Establishing chronologies from acid-insoluble organic ^{14}C dates on antarctic (Ross Sea) and arctic (North Atlantic) marine sediments

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To compare north and south polar marine paleoenvironments over the last 30,000 years, comparable chronological (radiocarbon) records must be developed and refined. Many areas in the polar regions do not preserve marine carbonates (foraminifera, mollusks), and thus age determinations, of necessity, are based on the acid-insoluble organic (AIO) fraction of the sediment. Although AIO ages are problematic and rarely used in the Arctic, they provide reasonable and consistent chronologies for the Ross Sea, Antarctica. AIO dates are meaningful in the Ross Sea because there are relatively high levels of productivity, good preservation of marine biogenic material in the sediment, and little input of terrigenous sediment and old/dead carbon. Event stratigraphy based upon proxy records of biogenic silica and δ^{13}C can be used to assess the reliability of the AIO dates and surface age corrections. Reconstructed time-series of changes in the biogenic silica content of cores from the western Ross Sea show apparent similarities with the 'classic' deglacial climate sequence of the northern North Atlantic. Once the absolute ages of the antarctic AIO dates are constrained by independently dated records to validate surface age corrections, it will be possible to directly compare the timing of events such as ice-rafting events in the sedimentary record.

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Introduction

In both the arctic and antarctic marine environments (Fig. 1), our knowledge of changes in ice extent, chronology of events, and ice sheet/ocean interactions has increased significantly over the last few years. This is in part due to an increase in spatial coverage of sites in both polar regions but also to a large extent due to our improved ability to date late Quaternary sedimentary records by means of AMS ^{14}C dating. Notwithstanding the impressive increase in our database, the fact remains that for a variety of reasons, well-dated high-resolution records in the Antarctic (i.e. records with resolutions of decades to centuries) are limited when compared to the arctic marginal seas (e.g. Andrews et al. 1996). There are, of course, exceptions (Domack et al. 1993; Leventer et al. 1996), but these are rare and most records from the antarctic margin face the problem of establishing a reliable radiocarbon chronology. This issue becomes critical when we attempt to compare the marine proxy data with that from the terrestrial realm (e.g. Ingólfsson et al. 1998).

The purpose of this paper is to evaluate the significance of acid-insoluble organic (AIO) and carbonate dates at sites in both polar regions; we will briefly discuss attempts to use AIO dates in the Arctic and then discuss in more depth the problems of dating the carbonate-poor Ross Sea marginal marine sediments. We also discuss proxy records, such as biogenic silica and δ^{13}C, which can be used to evaluate the validity of core-specific age corrections for AIO dates through event correlation. Finally, we highlight the importance of obtaining reliable absolute ages to evaluate the synchronicity of events, such as ice-rafting events, in the geologic record.

Relative timing of events in both polar areas is a critical issue (Bender et al. 1994; Sowers & Bender 1995); it is important to note that insolation changes at 65° latitude in both hemispheres are not identical (Fig. 6). Besides insolation changes, sea level variations must also be considered as a forcing function for ice sheet changes. Although Antarctica's glacial history is frequently argued to be coupled to eustatic sea level, actual relative sea level change at the ice
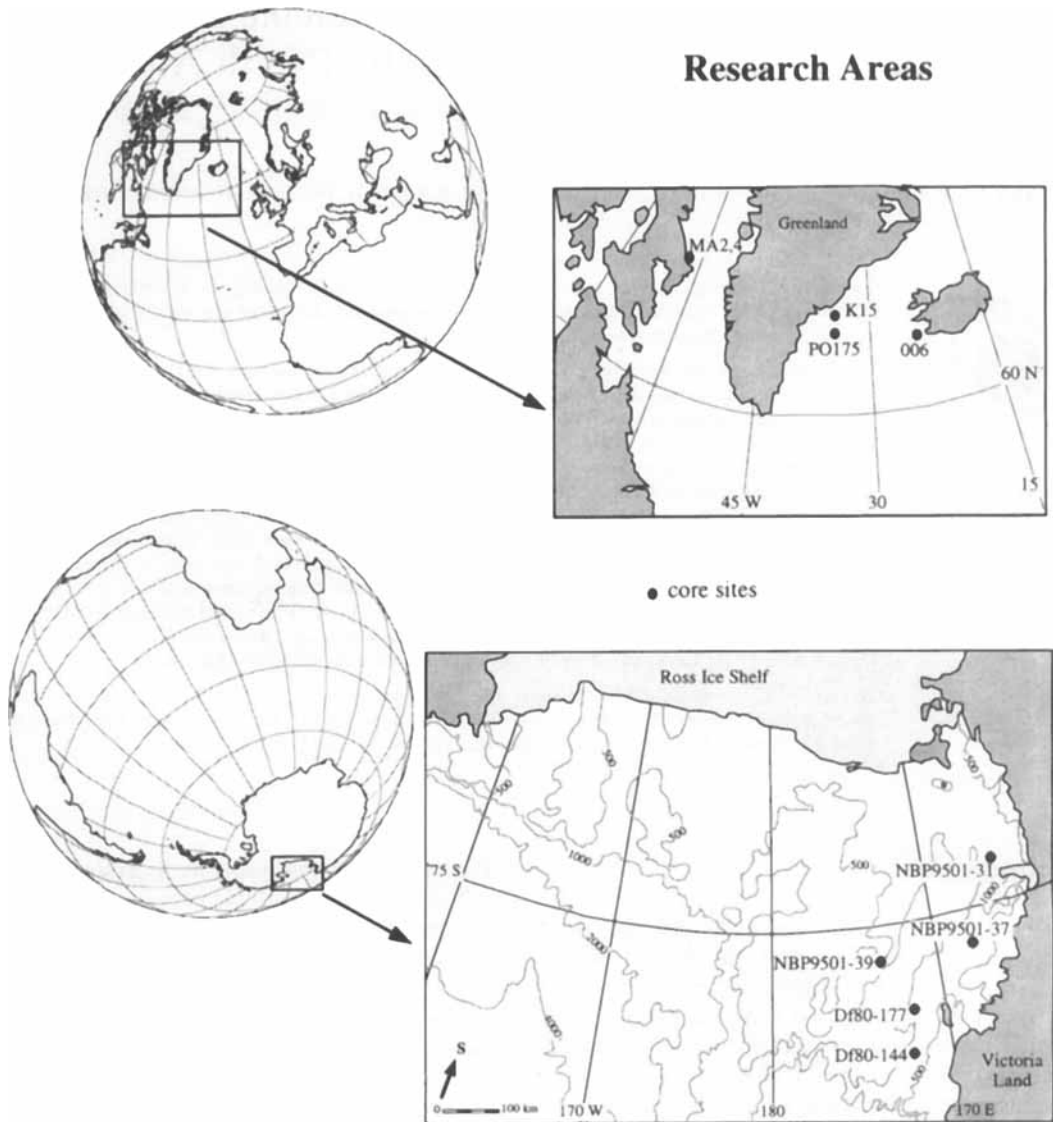
Fig. 1. Locations of our major research areas along with core sites discussed in the text in the Denmark Strait, Labrador Sea, and the Ross Sea, Antarctica.

