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Repeated advance and retreat of the East Antarctic Ice Sheet on the continental shelf during the early Pliocene warm period

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ABSTRACT

Diatom analysis of a sediment core recovered at IODP Site U1358 on the continental shelf off the Adélie Coast indicated that the lower section of the core contained an assemblage dating back to the *Thalassiosira innura* Zone of the lower Pliocene that ranges from 4.2 to 5.12 Ma. Based on lithological descriptions at both a macro- and micro-scale of this early Pliocene part of the core, four facies were interpreted from the diamictons representing the progressive advance and retreat of the grounding line over the site. Facies 1a and 1b contain a distinct directional signal from the orientation of the a-axis of clasts with several phases of fabric development along with both brittle and ductile deformation features that are common in sediments that have been subglacially deformed. Facies 1c and 1d are finely laminated and were deposited in open marine conditions. The four facies within the depositional model provide for the first time direct evidence for ice advancing across the shelf adjacent to the Wilkes Subglacial Basin on at least four occasions separated by three periods of open marine conditions indicating retreat of grounded ice inland of the site during a warmer than present early Pliocene. The times of open marine conditions are correlated with previous findings from the neighbouring rise sites that also indicated an oscillating ice margin. This has significant implications because firstly it suggests a dynamic East Antarctic Ice Sheet (EAIS) that is probably far more sensitive to climatic and oceanic forcing even during relatively short time periods than had previously been thought. Secondly it suggests that proxies used to interpret the advance and retreat of the grounding line from the rise can be linked with direct evidence of grounding line migration from the shelf. It also has important implications for the future behaviour and sensitivity of the EAIS under present continuing warming conditions. Together with results from the rise, this paper provides a crucial ice extent target for a new ice sheet model of this region during the Pliocene.

1. Introduction

Polar ice and the expansion and retreat of ice sheets are an important component of the modern climate system, affecting global sea level, ocean circulation, heat transport, marine productivity and planetary albedo among others. With the current rise of atmospheric greenhouse gas concentrations and rapidly increasing global temperatures (IPCC, 2013), studies of polar climates, ice sheet dynamics and (in-)stability are prominent on the research agenda. IPCC (2013) forecasts rising levels of atmospheric CO_2 between 550 and 950 ppm and possible >4 °C warming by 2100 which have not been experienced on our planet since the early to middle Pliocene at ~4.2 to 3.0 Ma (Pagani et al., 2010), with the higher temperature estimates possibly not having been experienced since about 10 to 15 Ma ago. During the early to mid Pliocene, sea level estimates of 22 m above present (Miller et al., 2012) indicate the collapse of not only the Greenland Ice Sheet (7 m sea level equivalent — SLE) and the West Antarctic Ice Sheet (WAIS) (5 m SLE) but also sectors of the EAIS.

While recent satellite observations reveal that the Greenland Ice Sheet and WAIS are losing mass in response to climatic warming, the response of the EAIS has been more variable with increased mass loss through speed up and thinning of outlet glaciers compensated by increased surface accumulation (Pritchard et al., 2009; Shepherd et al., 2012). The EAIS vulnerability to warmer-than-present temperatures may be particularly significant in areas where the EAIS is grounded below sea level and also where the base of the ice sheet is in contact with the Southern Ocean, such as the Wilkes Subglacial Basin. This vulnerability can be studied using the geological record from intervals

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with similar environmental conditions to those predicted for the near future. Studies from the continental rise and slope as well as the deep ocean have used multiple proxies such as sediment facies and grain size, IRD concentrations, siliceous microfossils, biogenic opal, geochemical composition and clay mineralogy to interpret ice sheet dynamics in response to varying palaeoenvironmental conditions (e.g. Bart et al., 2007; Escutia et al., 2009; Williams et al., 2010; Passchier, 2011; Cook et al., 2013). During the early Pliocene (3.6 to 5.3 Ma), Southern Ocean sea surface temperatures (SST) north of Prydz Bay reached over 5 °C warmer than present (Bohaty and Harwood, 1998; Whitehead and Bohaty, 2003; Escutia et al., 2009), and winter sea ice was reduced up to 78% compared to present day (Whitehead et al., 2005). Although these data are relevant for palaeoenvironmental conditions linked to the advance and retreats of the ice sheet during glacial and interglacial cycles respectively, they cannot trace the migration of the grounding line and thus cannot constrain the lateral extent of grounded ice. This constraint is critical if estimations are to be made regarding sea level change. The location of the grounding line in turn can only be determined from continental shelf records. For example, the ANDRILL (AND-1B) core drilled below the Ross Ice Shelf allowed Naish et al. (2009) and Pollard and DeConto (2009) to model total collapse of WAIS during warm early Pliocene times while at other times during the Pliocene the ice cover in the Ross Sea was greater than the current modern extent.

The aim of this paper is to provide direct evidence of either open marine conditions or the presence of grounded ice offshore from the Wilkes Subglacial Basin during the early Pliocene warm interval (i.e., 3.6 to 5.3 Ma) and thus test the interpretations made from other rise and deep ocean sites that assert a dynamic EAIS with several advances and retreats of the grounding line across the shelf (Bart, 2001; Escutia et al., 2005, 2009, 2011; Williams et al., 2010; Cook et al., 2013). Thus, the opportunity is provided to link the fluctuations and glacial–interglacial cyclicity reported from both the rise and deep ocean sediments in addition to those predicted by ice sheet models (Mengel and Levermann, 2014), with direct evidence of grounding line migration.

