Reconstruction of glacial history of the area north of Svalbard/Spitsbergen

An article by DILIP ADHIKARI

Since the mapping of the past ice sheets in the Arctic margins are still an ongoing process, updates to the various regions regarding the subject is essential. Past studies have suggested that Svalbard-Barents Sea Ice Sheet seem to have progressed towards north through the Yermak Plateau not many times during the Quaternary. Some others have also suggested that in the Fram Strait where ice had to transit through the Yermak Plateau on its way out of Arctic, should have been deformed by thick ice shelf or icebergs, which could provide some clues on past Arctic Ocean glaciations. Therefore, the geophysical records are important in the reconstruction of maximum extent, dynamics and timing of the ice sheet.

Svalbard-Barents Sea ice sheet | Yermak Plateau | ice shelf | icebergs | Quaternary

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1 Introduction

Research works have been ongoing since decades to unravel the behaviour of the former glaciers to know their sizes and direction of movements at the end of the past glaciations. By knowing about the past and ongoing processes in the present together, one can better anticipate the glacial environments in the future. To know how glaciers interact with climate and ocean, reconstruction of the past ice is important. Reconstruction is possible since glaciers and icebergs leave behind diagnostic and distinctive scars on the seafloor producing subglacial bedforms (Jakobsson et al. 2010).

The Yermak Plateau and the northern continental margin of Svalbard are located on the eastern side of the Fram Strait, the only deep-water access between the Arctic Ocean and the North Atlantic, which conquer an area that is key to understand the ice and water between the Arctic Ocean and the North Atlantic during the Quaternary (Dowdeswell et al. 2010). Our understanding of the timing and dimensions of the marine-based ice sheets in the Svalbard-Barents Sea region during the Quaternary today is still limited. The main aim of this article is to improve the knowledge of the glacial history of the aspect of when and how the Arctic Ocean with the ice sheets has been reconnected through the Yermak Plateau.

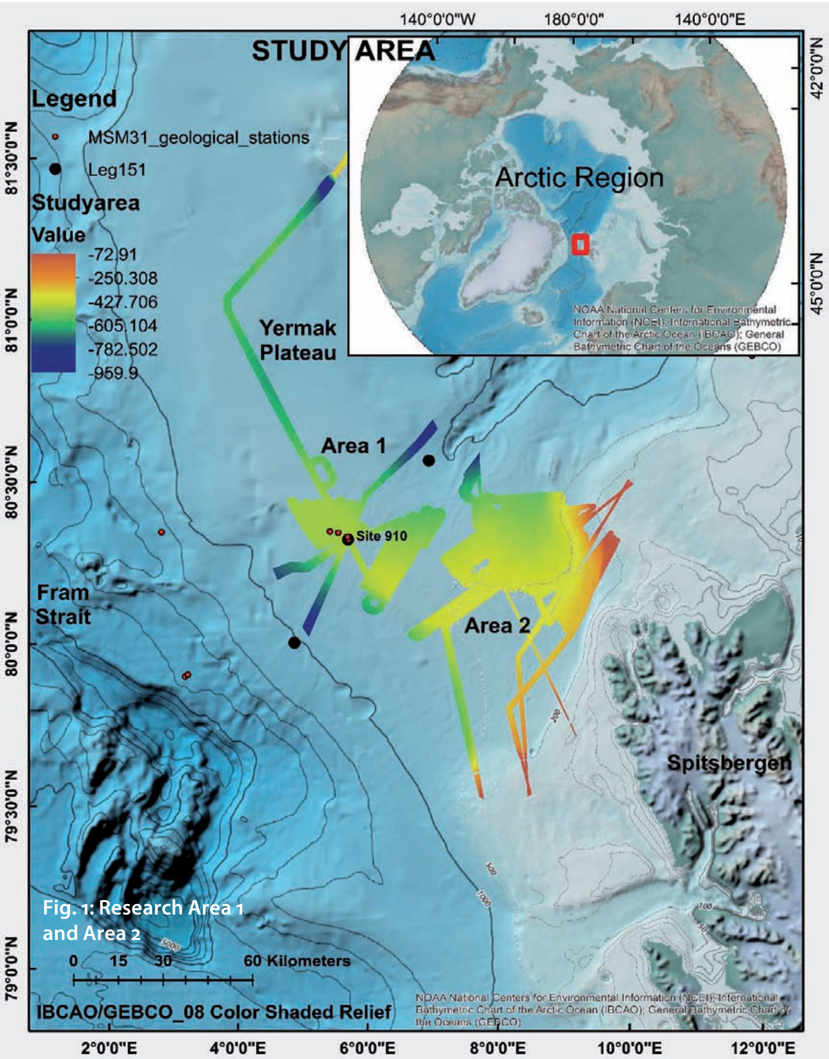

Fig. 1: Research Area 1 and Area 2

Background map: IBCAO/GEBCO_08 Color Shaded Relief (NOAA National Centers for Environmental Information)

