the material is deposited on the continental margin and in the deep sea due to the presence of over-deepened ice-free fjords, which act as sediment traps for erosional products from the land. On the continental shelf and upper slope, sediments undergo redistribution by ocean currents. The relatively warm current flows northward over the outer shelf and upper slope, resulting in the selective removal of finer sediments down to depths of 700-800 meters.

2.3.5 bottom current and sedimentary features

Under the effect of bottom current Sedimentological features like contouritic drifts are formed through the resuspension, transport, and deposition of sediment by persistent bottom currents (Rebesco et al., 2008). These deposits, known as sediment drifts or contouritic drifts, exhibit elongated, mounded shapes that are generally parallel to the continental margin and aligned with the direction of the contour currents (Rebesco et al., 2008; Rebesco et al., 2013b) (Fig. 1.6). Two such elongated mounded drifts have been identified on the slope of the Western Spitsbergen margin in the NW Barents Sea, located in front of the Isfjorden TMF and Bellsund TMF (Rebesco et al., 2013b).

In a depositional system influenced by glaciation, sediment flux and the strength of bottom currents are controlled by climatic and oceanographic conditions. Consequently, high-latitude contourite drifts serve as high-resolution paleoceanographic archives (van Weering et al., 2008). With their high and nearly continuous accumulation rates, these drifts provide valuable records for reconstructing the paleoclimatic changes that affected the Svalbard-Barents Sea Ice Sheet (SBSIS) along the NW-Barents Sea continental margin during the Late Pleistocene deglaciation.

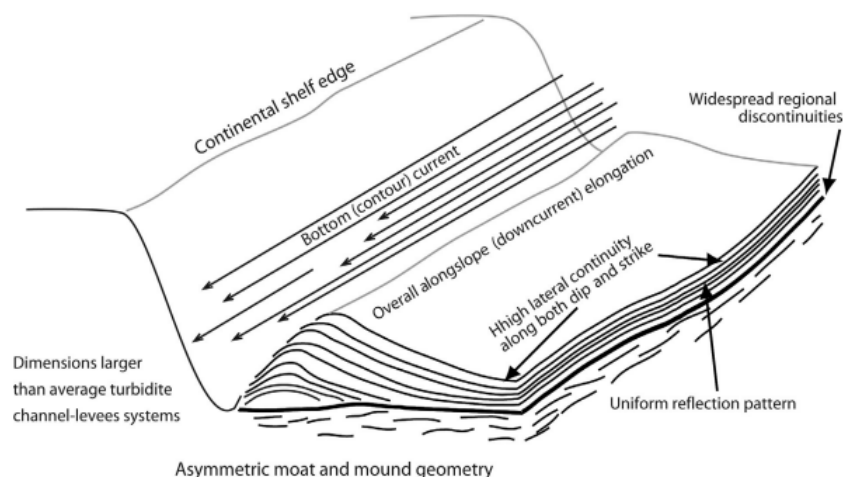


Figure.2-5: A sketch of contourite drift shape, From Rebesco et al., 2014

2.4 Significance of clay minerals along the margin of svalbard

Clay minerals play a crucial role in sediment analysis, providing valuable information about sediment source areas and transport pathways. Numerous studies in the Barents Sea have used clay mineral composition to reconstruct paleoclimatic conditions. Clay minerals are the primary components of deep-sea sediments and have been studied since the 1960s as indicators of paleoclimatic and paleoceanographic conditions. They serve as proxies for determining the origin of fine-grained terrigenous sediments. The $<2\mu\text{m}$ -sized fraction of deep-sea sediments contains various minerals, including smectite, illite, kaolinite, chlorite, quartz, feldspars, mixed-layer minerals, and other non-clay minerals. Clay minerals belong to the phyllosilicate family and consist of two-dimensional tetrahedral and octahedral sheets arranged in a regular array. Sedimentary clays in deep-sea sediments can be categorized into detrital clays, resulting from the physical weathering of continental land masses, and authigenic clays, formed through the weathering or hydrothermal alteration of basalts.

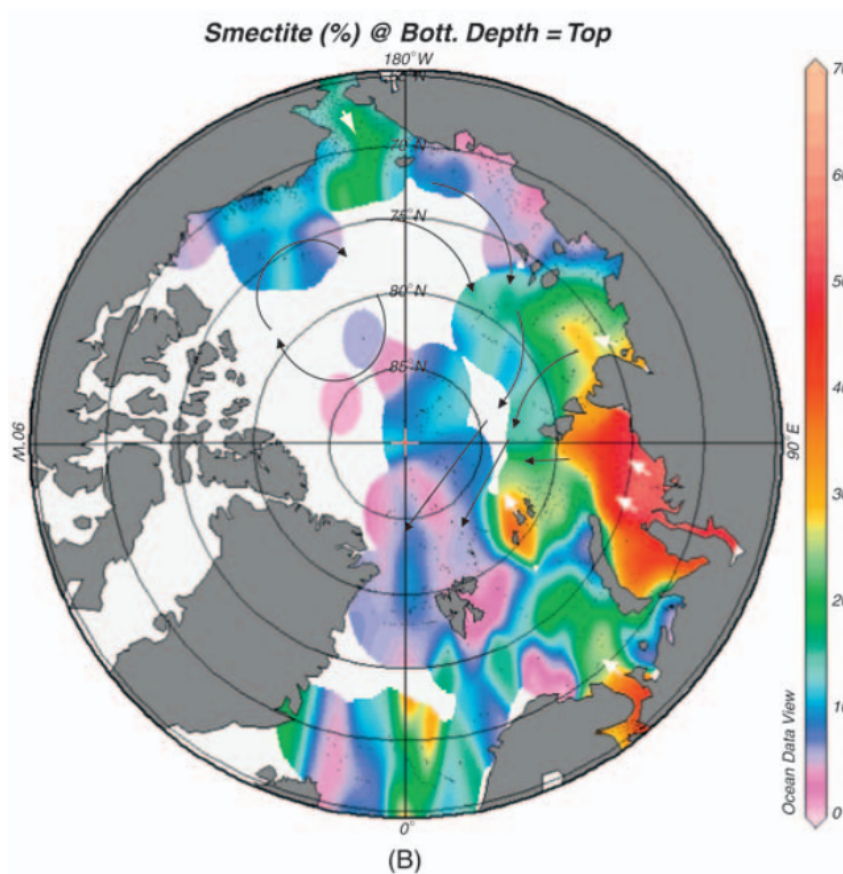
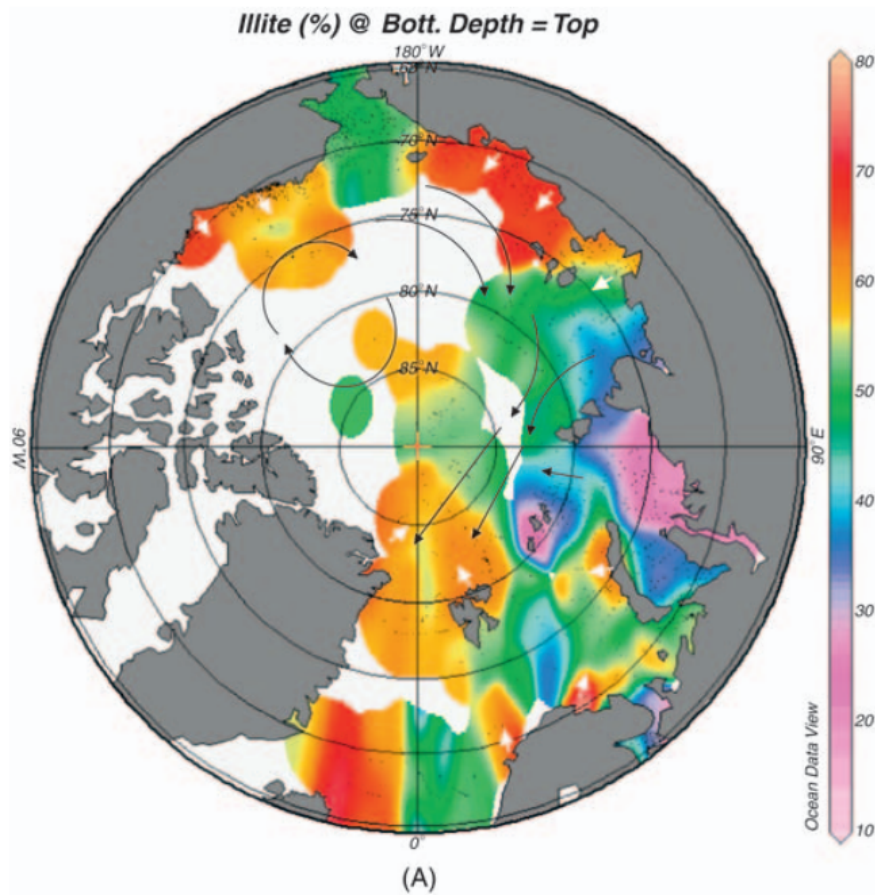
Illite, a characteristic clay mineral for cold regions, is abundant in the Barents Sea and transported from multiple sources. Concentrations of illite are highest north of Svalbard and on the Morris Jesup Rise, indicating the transport of illite-rich material from northern Greenland and Svalbard. Illite is a major component on the northern Barents Sea shelf, sourced from Quaternary moraines on the Kola Peninsula, sediments from the White Sea, and the Pechora River. Novaya Zemlya serves as a source area for illite-rich sediments in the eastern part (Bischof et al., 1996; Vogt, 1997; Saukel, 2006.). In the Kara Sea, lower illite concentrations result from dilution by the high smectite content supplied by the Ob and Yenisey rivers. Illite is associated with physical weathering processes, suggesting glacial climatic conditions (Vogt and Knies, 2009).

Smectite, a minor clay mineral component in the western Barents Sea, is predominantly found in the Svalbard area (Vogt and Knies, 2009). The primary sources of smectites are the hydrolysis, submarine weathering, and diagenetic alteration of volcanogenic material. However, smectites can also form under intense weathering conditions in warm and wet climates (Griffin et al., 1968; Tucker, 1988). It is unlikely that the rocks exposed in the Svalbard area contribute significantly to the production of smectites, as warm and wet climatic conditions have not prevailed in the region since the Miocene Climatic Optimum (Winkler et al., 2002; Knies and Gaina, 2008). Studies conducted by Eisma and van der Gaast (1983), Kuhlemann et al. (1993), and Berner and Wefer (1994) in the Norwegian-Greenland Sea towards the Fram Strait demonstrated a decrease in smectite content from the basaltic

Greenland-Farøe Ridge towards the north along the Norwegian Coast. They also observed minimal presence of smectite in their northernmost samples, which might have been transported by the Norwegian Atlantic Current. As a result the smectite is produced by the alteration of young basaltic rocks on the ocean ridge and transported northwards by the Norwegian Atlantic Current.

The availability of potential source areas for kaolinite in Arctic Ocean sediments is highly limited. The main regions serving as sources for kaolinite are found in the central Barents Sea and on Franz Josef Land (Birkenmajer, 1989; Elverhøi et al., 1989). Local accumulations of kaolinite in the Barents Sea can be attributed to the presence of Triassic and Jurassic sedimentary rocks south of Svalbard and on certain shallow banks. Kaolinite is the result of chemical weathering of soils under warm conditions. However, its occurrence in the Polar regions is attributed to the reworking of pre-existing sediments that contain kaolinite (Chamley, 1989; Junttila et al., 2008).

The distribution of chlorite in surface sediments of the Arctic Ocean is relatively even, without any specific shelf areas exhibiting exceptionally high values in the Eurasian part. Mean chlorite concentrations range from 14% to 25%. However, slightly higher chlorite concentrations are observed along the western coasts of the Novaya Zemlya Island (Nuřnberg et al., 1995) and south of the St. Anna Trough, indicating a local source. In the study area chlorite is commonly found as it is a characteristic component of highly crystalline and metamorphic rocks. These rock types are prevalent in Northern Scandinavia and various highs within the Barents Sea (Elverhøi et al., 1989, 1995). In this region, the presence of clastic rocks, which originate from the erosion of ancient continental shield rocks, also contributes to the abundance of chlorite (Vogt and Knies, 2009). The relatively high content of chlorite in source rocks from Southern Spitsbergen, coupled with physical erosion in cold and nearly arid conditions, explains the occurrence of elevated chlorite values in surface sediments.



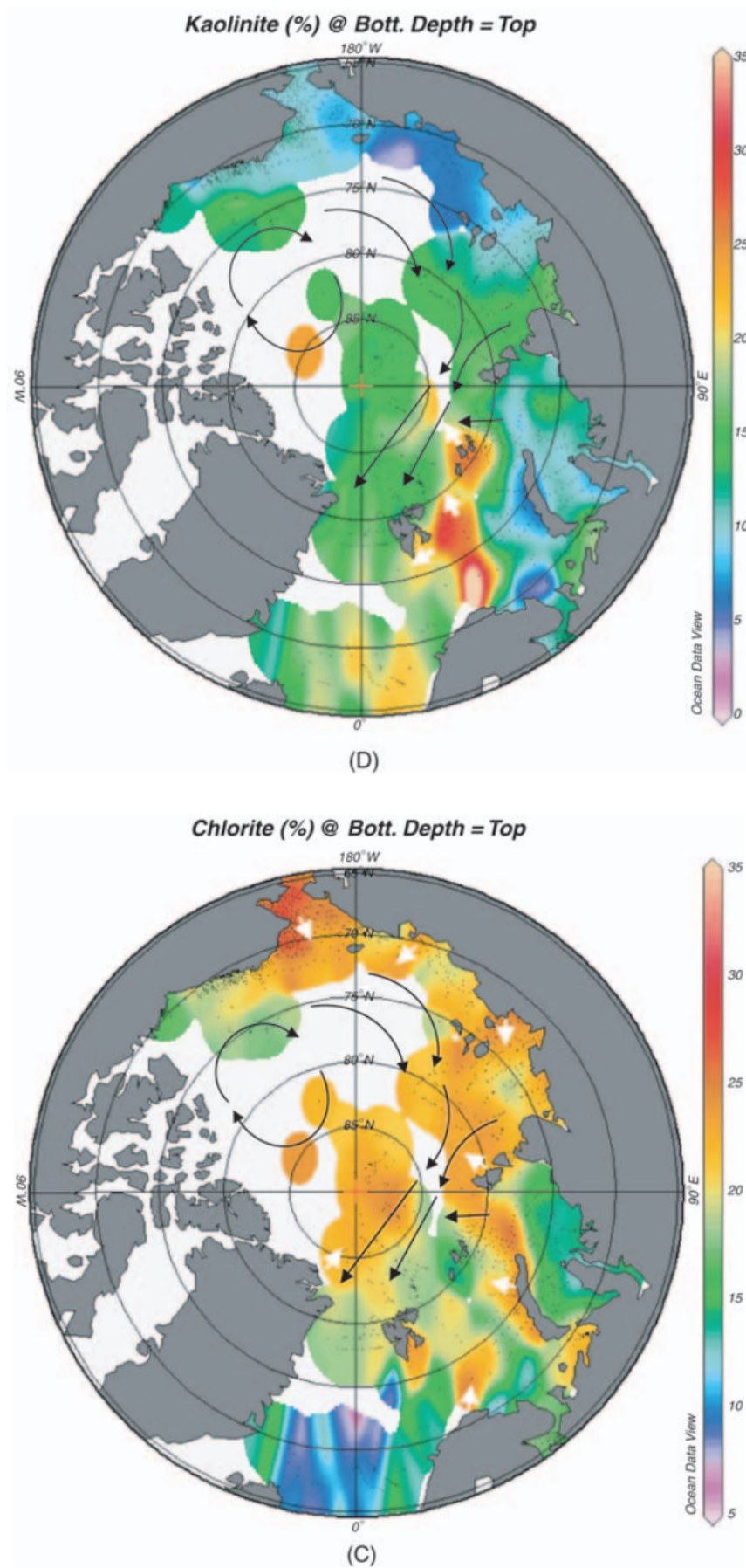


Figure.2-6: Clay mineral distribution in the arctic ocean, from Stein 2008

CHAPTER 3: MATERIALS AND METHODS

This chapter describes the materials used for this study and the methodology adopted during the data acquisition and the analysis of the sediment cores.

3.1. Materials

Within the present PhD project 3 sediment cores derived from 2 scientific projects were analyzed. Additional 2 cores were considered for correlation and validation of the obtained data (Tab 3-1).

Core GS191-02PC was collected during the Eurofleets2-PREPARED cruise (Present and past flow regime on contourite drifts west of Spitsbergen), onboard the Norwegian RV G.O.Sars (Tromsø–Tromsø, 05–15/06/2014, [Lucchi et al., 2014](#)). The core was retrieved from the upper part of the continental slope in a proximal area of the Isfjorden Sediment Drift (**Fig. 3-1**) at 1322 m wd (Tab. 3-1). The core is 17.37 m long, and it was divided in 19 sections.

Core CAGE19-3KH-05GPC-02 and core CAGE19-3KH-15GPC-01 were collected during the CAGE (UiT, Norway) expedition CAGE19-3KH (Calypso giant piston coring in the Atlantic-Arctic gateway- Investigation of continental margin development and effect of tectonic stress on methane release), onboard the Norwegian icebreaker Kronprins Haakon (Longyearbyen–Longyearbyen, 19/10–09/11/2019, [Knies et al., 2019](#)). Core CAGE19-3KH-05GPC-02 was collected from the eastern termination of the Vestnesa Ridge (**Fig. 3-1**) at 1321 m wd (Tab. 3-1). The core is 15.67 m long, and it was divided in 16 sections. After preliminary, scan analyses (see below), this core was subsampled with whole-round samples for geotechnical analyses performed for another research project. Core CAGE19-3KH-15GPC-01 was collected from a distal area of the Isfjorden Sediment Drift at 1579 m wd, at only some 15 km down-slope with respect to core GS191-02PC. Core CAGE19-3KH-15GPC-0 is 15.73 m long, and it was divided in 16 sections.

3.2. Field data acquisition

All the studied sediment cores of the PhD project were collected with a Calypso giant piston corer. In the following it is reported a short presentation of this acquisition system.

Table 3-1. Core location. Grain size analyses were made available for this study, as well as the dataset of two additional cores

Project	Core ID	Water depth (m)	Lat N	Long E	Core length (m)	N. of sections	Location	XRD	Grain size
PREPARED	GS191-02PC	1322	77.5891	10.0915	17,37	19	Isfjorden Drift	183	178
CAGE19-3KH	CAGE19-3KH-05GPC-02	1321	79.1427	05.2749	15.67	16	Vestnesa Ridge	0	121
	CAGE19-3KH-15GPC-01	1579	77.5263	09.8218	15.79	16	Isfjorden Drift	229	168

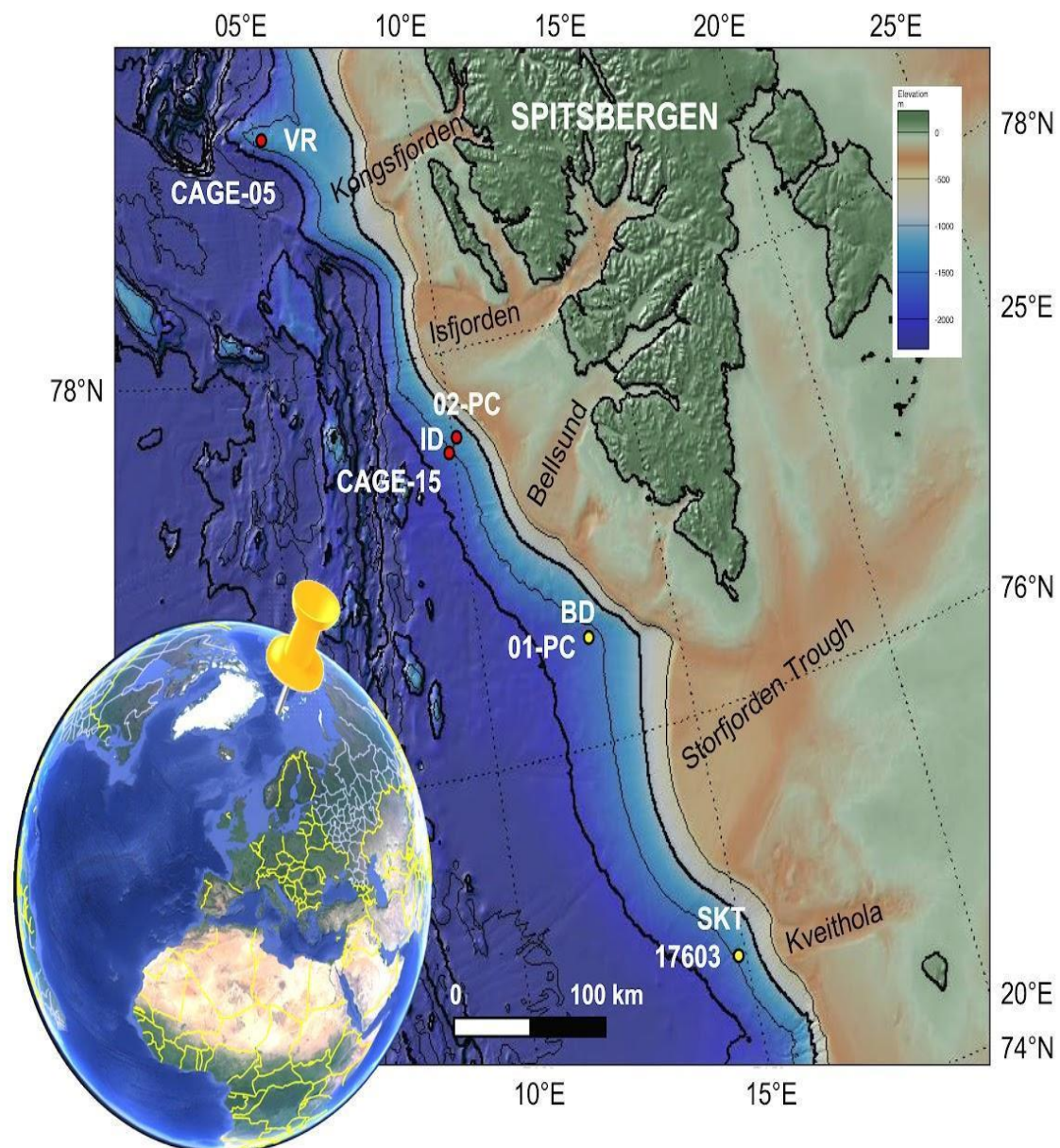


Figure 3-1. Map of the study area (GeoMapApp, Polar Projection, bathymetry IBCAO v3, Jakobsson et al., 2012). Red dots indicate the location of studied sediment cores recovered from the Isfjorden sediment drift (ID, cores 02-PC, CAGE-15) and on the Vestnesa Ridge (VR, core CAGE-05). Bathymetric contours at every 500 m depth (bold lines at every 1000 m). The names of the major glacial troughs are indicated.

3.2.1 The CALYPSO giant piston coring system

The CALYPSO piston corer was developed in the 1980s by the French Research Institute for the Exploitation of the Sea, IFREMER, and allows the penetration of very soft sediments over 60 meters. ([Wiseman, 1947](#); [Hollister et al., 1973](#)).

