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Warm fjords and vegetated landscapes in early Pliocene East Antarctica

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Abstract

The response of the Antarctic ice sheets to future warming is uncertain. The IPCC are predicting minimal melt from Antarctica while others suggest increased meltwater contributions are possible. The Pliocene period (5.333 Ma to 2.58 Ma) may provide insights into future ice sheet response, because atmospheric CO_2 concentrations were similar to today (350 - 450 ppmv) and the earth surface was between 2°C an 4°C warmer than the preindustrial conditions. Geological records indicate that Antarctica's ice sheets were smaller and more dynamic at this time and many sea-level estimates require meltwater input from the Greenland, West (WAIS) and East Antarctic Ice sheets (EAIS). However, only a few records exist proximal to the Antarctic ice sheet which allow for reconstruction of the Pliocene climate state. We present a multiproxy climate reconstruction from a sedimentary succession that was deposited in an ancient fjord within the Transantarctic Mountains, covering discrete intervals between the early Pliocene and the late Pleistocene. In contrast to modern frigid conditions, our records indicate sea surface temperatures of about 5.6°C at c. 4.1 Ma, the presence of a plant community at the fjord margins and evidence of soil formation. Simulations of potential vegetation cover in the Pliocene indicate our reconstruction is most compatible with a complete collapse of the WAIS and a large scale retreat of the EAIS from the subglacial basins with atmospheric CO_2 levels of less than 450 ppmv. Our study indicates that under present day atmospheric CO_2 conditions, in the early Pliocene, the Antarctic ice sheets retreated significantly. Understanding the mechanisms driving this large-scale ice sheet retreat would enable us to assess whether current atmospheric CO_2 concentrations will lead to the same ice sheet configuration once the Earth system has come to a new equilibrium state.

Keywords: Pliocene; East Antarctic Ice Sheet; environmental magnetism; sedimentary biomarkers; modelling; BIOME4

1. Introduction

Antarctica's ice sheets hang in a delicate balance where snow accumulates in the interior, becomes ice and flows to the edges where it floats on the ocean forming an insulating ice shelf. Ocean circulation, specifically the introduction of 'warm' water adjacent to and beneath ice margins, is thought to be the principal influence on long-term stability of the modern WAIS and the Wilkes Land and Aurora sector of the EAIS. Today ice shelves in the Amundsen Sea region appear to be destabilising because 'warm' deep ocean water is coming into contact with the ice (Mouginot et al., 2014) and modelling studies indicate rapid ice margin retreat could occur soon (Golledge et al., 2019). The effect of warm waters in contact with Antarctic ice over many centuries can by explored by studying ancient records deposited near the ice margin when atmospheric CO_2 and surface temperature were similar to what is predicted in the coming decades (Naish et al., 2009; Mckay et al., 2012; Levy et al., 2012, 2016). The most suitable time period for such comparisons is the Pliocene: it is the most recent, and best understood, epoch with strong similarities to the present day. The ANDRILL AND-1B succession showed that the Ross Ice Shelf (an extension of the WAIS) was dynamic and retreated repeatedly (Naish et al., 2009; Mckay et al., 2012) and Integrated Ocean Drilling Program Exp 318 showed that the Wilkes Land margin (A marine sector of the EAIS) was also dynamic during the Pliocene (Cook et al., 2013; Patterson et al., 2014). Sea-level records provide supporting evidence of dynamic ice sheets with higher average sea-level and higher frequency variations during the Pliocene (Grant et al., 2019). However, determining sea surface water temperatures (SSTs) and other environmental metrics from the Pliocene ice margin have been thus far difficult to reconstruct owing to a paucity of appropriate sedimentary records and a lack of reliable SST proxies. Here we present geological drill core evidence of ice margin response during the Pliocene from a fjord in the Transantarctic Mountains. Our data indicate warm and wet conditions on land, elevated sea surface temperatures and the presence of a local, higher order plant community. Numerical simulations to identify ice sheet configurations which are most compatible with our proxy reconstructions, indicate large scale retreat of the EAIS from subglacial basins during the Pliocene is most consistent with the data presented here.

