Contrasting sub-ice shelf, sub glacial and glacial marine deposition: Implications for ice shelf stability

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Summary Data from cores collected from sites that were beneath the Ross Ice Shelf until 2000 and 2002 indicate that sub-ice shelf lithofacies are distinguishable from sub-glacial and glacial marine facies. Glacial marine sediment is characterized by diatom-rich, low-density, olive-green, sandy-muds, whereas sub-ice shelf sediment is defined by a lack of diatoms and muds that are enriched in silt and fine sand. Sub-glacial sediment is composed of diatom-poor, high density, coarse grained sandy-mud, rich in fine to coarse sized pebbles. Repetitive, fining-up packages, composed of fine-sand/silty-mud (distal sub ice-shelf deposits), grading into coarse pebbly-mud (sub ice-shelf proximal to the grounding line), suggest cyclicity in the movement of the grounding line over the last 11,000 yrs in the eastern Ross Sea. This research may facilitate a new understanding of ice-shelf dynamics, and possibly refine the current models for the Ross Ice Shelf's recent glacial history.

Introduction

Throughout its 40 million year history, Antarctic ice sheets have played an integral role in regulating the Earth's climate. Antarctica comprises ninety percent of the Earth's ice volume (Denton et al., 1991), thus, cyclic melting has a significant effect on global eustasy, thermohaline circulation (Anderson, 1999), and atmospheric circulation (Mullan and Hickman, 1990). Furthermore, this isolated continent presents a unique opportunity to study glacial and glaciomarine sedimentation and to use our knowledge of facies associations to further understand the climatic and glacial record in Antarctica. The continental shelf beneath the Ross Sea holds much of the sedimentological evidence of the East and West Antarctic ice sheet's distinct behaviors since the Mid-Late Eocene (Hambrey and Barrett, 1993). Thirty percent of the continent's drainage is confined to the Ross Sea (Anderson et al., 1984) (Figure 1), where both the wet-based West Antarctic ice sheet, and terrestrial East Antarctic Ice sheets drain, depositing terrigenous sediment across the shelf (Anderson,1999). This juxtaposition of two very different glacial regimes and their corresponding erosional and depositional features makes the Ross Sea an ideal location for the research and comparison of glacial and glaciomarine deposits.
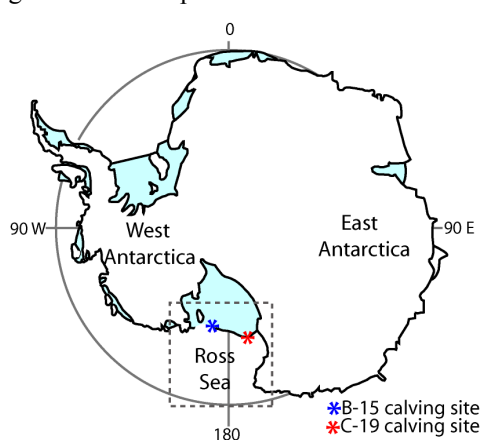

Figure 1. Location Map, indicating location of B-15 and C-19 calving events. Study location denoted by dashed box.

Numerous studies (Hambrey and Barrett, 1993; Anderson et al., 1984; Jacobs,1989; Hambrey et al., 2002; Shipp et al., 1999) have focused on sediments recovered from coring or drilling on Antarctica's continental shelf, from which researchers have used aspects of the current glaciomarine models (Anderson et al., 1983b; Elverhoi, 1984; Domack, 1988; Kellogg and Kellogg, 1988) and the character of sedimentological deposits in conjunction with radiocarbon, biostratigraphic, and paleomagnetic dating methods to make inferences about the timing of glacial advance and retreat in the Ross Sea. Despite recent acquisition of longer and more complete drill cores and higher resolution seismic data, much about glacial marine sedimentation remains poorly understood, because some of the environments in which sedimentation occurs are inaccessible and/or perpetually evolving. Although drilling in the Ross Sea has provided an extensive glacial record, the recent (Holocene) behavior of the West and East Antarctic ice sheet is relatively unconstrained. The key to interpreting this recent behavior may involve exploring variations in sub-ice shelf sediments, which are often difficult to identify and distinguish from glaciomarine sediment.