margin is complicated by isostatic depression and recovery (Thomas & Bentley 1978) such that true changes in water depth at a grounding line may be out of phase with trends in global sea level. Given these out-of-phase forcing functions, marine sedimentary records with comparable chronological resolution must be developed to assess the temporal relationship between events observed at high latitudes. Although we tend to view the polar regions as being physically distinct, several papers have pointed to a connection between the two

regions through thermohaline circulation of the ocean (e.g. Broecker & Denton 1989). North Atlantic Deep Water (NADW) is produced in the general vicinity of Iceland and upwells in the southern oceans, whereas Antarctic Bottom Water (AABW) produced off the area of the Weddell Sea moves northward to underlie NADW in the sub-tropical North Atlantic. Changes in the flux of heat and salt in this conveyor might be linked across the equator to changes in polar oceanographic conditions and may impact ice sheet

histories. Broecker (1998) commented on these linkages and noted that the projected heat release from the Southern Ocean was out of phase with the North Atlantic. Conversely, Steig et al. (1998) find that changes in the Taylor Dome ice core occur almost simultaneously with the GISP2 record and conclude that variations in NADW production directly affect Circumpolar Deep Water temperatures in the Ross Sea. We and other research groups are actively working to understand antarctic ^{14}C dating complexities and to reduce the errors associated with the marine record so that meaningful comparisons may be made between arctic and antarctic terrestrial and marine sedimentary sequences.

Radiocarbon dating, arctic versus antarctic marine sediments

Investigating the paleoceanography of the last 30,000 yrs in polar regions requires the development of well-constrained depth/age relationships for sediment cores. The reliability and correlation potential of ^{14}C records are limited by (a) the type of material available for dating, (b) the degree to which the appropriate reservoir correction is known, and (c) our ability to assess the extent of sediment reworking (especially with respect to lithofacies changes). Although AIO dates are generally understood to be unreliable and are rarely used in the arctic marginal seas (e.g. Fillon et al. 1981), they make up a significant part of the antarctic chronology. Recent studies suggest that, given the proper correction factors, AIO dates are useful in developing age models for antarctic sediments and provide significant new constraints on sediment accumulation rates and timing of ice retreat (Licht et al. 1996; Domack et al. 1998; Cunningham et al. 1999; Andrews et al. in press a, Domack et al. in press).

Arctic marginal shelves

Recent studies of high-resolution records of ice sheet/ocean interactions (e.g. Bond et al. 1992; Keigwin & Jones 1993; Keigwin et al. 1994; Bond & Lotti 1995; Keigwin 1996; Bond et al. 1997) place considerable emphasis on both the accuracy and precision of radiocarbon dating. In the arctic marginal seas (Baffin Bay, Labrador Sea, Green-land/Norwegian/Iceland (GIN) seas), the advent of AMS radiocarbon dating has revolutionised our ability to date sediment sequences which are characterised by high inputs of terrestrial materials and relatively low abundances of calcareous foraminifera (10^{1}–10^{2} foraminifera/g). The AMS method, along with a well-constrained reservoir correction, allows resolution of events to within ± 200 years. Although there are issues of reworking for shelf and trough sediments, by-and-large, a perusal of the literature indicates few age reversals (e.g. Hillaire-Marcel et al. 1994; Stein et al. 1994; Jennings et al. 1996; Stein et al. 1996; Hald & Aspeli 1997). The ocean reservoir correction for arctic calcareous foraminifera and mollusks is frequently assumed to be close to the twentieth century mean surface ocean reservoir age of 450 yrs, but the effective local reservoir effect varies by region and can be as large as 700 yrs (Hjort 1973; Mangerud & Gulliksen 1975). However, the mean reservoir value almost certainly changed by a few hundreds of years in the past due to changes in ocean circulation (Bard et al. 1994). This uncertainty is added to that resulting from the varying rate of ^{14}C production at the top of the atmosphere (Stuiver & Braziunas 1993).

It is difficult in some cases to obtain accurate radiocarbon dates in some arctic areas because of low abundances of calcareous foraminifera (Fillon et al. 1981). On the Eastern Canadian Arctic continental shelves, an oceanographic change over the last 5–7 ka resulted in the replacement of calcareous foraminifera by agglutinated species (Osterman & Nelson 1989; Jennings 1993; Williams et al. 1995a). Thus, sediments from the middle Holocene to present cannot be dated in this area using calcareous foraminifera. A similar but less extreme situation also occurs on the East Greenland margin (Jennings & Helgadóttir 1994; Williams et al. 1995b). To test whether we could obtain 'reasonable' dates from the organic cement of agglutinated foraminifera, we processed a surface sample of agglutinated foraminifera (*Rhabdamina* spp.) collected in core BS1191-K15 off East Greenland and obtained an uncorrected age of 8510 ± 90 yrs (AA-11684) (Manley & Jennings 1996). The expected age, based on ^{14}C dated calcareous foraminifera from the same core and same depth, was 85 ± 45 yrs BP (uncorrected). This result indicates that the organic cement of this particular agglutinated foraminifera incorporated old carbon and that dating aggluti-
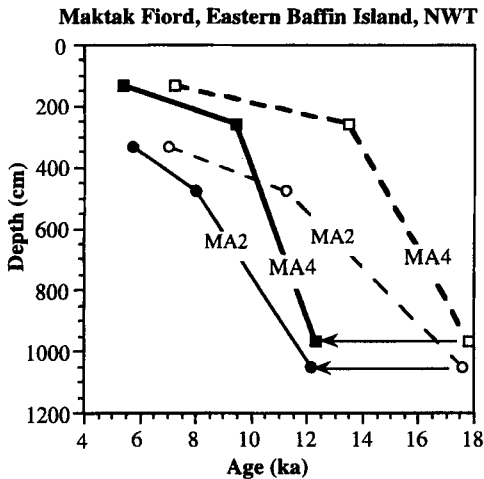
Maktak Fiord, Eastern Baffin Island, NWT

