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1 **Dynamic Behaviour of the East Antarctic Ice Sheet during Pliocene Warmth**

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39

40 **Warm intervals within the Pliocene Epoch (5.33 to 2.58 million years ago) were**
41 **characterised by global temperatures comparable to those predicted for the end of this**
42 **century¹ and atmospheric CO₂ concentrations similar to today^{2,3,4}. Estimates for global**
43 **sea level highstands during these times⁵ imply possible retreat of the East Antarctic Ice**
44 **Sheet, but ice-proximal evidence from the Antarctic margin is scarce. Here we present**

45 new data from Pliocene marine sediments recovered offshore of Adélie Land, East
46 Antarctica, that reveal dynamic behaviour of the East Antarctic Ice Sheet in the vicinity
47 of the low-lying Wilkes Subglacial Basin during times of past climatic warmth.
48 Sedimentary sequences deposited between 5.3 and 3.3 million years ago indicate
49 increases in Southern Ocean surface water productivity, associated with elevated
50 circum-Antarctic temperatures. The geochemical provenance of detrital material
51 deposited during these warm intervals suggests active erosion of continental bedrock
52 from within the Wilkes Subglacial Basin, an area today buried beneath the East
53 Antarctic Ice Sheet. We interpret this erosion to be associated with retreat of the ice
54 sheet margin several hundreds of kilometres inland. Our new data show that the East
55 Antarctic Ice Sheet was sensitive to climatic warmth during the Pliocene, with
56 implications for its future stability in a warmer world.

57

58 Recent satellite observations reveal that the Greenland and West Antarctic ice sheets
59 are losing mass in response to climatic warming⁸. Basal melting of ice shelves by warmer
60 ocean temperatures is proposed as one of the key mechanisms facilitating mass loss of the
61 marine-based West Antarctic Ice Sheet⁹. While thinning of ice shelves and acceleration of
62 glaciers has been described for some areas of the East Antarctic margin⁹, the mass balance of
63 the predominantly land-based East Antarctic Ice Sheet is less clear¹⁰. Its vulnerability to
64 warmer-than-present temperatures may be particularly significant in low-lying regions, such
65 as the Wilkes Subglacial Basin (Fig. 1).

66 This hypothesis can be tested by studying intervals from geological records deposited
67 under similar environmental conditions to those predicted for the near future. Warm intervals
68 within the Pliocene Epoch are such analogues, with mean annual global temperatures
69 between 2 and 3°C higher than today¹ and atmospheric CO₂ concentrations between 350 and
70 450ppm, 25 to 60% higher than pre-industrial values^{2,3,4}. Estimates for eustatic sea level
71 highstands during these times, reconstructed from benthic foraminiferal oxygen isotopes⁵ and
72 paleoshoreline reconstructions¹¹, are variable but indicate 22 ± 10 meters of sea level rise,
73 although estimates derived from paleoshoreline reconstructions may need corrections for
74 glacio-isostatic adjustments¹². Complete melting of Greenland and West Antarctica's ice
75 sheets could account for around 12 meters¹³ of eustatic sea level rise, indicating that most
76 estimates for Pliocene sea level require a contribution from the East Antarctic Ice Sheet.
77 While ice sheet modelling suggests that low-lying areas of the East Antarctic continent may

78 be candidates for Pliocene ice sheet loss^{6,7}, direct evidence from ice-proximal records on
79 locations of ice margin retreat are limited¹⁴⁻¹⁶.

80 To improve our understanding of the response of the East Antarctica Ice Sheet to past
81 warm climates, Integrated Ocean Drilling Program Site U1361 (64°24.5°S 143°53.1°E;
82 3465m water depth) was drilled during Expedition 318 into a submarine levee bank, 310
83 kilometres offshore of the Adélie Land margin, East Antarctica (Fig. 1). Approximately 50
84 meters of continuous Pliocene marine sediments, within the resolution of current
85 biostratigraphic and magnetostratigraphic data¹⁷, were recovered. Available physical
86 property¹⁸, sedimentology¹⁸, and paleomagnetic and micropaleontology data¹⁷ are here
87 combined with new opal (%) data, bulk geochemistry data, and radiogenic isotope data from
88 analyses of detrital sediments.

89 The Pliocene study section at IODP Site U1361 spans an interval between 5.3 and 3.3
90 million years ago and contains a sedimentary sequence alternating between eight diatom-rich
91 silty clay layers, and eight diatom-poor clay layers with silt laminations (Fig. 2). Diatom-rich
92 sediments have higher diatom valve and bulk-sediment biogenic opal concentrations and
93 distinctively lower signals in natural gamma radiation (Fig. 2), indicating lower clay content.
94 The diatom-rich units are also characterised by higher Ba/Al ratios (Fig. 2), pointing to
95 multiple extended periods of increased biological productivity related to less sea ice, and
96 warmer spring and summer sea surface temperatures. This inference is supported by diatom
97 and silicoflagellate assemblage and TEX₈₆ paleothermometry data from marine and land-
98 based records from the Antarctic Peninsula margin¹⁹, the Kerguelen Plateau²⁰, Prydz
99 Bay^{15,19,21} and the Ross Sea²². These reconstructions identify elevated mean annual Pliocene
100 sea surface temperatures^{15,19-21}, spring and summer sea surface temperatures between 2 to
101 6°C above modern levels²², and prolonged warm intervals spanning up to 200,000 years in
102 duration, superimposed on a baseline of warmer-than-present temperatures.