The studied cores were collected using a CALYPSO Giant Piston corer property of The Norwegian Institute of Marine Research (IMR) and the university of Bergen (UiB).

The whole CALYPSO system is transported within two units: the first unit contains the towing on board system formed by an annular winch containing 4800 metres of synthetic rope measuring 24 mm of diameter, and a control cabin from which the entire coring process can be monitored. The second unit contains the Calypso giant piston corer that is assembled onboard of the research vessel and later released into the sea for sediment sampling.

The CALYPSO coring system is composed of a core catcher which presents a closing system permitting the sediments to pass in a unique direction into the core liners. The core catcher is connected to the steel pipe, containing inside a plastic liner that holds the penetrated sediments. Above the steel pipe there is the core head weight of about 3 tons helping on the penetration of the corer into the sediment. The head weight is related to a trigger system which regulates the modality of core penetration. The trigger system is composed of a trigger arm that is connected to the head weight on one side and on the opposite side is connected with a cable to a counterweight, (**Fig. 3-2**) of about 40 kg, that holds the trigger arm in the horizontal, closing position during the deployment of the coring system. When the counterweight touches the seafloor the trigger cable releases the tension over the trigger arm that moves to the release position provoking the gravity fall of the coring system. The piston plays an important role in reducing the lateral friction during the sediment penetration favoring a deeper penetration, and by maintaining a constant internal pressure to avoid sediment deformations.

Since the inauguration of the Calypso piston corer system, some modifications were undertaken to improve the sediment core quality ([Skinner et al., 2003](#); [Bourillet et al., 2007](#)) by taking in consideration the trigger system bouncing back after the core release, that changes in relation with the type of the cable used during the deployment. The mitigation of this effect requires a precise calculation of the free fall loop length taking in account the free fall height and the possible trigger system bouncing effect.

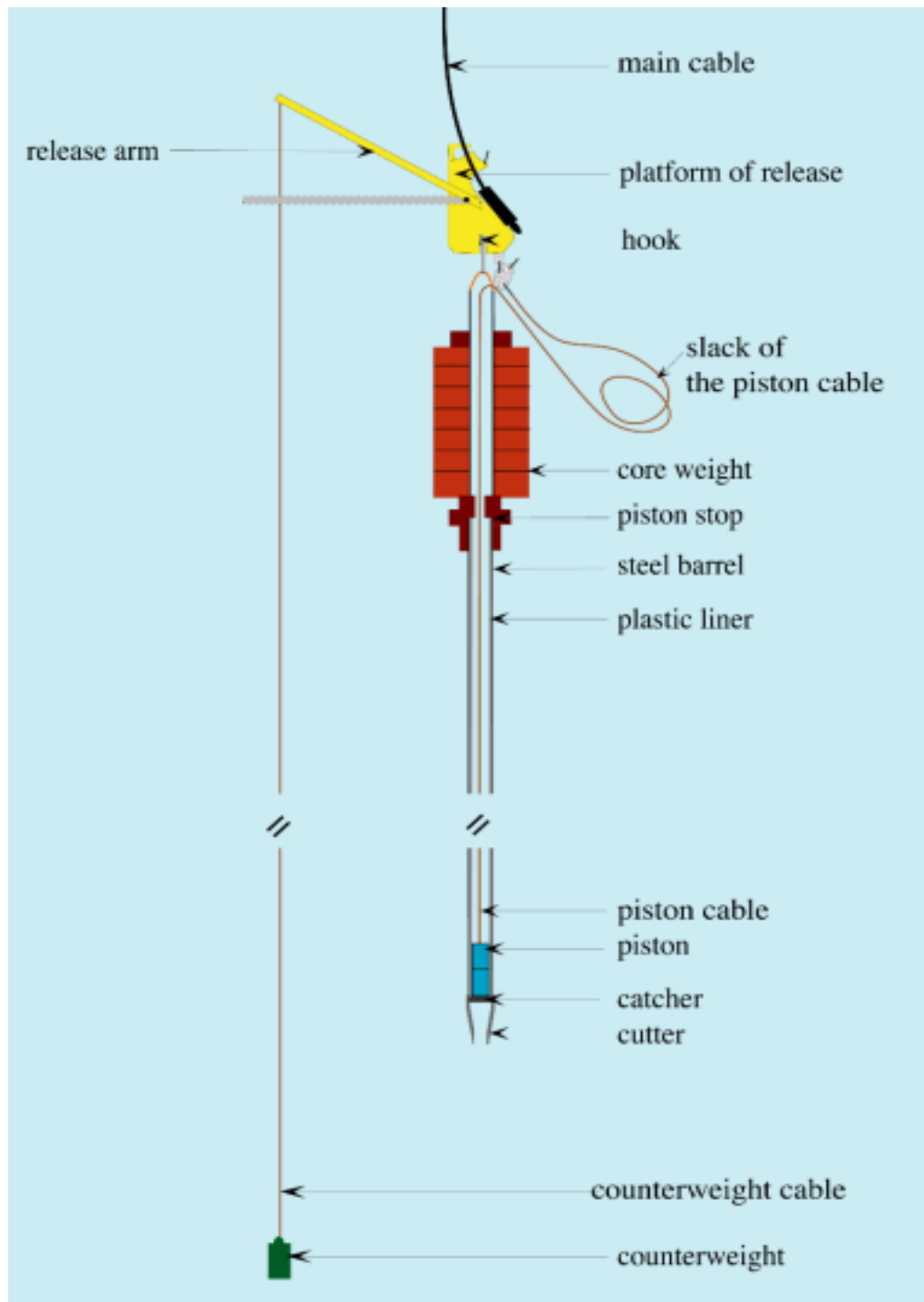


Figure 3-2. The calypso giant piston corer composition (from Bourillet et al., 2007)

3.3. Laboratory analysis

3.3.1 X-ray radiography

X-ray radiography is a non-destructive technique for sediment core analysis that allows for a better investigation of the sediment structures. The method has the same concept of the medical

X-ray body scanner working on the mean differential density. X-rays are generated by applying high energy directly to the cathode, causing electrons to flow through the vacuum tube and collide with the anode (Fujifilm, 2014) while an electron from the cathode and inner shell electron inside the anode hits it. It emits X-rays while the outer shell electrons fill the empty inner shells and produce additional energy (Schad, 2008).

The Multi-angle digital 2D X-ray system developed by GEOTEK (Fig. 3-3) was used in the current study mainly to perform scoutscan analyses that were performed on the whole, unsplit cores at UiT laboratory facilities for CAGE cores, and at ENI laboratories in Milan for the core GS191-02PC. Core CAGE-15 was re-logged after splitting using the GEOTEC XTC-MSCL available at the OGS/UniTS Core Logging Lab, whereas some sections of core CAGE15 containing laminated intervals were re-logged using a pseudo-3D laminography before splitting the core sediment.

A linear digital X-ray image (2D, scout-scan) was obtained on either whole or split cores. The Geotek X-ray core scan (MSCL-XCT) is a fully enclosed system which gives the possibility of being used safely in any laboratory without complicated sample preparation as the core section would be simply loaded horizontally between two motorized arms. The establishment of the scan parameters is made through the interface of the *Geotek acquisition software* (defined in relation with the objective of the study) where it is possible also to visualize in real time the scan operation progress. The core section passes under a 130-kV fixed X-ray source and the attenuation degree of the emitted radiations is captured by a flat panel detector.

Radiograph quality is affected by a variety of factors, including contrast, sharpness, and intensity of the object being imaged. The magnitude and distortion of the images are affected by the geometric configuration of the X-ray tube and/or detector, changes in the thickness of the core components, and the angle of the X-ray beam with the core and detector the connection (Fujifilm, 2014) method. Therefore, in order to obtain a better resolution two major parameters need to be adjusted: 1) The distance between the X-ray source, the sample and the detector, i.e. the distance between the detector and the X-ray source, which can be adjusted either transversely or longitudinally, 2) The image resolution range, which can vary between 30 μm and 350 μm , allowing a better investigation on the sediment structures.

After obtaining the images an adjustment of the brightness contrast is needed by canceling some borders' intensities of the histogram and eliminating the disturbed pixels in addition to some automatic editing on *GQuickView software* interface permitting at the end a better visualization of the core section.

Beside of the 31.46 m measured for the present study, a total of 206.56 m were analyzed during January 2020, as contribution to CAGE19-3KH cruise (Calypso giant piston coring in the Atlantic-Arctic Gateway). Additional X-Ray investigation on core CAGE19-3-KH-15-GPC01, was performed on 8 sections (3, 4, 5, 7, 9, 11, 14 and 15) using a 3D laminography technique, allowing to obtain a pseudo 3D scan image of the sediment cores. This approach is based on tomographic reconstruction of a multitude of 2D images collected at different angles. Generally, 5 tangent planes at different depths of the sediment core section cylinder (-45mm, -22mm, 0mm, +22mm, 45mm) are used to generate the final 3D image.

The X-ray images represent a valuable technique apt at the qualitative and quantitative (e.g. IRD counts) characterisation of sediment cores, and the images are useful to guide the sub-sampling strategy and to evaluate possible core disturbance issues. The images have been used since [Orsi et al., 1990](#) for characterizing sediment cores. Then this technique has undergone a significant evolution and become an important tool used on Paleoclimatic studies (e.g. [St-Onge et al., 2009](#)), Gas hydrate investigation (e.g. [Sun et al., 2021](#)) and even for the determination of structure for compressed fossils by using the laminography approach ([Zuber et al., 2016](#)).



Figure 3.3. The GEOTEK multiangle digital 2D X-ray system at University of Tromsø _UiT.

3.3.2 Multi sensor core logger (MSCL)

Since the late 1980s the Geotek Multi Sensor Core Logger (**Fig. 3-4**) became a crucial instrument for all the geological fields because it measures in a non-destructive way and in a short time several parameters giving a primary idea about the nature of the sediment ([Schultheiss et al., 1992](#)). With this instrument it is possible to operate on a whole or split sediment core measuring several parameters. For this study the following sensor has been used: 1) the magnetic susceptibility determining the amount of magnetically material present in the sediment, 2) the sediment wet bulk density by evaluating the porosity which is in relation with sediment composition and compaction degree.

Other secondary measurements need to be accomplished simultaneously because they enter on the calculation of the previously cited parameters for which it is necessary to evaluate the core thickness (CT) and the temperature (T) by using a platinum resistance thermometer, as reported in [Marum](#) (**Fig. 3-5**). To prevent unwanted effects, the sections were stored overnight in the laboratory prior to measurement. A room temperature of approximately 20.1°C was measured using a thermometer mounted on the device. All parts were assumed to be at room temperature.

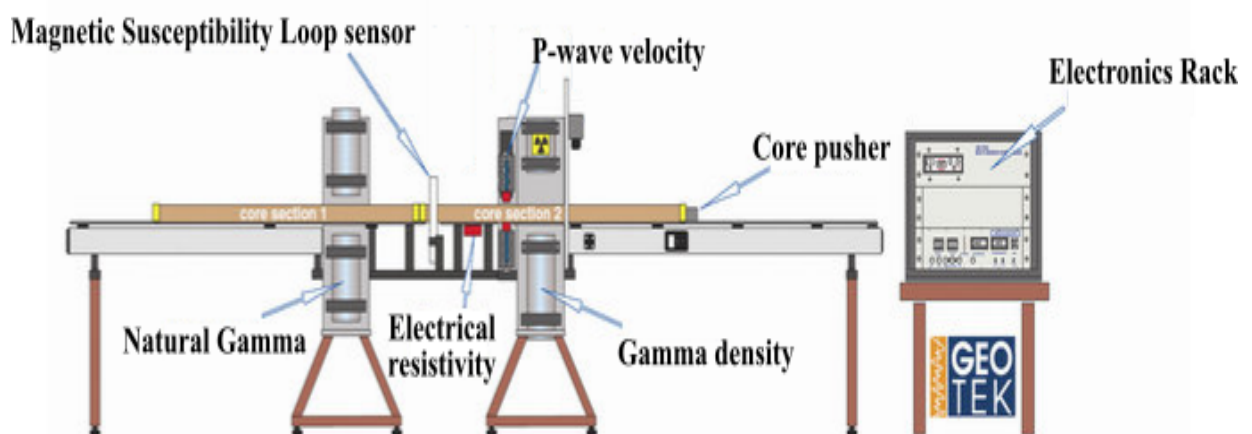


Figure 3.4. A sketch of the multi-sensor core logger setup (GEOTEK, 2000), modified from Vatandoost et al., 2011

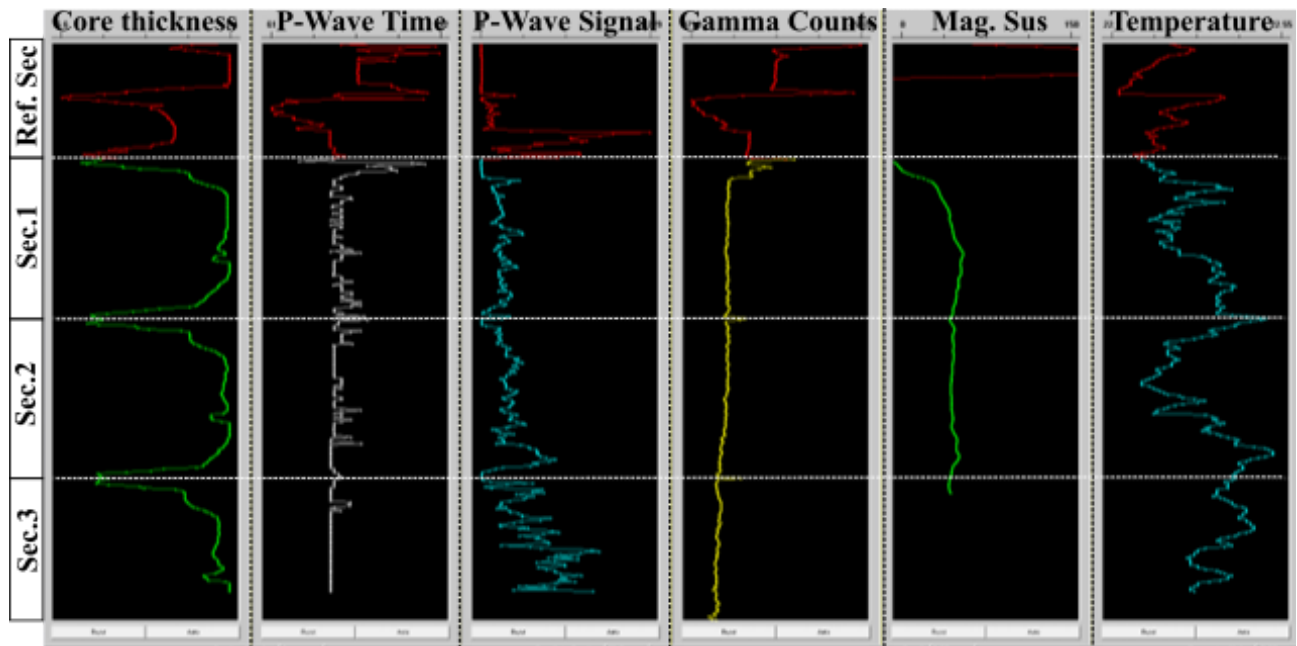


Figure 3-5. Acquisition parameters with the GEOTEK Multi Sensor Core Logger. The red curves in the upper part of the graph are related with the calibration section used always to obtain reference values. The other curves present the acquisition values of the studied sediment core.

3.3.2.1 Magnetic susceptibility

The magnetic susceptibility is the capacity of a material for being magnetized in the presence of an external magnetic field (Thompson, 1986). It can be calculated as the ratio between the interior magnetization of the material and the inducing field, both expressed per unit volume.

The magnetic susceptibility presents a valuable proxy for the core-to-core correlation and for the determination of the sediment's lithological characteristics like the sediment composition. A positive, weak value of the magnetic susceptibility may indicate the presence of *para-magnetic* minerals such as biotite and olivine, whereas the presence of even small quantities of *ferri-* and *ferro-magnetic* minerals (e.g. magnetite, pure iron, some iron oxides) can generate a strong peak in the magnetic susceptibility profile. If the concentration of ferromagnetic materials is low, the measurement record will also include contributions from paramagnetic minerals (such as clay and ferromagnetic silicate) and diamagnetic minerals (such as biogenic carbonate and silica) Stoner et al, 1996. A weak negative value of magnetic susceptibility is in relation with the presence of *dia-magnetic* material such as quartz, carbonate, feldspar, organic matter. It was demonstrated that the values of the magnetic susceptibility can be related with the paleoclimate condition and sedimentary processes (Begè et al., 1990; Smith et al., 2000; Jardanova et al., 2021.) in addition to core-to-core correlation.

There are two different ways of acquisition of the magnetic susceptibility data: a Bartington point sensor MS2E can be used on split sediment core giving a generally better spatial resolution as the sensor is directly in touch with the sediments, instead for the whole sediment cores a Bartington loop sensor MS2C was installed to measure the magnetic susceptibility giving an average value over an interval of 3 cm (minor resolution).

3.3.2.2 Gamma density (wet bulk density)

The sediment bulk density (ρ) is the ratio between the mass (M) of a sediment compound (including minerals, biogenic fraction, and pore water) and its volume (V). The value is usually expressed in kilograms per cubic meter (kg/m^3) or in grams per cubic centimeter (g/cm^3). The wet bulk density is in relation with the sediment grain size, the degree of compaction, the porosity and therefore the water content.

On the multi sensor core logger a non-conventional method was adopted for the determination of the wet bulk density using the gamma ray attenuation porosity evaluator hence the nomenclature of Gamma density or GRAPE density (Evans, 1965). The gamma ray source contains an active element: CsCl, Caesium 137 (^{137}Cs) and it could be beamed in two modalities depending on the collimator's diameter 5 mm or 2.5 mm. This radiation passes through the core section to a specific detector. The difference between the two radiations is proportional to sediment density.

3.3.3 X-ray fluorescence (XRF) core scan

X-ray fluorescence (XRF) is another non-destructive analytical technique that has been used in this study to determine the element composition of the sediments.

The XRF analyses are based on the detection of fluorescence-X obtained during the scan of the core section by the X-ray beam. The primary electromagnetic radiation is generated by an X-Ray source which is composed of a cathode (High – voltage) and anode (High + voltage) assembled together in a glass envelope under vacuum conditions. At a first step, the cathode is heated with high voltage producing a beam of electrons by thermionic emission forwarding to the anode where the electrons generate an Electromagnetic radiation characterized by a short wavelength (λ) and high energy called X-ray. The primary X-rays irradiate a sediment surface causing instability conditions for the atoms. This disturbance is created by the excitation which is translated on the atomic level by the ejection of an electron from the K-shell leading to the creation of a vacancy. As the atom aims to return to a stable condition the inner shell vacancy is always filled by an electron from an outer shell and during this transition the surplus of energy is emitted as a specific X-ray in relation with the difference between the two binding energies of the corresponding shells.

The emitted X-ray produced during this movement is in a proportional relation with the atomic number (Z) and presents a unique entity characterizing each element. The process for which the X-ray leaves carrying the excess of energy is called X-ray Fluorescence (XRF), and the transmission of the XRF from the irradiated surface to the detector occurs through a He-flushed chamber. The XRF detection is based on the transformation of the photon emitted energy to an electric signal which will be transformed into a spectrum (**Fig. 3-5**).

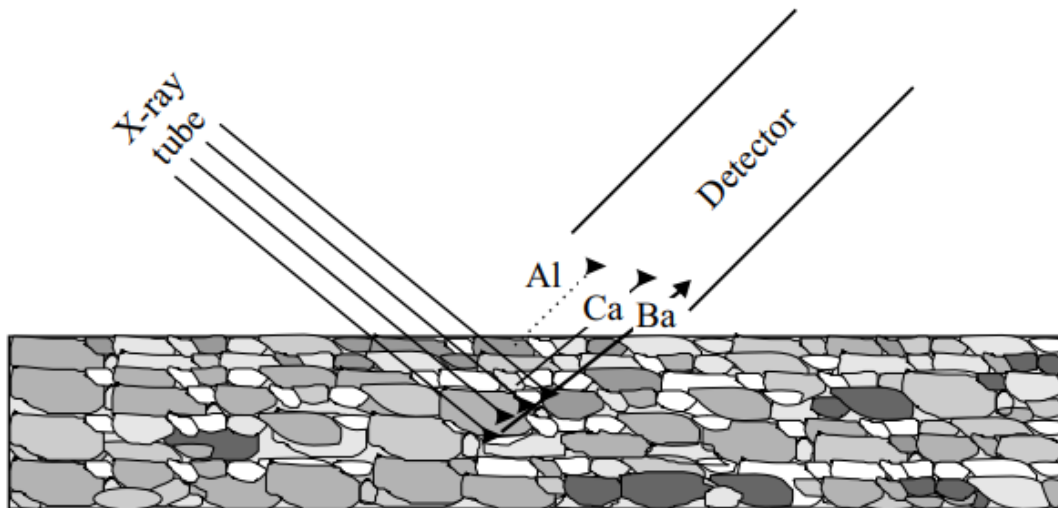


Figure 3-5. A sketch describing the principle of XRF logging on split cores (from Richter et al., 2016)

The power voltage of the X-ray source, that can be set from 5 to 50 kV and from 1 to 2000 μA , has an important impact for the determination of the required elemental range. For this study the analyses were performed using an Avaatech XRF core scan, in which the range of the elements vary according to the atomic weight (Z). The more Z is elevated, the higher energy we need to provide on the source (Richter et al., 2006).

Generally, the measurements are performed in multiple runs using different currents (I), voltage (U) and filters which are applied only to quantify the heavier elements avoiding noise from the lighter elements. The measurement of the light elements from Mg ($Z=12$) to Co ($Z=27$) requires a setting of 10 kV and 1000 μA ; the medium-heavy elements from Ni ($Z=28$) to Mo ($Z=42$) requires a higher energy corresponding to a setting of 30kV and 2000 μA , associated to the use of a Pd-thick filter; and the heavy element from Mo ($Z=42$) to U ($Z=92$) requires a setting of 50kV, 2000 μA and a Cu-filter (Forwick. M, 2013)

Additional parameters can be modified to have a better resolution, such as the measuring time, the size of the investigated areas, and the distance between two consecutive measurements that can be pluri-cm to sub-mm.

The Avaatech XRF core scan acquires the elemental spectra of the inner shells (K and L) which are unique elements occurring at predefined positions (counts Vs Kev 10, 30, 50). Transforming the XRF spectra to counts processing the data through the WinBatch software.

Before starting the XRF core scan, it is mandatory to prepare the core section in an appropriate way in order to obtain a good result. The first step consists of smoothing the sediment surface by eliminating all the uneven areas. The irregularities (e.g. presence of pebbles) on the sediment surface should be flattened to provide a good contact of the XRF sensor on the sediment surface, this includes a check of both section's ends where the presence of the core's caps can prevent a proper measurements. After said sediment preparation, the surface is carefully covered by a very thin (4µm thick) ultralene film, preventing the formation of any trapped air-bubble, reducing the X-ray transmission to the sediments. This operation is necessary to uniform the transmission of X-rays through the sediments and to prevent the contamination of the sensor that is repeatedly placed on the sediment surface during the measurement along the core.