1.1. Drill core of the Pliocene to modern climate transition

The 327.96 m long, DVDP-11 succession (McKelvey, 1981) spans the last 5.5 Ma and provides a unique insight into the Pliocene warm period in the Taylor fjord (Transantarctic Mountains, Fig. 1). We identify two sedimentary regimes (Fig. 2) that were deposited under different environmental and climatic conditions. Between 0 m and 195.22 m (0 Myr to c. 2.8 Myr (Ohneiser and Wilson, 2012)) sediments are dominated by volcanic rich sands, diamicts and conglomerates (Porter and Beget, 1981) that were deposited in a lacustrine, fluvial or shallow marine setting with persistent multi-year sea-ice (Levy et al., 2012). The lower section, below 195.22 m (c. 4.1 Myr to 5.5 Myr (Ohneiser and Wilson, 2012)) is more complex. It contains massive to well stratified diamictites, interbedded with thinner, bioturbated, mudstone beds that are rich in diatoms (Winter and Harwood, 1997), marine benthic microfossils (Ishman and Rieck, 1992) and were deposited in a deep (600 and 900 metres) fjord setting (Ishman and Rieck, 1992) with productive surface waters (Winter et al., 2012). Diamictities were deposited under an expanded Taylor Glacier and can be inferred to cooler climate conditions. In this study we conducted organic geochemical, palynological, and magnetic mineral analyses on drill core sediment samples to reconstruct the oceanic and terrestrial setting.

2. Methods

2.1. Palynology.

Eight sediment samples from the DVDP-11 drill core were analysed for palynology. With the exception of common unidentified algal remains in two samples, palynomorphs were extremely sparse in all samples, and none contained more than a few grains of fossil pollen. The samples were processed for palynology at GNS Science using standard methods: 10% hot HCl wash, 50% HF, a further 10% HCl, float in sodium polytungstate at 2.0 s.g., filter through a 6 μm mesh, mount on glass cover slips in glycerin jelly. The entire residue of each sample was examined under a light microscope. The shallowest sample examined, 16.32 m, contained the greatest abundance and diversity of palynomorphs (spores, pollen, algae), dominated by an unidentified dinoflagellate cyst (Fig. 3A). The sample also contained dark spherical forms interpreted as fungal fruiting bodies (possibly contaminant), and other clear hyaline forms possibly of algal origin (cf. *Leiosphaeridia*). The sample at 240.06 m contained abundant unidentified approximately spherical pigmented forms of variable size with small protrusions, possibly of algal origin (Fig. 3B).

2.2. Biomarker extraction and analyses.

We selected the long chain diol index (LDI) for our SST reconstruction because these are the most effective SST proxy at high latitudes. Reconstructing ancient SSTs at high latitudes until recently has been difficult because of ecological intolerance of the organisms that produce alkenones and problems with the diagenesis and preservation of calcareous microfossils used for Mg/Ca paleothermometry (Beltran et al., 2016). In contrast LDIs are found from low to high latitudes, have a temperature range of -3°C to +27°C (Rampen et al., 2012) and a calibration error of ±1°C which is comparable to alkenone derived SSTs.

Organic geochemical analyses were conducted at the University of Otago

Centre for Organic Geochemistry and Paleoclimate studies (COrGePS). n-alcohols and LDIs were extracted from freeze-dried sediments (4 to 10 g of sediments) using a Dionex 300 Accelerated Solvent Extractor with dichloromethane and methanol (9:1, v/v) at 1500 psi and 100°C.

Compound identification of the LDIs was conducted using an Agilent 6890N gas chromatograph (GC) equipped with an Agilent 5975B mass selective (MS) detector in selective ion monitoring mode operated at 100 eV (EI Source). LDI were separated using a fused silica capillary column (ZB-5MS, 30 m long, 0.32 mm internal diameter, 0.25 μm film thickness). The initial oven temperature started at 70°C and increased at a rate of 30°C min-1 to 120°C and subsequently at a rate of 5°C min-1 to the final temperature of 300°C, which was held for 10 min. The relative abundance of long chain diols was measured using single ion monitoring of m/z 299, 313, 327, and 411.

