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34. A Synthesis for Site 1098: Palmer Deep[1]

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ABSTRACT

Site 1098 in Palmer Deep recovered the first ultra high resolution Holocene to late Pleistocene time series from the Antarctic continental margin. The sedimentary record is similar to others obtained by the Ocean Drilling Program in the Cariaco Basin, Saanich Inlet, and Santa Barbara Basin. Whereas Palmer Deep is a deep enclosed basin in an area of high seasonal productivity, anoxic bottom-water conditions have never developed. Rather, the preservation of laminated sediments is a product of sediment focusing and high but short-lived productivity that overwhelms bioturbation. A complementary data set including diatoms, foraminifers, physical properties, grain size, trace elements, organic geochemistry, and sediment color is controlled by a detailed radiocarbon chronology from the composite core stratigraphy. Results indicate a climate record characterized by climate oscillations during the late Pleistocene to Holocene transition, a middle Holocene climatic optimum, and a late Holocene neoglacial. The neoglacial paleooceanographic setting was characterized by alternating Circumpolar Deep Water and saline shelf water at the bottom of the basin. All studies performed to date are in agreement in recognizing the Little Ice Age as a prominent episode in the latest Holocene from 0.7 to 0.2 ka. Detailed studies of laminated intervals indicate that a significant number of productivity events (seasons) are missing; hence, the record is not a complete continuous time series but is nevertheless extremely useful in establishing a paleoenvironmental reference for the circum-Antarctic.

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INTRODUCTION

Sites 1098 and 1099 in Palmer Deep were the first ultra high resolution Ocean Drilling Program (ODP) targets in the Southern Hemisphere and represented the first coordinated effort aimed at obtaining such a record from the Antarctic continental shelf (Barker, Camerlenghi, Acton, et al., 1999; Barker et al., 1998). Three offset holes at Site 1098 (1098A, 1098B, and 1098C) and two intersecting holes at Site 1099 (1099A and 1099B) were drilled during Leg 178. To date, detailed investigations have been completed at only Site 1098, focused around the completion of a composite depth scale (Acton et al., **Chap. 5,** this volume) and a detailed radiocarbon chronology (Domack et al., 2001). The chronology and stratigraphy of Site 1099 will be reported at a later date. The purpose of this paper is to summarize the scientific results dealing with Site 1098.

At Site 1098, ~45 m of diatomaceous mud and ooze underlain by a stiff glacial diamicton was recovered. The sequence represents a single deglaciation through the Holocene with unprecedented temporal resolution for Antarctic sediments. Hence, one of the stated objectives of Leg 178 was met by the completion of drilling at this site. Published studies for Site 1098 cover the following topics:

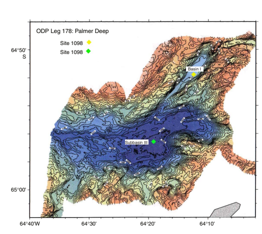
1. Diatom abundance and assemblages (Taylor and Sjunneskog, 2002; Sjunneskog and Taylor, in press, Leventer et al., 2002, Osterman et al., **Chap. 7,** this volume);
2. Foraminifer abundance and oxygen isotope geochemistry (Osterman et al., **Chap. 7,** this volume; Ishman and Sperling, 2002; Shevenell and Kennett, 2002);
3. Particle size distribution (Warner and Domack, 2002);
4. Sediment color (Nederbragt and Thurow, **Chap. 3,** this volume; Wolf-Welling et al., **Chap. 21,** this volume);
5. Organic geochemistry (Dunbar et al., 2000);
6. Paleomagnetism and magnetic mineralogy (Brachfeld et al., 2000, 2002);
7. Sediment microfabric (Pike et al., 2001, **Chap. 18,** this volume);
8. Radiolarian abundance and assemblages (Weinheimer, **Chap. 33,** this volume);
9. Physical properties (Hatfield et al., **Chap. 30,** this volume); and
10. Biogenic opal (Anderson and Ravelo, **Chap. 1,** this volume).