Fig. 2. Radiocarbon dates on the AIO fraction of two cores from Maktak Fjord, Baffin Island, NWT. Dashed lines are uncorrected dates and solid lines are corrected dates. Corrections are based on the linear relationship at a nearby site of AIO versus shell dates.

nated foraminifera may be problematic. However, additional samples need to be dated to determine whether this is the case in all regions with all types of agglutinated foraminifera.

Dating the AIO fraction of sediment presents a viable dating alternative in the absence of carbonate material; however, the interpretation of AIO ages in the Arctic is extremely complex because of a high volume of terrigenous organic carbon relative to marine organic carbon. In Maktak Fjord, Baffin Island NWT, no calcareous foraminifera were found in two cores (MA2,4), so dates were obtained on the acid-insoluble fraction of the sediment (Syvitski & Andrews 1994) (Fig. 2). These cores from Maktak Fjord lie entirely within bedrock of PreCambrian granites and gneisses (Syvitski & Blakeney 1983); therefore, contamination by dead carbon from the bedrock was expected to be minor. However, pollen studies on fjord sediments (Short et al. 1989) showed minor contamination by reworked 'old' pollen in some Baffin Island fjord sediments, including Maktak Fjord. Paired AIO and carbonate dates (i.e. from the same level in a core) have been used to calibrate AIO ages to carbonate ^{14}C ages for this region (see Fig. 3, Table 1, Andrews et al. 1985); the suggested AIO corrections result in sedimentation rates and a chronology for the Maktak Fjord cores that compare well with their stratigraphic levels, but it is difficult to demon-

strate that the temporal scales are correct to within ± 10%. A similar problem occurs in fjord sediments in East Greenland where AIO dates were significantly older than expected and were extremely difficult to interpret based on core stratigraphy and typical sedimentation rates for the region (Manley & Jennings 1996).

Antarctic margin

The problem of obtaining reliable ^{14}C dates is even more severe in many areas of Antarctica where the low numbers and/or dissolution of foraminifera (Jennings et al. 1995) limits our ability to acquire ^{14}C dates on carbonate. As an example, calcareous foraminifera are so sparse that out of 135 dates we have obtained since 1992, only 23 were on foraminifera or mollusks (see Manley & Jennings 1996). Our ability to date the Holocene muds on the Ross Sea shelf using carbonate dates has been especially inhibited because calcareous foraminifera occur more commonly in glacial marine diamictons than in the post-glacial muds (Jennings et al. 1995). Although the factors controlling the age of AIO dates render an absolute age correction somewhat complex (Andrews et al. in press a), in contrast to the Arctic, AIO ^{14}C dates have been used to obtain reasonable chronologies on marine sediment sequences in the western Ross Sea (Licht et al. 1996; Cunningham et al. 1999; Andrews et al. in press a; Domack et al. in press) and around the Antarctic Peninsula (Domack et al. 1993; Leventer et al. 1996 and unpublished data).

Around Antarctica, the present-day ocean reservoir correction for marine carbonates is 1200–1300 yrs (Gordon & Harkness 1992; Berkman & Forman 1996), but there is no information as to how constant that figure has been during the late Quaternary. In contrast, AIO dates on material collected in the Ross Sea at the sediment/water interface are frequently between 2000 and 4000 ^{14}C years old, 800 to 2800 ^{14}C years older than the age of marine waters (DeMaster et al. 1996; Jacobson 1997; Andrews et al. in press a). Many hypotheses have been advanced to explain the anomalously old AIO ages (Domack et al. 1989; Domack 1992; Harden et al. 1992; Harris et al. 1996). While some authors attribute old AIO ages to phytoplankton incorporation of old C in surface waters (Domack

Table 1. Previously unpublished radiocarbon dates used in paired date comparison from core NBP9501-7pc. Lab number follows date. Foram dates are corrected by 1200 years.

Depth (cm)	AIO date (uncorrected)	Foram date (corrected)	Age difference (yrs)
2–4	22,975 ± 210 (AA23405)	20,780 ± 290 (AA23418)	2195
20–22	25,695 ± 300 (AA23406)	16,590 ± 195 (AA23417)	9105
63–66	20,780 ± 220 (AA23407)	13,770 ± 135 (AA23222)	7010

et al. 1989; Domack 1992), others suggest that at least some old AIO ages may result from dilution of modern carbon by 'old' organic compounds (Sackett et al. 1974; Truswell & Drewry 1984; Venkatesan 1988; Domack et al. 1995; Domack & McClennan 1996) via remobilisation from older sediments via glacial erosion, iceberg scouring, current transport, winnowing, and deep benthic mixing (Domack 1992; Harden et al. 1992; Harris et al. 1996). Although the source of the anomalous ages is not well known at present around Antarctica, there is good evidence that correcting AIO ages by subtracting the age of the sediment at the sediment/water interface from the subsequent dates in any given core provides a reasonable absolute age (Andrews et al. in press a). Although it seems that this strategy might not be appropriate for dates in a different lithofacies, our calibration data suggest that it appears to be a reasonable correction except for significantly reworked subglacial deposits. If we assume this correction is correct for subsequent dates, then the error associated with the dates is only the reported laboratory error (typically ±100 yrs). If this assumption is not appropriate, the error associated with the absolute age may be as large as several thousand years. Regardless of the correction applied to the Ross Sea AIO dates, the sequence of ages acquired on the AIO fraction of the sediment lacks significant reversals and therefore provides useful chronological information. Although the errors are not yet small enough to compare high resolution records, these dates provide reasonable estimates which can be refined with improved dating techniques.

