Polarforschung 79 (2), 123 – 137, 2009 (erschienen 2010)

Pleistocene Glacial Marine Sedimentary Environments at the Eastern Mendeleev Ridge, Arctic Ocean

by Jens Matthiessen[1], Frank Niessen[1], Ruediger Stein[1] and B. David Naafs[1]

Abstract: The stratigraphic distribution of lithofacies and the occurrence of coarse ice-rafted debris (>2 mm) have been studied on three sediment cores based on x-radiograph analysis, that were recovered during RV "Polarstern" expedition ARK-XXIII/3 from different depositional settings at the eastern Mendeleev Ridge. Various mud lithofacies with generally low contents of ice-rafted debris dominate the lithology while diamictons are restricted to possibly middle to late Pleistocene sediments. The muds have been possibly formed by the release of fine-grained sediments from melting sea ice while the diamictons are derived from iceberg and subordinate sea-ice rafting. The rapid sedimentation of diamictons has overprinted the long-term deposition of muds indicating that sedimentation rates must have been quite variable in the diamicton-bearing lithological Unit I of STEIN et al. (2010b).

The lithofacies distribution has been compared with wet bulk density, p-wave velocity and magnetic susceptibility data of the sediment cores revealing a correlation of some lithofacies with the physical properties of sediments. The diamictons are characterized by maxima in wet bulk density and p-wave velocity showing that they may form distinct acoustic reflections in seismic records that are potentially useful for correlation of sediment cores recovered during ARK-XXIII/3.

There is not a unique correlation between sediment colours and lithofacies. However, brown colours are mainly confined to bioturbated muds in sediment cores PS72/392-5 and PS72/396-5, while diamictons have usually light colours. In sediment core PS72/340-5 from the East Siberian continental margin, brown colours occur both in bioturbated muds and diamictons while laminated muds are always greyish.

Zusammenfassung: Die stratigraphische Verbreitung der Lithofazies und des Eis transportierten Materials (>2 mm) wurden mit Hilfe von Radiographien an drei Sedimentkernen untersucht, die auf der Expedition ARK-XXIII/3 mit RV "Polarstern" in verschiedenen Ablagerungsräumen am östlichen Mendeleev-Rücken genommen wurden. Verschiedene Schlammlithofazies mit überwiegend geringem Gehalt an eistransportierten Material beherrschen die Lithologie, während Diamicte auf vermutlich mittel- bis spatpleistozäne Sedimente beschränkt sind. Die Schlämme wurden vermutlich durch das Freisetzen von feinkörnigen Sedimenten aus schmelzendem Meereis freigesetzt, während die Diamikte durch Ablagerung von Eisberg und untergeordnet Meereis transportiertem Material entstanden sind. Die rasche Ablagerung der Diamikte hat die langfristige Ablagerung der Schlämme überprägt, so dass die Sedimentationsraten in der Diamikt führenden Unit I (STEIN et al. 2010b) sehr variabel gewesen sein muss.

Der Vergleich der Lithofaziesverteilung mit der Nassraumdichte, Kompressionswellengeschwindigkeit und magnetischen Suszeptibilität der Sedimentkerne ergab, dass bestimmte Lithofazies bestimmte physikalische Eigenschaften zugeordnet werden können. Die Diamikte zeichnen sich durch hohe Nassraumdichten und Kompressionswellengeschwindigkeiten aus, so dass diese deutlich Reflektoren in seismischen Profilen bilden, die eine Korrelation der Sedimentkerne der Expedition ARK-XXIII/3 erlauben.

Die Korrelation der Lithofazies mit Sedimentfarben ist nicht eindeutig. Jedoch sind braune Farben überwiegend auf bioturbierte Schlämme in den Sedimentkernen PS72/392-5 und PS72/396-5 beschränkt, während Diamikte überwiegend helle Farben aufweisen. Im Sedimentkern PS72/340-5 vom ostsibirischen Kontinentalhang können sowohl bioturbierte Schlämme und Diamikte braun sein, während lamierte Schlämme immer grau sind.

[1] Alfred Wegener Institute for Polar and Marine Research AWI, Am Alten Hafen 24, 27568 Bremerhaven, Germany

Manuscript received 28 September 2009, accepted in revised form 25 January 2010

INTRODUCTION

The Pleistocene sediments in the Central Arctic Ocean (CAO) are generally composed of fine-grained siliciclastic muds with variable contents of sand and gravel that were deposited in a glacimarine setting. Biogenic components are of minor importance but foraminifers and coccoliths may be common in certain intervals (e.g. CLARK et al. 1980, POORE et al. 1993, BISCHOF & DARBY 1997, POLYAK et al. 2004, NØRGAARD-PEDERSEN et al. 1998, SPIELHAGEN et al. 2004, STEIN et al. 2010b). It has been recognized already during earlier studies that Arctic Ocean sediments are also characterized by distinct alternations of brownish and light brownish colours (e.g., ERICSON et al. 1964, HUNKINS et al. 1971, DARBY et al. 1989 *cum lit.*). Comprehensive sedimentological studies, based on identification of sedimentary textures and structures by visual examination of hundreds of sediment cores, x-radiography images, colour variations and petrographic composition, led CLARK et al. (1980) to introduce a standard lithostratigraphy (Units A to M) for structural highs in the Amerasia Basin of the CAO. This lithostratigraphy has been confirmed by subsequent sedimentological studies, and the units have only been slightly modified and supplemented by new units (MINICUCCI & CLARK 1983, MUDIE & BLASCO, 1985, CLARK et al. 1990). The most conspicuous lithologic marker beds such as the foraminifer- and manganese-rich brown layers, and distinct carbonate-rich pink-white and white layers have been frequently used to correlate sediment cores within the Amerasia Basin (e.g., PHILLIPS & GRANTZ 1997, 2001, POLYAK et al. 2004, NØRGAARD-PEDERSEN et al. 2007b, STEIN et al. 2010a,b).

Since CLARK et al. (1980) have introduced their standard lithostratigraphy, sediment core descriptions have often been used exclusively in order to identify the standard units for stratigraphic purposes rather than to interpret the sedimentary texture and structure (e.g. MORRIS & CLARK 1986, SCOTT et al. 1989, CLARK et al. 1990, POORE et al. 1993, BISCHOF et al. 1996, CLARK 1996, BISCHOF & DARBY 1997). Much information about the depositional environment is thus lost and, as a consequence, a thorough genetic interpretation of sedimentary sequences as carried out by CLARK et al. (1980) becomes almost impossible. In contrast, few studies showed the potential of interpreting the sedimentary facies. DARBY et al. (1989) already recognized that units in CLARK'S et al (1980) lithostratigraphic scheme are possibly genetically linked and suggested that lithostratigraphic units A to M consist of at least six distinct sedimentary cycles. These cycles comprise coarsening upward sequences beginning with silty lutite, grading upwards into sandy lutite. Lateron, PHILLIPS & GRANTZ (1997, 2001) identified 44 sedimentary cycles within units A to M in sediment cores on Northwind Ridge that consist of an interglacial basal unit of strongly oxidized ochre sandy to gravelly mud and an overlying glacial unit of less oxidized olive grey silty clay.

Analysis of x-radiograph images are a useful tool to interpret sedimentary texture and has been used frequently to supplement visual core descriptions of arctic and sub-arctic sediments and to interpret sedimentary facies (e.g. CLARK et al. 1980, VORREN et al. 1984, MUDIE & BLASCO 1985, HENRICH et al. 1989, HEIN et al. 1990, DOWDESWELL et al. 1994, ANDERSEN et al. 1996, PHILIPPS & GRANTZ 1997, 2001, KNIES et al. 2000, Ó COFAIGH et al. 2001, EVANS et al. 2002, SVINDLAND & VORREN 2002, HOWE et al. 2008). This is a relatively fast method that provides continuous information down-core comparable to multi-sensor core logging of physical properties, x-ray fluorescence and digital colour scanning. Three sediment cores, retrieved during RV „Polarstern“' expedition ARK-XXIII/3 in 2008 from different depositional settings (JOKAT 2009), have been selected for an initial study to define sedimentary facies and compare these with physical property (NIESSEN et al. 2009) and sediment colour data. This study will form the basis for a more comprehensive sedimentological study of textural and structural aspects of "Polarstern" cores from the Arctic Ocean to evaluate the origin of sediment colours and to assess the local or regional character of lithological marker beds and sedimentary cycles as interpreted by e.g. DARBY et al. (1989), PHILLIPS & GRANTZ (1997), and POLYAK et al. (2009).

MATERIAL AND METHODS

The sediment cores used in this study have been selected from two sediment core transects located at the East Siberian continental margin (STEIN et al. 2010a). Gravity core PS72/392-5 (80°27.81' N, 158°49.75' W, water depth 3624 m) and Kastenlot core PS72/396-5 (80°34.74' N 162°19.01' W, water depth 2722 m) have been collected on the northern transect at the eastern flank of the Mendeleev Ridge from the abyssal plain and on a seamount, respectively. Gravity core PS72/340-5 (77°36.31' N, 171°29.09' W, water depth 2349 m) has been taken on the southern transect close to the East Siberian continental shelf (Fig. 1).

The lithostratigraphy has been described during the expedition (STEIN et al. 2009) and subsequently related to the lithostratigraphic zonation of CLARK et al. (1980) for the sediment cores from the northern transect (STEIN et al. 2010a,b). These authors also discuss the problems related to the Pleistocene chronostratigraphy of sediment cores from the CAO, and establish a preliminary age model for both transects (see STEIN et al. (2010a,b). Further information on the petrographic and mineralogic composition of the sediments has been obtained from NAM (2009), KRYLOV (2009) and STEIN et al. (2010a). The physical property data (wet bulk density ($g\ cm^{-3}$); volume-specific magnetic susceptibility (κ_{lf}, 10^{-6} SI); compressional (p)-wave velocity ($m\ s^{-1}$) have been measured by NIESSEN et al. (2009).

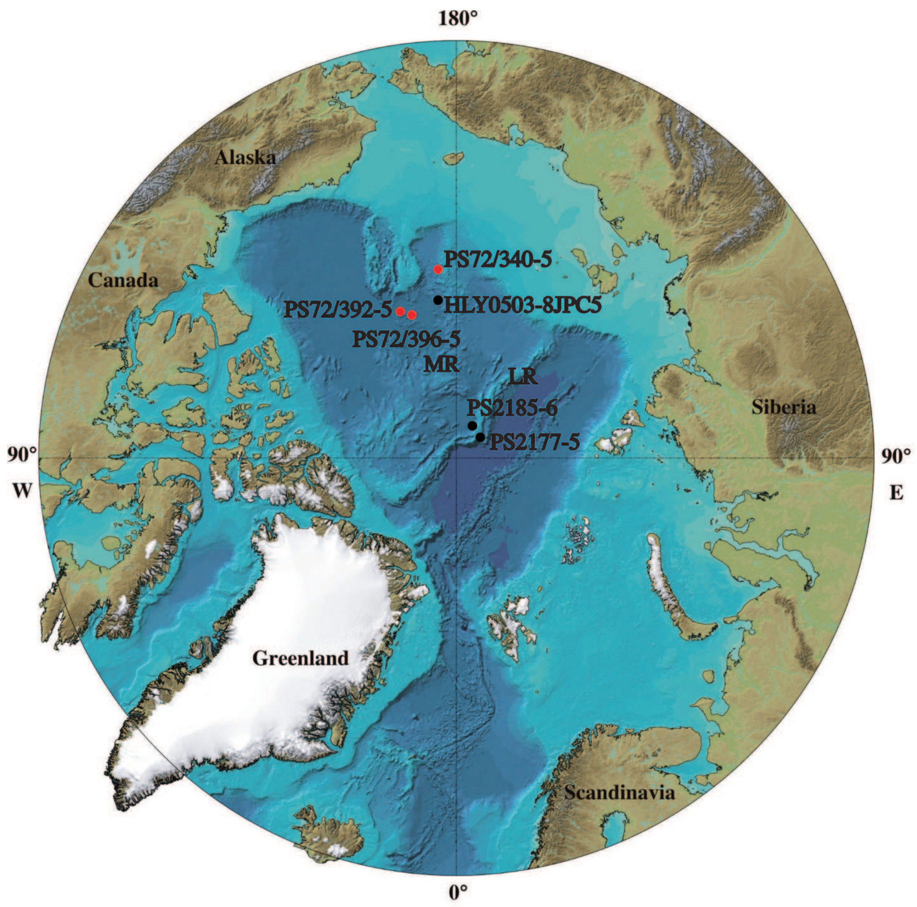


Fig. 1: Geographic location of studied sediment cores PS72/340-5, PS72/392-5 and PS72/396-5 at the eastern Mendeleev Ridge (red dots). Black dots = sediment cores referred to in the text (physiography after JAKOBSSON et al. 2000a).