These results provide a consensus regarding general stratigraphy and paleoenvironmental interpretation. They also indicate some divergence of opinion regarding the paleoceanographic history of Palmer Deep. This paper summarizes the general consensus as well as different interpretations. The paper is organized around thematic issues related to basin physiography, origin of laminated intervals, sediment provenance, and deepwater vs. surface water signals during the Holocene. Suggestions for future avenues of study are highlighted.

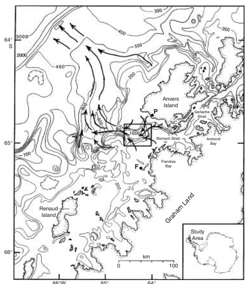
Palmer Deep

Palmer Deep is an informal name given to an inner shelf depression of unusual depth and relief recently surveyed with swath mapping (SeaBeam) during cruise NBP-99-03 of the *N.B. Palmer* (Fig. **F1**). Palmer Deep appears to be located at an intersection of three ice drainage sys-

F1. SeaBeam map of Palmer Deep, p. 12.



tems and contains at least two distinct subbasins (Figs. F1, F2). Glacial drainage systems included those from the Anvers Island ice cap in the northeast, valley glaciers that reached the area across the shelf from the south, and ice that entered the eastern end of Palmer Deep from the Bismark Strait via the Neumayer Channel and southernmost Gerlache Strait (Fig. F2). Palmer Deep is tectonically controlled by a half-graben that is still an active structure (Rebesco et al, 1998; Sniffen, 2001). The convergence of flow probably helped to overdeepen the basin and most probably originated an ice stream that extended some 200 km across the entire continental shelf until the shelf break (Fig. F2). The basin is one of the deepest inner shelf basins found along the Antarctic margin. Crystalline rocks of the Peninsula Volcanic and Trinity Groups comprise most of the underlying bedrock (British Antarctic Survey, 1982). Only in the deepest reaches of Subbasin III does postglacial deposition clearly mask the scoured bedrock surface.



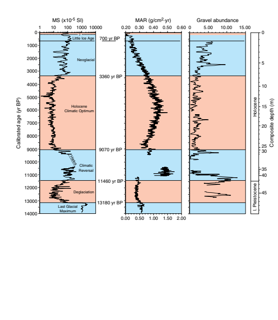
F2. Regional bathymetry, p. 13.

Site 1098 is located in the axis of the ~2-km-wide perched Subbasin I, which trends in a southwest–northeast direction (Fig. F1). Acoustic imagery revealed a draped sequence of pelagic and hemipelagic sediments at this site (Rebesco et al., 1998; Barker, Camerlenghi, Acton, et al., 1999). Although the contour trend does allow connection between Subbasins III and I, the floors of the two subbasins within Palmer Deep are clearly separated by a narrow sill of 10-m relief (Fig. F1). Early bathymetric maps of Palmer Deep (Griffith 1987; Kirby et al., 1998) indicated a third subbasin ("Basin II"); however, this feature is an artifact of imprecise navigation and incomplete bathymetric soundings.

Palmer Deep Subbasin III reaches depths >1400 m and is elongated in an east-west direction, occupying ~192 km² (Kirby et al., 1998; Rebesco et al., 1998). Steep and irregular basement rocks encircle Subbasin III, shallowing abruptly to depths of 300 to 400 m (Fig. F1). The floor of Subbasin III is characterized by a more or less flat eastern deep that slopes gently up to depths of ~1100 m toward the western end. Here, the subbasin floor is dissected by a nearly straight (west to east) canyon that feeds into the deeper, eastern end of the basin. This canyon itself is incised 100 m into the subbasin floor and has tributaries from the southern margin that deepen toward the northwest before merging with the main axial canyon as it turns eastward. Site 1099 and previous piston cores, located within the eastern, deeper portion of Subbasin III, not surprisingly, recovered an alternation of hemipelagic diatom mud/ooze and thick (>30 m) diatom mud turbidites to depths of just over 108 meters below seafloor (mbsf) (Barker, Camerlenghi, Acton, et al., 1999; Kirby et al., 1998).