The geochemical composition of sediments and sedimentary rocks is greatly influenced by factors such as source area composition, climatic conditions, sediment transport type, depositional environment and so on. This framework provides detailed information on sediment origin, sediment transport characteristics and directions, paleoclimate, marine cycles, organic matter production, seafloor and sediment oxygenation. Consequently, sedimentation of the complex structure provides valuable insights into marine paleoceanography and paleoclimate (Calvert et al., 2007). Several networks exemplify this relationship. For example, heavy minerals such as zirconium (Zr) and titanium (Ti) are often associated with lower parts of turbidites. Clay minerals rich in potassium (K) are generally associated with turbidite mud. Indicative elements include aluminum (Al), iron (Fe), titanium (Ti), and zirconium (Zr), while silicon (Si) is an indicator of soil composition and yield a lot of work (Croudace et al., 2006; Bertrand et al., 2012). Higher calcium (Ca) content indicates more carbonate in the sediment. Inclusion of iron (Ca/Fe) can determine the ratio of biogenic carbonate to residual clay, indicating an increase in foraminifera in the sample (Rothwell et al., 2006).

The standardized method described in Crowdes and Rothwell (2015) and related materials were used to normalize the selected materials against titanium (Ti). This study used the following ratios as paleoenvironmental indicators: Zr/Rb, which is a proxy for grain size to indicate the high percentage of coarse silt and sand (Wu et al., 2020) Ca/Ti, which was used to calculate differences between biogenic carbonate (Ca) and detrital (Ti) fractions (Olsen, et al., 2012; Lucchi et al., 2013, 2015); Br/Ti was used as an indicator of organic productivity (Thomson et al., 2006.,

[Agnihotri et al., 2008](#); [Itambi et al., 2010](#) [Caley et al., 2011](#)) and Mn/Ti proxy was used as an indicator of Oxy/redox transitions which suggest an oxygenation of the water column ([Crowdes et al., 2015](#); [Moreno et al., 2007](#); [Kylander et al., 2011](#)).

3.3.4 Core visual description

The core visual description takes place after splitting the sediment core section and it can be performed either on the working or the archive half section depending on the established workflow. This investigation consists of a macroscopic description of all the distinguishable sediment characteristics. During this operation several features should be determined and reported on specific forms such as:

- The effective sediment core section length,
- The coring acquisition quality, in terms of possible sediment disturbance like the presence of flow-in that may occur during the coring operation,
- The preliminary qualitative lithology (detritic/terrigenous, biological) including the texture (pebbles, sand, silt, clay, etc.) and sediment consistence (soupy, soft, stiff, etc.),
- The color by using the [Munsell](#) soil color chart permitting a codification of the sediment color. It is always recommended to make the color description forthwith splitting the sediment core to avoid any color alteration due to sediment oxidation,
- The description of sedimentary structures resulting from specific processes that could be either physical, chemical or biological, syngenetic or post-depositional. Such features could include bioturbations generated by biogenic activities, laminations either planar or cross laminations, occurring in relation with the depositional process and environment, lithological contacts that can be gradual, sharp, erosive, irregular, and the presence of micro-faults associated to sediment compaction.

This step has an important value because it provides the preliminary data informing about the possible depositional process and environment and it can guide the sampling strategies that will be adopted for further analysis.

3.3.5 X-ray diffraction (XRD)

Differently to the XRF technique that permitted the determination of the sediment's chemical composition (elemental analysis) the X-ray Diffraction (XRD) is used to identify the mineralogy composition of the sediment. In this project The XRD technique was used to identify the clay minerals assemblage composed of smectites, illites, kaolinites, and chlorites.

The X-ray diffraction derives from an interference between a monochromatic x-ray and a crystalline sample available on the sediment (Hull, 1919). The radiation is produced by a X-ray tube containing an earthed anode in connection with an X-ray generator, both enclosed in a tube stand for protection. During the acquisition time the sample is always in rotation at a constant angular velocity while the detector is in rotation at a double angle of the sample. When the conditions satisfy Bragg's law, the X-ray is diffracted by the sample and the intensity of the signal is recorded by a detector and then converted to a count rate. The Bragg's Law (Bragg, 1912) is the relation between a wavelength (λ) and incident angles (θ) that can provoke intense peaks of reflected radiation described by the following equation:

$$n\lambda = 2d\sin\theta$$

Where n is the diffractor order, d is the lattice interplanar spacing of the crystal, and θ is the X-ray incidence angle.

By the end of the acquisition a curve called *diffractogram* appears on the monitor reporting the peak position where the X-ray beam has been diffracted by the crystal lattice from which the determination of the mineralogy is made.

In this study we used a Siemens D-500 diffractometer with CuK α radiation, and generator setting of 20 mA, 40 kV, belonging to the department of Mathematics and Geosciences at the University of Trieste.

The protocol sample preparation adopted in this study follows the one described by Ebrahimian et al., 1992. About 5 cc of sediment collected with a syringe, frozen and freeze dried permitting the elimination of the pore water through ice sublimation. The samples were then wet sieved with distilled water using a 63 μm mesh in order to separate the sand fraction ($> 63 \mu\text{m}$) from the mud fraction (clay and silt). The fine fraction was treated 12 hours in a peroxide solution at 10 vol. to remove the organic matter and to ensure a better disaggregation of the sediment sample. The separation of the silt from the clay fractions was obtained through centrifugation. The sample was initially centrifuged for 1 minute at 1050 rounds/minute permitting to settle the silty fraction (2–63 μm) on the bottom of the tube. The clay fraction was then settled through 10 minutes of centrifugation at 3980 rounds/minutes. The centrifugation time and velocity were determined after Poppe et al., 1988 that took in consideration the parameters of the Stokes law (Stokes, 1851) including the particle's size, the type of the sediment (composition), density and viscosity. The clay fraction obtained at the end of the centrifugation would be smeared on glass slides ready for the XRD analysis.

Each sample was analyzed with 3 different settings. The first analysis was performed on an air-dried sample scanning between 2° and 40° 2θ with a step size of 0.02° . The obtained diffractogram is considered a control or reference diffractogram. A second run was executed under the same parameters but on a glycolate sample. The sample glycolation permits a better identification of the smectite peak because it swells and expands during this operation. For this, the samples were placed on an oven at 60°C with ethylene glycol solution for 12 hours before the analyses. The third scan was performed on the glycolate samples between 23° and 26° 2θ and step size of 0.01° . This slow scan gives a better resolution and allows the separation of the chlorite-kaolinite twin peaks (**Fig. 3-6**)

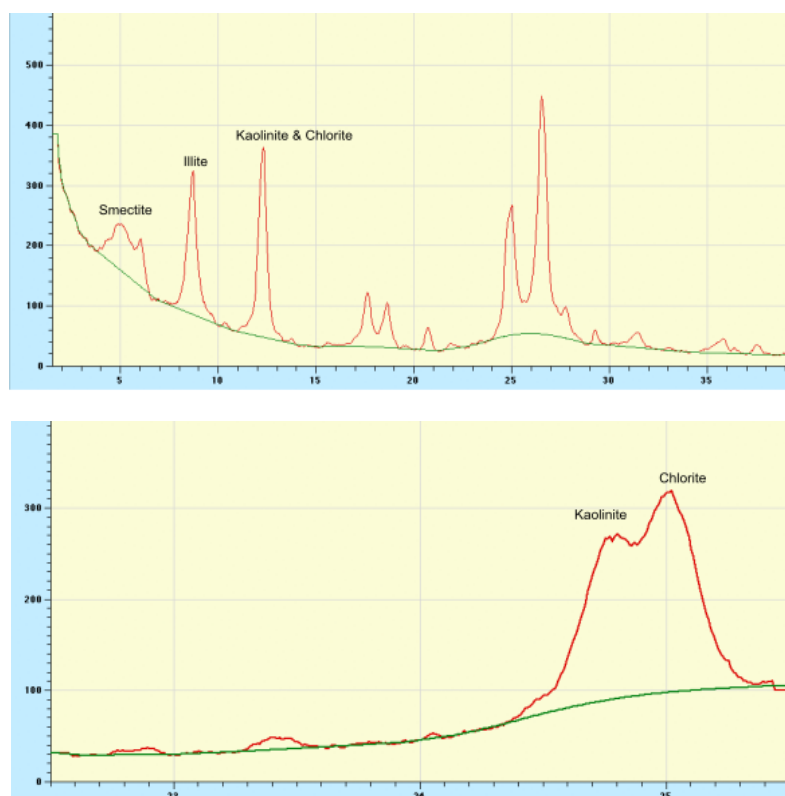


Figure 3-6. Identification of clay mineral peaks on 2 glycolated diffractograms. upper panel: scanned between 2° and 40° 2θ with a step size of 0.02° for smectite and illite; lower panel: scanned between 23° and 26° 2θ and step size of 0.01° for kaolinite and chlorite. (Y Axis= the counts, X axis= value of 2θ CuKα)

The qualitative estimation of the clay mineral percentage was obtained from the glycolate diffractograms using the MacDiff software version 4.2.6 (Petschick, 2010), whereas the identification of the clay mineral groups was based on their specific peaks detectable on the diffractogram according to Biscaye, 1965. The smectite group expands on the base at $17 \text{ \AA}$ on a glycolate phase; the illite is identified at $10 \text{ \AA}$ peak and it is not affected by the glycolation step; the kaolinite and the chlorite have a jointed peak at $7 \text{ \AA}$ but they can be distinguished at $3.54 \text{ \AA}$

for the chlorite and 3.58 Å for the kaolinite. The diffractograms' processing using the MacDiff software starts with a peak analysis based on a peak fitting method that uses the Pseudo Voigt functions. This first step allows to measure the peak areas of the smectite, illite and the jointed chlorite-kaolinite, whilst the chlorite and kaolinite percentages were determined using the weighting factors described by [Biscaye, 1965](#).

The Determination of the abundance of each clay mineral group takes in consideration the following two assumptions:

- 1) The weighting factors for each clay mineral group is applied equally to all the particles belonging to that mineral group in the sediment sample, and the sum of the weighted peak areas accounts for 100% of the clay minerals contained in the sample.
- 2) The peaks and weighting factors were multiplied by: 1x for the smectite glycolate peak area (17 Å) , 4x for Illite glycolate peak area (10 Å) , 2x for kaolinite-chlorite twin glycolate peaks area (7 Å), taking in consideration the intensity of each mineral detectable on the low scan diffractogram, (second and third run). The semi-quantitative analysis of the clay mineral assemblages was determined as the following mathematical equations and it was assumed values fluctuations of about 2% according to [Junttila et al., 2010](#):

$$\% \text{ smectite} = \frac{\text{smectite}_{\text{area}} * 100}{\text{smectite}_{\text{area}} + 4 \text{ illite}_{\text{area}} + 2 (\text{kaolinite} + \text{chlorite})_{\text{area}}}$$

$$\% \text{ illite} = \frac{4 \text{ illite}_{\text{area}} * 100}{\text{smectite}_{\text{area}} + 4 \text{ illite}_{\text{area}} + 2 (\text{kaolinite} + \text{chlorite})_{\text{area}}}$$

$$\% \text{ kaolinite} = \frac{2 \text{ kaolinite}_{\text{intensity}} * 100}{\text{smectite}_{\text{area}} + 4 \text{ illite}_{\text{area}} + 2 (\text{kaolinite} + \text{chlorite})_{\text{area}}}$$

$$\% \text{ chlorite} = \frac{2 \text{ chlorite}_{\text{intensity}} * 100}{\text{smectite}_{\text{area}} + 4 \text{ illite}_{\text{area}} + 2 (\text{kaolinite} + \text{chlorite})_{\text{area}}}$$

$$\text{kaolinite}_{3.58\text{\AA} \text{ peak area}} = \frac{(\text{kaolinite} + \text{chlorite})_{7\text{\AA} \text{ peak area}} * \text{kaolinite}_{3.58\text{\AA} \text{ peak intensity}}}{\text{kaolinite}_{3.58\text{\AA} \text{ peak intensity}} + 4 \text{ chlorite}_{3.54\text{\AA} \text{ peak intensity}}}$$

$$\text{chlorite}_{3.54\text{\AA} \text{ peak area}} = \frac{(\text{kaolinite} + \text{chlorite})_{7\text{\AA} \text{ peak area}} * \text{chlorite}_{3.54\text{\AA} \text{ peak intensity}}}{\text{kaolinite}_{3.58\text{\AA} \text{ peak intensity}} + 4 \text{ chlorite}_{3.54\text{\AA} \text{ peak intensity}}}$$

3.3.6 Total Organic Carbon and Total Nitrogen

For total organic carbon (TOC) and total nitrogen (TN) analyses, the sediment samples were subjected to the following steps: freeze-drying, grinding in ceramic mortars, and sieving through 250 µm iron-steel sieve (Endecotts LTD, UK). Triplicate subsamples weighing approximately 8-12 mg were measured using a micro ultrabalance with an accuracy of 0.1 µg. These subsamples were then placed directly into silver capsules for TOC analysis and into tin capsules for TN analysis. Subsamples of the capsules were treated with increasing concentrations of HCl (0.1 N and 1 N) to remove the carbonate fraction prior to TOC determination (Nieuwenhuize et al., 1994). The carbon-nitrogen content was determined using a CHNO-S elemental analyzer (mod. ECS 4010, Costech, Italy) using the method described by Pella et al., 1973 and stained with standard acetanilide (Costech, purity $\geq$ 99.5%); used to calibrate the instrument, and empty capsules were analyzed for any external contamination. The quality of the measurements was controlled by calculating internal values, the carbon measurements were used against sea in a certified sediment reference PACS-2 (National Research Council of Canada). The relative standard deviations of three replicate determinations were less than 3%. TOC and TN concentrations mg C g⁻¹ d.w. (dry weight) and mg N g⁻¹ d.w., respectively. The analysis was performed at the chemical oceanography laboratory of the National Institute of Oceanography and Applied Geophysics_OGS.

3.3.7 Grain size analysis

Sediment grain-size analyses were performed with a BECKMAN COULTER LS 13 320 Laser Diffraction Particle Size Analyzer, measuring the 0.017–2000 µm fraction. The samples were pre-treated with 10 % m/v hydrogen peroxide, dispersed with 5 % m/v sodium hexametaphosphate and sonicated for 1 min before measurement. Grain-size classes were determined using the Udden-Wentworth (Wentworth, 1922). Grain size analysis of core 02-PC was performed at the university of Barcelona while analysis of core CAGE-15 was performed at the chemical oceanography laboratory of the OGS. whereas Grain size distribution in core CAGE-5 was obtained by wet sieving at 63 microns allowing to distinguish the mud (clay and silt) fraction from that coarser than 63 microns (coarse fraction).

CHAPTER 4: RESULTS

4.1 Lithological sediment characteristics

The geological dataset is characterized by a generally fine grained lithology (sand 15%, silt 45%, clay 40%) with coarser intervals containing Ice Rafted Debris (IRD). Core GS191-02PC, located in a proximal location with respect to the continental shelf edge, is the one that contains coarser-grained sediment compared to the distal core CAGE19-3KH-15GPC, located down-slope with respect to the former core, and with respect to core CAGE19-3KH-5GPC located in the western termination of the Vestnesa Ridge. Through the visual cores description 4 main sedimentary facies have been identified:

4.1.1 Bioturbated facies

This facies is principally present in the upper part of all the studied sediment cores where it can reach a thickness of up to 2 m (core CAGE19-3KH-5GPC), but it was also present in smaller intervals (up to 20 cm of thickness on core GS191-02PC) within the sediment record. This facies is characterized by a relatively light color, that varies between gray (2.5Y5/1) and dark gray (5Y4/1) according to the Munsell color chart. The grain size distribution is generally marked by the absence of IRD and the dominance of silt and clay fractions which together can represent 85 % of the whole grain size. The bioturbated facies is characterized by the lowest bulk density values, ranging from 1.2–1.4 g/cm³, and by moderately low K/Ti values (2.5 % average). In addition, the sediment exhibits diffuse bioturbation structures (mottling) and is rich in calcareous and silicated biogenic fraction suggesting favorable environmental conditions for the biological activity ([Torricella et al., 2021](#)). The evidence of relatively high bio productivity is confirmed by the XRF indicators such as Si/Al, Ca/Ti and Br/Ti, which together register the higher values of the recovered marine records with averages of 12 % , 15 % , and 0.4 % respectively.

4.1.2 Laminated facies

This facies was identified on all the studied sediment cores although it is more developed in core GS191-02PC, which contains 5 intervals of laminated sediments up to 120 cm thick, for a total of about 4 meters. The color of this facies varies from dark gray (5Y 4/1) to very dark gray (5Y 3/1)

according to the Munsell color chart. The sediment texture consists of an alternation of generally coarse grained sediments composed by medium-coarse silt or by sand (clayey silt – sand) locally containing IRD, and fine grained sediments (fine to very fine silt and clay). The alternation of the two lithologies is outlined by the trend of the textural proxy Zr/Rb that shows several fluctuations with high values (up to 6%) corresponding to coarser grained intervals, coherently with the grain size distribution (Fig. 4.1). Within the laminated facies, the grain size tends to decrease upward, as was observed in core CAGE19-3KH-15GPC, in the interval between 1010–1040 cm bsf (averages from 4% to 2%), and in core GS191-02PC, between 480–570 cm bsf (averages from 3% to 2%). Furthermore, core GS191-02PC (proximal area of deposition) was found to have coarser laminated sediments than core CAGE19-3KH-15GPC, located downslope and core CAGE19-3KH-5GPC located north (Vestnesa Ridge) both recovered in distal depositional areas. In contrast with the bioturbated sediments, the laminated facies is characterized by the absence of biogenic activity as outlined by the absence of bioturbation, the almost barren sediments, And the very low XRF indicators of productivity Ca/Ti and Br/Ti that are almost proximal to zero (averages of 1% and 0.05% respectively), with the only exception of the Si/Al ratio, which can sign a slight increase (locally up to 12%). In all the studied sediment cores, the laminated intervals are characterized by low K/Ti values (2% average).

4.1.3 IRD-rich Facies

This is the most common facies throughout the sediment cores representing about 60 % of the record. The color of the IRD-rich facies varies between dark gray (2.5Y 4/1) and very dark gray (2.5Y 3/1) according to the Munsell color chart.

This facies was distinguished in 2 sub-facies:

i) Layered, massive IRD sub-facies, characterized by massive occurrence of IRD within well-defined layers that can be sub-cm or several cm thick. Coherently, the bulk density of the IRD massive facies is relatively high (max 1.8 g/cm³). The presence of IRD and the consequent increase in grain size is registered by the Zr/Rb ratio which peaks in correspondence of such layers (maximum of 6% and averages of 1.5%) coherently with the percentage of sand fraction, which can exceed the 20% of the total weight, like in core GS191-02PC at the interval between 1460–1500 cm bsf, or the 40% of the total weight like in core CAGE19-3KH-15GPC at 800 cm bsf. This subfacies is characterized by low values of XRF bioindicators ratios (averages of Ca/Ti 3%, Si/Al 7% and Br/Ti 0.2%), with high K/Ti ratio (averages of 4%). The layered, massive IRD sub-facies is often characterized by the presence of a prominent Mn/Ti peak at the base of the layer.

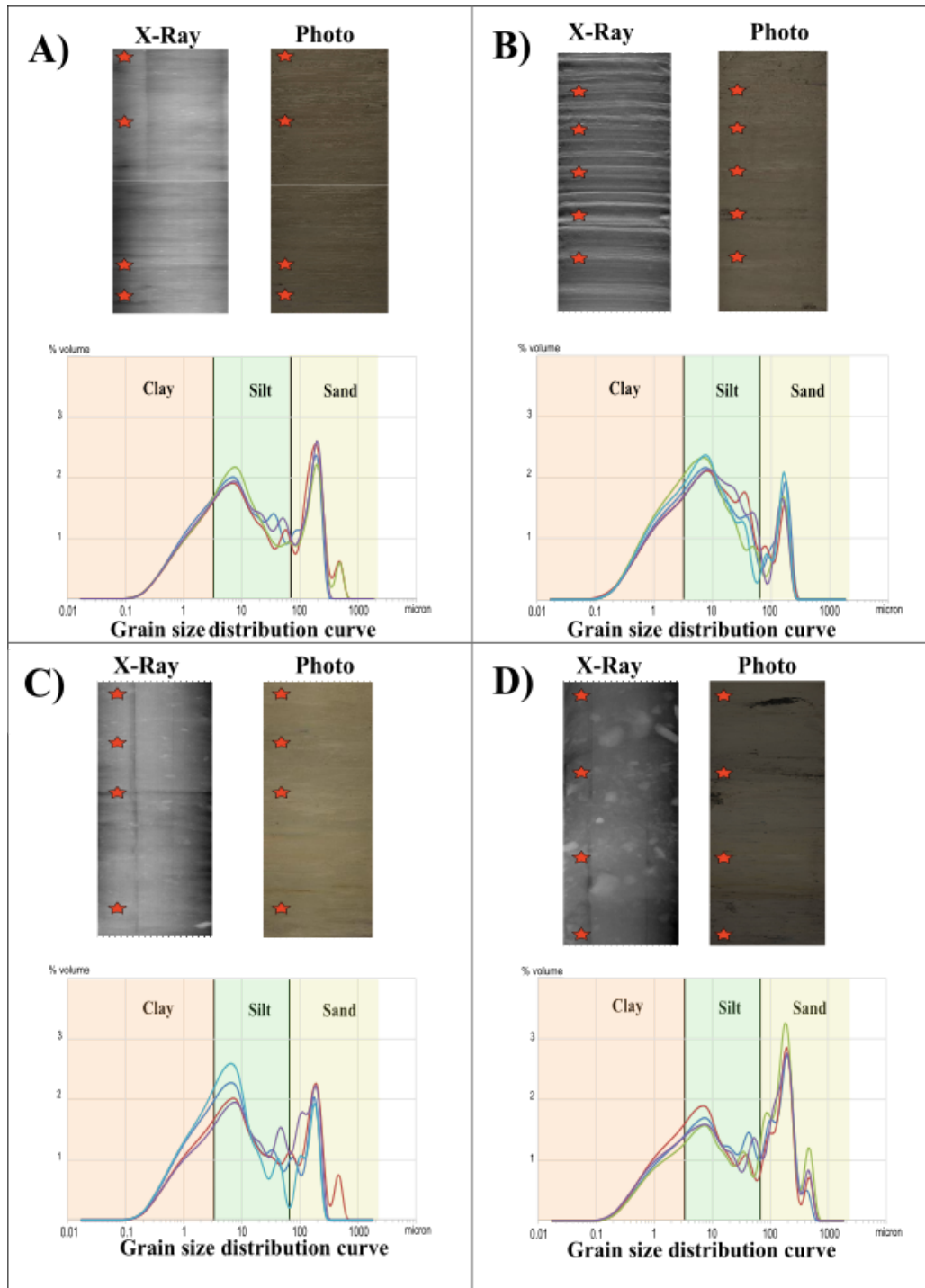


Figure 4-1: The 4 main identified lithofacies with X-Ray, Photo and frequency curve. A) Bioturbated facies, B) laminated facies, C) Bioturbated IRD-rich facies, D) Layered, massive IRD facies.

ii) Bioturbated IRD-rich facies composed by randomly distributed grains and pebbles in a clayey silt matrix, so that the grain size of this sub-facies is finer-grained than for facies 3a. The bioturbated IRD-rich facies is characterized by a silt content average of about 50%, with a maximum sand content of 10%. This facies has a moderate bulk density that is generally lower than that of the massive IRD subfacies, with averages of 1.5 g/cm^3 in core CAGE19-3KH-15GPC located in the distal area of the

Isfjorden sediment drift, and 1.4 g/cm^3 in core CAGE19-3KH-5GPC located in the western termination of the Vestnesa Ridge, also representing a distal area of deposition with respect to the continental shelf break. The detritic origin of this kind of sedimentation is confirmed by the relatively high values of the K/Ti ratio (3% average) if compared with the bioturbated facies. In contrast to the massive IRD sub-facies, the bioturbated IRD-rich facies contains sedimentary structures indicating biogenic activity (bioturbation), which is also outlined by the XRF bio-indicators (averages of 10% Si/Al, 12% Ca/Ti and 0.3% Br/Ti), which increases slightly in these intervals with respect to the massive IRD facies.