Abb. 1: Geographische Lage der untersuchten Sedimentkerne PS72/340-5, PS72/392-5 und PS72/396-5 am östlichen Mendeleev-Rücken (rote Punkte). Schwarze Punkte = Sedimentkerne, auf die sich in dieser Arbeit bezogen wird, (Physiographie nach JAKOBSSON et al. 2000a).

X-radiograph analysis

Sediment slabs (250 x 100 x 8 mm) were continuously prepared down-core for x-radiography during the expedition (MATTHIESSEN et al. 2009). Plastic slabs (252 x 103 x 12 mm) were slowly pushed into the scraped and smoothed sediment surface and were carefully removed. These slabs were sealed in a plastic cover and the air was evacuated in order to stabilize the sediments. The slabs were placed on 100 x 300 mm large film stripes (Industrial X-Ray Film Agfa-Gevaert Structurix D4 FW 30 x 40) in a cabinet x-ray system (Hewlett-Packard Faxitron Series) and were exposed on the average for 6 min. at 40 kV. The films were developed for 3 min. (Agfa-Gevaert Developer Structurix G 128), washed for 1 min. and then fixed for 3 min. (Agfa-Gevaert Fixing Bath Structurix G335). After washing in a water bath for 10 min. the film negatives were dried and finally stored in a transparent cover.

The negatives were studied on a light table to describe sedimentary structures and to count gravel particles (>2 mm) at 1 cm intervals across the x-ray slab. The number of gravel particles in fields of 10 x 1 x 1 cm is routinely used as a measure of ice-rafted debris (IRD) and is tabulated as number of particles 10 cm^{-3} (GROBE 1987). The gravel particles in the studied cores generally have an angular to sub-angular shape indicating a glacial origin.

The depth ranges of the individual x-ray slabs from kastenlot cores were adjusted to the core depth scale by correlating lithological marker beds between slabs and archive sections because the thin plastic rims have not been included in the depth measurements of the plastic slabs leading to progressively larger depth offsets.

Shear strength

Undrained shear strength was measured in core PS72/340-5 with a hand held shear vane (Geovane GEO 709), equipped with a 19 mm blade (Geotechnics, Auckland, New Zealand), after the core has been opened onboard “Polarstern” (NAAFS et al. 2009). The measurements were conducted at irregular intervals in the centre of the split cores. Depending on the shear strength of the sediment, the device depicts a division between 0 and 140. A calibration chart provided by the company was used to convert the shear strength divisions into undrained vane shear strength (in kPa).

Digital colour imaging

Systematic line-scan digital core images were obtained using the Avaatech digital imaging system (camera system Jai 3CCD CV-L105 with manually controlled Cosmicar/Pentax YF5028 50mm F2.8/22 lens). The image resolution is ±150 pixels cm^{-1} in cross-core and down-core direction (colour sampling 8 bits). The image covers approx. 13 cm in cross-core and approx. 125 cm maximum in down-core direction. Individual pixel calibration was conducted on a white reference tile every morning. All cores were imaged using an aperture setting of f/8.

The output from the digital imaging system includes a Windows bitmap (.bmp) file and a compressed (.jpeg) file. The bitmap file contains the original data with no compressional algorithms applied. The RGB and CIELAB values were produced for undisturbed core sections by averaging across a strip of variable width and 5 mm length at consecutive intervals of 0.066 mm downcore. Output files (.txt) are the L*a*b* colour space that is also referred to as CIELAB space (Commission Internationale de l’Éclairage L*a*b colour space 1976) and the RGB colour values (wave lengths: red: 630 nm, green: 535 nm, blue: 450 nm) (CIE 1931). Lightness L* (grey scale) is recorded from 0 % (black) to 100 % (white), the red-green colour space a* from green (negative) to red (positive), and the yellow-blue colour space b* from blue (negative) to yellow (positive). The final data set was corrected for obvious outliers occurring mainly at the top and base of each section.

The uncorrected colour data are only used to more objectively define the sedimentary colours. Further evaluation of the data requires careful calibration and correction because the split core surface was sometimes uneven or contained small holes due to coarser lithologies.

Granulometry

The grain-size compositions of a selected number of samples from sediment core PS72/340-5 have been analysed to provide quantitative information on the granulometric composition of lithofacies. Samples have been freeze-dried, weighed and washed on a 63 μm precision sieve to obtain weight percentages of the fine (<63 μm) and coarse fractions (>63 μm).

RESULTS

Lithofacies

The lithofacies have been distinguished based on sedimentary texture and structure (grain size, content of gravel and mud clasts, stratification, bioturbation). Different types of trace fossils have been recognized (see sediment core descriptions, www.wdc-mare.org) but these have not been distinguished in this initial study. The applied lithofacies concept of EYLES et al. (1983) has been frequently used for the interpretation of sedimentary processes of arctic and subarctic sediments (DOWDESWELL et al. 1994, ANDERSEN et al. 1996; ÓCOFAIGH et al. 2001, EVANS et al. 2002, HOWE et al. 2008). Examples of lithofacies are illustrated in Figures 2 and 3. In addition to lithofacies, the bedding contacts between the various lithofacies have been described.

It should be noted that X-radiography images only allow a rough interpretation of grain sizes. Therefore, the predominant sediment types silty clay and clayey silt in the sediment cores recovered during expedition ARK-XXIII/3 (STEIN et al. 2009) have collectively been termed mud (mixture of silt and clay). In case coarser components (coarse sand, gravel) that may be easily identified in x-radiographs are common, a modifier precedes this term.

Muds (F = fine-grained) and diamictons (D) have been identified as major lithofacies forming distinct cycles in parts of the sediment cores (Tab. 1, Figs. 2 to 6). The stratigraphic distribution of diamictons appears to be related to the coarse-grained units in CLARK's et al. (1980) standard lithostratigraphy (Figs. 5, 6). A data set on the granulometric composition of selected lithofacies is available for core PS72/340-5 (Tab. 1).

Different mud lithofacies have been distinguished based on stratification and bioturbation. High amounts of coarse sand and gravel (Fm(s)) or mud clasts (Fm(c)) are rare but most mud lithofacies contain scattered coarse sand and gravel except for laminated muds (Fl) and muds rich in mud clasts (Fm(c)) that are almost barren of any coarse material. Some mud lithofacies can also be distinguished by their average coarse fraction contents obtained from grain size analysis (Tab. 1). There is a gradient from high contents in bioturbated to laminated sandy muds (Flb(s)) to almost negligible coarse fraction contents in laminated muds (Fl). Bioturbated to laminated muds (Flb) and bioturbated muds (Fb) generally comprise low amounts of gravel and coarse sand that may either be scattered and/or are enriched in distinct thin layers.

The muds comprise variable textures being massive, bioturbated or laminated. Deformation structures occur occasionally in the lower part of core PS72/396-5. Laminated mud (Fl) comprises generally mm to sub-mm scale laminae but occasionally also thicker laminae (Fig. 2). The grain-size composition of individual laminae is variable because of density contrasts between laminae in x-radiograph images. Higher contrasts probably reflect siltier laminae that occasionally grade into finer sediments. Bioturbation has sometimes overprinted lamination that may be still visible in x-radiograph images (bioturbated to laminated mud, Flb) or was completely erased (bioturbated mud, Fb) (Fig. 2). Stratified muds (Fs) contain thicker beds (cm-scale) while massive muds (Fm) appear almost homogenous without any internal structure. Contacts between the mud lithofacies are usually gradational.

Diamicton		coarse fraction	
Dmm	diamicton, matrix supported, massive, and bioturbated with dispersed to clustered coarse sand and gravel	17.0 %	n = 6
Dmmc	diamicton, matrix-supported, massive, and bioturbated with dispersed to clustered coarse sand, gravel and mud clasts		
Dms(r)	diamicton, matrix-supported, stratified and bioturbated with dispersed to clustered coarse sand and gravel, evidence of re-sedimentation		
Fine-grained (mud)			
Fm	mud, massive, dispersed coarse sand and gravel		
Fm(s)	sandy mud, massive, dispersed coarse sand and gravel		
Fm(c)	mud, massive, rarely dispersed coarse sand and gravel, abundant mud clasts		
Fb	mud, bioturbated, dispersed coarse sand and gravel	4.4 %	n = 20
Flb	mud, bioturbated to laminated, parallel lamination is overprinted by bioturbation, dispersed coarse sand and gravel	2.2 %	n = 7
Flb(s)	sandy mud, bioturbated to laminated, parallel lamination is overprinted by bioturbation, dispersed coarse sand and gravel	6.4 %	n = 3
Fl	mud, laminated, parallel lamination (mm to sub mm scale, rare thicker laminae, occasionally silt grading into clay), rarely dispersed coarse sand and gravel	0.3 %	n = 34
Fs	mud, stratified		

Tab. 1: Description of lithofacies in sediment cores (after EYLES et al. 1983) and mean coarse fraction contents (>63 μm) of selected lithofacies based on grain-size analysis (n = number of samples analysed).

Tab. 1: Beschreibung der Lithofazies in den Sedimentkernen (nach EYLES et al. 1983) und Mittelwert der Grobfraktionsgehalte (>63 μm) ausgewählter Lithofacies aufgrund der Korngrössenanalyse (n = Anzahl der untersuchten Proben).

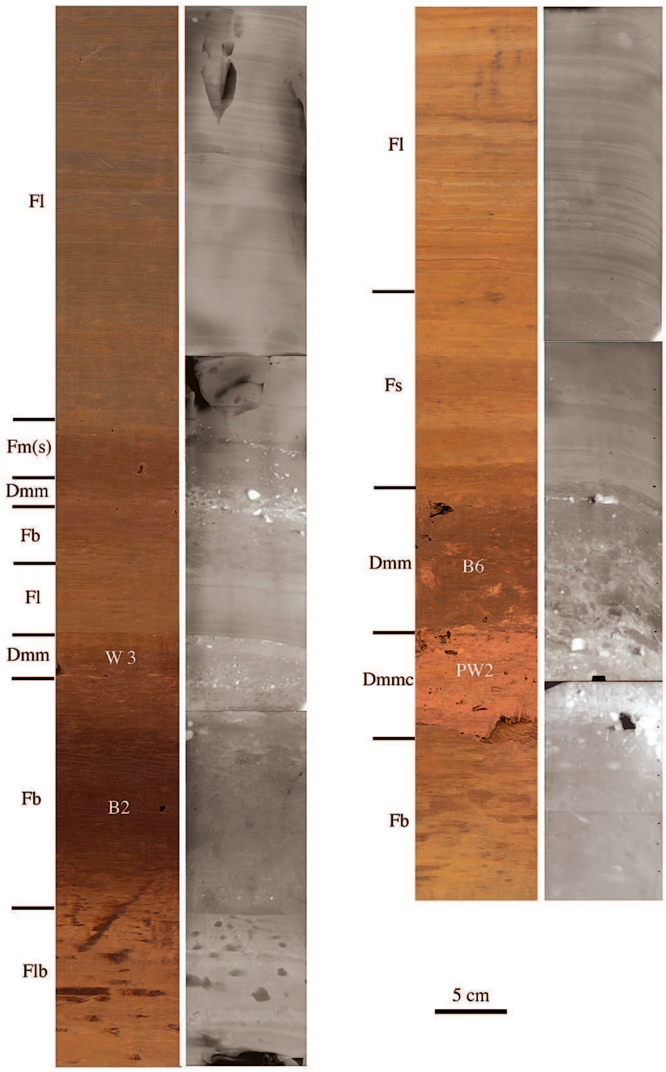


Fig. 2: Line scan and x-radiograph images of lithofacies of sections 56-128 cm (left column) and 462-527 cm (right column) in sediment core PS72/340-5. The white diamicton W3 and the pink-white diamicton PW 2 as well as the associated brown layers B2 and B6 are marked. Note that the brown layers are both related to the bioturbated mud and the diamicton. Bedding contacts are distinct at the top of the diamictons rather than at the base. Bioturbation is clearly reflected both in colour mottling and density contrasts of the x-ray images. Abbreviations: Fl = laminated mud; Fm(s) = massive sandy mud; Dmm = massive diamicton; Fb = bioturbated mud; Flb = laminated to bioturbated mud.