STRATIGRAPHIC SUCCESSION

Figure F3 shows the composite stratigraphy and mass accumulation for Site 1098 based on radiocarbon analyses, magnetic susceptibility (MS), and gravel abundance (Domack et al., 2001). This stratigraphic template served as the basis for subsequent micropaleontologic, physical properties, and sedimentologic studies. The sediments at Site 1098 are divided into five sequences:



F3. Composite age model, p. 14.

1. Glacial diamicton of late Pleistocene age (>13.2 ka);
2. Interlaminated diatom ooze and diatomaceous sandy mud representing a deglaciation period (13.2–11.5 ka);

3. A massive, sandy diatomaceous mud and diatomacous mud turbidite (11.5–9.0 ka), reflecting a climate reversal;
4. Interlaminated diatomaceous ooze and diatomaceous mud (9.0–3.36 ka), representing the Holocene climatic optimum; and
5. An interbedded laminated diatom ooze and bioturbated diatom slightly sandy mud (3.36 ka to present), representing the neoglacial.

Deglacial Interval

At Site 1098, the last deglacial episode is marked by a pale olive diamicton that underlies an interlaminated sequence of diatom ooze and sandy diatomaceous mud. This deglacial sequence dates to between ~13.2 and 11.5 ka. Radiocarbon dates from this interval assume a modern reservoir correction of 1.2 k.y. (Domack et al., 2001). Distinctive laminations within the interval comprise ~176 couplets of diatom ooze and siliciclastic-rich diatom mud that are interpreted as varves (Nederbragt and Thurow, **Chap. 3,** this volume; Pike et al., **Chap. 18,** this volume, Leventer et al., 2002). These couplets are considered truly rhythmic because the ice-proximal conditions in which they were deposited led to seasonal contrasts in siliciclastic supply under "warmer-than-modern" conditions (Leventer et al., 2002). Such conditions were never again established in Palmer Deep after 11.5 ka. In contrast, subsequent laminated sequences in the Holocene show variations in total organic carbon and/or biogenic silica (dark laminations) against a near-constant background of mud with a relatively high content of terrigenous grains (light laminations) (Nederbragt and Thurow, **Chap. 3,** this volume).

During this deglaciation, Palmer Deep was still partially encircled by tidewater glaciers (those grounded at the calving line below or near sea level) or ice shelf, most probably blocking off the Bismarck Strait and southern Gerlache Strait (Fig. F2). This would have prevented flow of tidal and wind-driven currents through the straits, constricting circulation across the basin. Estuarine flow and dispersal of sediment-laden icebergs would have been enhanced along the embayed glacial margin and provided the conditions necessary for the development of the ooze/mud couplets (Leventer et al., 2002). The noticeably inclined bedding in parts of this interval is the result of sediment draping upon an irregular glacial surface, as demonstrated in acoustic imagery (Barker, Camerlenghi, Acton, et al., 1999). Postdepositional slumping is evident from soft sediment folds and a lack of complete correlation between Holes 1098A, 1098B, and 1098C (Nederbragt and Thurow, **Chap. 3,** this volume). Diminutive foraminiferal faunas are present within this interval, and their assemblage led Ishman and Sperling (2002) to conclude that saline shelf water (SSW) occupied the basin at this time. Oxygen isotopic analyses have not yet been undertaken on the foraminifers in the deglacial sequence.

Climatic Reversal

The climatic reversal recognized between 11.5 and 9.07 ka is characterized by lower diatom abundance and an assemblage characteristic of more persistent sea ice (Taylor and Sjunneskog, 2002; and Sjunneskog and Taylor, in press). Higher coarse-fraction (gravel) abundance and higher magnetic susceptibility indicate greater terrigenous input during this time (Domack et al., 2001). Mass accumulation rates are higher (>1 g/cm²/yr) in this interval, suggesting not only suppressed productivity but enhanced siliciclastic deposition. These observations along with the presence of a massive turbidite suggests that the climatic reversal involved a resurgence of grounded glacial ice around the Palmer Deep Basin. Yet, the clearance of glacial ice from the Bismark and southern Gerlache Straits must have had a profound influence upon deposition in the Palmer Deep Basin, and perhaps this change is marked by the massive turbidite that ends the climate reversal sequence. Testing of this hypothesis awaits swath mapping and chronologic studies on existing cores from the Gerlache Strait and surrounding fjords.