On board the R/V Nathaniel Palmer, during research cruises NBP03-01 and NBP03-06, an opportunity to collect sediment cores from a sub ice-shelf location (Figure 2) was presented as a result of the B-15 and C-19 calving events in March of 2000 and May 2002 respectively. Approximately 37 kilometers (11,000 km^2) of previously sub ice-shelf continental shelf became exposed and accessible as a consequence of B-15's separation from the Ross ice shelf. The sediment recovered from these regions accumulated within a sub-ice shelf environment prior to these calving events. Thus examination and interpretation of these facies, utilizing both the cores and seismic data from the Ross Sea, will

help refine existing glaciomarine depositional models, and improve our ability to reconstruct the climatic and glacial history in this region during the Holocene, the implications of which are quite provocative. The objective of this research is therefore to test the validity of the established links between facies and depositional environment by: (1) test the hypothesis that sub-ice shelf lithofacies should have characteristics that distinguish them from sub-glacial and glaciomarine facies. and furthermore, (2) testing the hypothesis that there is a cyclicity associated with the movement of the West and East Antarctic ice sheets in the Ross Sea during the Holocene.

Examination of lithofacies successions within the NBP03-06 cores, which are hypothesized to record deposition by the ice sheets as their positions changed over time should provide the means to test these ideas. These facies can be compared to glaciomarine and sub-glacial facies in cores from the Ross Sea to determine whether sub-ice shelf environments in the Ross Sea do indeed produce a distinctive lithofacies that can be used in paleoenvironmental reconstructions.
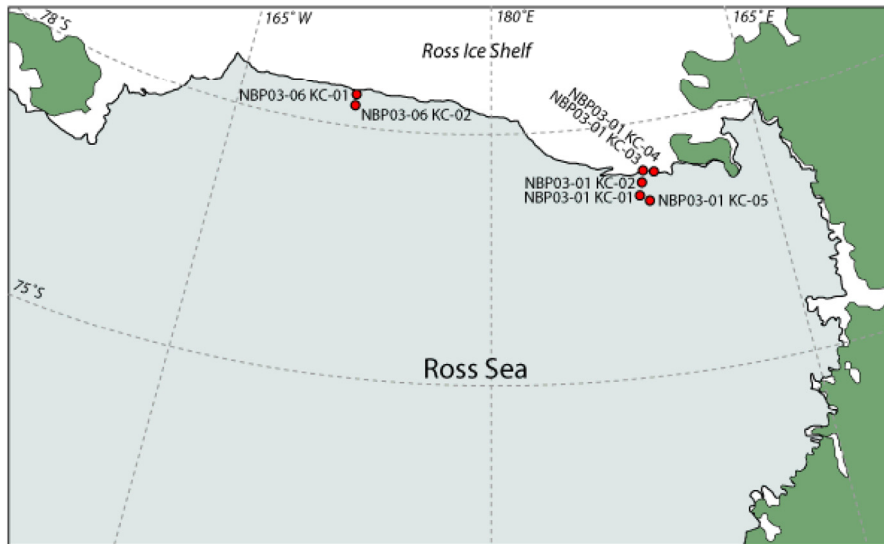

Figure 2. Ross Sea, Antarctica and location of NBP03-01 and NBP03-06 cores.

Repetitive stacking of lithofacies within the NBP03-01 and 06 cores suggest that there may be a cyclicity in the Ross ice shelf's dynamics. Close examination of the characteristics of these "cyclic" successions in the core provides the opportunity to test the hypotheses related to cyclic behavior in the expansion and contraction of the Ross Ice Shelf during the Holocene. Data from these cores may indicate that the ice shelf's equilibrium position is the present location of the ice shelf edge, and that the location prior to the calving events was anomalous. In addition, the deposits from beneath the ice shelf may also reveal that climatic forcing causes frequent calving events in order to draw the ice shelf back to its equilibrium position. Evidence of shorter time-scale cyclicity would manifest itself as coarsening up sequences containing diatomaceous mud grading up into mud with increasingly higher ice rafted debris content until a sharp boundary is reached and sediment composition shifts again to fine diatomaceous mud etc.. Four mechanisms involving changes in autogenic glacial processes or changes in environmental conditions are hypothesized to be responsible for creating such facies successions.