2 Materials and methods

The Yermak Plateau (Fig. 1) is the northernmost plateau of the Eurasian plate bounded by Svalbard archipelago to the south, the Fram Strait to the west, and the Nansen Basin to the north and east. The morphology of the plateau at present is characterised by a bevelled seabed slanting on either side but slightly steeper slope along the western side. The water depth over the plateau is usually between 600 and 800 m, however, its central crest part is 500 to 600 m deep.

2.1 Acoustic data acquisition and processing

The geophysical data sets were acquired during RV »Maria S. Merian« expedition MSM31 in August and September 2013 (Geissler et. al. 2014), and RV »Polarstern« expedition PS92 in May and June 2015 (Peeken 2016). On RV »Maria S. Merian«, the bathymetric data were acquired with a Kongsberg Simrad EM122 (12 kHz, 2° × 2° beam width, 120-132° up to 150° swath angle, equidistant mode) hull-mounted deep-water system and a Kongs-

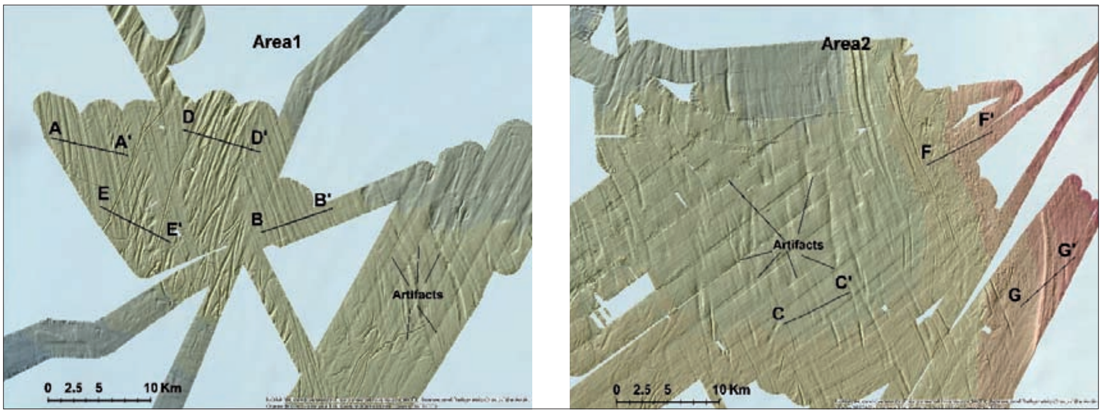

Fig. 2: Glacial features revealed from the study areas along with their regions of cross-section profiles

berg Simrad EM1002 (up to 95 kHz) shallow-water system mounted through moon-pool (Geissler et. al. 2014). On RV »Polarstern«, the bathymetric data were acquired with an Atlas Hydrosweep DS-2 (15.5 kHz, 2° × 2.3° beam width, 90-120° swath angle, equidistant mode) deep-water multibeam echo sounder (MBES).

The multibeam data were processed using Caris HIPS & SIPS. With the help of »Swath Editor«, »Subset Editor« and a ping-by-ping data-cleaning editor within the software, the data was cleaned, filtered and anomalous pings were removed. These cleaned data were imported to DMagic software (QPS-Fledermaus) and merged together. The merged file was gridded into 25 m × 25 m grid and projected into polar Stereographic Projection. The gridded file was brought into ArcGIS for analysis and map generation.

Sub-bottom profiler data from both MSM31 and PS92 expeditions were collected with the Atlas Parasound DS-3 P-70 (a deep-sea parametric hull-mounted sub-bottom profiler) system. The acquisition settings of the Parasound system used during the expeditions can be found on their respective cruise reports (Geissler et. al. 2014; Peeken 2016). All acquired SLF (secondary low frequency) data from Parasound (ps3) were converted to SGY format (a standard data format for storing geophysical data) using »ps32sgy« tool (University of Bremen). These SGY data were imported into KingdomSuite for data visualisation and further processing. For getting the comparable depth values to bathymetric values, two-way travel time was converted to water depth by using an average sound velocity of 1500 m/s.