1.1. Ice sheet fluctuations during the early Pliocene

Some of the earliest models of the Antarctic ice sheets suggested that warmer than present climatic conditions would lead to an increase in ice volume (Oerlemans, 1982; Huybrechts, 1994) and more recently studies indicate that since their inception, the Antarctic ice sheets have been very dynamic, waxing and waning (DeConto and Pollard, 2003). This includes the margins of the EAIS, particularly those parts grounded below sea level (i.e., in the Wilkes Subglacial Basin) and the marine-based WAIS (Pollard and DeConto, 2009; Mengel and Levermann, 2014). Some of these models also indicated significant variations in ice sheet volume during the Pliocene (Hill et al., 2007; Dolan et al., 2011; Haywood et al., 2012). Seismic stratigraphy from the Antarctic margin has also identified major erosional events linked to glacial cycles (e.g. Eittreim et al., 1995; Escutia et al., 1997, 2005; Barker et al., 1999; Bart et al., 1999; Bart, 2001; De Santis et al., 2003; Rebesco et al., 2006; Cooper et al., 2009).

Diatomite units recovered in the early Pliocene section of the AND-1B core point to persistent open marine conditions with grounded ice inland of the site (McKay et al., 2009; Naish et al., 2009). It is during these periods that models also show the collapse of WAIS (Pollard and DeConto, 2009). It is unclear whether similar advance and retreat phases occurred on the shelf of other regions bordering the EAIS. However, Cook et al. (2013) have used geochemical provenance of detrital material in sediments from the continental rise to suggest active erosion of continental bedrock from within the Wilkes Subglacial Basin and retreat of EAIS in this area several hundred kilometres inland during early Pliocene times. In addition, Williams et al. (2010) show that the provenance of ice-rafted detritus also on the continental rise of East Antarctica at 3.5 Ma and 4.6 Ma saw significant increases in iceberg production into the Southern Ocean from along the Wilkes Land and Adélie Land margins.

Direct evidence of grounded ice migration can only be derived from shelf sites. Micromorphological and fabric analyses of sediment cores from the shelf provide a key piece of evidence when trying to differentiate between subglacial and glacimarine sediments because they are deposited by different processes and thus have different micro-scale sedimentary signatures (Reinardy et al., 2011a,b).

2. Drilling site and regional setting

Integrated Ocean Drilling Program (IODP) Expedition 318 drilled a transect of sites across the Wilkes Land margin of Antarctica to provide a long-term record of the sedimentary archives of Cenozoic Antarctic glaciation and its relationship with global climatic and oceanographic change. Drilling was undertaken to constrain the age, nature, and palaeoenvironment of the previously only seismically inferred glacial sequences (Escutia et al., 2005, 2011). Site U1358 is situated on the outer continental shelf off the Adélie Coast at the mouth of the north western end of the George V Basin at 499 mbsl and receives drainage from the EAIS through the Wilkes Subglacial Basin (Fig. 1). The location of the site is significant because the EAIS in this sector is grounded below sea level and it has the potential to become unstable and could have contributed to sea level rise during past times of warmth (Escutia et al., 2005, 2011; Cook et al., 2013; Mengel and Levermann, 2014).

Site U1358 and the regional stratigraphy based on seismic data are described in detail in Escutia et al. (2005, 2011) and are only briefly mentioned here. It is important to note that glacimarine and subglacial deposits cannot always be differentiated from seismic data because both can have very similar acoustic characteristics and the interpretation of glacial stratigraphy using seismic data alone can be problematic (Stoker et al., 1992). Hole 1358B penetrated 35.6 mbsf into steep foresets above unconformity WL-U8 which has previously been suggested to be deposited in front of grounded ice sheets that extended intermittently onto the outer shelf (Eittreim et al., 1995; Escutia et al., 2005; Cooper et al., 2009). Because the hole had to be terminated before weight-on-bit could be applied, the total cored interval for 1358B was 35.6 m but the total core recovery was only 8 m of diamicton.

3. Methods

Cores from Hole U1358B were recovered using a rotary core barrel system. This study focuses on the two lower cores below 17.3 mbsf. These are core 3R consisting of 3 sections, 3R-1 to 3 and core 4R also consisting of 3 sections, 4R-1 and 2 and 4R-CC (Fig. 2). 3R and 4R have been assigned a Pliocene age by Escutia et al. (2011) and Orejola et al. (2014). The diatom assemblage was used to refine this age model (see discussion below). For dating and micromorphology, it is important to note that cores 3R and 4R were not significantly disturbed by the coring process (Escutia et al., 2011).

3.1. Micromorphological analysis and fabric data

Both macro- and micro-scale descriptions and interpretations were carried out on cores 3R and 4R. Micromorphology is a particularly effective technique used to interpret depositional environments from sediments that appear massive at a macro-scale and where there are only limited exposures as is the case with sediment cores. Micromorphology has previously been used to provide evidence of grounded ice at Cape Roberts (van der Meer and Hiemstra, 1998; Hiemstra, 1999; van der Meer, 2000). The technique has also been used on Antarctic sediments to indicate basal thermal regime (Baroni and Fasano, 2006), deformation processes (Evans et al., 2005; Ó Cofaigh