Abb. 2: Farbaufnahmen und Radiographienegative der Lithofazies in den Abschnitten 56-128 (links) und 462-527 cm (rechts) des Sedimentkernes PS72/340-5. Der weiße Diamikt W3 und der rosa-weiße Diamikt PW2 sowie die braunen Lagen B2 und B6 sind eingezeichnet. Auffällig ist, dass die braunen Lagen sowohl im bioturbierten Schlamm als auch im Diamikt vorkommen. Die Grenzen sind an der Oberkante der Diamikte deutlicher als an der Basis. Die Bioturbation ist deutlich sowohl an den Farbflecken als auch Dichteunterschieden (Grautöne) in den Radiographien erkennbar. Abkürzungen: Fl = laminierter Schlamm; Fm(s) = massiger sandiger Schlamm; Dmm = massiger Diamikt; Fb = bioturbierter Schlamm; Flb = laminierter bis bioturbierter Schlamm.

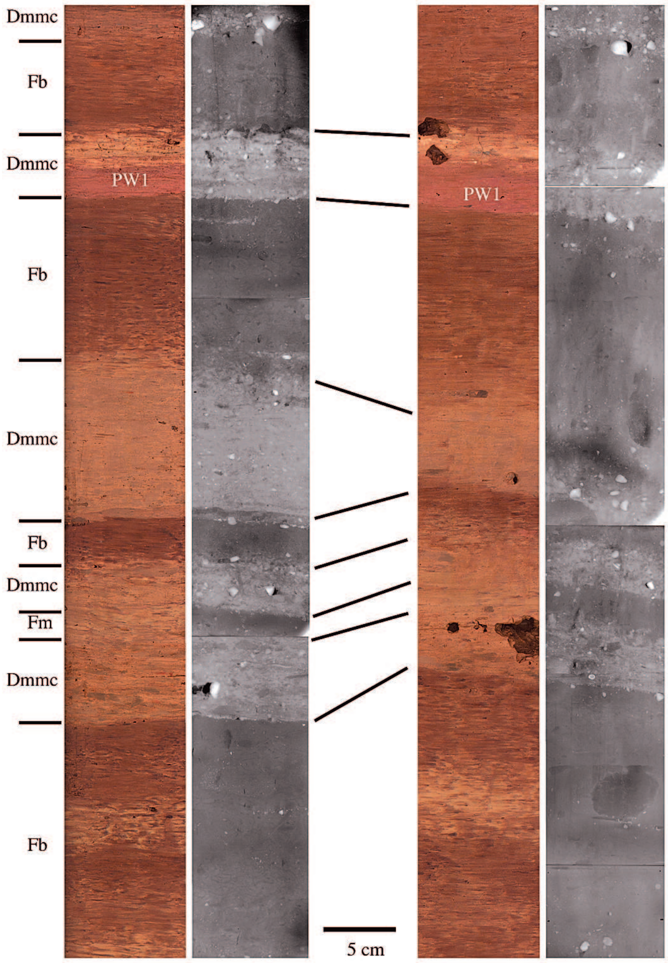


Fig: 3: Line scan and x-radiograph images of lithofacies of sections 114.5-184.5 cm (left column) and 119-189 cm (right column) in sediment cores PS72/392-5 and PS72/396-5, respectively. The pink-white diamicton PW 1 is in both sediment cores only the lower part of thicker diamicton. Note that the brown layers are related to the bioturbated muds. Bedding contacts are more distinct in sediment core PS72/392-5 than PS72/396-5. Bioturbation is distinct in colour mottling but it is not as clearly visible in x-radiograph images. Abbreviations: Dmmc = massive mud clast rich diamicton; Fb = bioturbated mud; Fm = massive mud.

Abb. 3: Farbaufnahmen und Radiographienegative der Lithofazies in den Abschnitten 114.5-184.5 cm (links) und 119-189 cm (rechts) der Sedimentkerne PS72/392-5 und PS72/396-5. Der rosa-weiße Diamikt PW1 umfasst in beiden Sedimentkernen nur den unteren Teil eines Diamiktes. Auffällig ist, dass die braunen Lagen nur in den bioturbierten Schlämmen vorkommen. Die Grenzen der Einheiten sind deutlicher im Sedimentkern PS72/392-5 als im PS72/396-5. Die Bioturbation ist deutlich an den Farbflecken aber nicht in den Radiographien erkennbar. Abkürzungen: Dmm(c) = massiger mit Schlammklasten angereicherter Diamikt; Fb = bioturbierter Schlamm; Fm = massiver Schlamm.

Distinct but mainly relatively thin beds of massive matrix-supported diamictons occur in the sediment cores (Figs. 2-6). These are poorly sorted sandy muds that contain on the average 17 % coarse fraction in sediment core PS72/340-5 (Tab. 1). The coarse sand and gravel is mostly randomly oriented, and abundance maxima of subangular to subrounded gravel (particles >2mm 10 cm^{-1}) are clearly associated with the diamictons (Figs. 4-6). Moreover, pebbles frequently occur in this facies (KRYLOV 2009, STEIN et al. 2010b, Fig. 8). Diamictons in cores PS72/396-5 and PS72/392-5 may contain similar amounts of gravel as the bioturbated muds (Fb). The diamictons comprise either almost exclusively lithogenic clasts (Dmm) or a mixture of lithogenic and mud clasts (Dmmc). Mud clasts may be enriched in diamictons, but then these beds appear to be somewhat finer grained, i.e. the coarse-fraction content is lower and gravel is absent.

Internal stratification is absent except for coarse sand and gravel sometimes enriched in layers that often occur at the top of beds. Deformation structures (Dms(r)) have been recognized in a single diamicton in sediment core PS72/396-5. The top contacts of diamictons are mostly distinct in core PS72/340-5, while the base usually grades into bioturbated muds. The opposite is characteristic for the sediment cores PS72/392-5 and PS72/396-5. Bedding contacts are often disturbed by bioturbation.

Distribution of lithofacies in the sediment cores

The distribution of lithofacies in sediment core PS72/340-5 differs distinctly from those of the other cores. Relatively thin beds of diamictons with variable gravel content alternate with thick beds of laminated muds in the upper 630 cm (Fig. 4). The laminated muds are the most fine-grained lithofacies in any of the studied cores and are exclusively restricted to sediment core PS72/340-5. Bioturbated muds usually under- and/or overly the diamicton facies. The lithofacies types are arranged in distinct cycles usually starting with laminated muds that grade into bioturbated muds and diamictons. The top is almost always marked by a distinct contact at the top of the diamictons as indicated by a sharp decrease in gravel contents (Fig. 4).

Although the sediment cores PS72/392-5 and PS72/396-5 were collected from different depositional settings they generally show a similar lithofacies distribution with a predominance of bioturbated muds alternating with diamictons in the upper part (Unit I of STEIN et al. 2010b), and uniformly bioturbated muds in the lower part (Unit II of STEIN et al. 2010b) (Figs. 5, 6). Similar lithological changes can be recognized in Unit I of both cores but the thicknesses of individual beds may vary (Fig. 3). Correlation of a few beds in the upper part of both cores is somewhat obscure and some beds may be missing in sediment core PS72/396-5. Bedding contacts between both lithofacies appear to be more distinct in PS72/392-5 than in PS72/396-5 (Fig. 3). Bioturbation might have been more intensive in sediment core PS72/396-5 possibly because of a stronger benthic activity at shallower water depths (see also POLYAK et al. 2009). The base of the diamictons is mostly even and sharp while the top contact is rather uneven and gradational.

Both cores show a pronounced cyclicity in Unit I, starting with diamicton deposition above a sharp contact to underlying bioturbated muds. The diamictons grade upwards into bioturbated muds that partly contain layers enriched in coarse sand and gravel.

Relation of lithofacies to physical properties and sediment colour

The physical property data show a distinct relationship to lithofacies. Wet bulk density and p-wave velocity are possibly related to the variable grain-size composition while magnetic

