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Dynamics of the late Plio–Pleistocene West Antarctic Ice Sheet documented in subglacial diamictites, AND-1B drill core

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ABSTRACT

Geologic studies of sediment deposited by glaciers can provide crucial insights into the subglacial environment. We studied muddy diamictites in the ANtarctic geological DRILLing (ANDRILL) AND-1B drill core, acquired from beneath the Ross Ice Shelf in McMurdo Sound, with the aim of identifying paleo-ice stream activity in the Plio–Pleistocene. Glacial advances were identified from glacial surfaces of erosion (GSEs) and subglacial diamictites within three complete sequences were investigated using lithofacies associations, micromorphology, and quartz sand grain microtextures. Whereas conditions in the Late Pliocene resemble the modern Greenland Ice Sheet where fast flowing glaciers lubricated by surface meltwater terminate directly in the sea (interval 201–212 mbsl) conditions in the Late Pleistocene are similar to modern West Antarctic Ice Sheet (WAIS) ice streams (38–49 mbsl). We identify the latter from ductile deformation and high pore-water pressure, which resulted in pervasive rotation and formation of till pellets and low relief, rounded sand grains dominated by abrasion. In the transitional period during the Mid-Pleistocene (55–68 mbsf), a slow moving inland ice sheet deposited tills with brittle deformation, producing lineations and bi-masepic and unistrial plasma fabric, along with high relief, conchoidally fractured quartz grains. Changes in the provenance of gravel to cobble-size clasts support a distant source area of Byrd Glacier for fast-flowing paleo-ice streams and a proximal area between Darwin and Skelton Glaciers for the slow-moving inland ice sheet. This difference in till provenance documents a shift in direction of glacial flow at the core site, which indirectly reflects changes in the size and thickness of the WAIS. Hence, we found that fast ice streaming motion is a consequence of a thicker WAIS pushing flow lines to the west and introducing clasts from the Byrd Glacier source area to the drill site. The detailed analysis of diamictites in AND-1B demonstrates that Pliocene glacial intervals were warmer than in the Pleistocene when polar ice sheets grew from local inland ice to regional ice streams.

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1. Introduction

In the stratigraphic record of polar regions, diamicts are commonly interpreted to represent deposits from glacial advances although it is recognized that they may form by a variety of processes in a range of depositional environments. This is especially true in the case of marine terminating glaciers because diamicts can form both subglacially and in ice proximal settings (Carr, 2001; Menzies and Zaniewski, 2003; Hiemstra et al., 2005; Ó Cofaigh et al., 2005; Menzies et al., 2006; Kilfeather et al., 2010; Hambrey and Glasser, 2012). Reconstructions of ice sheet advance, retreat, and glacial thermal regime hinge on the ability to infer depositional processes from a diamict. This is certainly the case in sampling the deep time record with drill cores, where dimensions often make it impossible to use clues from macrofabric and structural field relationships. At best, drill cores may be supplemented by seismic reflection profiles and downhole geophysical logs to yield more regionally complete interpretations. Recently, micromorphological analyses from thin sections have become widely recognized as an important additional tool for identifying subglacial deformation (van der Meer et al., 2003; Menzies et al., 2006, 2010; van der Meer and Menzies, 2011).

The dynamic history of the West Antarctic Ice Sheet (WAIS) in the Ross Embayment was recently described from a 1284.87-m-long drill core recording deposition over 13 Ma (Naish et al., 2007, 2009; McKay et al., 2009; Levy et al., 2012; McKay et al., 2012). The drill core, AND-1B contains ~58 geologic sequences, in which advance and retreat of grounded ice are recorded under different styles of glacial and thermal regimes (McKay et al., 2009). The analysis by McKay et al. (2009, 2012) of key glacial and interglacial lithofacies was accompanied by studies of clast provenance (Talarico and Sandroni, 2009; Talarico et al., 2010) and the marine microfossil record (Scherer et al., 2007),

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showing collectively the variable nature of the Antarctic Ice Sheet over time. The geologic record from the core has also provided important constraints for ice sheet modeling (Pollard and DeConto, 2009).

Here our aim is to investigate subglacial conditions by assessing deformation within subglacial tills at scales ranging from 1) macroscopic — based on core description and X-radiography, 2) microscopic — using thin section analyses of skeleton grains and fine-grained matrix (plasma) and 3) scanning electron microscopy (SEM) — to evaluate comminution of quartz grains during glacial transport. Three intervals within AND-1B drill core were selected for study that represent the Late Pleistocene (38–49 m below sea floor (mbsf)), Mid-Pleistocene (55–68 mbsf) and Late Pliocene (201–212 mbsf) (Table 1). Each interval has its lower boundary at a glacial surface of erosion (GSE) and encompasses a complete sequence of advance and retreat of the ice sheet over the drill site. Both intervals in the Pleistocene are interpreted as having been deposited during cold periods, when the WAIS advanced and formed the Ross Ice Shelf (McKay et al., 2009, 2012). The Late Pliocene interval was warmer, with Transantarctic Mountain (TAM) glaciers advancing and retreating in open marine environments in the Ross Sea (McKay et al., 2009). However, these paleoenvironmental conditions were inferred from interglacial sediments because the glacial advance deposits appear macroscopically as massive muddy diamictites.