Climatic Optimum

The Holocene Climatic Optimum recognized between 9.07 and 3.36 ka (30–7.5 mbsf) (Fig. **F3**) is described by a comprehensive data set on sedimentary structures, particle size, micropaleontology, and geochemistry. This interval is characterized by well-preserved lamination with definite varved subintervals, yet the varved record is incomplete (Nederbragt and Thurow, **Chap. 3,** this volume). Amalgamation of light laminations results from the suppressed biotic flux during heavy ice years, which prevents the deposition of dark (biogenic rich) laminations (Nederbragt and Thurow, **Chap. 3,** this volume). This leaves many years out of the sedimentary record and distinguishes the Palmer Deep record from more complete varved sequences recovered during ODP cruises from Saanich Inlet and the Cariaco Basin. In these settings, bottom-water anoxia prevents benthic mixing and temperate-to-tropical conditions do not include semipermanent sea ice cover, which periodically eliminates biogenic deposition during summer in Palmer Deep.

Nevertheless, high-resolution studies on the diatom floras indicate that the early part of the Holocene Climatic Optimum was characterized by the advection of subpolar surface water conditions across Palmer Deep (Leventer et al., 2002). Recognition of this process is based upon the abundance of warm water forms of *Eucampia antarctica* (9.0–6.7 ka) (Leventer et al., 2002). Diatom abundance also reaches a maximum in this sequence, with a secondary maximum between 5.0 and 4.4 ka (Sjunneskog and Taylor, in press).

Even higher-resolution sampling (at 2.5-cm intervals throughout the core) for particle size and organic geochemistry provides more detail on the timing of biotic maxima. Both fine to medium silt abundance (a proxy for diatom frustule abundance) and the flux of preserved total organic carbon reach distinct maxima between 7.0–5.5 and 4.7–4.0 ka (Warner and Domack, 2002; Dunbar et al., 2000). Slight discrepancies in the timing of these events may be due to the 20-cm sampling intervals chosen by Taylor and Sjunneskog and/or the decoupling between organic matter flux and diatom productivity when other (nonsiliceous) phytoplankton dominate the euphotic zone (Nederbragt and Thurow, **Chap. 3,** this volume). It is imperative that biomarker studies be carried out on these sediments to more fully evaluate the nature of paleoproduction during the climatic optimum.

The interpretation of the deepwater signal is uncertain; Osterman et al. (**Chap. 7,** this volume) and Shevenell and Kennett (2002) suggest a dominance of Circumpolar Deep Water (CDW) throughout the early to middle Holocene. A more comprehensive evaluation of foraminiferal assemblages by Ishman and Sperling (2002) suggests a dominance of SSW during the middle Holocene. Dissolution of calcareous foraminifers has taken place since core collection (Osterman et al., **Chap. 7,** this volume), thus influencing postcollection assemblage studies. The extent of postcollection diagenesis is unknown, since Osterman et al. (**Chap. 7,** this volume) examined four short (decimeter thick) intervals, whereas Ishman and Sperling examined the entire 45-m sequence. Yet the nature of deep-water variation is an important parameter to quantify since it would control the ^{14}C activity and, hence, the reservoir correction for ^{14}C, which has been assumed constant at a modern level of ~1250 yr (Domack et al., 2001).