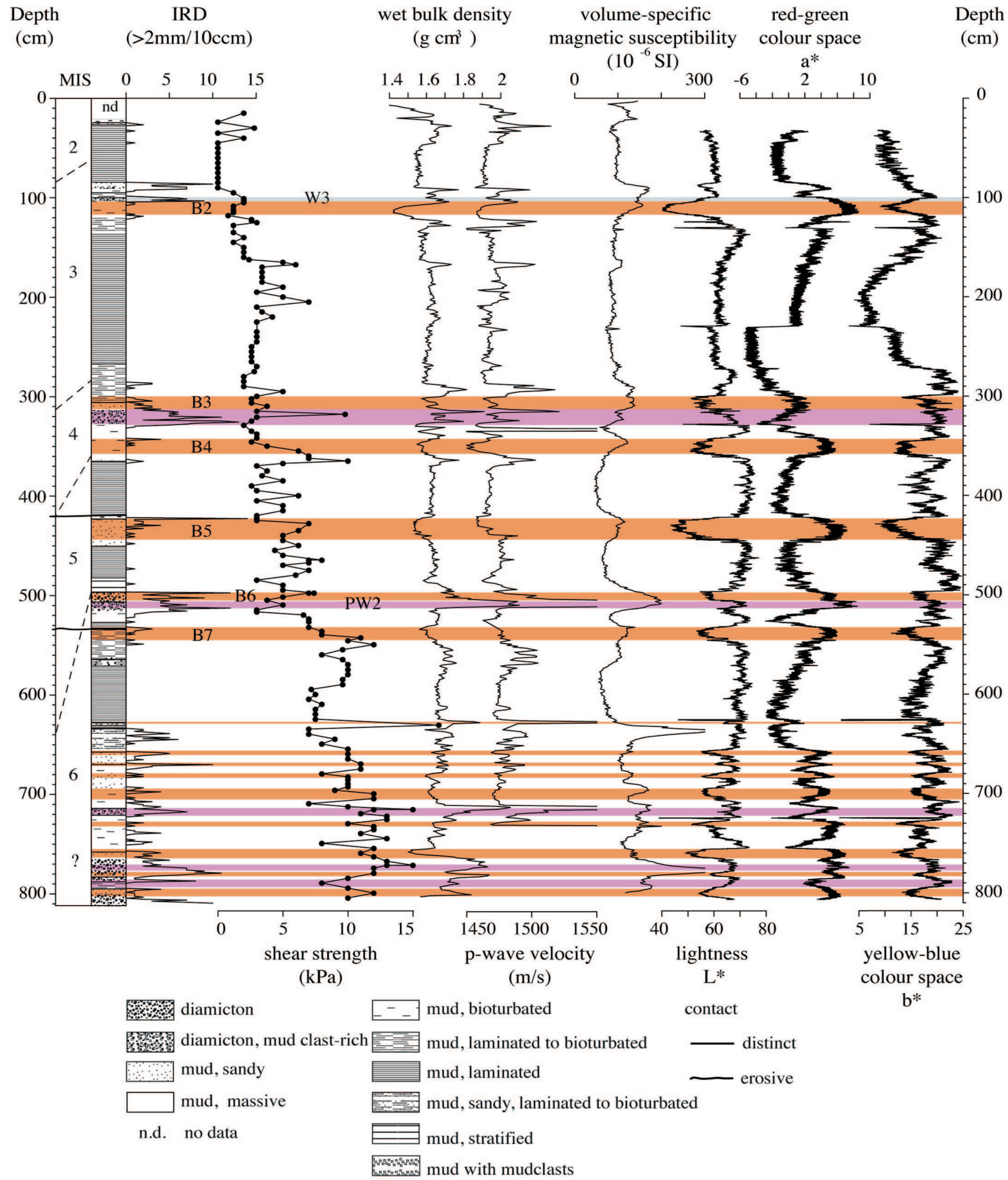


Fig. 4: Lithofacies distribution in sediment core PS72/340-5. Marine isotope stages (MIS), pink-white (PW), white (W) and brown (B) layers are after STEIN et al. (2010a). Diamictons are clearly reflected in gravel contents and maxima in wet bulk density and p-wave velocity. The brown layers correspond to different lithofacies but show mostly low wet bulk densities and p-wave velocities. An increase in shear strength at 540 cm core depth corresponds to an erosional contact at the top of brown layer B7. A second erosional contact at the top of brown layer B5 is not reflected in shear strength but may be related to glacial erosion reported from adjacent sediment core PS72/342-1 and the Chukchi Borderland (for discussion see STEIN et al. 2010a).

Abb. 4: Verteilung der Lithofazies im Sedimentkern PS72/340-5. Marine Sauerstoffsotopenstadien (MIS), rosa-weiße (PW), weiße (W) und braune (B) Lagen nach STEIN et al. (2010a). Die Diamikte sind deutlich am hohen Kiesgehalt und Maxima in der Nassraumdichte und Kompressionswellengeschwindigkeit erkennbar. Die braunen Lagen kommen in verschiedenen Lithofacies vor, zeichnen sich aber überwiegend durch geringe Nassraumdichten und Kompressionswellengeschwindigkeiten aus. Eine Zunahme in der Scherfestigkeit in 540 cm Kerntiefe entspricht einem erosiven Kontakt an der Oberkante der braunen Lage B7. Eine zweiter erosiver Kontakt an der Oberkante der braunen Lage B5 wird nicht in der Scherfestigkeit deutlich, könnte aber in Beziehung zur glazialen Erosion im benachbarten Sedimentkern PS72/342-1 und auf dem Tschuktschenplateau stehen (Diskussion in STEIN et al. 2010a).

susceptibility may be influenced by both variable grain size and provenance of sediments.

Laminated muds are almost free of coarse material (Tab. 1), associated with moderate density and p-wave velocity. The magnetic susceptibility obtains its lowest values, and partly shear strength values are low (Fig. 4). Laminated to bioturbated muds, bioturbated muds and sandy muds have a variable but usually low to moderate content of coarse material. Density and velocity are variable as well, and some distinct maxima occur in bioturbated and bioturbated to laminated muds. Generally minima of density and velocity occur in bioturbated muds, being often related to brown layers (ADLER et al. 2009, STEIN et al. 2010b) while magnetic susceptibility obtains maxima.

The relatively few granulometric data of core PS72/340-5 indicate that diamictons are probably the coarsest lithofacies type with maxima in gravel contents that are reflected in density and velocity maxima. These diamictons may therefore form distinct acoustic reflectors in seismic records that are potentially useful for correlation between different sites.

In core PS72/340-5, shear strength shows a general increase downcore but a distinct step is noted between 520 and 540 cm core depth associated with an erosional contact in the lithology (Figs. 4).

The sedimentary colours are partly linked to specific lithofacies. All pink white (PW) and white layers (W) are diamictons (Figs. 2 – 6). Brown layers are characterized by low lightness and high a* values (e.g. ADLER et al. 2009) and additionally minima in b* values. They are not associated with a single lithofacies type but generally occur in finer grained lithofacies (ADLER et al. 2009).

A number of brown layers are related to bioturbated to laminated and bioturbated muds that have a low density and velocity, but they are also associated with coarser lithofacies including diamictons (Fig. 5). Bioturbated muds can be either brown or greyish/yellowish such as in sediment cores PS72/392-5 and PS72/396-5. This is possibly due to subtle changes in the proportions of sand, silt and clay with slightly finer sediments associated with brown layers (cf. O'REGAN et al. 2008).

Various lithofacies have lighter colours (grayish/yellowish units *sensu* ADLER et al. (2009) with high L* and low a* values). The laminated lithofacies and most diamictons are light. This supports the observation by ADLER et al. (2009) that grain-size composition of light units is heterogenous.

Colour contacts are often more pronounced than lithofacies contacts. The top of brown layers is usually distinct (Figs. 2, 3; see ADLER et al. 2009, STEIN et al. 2010b) while the basal contact is more gradual due to bioturbation.

DISCUSSION

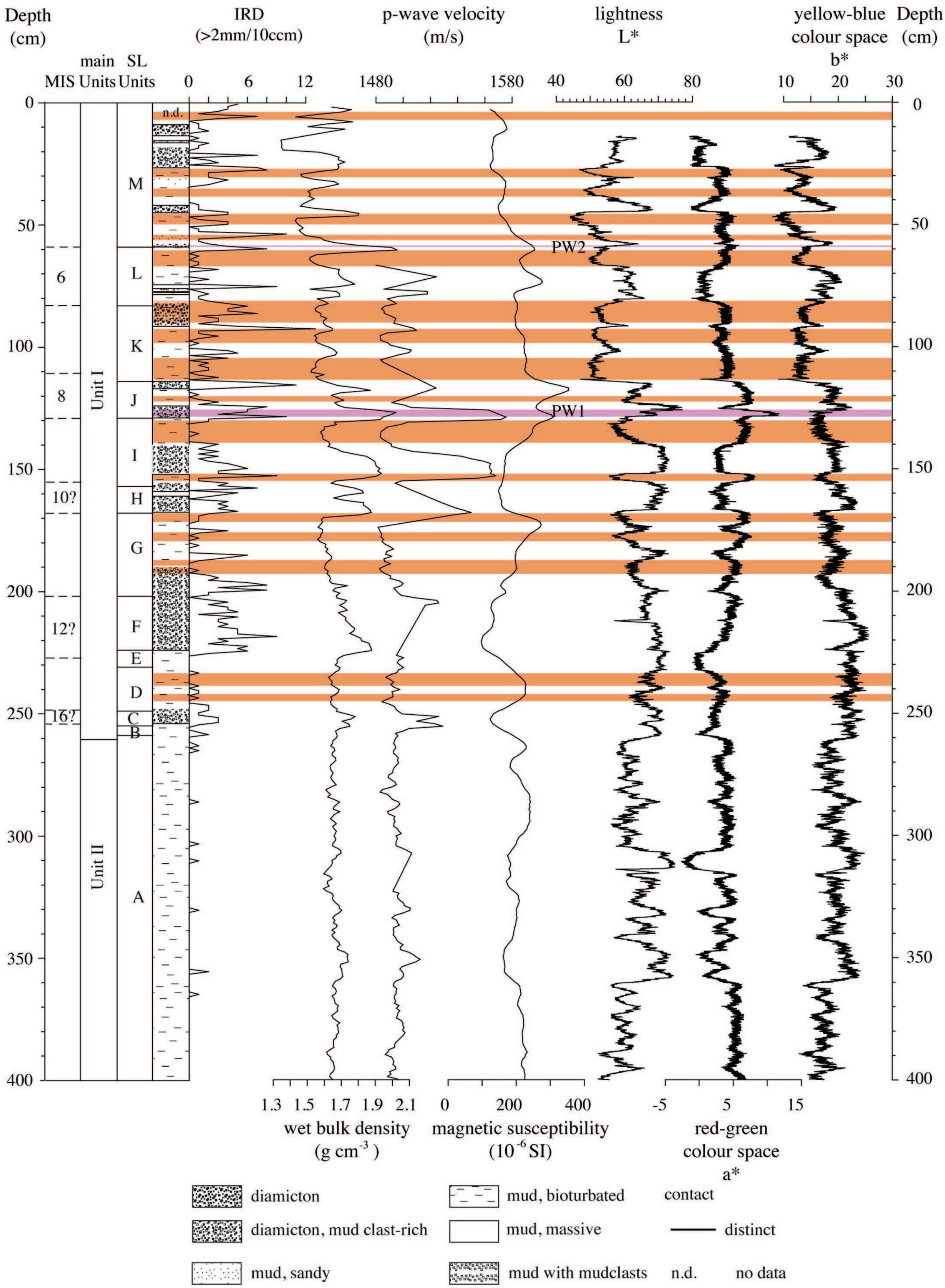
Preliminary interpretation of lithofacies

The lithofacies of the analysed sediment cores are generally characterized by an alternation of muds and diamictons. The overwhelming predominance of muds probably indicates that the continuous deposition of clays and silts is occasionally overprinted by deposition of coarser sediments.

The origin of massive diamictons may be explained by different depositional processes (e.g., DOWDESWELL et al. 1994 *cum lit*). In the studied sediment cores, they may have been formed in a glaciomarine environment by a release of debris by basal melting beneath floating ice shelves close to the grounding line, dumping from icebergs, rain out and suspension settling from melting icebergs, and/or debris flows (DOWDESWELL et al. 1994 *cum lit.*, VORREN et al. 1983). An origin from debris flows is ruled out except for the upper part of a diamicton in sediment core PS72/396-5 (190-200 cm core depth) because the characteristic lens-shaped acoustically transparent seismic facies was not recorded at the core locations (NIESSEN unpubl. data). The diamicton in sediment core PS72/396-5 shows deformation structures indicative of reworking. However, due to the core location on a seamount, the transport distance must have been short. The occurrence in different bathymetric settings (continental slope, sea mount, abyssal plain) and the basinwide distribution of the visually conspicuous white to pink white diamictons (e.g. CLARK et al. 1980, MINICUCCI & CLARK 1983, MUDIE & BLASCO 1985, PHILLIPS & GRANTZ 1997, STEIN et al. 2010b) indicate that the massive diamictons were most likely formed by the rapid release of sediments from melting icebergs and subordinate sea ice. However, it should not be ruled out that sediment core PS72/340-5 located close to the continental slope were at times located underneath a floating ice shelf (see e.g. JAKOBSSON et al. 2008). The sandy lutites in CLARK'S et al. (1980) lithostratigraphy were interpreted to indicate sedimentation from icebergs (CLARK et al. 1980, CLARK & HANSON 1983, MINICUCCI & CLARK 1983).

The available AMS ^{14}C datings for the white diamicton W 3 located above brown layer B2 in sediment core HLY0503-8JPC that is located between the studied sediment cores (Fig. 1) indicate that diamictons may represent (sub-) millennial-scale sedimentation events (POLYAK et al. 2009). AMS ^{14}C ages of 41 and 37 ka above W3 are not significantly younger than ages of 43 and 36 ka below the diamicton (ADLER et al. 2009, POLYAK et al. 2009). The drift of icebergs and the subsequent disintegration may have been linked to relatively warmer climate conditions when a closed sea-ice cover broke up thus allowing icebergs and sea ice to drift freely (ÓCOFAIGH & DOWDESWELL 2001).