Epicuticular waxes (n-alcohols) on the surfaces of plants help regulate the water balance of the plant. The waxes can be preserved in sediment and provide an alternative means (from pollen analyses) to identify a plant community. n-alcohols were isolated by silica gel chromatography using solvents of increasing polarity following a standard procedure (Sicre et al., 2001). The fractions containing n-alcohols were concentrated, transferred to clean glass-vials, evaporated under nitrogen, and derivatized after reaction with N,O-bis (trimethylsilyl) trifluoroacetyl acetamide (BSTFA-TMS).

Gas chromatographic analyses were performed on a Hewlett Packard 6890 gas chromatograph with a flame ionisation detector using a fused silica capillary column (Rxi-1ms, 50 m long, 0.32 mm internal diameter, 0.25 μm film thickness). Helium was used as a carrier gas. 5(alpha)- androstane was used as an internal standard and was spiked into the final extracts immediately before injection onto the GC. Recoveries were calculated by comparing the target to internal standard ratio. GC/FID quantification was performed using a calibration curve (0 ng mL -1 to 250 ng mL -1) with commercial standards (C22, C24, C28 n-alcohols).

2.3. Magnetic mineralogy studies.

All magnetic analyses were conducted at the Otago Paleomagnetic Research Facility at the University of Otago, New Zealand. Thermomagnetic analyses (Fig. 4E, F) were conducted on crushed/powdered samples that were progressively heated to 700°C in air on an AGICO MFK-1CS Kappabridge system. Samples were disaggregated using a mortar and pestle and rock fragments were removed by sieving in a (250 micron sieve) to ensure only the fine fraction was measured because the signal of minerals with lower saturation magnetisation could easily be masked by the presence of a small basaltic rock fragment. Curie/Néel temperatures were determined using the differential method. FORC (Fig. 4 A-D), IRM and hysteresis analyses were conducted on c. 0.15 g samples using a Princeton Measurements Corporation vibrating sample magnetometer (VSM, Micro-Mag 2900). FORC (Pike et al., 1999) measurements were made with a field spacing of 2 mT, Hc between 0 and 100 mT, and Hu between -60 and +60 mT. Data were processed using the FORCinel (Harrison and Feinberg, 2008) with a smoothing factor of between 3 and 7 depending on the magnetic mineral concentration and hence the noise level of the measurements.

2.4. Numerical simulations.

HadCM3, the UK Met Office Unified Model General Circulation Model (GCM), was used for each of the climate model simulations in this study (Gordon et al., 2000). The atmosphere has a horizontal resolution of 2.5° in latitude and 3.75° in longitude, with 19 vertical layers (Pope et al., 2000). The radiation scheme represents the effects of minor trace gases (Edwards and Slingo, 1996) and has a parameterised background aerosol climatology (Cusack, 1998). These simulations use the fixed land-surface scheme of (Cox et al., 1999) and the ocean component is a 1.25° x 1.25° resolution, 20 level version of the (Cox and Geophysical Fluid Dynamics Laboratory, 1984) ocean model. The sea-ice model is a simple thermodynamic scheme, with parameterised ice drift and sea-ice leads (Cattle and Crossley, 1995).

Four simulations have been run including a pre-industrial control and three simulations (Table 1). The Pliocene simulations use the alternative boundary conditions from PlioMIP (Bragg et al., 2012), which incorporate changes in atmospheric carbon dioxide concentrations, vegetation, orography and ice sheet coverage, but not changes to the modern land-sea mask. These boundary conditions have been modified only over East Antarctica (Fig. 6) to represent a large scale retreat scenario and a modern EAIS scenario, encompassing the uncertainties in the size of the EAIS in the Pliocene de Boer et al. (2015). The simulation with enhanced southern hemisphere insolation has an orbital configuration equivalent to 3.049 Ma (Dolan et al., 2011). BIOME4 is a coupled carbon and water flux model, which predicts global steady state vegetation distribution, structure and biogeochemistry (Kaplan et al., 2003). BIOME4 simulates twelve plant functional (PFT) types, each with a specific range of climate tolerances, ranging from high latitude to tropical flora. BIOME4 determines which of 28 biomes is most likely to occur in a grid square based on biogeochemical variables. The model is forced by monthly mean temperature, precipitation and available sunlight. Atmospheric carbon dioxide concentrations are specified. BIOME4 has been run on the latest land-sea mask configuration over Antarctica (Dowsett et al., 2016), as this shows the areas of land most likely to be subaerial during times in the Pliocene when the WAIS is collapsed.

