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Status and scope of Pleistocene palaeoenvironmental studies of Svalbard coastal sediments

Abstract

The late Quaternary terrestrial sequences of Svalbard hold important information about the inception, duration, and termination of glaciations, deglaciations as well as related sea-level fluctuations. It was previously believed that the sedimentary record of older glaciations would have been eroded by preceding glaciations. This idea was modified by the later investigations reporting the presence of deposits of the Saalian age.Although the records are fragmentary they are found exposed at several sites around coastal Svalbard. Several investigations have been conducted to decipher the sedimentology, lithostratigraphy and geomorphology. Aminoacid geochronology, radiocarbon dating, and other absolute dating methods have been used to put the glacial, deglacial, and marine depositional events in a strong chronological framework. The successive efforts to refine the chronology of the events recorded in these sequences have provided the revised ages for important climate events and have also led to the identification of previously unknown events. On the contrary, the microfossil-based studies of the sedimentary sequences that were initiated along with the chronological studies have not been investigated in comparable detail and thus remain understudied. The foraminifer forms the only microfossil and/or microfaunal group widely recovered from various sedimentary units of these sequences. They have been studied along with mollusc fossils and have added to the utility of fossil-based reconstruction of environmental conditions of the past. This study is aimed to provide a synthesis of the late Quaternary paleoclimate and paleoenvironmental studies conducted in the High Arctic Region of Svalbard that has utilized the potentially important fossil remains preserved in the raised marine sedimentary sequences. The overview of the studies reflects that microfossilscan be used to infer depth, salinity, turbidity, nutrient availability, oxygenation of the watercolumn, temperature, and ocean currents. It is also noteworthy that the foraminifer and mollusc have not been able to provide a definitive distinction between interglacial and interstadial environmental/oceanographic signatures. This could be addressed by concerted attempts and detailed studies to assess the full potential of exposed coastal sedimentary successions by studying the preserved microfossils.

Keywords: Middle Weichselian, foraminifera, molluscs, palaeoceanography, microfossils, interglacial

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Abbreviations: OSL, optically stimulated luminescence; IRSL, infrared stimulated luminescence; ESR, electron spin resonance; TL, thermoluminescence

Introduction

The coastal Quaternary sequences of Svalbard have attracted the attention of researchers ever since the beginning of the nineteenth century and have been studied primarily to understand the Svalbard Barents sea ice sheet extent, dynamics, and the geomorphologic evolution of the Svalbard archipelago (Figure 1).[1-6] The studies concentrated on glacial geology, amino acid stratigraphy, litho-stratigraphy, sedimentology, geomorphologic changes, and also fossil/microfossil based palaeoenvironmental reconstructions were used to understand climatic changes that occurred after the last glacial maximum (Figure 1).[7-20] The Quaternary landscape of the Svalbard region has been shaped by the alternating glacial/ stadial and interglacial/interstadial cycles and the relative sea-level changes. Glaciation events were characterized by an increase in the glacier extent and thickness, during which a glacier progrades and the thick glacierload causes the isostatic depression of strata followed by deglaciation, removal of load, and the upheaval of the strata. Several cycles of glaciation and deglaciation have occurred during the Late Quaternary before the Holocene and the signatures of these events are recorded in the coastal sedimentary sequences.

The chronology of these events is based on absolute dating using Optically stimulated luminescence (OSL), Infrared stimulated Luminescence (IRSL), Electron spin resonance (ESR), Thermoluminescence (TL), U/Th, C14, amino acid through successive studies during the past few decades.[21,22] This has resulted in the identification of several glacial/stadial and interglacial/interstadial cycles during the late Quaternary. The later part of Weichselian glaciation is well understood as compared to Early and middle Weichselian.[23-28] The microfossils have been recovered from the coastal sequences of Svalbard and were utilized for the reconstruction of palaeoenvironmental conditions.[11,12] The initial studies encompassing the Quaternary have used the fossilized remains of whale bones, driftwoods, and molluscs primarily for radiocarbon and amino acid dating (Figure 1).[13,29] The fossilized remains of Molluscs and foraminifera recovered from the Quaternary sedimentary sequences were the first to be used for biostratigraphy and palaeoenvironmental reconstruction.[8,9,11,30] The microfossils from the coastal sequences have proved to be useful for understanding palaeoclimate and palaeoecological conditions.[15] The microfossils could provide valuable information about the paleoenvironmental conditions and palaeoecological interactions among the organisms during the interglacial/interstadial cycles and the environmental changes caused by the disruption of warm ocean currents during the glacial events. The fossils are commonly preserved in silt and

sand deposits and have also been recovered from the gravel-rich sediments.[11]