The grain-size composition is variable and a few diamictons are finer-grained because of abundant mud clasts. This might indicate a stronger contribution of sea-ice transported sediments. The relatively sharp top contacts in core PS72/340-5 and some coarse-grained layers within the diamictons might have been caused by winnowing of fines and/or an abrupt termination of iceberg or sea-ice sedimentation. The relatively sharp basal contacts in PS72/392-5 and PS72/396-5 indicate that sedimentation from melting icebergs/sea ice commenced instantaneously whereas the gradational contacts in PS72/



Depth (cm)
MIS
main Units
SL Units
IRD (>2mm/10ccm)
p-wave velocity (m/s)
lightness L*
yellow-blue colour space b*
Unit I
Unit II
PW2
PW1
n.d.
wet bulk density (g cm-3)
magnetic susceptibility (10-6 SI)
red-green colour space a*
diamicton
diamicton, mud clast-rich
mud, sandy
mud, bioturbated
mud, massive
mud with mudclasts
contact
distinct
n.d. no data

340-5 may rather reflect a gradual and continuous onset. Previously, CLARK et al. (1980), CLARK & HANSON (1983) and MINICUCCI & CLARK (1983) observed that their coarse grained units (sandy lutites) have a relatively sharp base.

Detrital carbonates are a significant component in the white and pink white diamictons but they are not restricted to these diamictons (STEIN et al. 2010b). A visual comparison of the dolomite contents in sediment core PS72/392-5 (Stein et al. 2010a, Fig. 8) and the lithofacies distribution (Fig. 5) reveals a rough correlation of dolomite maxima with the occurrence of diamictons. However, high-resolution petrographic, mineralogic and inorganic geochemical studies are required to clearly distinguish detrital carbonate-rich diamictons with a North American provenance from other diamictons that may have an Eurasian provenance (PHILIPS & GRANTZ 2001). The diamictons also contain marine microfossils such as foraminifers but apparently the abundances are lower than in some mud lithofacies. Previous studies already revealed that coarser sediments are often associated with low foraminifer abundances (SPIELHAGEN et al. 1997, 2004, NØRGAARD-PEDERSEN et al. 1998, ADLER et al. 2009).

Although various mud lithofacies have been observed in the three studied sediment cores a common origin of these sediments appear to be likely. The occurrence of laminated, laminated to bioturbated, bioturbated, and massive muds suggests a genetical relationship between these lithofacies. The laminated muds are a particularly interesting lithofacies restricted to sediment core PS72/340-5. Laminated sediments may occur in various depositional settings (ÓCOFAIGH & DOWDESWELL 2001 *cum lit.*), and an interpretation based only on x- radiograph images is difficult. The exclusively parallel lamination, almost absence of coarse-fraction and only occasionally occurring gravel may indicate suspension settling from turbid meltwater plumes (ÓCOFAIGH & DOWDESWELL 2001 *cum lit.*). The almost absence of coarser sediment components may have been caused by a suppressed iceberg drift due to a relatively stable sea-ice cover during colder climate conditions. This interpretation is supported by the preliminary age model of STEIN et al. (2010b) that dates lamination to glacial or interstadial marine isotope stages. Alternatively, the lamination may be formed by current transport (distal fine-grained turbidites and/or contourites), and further sedimentological and micropaleontological studies are required to interpret these deposits.

The absence of bioturbation may be related to high sedimentation rates inhibiting benthic activity, and increasing bioturbation with decreasing sedimentation rates (increasing distance from source) may have led to bioturbated muds and finally homogenous massive muds without any internal stratification (see EVANS et al. 2002). However, enhanced bioturbation might also reflect improved climatic conditions with a reduced sea-ice cover leading to a higher flux of food to the sea floor because some bioturbated intervals have somewhat higher abundances of foraminifers and contain in addition subpolar species (STEIN et al. 2010b).

A succession of laminated muds to bioturbated muds has been also recognized in deglacial sequences indicating an increasing distance from the source over time. The deposition of laminated muds may indicate rather cold conditions with extensive sea ice cover (multi-year sea ice) that almost inhibited any iceberg drift while bioturbated muds are associated with warmer conditions and deposition of iceberg rafted debris (PHILLIPS & GRANTZ 1997, ÓCOFAIGH & DOWDESWELL 2001 *cum lit.*). Laminated muds might have been partly formed during extensive glaciations when the CAO was covered with an extensive, possibly year round, sea-ice cover such as during the Last Glacial Maximum (e.g. NØRGAARD-PEDERSEN et al. 1998). AMS ^{14}C datings indicate low sedimentation rates during the last glacial in the CAO and the presence of a hiatus in some areas (NØRGAARD-PEDERSEN et al. 1998, POLYAK et al. 2009). A comparable more stable ice-pack has been suggested by O'REGAN et al. (in press) to explain the fine-grained sediments with low abundance of IRD on the Lomonosov Ridge until MIS 6. However, micropaleontological studies are required to characterize the climate conditions during the deposition of bioturbated muds.

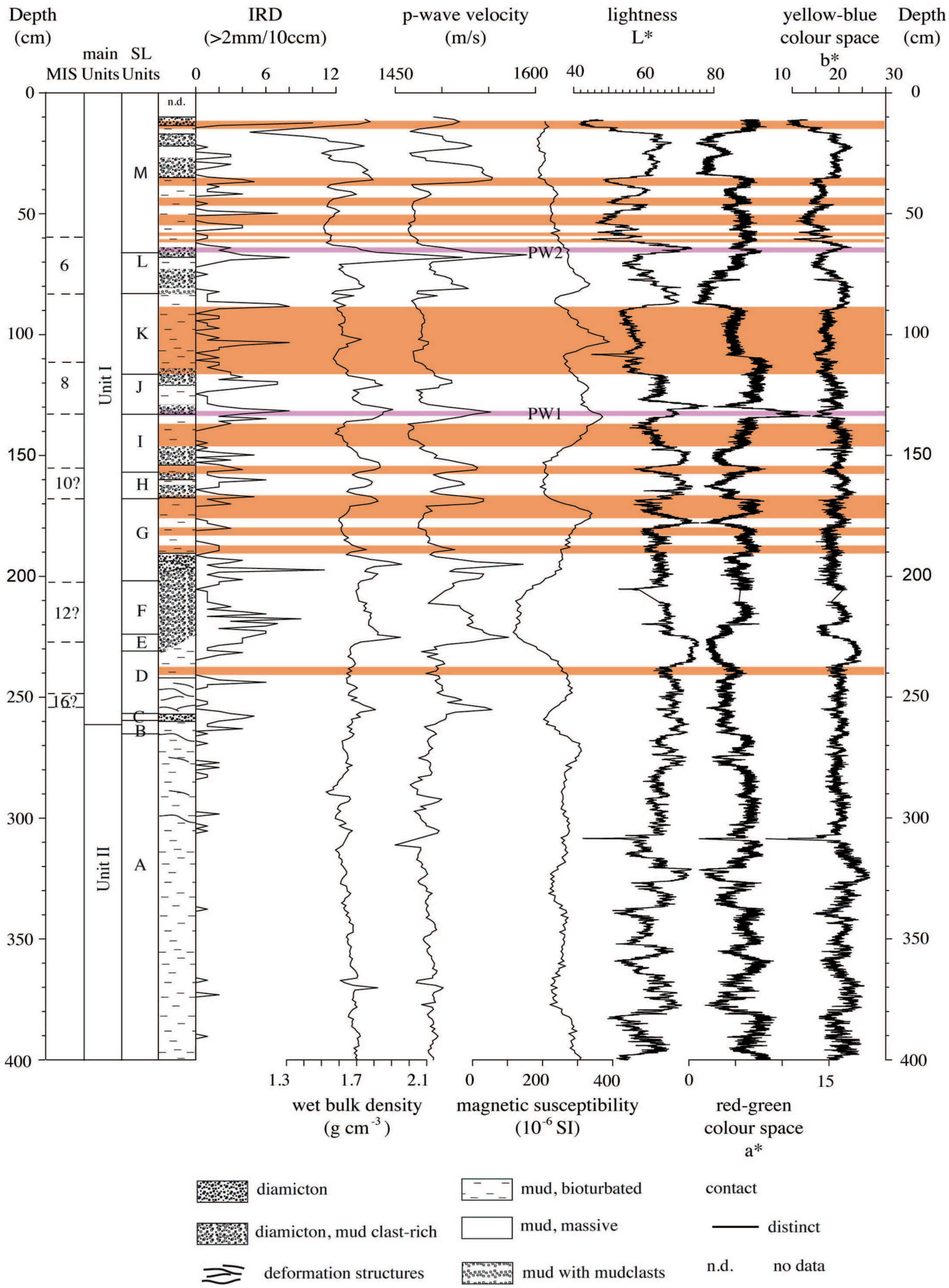
The succession from laminated to bioturbated muds in sediment core PS72/340-5 may represent deglacial sequences with a transition from relatively cold to relatively warm conditions. This might be supported by somewhat higher abundances of foraminifers including subpolar species in some bioturbated muds (STEIN et al. 2010b). The transition of bioturbated muds into diamicton lithofacies may reflect a climatic warming that resulted in (at least periodically) open water conditions, allowing enhanced iceberg and/or sea-ice rafting (floating ice masses).

The exclusively bioturbated muds in sediment cores PS72/392-5 and PS72/396-5 may represent such environmental conditions as well, but the absence of lamination may represent both lower sedimentation rates and somewhat more open water conditions in ice distal setting. Thus, the laminated muds in sediment core PS72/340-5 may have been deposited under a thick sea ice cover closer to a melt-water source than sediment cores PS72/392-5 and PS72/396-5. Preliminary shipboard studies of all cores obtained during ARK XXIII/3 showed that PS72/340-5 is the only core with laminated lithofacies (JOKAT 2009).

The mud and diamicton lithofacies form distinct sucessions in sediment core PS72/340-5 and in Unit I of sediment cores PS72/392-5 and PS72/396-5. The alternation of bioturbated muds and diamicton beds in sediment cores PS72/392-5 and PS72/396-5 resembles the laminated diamicton facies, in sediment cores PS2185-6 and PS2177-5 from the Lomonosov Ridge (Fig. 1) that indicated deposition from sea-ice or

Fig. 5: Lithofacies distribution of sediment core PS72/392-5. Marine isotope stages (MIS), standard lithostratigraphic units (SL units) A to M and main lithological units Unit I and Unit II after STEIN et al. (2010b). Note that only the upper 400 cm are shown and that brown units are marked only in Unit I. The diamictons including PW 1 and PW 2 are clearly reflected in ice-rafted debris content, wet bulk density and p-wave velocity. Brown layers occur mainly in bioturbated muds.

Abb. 5: Verteilung der Lithofazies im Sedimentkern PS72/392-5. Marine Sauerstoffisotopenstadien (MIS), standard lithostratigraphische Einheiten (SL Einheiten) A bis M und Hauptsedimenteinheiten Unit I und Unit II nach STEIN et al. (2010b) entnommen. Nur die oberen 400 cm des Sedimentkernes sind dargestellt. Braune Lagen sind nur in Unit I eingezeichnet. Die Diamikte einschliesslich PW 1 und PW 2 zeigen sich deutlich anhand der hohen Gehalte an Eis transportiertem Material, Nassraumdichte und Kompressionswellengeschwindigkeit. Braune Lagen erscheinen hauptsächlich in bioturbierten Schlämmen.