3. Results

Palynomorphs were extremely rare in all samples. However, the absence of pollen in DVDP-11 sediments does not indicate an absence of an ancient terrestrial plant community because under oxidative conditions or in the absence of sorptive preservation media pollen can be easily degraded (Versteegh et al., 2010). In absence of palynomorphs, we studied the distributions of n-alcohols in the extractable organic matter fractions from 14 samples to explore further the possible signature of vegetation.

All samples analysed contained n-alcohols with concentrations varying between 7.6 ng/g (nanogram per gram of sediment) and 83.6 ng/g of sediment (Fig. 2A). The highest concentrations were in the lower half of the core (207.39 m to 325.62m). High molecular weight (HMW) n-alcohols (from n-C_{21} up to n-C_{32}) were found in the mudstone intervals below 205 m with evidence of higher order plant waxes with the typical even/odd predominance in the HMW homologues (Logan et al., 1995) recognized in the samples between 207.39 and 223.58 m and at the base of the record (325.62 m). In parallel, summer sea surface temperatures were reconstructed from the LDI (Rampen et al., 2012). Long chain alkyl diols are produced by Proboscia diatoms, which modify chain length and degree of unsaturation of cell membrane lipids in response to ocean temperature to maintain constant membrane fluidity. Proboscia diatoms have existed in Antarctic waters since c. 18 million years ago and are reported in the DVDP-11 (Proboscia barboi between 203.07 m and 247.81 m depth). Our analyses identified long chain alkyl 1,13- and 1,15-diols (see methods) in five samples between 207.4 m and 248.8 m (Fig.3) that resulted in temperatures ranging between 1.1°C and 5.6°C (Fig. 2B).

4. Environmental magnetic records

Magnetic mineral type, grain-size, and concentration, are controlled by environmental, depositional, and/or post depositional processes (Sagnotti et al., 1998; Roberts et al., 2013). We observe that the upper and lower parts of the core have contrasting magnetic mineralogy and concentrations (Fig. 2C and Supplementary Fig. S1). Above 195 m (younger than 2.8 Ma) magnetite is dominant with curie temperatures of c. 580°C and high concentrations. First Order Reversals Curves (FORC) indicate a mixed magnetic grain-size, which is dominated by super-paramagnetic (SP) grains (Fig. 4 A and B) as evidenced by the shift of the FORC distribution to the origin and the appearance of positive contours along the vertical axis of the lower quadrant (Lanci and Kent, 2018). Magnetic mineral concentrations are lower below 195 m (older than 4.1 Ma) and comprise alternating pristine and modified mineral input. Thermomagnetic data indicate mixtures of magnetite, maghemite or minor hematite (Figs. 4 and 5) in muddy intervals and pure magnetite dominated mineralogy in coarser lithgologies (i.e. diamictite). Analyses of rock and surface sediment samples from this sector of the Transantarctic mountains identified magnetite as the dominant magnetic mineral in rocks and surface sediments (Ohneiser et al., 2015). Maghemite and hematite may have a pedogenic origin which is climate rather than time dependent (Maher, 2011; Nie et al., 2010). In DVDP-11 the occurrence of haematite and maghemite in only the fine grained sediments suggests a climate control on magnetic grain production. Therefore we suggest that maghemite and or hematite found in DVDP-11 was produced at the fringes of the fjord and was transported to the sea by rivers. FORC analyses of mudstone and diamictite samples (Fig. 4 C and D) indicate the presence of larger magnetic grains ranging from pseudo single domain to multi domain grains and a potential contribution of biogenic magnetite (Roberts et al., 2014). We find no evidence of SP grains in this lower section indicating that they are either absent or their signature is masked by larger grains.