2.2 Sediment cores analyses

Around the Ocean Drilling Program (ODP) site 910, four gravity cores sampling was carried out during the MSM31 expedition (Fig. 1). First, undrained shear strength measurements of the cores were carried out with Hand Held Shear Vane, Geovane (Geotechnics, New Zealand). Secondly, the consolidation test was done following the methods explained in O'Regan et al. (2010). At last, the core MSM31/557-4 was chosen for grain-size distribution and the fractions of the gravels (bigger than 2 mm) and sand (bigger than 63µm) were calculated.

3 Results

3.1 Seafloor morphologic features

Fig. 2 shows glacial features revealed from the study areas along with their regions of cross-section profiles. The cross-sections AA', BB' and CC' are so-called mega-scale glacial lineations, MSGL (Fig. 3). The cross-sections DD', EE' and FF' show profiles of plough marks (Fig. 4). Cross-section GG' is an example for a grounding zone wedge, GZW (Fig. 5).

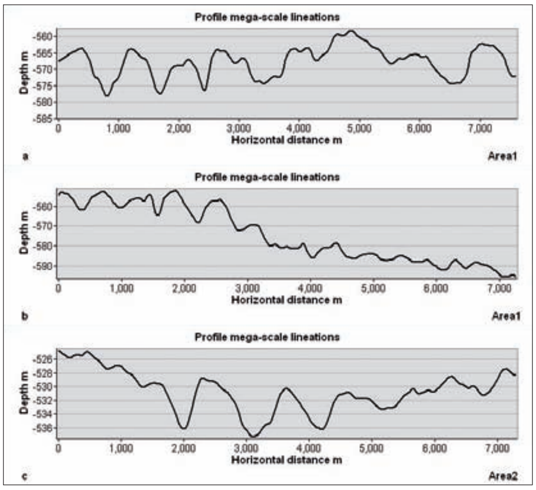

Fig. 3a: MSGL cross-section AA' on the northwestern part of Area 1. **b:** MSGL cross-section BB' on the middle part of Area 1. **c:** MSGL cross-section CC' on the middle part of Area 2

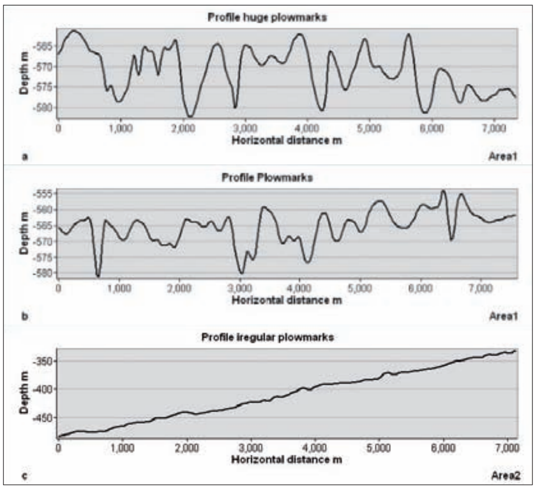

Fig. 4a: Cross-section of huge plough marks DD' on the northeastern part of Area 1. **b:** Cross-section of fresh-looking plough marks EE' on Area 1. **c:** Cross-section of irregular plough marks FF' on Area 2

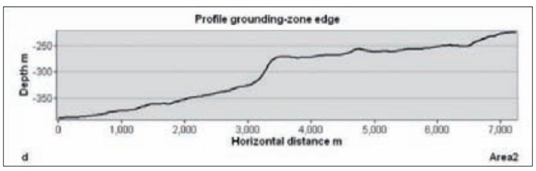

Fig. 5: Cross-section of GZW GG' from the southeastern part of Area 2

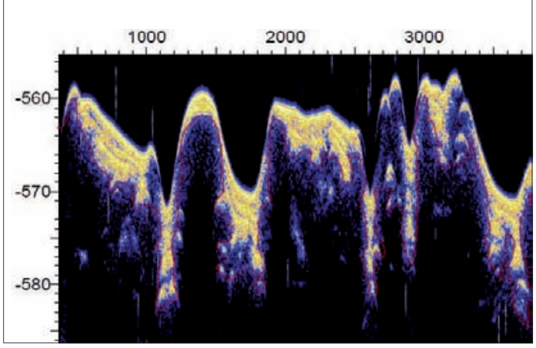

Fig. 6: Facies 1.