1. A gradational increase in coarse, variable size ice rafted debris (IRD) would be evident in facies if the grounding line approached the core site over time.
2. A second interpretation of the variation in IRD can be attributed to a variation in the rate at which the ice sheet is flowing. With the grounding line stationary, the ice sheet may periodically "surge", therefore allowing ice to transport coarse debris, which would normally be melted out close to the grounding line, to a more distal location. Surges can last for 1-2 years (Paterson, 1981), and are characterized by rapid advancement of the glacial front (Solheim and Pfirman, 1985). Alternatively, it is possible that surges are due to changes in autogenic glacial processes. It is possible that as a result of faster ice movement, brittle deformation supplants normal plastic deformation, causing large cracks to form within the ice sheet. Consequently, when icebergs break away, they may be inherently larger due to the cracks, and may leave the ice shelf edge farther back after calving. This may indicate that the normal location of the shelf edge is at its current position, as opposed to the down dip location prior to the B-15 and C-19 calving events.
3. A third hypothesis involves fluctuations in the thermal conditions at the base of the ice shelf due to changes in circulation in the Ross Sea and variation in water temperature. In this situation, the grounding line would again remain stationary and the flow rate would remain constant as well. In a situation such as this, there may be temporal changes in the amount of subglacial material that reaches the core site as a result of different melt out rates.
4. An interaction of the above mechanisms may also be responsible for the cyclic changes in facies. If the grounding line were advancing, the ice surging while deep water temperature changes occurred, or some combination therein, the facies could possibly exhibit the same coarsening up signal. All of the mechanisms (g.l. advance, glacial surge, shift in thermal conditions) should first be individually discounted in order to consider a combination of them as responsible for the facies changes.

Methods

Cores from NBP03-01 and NBP03-06 were described in detail according to color, texture, and compositional variations. X-radiographs were examined for textural (grain size and grain shape) variations, and sedimentary structures. Smear slides taken from 2-5cm intervals within the cores are being analyzed using a BX40 Olympus microscope for petrological composition of the sediments, and for preliminary "quick and dirty" diatom analyses (bulk content and fragmentation). Magnetic susceptibility, bulk density and resistivity were measured utilizing the GEOTEK Multi sensor core logger at Florida State's Antarctic Research Facility in Tallahassee, Florida.

Grain size analysis will be preformed in the coming months on bag samples taken from 5 cm intervals in selected cores. In addition, radiocarbon dates will be obtained from observable facies boundaries demarcating changes in environment (sub-ice shelf/ sub glacial), in order to determine sedimentation rates under the ice shelf, and determine over what time-scale the variations (potentially ice sheet movement) occur.

In order to view the depositional environments in a broader context, Multibeam and CHIRP high resolution 2-D SCS data collected onboard the R/V Nathaniel Palmer were examined. Both single-channel and multi-channel data were collected and provide a larger scale understanding of the complex history of Ross Sea stratigraphy.
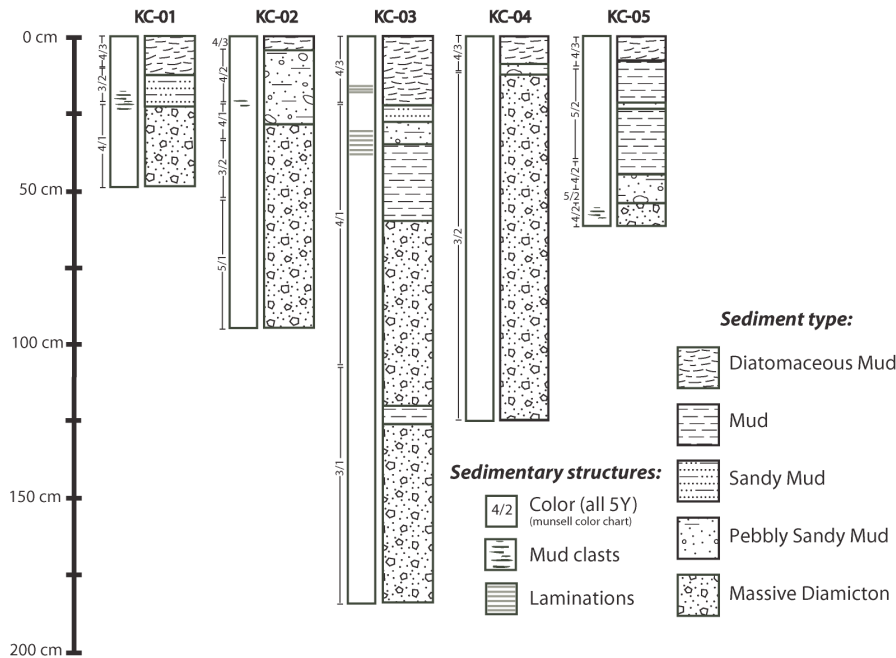