4.2 Core GS191-02PC: upper slope of the Isfjorden Drift

4.2.1 General core description

Core GS191-02PC (hereafter indicated as core 02-PC) contains in the upper 180 cm (0–180 cm bsf), bioturbated sediments, overlaying 90 cm of bioturbated IRD-rich sediment (180–290 cm bsf). Between 290–410 cm bsf, the marine sediment record registered a first laminated interval having a thickness of 120 cm. This is followed between 410–480 cm bsf by the two subfacies of IRD-rich sediment: the layered, massive IRD facies, which is about 20 cm thick (410–430 cm bsf), containing a marked oxidized interval at its base, and a bioturbated IRD-rich facies about 40 cm thick located between 440–480 cm bsf. From 480 to 570 cm bsf, a second laminated interval was identified, overlying 160 cm of bioturbated sediment located between 570–730 cm bsf. Between 730–820 cm bsf, another laminated facies was recorded having a thickness of 90 cm, and characterized by abundant IRD concentrated in the upper 30 cm. From 820 to 1650 cm bsf, the sedimentation within 02-PC core is marked by a succession of interbedded layered, massive IRD facies and bioturbated IRD rich sediments, except for a short laminated interval measuring about 20 cm and situated between 1080–1100 cm bsf. The deepest part of the core (1650–1736 cm bsf) contains another laminated interval, about 50 cm thick, that has a finer grain size compared to the other younger laminated facies. The older laminated interval is followed down-core by IRD rich sediment to the bottom of the core.

4.2.2 Physical parameters (grain size)

The trend of sand distribution (Fig.4-2) through the core is generally flat and slightly decreasing in the uppermost 710 cm bsf, while the trend of the silt fraction is more variable down core (Fig.4-2). In detail: in the upper 410 cm (0–410 cm bsf) the sandy fraction gradually decreases from 20% to 5% at

410 cm, except for an isolated peak registered at 240 cm bsf, corresponding to the IRD-rich facies where the sandy weight reaches 25%. The decrease in sand content in the uppermost part of the core is accompanied by an opposite trend of silt as the values show a general slight increase from 45% to 50%, except for a short interval located between 180–290 cm bsf where values decrease by 3% (from 50% to 47%) . The rest of the core (410–1736 cm bsf), is marked by a very low sand content, varying between 0% and 5%, with local pronounced peaks corresponding to the laminated facies like between 730–820 cm bsf, and 1080–1100 cm bsf, with sand up to 30% and 40% respectively, and layered, massive IRD facies like at 1350 cm bsf, between 1460–1500 cm bsf with sand picking at 25% and at 1580 cm bsf, where the sand is up to 15%). On the other hand, the silt curve shows more variations; between 410–900 cm bsf the silt content shows an average value of 40% with two higher intervals located between 480–570 cm bsf and 730–820 cm bsf, both corresponding to laminated sediments where the silt increases up to 50%. In the deeper part of the sediment core (900–1537 cm bsf), the silt fraction maintains an average of about 48% except at 1090 cm bsf, where it peaks at 60%, in correspondence to the short laminated interval.

The wet bulk density data for core 02-PC were not reliable due to the presence of sea water on the upper sections.

4.2.3 Chemical composition of the 02PC

4.2.3.1 XRF core scan analyses

The Zr/Rb varies from 1 to 3 (2 average) through the core (Fig.4-2). The curve appears strongly correlated with the curve of the silt content. In the upper 220 cm (0–220 cm bsf), the Zr/Rb ratio shows a slight decrease as values gradually decrease from 3 in the uppermost part of the core to 2 at 220 cm bsf. From 220 to 820 cm bsf, the Zr/Rb curve shows several alternations of intervals characterized by high values (mean value 3) and intervals with low values (mean value 1.5).

The three main intervals with high values are located between 220–420, 480–570, and 720–830 cm bsf corresponding to the laminated facies containing several fluctuations with high values associated with the coarser grained layers. The laminated interval located between 720–830 cm bsf, is characterized by generally high values of Zr/Rb ratio, and by marked, progressive up-core increase of the values due to the consistent presence of massive IRD occurring in the upper part (720–770 cm bsf) of the laminated interval, with a maximum peak of 6. The intervals with low values are situated between 420–480, and 570–720 cm bsf, corresponding to the bioturbated facies. Between 830–1070 cm bsf, the Zr/Rb values tend to increase slightly, with local peaks up to 4 located at 870, 920, and

1010 cm bsf in correspondence with layered, massive IRD intervals. From 1080 to 1110 cm bsf the values increase again within a 20 cm thick laminated interval with mean values of 3.5. In the deepest part of the core (1110–1734 cm bsf) the Zr/Rb values appear to stabilize at 1.5 with several local peaks corresponding to massive IRD horizons/layers and laminated intervals. The deepest laminated interval located between 1650–1700 cm bsf, unlike the preceding laminated intervals, does not show significant increasing values maintaining moderately low values of about 2.

The Si/Ti ratio does not show significant variations over the sediment record (Fig.4-2). The curve shows a gradual increasing trend down-core, with values up to 3 in the uppermost part of the core, and up to 5 in the lower part of the core. Some minor fluctuations were observed within the core with peaks between 420–480, 570–720, and 1020–1050 cm bsf, which are related to the bioturbated IRD-rich facies. Furthermore, the curve registers a local minimum in the interval between 480–570 cm bsf corresponding to the second laminated interval

The K/Ti ratio varies from 2 to 4, showing drastic changes in correspondence of some depositional facies (Fig.4-2). In the uppermost 220 cm of the core (0–220 cm bsf) the mean values are stable around 2.7 (bioturbated facies). The K/Ti values remarkably decrease in the interval between 220–420 cm bsf, where values remain consistently around 2 in correspondence with the laminated interval. Between 420–480 cm bsf, the K/Ti values increase rapidly peaking at 3.7, then in the following 90 cm (480–570 cm bsf), the values suddenly drop down to 2.5 in correspondence of the second laminated interval. From 570 to 720 cm bsf, within the bioturbated facies, the K/Ti ratio rises again with maximum values of 3.8 and mean value of 3.3. The laminated interval located between 720–830 cm bsf, is characterised by generally low (2 average) K/Ti values, with particularly low values (2.5 average) in the upper 60 cm (720–780 cm bsf) containing also massive IRD. In the deeper part of the core (830–1734 cm bsf), the K/Ti ratio gradually decreases with minimum values of 2 (average) located between 1630–1720 cm bsf in correspondence of the deepest laminated interval.

The Mn/Ti ratio is characterized by very low values ranging from 0 to 0.2 (Fig.4-2), but the down-core trend shows several significant peaks: at 570, 830, and 1100 cm bsf in correspondence with the base of laminated intervals, and at 1320, and 1520 cm bsf in correspondence with the base of massive IRD-rich layers. These local peaks always occur before an increase in the XRF bio-indicators ratio which is particularly evident in Si/Al ratio. Furthermore, two distinct intervals with slightly higher values were identified between 570–720 cm bsf and 830–900 cm bsf in association with bioturbated IRD rich facies.

The Si/Al ratio varies from 10 to 15 with 12 on average (Fig.4-2). The ratio is characterized by a large variability in the uppermost 180 cm (0–180 cm bsf) with values varying between 12–18. Between 180–290 cm bsf the trend is characterized by a progressively reduced variability and decrease from 12 to 10. Between 290–480 cm bsf, the values do not show much variation and remain stable with an average of 10. Then, for the following 90 cm (480–570 cm bsf), the Si/Al values increase to an average of 13 in correspondence with a laminated interval. From 570 to 770 cm bsf, the Si/Al ratio shows a slight decrease (from 10 to 9) reaching the minimum of 9 in correspondence with the laminated facies containing massive IRD. Following down-core, although the general decreasing trend, the curve is characterized by an interval of higher values (average 11) occurring between 680–720 cm bsf corresponding to IRD free bioturbated interval. From 770 to 1100 cm bsf, the Si/Ti curve shows a slight increase and reaches a maximum value of 5.5 between 1080–1100 cm bsf in correspondence with a short laminated interval. On the deeper part of the sediment core (1100–1734 cm bsf), the Si/Ti ratio shows a general decrease from 5.5 to 4.5 marked by some local minima in correspondence with layered, massive IRD intervals.

Ca/Ti and Br/Ti have a very similar trend, generally characterized by low values (0–3 for Ca/Ti and 0.1–0.15 for Br/Ti) with some local exceptions (Fig.4-2). In the uppermost 220 cm (0–220 cm bsf) Ca/Ti and Br/Ti ratios show higher values (average 4 for Ca/Ti, and average 0.25 for Br/Ti) in correspondence with the bioturbated facies. Between 220–880 cm bsf, both curves record an alternation between intervals of low and high values, with the low values occurring within the laminated sediment located at 220–420, 480–570, and 720–830 cm bsf, while the intervals of higher values correspond to the bioturbated sediment located at 420–480, 570–720, and 830–880 cm bsf. In the deepest part of the core (880–1734 cm bsf), both values remain stable with low values having an average of 3 for Ca/Ti, and average of 0.1 for Br/Ti.

4.2.2.2 Total organic carbon (TOC) and total nitrogen (TN)

The TOC / TN shows some local peaks that corresponding with IRD rich interval and laminated intervals located at 1650, 1500 1100, 750, 500 m bsf

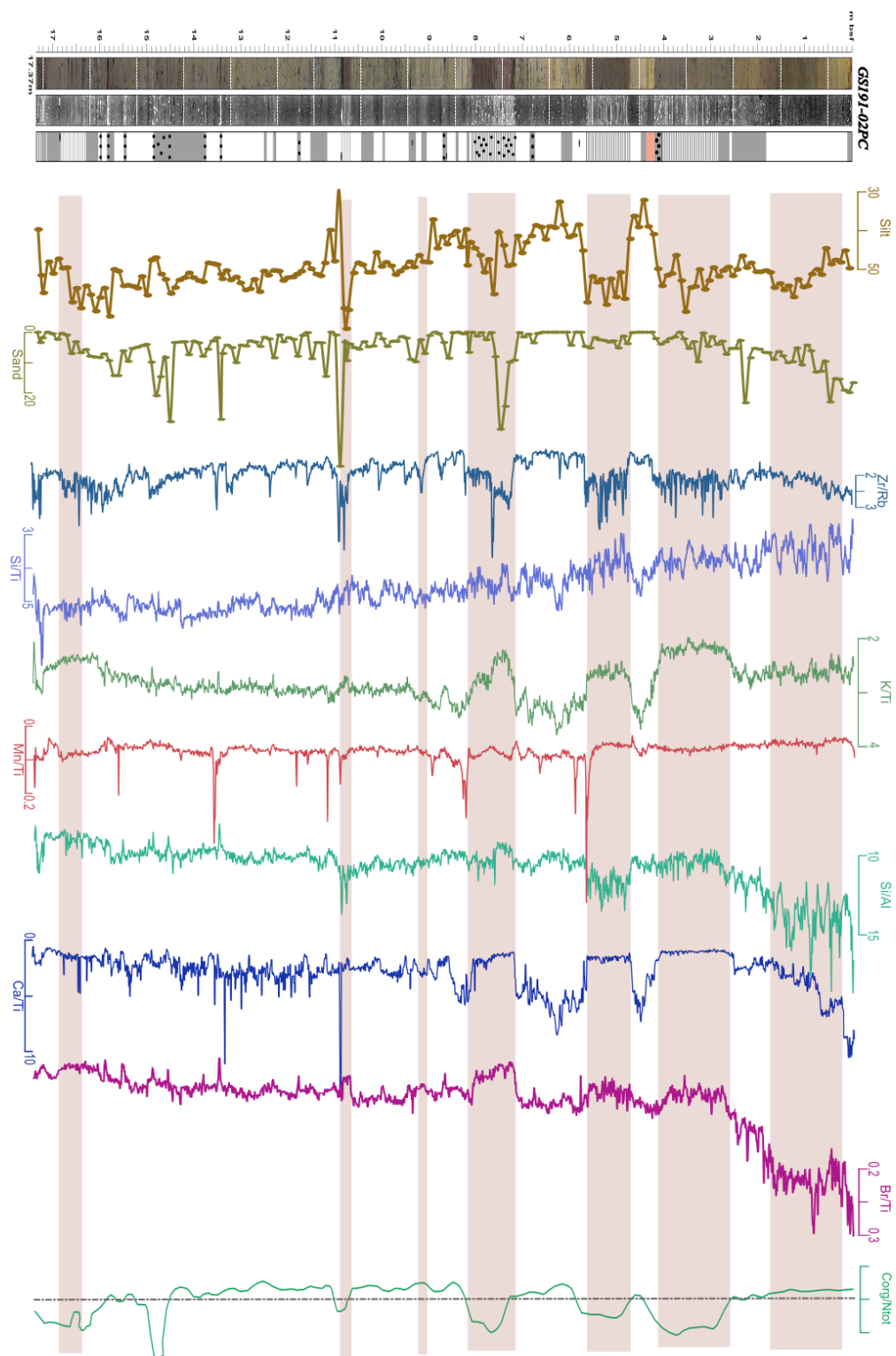


Figure 4-2: Physical (Silt, sand distribution) and chemical (XRF ratios and TOC/TN) characterisation for GS191-02PC core.

4.2.3.3 XRD analysis (clay mineral assemblage)

The predominant clay mineral within core 02-PC is illite with values varying from 40%, observed in almost all the laminated facies, to 65% in the rest of the core. Kaolinite and chlorite are the second most abundant clay minerals observed on the western margin of Svalbard, both having values between 10% and 30%. Smectite has the lowest percentages, with maximum values of 15% (Figure 4-3).

In the uppermost part (0–230 cm bsf), the illite values are stable at around 60% of the assemblage. From 240 to 420 cm bsf, the illite content decreases rapidly until it reaches 40% in correspondence to the youngest laminated facies. In the interval between 420–720 cm bsf, the illite is generally stable at an average of 65%; whereas, a very slight decrease of 3% was observed in correspondence with a laminated interval, with values decreasing from 63% to 60%. From 720–770 cm bsf, the illite content decreases again and reaches a minimum value of 40%, corresponding to the upper part of a laminated layer characterized by the presence of massive IRD content. Between 770–920 cm bsf, the illite curve shows a progressive increase from 60% to 70% corresponding to an alternation between bioturbated and IRD rich sediments respectively. In the deepest part of the core, from 920 to 1734 cm bsf, the illite content tends to decrease gradually, marking some local minima at 1010, 1090, 1170 and 1360 cm bsf. With Exception of the minima located at 1090 cm bsf that correspond to a short laminated layer, all the others are unusually associated with layered, massive IRD intervals as the facies is commonly characterised, in the core, by high values of illite. A distinct minima interval is recorded at the bottom of the core (1620–1710 cm bsf), corresponding to the deepest laminated interval recovered in the core.

Kaolinite and chlorite show a very similar pattern of curves, except for some local peaks that are more pronounced in one clay mineral than in the other. The down-core trend of kaolinite and chlorite is opposite to that observed for the illite. In the upper 240 cm (0–240 cm bsf), the values are generally stable, the kaolinite shows an almost flat pattern ranging about 15% of the assemblage, while the chlorite content is estimated to an average of 19%, with some slight variations between a minimum of 17% and a maximum of 21% located between 120–150 cm bsf. From 240–410 cm bsf, the kaolinite and chlorite values increase suddenly both reaching about 30% of the assemblage in correspondence of the youngest laminated interval.

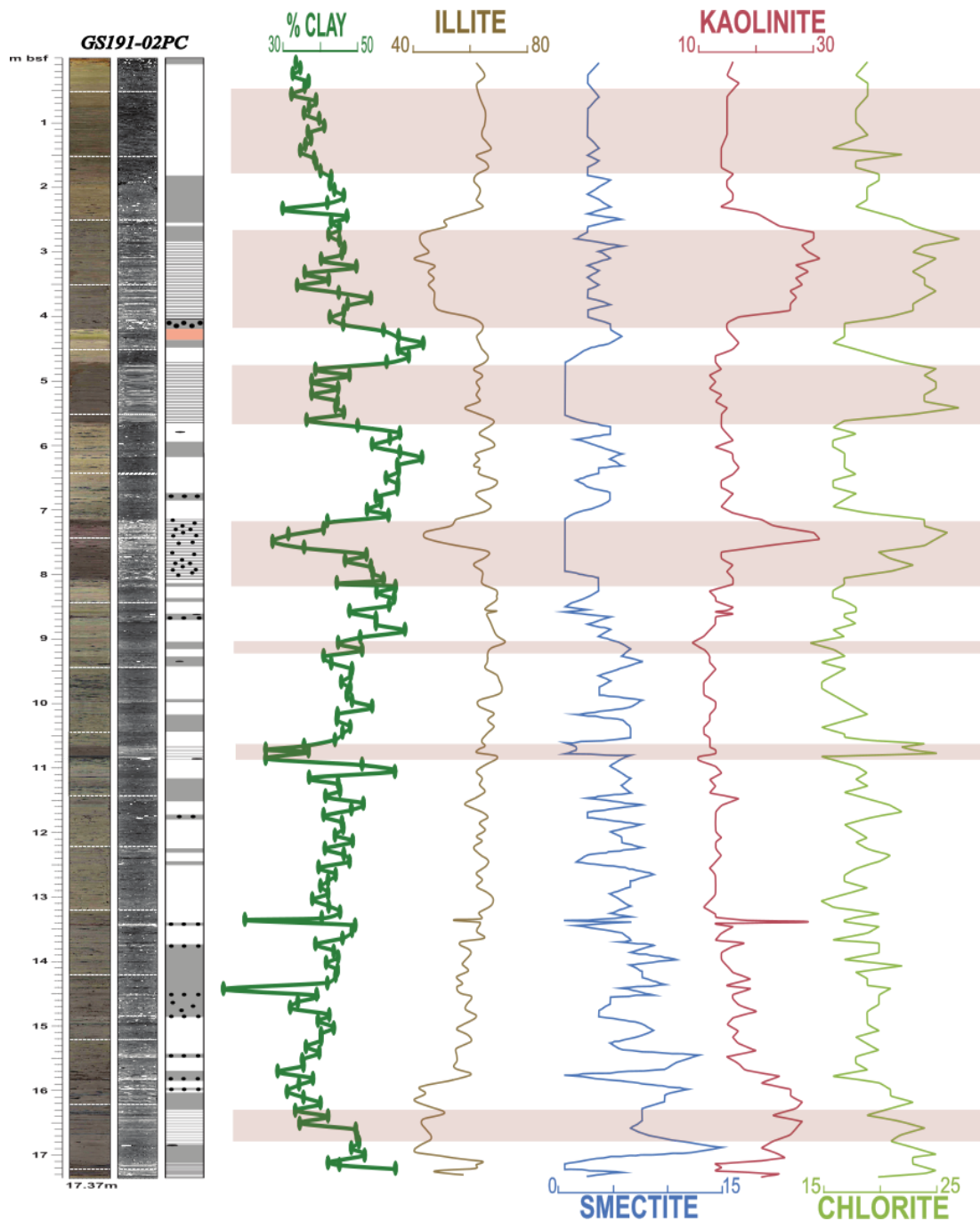


Figure 4-3: Clay mineral distribution within GS191-02PC core

From 410 to 520 cm bsf, the chlorite values increase and reach a maximum of 27%, corresponding to a laminated layer, and later decrease to 17% by 720 cm bsf. This increase was not observed on the kaolinite curve, where the values remain stable at around 15% of the assemblage within the interval located between 410–720 cm bsf. Between 720–770 cm bsf, both curves register a peak value of 28% in correspondence with the upper part of the laminated facies containing massive IRD. From 770 to 1590 cm bsf, both values tend to decrease and stabilise at around 15% for the kaolinite and around

17% for the chlorite. Despite the stable trend of the two clay minerals, the curve has some local peaks. For example, at 1080 cm bsf, in correspondence with the laminated interval, the chlorite increases to about 25% of the assemblage, while kaolinite does not show any significant change. At 1360 cm bsf, only the kaolinite shows a 30% peak in correspondence with a layered, massive IRD horizon, while the chlorite does not show any variation. In the deepest part of the core (1620–1736 cm bsf), both kaolinite and chlorite increase, reaching 30% and 25% respectively in correspondence with the laminated interval.

The smectite content is stable at 5% in the uppermost 420 cm (0–420 cm bsf). Unlike the other clay minerals, the smectite curve shows no significant changes within the first laminated interval. Between 420 and 570 cm bsf, the smectite content decreases significantly in correspondence with the laminated intervals almost disappearing from the clay assemblage. Then, for the following 150 cm (570 – 720 cm bsf) of a bioturbated facies, the smectite value rises to 5%. From 720–820 cm, within a laminated facies, the kaolinite content drops rapidly to 0%. In the deepest part of the core (820–1736 cm bsf), the smectite content gradually increases again, from 5% (at 820 cm bsf) to 15% (at 1736 cm bsf) except for some local minima located at 1090, 1360, 1600, and 1720 cm bsf, where the smectite disappear from the assemblage (values of 0%), in correspondence with the laminated intervals or the layered, massive IRD facies.

4.3 Core CAGE19-3KH-15GPC-01: Lower slope of the Isfjorden Drift

4.3.1 General core description

Core CAGE19-3KH-15GPC-01 (hereafter indicated as core CAGE-15) is formed in the upper 160 cm (0-160 cm bsf) by bioturbated, IRD free sediments overlying 100 cm of bioturbated IRD-rich sediments (160-260 cm bsf). Between 260-350 cm bsf the sediment core registers the younger laminated interval, 90 cm thick. From 350 to 1010 cm bsf, the core contains a succession of well-developed bioturbated IRD rich facies up to 80 cm thick, interbedded with thinner layers of massive IRD facies up to 20 cm thick. Between 1010–1040 cm bsf there is a second laminated interval. The deepest part of the sediment record (1040–1573 cm bsf) is characterised by an alternation of bioturbated IRD rich facies and massive IRD layers, the latter of which increases in frequency in the deeper 120 cm of the core (1450-1573 cm bsf).