Compositional studies of both the magnetite mineralogy and bulk trace element abundance suggest that the middle Holocene was distinctive in Ti-rich magnetite and dominance of pseudo-single-domain magnetite (Brachfeld et al., 2002). Kryc et al., (2001) also measure a slight but consistently lower Al/Ti ratio during the climatic optimum compared to the neoglacial interval. The trace element data suggest less locally derived siliciclastic detritus, consistent with the magnetite mineralogy. Yet the middle Holocene is also characterized by greater mass accumulation rates (MARs) and less abundant coarse ice-rafted detritus (IRD), suggesting a dilution effect within a multicomponent system. Particle size data are comparable with MAR, showing an increase in fine to medium silt (3.9–31 µm) and a decrease in clay in the middle Holocene (Warner and Domack, 2002). Since particle size (clay percent) is closely in phase with MS in the neoglacial interval (Warner and Domack, 2002), it is likely that provenance changes are simply reflecting first-order changes in particle size in the fine fraction coupled with changes (increases) in biogenic flux (Nederbragt and Thurow, **Chap. 3,** this volume). Further work is clearly needed to resolve these competing hypotheses.

Neoglacial Interval

The onset of the neoglacial interval (3.36 ka) is consistently recognized in all paleoenvironmental proxy data (Taylor and Sjunneskog, 2002; Sjunneskog and Taylor, in press; Leventer et al., 2002; Warner and Domack, 2002; Shevenell and Kennett, 2002; Nederbragt and Thurow, **Chap. 3,** this volume; Dunbar et al., 2000; Ishman and Sperling, 2002; Brachfeld et al., 2002; Osterman et al., **Chap. 7,** this volume). This interval is recognized by a decrease in MAR, increase in coarse-fraction IRD, and higher but fluctuating MS (Leventer et al., 1996, Domack et al., 2001). Shevenell and Kennett (2002), Ishman and Sperling (2002), and Osterman et al. (**Chap. 7,** this volume) concur that fluctuating water masses play a major role in the changes in isotopic and assemblage character of foraminifers. They agree that intensity of CDW flow and its movement across the shelf fluctuated many times in the last 3 k.y.

These changes in water mass character are also reflected in the changes in surface water productivity. Diatom abundance and assemblage data fluctuate in a manner consistent with alternating periods of more intense (seasonally persistent) sea ice and open water, when compared to the middle Holocene (Taylor and Sjunneskog, 2002; Sjunneskog and Taylor, in press). The loss of warm-water varieties of *E. antarctica* preceded the onset of the neoglacial, and the complete absence of this form from the neoglacial interval indicates that surface waters were never warm long enough for subpolar species to become established (Leventer et al., 2002).

The reduction in the number of dark (biogenic rich) laminae in the neoglacial interval (Nederbragt and Thurow, **Chap. 3,** this volume) is consistent with reduced fluxes of total organic carbon and biogenic silica and more enriched $\delta^{13}C$ of preserved organic matter (Dunbar et al., 2000). Together, these data imply lower rates of surface production and increased benthic mixing consistent with lower MAR and higher bulk densities (Domack et al., 2001; Nederbragt and Thurow, **Chap. 3**, this volume).

Changes in MS and Al/Ti are thought to reflect a change in provenance to multidomain magnetite and more locally derived terrigenous detritus (Brachfeld et al., 2002; Kryc et al., 2001). Yet reduced MAR and changes in grain size (to more clay-rich sediments) (Warner and Domack, 2002) again highlight the need to resolve the provenance vs. dilution effect hypotheses.

The most thorough interpretation of the Neoglacial interval is provided by the isotopic data discussed by Shevenell and Kennett (2002). They document consistent and rapid alternations in shelf water temperatures of 1.0° to 1.5°C, significant differences for the Antarctic shelf. They suggest that such changes reflect atmospheric forcing via westerly wind strength on the axial flow of the Antarctic Circumpolar Current (ACC). Today, the southern arm of the ACC in the form of upper CDW passes across the Bellingshausen Sea continental shelf (Smith et al., 1999a, 1999b; Hoffman and Klink, 1998) and Palmer Deep and abuts the southern tongue of colder modified Weddell Sea water in the Bismarck and Gerlache Straits (Domack and Ishman, 1993; Ishman and Domack, 1994) (Fig. **F2**). Shevenell and Kennett (2002) suggest that teleconnections must exist between the tropical Pacific and the Southern Ocean via the influence of El Niño Southern Oscillation (ENSO) (Domack and Mayewski, 1999), which intensified at ~4 ka. (Rodbell et al., 1999). A connection to the tropics is also suggested by the recent data from the Cariaco Basin (Haug et al., 2001) that indicate southward migration of the Inter-Tropical Convergence Zone (ITCZ), coincident with the onset of the neoglacial in Palmer Deep (Fig. **F3**).