The acquisition of meaningful AIO dates in any region requires a marine system containing (a) a relatively high influx of biogenic material (resulting from marine primary production) contemporaneous with the sediments, (b) a low influx of
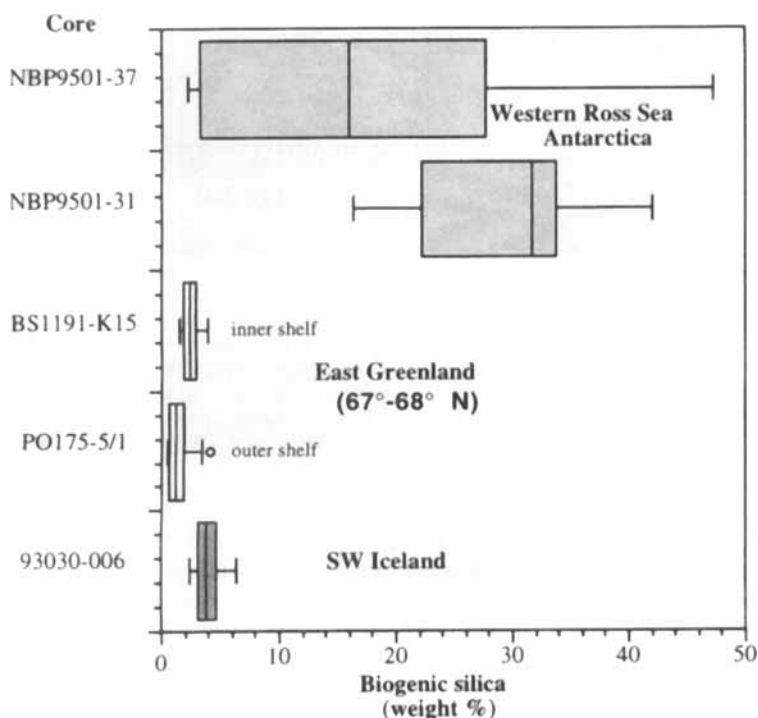

Fig. 3. Comparison of the biogenic silica content of cores from East Greenland, southwestern Iceland, and the Ross Sea, Antarctica (Antarctic data from Cunningham 1997). Line within box gives median value, box contains 50% of data, whiskers encompass 90% of data, and open circles are outliers.

terrigenous material, and (c) little 'old' carbon (reworked from older sedimentary units). Western and central Ross Sea sediments contain much higher percentages of biogenic silica, which covaries with total organic carbon in surface sediments (Dunbar et al. 1985; DeMaster et al. 1996), than sediments of similar age from E. Greenland and southwestern Iceland (Fig. 3). Three possible explanations for the high values of biogenic silica in the Ross Sea are (a) high levels of siliceous marine primary productivity, (b) a high degree of silica preservation, and/or (c) little dilution by non-biogenic terrigenous sediment. Although the reasons for high biogenic silica content in antarctic versus arctic sediments are complex (Dunbar et al. 1985; Ledford-Hoffman et al. 1986; DeMaster et al. 1992, 1996; Nelson et al. 1996), the observed covariance between sedimentary biogenic silica and total organic carbon in the Ross Sea suggests that sediments with high percentages of biogenic silica contain higher fractions of marine-derived organic carbon contemporaneous with the sediments. Thus, in areas and lithofacies with high percentages of sedimentary biogenic silica, we can have more confidence that a large fraction of the organic carbon that has been dated is, in fact, primary, and not reworked from older deposits. A second reason AIO dates are more useful in the Antarctic than in the Arctic centres around differential input of 'old' terrigenous sediment to each marine system. The Ross Sea receives little terrigenous sediment because it lacks significant sediment input sources, such as rivers and meltwater runoff, that are much more common in the Arctic. Since the terrigenous material acts to dilute the marine-derived organic material in the Arctic with 'old' organic compounds, AIO dates from the Arctic are more problematic.

Depth/age relationships in some Ross Sea cores

In this section we present radiocarbon data from a series of cores from the Ross Sea (Fig. 1) and examine the following issues in a core-specific context: (a) calibration of AIO dates to carbonate dates, (b) changes in the fraction of old carbon contamination across lithofacies boundaries, and (c) the development of depth/age models.

AIO dates appear to be useful to establish relative chronologies in the Ross Sea; however, calibration to an absolute chronology is challen-
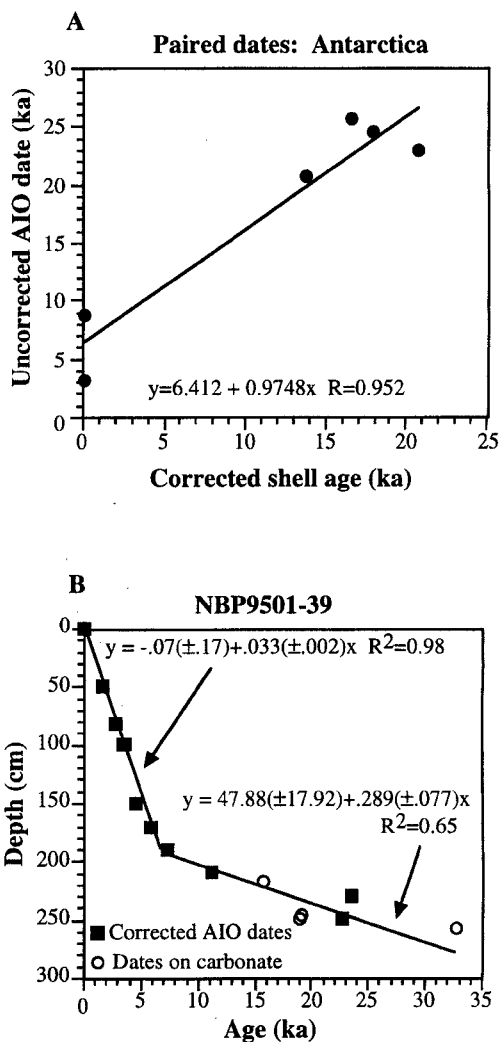