5. Numerical simulations

Previous climate model simulations using the best available Pliocene boundary conditions have not produced Antarctic climates similar to those suggested by these data (Haywood et al., 2013). Although, it seems clear that the WAIS saw significant reductions during the Pliocene and Pleistocene (Naish et al., 2009; Beltran et al., 2020), the state of the EAIS is much less certain and the details of this could have a large impact on Dry Valleys climate. Here we present the results of new climate model simulations using the UK Met Office Unified Model coupled ocean-atmosphere General

Circulation Model (GCM), HadCM3, looking at different scenarios of EAIS retreat. We also reconstruct the vegetation that could have been present in the Dry Valleys at the time using the BIOME4 mechanistic vegetation model. We compare model-predicted temperatures from three Pliocene simulations (Table 1); one with a modern EAIS and no retreat, one where no retreat is prescribed but the Southern Hemisphere orbital forcing has been enhanced and a final simulation with large-scale retreat of the EAIS (Fig. 6E). The simulations show that in order to support summer temperatures significantly above freezing (Table 1; Fig. 5) and more than the most simple of tundra environments in the Dry Valleys region (Fig. 6E), large scale retreat of the EAIS is required. In this modelling framework, retreating the EAIS to as far south as Taylor Dome prevents cold air masses from entering the Dry Valleys causing summer temperatures of more than +4°C. BIOME4 mechanistic vegetation model results only allow for cushion forb and prostate tundra environments in the Dry Valleys unless large scale EAIS retreat is prescribed, when more productive tundra environments are simulated (Fig. 6E).

6. Discussion and Conclusions

Our data indicate that between c. 4.1 and 4.25 Ma (c. 201m and 225 m) the ocean temperature in Taylor fjord was between 5.6±1°C (Fig. 2) and 2.6±1°C, similar to contemporaneous $TEX_{86}{}^{L}$ derived temperatures (Mckay et al., 2012) from the Ross Sea (AND-1B) (Fig. 2E).

The elevated annual average and peak seasonal temperatures imply a dramatically different hydrologic system when compared with today. We find supporting evidence of warmer, wetter terrestrial conditions in the magnetic minerals and organic geochemical records and simulations indicate mean summer temperatures of ca. 8°C and enhanced precipitation over Taylor fjords.

Rees-Owen et al. (2018) recently reconstructed the ancient plant community and continental surface temperature using biomarkers on the Neogene fossil-bearing Sirius Group deposits at Olivers Bluff (c. 850km south of Taylor Valley). They determined an average continental summer temperature of c.5°C from tetraether lipids which was warm enough to allow a low, diversity plant community to exist (Rees-Owen et al., 2018).

We selected high molecular weight n-alcohols for our reconstruction because they are most likely derived from a local plant community (Gagosian et al., 1987) where as n-alkanes are common in soils, carbon bearing formations, and sediments (Eglinton, 1969) and could be recycled from older formations or transported over long distances (Gagosian et al., 1987). We did not identify altered biomarkers which could be sourced from the much older Beacon Supergroup sediments (Matsumoto et al., 1990).

Feakins et al. (2012) suggested, because biomarkers and palynomorphs in the nearby ANDRILL AND-2A succession were not ubiquitous that they indicate the sporadic appearance and disappearance of a local plant community. We suggest that the n-alcohols in DVDP-11 were derived from local, woody plant community on the shore of the Taylor fjord because n-alcohols are unlikely to survive long distance transport or recycling (Gagosian et al., 1987). The numerical vegetation simulations that were conducted under temperature conditions comparable to the SST record indicate conditions were sufficiently warm for dwarf shrub and tundra to occupy the Transantarctic

Mountains.