Figure 3a. Initial sedimentological interpretation of NBP03-01 cores (Western Ross Sea)

Figure 3b. Initial facies interpretation of NBP03-01 cores (Western Ross Sea)

Preliminary results

Kasten cores from cruise NBP03-01 were collected in the Western Ross Sea (East Antarctica) in a transect designed to span glacial marine, proximal glacial marine, and sub-ice shelf environments prior to the calving event. *KC-01* and *KC-05*, were collected 10km apart, (but essentially equidistant from the 2002 ice shelf edge) in what was an open marine area prior to the calving event. These cores contain approximately 10-15cm of diatomaceous mud (Figure 3a), and fine-grained sandy-mud beneath, defined by their lack of diatoms and relatively low density. In comparison to *KC-01*, *KC-05* exhibits a thicker accumulation of fine-grained mud, like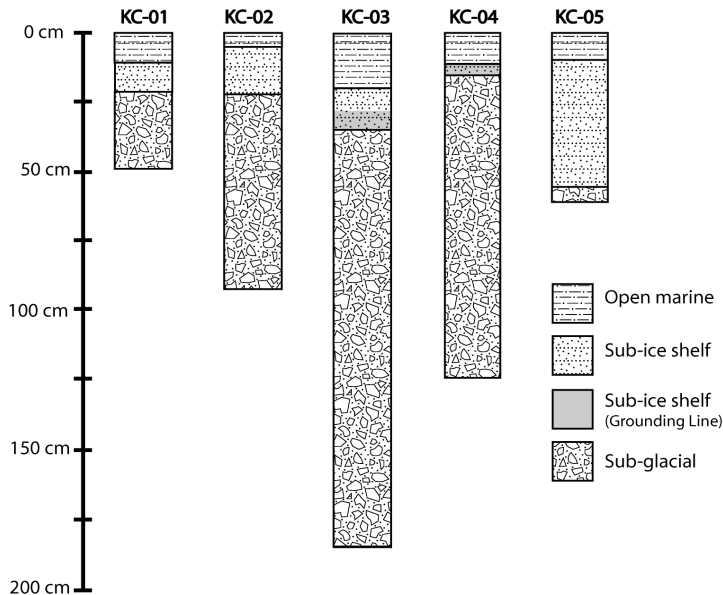ly a result of the trough in which this core site was located (allowing for accumulation of fines, and protection from current winnowing). Beneath the mud layers in *KC-01* and *KC-05* there is a distinct density, color, and compositional contrast below which is a dark grey med-coarse pebble rich mud (diamicton).

NBP03-01 KC-02 was recovered from a site located at, or near the ice-shelf edge until 2002. The surface sediments are composed of olive-green diatomaceous mud, below which is a relatively low density unit with low diatom content, and very fine to fine subrounded pebble content (Figure 3a). The sediment below 30 cm undergoes a sharp increase in density and coarse pebbles which show a distinct orientation perpendicular to the length of the core.

Cores *NBP03-01 KC-03* and *NBP03-01 KC-04* were collected from a location that was beneath the East Antarctic Ice Sheet in 2002,

prior to the C-19 calving event. Core locations were approximately 15 kilometers apart, with recovery depths differing by 26 meters. Therefore, variations in the presence and thickness of stratigraphic units exist between the two cores (Figure 3a). *KC-03* and *KC-04* surface sediments are composed of olive green, diatom rich sediment, although the thicknesses of the units vary between the cores. *KC-03* contains a distinct color and compositional change at 24 cm, which corresponds to a dramatic decline in diatom abundance. The sediment below increases in sand and pebble content with depth, until a sharp contact with a very fine grained mud unit, and another at 60 cm with a high density diamicton. The rest of *KC-04* is composed of small package of sand/fine pebble rich mud, with a low diatom content and relatively low bulk density and a thick diamicton unit beneath.