Depth (cm)
MIS
main Units
SL Units
IRD (>2mm/10ccm)
p-wave velocity (m/s)
lightness L*
yellow-blue colour space b*
Depth (cm)
n.d.
M
L
K
J
I
H
G
F
E
D
C
B
A
6
8
10?
12?
16?
Unit I
Unit II
PW2
PW1
wet bulk density (g cm-3)
magnetic susceptibility (10-6 SI)
red-green colour space a*
diamicton
diamicton, mud clast-rich
deformation structures
mud, bioturbated
mud, massive
mud with mudclasts
contact
distinct
n.d. no data

icebergs (SVINDLAND & VORREN 2002). This lithofacies consists of thin laminae or beds of diamicton with sediment pellets and clasts that are interbedded with laminae of sandy mud. The homogenous mud facies in the lower part of cores PS2185-6 and PS2177-5 correspond most likely to the bioturbated muds in Unit II of cores PS72/392-5 and PS72/396-5 that represent a consistent supply of suspended and/or sediments from melting sea ice.

The succession in core PS72/340-5 is similar to the lithostratigraphic cycles described by PHILIPS & GRANTZ (1997) from Northwind Ridge. These cycles comprise olive-gray laminated muds barren of microfossils that were deposited during an extensive sea-ice cover preventing the drift of icebergs, and coarse sediments that reflect the abrupt thinning and break up of the sea-ice cover at the end of glacials permitting icebergs to reach Northwind Ridge. The brown units in core PS72/ 340-5 may represent interglacial deposits with a higher biological productivity. Core PS72/340-5 may correlate to this suite of cores from Northwind Ridge marking the most distal part of this thick sea ice cover.

However, part of the deglacial cycles terminated rather than started with diamicton deposition. These diamictons were preceded possibly by warmer conditions as indicated by underlying brown biogenic carbonate rich sediments (STEIN et al. 2010b). This warming led in conjunction with sea level rise to a disintegration of ice shelves and marine based ice sheets. The laminated muds are likely both representing glacial conditions and, at the transition to bioturbated muds, deglacials.

Sediment accumulation might have been rather asymmetric during deposition of Unit I. The proposed higher sedimentation rates of diamictons than that of the mud lithofacies result in a sawtooth pattern of sedimentation cycles. Diamictons make up about 40 % of the sediments in Unit I of sediment cores PS72/392-5 and PS72/396-5 showing that the temporal resolution might have changed from mm-scale to cm-scale ka^{-1} at the transitions from glacials to interglacials. BISCHOF et al. (1996, 752) suggested that variable accumulation of sediments may have led to condensed interglacials and thick glacial sequences rapidly deposited from melting icebergs. Within the frame of radiocarbon dating, previous studies already showed highly variable sedimentation rates in the CAO (POORE et al. 1994, NØRGAARD-PEDERSEN et al. 1998, ADLER et al. 2009, POLYAK et al. 2009).

Colour cycles and lithofacies

Middle Pleistocene to Holocene sediments from the CAO show a pronounced cyclicity in sediment colours from brown to light brown, yellowish or grey. Variability in manganese contents have been used to establish a chemostratigraphy with Mn-rich brown layers representing interglacial/interstadial periods and lighter beds glacial or stadial and deglacial periods (POORE et al. 1993, ISHMAN et al. 1996, JAKOBSSON et al. 2000, PHILIPPS & GRANTZ 2001, POLYAK et al. 2004, MORAN et al. 2006, NØRGAARD-PEDERSEN et al. 2007a,b, O'REGAN et al. 2008, ADLER et al. 2009). Brown beds (low lightness, high a* values) contain low to moderate amounts of sand and partly elevated concentrations of organic matter, abundant calcareous microfossils, and low bulk densities. The upper boundary is mostly distinct, while the lower boundary is often disturbed by bioturbation. Grey/yellowish beds (high lightness, low a* values) are almost barren of fossils and largely fine-grained with very low sand content but elevated bulk density and sandy and even coarser intervals usually at the bottom or top of grey units. Whereas brown beds are usually bioturbated, bioturbation is rare or absent in the olive grey beds (CLARK et al. 1980, POORE et al. 1993, PHILIPPS & GRANTZ 1997, POLYAK et al. 2004, NØRGAARD-PEDERSEN et al. 2007a,b, ADLER et al. 2009, STEIN et al. 2009). Several stratigraphic marker beds with distinctly pinkish-yellow and/or white carbonate clasts occur in the western Arctic Ocean.

This relatively simple relationship between sediment colour and lithology is probably only reflected in the lithofacies of Unit I of sediment cores PS72/392-5 and PS72/396-5. The brown colours are almost exclusively restricted to the bioturbated muds while the diamictons have lighter colours. However, there are a few exceptions from this rule (Fig. 5). In the Unit II of sediment cores PS72/392-5 and PS72/396-5, and in sediment core PS72/340-5, laminated and laminated to bioturbated muds have light brown, yellowish to greyish colours whereas bioturbated muds have both greyish and brownish colours. Diamictons are predominantely greyish but may also have brown colours in sediment core PS72/340-5 (Fig. 4). In this core, brown colours are often associated with transitions in lithofacies and finer-grained sediments.

Potential significance of diamictons for stratigraphic correlation

The correlation of sedimentary facies is seriously hampered by the still low-resolution age models of CAO sediment cores. Although it is now generally accepted that most short sediment cores (<10 m length) only comprise Pleistocene sediments (e.g. BACKMAN et al. 2004), the interpretation of stratigraphic data with respect to marine isotope stages often leads to considerable offsets in the placement of marine isotope stage boundaries. Thus, various age models have been published for sediment cores in the Mendeleev Ridge area (POLYAK et al. 2004, DARBY et al. 2006, NØRGAARD-PEDERSEN et al. 2007, ADLER et al. 2009, BACKMAN et al. 2009, for a comparison of age models see STEIN et al. 2010b). STEIN et al. (2010a) discussed these age models and proposed a tentative chronostratigraphy for the sediment cores recovered during ARK-XXIII/3. The exact definition of isotope events remains

Fig. 6: Lithofacies distribution of sediment core PS72/396-5. Marine isotope stages (MIS), standard lithostratigraphic units (SL units) A to M and main lithoslogical units, Unit I and Unit II after STEIN et al. (2010a). Note that only the upper 400 cm are shown and that brown units are marked only in Unit I. The diamictons including PW 1 and 2 are clearly reflected in ice-rafted debris content, wet bulk density and p-wave velocity. Brown layers occur mainly in bioturbated muds.

Abb. 6: Verteilung der Lithofazies im Sedimentkern PS72/392-5. Marine Sauerstoffisotopenstadien (MIS), standard lithostratigraphische Einheiten (SL Einheiten) A bis M und Hauptsedimenteinheiten Unit I und Unit II nach STEIN et al. (2010b). Nur die oberen 400 cm des Sedimentkernes sind dargestellt. Braune Lagen sind nur in Einheit I eingezeichnet. Die Diamikte einschliesslich PW 1 und PW 2 zeigen sich deutlich anhand der hohen Gehalte an eistransportiertem Material, Nassraumdichte und Kompressionswellengeschwindigkeit. Braune Lagen erscheinen hauptsächlich in bioturbierten Schlämmen.

still questionable, because of conflicting evidence from stable isotopes, benthic foraminifers and calcareous nannofossils (ADLER et al. 2009, BACKMAN et al. 2009). Here, we use beyond the range of AMS ^{14}C dating calcareous nannofossils (BACKMAN et al. 2009) to identify late MIS5 to MIS3 because these are considered as more reliable than other age information. The age models presented by STEIN et al. (2010a,b) for the whole set of sediment cores collected during expedition ARK-XXIII/3 appear to be rather consistent since MIS 6 but there are considerable uncertainties in the age control of the older deposits in Unit I and no age model has been suggested for Unit II.

Diamictons are apparently a common feature in sediment cores located on basement highs across the CAO. SVINDLAND and VORREN (2002) studied the lithofacies, grain-size composition and clay mineralogy along a transect from the Amundsen Basin to the Lomonosov Ridge and distinguished a lower homogenous mud facies from an upper laminated diamicton facies in sediment cores PS2185-6 and PS2177-5 from the Lomonosov Ridge. The diamicton units are related to high weight percentages of sand but low numbers of gravel particles. The laminated diamicton facies may correspond to Unit I in sediment cores obtained during ARK-XXIII/3 that contain numerous diamictons. Although diamictons have not been explicitely interpreted from lithological core descriptions previously, the conspicuous pink-white and white layers and the coarse-grained partly poorly sorted lithologies (sandy lutites) of CLARK et al. (1980), CLARK & HANSON (1983) and MINICUCCI & CLARK (1983) are tentatively interpreted as diamictons since the sedimentological description of some units strongly resembles that of the diamicton lithofacies (e.g. unit F of CLARK et al. 1980, unit F' of MINICUCCI & CLARK 1983). These units have been also attributed to iceberg transport (CLARK et al. 1980, MINICUCCI & CLARK 1983). Furthermore, PHILLIPS & GRANTZ (1997) described a number of depositional cycles that contain *"bioturbated sandy/pebbly yellow to olive grey mud with white or pink sandy/pebbly mud beds"*. These might be diamictons as well. Since SVINDLAND & VORREN (2002) have interpreted the coarse-grained uppermost sediments in cores PS2177 and PS2185 from the Lomonosov Ridge as diamicton facies, such coarse-grained types of sediments may be generally interpreted as diamictons in the Eurasian Arctic as well. The coarse-fraction content has been used as tool for correlation of sediment cores on Lomonosov Ridge and across the Arctic Ocean (JAKOBSSON et al. 2001, SPIELHAGEN et al. 2004, O'REGAN et al. 2008) and it may be inferred that diamictons are a widespread phenomenon in the whole Arctic Basin in the Middle to Late Pleistocene.

The onset of diamicton deposition is apparently diachronous at the southern Mendeleev Ridge and the Lomonosov Ridge. In core PS2185-6, diamicton occurred at the MIS6/7 transition (SPIELHAGEN et al. 2004) after a continuous sedimentation of fine-grained sediments since the early part of the Pleistocene (O'REGAN et al. in press). In contrast, the first diamicton occurred in sediment cores recovered during ARK-XIII/3 at the base of Unit I, corresponding to unit C in CLARK's et al. (1980) lithostratigraphy, tentatively dated to MIS 16 by STEIN et al. (2010a,b). Moreover, MINICUCCI & CLARK (1983) observed sandy lutites (interpreted here as diamictons) even in their unit A from the eastern Alpha Ridge. These must be older than MIS 16 according to the age model of STEIN et al. (2010a). This diachroneity might have been caused by different glaciation histories of the Amerasian and Eurasian hinterlands with earlier glacial advances to the shelf in North America and a circulation system that has restricted iceberg drift to the Beaufort Gyre prior to MIS 6/7 resulting in a much earlier deposition of coarse ice-rafted debris in the Amerasian than Eurasian Basin. Furthermore, glaciations in Eurasia prior to MIS 6/7 might have first eroded fine-grained sediments on the extensive Siberian shelf areas leaving older glaciations lithologically undetected in marine records.

Here we suggest that an additional age model for the expedition ARK-XXIII/3 sediment cores should be tested that assumes a coeval onset of diamicton deposition in the CAO. Compared to the continuous and slow background sedimentation of fine-grained muds with low coarse fraction content that prevailed at least since the middle Miocene in the CAO (ST. JOHN 2008, O'REGAN et al. 2008), diamictons were probably deposited within a much shorter period as it is indicated by AMS ^{14}C dating of diamicton W3. Consequently, they could provide excellent correlation lines in the basin if they can be unequivocally related to a single event. The cause of such a coeval middle Pleistocene onset of iceberg rafting in the CAO remains however speculative. The initial development of ice streams and large ice shelves after MIS 6/7 might have resulted in a stronger supply of icebergs to the Arctic Ocean. However, a thick sea ice cover prior to MIS 6/7 might also have hampered the drift of icebergs. Furthermore, a re-organisation of the surface circulation might have led to a drift of icebergs across the CAO whereas it was confined to the marginal areas before this time.