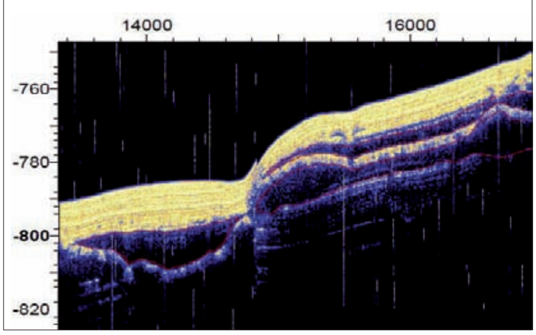

Fig. 7: Facies 2

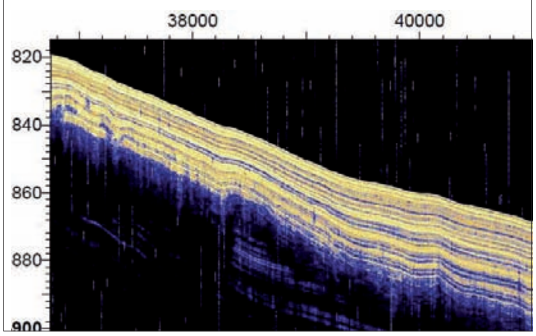

Fig. 8: Facies 3

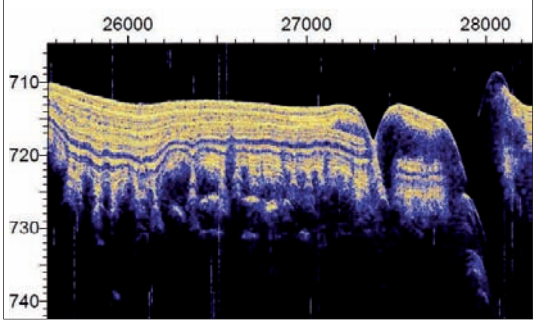

Fig. 9: Facies 4

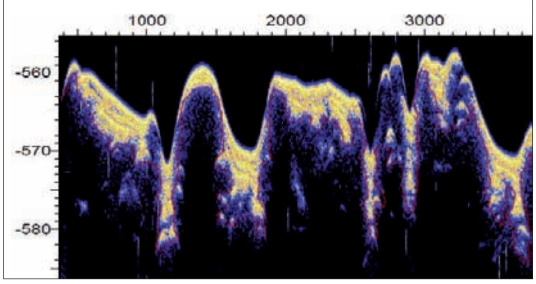

Fig. 10: Reflector 1

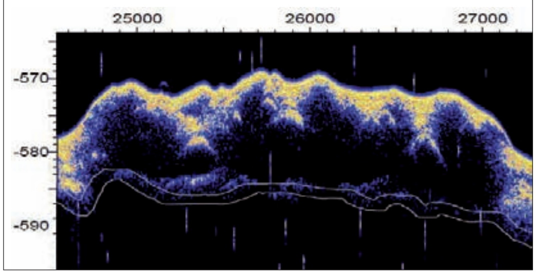

Fig. 11: Reflector 2

3.2 Acoustic terrain

In Area 1, nearby Area 1 and in the northeastern part of the Yermak Plateau four acoustic facies were identified. The acoustic facies have different characteristics:

- Facies 1: Acoustically laminated facies over an undulating surface reflector beneath it (Fig. 6).
- Facies 2: Acoustically laminated sediments over acoustically transparent lenses-like geometry (Fig. 7).
- Facies 3: Acoustically well-stratified strata with continuous, smooth and parallel internal reflectors (Fig. 8).
- Facies 4: Undulating acoustically laminated and stratified facies with continuous, sub-parallel internal reflectors over an undulating base (Fig. 9).

In Area 1 two acoustic reflectors were identified.

- Reflector 1: An irregular surface reflector found within few meters below seafloor over a highly eroded surface full of plough marks and below it, there is not much acoustic penetration (Fig. 10).
- Reflector 2: An irregular reflector found roughly at 15 to 20 m below seafloor over the seabed containing only MSGLs and below the reflector there is no more penetration (Fig. 11).