Middle-late Pleistocene sedimentary succession of Svalbard

The coastal Quaternary coarsening upwards sequences came into existence due to several glacial and deglacial cycles. The glacial diamict / till is deposited by the prograding glacier, the thick glacial load results in isostatic depression of the strata and a sea-level highstand. The deposition of glaciomarine fine-grained suspended sediment occurs under low energy deposition during high sea-level conditions. During deglaciation, the strata start rising / rebounds due to the removal of the pressure of the overriding glacier. The gradual rebound of the strata deposits shallowing upward sequence with glacially derived till underlying the marine mud which deposits during high sea level (Figure 1). The process of gradual rebound results in a lowering of sea level and the turbidity currents lead to the deposition of shoreface sand and gravel.

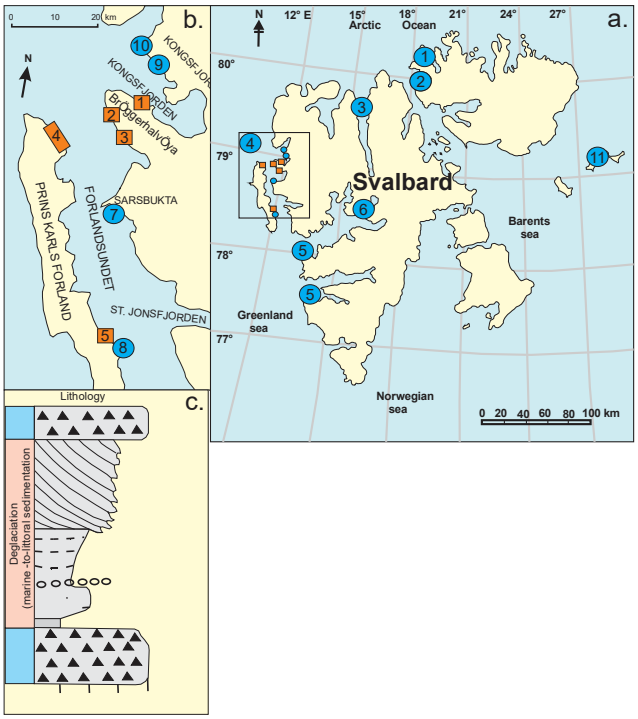

Figure 1 Map of Svalbard.

a. Showing location of Quaternary coastal sites of microfossil and mollusc-based studies. Sites 1. Lady Franklinfjorden (Forman et al., 2004); 2. Murchisonfjorden (Kaakinen et al., 2009; Kubischta et al., 2010); 3. Wijdefjorden (Allart et al., 2020); 4. Leinstranda (Miller et al., 1989) and (Miller 1982, sites 1-5); 5. Skilvika and Lineelva (Lucinskaja 1974;Lycke et al., 1992); 6. Billefjorden, (Feyling-Hansen 1955, Boulton 1979); 7. Sarsbukta (Feyling-Hansen &Ulleberg 1984); 8. Poolepynten (Bergsten et al., 1998); 9. Kongsfjordhallet (Houmark-Nielssen, M., Funder, S., 1999); 10. Kap Guissez (Mabillard, J., 1977) 11. Kongsoya (Ingolfsson et al., 1995).

b. The inset map is based on Miller 1982 showing his sites 1, 2, 3, 4, and 5 on Broggerhalvoya, PrinsKarlsForland. Site 7 at Sarsbukta studied by Feyling-Hansen &Ulleberg 1984 and site 8 at Poolepynten studied by Bergsten et al., 1998.

c. An idealised model of a lithostratigraphic coloumn showing a coarsening upward sequence representing one unit of a cyclic coastal sequence. This figure has been taken and modified from Ingólfsson, Ó. 2011 which was based on Mangerud, Jan, and John Inge Svendsen. 1992.

The Weichselian glacial history and palaeoenvironment of western Svalbard have been inferred based on geochronology, stratigraphy, and sedimentology.[12,29,31] The terrestrial record of the Late Weichselian glacial history is better understood and constrained by previous studies. However, there lies a gap in the understanding of early to middle Weichselian stratigraphy and palaeoenvironment because the younger glacial advance erodes older sediments leading to the preservation of the younger sedimentary record.