Although the last 3.36 k.y. is interpreted as the neoglacial, it should be kept in mind that originally the neoglacial was interpreted from the study of alpine glaciers as a middle Holocene glacial advance (Porter, 2000). The evidence in Palmer Deep clearly indicates climate cooling with more persistent sea ice, but linkages with glacial advance along the peninsula are still tenuous (Hansom and Flint, 1989; Hjort et al., 2001). The most prominent event in the neoglacial is the Little Ice Age recognized in Palmer Deep from 0.7 to 0.15 ka. Over this period the pelagic and hemipelagic record of more persistent sea ice, colder sea-surface and bottom-water conditions in Palmer Deep do indeed correlate with local glacial advances and ice core records (Shevenell et al., 1996; Shevenell and Kennett, 2002; Taylor and Sjunneskog, 2002; Sjunneskog and Taylor, in press; Leventer et al., 1996, 2002; Root, 2001; Warner and Domack, 2002; Domack et al., 1995; Kreutz et al., 1997).

A remaining puzzle is the observation that regional insolation during the Holocene seems to be out of phase with the inferred climatic interpretations of a middle Holocene warm period and a late Holocene neoglacial (Taylor et al, 2001; Shevenell and Kennett, 2002). The insolation curve reaches a maximum in the last 1.5 k.y. with a minimum in the middle Holocene (Berger and Loutre, 1991). This opposition of regional insolation with oceanographic and atmospheric temperatures supports the hypothesis of Shevenell and Kennett (2002), who call upon advection of warmer water via the ACC and ENSO influences in the South Pacific. Yet many variables remain unaddressed, such as the role of snow accumulation during warmer winters and the consequent delay in sea ice recession and suppressed biotic sedimentation due to thicker pack. Comparison of the Palmer Deep record with emerging data sets from the circum-Antarctic and Southern Ocean will help to resolve some of these questions (Kulbe et al., 2001; Hodell et al., 2001).

CONCLUSIONS

A review of the Palmer Deep studies to date highlights the following conclusions:

1. Palmer Deep does contain a sediment sequence with varved intervals, but the continuity of the time series is frequently interrupted by missing seasons (Nederbragt and Thurow, **Chap. 3**, this volume). This is probably due to the fact that Palmer Deep did not contain anoxic bottom waters and that summer productivity may have been suppressed by persistent pack ice.
2. Palmer Deep records a single glacial-to-Holocene sequence marked by distinctive climate intervals with both surface and deepwater changes in water temperature.
3. The most reasonable hypothesis that explains the changes in sediment and biotic characteristics is one that couples the ACC with the Southern Ocean and ENSO variability, most probably through westerly wind strength and southward migration of the ITCZ.
4. Alternative interpretations of sediment provenance and dilution effects remain unresolved within the middle Holocene to neoglacial transition.
5. The warmest sea-surface conditions were reached during the early to middle Holocene, as marked by subpolar diatom species.
6. Variations in phytoplankton composition beyond diatoms remain to be resolved, perhaps via biomarker studies.

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Figure F1. SeaBeam swath map of the Palmer Deep showing the locations of Sites 1098 and 1099 in Subbasins I and III, respectively. Contour interval is 50 m.