Core MSM31/557-4 sub-samples

Depth	Weight			Fraction			Percentage
	Total sediment	Sand > 63 µm	Gravel > 2 mm	Sand	Gravel	Sand and gravel	Sand and gravel
170 cm	8.53 g	1.54 g	0.16 g	0.18	0.02	0.20	20 %
180 cm	8.29 g	0.60 g	0.28 g	0.07	0.03	0.11	11 %
195 cm	8.25 g	3.24 g	0 g	0.39	0	0.40	40 %
200 cm	10.52 g	3.35 g	0.13 g	0.32	0.013	0.33	33 %

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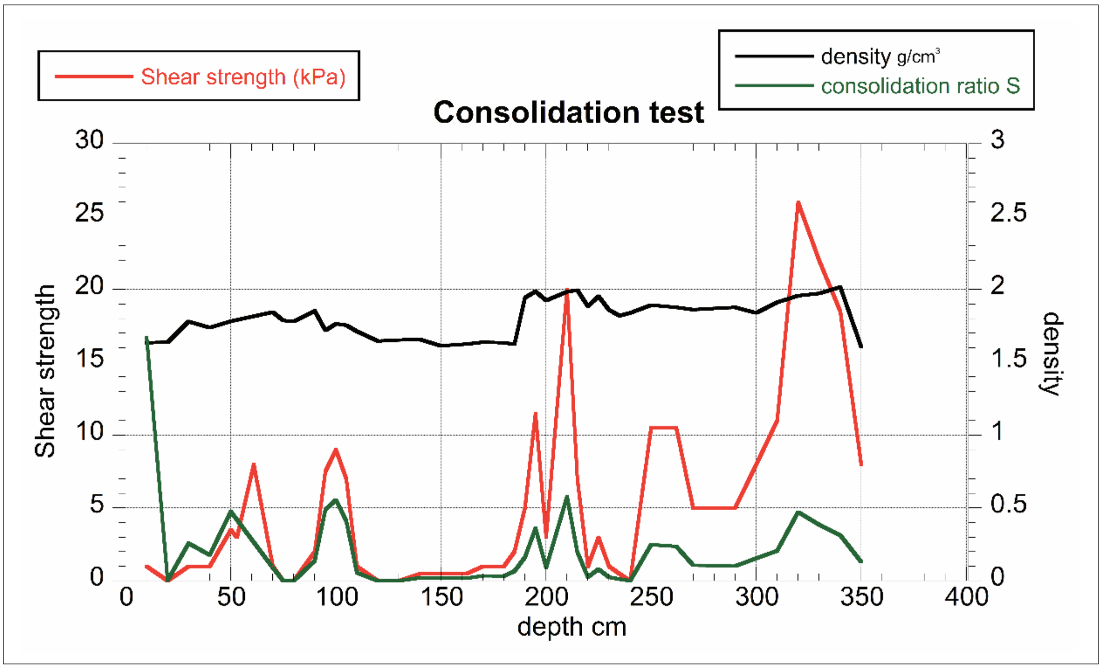

Fig. 12: Consolidation graph of the MSM31/557-4 core

3.3 Sediment core analyses

Consolidation test: Fig. 12 shows the consolidation graph of the MSM31/557-4 core. The Y-axis on the right side (from 0 to 2.5) represents the values for density and consolidation ratio and the Y-axis on the left side (from 0 to 30) represents the values for shear strength. The sediment depth in cm is given in the X-axis.

Grain-size distribution: The grain-size distribution of MSM31/557-4 core sub-samples from depths 170 to 200 cm is given in the table on the page before.

4 Discussion

4.1 Evidence of ice grounding

It has been documented that at least 500 m deep core of sediments have been penetrated at the ODP site 910 (Dowdeswell et al. 2010). Overconsolidated zone, 19 to 95 m bsf (below seafloor), has been identified as one of the initial findings of the Leg 151 (Dowdeswell et al. 2010 and reference therein). According to Knies et al. (2007), from an age model, the topmost sediments of the overconsolidated zone have been attributed to be deposited after MIS (Marine Isotopic Stage) 19/20 (~790 ka; thousand years).

Seafloor morphologic features

The observed subdued linear features are morphologically similar to MSGLs and other streamlined subglacial landforms (Clark 1993; Dowdeswell et al. 2010). The occurrence of the lineations predominantly NNW-SSE (North-northwest to South-southeast) oriented in Area 1 and NNE-SSW (North-northeast to South-southwest) oriented in Area 2 (Fig. 2 and Fig. 13), therefore, are interpreted as subglacial sediment deformations by the grounding of coherent ice mass (ice sheet or ice shelf) flowing either from Svalbard towards deep Arctic or by large ice shelf fragments from deep Arctic region towards Svalbard/Fram Strait. They are sharp and predominantly V-shaped in Area 1, whereas in Area 2, they seem to be very faint, relatively shallower and with flat U-shaped troughs (Fig. 2 and Fig. 3). The MSGLs near site 910 on the crest of the plateau, near Area 1 in this paper, have been attributed to be around MIS 6 (e.g. O'Regan et al. 2010; Dowdeswell et al. 2010).