A

Paired dates: Antarctica

$y = 6.412 + 0.9748x$ $R = 0.952$

B

NBP9501-39

$y = -.07(\pm.17)+.033(\pm.002)x$ $R^2 = 0.98$

$y = 47.88(\pm17.92)+.289(\pm.077)x$
$R^2 = 0.65$

■ Corrected AIO dates
○ Dates on carbonate

Fig. 4. A. Scatterplot of paired carbonate (corrected by 1200 yrs) and AIO (uncorrected) ^{14}C dates from the Ross Sea. B. Radiocarbon dates, from Ross Sea core NBP9501-39, on the corrected acid-insoluble organic fraction and on foraminifera (see Fig. 1 for location). Organic dates are corrected by the surface age of 3140 years and foraminifera dates are corrected by 1200 years. Organic dates are from INSTAAR and E. W. Domack (previously reported by Jacobson 1997; Cunningham et al. 1999; and Domack et al. in press).

ging. We present two approaches to address calibration. The first is to obtain AIO and carbonate dates from the same depth (paired dates) and the second approach is to assess downcore alternating AIO and carbonate dates. We show our available data for a series of paired dates in Fig. 4A (Table 1). The two youngest dates

are from shells, whereas the older ones are from foraminifera. Although the sample set is small (n = 6), and therefore requires more extensive study for validation, the slope of the linear regression is essentially 1 (there is no difference in the estimated slope of this relationship if we use the more suitable Reduced Major Axis method (Till 1974)), suggesting that there is no systematic increase in the AIO/carbonate offset with age. This is in contrast to our investigations in the Canadian Arctic where the slope for the same relationship was ~1.33 (see Fig. 3, Andrews et al. 1985).

The second approach to calibration is demonstrated by our analysis of Ross Sea core NBP9501-39 (Figs. 1 and 4B), where we were able to obtain samples from both the carbonate and organic fractions in the basal diamicton (see Cunningham et al. 1999 and Domack et al. in press for core details). Use of this approach requires a firm understanding of the depositional history of the sedimentary unit being dated. Two models can be advanced to explain the origin of the basal diamicton for NBP9501-39, which is located just seaward of the probable LGM limit of ice (Licht et al. 1999; Shipp et al. in press). The first is that the foraminifera and AIO material >7 ka are reworked, indicating significant disturbance by glacial ice (Domack et al. in press); the second hypothesis is that the site was not glaciated and records relatively continuous sedimentation over the last ~35 ka. Comparison of sedimentological, foraminiferal, and chronological data between this core and surrounding cores (Licht et al. 1999) indicates that the core 39 diamicton has similar characteristics to those interpreted as ice-proximal glacial marine diamictons (Licht et al. 1999). However, swath bathymetric data (Shipp et al. in press) reveal that this sedimentary unit is fluted suggesting modification by subglacial processes. By combining these two data sets, we suggest that the diamicton was deposited as glacial marine sediment and later modified only slightly by grounded ice. A gap in ^{14}C dates suggests that some sediment may have been eroded. It is unlikely that the dates >7 ka represent significant reworking because of the preservation of foraminifera (Jennings et al. 1995) and the fact that the radiocarbon data only exhibit one minor age reversal.

Since we interpret the basal diamicton from core 39 as an in situ deposit, we can assess the relationship between the AIO and carbonate dates.

A date from the AIO fraction of surface sediments resulted in an age of 3140 ± 50 BP, thus we corrected the AIO dates by subtracting the core top age of 3140 yrs from the dates in the rest of the core. This correction brings the AIO dates into relative agreement with the carbonate dates (Fig. 4B). An ordinary least squares (OLS) linear fit to the dates >7 ka give an R^2 of 0.65 (Fig. 4B). These data indicate that where the depositional history is known and the AIO surface age is subtracted from downcore dates, the corrected AIO ages can be calibrated with carbonate ages.

We might expect that the erosion of old carbon sources would account for higher proportions of the total carbon pool in the more ice-proximal environments, thus there would be a dramatic increase in age across the transition from the diamictons to the muds deposited during conditions of seasonally open water. The range of offset across the mud/diamicton transition in Ross Sea cores is ~2 to 15 ka (Fig. 5). This age increase may be attributed to (a) an erosional contact, (b) a hiatus in deposition, or (c) a significant increase in the fraction of old carbon delivered to the sediment during this time. Although diamictons contain significantly more terrigenous sediment than the overlying diatom-rich muds, the AIO ages acquired from the diamictons (interpreted to be glacial marine) provide a reasonable sequence of dates with few age reversals.

In core DF80-144 (Fig. 1) the transition from mud to glacial marine diamicton lies at only 12 cm (Fig. 5) (Licht et al. 1996), thus erosion and bioturbation must be considered when interpreting the radiocarbon dates. The predicted age for the 22.5 cm level, based on interpolation between the two carbonate dates, is 20,405 (corrected). This compares with the AIO date from 22.5 cm of 22,360 ± 140 (uncorrected). Thus a correction of ca. 2000 yrs would reconcile the carbonate and AIO ages – a 2000 yr correction is relatively small, but not unreasonable, on the basis of our analysis of 20–30 surface organic dates from the Ross Sea (Andrews et al. in press a; in press b).