Historical overview

The studies aiming at the paleoenvironmental reconstruction of the glacial isostatically raised coastal Weichselian sedimentary sequences were based on faunal elements foraminifera and molluscs (Figure 2).[6,8,11,12,15,18,19,30,32]

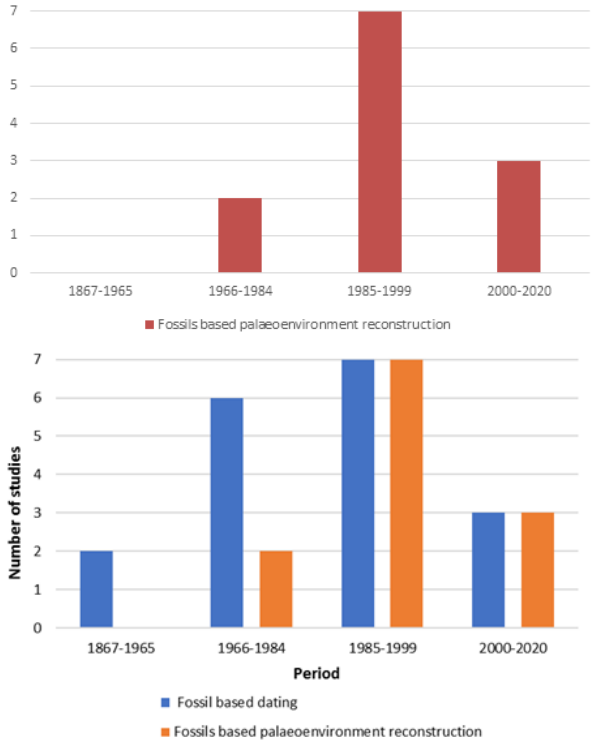

Figure 2 Studies based on fossils including microfossils that were conducted in Svalbard. Investigations from 1867-2020. The period of 153 yrs has been divided into four groups. The vertical axis shows the number of studies conducted from 1867-2020.

The foraminifer and mollusc-based studies of late Quaternary sediments of Svalbard were initiated by (Figure 1).[6,8,11,30,33] These studies opened a new avenue of microfossil-based palaeoecology, paleoenvironment, and biostratigraphy studies in the High Arctic region of Svalbard and served as background for further investigations. The later studies[10,11,15,18,34,35] generated foraminifer and mollusc based important baseline dataset of palaeoecology and palaeoenvironment.

Discussion

Palaeoenvironmental reconstructions of coastal sequences

The earliest studies of late Quaternary / Weichselian sediments were based on molluscs and foraminifera which involved both fossil and modern forms from Billefjorden and Skilvika areas (Figure 2).[30,33] The section near Skilvika had also been described.[36] This was

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followed by the palaeoclimate reconstruction of a Tertiary-Quaternary coastal cliff section at Blanusviken located near Forlandsundet on the western coast of Svalbard (Figure 2).[11] The foraminifera and mollusc assemblage recovered from the cliff sections was studied and compared with the recent assemblage. The analysis of the assemblage was done using the ratio of Arctic /Boreal species, species abundance, and species diversity. The analyses of mollusc shells revealed that temperature variation affected the size of a mollusc species. This led to the identification of the interglacial conditions of the Eemian stage. The chronology of the Tertiary and Quaternary sequence was based on C14 radiocarbon dating of mollusc shells. The molluscs were also used to establish the biostratigraphy of the same section. Foraminifera were used for the determination of depositional conditions in the water column such as turbidity and salinity.[37]

A detailed foraminifer-based biostratigraphic study[12] was conducted on the coastal cliff sections of Broggerhalvoya, west coast of Svalbard (Figure 2). The assemblage consisted of 72 taxa of benthic foraminifera recovered from silt, sand, and gravel sedimentary units that were grouped into five biostratigraphy zones that allowed for paleoenvironmental reconstruction.

After nearly a decade another attempt was made to study the stratigraphy and palaeoenvironment of the Late Weichselian and Holocene coastal sections at Skilvika located near Belsund and Linéelva near Isjfjorden of southwestern Svalbard using benthic foraminifera and molluscs (Figures 1,2). The assemblage provided evidence of early/ middle Weichselian interstadial or interglacial and the coastal cliff sections of the Weichselian and Holocene ages were also studied.[34,38] The assemblage of foraminifera and molluscs provides evidence of the influence of Atlantic water mass towards the west coast of Svalbard. The faunal assemblage consisted of Arctic – Boreal forms that preferred moderate to high salinity and a water column depth of about 50m. High energy conditions due to the prevalence of currents lead to the deposition of sorted sediments. This inference was supported by the presence of current tolerant foraminifera. The foraminifera and molluscs also proved helpful to understand the nutrient levels, inshore/offshore conditions, glacial proximal and distal environments. All these factors serve as important aspects for the interpretation of palaeoecological conditions.