In addition to the five western Ross Sea cores, two kasten cores (*NBP03-06 KC-01* and *NBP03-06 KC-02*) were collected in the Eastern Ross Sea, adjacent to the ice- shelf edge of the West Antarctic Ice Sheet. *NBP03-06 KC-02* was collected from an open marine setting (both currently, and prior to B-15 calving event in 2000), whereas *NBP03-06 KC-1* was located in a sub-ice shelf environment until 2000 (open marine today).
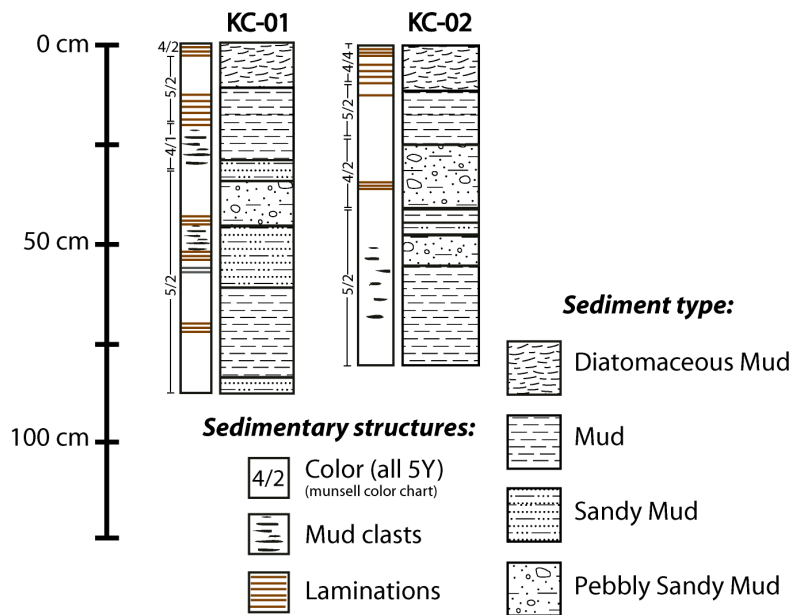

Figure 4a. Initial sedimentological interpretations of NBP03-06 cores (Eastern Ross Sea)
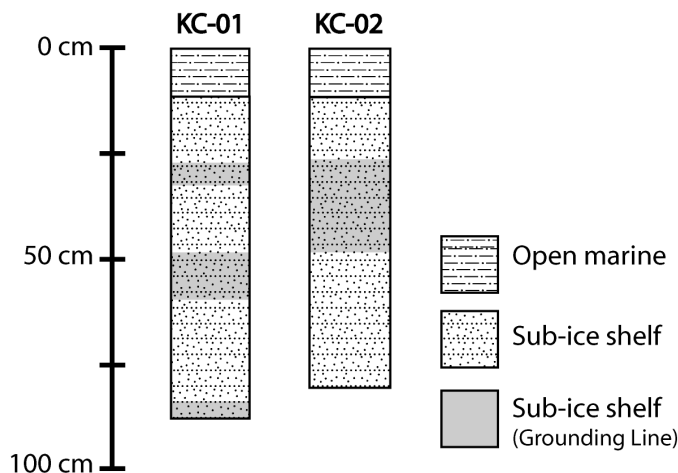

Figure 4b. Initial facies interpretation of NBP03-06 cores (Eastern Ross Sea)

As seen in Figure 4a, the first 30 cm of cores *NBP03-06 KC-01* and *KC-02* are similar in that they contain equal amounts of diatomaceous mud and a contact with fine mud at 12 cm. In *KC-01*, the interval below this contact is characterized by three distinct fining up sequences consisting of sand and fine pebble rich sediment grading into mud. Beneath the diatomaceous mud in *NBP03-06 KC-02*, a similar sequence is present. Within this sequence, the composition of the sediment changes from fine, to coarse, sandy mud, to fine mud again.