Three types of quasi-linear to curvilinear features revealed are interpreted as iceberg plough marks (Fig. 2, Fig. 4). First, the huge plough marks, lying parallel to one another for distances of several kilometres in Area 1 and oriented in NNE-SSW (Fig. 2 and Fig. 4), are either produced by multiple keels of a single megaberg or by the keels of several icebergs that are trapped together within multiyear sea ice which maintain their relative positions (Kristoffersen et al. 2004; Dowdeswell et al. 2010).

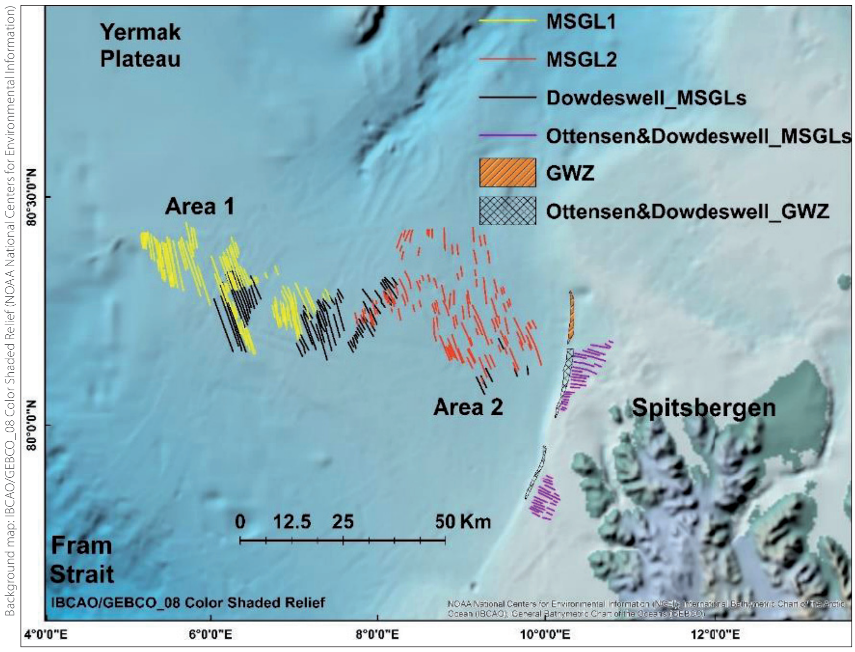

Fig. 13: Digitised MSGL 1 in Area 1 and MSGL 2 and a GZW in Area 2 along with MSGL from Dowdeswell et al. (2010) and MSGL and GZWs from Ottesen and Dowdeswell (2009)

Secondly, the large singular plough marks found heavily in both areas are interpreted to be formed by single deep-keeled icebergs. Last, highly irregular and small-scale features which are mostly developed just beyond northern Svalbard shelf-break, in Area 2 in shallow water less than 450 m, are very randomly oriented (Fig. 2 and Fig. 4). The bigger-scaled icebergs might have drifted north in North Svalbard Current and towards the west, in the Transpolar Drift after derived from Franz Victoria and St. Anna troughs (e.g. Dowdeswell et al. 2010; Kristoffersen et al. 2004).

The well-defined linear belt of the hummocky sedimentary environment at the shelf edge and the steep aspect immediately offshore from shelf-break suggest that the edge of the ice sheet must have been grounded to form such features (Fig. 2 and Fig 5). The grounding-zone wedge (GZW) is thus interpreted to be the grounding edge of the Late Weichselian ice sheet extended from Svalbard and might have been tidally induced with changing in buoyancy (Ottesen and Dowdeswell 2009).