Bergsten et al (1998) studied the biostratigraphy of the late Quaternary-raised marine sequences of Prins Karls Forland at Poolepynten based on the motivation provided by the previous work and to extend the same for understanding the palaeoenvironment and biostratigraphy using benthic foraminifera (Figure 2). This study also highlights the complex problem of the distinction between interglacial and interstadial based on the biotic assemblage that was attributed to the low-temperature gradient at a high latitude site. The same had been emphasized by other studies.[11,34,38]

The glacial geology and sedimentological analysis of a coastal sequence exposed on northeastern Svalbard provided information related to glacial advance and decay during the early, middle, and late Weichselian.[39] The OSL dating placed the inferred climate fluctuations of this section into a perspective of a chronological framework with other sections of Svalbard. Further study led to the paleoenvironmental analysis of Quaternary sedimentary sequence at Murchisonfjorden, Nordaustlandet, the northeastern part of Svalbard (Figure 2). Benthic foraminifera recovered from the marine sand and gravel units were used for palaeoenvironmental. reconstruction of late Quaternary marine sedimentary sections. A characteristic foraminiferal assemblage was identified for early Weichselian, middle Weichselian, and early Holocene. This study describes the first record of the middle Weichselian marine sediments and faunal elements from Svalbard. The foraminifera assemblage shows similarities as well as deviations from the previous faunal assemblage recovered from the other coastal sections of Svalbard.[39] Three periods of ice-free conditions during the Weichselian have been inferred with differing conditions of salinity and bottom current velocity.[10] A record of foraminifera, molluscs along with the plant, and insect macrofossils have been studied from the Weichselian sedimentary sequences located on the eastern side of Svalbard on Kongsoya, Kong Kars Land (Figure 2).[14] The fossil data were also compared with the studied sites of western Svalbard and revealed low recovery of foraminifera that were poorly preserved. The recovered assemblage contained foraminifer and mollusc indicators of warm conditions, inferred to have prevailed due to the Atlantic water masses. The recovered individuals were thick-shelled and showed signs of degradation on shell surface suffered due to dissolution. This study also pointed towards an inability of fossils to differentiate between an interglacial and interstadial at High latitude. The height of the cyclic sedimentary sequence indicates the extent of glaciation in the Northern Barents Sea.

One study[40] was performed on the trench sediment samples collected near the International Research town of Ny-Alesund, Svalbard during the first Indian Scientific Expedition to the Arctic (Norwegian) region. The expedition involved a reconnaissance survey and sediment sample collection from varied locations to explore the prospects for the initiation of palaeoclimate research in the drastically changing High Arctic region of Svalbard. The study of the late Quaternary sub-surface sediment samples involved the use of acid-resistant organic-walled microfossils and other dispersed organic matter contents. Two AMS radiocarbon dates on bulk sediment samples were obtained from the top and bottom sedimentary lithounits corresponding to the early Holocene and Late Weichselian ages, respectively. The palynological remains were categorised as terrestrial and marine and included dinoflagellate cysts, foraminiferal linings, pollen, structured terrestrial, charcoal, and degraded brown organic matter. The relative abundance data was used to differentiate the marine and terrestrial influence and paleoenvironmental conditions during the deposition of sediments.

Presence/preservation of microfossils

An assessment of the previous work depicts/marks/ the presence of the late Quaternary sedimentary succession sequentially deposited late Quaternary sedimentary deposits contain preserved microfossils. The foraminifera and molluscs have been recovered from silt, sand, gravel units of coastal sections in Svalbard and have helped in the assessment of depth of the water column, ocean currents, turbidity, and productivity. All these palaeoenvironmental factors are crucial in the reconstruction of glacial and oceanographic conditions that have been the drivers of paleoenvironmental/palaeoclimatic conditions.

It is always important to carefully observe and study the microfossil remains to identify in-situ, transported, and reworked microfossils that could prove useful for future microfossil-based studies to fully explore these potentially important sedimentary deposits.