In this study, we analyze diamictites in the AND-1B core at increasingly smaller scales in order to identify different styles of deformation, evaluate water pressure, and infer thermal conditions at the base of the Antarctic Ice Sheet during the last 2.8 Ma. Quartz sand grains were imaged with the SEM from samples collected throughout the core. Dominant sediment sources in the upper 250 m of the drill core were inferred from the provenance of clasts (diameter > 2 mm). Our analysis focuses on diamictite facies located stratigraphically below the associated interglacial retreat facies. This sequence offers the best opportunity for reconstructing paleoglacial conditions at the bed during glacial advances. To gain additional insight, our observations of diamictites in the AND-1B drill core are compared to sedimentary successions of the LGM in the Ross Sea (Domack et al., 1999; Licht et al., 1999; Shipp et al., 1999; Mosola and Anderson, 2006; Salvi et al., 2006) and diamictons sampled from under modern Antarctic ice streams (Alley et al., 1986, 1989; Tulaczyk et al., 1998; Christoffersen et al., 2010). Our over-arching goal is to describe the paleoglaciological evolution of ice sheets in the Ross Sea during the relatively warm Late Pliocene period and the colder Pleistocene epoch.

Table 1
Summary of glacial and interglacial characteristics of the intervals studied in this paper (chronology according to Wilson et al., 2012).

38–49 mbsf (Late Pleistocene, ~0.36–0.43 Ma)	
Subglacial thickness	4.6 m
Subglacial lithofacies	Sandy-muddy conglomerate, massive clast-rich diamictite, stratified clast-rich diamictite
Macroscopic deformation	Sharp angled glacier erosion surface
Interglacial thickness	1.2 m
Interglacial lithofacies	Laminated mudstone, massive silty claystone
55–68 mbsf (Mid-Pleistocene, ~0.53–0.57 Ma)	
Subglacial thickness	7.6 m
Fluctuating grounding-line	2.9 m
Subglacial lithofacies	Massive clast-rich diamictite, stratified clast-rich diamictite
Macroscopic deformation	Clasts aligned in shear zone; subtle mixing of mudstone into overlying diamictite
Interglacial thickness	0.8 m
Interglacial lithofacies	Graded fine to v. fine sandstone, massive silty claystone
201–212 mbsf (Late Pliocene, ~2.8 Ma)	
Subglacial thickness	6.3 m
Subglacial lithofacies	Massive clast-rich diamictite, stratified clast-rich diamictite
Macroscopic deformation	0.88 m thick interval of mixed diamictite and diatomite, irregular brecciated texture with discrete lenses and blocks of diatomite mixed into diamictite
Interglacial thickness	12.5 m: 8.9 m (open marine), 3.6 m (ice-proximal glacimarine)
Interglacial lithofacies	Open marine: massive and laminated diatomite, diatomite with dispersed clasts, glacimarine: stratified diamictite

2. Setting

A 1284.87-m-long sedimentary rock core (AND-1B) was drilled from beneath the northwestern corner of the Ross Ice Shelf ~5 km from the calving line (Fig. 1). The drill hole is located in the Terror Rift, which lies near the western margin of the larger Victoria Land Basin, one of the three major north–south trending sedimentary basins that form the West Antarctic Rift System of the Ross Embayment (Henrys et al., 2007). The Victoria Land Basin forms one of several north–south trending troughs on the Ross Sea continental shelf, and these troughs are thought to be sites of former ice streams that drained the WAIS and outlet glaciers of the East Antarctic Ice Sheet (EAIS) during the Last Glacial Maximum (Hughes, 1977; Denton and Hughes, 2002; Mosola and Anderson, 2006). The Terror Rift contains ~3.5 km of sediments, accumulated along its central axis since its inception during the Middle Miocene (Henrys et al., 2007). The sedimentary cycles within AND-1B store information about glacial advances and retreats of a marine-based ice sheet within the Ross Embayment since Miocene (McKay et al., 2009; Naish et al., 2009; McKay et al., 2012). During the Last Glacial Maximum an ice sheet extended across the continental shelf of the Ross Embayment and was supplied by ice from both East and West Antarctica (Denton and Hughes, 2002; Licht et al., 2005). Provenance studies of granule-to cobble-sized clasts incorporated into AND-1B diamictites indicate that subglacial ice was sourced from EAIS outlet glaciers of South Victoria Land, to the south of the drill site (Talarico and Sandroni, 2009; Talarico et al., 2010). Today the Ross Ice Shelf ends near Ross Island and two-thirds of its ice is supplied from the WAIS with the remaining ice coming from EAIS outlet glaciers (Fig. 1; Fahnestock et al., 2000). The core chronology used in this paper is based on the AND-1B age model developed from $^{40}Ar/^{39}Ar$ dates, microfossil biostratigraphy, and magnetostratigraphy (Wilson et al., 2012). In addition, the two glacial advance and retreat sequences in the Pleistocene have been correlated to marine isotope stages (MIS) 9–10 and 13–14 by McKay et al. (2012) and the age of the Late Pliocene sequence has been dated to ~2.8 Ma by Levy et al. (2012).

3. Methods

3.1. Lithofacies descriptions

This study focuses on three strategic time intervals each containing a complete glacial–interglacial sequence between two GSEs. All undisturbed cores within each interval were X-rayed at the Antarctic Marine Geology Research Facility in Tallahassee, Florida. The radiographs were then printed to scale and used along with the initial sedimentologic description to draft a lithofacies log at a cm-scale (Fig. 2). The X-rays were especially useful in identifying contacts between facies, sedimentary structures and the presence and orientation of clasts not observed on the split core surface.

3.2. Micromorphology

Rock slabs were cut for 18 large thin sections (45 × 60 mm) from diamictite beds within the study intervals. Thin sections were oriented with respect to vertical but their orientation relative to the ice flow direction is unknown. Friable samples were impregnated with epoxy (Petropoxy 154) before being sectioned. Thin sections were scanned on a high-resolution flatbed scanner to produce a digital low-magnification

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