Core DF80-177 similarly has 6 cm of mud overlying a glacial marine diamicton (Licht et al. 1996; Licht et al. 1999). The near surface (1.5 cm) AIO age of 7470 ± 70 contrasts with the underlying 3 carbonate dates in the diamicton which are much older and progressively increase in age with depth at a rate of ca. 45 cm/ky compared to 16 cm/ky in DF80-144. The offset across the transition in this core is much greater than in core Df80- 144
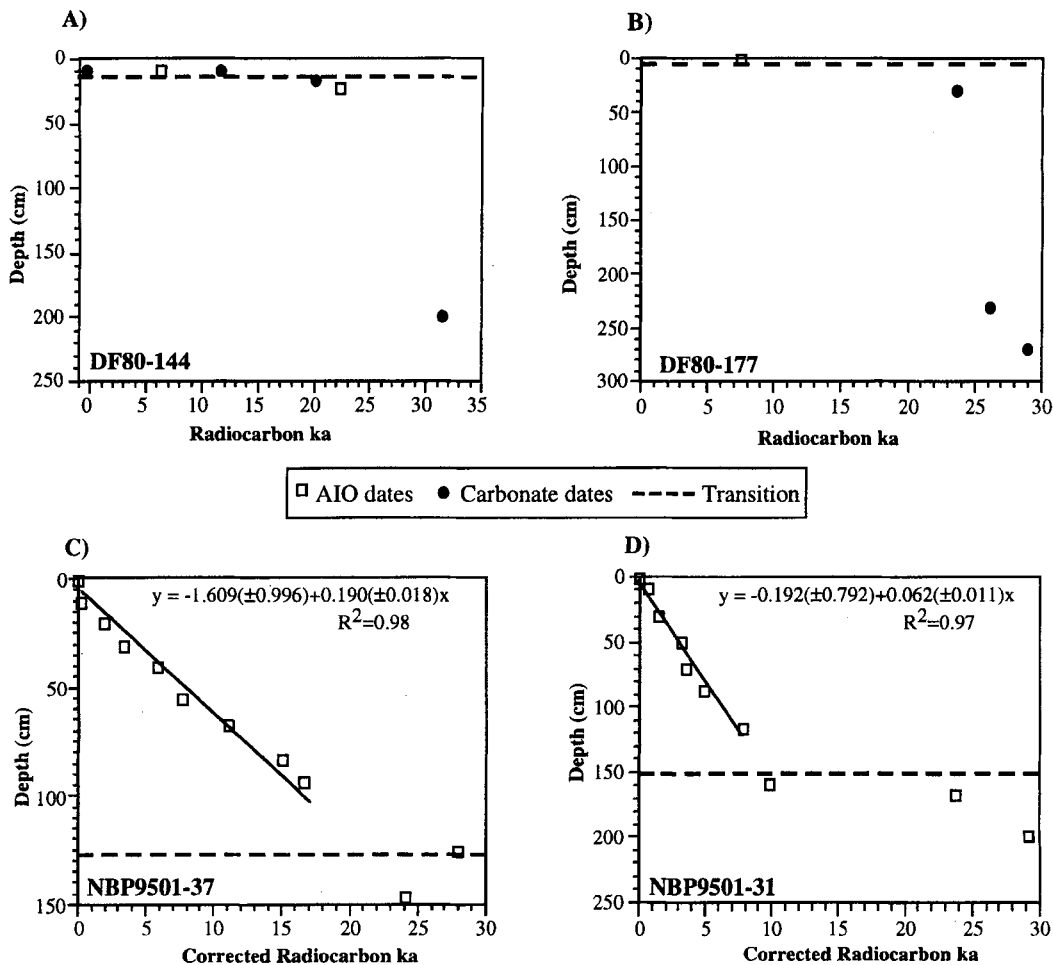
Fig. 5. Depth/age plots for Ross Sea cores DF80-144, DF80-177, NBP9501-31, and -37. All carbonate dates are corrected by 1200 years. AIO dates from Df80-144 and Df80-177 are uncorrected because of the lack of a reliable surface AIO age. The AIO surface ages for cores NB P950 1-31, -37 were subtracted from subsequent downcore dates. Dashed line represents the transition from post-glacial sediments to diamictons (glacial marine or till).

(Fig. 5). The different results given by these two cores suggests that the age change across the transition should be assessed on a case by case basis.

Acquiring AIO dates allows the development of depth/age models from which we can derive sediment accumulation rates and compare changes in the sedimentary record. Depending on the net rate of sediment accumulation since deglaciation, which is related in part to spatial variations in surface water productivity and advection by currents (DeMaster et al. 1983; Ledford-Hoffman et al. 1986; Harden et al. 1992; DeMaster et al. 1996), diatomaceous mud in the

Ross Sea varies in thickness from a few centimetres to several metres. Measured net sediment accumulation rates (SAR, cm/ky) vary by at least an order or magnitude.

Cores NBP9501-31, -37, and -39 (Fig. 1), for which we have calculated age/depth models, all have similar stratigraphy. The upper unit is a thick diatom-rich mud underlain by thin transitional sediments and a diamicton. The diamictons are interpreted as either ice-proximal glacial marine sediments or subglacial till. AIO dates for the upper unit of these cores and details of the sedimentology and biostratigraphy are reported in Cunningham (1997), Jacobson (1997), Cunning-
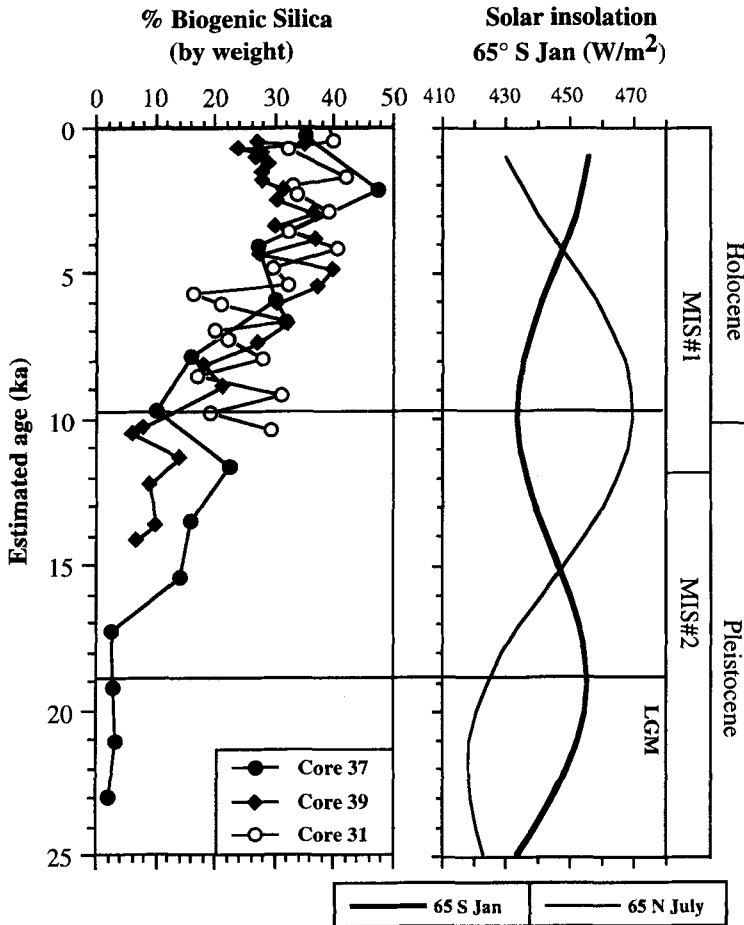
Fig. 6. Biogenic silica weight percent for NBP9501-31, -37, -39 (Cunningham 1997) and January insolation for 65° north and south. Note that the right hand time axis is sidereal years whereas the biogenic silica is graphed against radiocarbon years. MIS is marine isotope stage and LGM is last glacial maximum.