Discussion

A layer of sediment located at the surface of each NBP03-01 and NBP03-06 core and characterized by variable thickness (dependent on current strength, bottom topography, etc.), a high diatom content, olive-green color, and low density (Figures 3b & 4b) is interpreted as a glaciomarine facies. Beneath the glacial marine muds is, in each core, a sharp boundary, in terms of diatom content. Deposits with low/no diatom occurrence, composed of silt and fine sand-rich muds, with or without pebbles are interpreted as sub-ice shelf facies (distal from the grounding line). Most of these facies are associated with the fine-scale laminations and mud clasts seen in the cores, as well as low/medium bulk density values (relative to other sediment present), and are often an olive grey/grey color (5Y 4/3 4/2). Units composed of high percentages of fine-coarse sand and pebbles, low bulk density, and low/no diatom content are interpreted as sub-ice shelf deposits, associated with grounding line proximal locations. However, distinguishing these facies from subglacial tills is difficult at this stage of research. In general, coarse-grained sandy muds with very high fine-coarse pebble content, in conjunction with high bulk density, dark grey color, and low/no diatoms are considered subglacial diamictons. These preliminary findings indicate that classifications of sub-ice shelf deposits developed here, using NBP03-01 and NBP03-06 cores, are consistent with, and therefore support interpretations of the presence of sub-ice shelf lithofacies in the cores studied by Domack and Harris (1998), and

Domack et al., (1999). Further research, including grain-size analysis, will determine the extent of the correlation. This research does provide evidence of consistently thicker accumulations of sub-ice shelf deposits on the shelf, relative to those observed by Domack and Harris (1998) and Domack et al., (1999).

The preliminary environmental interpretations of NBP03-01 and NBP03-06 cores based on these (Figures 3b, 4b) observations suggest that the West and East Antarctic Ice Sheets have not behaved synchronously in the recent geologic past, to the extent that it is possible to use ice shelf dynamics as a barometer of ice sheet expansion and contraction. It appears that the cores from the Western Ross Sea (*NBP03-01*) indicate a general retreating trend, excluding *KC-03;* the fine-coarse-fine sequence between ~25 and 60 cm may indicate localized movement of the grounding line. If the multiple sequences of fine mud grading to fine-sand/silty mud grading to coarse sandy/pebbly mud visible in *NBP03-06 KC-01* are in fact related to grounding line migration, it follows that the West Antarctic Ice Sheet experiences more frequent advance/retreat cycles, possibly as a result of it's rheology. In order to determine that these facies changes do not represent localized sedimentary changes, but the widespread movement of depositional regimes across the core location, cores from cruises NBP99-02 and NBP94-07 (collected down dip, farther out on the continental shelf) near the NBP03-06 site were examined. Four of the six closest available cores (*NBP99-02 TC/PC-04 & TC-06, NBP94-07 TC-64 & TC-67*) exhibit a transition between fine mud, and fine-grained sandy/silty grayish sediment at approximately 30cm depth. This is the same depth at which NBP03-06 KC-01 and KC-02 transition into a coarser grained sediment that is interpreted as a proximal sub-ice shelf unit. This implies that what is interpreted in the NBP03-06 cores as a grounding line advance and retreat cycle, is evident close to the ice shelf edge as well as farther out on the continental shelf. Mapping by Keys et al. (1998), indicates that the ice shelf edge has expanded northward since the early 1900s. Furthermore, preliminary interpretations of seismic data from this area (Eastern Ross Sea), as well as Multibeam swath bathymetry records from NBP99-02 reviewed in Mosola and Anderson, (2006) demonstrate evidence of the ice sheet grounding near the core sites.

More data is required to test the validity of these interpretations and to determine whether the other mechanisms discussed previously are responsible for these facies variations. Radiocarbon dates will help distinguish when facies transitions from glaciomarine to sub-ice shelf occur, and whether sandy units from NBP03-06, NBP99-02 and NBP94-07 cores represent the same events. In addition, detailed grain-size analyses and analyses of the variation in composition of bulk diatom assemblages will help eliminate the other possible mechanisms, and ultimately permit an assessment of the processes responsible for the genesis of these deposits.

Summary

Cores from research cruises NBP03-01 and NBP03-06 contain facies that indicate that in the Ross Sea, sub-ice shelf facies are distinctive from sub-glacial and glaciomarine facies. Facies successions within these cores suggest that there is a cyclicity associated with the movement of the West and East Antarctic ice sheets during the Holocene.

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