The usefulness of microfossils

The microfossils are the microscopic remains of living micro or macro biota that is preserved in the sedimentary record under the influence of different taphonomic factors. The microscopic size of these fossils endows them with the ability to accumulate in large numbers along with the sediment.[41] The coastal sequences display sedimentary depositional environments with a wide range of ecological niches available for the growth and proliferation of

various micro-organisms across a variety of environmental variables from freshwater to marine conditions.[42,43] The microfossils help in the retrieval of reliable and meaningful data for palaeoenvironmental reconstruction. Foraminifera are protozoans that have a secreted test which could be carbonate, organic or siliceous in nature. The foraminifers form agglutinated test by incorporating particles present in their vicinity. The test acts as an exoskeleton and is preserved in the sedimentary record similarly mollusc shells are also preservable.[44]

The palaeoenvironmental / palaeoclimate studies based on microfossil remains provide information about the physical parameters supporting survival and growth. The microfossil assemblage consisting of varied forms provides a glimpse of the ecological interactions between organisms within an ecosystem and with the physical environment around them. The microfossils including foraminifera help to understand and reconstruct various environmental factors like temperature, nutrients, light, oxygen affecting the survival of organisms.[45,46] The response of organisms to various environmental stresses shapes the community structure which in part is displayed by the recovered microfossil assemblage. The microfossils have thus been widely used for the study of sedimentary successions spanning different time scales for biostratigraphy, palaeoecology, micropaleontology, etc.

Understanding the late quaternary fossil assemblage using modern analog

The modern distribution of various microorganisms and the related microfossils found preserved in the surface sediments are indicators of the microorganism's preferred environmental conditions. The microfossil assemblage recovered from surface sediments acts as a modern analog to provides crucial paleoenvironmental information when it is compared with fossil assemblage. This approach has also been uitilzed by previous investigations on coastal sequences of Svalbard.[10,15,30,33,38] The studies attempted on the late Quaternary sediments helped in the recovery of the microfossil remains to display a diverse microfaunal assemblage from varied sections on the west coast of Svalbard.

The fossils are preserved in the late Quaternary / Weichselin sedimentary deposits of Svalbard that came into existence during the deglaciation events under the sequential influence of glacial progradation, subsidence, high sea level, glacial receding, upliftment of strata, and lowering of sea level. The fossils are deposited by glacial meltwater and marine deposition during rising sea levels and reflect the environmental conditions prevailing at that time. The living microorganisms and their preserved fossil remains deposited on the west coast of Svalbard during the present-day interglacial conditions serve as a modern analog to understand palaeoenvironmental and palaeoecological conditions. This approach has been used to reconstruct the glacial, deglacial, and marine environmental conditions during the Late Quaternary/Weichselian time.

The microfossils from modern fjord sediments have been used as modern analogue for warm deglacial periods.[10,15,38] The late Quaternary sites of Skilvika, Linnelva near Bellsund were investigated for benthic foraminifera (Figure 2). The foraminifer assemblage was described from the Early Weichselian sediments of Murchisonfjorden, Nordaustlandet and the most notable is the first report of Middle Weichselianforam assemblage(Figure 2).[10] The late Quaternary palaeoenvironmental conditions like temperature, salinity, water depth, and ocean currents have been reconstructed with the help of the ecology and distribution of foraminifera and molluscs in modern fjord systems of Svalbard.

Conclusions

a. The Svalbard region has attracted researchers since the early nineteenth century but the studies are fragmentary and low in numbers as compared to other regions of the world. This could be because of the remoteness and inaccessibility of this High Arctic archipelago.

b. The late Quaternary coastal sequences of Svalbard contain Saalian, Weichselian, and younger sedimentary deposits. Although these deposits are fragmentary but at varied sites and locations Saalian, early Weichselian, and middle Weichselian sediments are preserved. Thorough reinvestigations of the complete sequences at previously known sites should be carried out also new sites or locations could be searched for better preserved sedimentary successions and microfossils.

c. The study of the relative abundance, ecological preference, geographical distribution, and comparison with the modern distribution of the foraminifera helped in the evaluation of paleoenvironmental conditions and the influence of warm ocean currents up to the west coast of Svalbard during the marine isotope stage 5e.

d. The previous studies on coastal sequences have produced important data for the understanding of glaciation, geochronology with relatively few but important studies on paleoclimate, palaeoenvironment, palaeoecology, and palaeoceanographic conditions at the High Arctic region of Svalbard. These have highlighted the potential of microfossils of late Quaternary coastal sediments in deciphering the palaeoenvironmental conditions.

e. Future investigations involving microfossils could also enable differentiation of interglacial and interstadial conditions.

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Conflicts of interest

None.

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