4.3.2 Physical parameters (wet bulk density and grain size)

The wet bulk density curve (Fig.4-4) shows values that fluctuate between 1.2 g/cm³ and 1.8 g/cm³. The upper part of the core (0–160 cm bsf) is characterised by general low density values (average of 1.3 g/cm³) except at 90 cm bsf, where a peak value of 1.4 g/cm³ is recorded. From 160–1190 cm bsf the density values increase, reaching a maximum of 1.8 g/cm³ at 480 cm bsf, with several secondary peaks of 1.7 g/cm³ coincident with massive IRD layers situated at 380, 800, 1080, and 1190 cm bsf. On the deeper 350 cm (1190–1573 cm bsf) there is a general decrease in value of bulk density from 1.5 to 1.35 g/cm³, with some local peaks at 1380 cm (1.7 g/cm³), 1450 cm (1.75 g/cm³) and 1490 cm (1.7 g/cm³), associated with the layered massive IRD facies.

The sand and silt downcore distribution (Fig.4-4) show a trend of fining down-core on the upper 340 cm of the core (0–340 cm bsf), in which the sandy fraction decreases from 40% in the uppermost sediments to less than 10% at 340 cm. This is in contrast with the silt pattern, which shows an enrichment from an average of 40% weight in the uppermost few centimeters of the core to 57% at 340 cm bsf. In the interval between 350–790 cm bsf, after a peak in the sand content that reaches almost 40% at 350 cm bsf, the curve shows a gradual decrease until it reaches 10% of content at 790 cm bsf. In the same interval, the silt content shows an opposite trend, starting with a minimum of 30% at 350 cm bsf, that is followed by a progressive increase to about 50% at 790 cm bsf. At 800 cm bsf, a coarse horizon is characterized by over 55% of sand, representing the highest value recorded in the core. At the same level, a minimum of 30% was observed in the silt content. This horizon corresponds with a layered, massive IRD facies. From 810–1010 cm bsf, the textural values gradually change from about 20% sand and 50% silt, to an average of 30% sand and 40% silt until the depth of 1190 cm bsf. In the lowermost part of the core (the last 370 cm), the sediment record show a dominance of the silty fraction, which reaches to about 50% with the sand fraction not exceeding the 15%, except for two levels located at 1340 and 1440 cm bsf respectively, where the sand represents the 40% of grain size.

4.3.3 Chemical composition of core CAGE-15

4.3.3.1 XRF core scan analyses

The trend Zr/Rb curve shows a similar and coherent pattern with the trend of the silt content (Fig.4-4). In the uppermost 160 cm bsf, there is a slight decrease of the Zr/Rb ratio. Between 160–350 cm bsf, the Zr/Rb ratio is characterized by relatively high values with several fluctuations corresponding to the laminated facies with higher values corresponding to the coarser grained (sand

and silt) layers. In the interval between 350–490 cm bsf, the Zr/Rb ratio generally decreases although it records two peaks at 380 cm bsf and between 460–500 cm bsf corresponding to bioturbated IRD-rich facies. From 500–1010 cm bsf, the Zr/Rb register a progressive increase with some local peaks located at 630, 650, 800, and 930 cm bsf that are associated with the layered, massive IRD facies. Between 1010–1200 cm bsf the Zr/Rb ratio shows a highly variable trend fluctuating between the absolute minimum of 1 to maximum of 3, which can be explained by the occurrence of the IRD rich intervals. In the deeper part of the core, from 1200–1573 cm bsf, the Zr/Rb values are generally low (1.5), except for three peaks located between 1350–1380 cm bsf, at 1440 cm bsf, and at 1480 cm bsf.

The Si/Ti ratio does not show much variation through the core (Fig.4-4), although 3 intervals were identified. In the upper 90 cm (0–90 cm bsf), the Si/Ti ratio decreases rapidly from 5 to 3. From 90 to 330 cm bsf, the trend records stable, moderate values of about 4. In the deeper part of the marine sediment record (330–1573 cm bsf), the Si/Ti ratio remains relatively high with average value about 5, except for the interval between 1310–1380 cm bsf, where the Si/Ti ratio is stable at a low value of about 3.

The K/Ti trend is similar to that of the Si/Ti ratio (Fig.4-4), showing a rapid decrease from the top of the core to 90 cm bsf, followed by an increase down to 180 cm bsf. Between 180–330 cm bsf, K/Ti values gradually decrease and it is maintained low in correspondence with the laminated interval. From 330 to 490 cm bsf, the K/Ti values show an abrupt increase from 2 to 4, and they are maintained relatively high except for two local minima located at 380 cm bsf and between 470–490 cm bsf. Thereafter, in the interval between 490–1060 cm bsf, the K/Ti curve records a gradual decline. In the deeper part of the sediment core (1060–1573 cm bsf), the K/Ti ratio appears to be stable with moderately high values, with some slight decreases located at 1080, 1140, 1340, and 1460 cm bsf.

The Mn/Ti ratio generally has very low values, ranging from 0 to 0.1 (Fig.4-4), but it shows some significant peaks that are recorded at 440, 480, 520, 810, and 1330 cm bsf in correspondence with the base of massive IRD-rich layers. Furthermore, these local abrupt fluctuations always occur before the consistent increase of the XRF bio-indicators (Si/Al, Ca/Ti and Br/Ti). In addition to said prominent peaks, the Mn/Ti curve contains two distinct intervals of higher values: the first is located in the upper part of the core between 390–520 cm bsf, the second is located in the lower part of the core between 1190–1330 cm bsf. Both intervals correspond to the bioturbated IRD-rich facies.

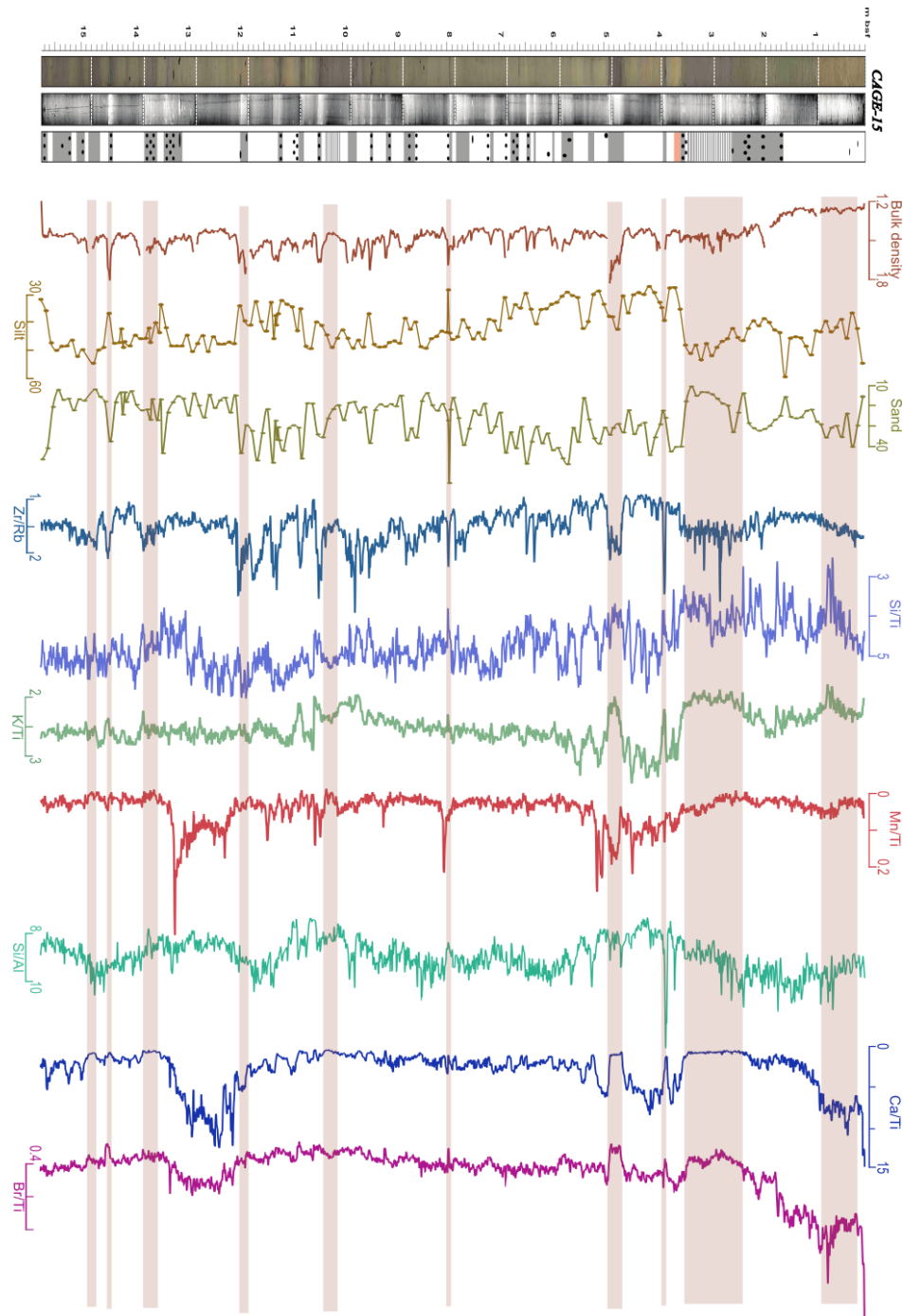


Figure 4-4: Physical (wet bulk density, silt, sand distribution) and chemical (XRF ratios) characterisation for CAGE19-3KH-15GPC core.

The Si/Al curve (Fig.4-4) shows a slight increase in the uppermost 90 cm (0–90 cm bsf) from 9 to 10, and the relatively high values are maintained till the depth of 240 cm bsf. From 240 to 470 cm bsf, the curve generally decreases down to the value of 8, except for a peak of 13 located at 380 cm bsf. In the interval between 470–980 cm bsf, the Si/Al ratio does not show many fluctuations and maintains relatively high values (average of 9). In the deeper part of the core (980–1573 cm bsf), the Si/Al curve generally decreases, except for two intervals about 100

cm-thick, that corresponds to a bioturbated IRD-rich facies, located between the 1100–1190 cm bsf and 1380–1480 cm bsf. The first interval is marked by a trend very similar to that of the Ca/Ti ratio, although it is slightly displaced up core with respect to the Ca/Ti increasing trend.

Ca/Ti and Br/Ti show similar trends (Fig.4-4). The curves generally have very low values proximal to zero (0–3). Despite the generally low and flat trend, three intervals with higher values can be distinguished. The first is located in the uppermost part of the core (0–100 cm bsf), and it is particularly more developed for the Br/Ti ratio extending down to 160 cm bsf). The second increasing interval is located between 350–470 cm bsf, containing a minimum value at 380 cm bsf, which is opposite to the peak recorded in the Si/Al down-core trend. The third and last interval is registered between 1200–1350 cm bsf corresponding to bioturbated IRD-rich facies. In general, the lowest values of Ca/Ti and Br/Ti are registered in the interval between 350–250 cm bsf, corresponding to the laminated facies.

4.3.3.2 XRD analysis (clay mineral assemblage)

The predominant clay mineral in core CAGE-15 is the illite with values between 45% (Laminated facies) and 75% (IRD-rich Facies). The second most common clay minerals are kaolinite and chlorite both with average between 10–30%. The smectite is commonly present in traces, or locally absent, with maximum values of 20% (Figure 4-5).

The illite between 0–210 cm bsf, has a flat trend with about 60 % of the clay assemblage. Between 210–50 cm bsf, the illite content drops from 65 to 45%, maintaining low values between 250–350 cm bsf in correspondence to the laminated facies. At the base of the laminated facies, from 350–360 cm bsf the values rise rapidly to 65% of the assemblage. This value is maintained till 650 cm bsf, with the only exception of the interval between 460–490 cm bsf where the value drops down to 45% in correspondence with an interval of laminated sediments. Between 650–1050 cm bsf, the illite curve shows a progressive decline down to 45% at the base of this interval. In the deeper part of the sediment record (1050–1573 cm bsf), the illite increases again to 65%, with three minima values located at 1090 cm bsf, from 1360–1390 cm bsf and at 1450 cm bsf in correspondence of massive IRD layers.

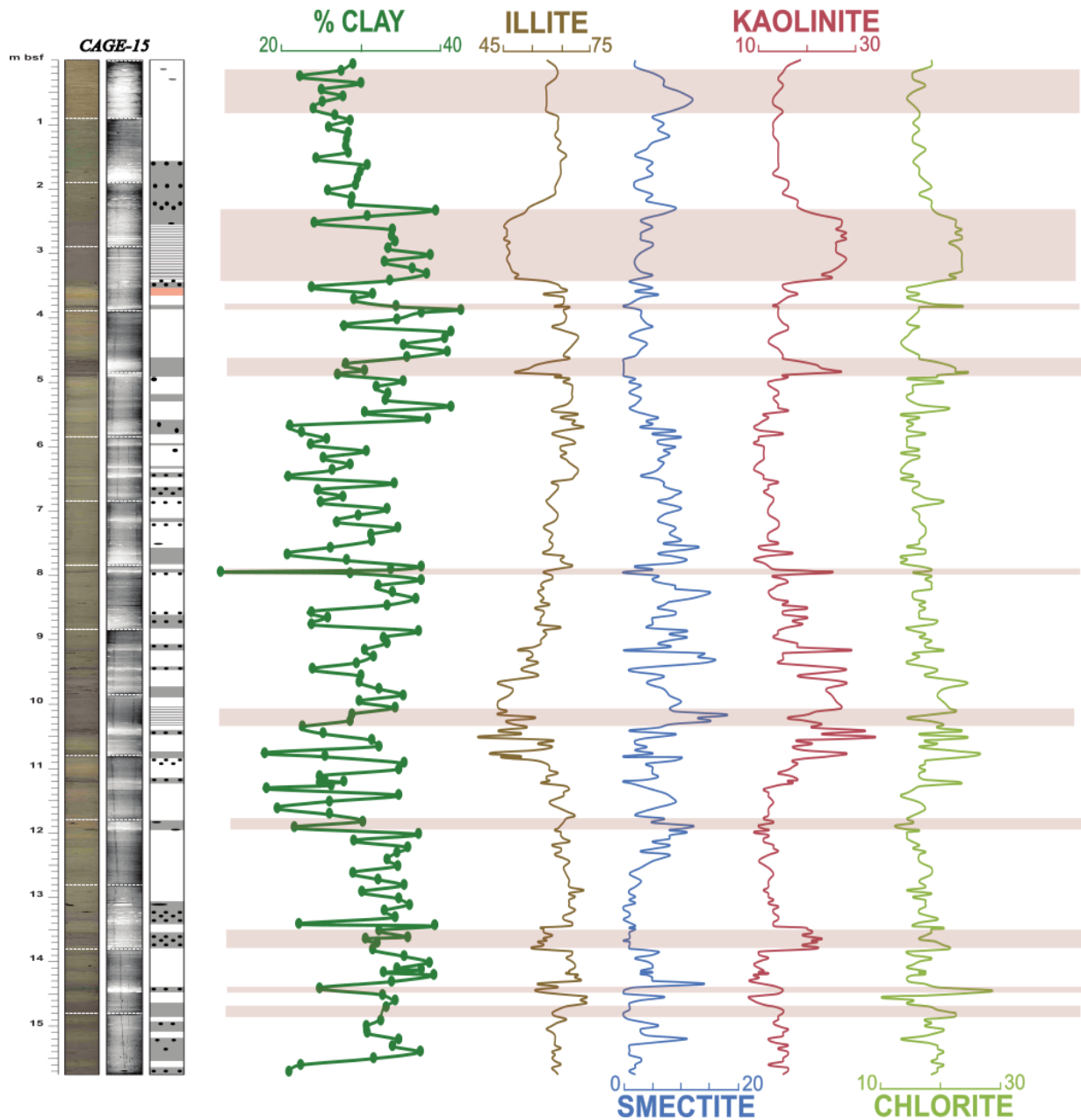


Figure 4-5: Clay mineral distribution within CAGE19-3KH-15GPC core.

Kaolinite and chlorite generally show a similar pattern, that appears opposite to the illite trend. In the upper 210 cm (0–210 cm bsf), the values are stable, both counting for about 20% of the clay mineral assemblage. Contrarily to the illite, from 210–350 cm bsf, the kaolinite and chlorite record is characterized by an enrichment peaking to 30% in correspondence with the laminated interval. This increase is better marked on the kaolinite, as the values pass from 20% to 30%, while the chlorite increases by only 5% (from 20 to 25 %). Between 350–790 cm bsf, kaolinite and chlorite tend to decrease gradually, except at 490 cm bsf, where both curves register a peak (30% and 25% respectively). Between 790–1050 cm bsf both clay minerals show a progressive increase

characterized by more pronounced peaks on the kaolinite curve located at 790, 910, and 1050 cm bsf. In the deeper part of the sediment core (1050–1573 cm bsf), both kaolinite and chlorite decrease, with two different peaks: A kaolinite peak located between 1360–1390 cm bsf without a substantial change of the chlorite; and a chlorite peak located at 1450 cm bsf, without a substantial change of the kaolinite.

The smectite content decreases down-core in the uppermost 480 cm (0–480 cm bsf) from about 12% to nearly 0%, with the main decreases corresponding with the laminated and IRD rich facies. From 480 to 1050 cm bsf, the smectite content gradually increases, rising from nearly 0% to 15%, except at 790, 910, and 1050 cm bsf, where it has local minima (traces of smectite) that correspond to the layered, massive IRD facies. In the deepest part of the sediment record (1050–1573 cm bsf), the smectite tends to decrease again, reaching almost 0% at the bottom of the core. In this interval, the smectite pattern shows an opposite pattern to the other clay minerals, when the smectite content increases, the values of the other clay minerals decreases.

4.4 Core CAGE19-3KH-05GPC-02: Western termination of the Vestnesa Ridge

4.4.1 General core description

Core CAGE19-3KH-05GPC-02 (hereafter indicated as core CAGE-5) contains bioturbated sediments without IRD in the upper 260 cm (0–260 cm bsf), overlying 90 cm of bioturbated IRD-rich sediment (260–350 cm bsf) (Fig. 4-6). A first laminated interval was recorded from 350 to 420 cm bsf that is followed by a layered, massive IRD interval 20 cm thick (420–440 cm bsf), underlined by an oxidized interval. Between 440–480 cm bsf a bioturbated interval overlay a second short laminated interval having a thickness of 30 cm was recovered between 480–510 cm bsf. From 510–1120 cm bsf, the sedimentation is characterized by bioturbated sediments interbedded with several bioturbated IRD-rich layers, and layered, massive IRD short intervals the latter located between 710–730, 850–870, and 1020–1040 cm bsf. From 1120–1160 cm bsf, a third laminated interval was identified, followed by 110 cm (1160–1270 cm bsf) of IRD-rich facies interbedded with some short intervals of bioturbated sediments. Between 1270–1450 cm bsf, the sediment is characterized by bioturbated sedimentation with a 30 cm interval of layered, massive IRD located between 1310–1340 cm bsf. In the deepest part of the core (1450–1564 cm bsf) three layered, massive IRD intervals each measuring about 25 cm, alternate with bioturbated layers.

4.4.2 Physical parameters (wet bulk density and grain size)

The wet bulk density trend shows values that generally vary between 1.2 g/cm³ and 1.6 g/cm³ (Figure 4-6). The upper 270 cm (0–270 cm bsf) are characterised by generally low density values (average 1.2 g/cm³), corresponding to bioturbated sediments. From 270–1340 cm bsf, the bulk density values increase to an average of 1.5 g/cm³ with several peaks like those located at 480 cm bsf (1.8 g/cm³), 680 cm bsf (1.57 g/cm³), 950 cm bsf (1.63 g/cm³), 1100 cm bsf (1.7 g/cm³), and 1170 cm bsf (1.6 g/cm³) corresponding to massive IRD intervals. In the deepest part of the core (1340–1564 cm bsf), there is a general decrease in wet bulk density from 1.5 to 1.4 g/cm³, with some local peaks located at 1480, 1540, and 1560 cm bsf that are consistent with the layered, massive IRD facies.

The distribution of the coarse fraction through the core CAGE-5 (Figure 4-6) shows high values in the upper 220 cm (0–220 cm bsf) with an average value of 20%. Between 230–420 cm bsf, the coarse fraction drops from 20% to 10%, except for a peak recorded at 360 cm bsf in correspondence with a IRD-rich interval located within the laminated facies. From 420–530 cm bsf, the coarse fraction gradually decreases from 20% to 5%. In the interval between 550–930 cm bsf, the coarse fraction remains stable at an average value of 5% with some local peaks corresponding to IRD-rich intervals. From 930–1110 cm bsf, the coarse fraction distribution shows several fluctuations with values between 5% and 20%, corresponding to the IRD-rich intervals. Between 1110–1190 cm bsf, there are reduced fluctuations ranging between 3% and 7% within a laminated interval. In the deeper part of the sediment core only a few samples were processed losing in data resolution, however, two peaks located at 1200 cm bsf (20%) and 1460 cm bsf (16%) can be identified in correspondence with IRD-rich intervals.

4.4.3 Chemical composition of the CAGE-05

4.4.3.1 XRF core scan analyses

The Zr/Rb ratio varies between 1.5 and 2.5 within the CAGE-5 core (Figure 4-6). In the uppermost 30 cm (0–30 cm bsf), the Zr/Rb ratio shows a slight increase in values from 2 in the uppermost part to 2.5 at 30 cm bsf, whereas the values decrease from 30 to 350 cm bsf down to 1.8. Between 350–440 cm bsf, the Zr/Rb curve increases (average value 2.2) accompanied by several fluctuations corresponding to the laminated facies with higher values corresponding to the coarser grained layers (sand and silt). From 440–480 cm bsf, decrease again to an average value of 1.5, corresponding to a bioturbated interval. Then, within the second short (30 cm thick) laminated interval located between 480–510 cm bsf, the Zr/Rb increases to about 2.5. In the interval between

510–930 cm bsf, the Zr/Rb ratio shows a relatively low value (average 1.5) corresponding to bioturbated sediments. This trend of low values exhibits some local peaks corresponding to IRD-rich sediments, allowing Zr/Rb values to reach 2.5 at 590, 720 and 820 cm bsf. From 930–1330 cm bsf, the Zr/Rb ratio increases and maintains an average value of 2 with some local peaks corresponding with the layered, massive IRD facies located at 1020, 1170, and 1200 cm bsf, whereas local minima are associated with the bioturbated sediment like at 1040 and 1180 cm bsf. In the deepest part of the core (1330–1564 cm bsf), the Zr/Rb values decrease again as bioturbated facies dominates, except for two intervals with higher Zr/Rb values located between 1450–1480 cm bsf and 1520–1540 cm bsf, corresponding to IRD-rich facies.