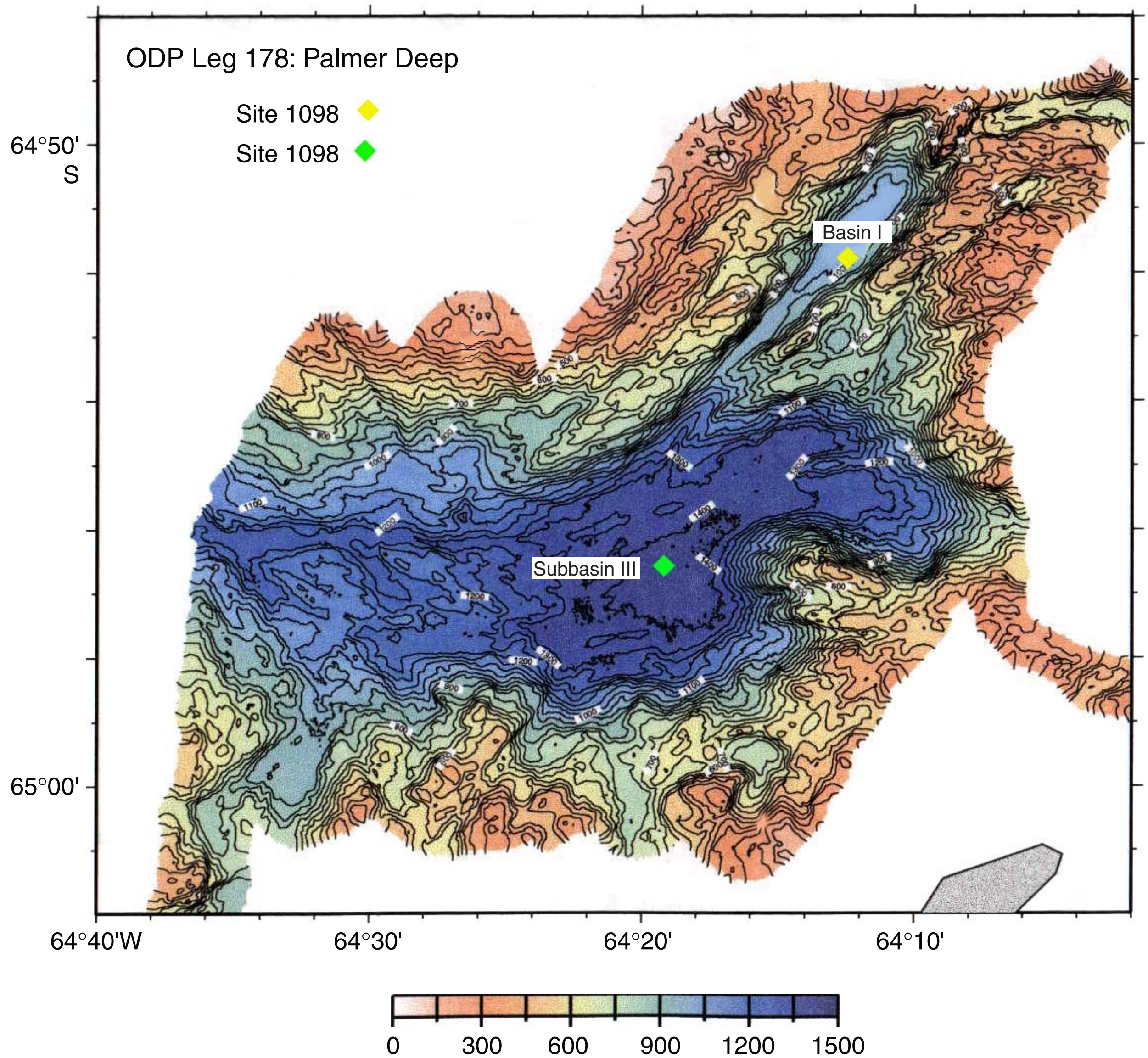

Figure F2. Regional bathymetery in the vicinity of the Palmer Deep (PD) with locations mentioned in the text. (NC = Neumayer Channel, F = Faraday Station, now Vernadsky, P = Palmer Station). Contour interval = every 100 m below 200-m isobath. Arrows show inferred ice flow during the last glacial maximum.