The assumption of a synchronous onset of diamicton deposition is supported by a re-examination of lithostratigraphic schemes based on visual core descriptions, sediment colour, foraminiferal abundance and coarse fraction by SELLÉN et al. (2008). These authors suggested possible correlations of cores across the CAO by means of direction changes of the paleomagnetic polarity, the occurrence of calcareous foraminifers and increase of coarse fraction. Since the three different correlation lines do not run parallel (Fig. 4 in SELLÉN et al. 2008) different sedimentation rates for the upper part of the sequences were calculated. The onset of predominantely coarse-fraction sedimentation on the Lomonosov Ridge has been correlated to CLARK's unit H leading to a MIS 7.1 age for this unit according to the age model of SPIELHAGEN et al. (2004). This is younger than the assignment of unit H to MIS 10 by STEIN et al. (2010b). However, it must be kept in mind that currently accepted age models of sediment cores from the Amerasian Basin do not support a coeval onset of diamicton formation (ADLER et al. 2009, BACKMAN et al. 2009, POLYAK et al. 2009).

Diamictons may theoretically form exceptional stratigraphic marker beds with basin-wide distribution because they can be easily identified by X-radiographs and/or peaks in sand and gravel content (e.g. CLARK et al. 1990, SCOTT et al. 1989, MUDIE & BLASCO 1985, PHILIPS & GRANTZ 1997, STEIN et al. 2010a,b). Furthermore, they were possibly deposited within a short period of time compared to the mud lithofacies (MINICUCCI & CLARK 1983, POLYAK et al. 2009). Coeval diamicton beds will then show that certain glacial events are recorded throughout the Arctic Ocean (cf. ADLER et al. 2009) and thus may serve as time lines. It is tempting to suggest a possible correlation of individual diamicton beds across the Arctic Ocean but age models of sediment cores must be better synchronized to assess a possible synchronicity of diamicton layers.

The basinwide correlation of individual diamicton beds within the diamicton-bearing Unit I based on pure visual core descriptions and x-radiograph images is generally hampered by the large number of beds and a decrease in thickness with increasing distance from the source (MINICUCCI & CLARK 1983, PHILLIPS & GRANTZ 2001, NØRGAARD-PEDERSEN et al. 2007a). However, a local correlation between cores PS72/392-5 and PS72/396-5 appears feasible as suggested by STEIN et al. (2010b) based on colour cycles and the occurrence of characteristic white and pink-white detrital carbonate-rich layers (W3, PW2, PW1) that have been introduced by CLARK et al. (1980) as lithological marker beds. A correlation with regional records should be regarded with caution, because several studies showed that the number of detrital carbonate-rich beds is variable between the different regions of the Arctic Ocean (MINICUCCI & CLARK 1983, MUDIE & BLASCO 1985, MORRIS & CLARK 1986, SCOTT et al. 1989, POORE et al. 1993, PHILIPS & GRANTZ 1997, NØRGAARD-PEDERSEN et al. 1998, ADLER et al. 2009, STEIN et al. 2010b). Due to the numerous diamictons that cannot be distinguished by visual core description, petrographical, mineralogical and geochemical fingerprints are required to identify individual events. Exact correlation may be further complicated by a heterogenous composition of the diamictons because different source areas may interfinger in these units. In particular, the provenance and composition of individual detrital carbonate-bearing layers that probably have a basinwide distribution (CLARK et al. 1980, MUDIE & BLASCO 1985, SPIELHAGEN et al. 1997, NØRGAARD-PEDERSEN et al. 1998, 2007a,b, PHILIPS & GRANTZ 2001, STEIN et al. 2010a,b) and that presumably are related to ice-stream activity in the Canadian Arctic (SELLÉN et al. 2008) must be considered in addition to grain-size analysis. Diamictons containing detrital carbonates may be thus used to correlate cores from the Lomonosow Ridge to the Beaufort Sea.

A decrease in thickness with increasing distance from the source may also be reflected in a distinct decrease in gravel content in the Pleistocene and Holocene sediments across the Arctic Ocean, as it has been observed in a transect from the Beaufort Sea towards the Eastern Arctic Ocean (PHILLIPS & GRANTZ 2001, SVINDLAND and VORREN 2002). The generally low gravel contents in the Eastern Arctic Ocean may be related to the fine-grained texture of sediments in the source areas rather than a lower supply of glacial ice to the Eastern Arctic Ocean. Therefore, diamictons may not be easily identified by lithofacies analysis due to their fine-grained composition.

CONCLUSIONS

The analysis of x-radiograph images from three sediment cores recovered during RV "Polarstern" expedition ARK-XXIII/3 revealed that muds with a variable sediment texture are the dominant lithofacies at the southeastern Mendeleev Ridge in the Middle to Late Pleistocene. In sediments younger than presumably MIS 16, massive diamictons are intercalated in these muds. These diamictons comprise up to 40 % of the sediment volume. They have variable coarse fraction and mud-clast contents and they are clearly reflected in physical property data (wet bulk density, p-wave velocity). Thus, they provide the potential for distinct acoustic reflections that may allow a regional correlation of sediment cores. In accordance with previous studies the muds are interpreted to have been predominantly formed by the release of fine-grained sediments from melting sea-ice while the diamictons are the product of iceberg and subordinate sea-ice sedimentation.

Sedimentation rates may have been variable in the diamicton-bearing Unit I ranging from mm to cm per ka for the muds and increasing possible to several cm per ka when more open water conditions allowed drift of icebergs and rapid deposition of diamictons. The sedimentation rates appear to have been rather variable during deposition of Unit I, i.e. a slow background sedimentation of fine-grained material was punctuated by rapid (sub-)millennial-scale sedimentation events.

The diamictons may form excellent marker beds for stratigraphic correlation if individual beds had a unique petrographical, mineralogical, and geochemical composition that allows assignment to a single event. Diamictons have been likely described as coarse-grained lithologies in previous studies on sediment cores from the Central Arctic Ocean. The most conspicuous diamictons are the white and pink-white layers that contain increased amounts of detrital carbonates probably originating in the Canadian Arctic Archipelago.

Comparison with sediment records from the Central Arctic Ocean revealed that diamictons were probably first deposited in the Middle Pleistocene. The onset was diachronous based on proposed age models and apparently started much earlier in the Amerasian Basin than in the Eurasian Basin. Diamicton formation was an important process only in Middle to Late Pleistocene sediments from the Central Arctic Ocean, and further chronstratigraphic studies are required to test the hypothesis of a basin-wide coeval onset of diamicton deposition.

ACKNOWLEDGMENTS

The authors thank the master Stefan Schwarze and his crew of RV "Polarstern" for their support at sea.
The members of the geological shipboard scientific party are acknowledged for their dedicated work during the expedition ARK-XXIII/3:
Evgenia Bazhenova, State University of St. Petersburg, POMOR, St. Petersburg 199178, Russia,
Sebastian Eckert, and Christian März, Institute for Chemistry and Biology of the Marine Environment ICBM, Oldenburg University, 26111 Oldenburg, Germany,
Alexey Krylov, All-Russian Research Institute for Geology and Mineral Resources VNII Okeangeologia, St. Petersburg 190121, Russia,
Juliane Müller, Michael Schreck and Isabell Schulte-Loh, Alfred Wegener Institute for Polar and Marine Research AWI, Am Alten Hafen, 27568 Bremerhaven, Germany,
Seung-Il Nam, Korean Institute of Geoscience and Mineral Resources (KIGAM), Yuseong-gu, 305-350 Daejeon, Korea.
Christelle Not, Centre de recherche en Géochimie et en Géodynamique GEOTOP, Université du Quebéc a Montréal, Montréal, Quebéc, Canada, H3C 3P8,

David Poggemann, Leibniz Institute for Marine Sciences IFM-GEOMAR, Kiel University, 24148 Kiel, Germany.
The authors very gratefully acknowledge Matthias Forwick, Tromsø, and Niels Nørgaard-Pedersen (Copenhagen) for their constructive reviews that helped very much to improve a first version of the manuscript.

References

Adler, R.E., Polyak, L., Ortiz, J.D., Kaufman, D.S., Channell, J.E.T., Xuan, C., Grottoli, A.G., Sellen, E. & Crawford, K.A. (2009): Sediment record from the western Arctic Ocean with an improved Late Quaternary age resolution: HOTRAX core HLY0503-8JPC, Mendeleev Ridge.- Global Planet. Change, 68: 18-29.

Andersen, E.S., Dokken, T., Elverhøi, A., Solheim, A. & Fossen, I. (1996): Late Quaternary sedimentation and glacial history of the western Svalbard continental margin.- Mar. Geol. 133: 123-156.

Backman, J., Jakobsson, M., Lovlie, R., Polyak, L. & Febo, L.A. (2004): Is the central Arctic Ocean a sediment starved basin?- Quat. Sci. Rev. 23: 1435-1454.

Backman, J., Fornaciari, E. & Rio, D. (2009): Biochronology and paleoceanography of late Pleistocene and Holocene calcareous nannofossil abundances across the Arctic Basin.- Mar. Micropaleontol. 72: 86-98.

Bischof, J., Clark, D.L. & Vincent, J.-S. (1996): Origin of ice-rafted debris: Pleistocene paleoceanography in the western Arctic Ocean.- Paleoceanography 11: 743-756.

Bischof, J.F. & Darby, D.A. (1997): Mid to Late Pleistocene Ice drift in the western Arctic Ocean: Evidence for a different circulation in the past.- Science 277: 74-78.

Clark, D.L. & Hanson, A. (1983): Central Arctic Ocean sediment texture: a key to ice transport mechanisms.- In: B.F. MOLNIA (ed), Glacial-marine sedimentation, New York, London: Plenum Press, 301-330.

Clark, D.L., Whitman, R.R., Morgan, K.A. & Mackey, S.D. (1980): Stratigraphy and glacial-marine sediments of the Amerasian Basin, Central Arctic Ocean.- Geol. Soc. Amer. Spec. Pap. 181: 1-57.

Clark, D.L., Chern, L.A., Hogler, J.A., Mennicke, C.M. & Atkins, E.D. (1990): Late Neogene climate evolution of the Central Arctic Ocean.- Mar. Geol. 93: 69-94.

Darby, D.A., Naidu, A.S., Mowatt, T.C. & Jones, G. (1989): Sediment composition and sedimentary processes in the Arctic Ocean.- In: Y. HERMAN (ed), The Arctic Seas: Climatology, Oceanography, Geology, and Biology, Van Nostrand Reinhold Company, New York, 657-720.

Dowdeswell, J.A., Whittington, R.J. & Marienfeld, P. (1994): The origin of massive diamicton facies by iceberg rafting and scouring, Scoresby Sund, East Greenland.- Sedimentol. 41: 21-35.

Ericson, D.B., Ewing, M. & Wollin, G. (1964): Sediment cores from the Arctic and Subarctic Seas.- Science 144: 1183-1192.

Evans, J., Dowdeswell, J.A., Grobe, H., Niesen, F., Stein, R., Hubberten, H.-W. & Whittington, R.J. (2002): Late Quaternary sedimentation in Kejser Franz Josef Fjord and the continental margin of East Greenland.- In: J.A. DOWDESWELL & C. Ó COFAIGH (eds), Glacier-influenced sedimentation on high-latitude continental margins.- Geol. Soc. London, Spec. Publ. xxx: 149-179.

Eyles, N., Eyles, C.H. & Miall, A.D. (1983): Lithofacies types and vertical profile models: an alternative approach to the description and environmental interpretation of glacial diamict and diamictite sequences.-Sedimentol. 30: 393-410.

Grobe, H. (1987): A simple method for determination of ice rafted debris in sediment cores.- Polarforschung 57: 123-126.