Acoustic terrain

Facies 1 has very little or no acoustic penetration after reaching the end of the laminated topmost sediments (Fig. 6 to Fig. 9) which might have been caused by the high acoustic impedance of sediments disturbed by past ice flow. The facies is interpreted as sediment reworking or erosion probably due to series of glacial and interglacial events. Facies 2, found on the western flank of the plateau below a water depth of about 650 m, has laminated strata of about 10 m over discontinuous transparent lenses-like or lobate geometry (Fig. 7). It is interpreted to be formed through sediment remobilisation and deposition by the mass-wasting process. The grounded ice might have eroded and scraped the sediment off from the crest of the plateau. As the eroded sediments seem to be stacked deposited on the leeward side of the grounded ice i.e. on the lower slope (west) of the crest, it might indicate the direction of the flow as well.

Facies 3 is found mostly below a water depth of 650 m or deeper on the eastern flank of the plateau crest and the acoustically stratified sediment thickens downslope (Fig. 8). It is suggested that the sediment, acoustically stratified, might have formed through the deposition of suspended sediments and ice-rafted debris (IRD) under low-energy marine conditions. Facies 4, which is quite similar to that of Facies 3, is generally found in the northern part (mostly northeastern) of the plateau commonly below a depth of 650 m or so (Fig. 9), over the past glacially eroded surface containing lineations and/or iceberg scours.

Reflector 1 is present just a couple of metres below the present seafloor and exists at the plateau

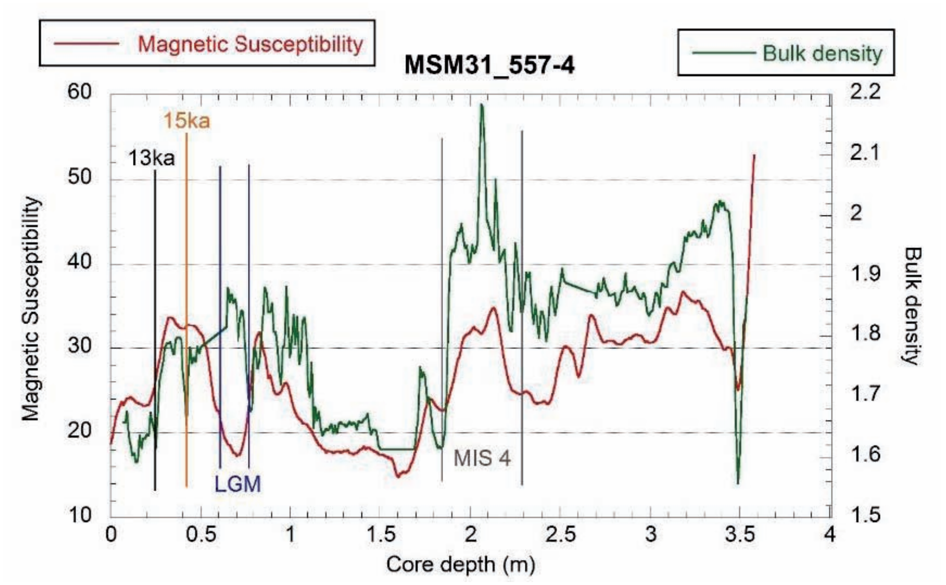

Fig. 14: Magnetic susceptibility versus bulk density graph of the MSM31/557-4 core. The green line represents bulk density (g/cm³) and the red line represents magnetic susceptibility (SI 10^{-6}). The core depth (m) is plotted on the X-axis. The sediments at certain depths are attributed to different ages; MIS 4, Last Glacial Maximum (LGM), 15 ka and 13 ka for example (Gebhardt Catalina, unpublished data, AWI, Bremerhaven)

crest mapped with heavily disturbed seafloor surface by iceberg plough marks (Fig. 10). Below the Reflector 1 there is hardly any acoustic penetration at all, which suggests high impedance of sediments due to the sediment erosion or reworking as a result of ploughing of deep-keeled icebergs over the surface several times. A very faint Reflector 2 is present at the water depth of 565 m nearly between 15 and 20 m bsf (Fig. 11). It exists below the area mapped with MSGLs in Area 1 and is inferred to have been formed at least earlier than MSGLs-producing event.

Gravity cores analyses

The increase in consolidation is usually encountered due to the sediments removal by erosion, or due to the glacial compaction. From around the sediment depth of 190 cm, the bulk density, the shear strength and the consolidation ratio all start to increase up to the depth of 210 cm (Fig. 12). This increasing trend on the parameters indicates that almost around at the depth interval of 190 to 210 cm there could have been the grounding of very thin ice which lasted for not very long. When considering one-directional vertical loading, the degree of consolidation is totally dependent on the applied overload and the duration of loading (O'Regan et al. 2010).