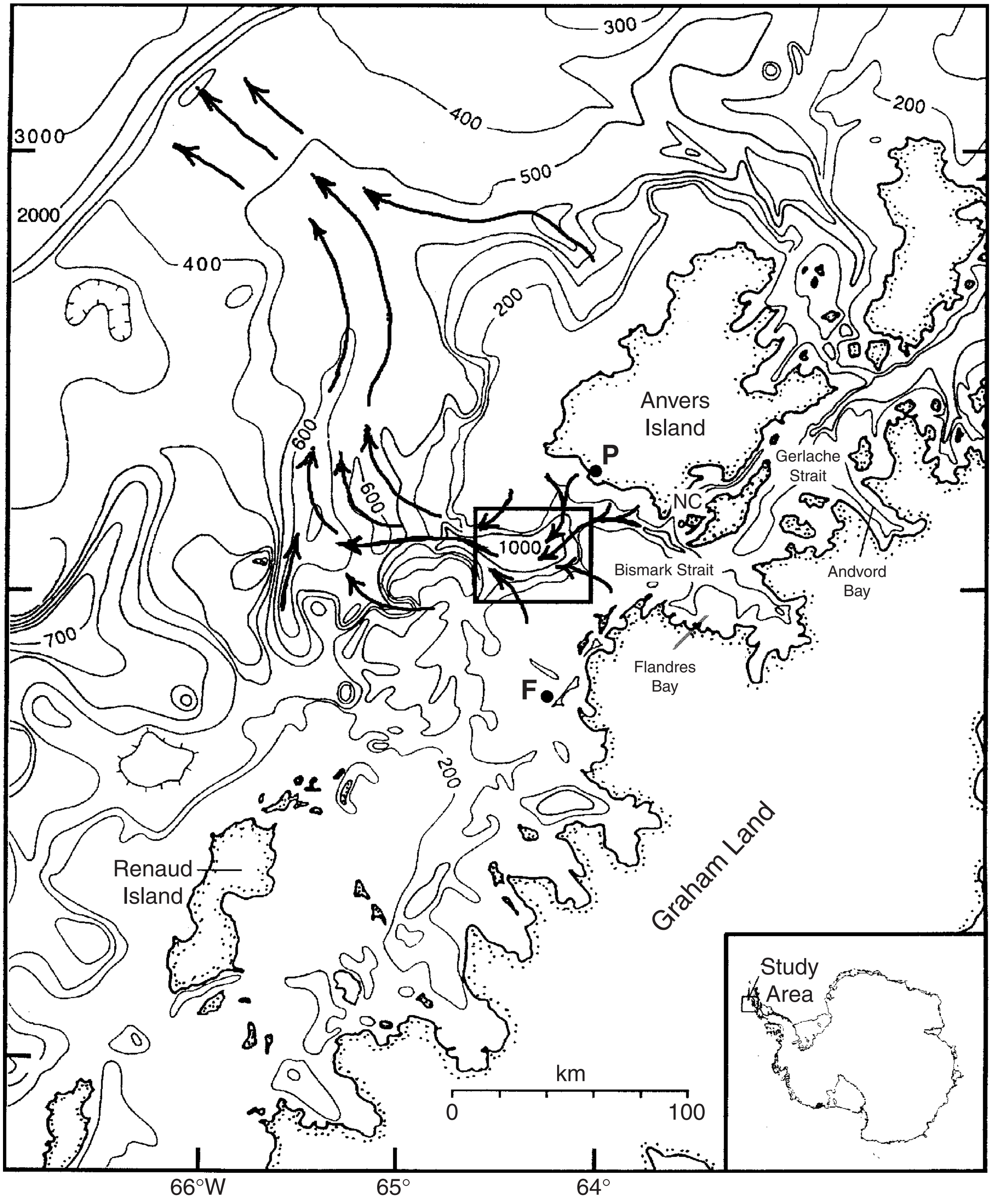

Figure F3. Composite age model for magnetic susceptibility, mass accumulation, and coarse fraction (ice rafted debris) at Site 1098 (after Domack et al., 2001). Timescale is in calibrated (calendar) years before present (BP). Change in MAR scale applied to pre-11 ka (lower scale) and post-11 ka (upper scale) and is not applicable to LGM interval.