Hein, F.J., van Wagoner, N.A. & Mudie, P.J. (1990): Sedimentary facies and processes of deposition: Ice Island cores, Axel Heiberg Shelf, Canadian Polar Continental Margin.- Mar. Geol. 93: 243-265.

Henrich, R., Kassens, H., Vogelsang, E. & Thiede, J. (1989): Sedimentary facies of glacial-interglacial cycles in the Norwegian Sea during the last 350 ka.- Mar. Geol. 86: 283-319.

Howe, J.A., Shimmield, T.M., Harland, R. & Eyles, N. (2008): Late Quaternary contourites and glaciomarine sedimentation in the Fram Strait.- Sedimentol. 55: 179-200.

Hunkins, K., Bé, A.W.H., Opdyke, N.D. & Mathieu, G. (1971): The Late Cenozoic history of the Arctic Ocean.- Flint Symposium Vol., Yale University Press, New Haven, 215-237.

Ishman, S.E., Polyak, L.V. & Poore, R.Z. (1996): Expanded record of Quaternary oceanographic change: Amerasian Arctic Ocean.- Geology 24: 139-142.

Jakobsson, M., Cherkis,N., Woodward, J., Coakley, B. & Macnab, R. (2000a): A new grid of Arctic bathymetry: A significant resource for scientists and mapmakers.- EOS Transact. Amer. Geophys. Union 81: 89, 93, 96.

Jakobsson, M., Løvlie, R., Al-Hanbali, H., Arnold, E., Backman, J. & Mörth, M. (2000b): Manganese and color cycles in Arctic Ocean sediments constrain Pleistocene chronology.- Geology 28: 23-26.

Jakobsson, M., Løvlie, R., Arnold, E.M., Backman, J., Polyak, L., Knutsen, J.-O. & Musatov, E. (2001): Pleistocene stratigraphy and paleoenvironmental variation from Lomonosov Ridge sediments, central Arctic Ocean.- Global Planet. Change 31: 1-22.

Jokat, W. (ed) (2009): The Expedition of the Research Vessel "Polarstern" to the Arctic in 2008 (ARK-XXIII/3).- Ber. Polar Meeresforsch. 597, 1-222.

Knies, J., Nowacyk, N., Müller, C., Vogt, C. & Stein, R. (2000): A multiproxy approach to reconstruct the environmental changes along the Eurasian continental margin over the last 150000 years.- Mar. Geol. 163: 317-344.

Krylov, A. (2009): Results of smear-slide analysis.- In: W. JOKAT (ed), The Expedition of the Research Vessel "Polarstern" to the Arctic in 2008 (ARK-XXIII/3), Ber. Polar Meeresforsch. 597: 47-53.

Matthiessen, J., Naafs, B., Bazhenova, E., März, C., Not, C. & Schreck, M. (2009): X-Ray photography: Sediment structures and IRD content.- In: W. JOKAT (ed), The Expedition of the Research Vessel "Polarstern" to the Arctic in 2008 (ARK-XXIII/3), Ber. Polar Meeresforsch. 597: 44-47.

Naafs, B., Poggeman, D., Müller, J. & Bazhenova, E. (2009): Shear strength measurements.- In: W. JOKAT (ed), The Expedition of the Research Vessel "Polarstern" to the Arctic in 2008 (ARK-XXIII/3), Ber. Polar Meeresforsch. 597: 29-30.

Minicucci, D.A. & Clark, D.L. (1983): A late Cenozoic stratigraphy for glacial-marine sediments of the eastern Alpha Cordillera, Central Arctic Ocean.- In: B.F. MOLNIA (ed), Glacial-marine sedimentation, Plenum Press, New York, London, 331-365.

Moran, K., Backman, J., Brinkhuis, H., Clemens, S.C., Cronin, T., Dickens, G.R., Eynaud, F., Gattacceca, J., Jakobsson, M., Jordan, R.W., Kaminski, M., King, J., Koc, N., Krylov, A., Martinez, N., Matthiessen, J., McInroy, D., Moore, T.C., Onodera, J., O'Regan, M., Pälike, H., Rea, B., Rio, D., Sakamoto, T., Smith, D.C., Stein, R., St John, K., Suto, I., Suzuki, N., Takahashi, K., Watanabe, M., Yamamoto, M., Farrell, J., Frank, M., Kubik, P., Jokat, W. & Kristoffersen, Y. (2006): The Cenozoic palaeoenvironment of the Arctic Ocean.- Nature 441: 601-605.

Morris, T.H. & Clark, D.L. (1986): Pleistocene calcite lysocline and paleocurrents of the Central Arctic Ocean and their paleoclimatic significance.- Paleoceanography 1: 181-195.

Mudie, P.J. & Blasco, S.M. (1985): Lithostratigraphy of the Cesar cores.- In: H.R. JACKSON, P.J. MUDIE & S.M. BLASCO (eds), Initial geological report on CESAR - the Canadian expedition to study the Alpha Ridge, Arctic Ocean, Geol. Surv. Canada Paper, 59-99.

Nam, S.-I. (2009): Results of coarse fraction analysis.- In: W. JOKAT (ed), The Expedition of the Research Vessel "Polarstern" to the Arctic in 2008 (ARK-XXIII/3), Ber. Polar Meeresforsch. 597: 53-60.

Niessen, F., Poggemann, D., & Schulte-Loh, I. (2009): Multi-sensor core logging.- In: W. JOKAT (ed), The Expedition of the Research Vessel "Polarstern" to the Arctic in 2008 (ARK-XXIII/3), Ber. Polar Meeresforsch. 597: 23-26.

Nørgaard-Pedersen, N., Spielhagen, R.F., Thiede, J. & Kassens, H. (1998): Central Arctic surface ocean environment during the past 80,000 years.- Paleoceanography 13: 193-204.

Nørgaard-Pedersen, N., Mikkelsen, N. & Kristoffersen, Y. (2007a): Arctic Ocean record of last two glacial-interglacial cycles off North Greenland /Ellesmere Island – Implications for glacial history.- Mar. Geol. 244: 93-108.

Nørgaard-Pedersen, N., Mikkelsen, N., Lassen, S.J., Kristoffersen, Y. & Sheldon, E. (2007b): Reduced sea ice concentrations in the Arctic Ocean during the last interglacial period revealed by sediment cores off northern Greenland.- Paleoceanography 22: No. 1, PA1218.

ÓCofaigh, C. & Dowdeswell, J.A. (2001): Laminated sediments in glacimarine environments: diagnostic criteria for their interpretation.- Quat. Sci. Rev. 20: 1411-1436.

ÓCofaigh, C., Dowdeswell, J.A. & Grobe, H. (2001): Holocene glacimarine sedimentation, inner Scoresby Sund, East Greenland: the influence of fast-flowing ice-sheet outlet glaciers.- Mar. Geol. 175: 103-129.

O'Regan, M., King, J., Backman, J., Jakobsson, M., Pälike, H., Moran, K., Heil, C., Sakamoto, T., Cronin, T.M. & Jordan, R.W. (2008): Constraints on the Pleistocene chronology of sediments from the Lomonosov Ridge.- Paleoceanography xx, doi: 10.1029/2007PA001551

O'Regan, M., St. John, K., Moran, K., Backman, J., King, J., Haley, B., Jakobsson, M., Frank, M. & Röhl, U. (in press): Plio- Pleistocene trends in ice rafted debris on the Lomonosov Ridge.- Quat. Internat., doi:10.1016/j.quaint.2009.08.010.

Phillips, R.L. & Grantz, A. (1997): Quaternary history of sea ice and paleoclimate in the Amerasia Basin, Arctic Ocean, as recorded in the cyclical strata of Northwind Ridge.- Geol. Soc. Amer. Bull. 109: 1101-1115.

Phillips, R.L. & Grantz, A. (2001): Regional variations in provenance and abundance of ice-rafted clasts in Arctic Ocean sediments: implications for the configuration of late Quaternary oceanic and atmospheric circulation in the Arctic.- Mar. Geol. 172: 91-115.

Polyak, L., Curry, W.B., Darby, D.A., Bischof, J. & Cronin, T.M. (2004): Contrasting glacial/interglacial regimes in the western Arctic Ocean as exemplified by a sedimentary record from the Mendeleev Ridge.- Palaeo-

geogr. Palaeoclimatol. Palaeoecol. 203: 73-93.
Polyak, L., Bischof, J., Ortiz, J.D., Darby, D.A., Channell, J.E.T., Xuan, C., Kaufman, D.S., Løvlie, R., Schneider, D.A., Eberl, D.D., Adler, R.E. & Council, E.A. (2009): Late Quaternary stratigraphy and sedimentation patterns in the western Arctic Ocean.- Global Planet. Change 68: 5-17.
Poore, R.Z., Phillips, R.L. & Rieck, H.J. (1993): Paleoclimatic record for Northwind Ridge, western Arctic Ocean.- Paleoceanography 8: 149-159.
Poore, R.Z., Osterman, L., Curry, W.B. & Phillips, R.L. (1999): Late Pleistocene and Holocene meltwater events in the western Arctic Ocean.- Geology 27: 759-762.
Scott, D.B., Mudie, P.J., Baki, V., MacKinnon, K.E. & Cole, F.E. (1989): Biostratigraphy and late Cenozoic paleoceanography of the Arctic Ocean: foraminiferal, lithostratigraphic, and isotopic evidence.- Geol. Soc. Amer. Bull. 101: 260-277.
Sellén, E., Jakobsson, M. & Backman, J. (2008): Sedimentary regimes in Arctic's Amerasian and Eurasian Basins: Clues to differences in sedimentation rates.- Global Planet. Change 61: 275-284.
Spielhagen, R.F., Bonani, G., Eisenhauer, A., Frank, M., Frederichs, T., Kassens, H., Kubik, P.W., Mangini, A., Nørgaard-Pedersen, N., Nowaczyk, N.R., Schäper, S., Stein, R., Thiede, J., Tiedemann, R. & Wahsner, M. (1997): Arctic Ocean evidence for late Quaternary initiation of northern Eurasian ice sheets.- Geology 25: 783-786.
Spielhagen, R.F., Baumann, K.-H., Erlenkeuser, H., Nowaczyk, N.R., Nørgaard-Pedersen, N., Vogt, C. & Weiel, D. (2004): Arctic Ocean deep-sea record of northern Eurasian ice sheet history.- Quat. Sci. Rev. 23: 1455-1483.
St. John, K. (2008): Cenozoic ice-rafting history of the Central Arctic Ocean: Terrigenous sands on the Lomonosov Ridge.- Paleoceanography 23: PA1S05, doi:10.1029/2007PA001483.
Stein, R., Krylov, A., Matthiessen, J., Nam, S., Niessen, F & the ARKXXIII/3 Geoscientific Party 2009: Main lithologies and lithostratigraphy of ARK-XXIII/3 sediment cores.- In: W. JOKAT (ed), The Expedition of the Research Vessel "Polarstern" to the Arctic in 2008 (ARK-XXIII/3), Ber. Polar-Meeresforsch. 597: 61-72.
Stein, R., Matthiessen, J. & Niessen, F. (2010a): Re-coring at Ice Island T3 site of key core FL-224 (Nautilus Basin, Amerasian Arctic).- Polarforschung 79: 81-96.
Stein, R., Matthiessen, J., Niessen, F., Krylov, R., Nam, S.-l & Bazshenova, E. (2010b): Towards a better (litho-)stratigraphy and reconstruction of Quaternary paleoenvironment in the Amerasian Basin (Arctic Ocean).- Polarforschung 79: 97-121,
Svindland, K.T. & Vorren, T.O. (2002): Late Cenozoic sedimentary environments in the Amundsen Basin, Arctic Ocean.- Mar. Geol. 186: 541-555.
Vorren, T.O., Hald, M. & Thomson, E. (1984): Quaternary sediments and environments on the continental shelf off northern Norway.- Mar. Geol. 57: 229-257.