The Si/Ti ratio does not show significant variations within the core (Figure 4-6), although 3 intervals were identified. In the upper 220 cm (0–220 cm bsf), the Si/Ti ratio shows several fluctuations, but within this interval the values remain relatively low with an average value of 3 corresponding to the bioturbated sediment. From 220 to 1564 cm bsf, Si/Ti generally exhibit relatively moderate values (mean 4), with the exception of two intervals located between 1170–1270 cm bsf and 1460–1564 cm bsf where the Si/Ti values increase and record their highest values (mean 4.5) in correspondence with IRD-rich intervals.

The K/Ti ratio generally varies between 2 to 4 (Figure 4-6). In the upper 350 cm (0–350 cm bsf), the K/Ti values gradually increase from 2 at the top to 2.5 at the end of said interval, corresponding to the bioturbated facies. Within the first laminated interval between 350–420 cm bsf, the K/Ti ratio drops and maintains low values (mean 2). From 420 to 480 cm bsf, the K/Ti values increase again and register a peak of 3, consistent with the bioturbated IRD-rich facies. As the depositional facies change from 480–510 cm bsf and another laminated facies interval occurs, the K/Ti curve decreases and reaches a minimum value of 2, as observed in the first laminated interval. Between 510–1170 cm bsf, K/Ti values gradually decrease from 3 to 2 and reach a minimum at 1120–1170 cm bsf in correspondence with a laminated interval. In the deeper part of the sediment core (1170–1564 cm bsf), the K/Ti ratio maintains a relatively high value (2.8) with some local minima located at 1270 and 1470 cm bsf in correspondence with layered, massive IRD intervals.

The Mn/Ti ratio is generally characterised by a flat curve and very low values between 0.1 and 0.2. Nevertheless, two significant peaks were observed at 960 and 1280 cm bsf in correspondence with the base of the IRD-rich intervals (Figure 4-6). Within the Mn/Ti curve, other distinct intervals with slightly higher values were identified, consistent with the bioturbated facies located

between 120–220 and 1380–1430 cm bsf, and with the laminated facies located between 350–420, 480–510, and 1160–1270 cm bsf.

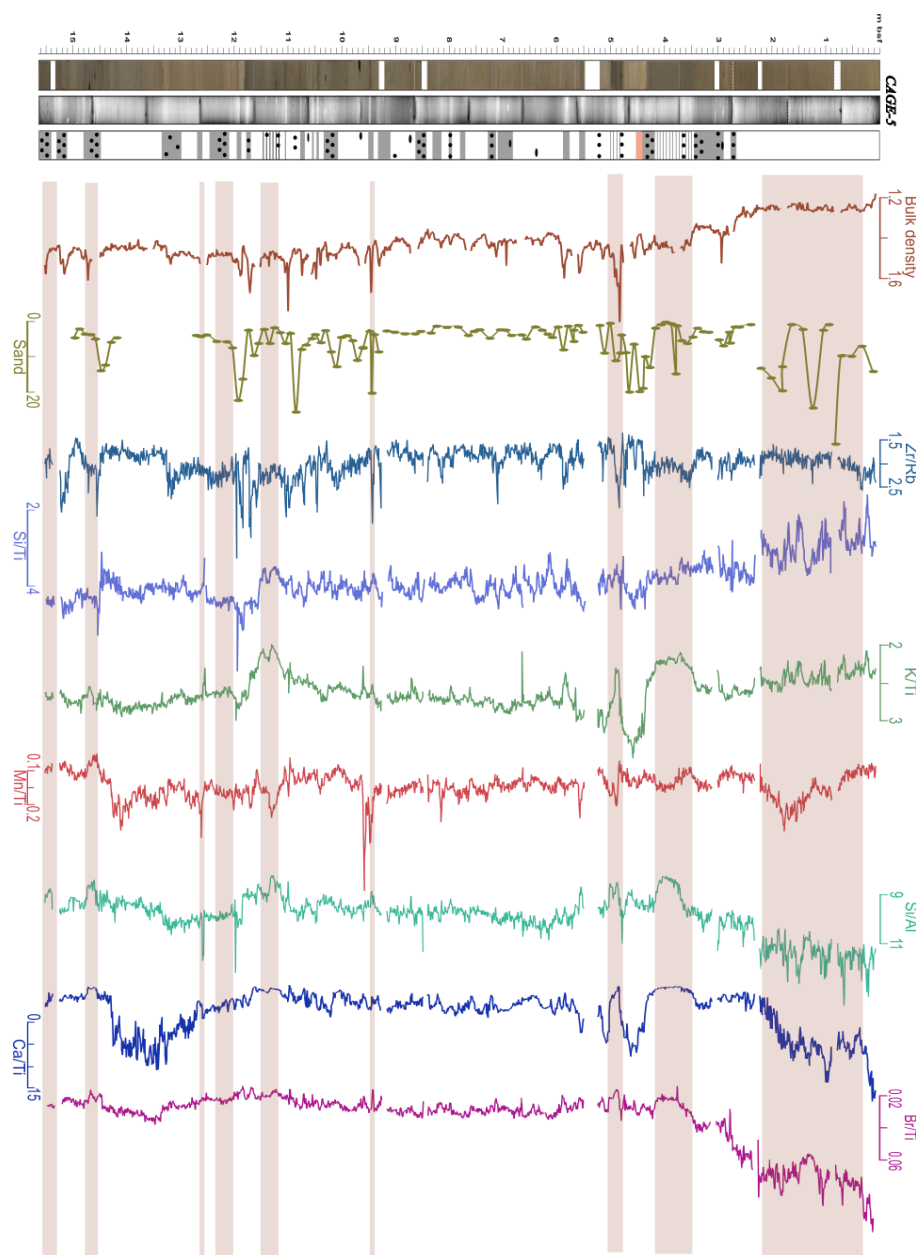


Figure 4-6: Physical (wet bulk density, silt, sand distribution) and chemical (XRF ratios) characterisation for CAGE19-3KH-5GPC core.

The Si/Al ratio varies between 9 and 13 (Figure 4-6). The curve shows a gradual decrease in the upper 420 cm (0–420 cm bsf) as the values pass from 13 in the uppermost part to 9 in the interval located between 360–420 cm bsf, corresponding to the laminated interval. From 420 to 480 cm bsf, the Si/Al values increase again within the bioturbated interval, but decrease rapidly between 480–510 cm bsf in correspondence with a short laminated interval. From 510 to 1120 cm

bsf, the Si/Al values remain stable at an average value of 10 with slightly higher values corresponding to the bioturbated intervals. Between 1120–1190 cm bsf, the Si/Al values drop again to an average value of 9, corresponding with the laminated interval. In the deeper part of the sediment core (1190–1564 cm bsf), the Si/Al ratio increases between 1190–1320 cm bsf and then gradually decreases toward the bottom of the core.

Ca/Ti and Br/Ti have a very similar trend (Figure 4-6). The curves show very low values near zero (0.02) for Br/Ti, and around 3 for Ca/Ti. Despite the generally low and flat trend, three intervals of higher values can be distinguished, all corresponding to the presence of the bioturbated facies. The first is in the uppermost part of the core between 0–240 cm bsf with average 5 for Ca/Ti, and average 0.08 for Br/Ti; the second interval occurs between 430–480 cm bsf with average 7 for Ca/Ti and 0.03 for Br/Ti; and the last interval is located between 1280–1430 cm bsf with average 9 for Ca/Ti and 0.03 for Br/Ti. In general, however, the lowest values for both Ca/Ti and Br/Ti are recorded within the three laminated facies identified on the CAGE-5 core (1 for Ca/Ti and 0.02 for Br/Ti).

CHAPTER 5: DISCUSSION

The discussion of this thesis will develop through the following points:

- 1) The core to core correlation based on the Magnetic Susceptibility and other sedimentological and compositional proxies (e.g. sediment facies, XRD data, and XRF proxies) measured on the sediment cores, with definition of the sediment ages;
- 2) The reconstruction of the environmental and climatic record recovered in the studied cores depicted by the sediment facies and compositional characteristics;
- 3) The definition of the complex interplay between along- vs down-slope depositional processes and their climatic significance.

5.1 Core to core correlation and sediment age

Core 02-PC was previously studied to define the age model based on the paleomagnetic record and a large number of ^{14}C radiocarbon dates measured on foraminiferal tests ([Caricchi et al., 2019, 2022](#)). In core 02-PC the age model allowed for the identification of marker beds associated with prominent climatic events that have regional distribution, including: the Meltwater Pulse-1A (MWP-1A, 14.60–14.30 kyBP, [Deshamp et al., 2012](#)), the Meltwater Pulse-1A₀ (MWP-1A₀, ca. 20 ky BP, [Caricchi et al., 2019](#)), and layers of massive IRD that are comparable to Heinrich events H2, H4 and H6 (24, 38, and 60 ky BP respectively, [Hemming 2004](#)).

The correlation between core 02-PC and the CAGE cores was obtained through the identification of the above marker beds based on their lithological sequence, and using magnetic susceptibility (MS) down-core trend as a base for correlation. According to the correlation, both cores CAGE-05 and CAGE-15 contain the record of the MWP-1A, and the Heinrich events H2, H4 and H6. Only MWP-1A₀ was recorded in cores on core 02-PC and CAGE-15.(**Fig. 5-1**).

The XRD data show that the illite and kaolinite pattern observed in core 02-PC is also found in core CAGE-15 on the upper 1130 cm, confirming that the latest core contains more condensed stratigraphy records permitting to study older sediment (**Fig. 5-1**). Based on the well defined age model of core 02-PC and the facies characteristics of each interval it was possible to identify MIS-1, MIS-2, MIS-3, MIS-4, MIS-5a and MIS-5b with MIS-5 existing only in the distal cores CAGE-15 and CAGE-05.

The MIS-1 is recorded in the first 280 cm of core 02-PC and is characterised by two distinct sedimentological facies: an IRD rich facies at the base and bioturbated sediments in the upper part. On the CAGE cores, the MIS-1 is registered in the first 250 cm of Core CAGE-15, while it is more pronounced on core CAGE-5, reaching a thickness of 350 cm. Within the MIS-1 interval it was possible to identify the 8.2 ky event ([Alley et al., 1997](#); [Barber et al., 1999](#), [Ellison et al., 2006](#); [Ebbesen et al., 2008](#); [Kar et al., 2018](#); [Seidenkrantz et al., 2013](#)) that always has the highest magnetic susceptibility value during the Holocene that it was registered in all the studied cores 02-PC, CAGE-15 and CAGE-5 at 110, 50 and 130 cm bsf, respectively (**Fig. 5-1**).

The MIS-2 was registered on core 02-PC with a length of 570 cm (from 280 to 850 cm bsf) and contains two laminated intervals with low values of MS, Ca/Ti, and Br/Ti in its upper part, corresponding to MWP-1A and MWP-1A0 events according to the age model. At the base of MIS-2 appears a third laminated interval, characterised by the presence of numerous IRD and also containing low values of MS, Ca/Ti, and Br/Ti, corresponding to the H2 event. For core CAGE-15, the MIS-2 contains only one laminated interval on the top (between 260–340 cm bsf). This corresponds to the MWP-1A event, as it contains an XRD signal characterised by a peak in kaolinite and a decrease in the illite content, observed on core 02-PC (**Fig. 5-1**). In contrast to what was observed in core 02-PC, MWP-1A0 was barely recorded, with a length of a few centimetres situated at 390 cm bsf. It registers a similar pattern on XRF bio-indicator proxies, characterised by low values of Ca/Ti and Br/Ti, while H2 measures about 30 cm and it is located between 460–490 cm bsf. Neither interval contained laminations and both are represented as IRD-rich intervals but the presence of the same footprint observed on the clay mineral assemblage, XRF ratios (Ca/Ti & Br/Ti) and magnetic susceptibility trend, permit the recognition of these intervals on CAGEs core.

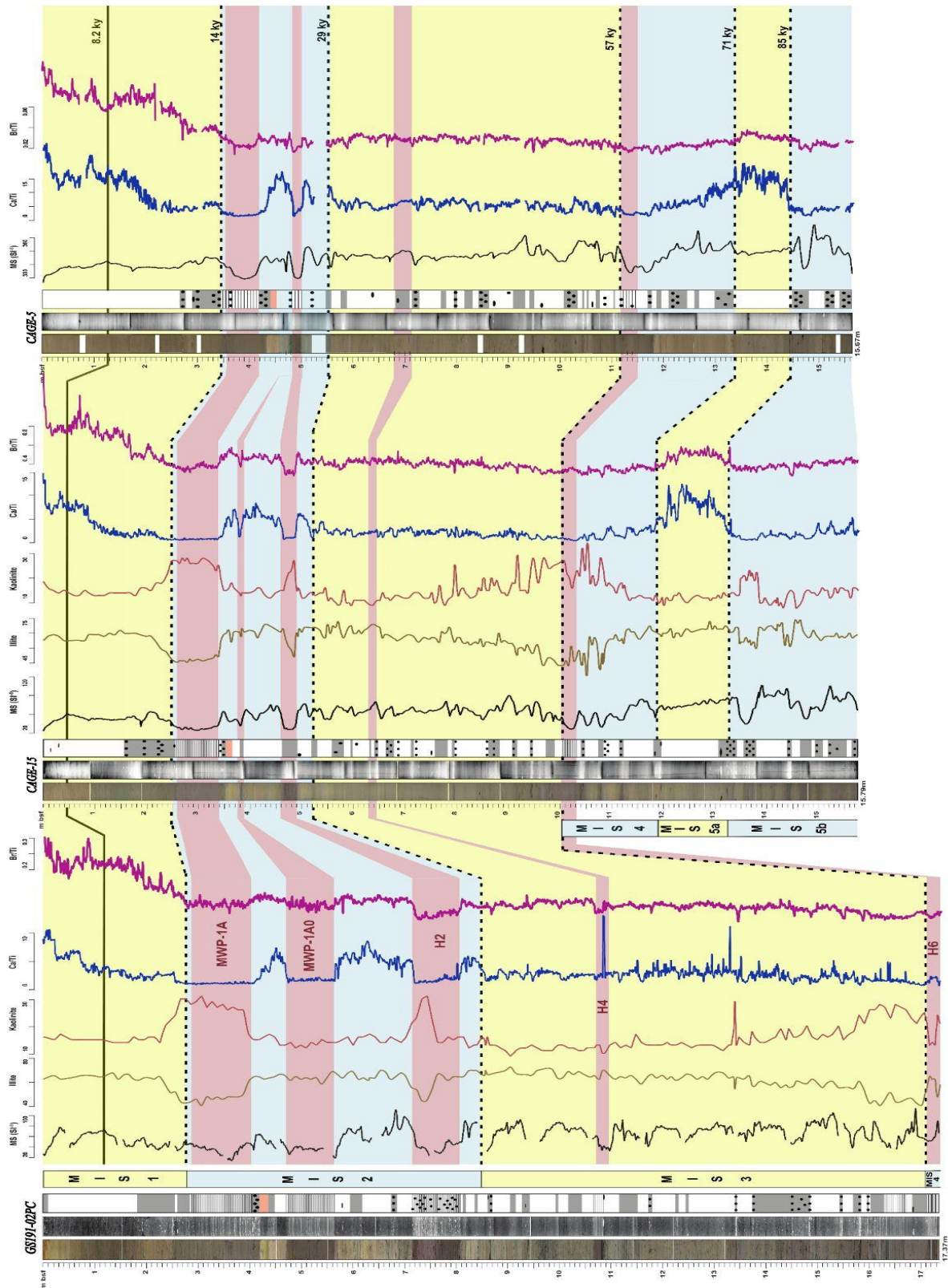


Figure.5-1: Core to core correlation of the studied cores based on the magnetic susceptibility, illite and kaolinite (XRD) content, and XRF bio-indicators proxies (Ca/Ti and Br/Ti).

For core CAGE-5, whereas the MWP-1A was identified between 350–420 cm bsf, a clear identification of the MWP-1A0 was not possible. The H2 event, of low magnetic susceptibility value, was registered as a laminated interval of 20 cm thick containing IRD.

The MIS-3 was recorded in all the studied cores with thickness variations. For core 02-PC, it occurs between 850 and 1720 cm bsf, bounded by H2 (beginning of MIS-2 ~24 ky) and H6 (end of MIS-4 ~60 ky). The H6 event occurs as a laminated interval in all the studied cores and marks the termination of MIS-4 and the beginning of MIS-3. This was used to correlate with the CAGE cores, which allow the identification of the base of the MIS-3 interval measuring 480 cm (from 520 to 1000 cm bsf) on core CAGE-15, while it measures 570 cm on core CAGE-5.

The core 02-PC has a laminated interval in the lower part, attributed to H6 according to the age model, which includes the termination of MIS-4, and that event permits the correlation of the termination of MIS-4 based on the CAGE cores.

For the deeper part of the CAGE cores, for which there is no robust age model, the correlation relied on sedimentological and compositional proxies such as magnetic susceptibility, XRF and XRD trends, and the comparison with three other cores: PS-1533, PS-2123, and JM10-02GC collected from the Yermak Plateau (**Fig. 5-2**) and contain an older sequence, including the MIS-5 reported on [Nowaczyk et al., 1994](#); [Vogt et al., 2001](#); [Chauhan et al 2013](#).

For core CAGE-15, we assume continuous sedimentation in the study area, as compared with the ODP site 986, which is in a more distal position below 2063 m water depth, and reached about 2.5 Ma ([Channel et al., 1999](#); [kniess et al., 2009](#); [Rebesco et al, 2013](#)). All studies conducted on ODP 986 dataset contain no evidence of hiatuses or interruption in the sedimentation in the upper part of the drilled core (e.g. [Smelror M. 1999](#); [Butt et al., 2000](#);; [Alexandropoulou et al., 2021](#)). Even for core CAGE-5 there is no hiatuses mentioned in previous studies that reached older sediments as the MeBo-125 and MeBo-126 drill cores ([Plaza-Faverola et al., 2015](#); [Bohrmann et al., 2016](#); [Dessandier et al., 2021](#)).

An initial estimate of the age of the deeper part of CAGE cores was obtained based on the sedimentation rate, taking in into account the events defined above cores, such as the meltwater pulses and the Heinrich events, as well as some marker beds, used as tie points to calculate the sedimentation rate. Furthermore, the trend of the magnetic susceptibility and compositional characteristics of cores CAGE-15 and CAGE-5 is very similar. According to the calculated

sedimentation rate (**Fig. 5-3**) the base of core CAGE-15 and CAGE-05 should have an approximate age of 89 ky BP and 86 ky BP respectively. The estimated age of the cores from CAGE, calculated on the basis of sedimentation rate, is a preliminary estimate that can be further refined by additional analysis. However, the values are not expected to differ significantly. This is because the upper part of the cores from CAGE has already been correlated with an existing age model, as mentioned earlier. In particular, the age estimate applies to the lower 539 cm of the core CAGE -15 and the lower 417 cm of the core CAGE -5. It's worth noting that alternative methods of age determination, such as paleomagnetism, can yield different age differences. These age differences are related to the different sedimentation rates observed during the different climatic phases within MIS -4 and MIS -5. The calculation of the sedimentation rate on CAGEs core imply that both CAGE-15 and CAGE-5 recovered a complete MIS-4 and the upper sequence of MIS-5 and more precisely, the warm interstadial MIS-5a and the cold stadial MIS-5b (71-85 ky and 85-90 ky respectively).

Since the MIS-4 represents a glacial period characterised by low biological activity, and taking into consideration the distribution of the XRF bio-indicator Ca/Ti and Br/Ti, the MIS-4 on core CAGE-15 was defined to be located between 1000–1190 cm bsf (190 cm thick) and on core CAGE-5 between 1120–1340 cm bsf (220 cm thickness).

The presence of the MIS-5 in the studied cores was confirmed by the correlation with three sediment cores located on the Yermak Plateau (cores PS-1533, PS-2123, and JM10-02GC) and studied by [Nowaczyk et al., 1994](#); [Vogt et al., 2001](#); [Chauhan et al., 2014](#) (**Fig. 5-2**). The age model of these cores was obtained by AMS-14C dating, magnetic susceptibility correlation and $\delta^{18}\text{O}$ -isotope records. The magnetic susceptibility curve of these cores shows a significant decrease (**Fig. 5-2**) in the upper part of MIS-5. This signal was recorded also in the studied cores, in fact CAGE-15 and CAGE-5 show a minimum value of magnetic susceptibility at 1360 and 1470 cm bsf, respectively, confirming that the deepest part of CAGE cores contains the MIS-5.

The magnetic susceptibility of both cores CAGE-15 and CAGE-5 shows an interval characterised by a particular pattern that occurs between 1180–1330 and 1340–1450 cm bsf, respectively, and it is characterised by a progressive increase in magnetic susceptibility values without the registration of a significant fluctuations, (**Fig. 5-1**). This interval, which has high Ca/Ti and Br/Ti content, was associated with the presence of calcareous microfossils and high bioproductivity, coherent with the warm interstadial MIS-5a (85–71 ky).

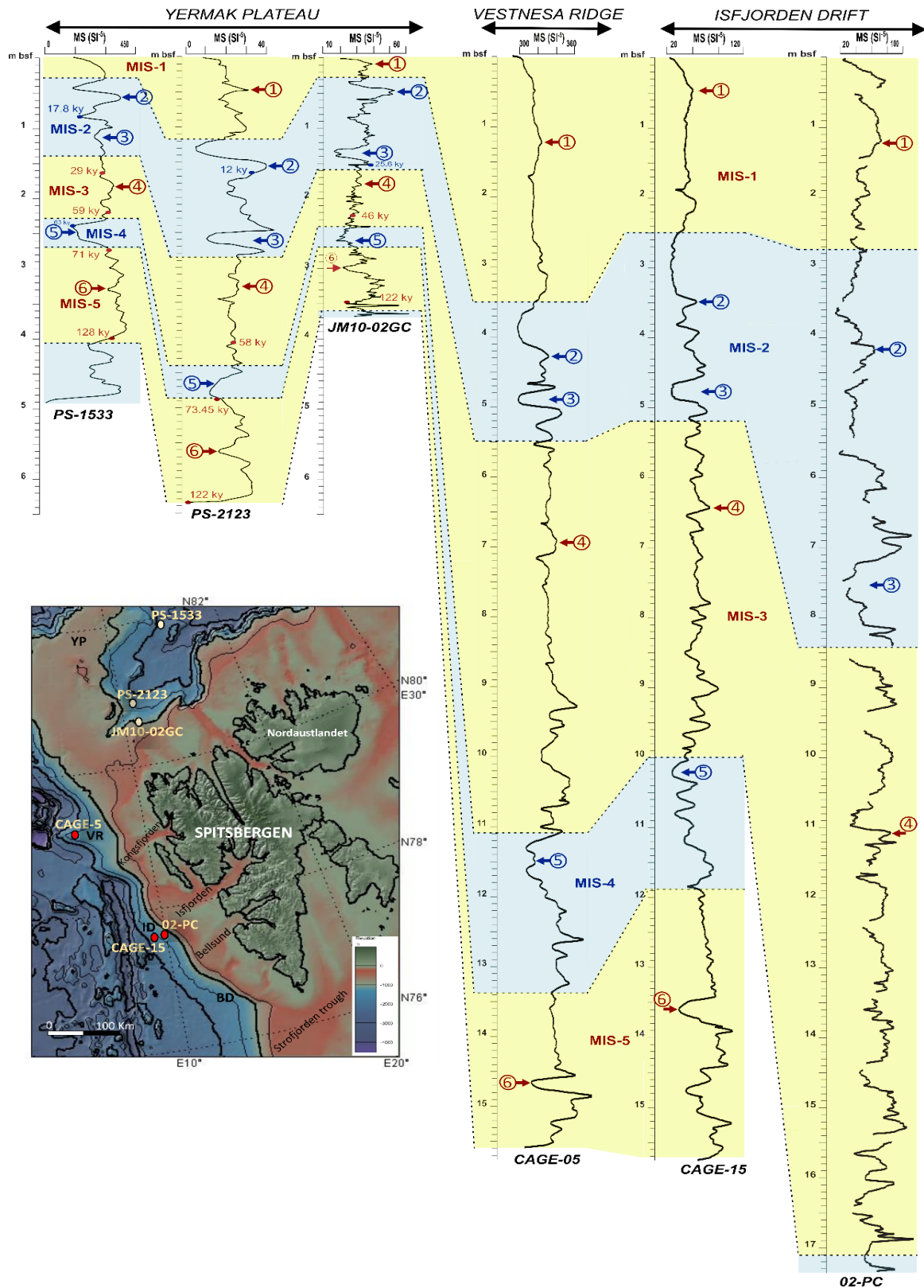


Figure.5-2: Correlation between the studied cores and other cores collected on the Yermak Plateau (modified after Chauhan et al., 2014). The sequentially numbered red (interglacials) and blue (glacials) arrows indicate tie points that were defined on the MS curve for core correlation.