The transition to cooler conditions in Taylor Valley occurred between 4.1 Ma and 2.6 Ma. In the Ross Sea the surface waters cooled at c. 3 Ma (Mckay et al., 2012) with fewer and shorter duration periods when the Ross Ice Shelf retreated (Naish et al., 2009). Similarly at the Wilkes Margin, precession driven (paced) cooling began at around 3 Ma (Patterson et al., 2014). The transition from a smaller, dynamic ice sheet to a larger, more stable ice sheet coincides with a shift in the long term, atmospheric CO_2 concentrations (Fig. 2F). Our drill core record indicates that under elevated atmospheric CO_2 conditions (Fig. 2) Taylor fjord was ice free with negligible or no delivery of icebergs to the fjord. Ocean temperatures were too warm to allow summer sea-ice and atmospheric conditions were warm enough that a plant community was present. Our climate model simulations indicate that this is plausible under very high insolation forcing or with the with loss of Taylor Dome; a small land based portion of the EAIS. The reduction in ice volume results in a significant sea-level increase with a contribution of more than 10 metres of sea-level rise from the EAIS. While studies indicate that current equilibrium climate sensitivity (ECS) estimates 1.5 - 4.5°K of warming per CO_2 doubling are probably accurate (Martinez-Boti et al., 2015) our study indicates that this sector of Antarctica (and likely the wider region) will experience significant warming (up to 6-7°K) and ice retreat under the current (and future) CO_2 conditions (400 ppm - RCP2.6).

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Figure 1: (**A** Location of the DVDP-11 drill site in Taylor Valley within the Transantarctic Mountains and the AND-1B successions (Naish et al., 2009). **B** Looking up the modern day Taylor Valley towards the East Antarctic Ice Sheet. The DVDP-11 drill site is near the foot of the Commonwealth Glacier (right of photo).

Figure 2: DVDP-11 stratigraphic record with magnetic polarity zones and glacial proximity as derived from sediment character. (**A**) high molecular weight alcohol concentrations (green leaf indicates woody plant biomarkers), (**B**) LDI derived Sea Surface Temperature, (**C**) magnetic susceptibility (Ohneiser and Wilson, 2012), (**D**) curie/néel temperature of magnetic grains within sediment, (**E**) TEX86 derived Sea Surface Temperature from McMurdo Sound (Mckay et al., 2012), (**F**) composite atmospheric CO_2 (see supplement for details on proxies used and their source), (**G**) benthic δ^{18}O record (Lisiecki and Raymo, 2005), (**H**) insolation at 77°S, (**I**) orbital eccentricity.

Figure 3: **A** Unidentified dinocyst, **B** Unidentified Algae spp. **C** Selected gas chromatography/mass spectrometry (GC/MS) chromatogram for a sample from 248.8 m depth.

Figure 4: FORC analyses indicate a peak response centred at between 0 and 5 mT above 185m **A** and **B**) which indicates the presence of significant quantities of superparamagnetic (SP) magnetite (Roberts et al., 2014; Lanci and Kent, 2018). The weak response up to 50 mT indicates smaller relative quantities of single domain grains. Below 185 m (**C** and **D**) the peak response is centred between 5 and 25 mT and the peak is more broad indicating larger grains are dominant such as multidomain grains (229 m) and a mixture of SD and pseudo single domain grains (Roberts et al., 2014). Thermomagnetic data of two samples from DVDP-11 with magnetite dominated mineralogy (**E**, 76.22 m) with a curie temperature of 580°C and (**F**, 207.36 metres) a mixed magnetic mineralogy with curie temperatures ranging from 580°C to 680°C.

Figure 5: A scatter plot of lithology versus Curie/Néel temperature as derived from 92 thermomagnetic analyses. All diamictites includes massive and stratified diamictites as well as three breccia and four conglomerate samples. A moderate correlation coefficient of 0.62 indicates a reasonable associate between lithologies associated with warmer depositional setting and a higher Curie/Néel temperature.

Figure 6: Results from climate model simulations where the red square indicates the location of the DVDP-11 record in Taylor fjord. (**A**) Mean Annual temperature, (**B**) Mean Summer temperature (DJF - Decembers, January, February), (**C**) Mean February sea surface temperature, (**D**) Mean annual precipitation, and (**E**) predicted vegetation coverage and type under prescribed atmospheric conditions. **E** also shows the extent of the ice sheet (land ice) prescribed in the climate model and also the land-sea mask applied in the climate model (barren).

Table 1: Dry Valleys climate variables from HadCM3 simulations of the pre-industrial and Pliocene sensitivity experiments.

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