On the other hand, if the consolidation has occurred as a result of the sediments removal due to erosion, consequently it might have been caused by transient grounding of huge tabular icebergs on the crest of the plateau while exiting from the Arctic Ocean through Fram Strait but still, the idea of the possible grounding of an ice shelf cannot be neglected (O'Regan et al. 2010).

From the grain-size distribution of the sediment subsamples (see the table), at the depth of 170 cm and 180 cm, only less than 20 % by weight of the sediment content is sand plus gravel together but at the depths of 195 cm and 200 cm, the sand plus gravel content is more than 33 % by weight. These coarser sediments might have settled down from the grounded ice i.e. ice-stream, ice shelf and/or icebergs.

Jessen et al. (2010) state that the magnetic susceptibility of ocean sediments has strong relation with the environmental conditions (e.g. oceanography and glacial activity) and thus it can be used as a correlative tool on ›local to basin-wide scales‹. Dowdeswell et al. (2010) have also indicated that ›down-hole variations‹ in magnetic susceptibility and density of the age models of the studied cores can be readily correlated. They have found a feature, common to all their studied short cores that a distinct interval categorised by low magnetic susceptibility and high bulk density, that occurs near the base of the MIS 2. At the depth interval of 0.6 to 0.8 m from the MSM31/557-4 core, the similar feature can be observed (Fig. 14) which can be attributed to MIS 2 (~20 ka; Last Glacial Maximum). Calculating the age of the sediments at the depth, the linear sedimentation rate comes out to be 3 to 4 cm ka^{-1}. It is still not clear that the cores recovered from MSM31 (all < 4 m) have reached the depth of ice grounding which was responsible for the lineations on the crest of the plateau during MIS 6 (~140 ka) since the translation of age passes beyond 4 m with the sedimentation rate at 3 cm ka^{-1}.

From the evidence of faint and undisturbed streamlined lineations in Area 2, and the presence of Reflector 2 at the depth of 15 to 20 m bsf and absence of overconsolidated sediments (from recovered cores) at the plateau crest, it suggests that the Svalbard-Barents Ice Sheet might not have extended further Svalbard shelf break after MIS 19/20 boundary. But this is still not certain until the whole Yermak Plateau is investigated properly.

Conclusions

- The MSGLs, at the plateau crest, are most likely formed during the MIS 6 (the Saalian) and are interpreted to be formed by ice shelf flowing from the deep Arctic region across the plateau crest while exiting through Fram Strait.
- The quasi-linear huge plough marks imprint over MSGLs, suggesting relatively younger age, are interpreted to be formed either by multiple keels of a single megaberg or by keels of several icebergs that are trapped together within a multi-year sea ice.
- Singular large plough marks cross-cut both huge plough marks and MSGLs and are interpreted to be formed by single keels of the icebergs.
- The highly irregular smaller plough marks are interpreted to be formed by keels of small icebergs trapped in the shallow water just beyond shelf edge.
- The icebergs usually of bigger dimensions are most likely been derived from Franz Joseph and St. Anna troughs during former Eurasian Ice Sheet development.
- The GZW is interpreted to be formed by an ice sheet at its maximum position at the shelf edge and represents the maximum extent of Late Weichselian (~MIS 2) ice sheet generated from Svalbard-Barents Sea.
- It is interpreted that: Facies 1 is formed after multiple erosion of sediments by more than one glacial events; Facies 2 is formed by deposition of sediments eroded by glacial events; Facies 3 is formed through settling of sediments under low-energy marine conditions; Facies 4, similar to Facies 3, has been formed at the areas containing former lineations and/or plough marks.
- Reflector 1 is associated with extremely eroded sediments layer of high impedance which is attributed to the reworking of sediments by several glacial events. Reflector 2, found at 15 to 20 m bsf in Area 1, is attributed to be the uppermost sediment layer of highly overconsolidated sediment supposed to be formed during MIS 19/20.
- The geotechnical properties (shear strength, bulk density and consolidation ratio) of the sediments do not possess any qualities of overconsolidation up to 4 m of recovered gravity cores but show a hint of slightly higher consolidation at certain depths (for e.g.: around 2 m depth of core MSM31-557/4) and implies that either the event is short-lived or erosional, most probably, the erosional.
- The Svalbard-Barents Sea ice might not have extended further Svalbard shelf break after MIS 19/20 boundary but this is still not certain until the whole Yermak Plateau is investigated properly. ⚓