The deepest part of the CAGE cores, correlated based on a local decrease in magnetic susceptibility observed on the northern sediment core located at the Yermak Plateau (red arrow number 6 on **Fig. 5-2**). The presence of low values of Ca/Ti and Br/Ti ratios indicate a decline in biogenic activity that could be attributed to the MIS-5b cold stadial as confirmed through several studies (e.g. [Matthiessen et al., 2001](#); [Bylinskaya et al., 2016](#)).

The presence of MIS-5a within the CAGE cores is compatible with the data obtained by the calculation of the sedimentation rate presented above, as the MIS-5a represents a warm interstadial interval that lasts about 14 ky (71–85 ky) and is characterised by an increase in biological activity as observed by several scientific studies ([Chauhan et al., 2014, 2016](#); [Dowdeswell et al., 2010](#); [Jessen et al., 2015](#); [Vogt et al., 2001](#)).

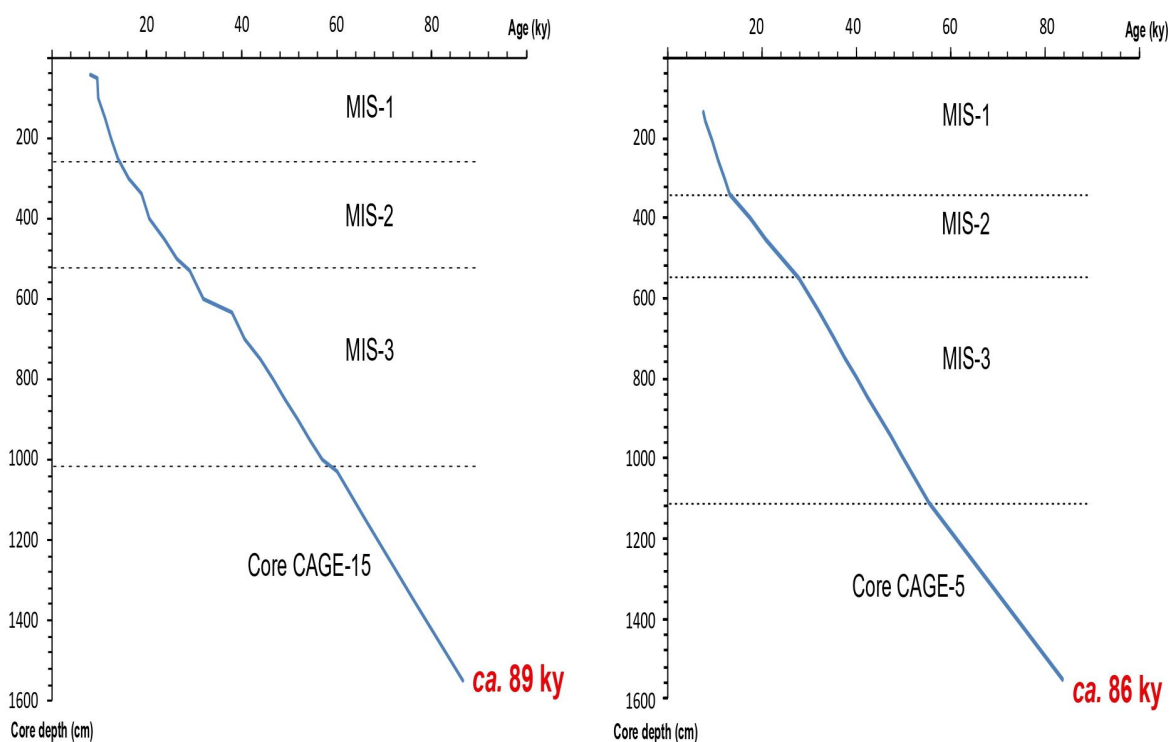


Figure.5-3: sedimentation rate of the CAGEs core with calculated sediment age.

5.2 Environmental and climatic characterization of stratigraphic units and events

According to the age model defined by [Caricchi et al. \(2019, 2020\)](#) on core 02PC, and the discussed core to core correlation made on the basis of the MS, the compositional (XRF, XRD) trends, and the sedimentation rate, the studied sedimentological record contains the Marine Isotopic Stages (MIS) -1, MIS-2, MIS-3, MIS-4, and in the cores CAGE-15 and CAGE-05, MIS-5a, and the MIS-5b.

In the following, a climatic and environmental characterization is provided taking into account the sedimentological analysis performed during the PhD project.

5.2.1 Marine Isotopic Stage-1: Late Weichselian-Holocene

In the studied cores, MIS-1 consist mainly of pervasively bioturbated sediments characterised by a progressive increase of the Ca/Ti ratio, corresponding to an increase of carbonate microfossils as described by [Carbonara K. \(2016\)](#) and [Gamboa-Sojo V. \(2020\)](#). The increase of the carbonatic fraction corresponds with a generally lighter colour of the sediments (2.5Y 4/3 of the Munsell colour chart) compared to the rest of the marine sediment record, suggesting that deposition occurred in an oxygen-rich environment. These enhanced aerobic conditions would have contributed to the increase in biological activity, which in addition to the Ca/Ti ratio, can be detected on the Si/Al ratio used as a proxy for biogenic silica production ([Dickson et al., 2010](#)), and the Br/Ti ratio, which is related to marine organic productivity ([Agnihotri et al., 2008](#)).

MIS-1 is characterised by two distinct sediment facies (**Fig. 5-4**) related to climatic conditions: the beginning of MIS-1 is marked by the presence of abundant, although sparse (not massive), IRD that was associated with the final phase of deglaciation between 14 to 11.7 ky, followed by stable interglacial conditions with the deposition of pervasively bioturbated sediments. This variation in sedimentary facies and environmental conditions is confirmed by the distribution of the C_{org} / N_{tot} ratio in cores 02PC (**Fig. 5-4**) and CAGE-15. In the deeper part of MIS-1, the C_{org} / N_{tot} ratio has values greater than 10 observed between 280–190 cm bsf for core 02-PC(**Fig. 5-4**) and between 250–150 cm bsf for core CAGE-15, indicating a continental origin of the organic matter that was supplied through icebergs melting together with IRD.

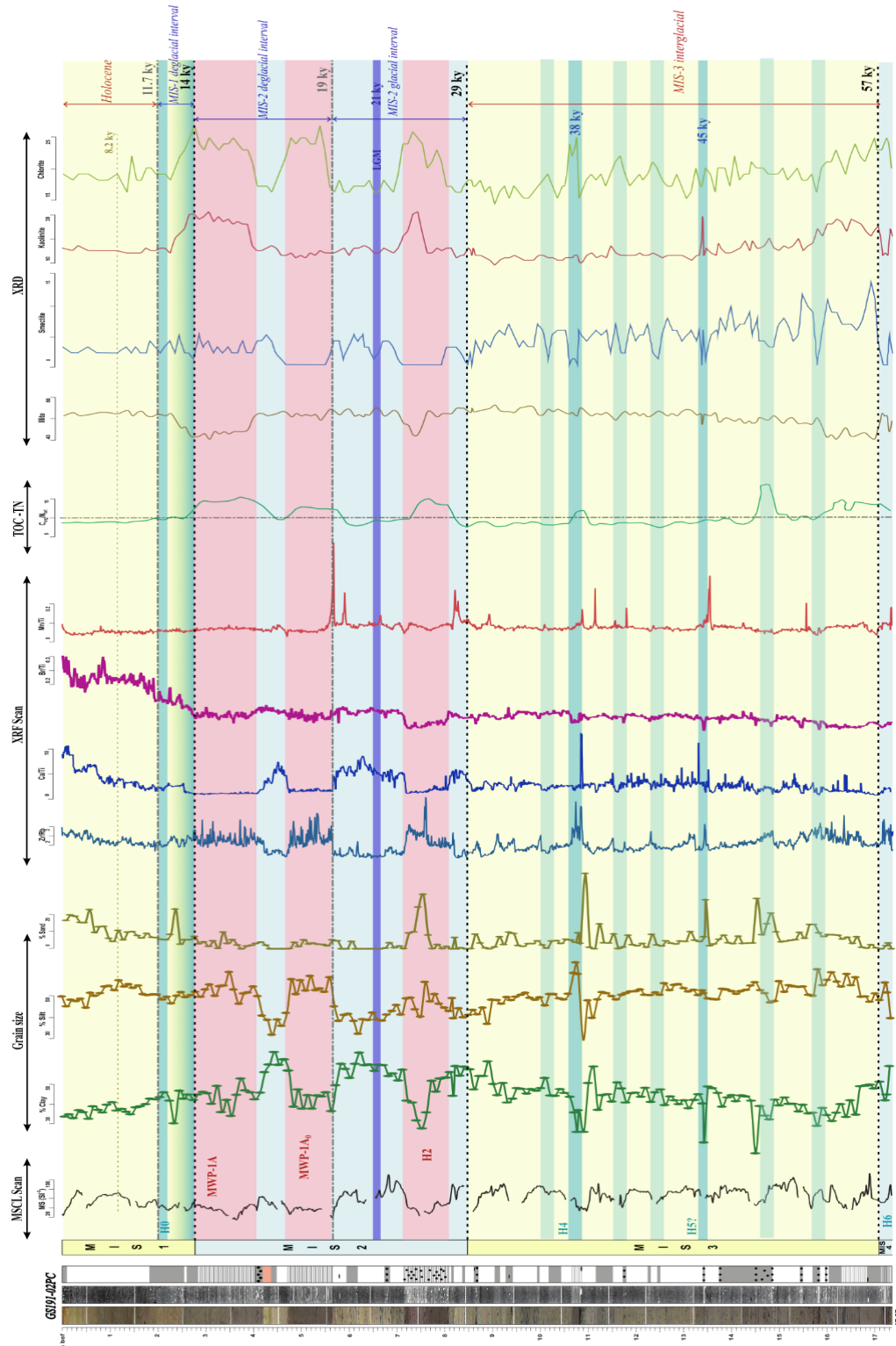


Figure.5-4: An overview of obtained data that sustained the discussion for cor 02-PC (MSCL Scan, Grain size, XRF proxies, TOC-TN, and XRD data .)

Those values are coherent with a deglaciation period, while in the upper part of MIS-1 that corresponds to the Holocene interval, the C_{org} / N_{tot} ratio is constantly below 10, indicating the dominance of marine organic matter. In core CAGE-5, the C_{org} / N_{tot} was not analysed, but the change between the end of deglacial conditions and the firm interglacial period is depicted through the change of sediment facies, XRF proxies, and sediment bulk density, which changes in agreement with the two cores from relatively high values in the interval containing IRD, to lower values on the uppermost heavily bioturbated facies (**Fig. 5-4**).

In core 02PC, the end of MIS-1 deglaciation is marked by an interval situated between 200–220 cm bsf, characterised by an enrichment of the sand fraction with an increase in illite and chlorite, and a decrease in XRF bioindicators such as Ca/Ti and Br/Ti and smectite (**Fig. 5-4**). According to the age model of core 02PC this interval was associated with the Younger Dryas cold stadial (H0, 12.9–11.7 ky) ([Łacka et al., 2020](#) [Allaart et al., 2023](#)). In particular, the decrease in smectite content suggests that the Younger Dryas was characterised by a weaker heat input from the WSC. Based on sedimentological and geochemical features observed during the H0 interval recorded in core 02PC (low values on Ca/Ti, Br/Ti, and smectite accompanied with an enrichment on illite and chlorite), this event was also identified in cores CAGE-15 and CAGE-5, where it was recorded at 150 and 260 cm bsf, respectively.

The onset of the Holocene is characterised by a peak in smectite content accompanied by a progressive increase of the Ca/Ti Si/Ti, and Br/Ti bioindicators (**Fig. 5-4**), indicating the resumption of warm WSC after the Heinrich event H0 (Younger Dryas) with a progressive diminution of the terrigenous input from the beginning of the Holocene to recent times. The sedimentation during the Holocene shows also some minor fluctuations indicating the occurrence of short cool stadials characterised by a local decrease on XRF bio-indicators proxies observed on all the studied cores on the uppermost parts as observed in ([Bond et al., 1997](#), [Anderson et al., 2004](#), [Ślubowska-woldengen et al., 2008](#), [Carbonara et al., 2016](#), [El bani Altuna et al., 2021](#), [Torricella et al., 2022](#)). These minor cooling events could suggest a decrease on the Atlantic water inflow which is confirmed by a diminution on smectite content.

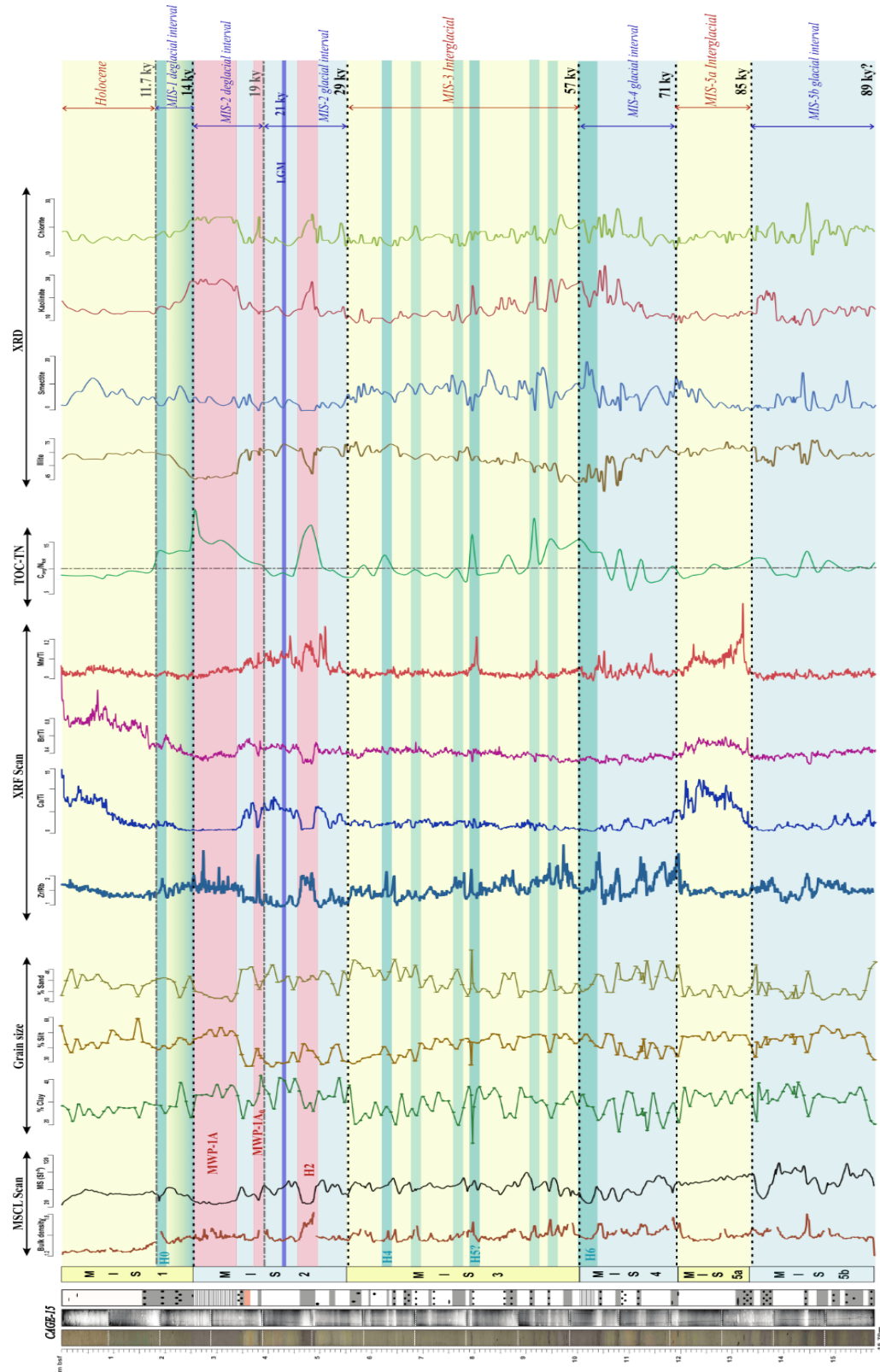


Figure.5-5: An overview of obtained data that sustained the discussion for cor CAGE-15(MSCL Scan, Grain size, XRF proxies, TOC-TN, and XRD data .)

5.2.2 Marine Isotopic Stage-2: Upper Weichselian (Late Pleniglacial)

The record of the MIS-2 is thicker on the proximal core 02PC with a thickness of 5.5 m than on the distal cores CAGE-15 and CAGE-5 in which the thickness is 3 m and 2.2 m, respectively. The MIS-2 contains 3 marked climatic events, from the base to the top: H2 (24 ky), MWP-1A₀ (19 ky) and MWP-1A (14.65–14.31 ky).

During the emplacement of the H2 event, the sedimentation was mainly controlled by a constant terrigenous input as the organic matter shows a continental origin with high values superior to 10 on the C_{org} / N_{tot} ratio observed on both cores 02PC and CAGE-15. This continental supply was detected also through the Zr/Rb XRF proxy indicating an increase of the grain size. XRD data shows low values on smectite content suggesting a decrease on the warm WSC current input compared with the MIS-3. The illite also registered a diminution although the values remain relatively high (about 30 %). The particularity was registered on the chlorite and the kaolinite contents that both show an important peak by reaching 25% and 30% respectively. Further, the onset of the H2 event is marked by a peak in the Mn/Ti content, suggesting oxygenation in the water column. We argue that H2 event represent a warm interval confirmed through the laminated facies that could be considered as plumite, deposited by a suspension plume (Dowdeswell et al., 2000). A warm climate during H2 event is also confirmed by the other sedimentological proxies (high kaolinite and chlorite content, several peaks on Zr/Rb ratio confirmed by enrichment on sandy fraction), which indicate a melting of the ice-sheet provoking the release of icebergs (calving process), which allows the registration of the current destabilisation of the ice sheet (by melting) with a different signal at a greater distance, since H2 is registered on 02-PC as a laminated interval, while the same signal is recorded at a distance of 10 kilometres as a rich IRD derived from Icebergs (on core CAGE-15). This anomaly registered during The H2 event leads to hypothesise that Heinrich events on the western margin of svalbard could not have the same dynamics as observed on the Labrador sea (Hesse et al., 1998)

After the H2 event, the main record of the glacial stage above the H2 including the Last Glacial Maximum-LGM (21 ky) is characterised by a low terrigenous input observed on the kaolinite and chlorite content that reaches their lowest values. Furthermore, this period is characterised by an enrichment on clay fraction which indicates a calm deposition environment during the LGM in relation with the extension of the SBSIS. Furthermore, the C_{org} / N_{tot} ratio

indicates a marine origin of the organic matter as all values during this interval are lower than 10 which is accompanied by a peak on the XRF bio-indicators proxies (high Ca/Ti and Br/Ti). During the glacial interval of MIS-2, several troughs were formed on the continental slope under the action of the ice streams. The current sedimentary record registered in the Trough Mouth Fans (e.g. Bjornoyrenna TMF, Storfjorden TMF and Bellsund TMF.) (Laberg et al., 1997; Vorren et al., 1997; Andreassen K et al., 2009; Rebesco et al., 2014)

The deglaciation interval of MIS-2, which started during the upper Weichselian is marked by two meltwater events: the MWP-1A₀ and the MWP-1A. The MWP-1A₀ is well registered only in core 02-PC, where it reaches a thickness of 1 m (from 470–570 cm bsf), whereas it measures only a few centimetres in core CAGE-15 (situated at 380 cm bsf). This event occurring as a laminated interval, deprived of IRD on core 02-PC, took place *ca.* 20 ky ago and it was associated with a prominent meltwater event (Caricchi et al., 2019) This interpretation is supported by a series of sedimentological and compositional characteristics. The beginning of MWP-1A₀ is marked by a switch on the type of organic matter as the C_{org} / N_{tot} ratio shows values higher than 10 implying the end of the marine sedimentation dominated during the glacial phase to a continental sedimentation characterised by an important continental input. The high Zr/Rb ratio indicates coarser grained sediments and the prominent Mn/Ti peak on the base of the event which indicates an oxygenation on the water column. The low values observed on XRF bioindicators (Ca/Ti and Br/Ti) implies a decrease in biogenic activity.

The MWP-1A was well registered in all the studied sediment cores with a thicknesses variation, it measures 130 cm (from 290 to 420 cm bsf) on the proximal core (02PC), 100 cm (from 240 to 340 cm bsf) on CAGE-15 core, and 70 cm (from 350 to 420 cm bsf) on CAGE-05. The MWP-1A is bounded at the top and the bottom by two massive IRD intervals. It is characterised by low values of magnetic susceptibility, variably-high Zr/Rb which is associated with the presence of coarse silt and sand/silt laminae generated during the melting of the ice sheet. This continental input was registered on C_{org} / N_{tot} ratio showing high values (>10) confirming the continental origin of the organic matter. During the MWP-1A event the XRF bioindicators proxies (Ca/Ti and Br/Ti) register a low biogenic activity. The XRD data show a particular pattern not observed in the previous laminated intervals, characterised by a peak in kaolinite and chlorite content complemented by relatively high values of smectite.