ham et al. (1999), and Domack et al. (in press). All three cores have linear sedimentation rates in the upper mud and a marked increase in age at or near the top of the diamicton (Fig. 5). For example, the SAR in the upper mud unit of core 31 is well fitted by a linear equation ($R^2 = 0.97$) with a slope (rate) of 16 cm/ky. In core 37 the nine dates in the upper mud unit are also well-fitted by a linear regression ($R^2 = 0.98$); this age model yields an SAR of 5.3 cm/ky. The predicted surface (0 cm) age of -1609 yrs occurs because the linear OLS equation does not account for the apparent rapid increase in SAR between the surface and 10.5 cm. The sequence of AIO dates from core 37 suggests that this core contains an intact sequence of sediments dating from <ca. 23 (i.e. from prior

to the global LGM) to the present. This result, although at first surprising given the location of the core (Fig. 1), is in agreement with sedimento-logical data from the region (Licht et al. 1999) and glaciological modeling of the LGM and deglacia-tion (Licht & Fastook 1998).

The depth/age plot of NBP9501-39 (Fig. 4B) shows two distinct rates of sediment accumula-tion; the data were fitted with two linear regressions. The upper part of the core (<7 ka), which is a diatom-rich mud, shows a SAR of ~30 cm/ky ($R^2 = 0.98$) while the lower part of the core (>7 ka) is characterised by a slower SAR of ~3.5 cm/ky ($R^2 = 0.65$). These data indicate an order of magnitude increase in the sediment accumulation rate from ice-proximal to open
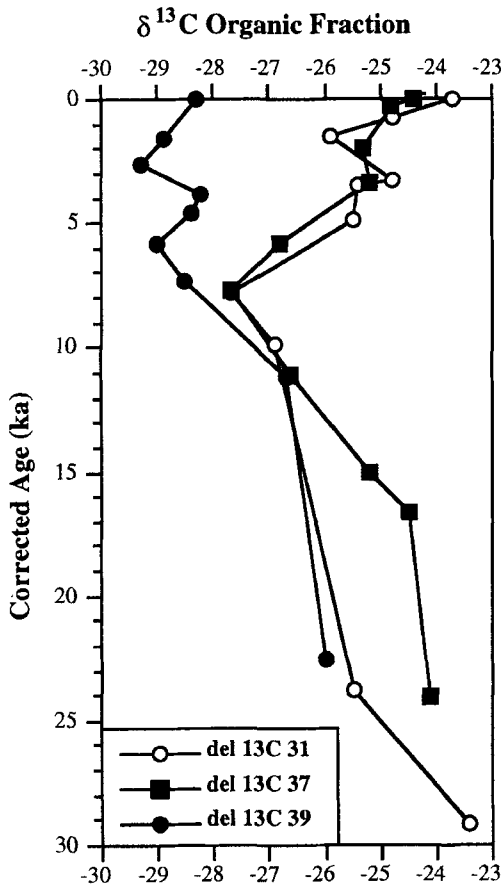
δ¹³C Organic Fraction

Fig. 7. Changes in $\delta^{13}C$ of the organic fraction in NBP9501-31, -37, -39 (Fig. 1) from the Ross Sea graphed against their corrected radiocarbon ages (see Domack et al. in press and Cunningham et al. 1999).

marine conditions in the western Ross Sea. This contrasts strongly with the Arctic where SAR's are generally highest for ice-proximal glacial marine sediments.

Validating AIO Dates Using Proxy Records

Biogenic silica – The data discussed above suggest that finite AIO dates in the range of >15 and <30 ka, should not (cannot?) be summarily dismissed (Figs. 4 and 5). However, decisions concerning the utility of an age model, especially one including ages between 15 and 30 ka, must be based on the core stratigraphy and other proxy information. We suggest that one means of evaluating the validity of an age model

is to compare proxy records between several spatially-associated cores. Based on the idea that spatially-associated cores might reflect similar depositional histories, changes in proxy records through time should occur simultaneously in each core if the age model is appropriate. As an example, biogenic silica data are plotted for cores 31, 37, and 39, whose age models have been 'calibrated' by subtracting the core top date for each core from subsequent dates (Fig. 6); Biogenic silica has been used as a proxy for diatom productivity in the upper water column (Ledford-Hoffman et al. 1986; Leventer 1992; DeMaster et al. 1996; Cunningham & Leventer 1998; Cunningham et al. 1999). Fig. 6 shows changes in percent biogenic silica over time. Since 10 ka BP, all three sites show a gradual increase in the biogenic silica to values of between 30 and 40 weight %. In core 37 and core 39 there is a broad plateau of ~10 and 20 weight % between ~15 and 10 ka. There is a trough in both records at the Holocene/Pleistocene boundary; this trough is in the general position of the Northern Hemisphere Younger Dryas cold interval. Prior to ca. 17 ka, the biogenic silica in core 37 is very low, between 2 and 4%. Although there is a broad association between the austral summer insolation curve over the last 10 ka, this is not true for the preceding 15 ky, most likely because these core sites were covered by grounded or floating ice during this time. The obvious parallelism in these three records gives us some confidence in our age model and that using a core-specific correction is reasonable to account for the reservoir effect and reworking at least for the last 15 ka. Our records in Fig. 7 have broad parallelism with the isotopic δD data from Taylor Dome (e.g. Steig et al. 1998), an ice core site situated close to our marine sites in the western Ross Sea (Fig. 1).

δ13C variations in the organic fraction – A second proxy we might use to evaluate the age models is the $\delta^{13}C$ of the organic fraction of the sediment. At the Arizona AMS Facility, the $\delta^{13}C$ of the bulk organic fraction is routinely obtained during the analysis procedures for radiocarbon dating. Joint dating efforts by Hamilton College and the University of Colorado have made these data from the 1995 cores available (in Jacobson 1997; Domack et al. in press; Cunningham 1997; Villinski & Domack 1998). In Fig. 7 we show the corrected age of the AIO against the $\delta^{13}C$ of the

organic fraction. The range in sedimentary $\delta^{13}C$ in the three cores is approximately 6 o/oo, which is comparable with the present day range of sedimentary $\delta^{13}C$ in surface sediments of the Ross Sea (Villinski pers. comm.). Our preliminary results indicate that sedimentary $\delta^{13}C$ values prior to 10 ka were less variable (range: <3 o/oo) than they are at present. Cores 31 and 37, both of which are located in the western Ross Sea, correlate remarkably well from 10 ka to present; both cores record relatively depleted (relative to the present) values of sedimentary $\delta^{13}C$ at ca. 8 ka, and both record a trend toward heavier sedimentary $\delta^{13}C$ from 8 ka to the present. The timing of individual fluctuations is essentially simultaneous given the resolution of the data. Although values of sedimentary $\delta^{13}C$ from core 39 are depleted relative to values from cores 31 and 37 for the last 10 ka, the relative changes between the coastal cores and core 39 are remarkably synchronous; all three cores record a sedimentary $\delta^{13}C$ depletion in the early Holocene, a trend toward heavier $\delta^{13}C$ values around 4 ka, a second depletion around 2 ka, and a final trend toward heavier $\delta^{13}C$ values from 2 ka to the present. The synchronicity of changes between these cores suggests that, although we are still not sure of an absolute age correction, applying a core-specific correction brings the cores into relative age agreement. Future detailed work on sedimentary $\delta^{13}C$ in these three cores (Villinski pers. comm.) will significantly enhance our ability to evaluate the age models determined for these three records.

Potential correlation of IRD records on polar margins

Previous studies suggest that Ross Sea surface sediments rich in biogenic silica and total organic carbon have the least error of all Ross Sea AIO dates (Andrews, et al. in press a; DeMaster et al. 1996). Biogenic-rich muds usually occur from ca. 12 ka to the present; therefore, the best chance of dating a Heinrich-equivalent event is limited to the latest Pleistocene and early Holocene (H–0 = 10–11 ka; e.g. Bond & Lotti 1995). It is ironic that although the arguments have been made over several years for the instability of the West Antarctic Ice Sheet (Alley & Whillans 1991; Behrendt et al. 1993; Bentley 1997; Bindschadler

1991; Burckle 1993; Hughes 1977; MacAyeal 1992; Mercer 1978; Thomas & Bentley 1978), in recent years indisputable evidence has been found in marine sediment cores of massive abrupt iceberg events in the North Atlantic (Bond et al. 1993; Bond et al. 1992; Broecker 1994; Broecker et al. 1992; Heinrich 1988) (for review see Andrews 1998). To our knowledge, equivalent events (not necessarily correlative, but abrupt, short lived IRD intervals) have not been reported from the antarctic margin of the Ross Sea, and in the Weddell Sea the data of Anderson & Andrews (in press) indicates that those IRD events are not coeval with Heinrich events in the North Atlantic. If some type of ice-rafting event were identified on the antarctic margin, it would be difficult to attempt correlation with Northern Hemisphere sedimentary records. Because of a lack of independent dating constraints on Ross Sea AIO dates, the absolute age the AIO dates represent is ambiguous. If the corrected AIO dates were linked to independently dated records such as ice cores, then we could attempt to reliably correlate events and assess leads and lags in the sediment record. However, without independent confirmation of AIO age estimates, events such has Heinrich events cannot necessarily be correlated because of the uncertainties in absolute ages. Future work involving dating of biomarkers (which would reduce the errors associated with AIO dates by removing effects attributed to contamination by old carbon) should markedly enhance our ability to correlate arctic and antarctic records.

Conclusions

In both the Arctic and Antarctic, it is essential that each new study area is evaluated on a case by case basis to demonstrate the validity of using AIO dates. Although AIO dates are not usually considered useful in arctic marginal marine sediments because of significant contamination by old carbon, they do provide useful chronological information for the Ross Sea, Antarctica. There appears to be a predictable linear relationship in the Ross Sea between paired carbonate and AIO dates (Fig. 4). AIO dates are useful to constrain sedimentation rates and relative timing of events in the Ross Sea, but the errors associated with the absolute age may be as high as thousands of years or as little as one hundred years

depending on which assumptions are made about the surface corrections. In contrast, errors associated with arctic chronologies constructed with carbonate dates are generally hundreds of years. To reduce the potentially large errors of Ross Sea radiocarbon dates requires comparison of AIO dates to independently dated records such as tephra layers contained in both ice cores and sediment cores. When AIO dates can be confidently calibrated, we will be able to reliably address leads and lags between Ross Sea (antarctic) and arctic records. Improved dating techniques (such as the ability to date biomarkers) and the acquisition of data tying together terrestrial and marine records will allow direct comparisons between paleoceanography and ice sheet/ocean interactions in arctic and antarctic regions to be made with more confidence. These data will also allow us to assess leads and lags given the out-of-phase nature of summer insolation at these high latitudes as well as correlation of specific events in the geologic record.

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