5.2.3 Marine Isotopic Stage-3: Middle Weichselian (Middle Pleniglacial)

The MIS-3, (57 - 29 ky), is classified as an interglacial period. However, several studies (e.g. [Hald et al., 2001](#); [Siddal et al., 2008](#); [Xiao et al., 2015](#); [Agosta et al., 2016](#);) have shown that it was a highly dynamic stage characterised by ice sheet instability and numerous climatic fluctuations confirmed by the occurrence of cold and warm events. The studied cores contain a several m-thick MIS-3 with thickness of 8.5 m for the core 02PC, 4.5 m for the core CAGE-15 and 5.5 m for the core CAGE-5. The minor cold events are registered on the all the figures with a light blue during MIS-3

The compositional and sedimentological proxies are consistently highly variable throughout the MIS-3. The Corg/Ntot ratio generally has values below 10, confirming the marine origin of the organic matter, which is coherent with the general interglacial context of the MIS -3. The Corg/Ntot curve locally shows some peaks above 10 in core 02PC and in core CAGE -15, corresponding with massive IRD layers which proves again the climatic instability of MIS-3. The Ca/Ti and Br/Ti ratios demonstrate biogenic activity on several occasions, although the highest values observed are not comparable to those observed in the uppermost core during the Interglacial period MIS-1. This leads to the consideration that environmental conditions were not entirely favourable for biogenic activity of calcareous organisms. Furthermore, The Mn/Ti curve has numerous peaks that indicate the transition to warmer phases and generate a water column ventilation. These peaks generally occurred before the presence of a rich IRD interval, and their frequency within this interval reconfirms again the climatic instability during MIS-3.

The higher values on Corg/Ntot ratio observed during the beginning of MIS-3 are related to the transition between the glacial stage of the MIS-4, and the interglacial conditions of the MIS-3.

H5 event was identified also in core 02-PC according to the age model proposed by [Caricchi et al., 2019, 2022](#), It is located at 1350 cm bsf and presented as an IRD rich interval, characterised by a peak on Corg/Ntot indicating the terrigenous input during such event accompanied by an increase on kaolinite content and a decrease on smectite and chlorite content (**Fig. 5-4**). The same signal was registered also on core CAGE-15 at 800 cm bsf (**Fig. 5-5**) and CAGE-5 at 950 cm bsf (**Fig. 5-6**) The low thickness of the H5 event observed in the sediment

record suggests a large distance from the ice sheet suggesting a brief time interval of this event estimated by several hundred to a few thousand years (Hemming 2004)

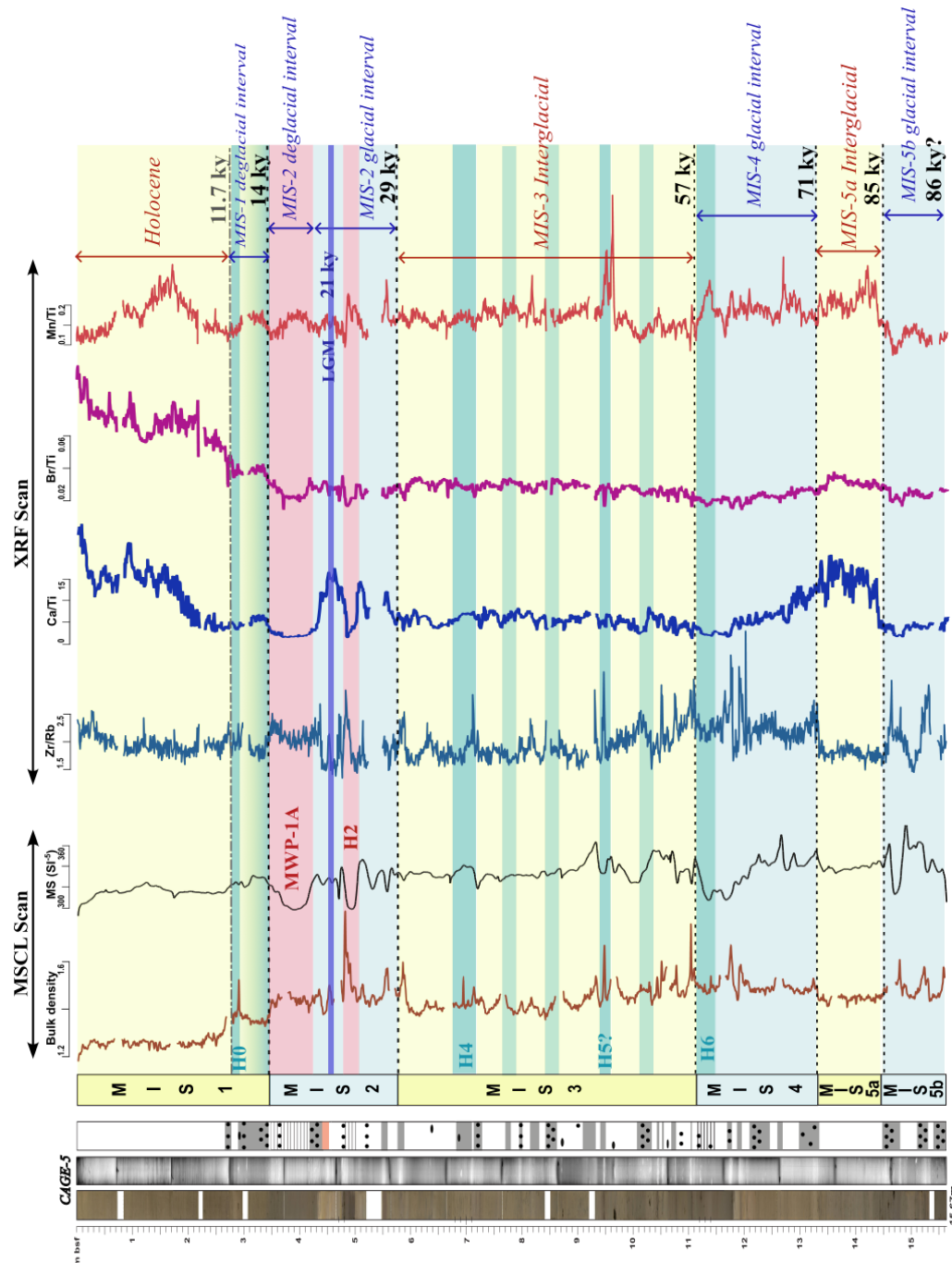


Figure.5-6: An overview of obtained data that sustained the discussion for cor CAGE-5(MSCL Scan, Grain size, XRF proxies, TOC-TN, and XRD data).

On core 02PC between 1070–1100 cm bsf, we note the existence of a laminated interval preceded by a peak in the Mn/Ti ratio that belongs to the H4 event according to the age model. It is characterised by Corg/Ntot values above 10 and a clay mineral association similar to that observed in MWP-1A₀, characterised by a low smectite content and an enrichment of chlorite content, while on core CAGE-15 the H4 event is represented as a few centimetres long IRD-rich interval located at 690 cm bsf, which does not have the same clay mineral association and was identified only considering the Corg/Ntot that value, which is above 10. This different signal observed in the two cores could be explained by the H4 event being too short so that the signal was only detected in the proximal core 02PC, or by the need for higher resolution by sampling this interval every 1 cm. The lamination of the H4 event indicates an ice sheet melting that resulted in ice sheet breakup by calving and release of IRD observed down slope. The significant occurrence of these IRD intervals generated by repeated ice sheet advances and retreats associated with episodic releases of icebergs, are further evidence of the complex and fluctuating nature of glacial activity during MIS-3.

5.2.4 Marine Isotopic Stage-4: Early Weichselian (Early Pleniglacial)

The MIS-4 was fully recorded only on CAGE cores, while on core 02PC only the termination of MIS-4 was registered, confirmed by the H6 event located between 1720–1737 cm bsf, which was represented as a laminated interval in all the studied cores. According to [Tutken et al. 2002](#), [Lambeck et al. 2010](#), and [Kremer et al. 2018](#) the MIS-4 glacial was characterised by considerable ice sheet growth throughout the Arctic region resulting in a global sea level decline that is estimated by - 81 m compared to the present day ([Cutler et al., 2003](#))

As observed during the MIS-2 glacial interval the MIS-4, is characterised by dominant marine sedimentation without terrigenous inputs as the Corg/Ntot ratio has values below 10, except for the end of MIS-4, where the ratio has values above 10 associated with the H6 and the transition toward the MIS-3 interglacial interval.

The MIS-4 recorded in both CAGE cores have generally low values for XRF bio-indicators (Ca/Ti and Br/Ti ratios) confirming a decline in biogenic activity during, but these generally cold conditions do not prevent the occurrence of some local small spikes in XRF bioindicators observed at CAGE-15 (e.g., at 1050, 1100, 1150 cm bsf) and at CAGE-5 (e.g., at 1140, 1270, 1300 cm bsf). These local peaks which present a typical indicator of biogenic activity of

calcareous microfossils during MIS-4 (increase on both Ca/Ti and Br/Ti) correspond also to other spikes observed on Mn/Ti ratio indicating an oxygenation of the column water ([Presti et al., 2011](#); [Lowermark et al., 2016](#)) which could generate an upwelling from nutrient-rich bottom water currents. [Chauhan et al., 2015](#), demonstrate the presence of polynea during the MIS-4 at the northwestern margin of Svalbard which explains the local spikes indicating a high biological activity during MIS-4.

The H6 event in all the studied cores, marking the end of MIS-4, shows some anomalies compared to the other Heinrich events described previously. The XRD data show an enrichment of smectite accompanied by low chlorite and kaolinite values as well as low values on bulk density values and even fine granulometry, which is confirmed by low Zr/Rb ratio values. This particular sedimentological pattern suggests that during H6, the WSC was present but it was less powerful allowing an accumulation of fine grains in this interval, and that melting was controlled by other water masses originating from surface melting of the ice sheet. In fact, [Strand et al., 2011](#) confirms the existence of flooding deposits in the arctic ocean during MIS-4 using sediment cores collected on the Lomonosov Ridge. In addition, [Rusmussen et al., 2014a](#), presented evidence for a significant impact of surface meltwater, possibly leading to reduced vertical water exchange. This may have impeded the transport of oxygen-rich water to the deeper ocean.

5.2.5 Marine Isotopic Stage-5 (MIS-5a & MIS-5b): Early Weichselian

Based on the core-to-core correlation presented above (see section 5.1) we hypothesised that both CAGE cores reached the uppermost part of the MIS-5 represented by two sub-stages: MIS-5a and MIS-5b. The subdivision of MIS-5 was presented for the first time by [Shackleton N. J. 1969](#) based on isotopic analyses and paleotemperature variations. The interstadial stage of MIS-5a occurred between 85–71 ky and shows a similar sedimentological signal characterised by a low bulk density as observed during the interglacial stages (MIS-1 and MIS-3). The onset of MIS-5a was preceded by a Mn/Ti peak indicating an oxygenation of the water column and improvement in climatic conditions, leading to an increase in biological activity confirmed by two peaks in the XRF bioindicators (Ca/Ti and Br/Ti). The clay minerals assemblages also confirm the increase of the intensity of the warm WSC current presence of a cold bottom water

flow deduced from the increase on smectite content during the MIS-5a. The increase in the strength of this current has been confirmed not only in northern Spitsbergen in the Yermak Plateau area based on foraminiferal study reported on [Chauhan et al., 2014, 2015](#), but also in the central Arctic, as presented by [Spielhagen et al., 2004](#).

MIS-5b recorded on the deepest part of the CAGE cores is characterised by an increased frequency of IRD-rich intervals causing an increase on the bulk density values which are similar to the one observed during glacial periods. These IRD intervals generate an increase on the sandy fraction confirmed also by higher values on the Zr/Rb ratio. XRF bio-indicators reveal a low biogenic activity observed within low values on Ca/Ti and Br/Ti. XRD data register locally an enrichment on smectite, kaolinite and chlorite content that is in relation with icebergs from Kara sea by passing later through the Barents sea ([Spielhagen et al., 2004](#))

5.3 Down and along-slope depositional processes and their connection with climatic conditions

The 02PC is the most expanded sedimentary core, as it has a higher sedimentation rate permitting to reach 60 ky on the bottom of the core, followed by the core CAGE-5, which could reach 86 ky according to the data discussed above, and the most condensate core is the CAGE-15 where the age of the bottom part is estimated at 89 Ky.

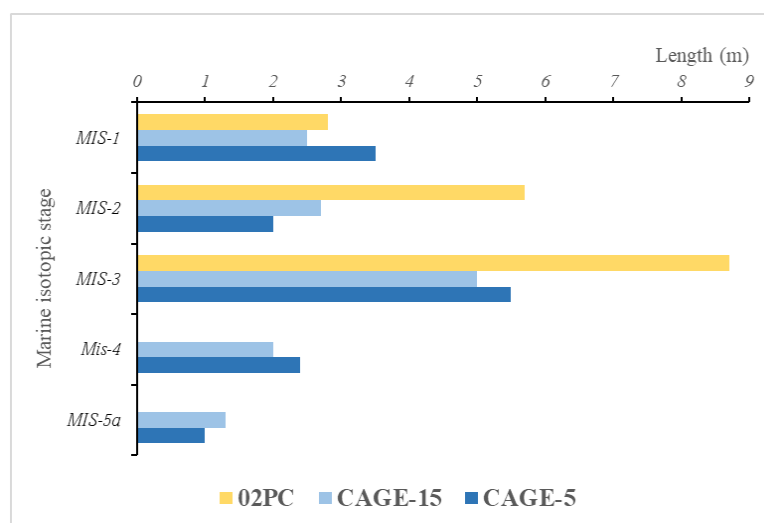


Figure.5-7: A diagram showing the length of each Marine Isotopic Stage on the three studied cores (02-Pc: yellow, CAGE-15: light blue, and CAGE-5: blue)

Fig. 5-7 shows a comparison between the extent of all MIS on the studied core. The data show that core 02PC does not always have a very expanded marine record compared to the CAGEs core. For example, during the warm interglacial MIS -1, all sediment cores studied had a similar length, varying from 2.5 m to 3.5 m. The length of the core is similar to that of the CAGEs core. In fact, the core on the upper slope (02-PC) is thicker MIS -1 than the distal core on the lower slope CAGE -15, measuring about 2.8 m and 2.5 m, respectively. The TOC-TN curve shows that significant terrigenous input was recorded in core 02-PC at the beginning of MIS-1 (14-11.7 ky) and not with this significance in CAGE-15, suggesting that during ice sheet retreat core 02- PC receives more continental input than the distal core CAGE-15, which is 10 km from the upper slope core. The core CAGE -5 contained a more detailed MIS -1, as it measured 3.5 m, but this was related to the topography, as the Vestnesa ridge could allow a higher sediment deposition and avoided sediment dispersion along the margin.

The same pattern was observed during the MIS-5a interstadial interval recorded only in CAGEs core, where both cores have an estimated expansion of 1.3 m on average (**Fig. 5-7**). This similarity of the sedimentation rate of the marine sediment record during interglacial intervals suggests that the depositional process was controlled by the same vector represented by the WSC and that the continental input should be limited which is confirmed by the chlorite and kaolinite content that have lower values (about 16%).

In summary, the retreat of the ice sheet at the beginning of the interglacial period allows the release of terrigenous sediment, which is recorded at large values in the upper slope core. All sediment cores also receive sediments from the warm bottom current (WSC) (**Fig. 5-8**).

On the other hand, sedimentary sequences in the upper slope core (02-PC) contain about 6 metres of sediments deposited during the glacial period (MIS-2), while the mid- slope CAGE sediment cores register only 2.3 m on average (**Fig. 5-7**). This difference in sedimentation thickness in the same stratigraphic interval suggests that the depositional process in the upper slope during the cold period is controlled by the large continental input produced by the advance of the ice sheet, while this input gradually decreases down slope due to the long transport distance (**Fig. 5-8**).

The three major events recorded during MIS-2 have a different sedimentological pattern with respect to the XRD data within the same core, suggesting different sedimentation dynamics and

sediment transport. The presence of the laminated facies in core 02PC indicates a proximal position to the ice sheet, which is continuously melting and releasing fusion water. The MWP-1A and MWP1-A0 present two warm intervals which are in accordance with the deglaciation during the upper Weichselian. The MWP-1A is well registered in all the studied cores with an important thickness that vary from 110 cm (core 02PC) to 70 cm (core CAGE-5) moving from the Isfjorden drift to the Vestnesa Ridge which imply that this melting event affect all the western svalbard margin simultaneously and the sediment deliberation was too important to be detected either upper to down slope. Instead the MWP-1A₀ was well recorded only on the 02PC core suggesting also a proximal position to the ice sheet grounding line on that time on the upper slope, while, only in one distal core (CAGE -15) an IRD-rich interval was recorded could be explained by the fact that the icebergs leave footprints due to the enhanced calving process triggered by basal melting. The fact that MWP-1A₀ was not recorded on the core CAGE-5 situated on the vestnesa ridge reconfirm that such area has not undergone an ice-sheet melting during the MWP-1A₀ or the core position was too far away from the grounding line and that event will not be recorded. The difference observed within the MWP-1A and MWP-1A₀ concerned the clay mineral assemblage as only chlorite was observed on the MWP-1A₀ whereas both kaolinite and chlorite were registered during the major event MWP-1A suggest that chlorite derives from a location near to the core position that could be the Isfjorden drift or the spitsbergen outcrop while kaolinite derives from more distant source situated souther that could be the Bjornoyrenna TMF or the Storfjorden drift. (Musco M. E. 2018; Lucchi et al., In prep).

The H2 event which was presented also in all the studied sediment cores with different sediment facies, laminated, rich with IRD on 02PC core, rich with IRD on CAGE-15, and laminated on CAGE-5, The presence of H2 as a laminated interval within the glacial MIS-2 stage suggests a melting on the ice sheet that could be provided by the fusion water drive from the surface of the ice sheet or a different dynamism of the H2 event on the western margin of svalbard in contrary to what was identified on labrador sea.

The interglacial interval MIS-3 was well recorded on core 02-PC, as it measures about 9 m, while it is 5 m on the cores on the middle slope. The important difference between the upper and lower cores within MIS-3 is related to the nature of this interval and its climatic variations, as the

occurrence of several cold climatic intervals allowed the registration of more extended intervals on the upper slope core (02-PC).

In summary, differences in sedimentation rates between the upper and middle slopes are more evident during intervals of ice sheet retreat/advance due to the interaction between continental inputs and bottom currents (during glaciation and deglaciation), whereas during the interglacial period only WSC control sedimentation (**Fig 5-8**).

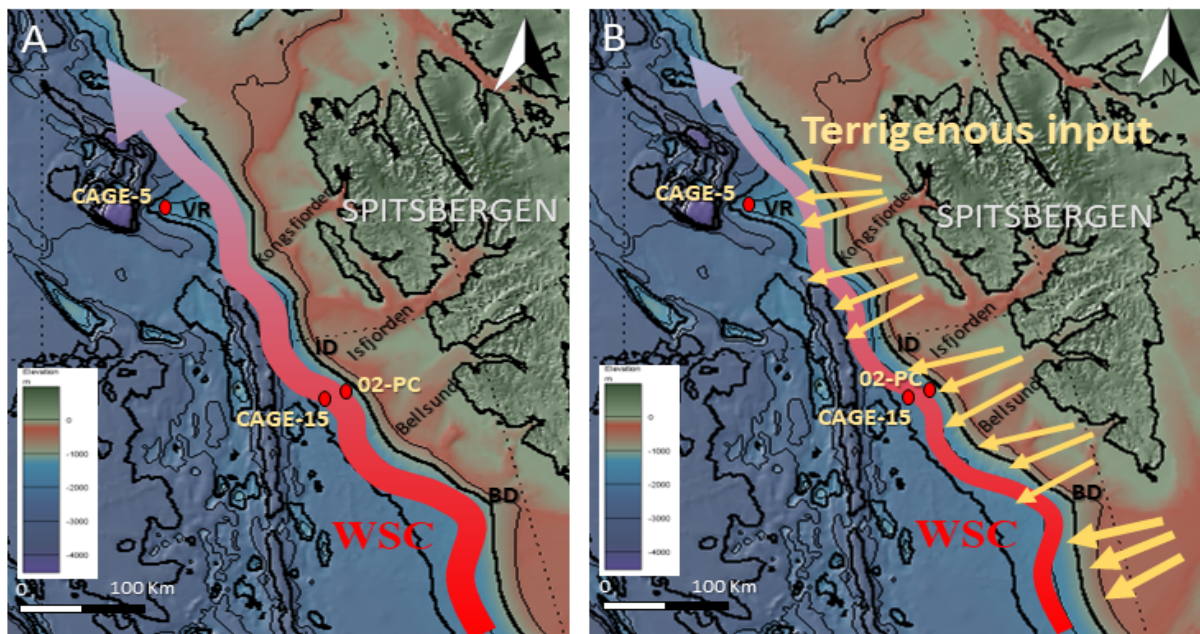


Figure.5-8: A) Sedimentation during the interglacial period is controlled by warm bottom currents. B) Sedimentation during ice sheet dynamics (retreat and advance) is controlled by the supply of terrigenous material and warm bottom currents.

CONCLUSIONS

Three sediment cores from the western margin of Svalbard were analyzed with several proxies such as the MSCL core scan, Macroscopic description, X-ray radiography, XRF scan, Photography, XRD analysis, Total Organic Carbon, TOC, Total Nitrogen, TN and grain size analysis.

It was possible to identify 3 sedimentological facies previously defined by Lucchi et al., 2013, 2015: Bioturbated facies characteristic of Interglacial interval, Laminated facies that derive from the meltwater plumes, and IRD rich facies characteristic of advance/retreat of the ice sheet.

correlation of the three sediment cores based on the pattern observed within the magnetic susceptibility, the sedimentary facies, the clay mineral assemblage, and the XRF signal, which permit the extrapolation of the age model published by Caricchi et al., 2019 within the first 60 ky, and estimated to MIS-5b the bottom of the CAGEs cores (around 90 ky).

Heinrich event 2 in the upper slope core (02-PC) is recorded as an IRD rich- laminated facies, interpreted as the production of meltwater flow. Thus, On the Isfjorden margin the H2 presents a warm interval controlled by Atlantic water inflow.

During the MIS-3 period, the influence of the Western Svalbard Current (WSC) was not significant in promoting warmer and stable climatic conditions, as the upper slope core had a higher sedimentation rate within this interglacial interval, but this is in relation with the climatic fluctuations of MIS-3 and the occurrence of several cold/warm short intervals.

Sedimentation rates exhibit more noticeable variations between the upper and middle slopes when the ice sheet undergoes periods of retreat or advance. These variations are primarily influenced by the interplay between continental inputs and bottom currents during glaciation and deglaciation. However, during interglacial periods, sedimentation is predominantly controlled by Western Svalbard Current (WSC) without the additional impact of ice sheet dynamics.

The Western margin of Svalbard presents a valuable location for studying all the climatic fluctuations, as for the characterisation of the climatic interval related with the dynamic of the ice sheet (retreat or advance) the sediment signal is better registered on the upper slope, while for a detailed interglacial characterisation the down slope core could be a tool for a high resolution paleoclimate reconstruction.

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