103 In order to constrain the effects of prolonged warming on the dynamics of the East
104 Antarctic Ice Sheet, we produced a Pliocene record of continental erosion patterns based on
105 detrital marine sediment provenance (<63µm grain-size fraction) from IODP Site U1361. We
106 used the radiogenic isotope compositions of neodymium (¹⁴³Nd/¹⁴⁴Nd, expressed as ε_{Nd},
107 which describes the deviation of measured ¹⁴³Nd/¹⁴⁴Nd ratios from the Chondritic Uniform
108 Reservoir in parts per 10,000) and strontium (⁸⁷Sr/⁸⁶Sr), both of which vary in continental
109 rocks based on the age and lithology of geological terranes. In IODP Site U1361 sediments,
110 both ratios show significant variations throughout the studied Pliocene interval, with ε_{Nd}
111 values ranging from -5.9 to -14.7, and Sr isotopic compositions from 0.712 to 0.738 (Fig. 2).

Notably, both ratios co-vary in a distinct pattern that parallels lithological units, physical properties and bulk sediment geochemistry (Fig. 2), with a more radiogenic Nd isotopic composition and a less radiogenic Sr isotopic composition characteristic of sediments deposited during periods of Pliocene warmth (ϵ_{Nd} : -5.9 to -9.5; $^{87}\text{Sr}/^{86}\text{Sr}$: 0.712 to 0.719) (Fig. 2-3).

East Antarctic continental geological terranes in the vicinity of IODP Site U1361 encompass a diverse range of lithologies and ages: (i) Archean to Proterozoic basement along the adjacent Adélie Land coast, (ii) Lower Paleozoic bedrock in the vicinity of the nearby Ninnis and Mertz Glacier's, along the Oates Land coast, in Northern and Southern Victoria Land, and in the Transantarctic Mountains, (iii) Jurassic to Cretaceous volcanic rocks (the Ferrar Large Igneous Province [FLIP] and associated sedimentary rocks of the Beacon Supergroup) along the George V Land coast, in Northern and Southern Victoria Land, and in the Transantarctic Mountains, and (iv) more distal Cenozoic volcanics of the McMurdo Volcanic Group. Each of these terranes can be characterised in Nd-Sr isotope space (Fig. 3). The provenance signatures of the two Pliocene sedimentary types at IODP Site U1361 (i.e. diatom-rich and diatom-poor) can be best explained by a mixture of FLIP bedrock (ϵ_{Nd} : -3.5 to -6.9; $^{87}\text{Sr}/^{86}\text{Sr}$: 0.709 to 0.719), and Early Palaeozoic bedrock (ϵ_{Nd} : -11.2 to -19.8; $^{87}\text{Sr}/^{86}\text{Sr}$: 0.714 to 0.753; Fig. 1) (Fig. 3; see Supplementary Section 1 for further details on local geology and potential end-members). Diatom-poor sediments have a provenance signature that matches Lower Palaeozoic bedrock, most likely sourced from granitic bedrock exposures in the hinterland of the nearby Ninnis Glacier (Fig. 1). In contrast, the provenance fingerprint of sediments deposited during warm Pliocene intervals (i.e. diatom-rich units) reveal that they are predominantly composed of FLIP material. This FLIP provenance fingerprint is not found in Holocene deposits at IODP Site U1361 or in sediments in its vicinity, and appears to be unique to diatom-rich Pliocene marine sediments over the past 5.3 million years (Fig. 3 and Supplementary Section 1).

We suggest that the most likely source of eroded FLIP material is the Wilkes Subglacial Basin, which requires Pliocene retreat of the East Antarctic Ice Sheet. Aeromagnetic data collected over the Wilkes Subglacial Basin between $\sim 70^\circ\text{S}$ and 74°S ²³ reveal anomalies that resemble exposed FLIP bedrock in Southern Victoria Land, indicating the presence of abundant intrusive sills, as well as two large several kilometre deep graben-like sub-basins²³ (Fig. 1). Recent subglacial topographic data compilations²² furthermore demonstrate that these sub-basins are directly connected to the Southern Ocean below sea

level, and aerogeophysical data suggests that the Central Basin contains unconsolidated sediments inferred to be FLIP in origin²³ (Fig. 1).

We propose that enhanced erosion of FLIP material in the Central Basin was achieved by multiple retreats of the ice margin. Ice sheet modelling and modern observations suggest that sub-surface melting at the ice edge in response to warm ocean temperatures drives retreat in areas where grounding lines lie below sea level⁹, such as the mouth of the Wilkes Subglacial Basin²⁴ (Supplementary Section 1). Warm Pliocene ocean waters would have facilitated retreat into the Central Basin, contemporaneous with ice shelf collapse and ice margin retreat in other circum-Antarctic locations, such as in the Prydz Bay area^{15,16,24}, and the Ross Sea²⁵.

Zones of maximum glacial erosion are typically associated with the margins of an ice sheet^{26,27}, suggesting that the retreated Pliocene ice margin was situated on FLIP bedrock within the Central Basin. Existing ice sheet models imply that between ~3m²⁸ (line A, Fig. 1) and ~16m⁷ (line C, Fig. 1) of Pliocene glacio-eustatic sea level rise could be derived from retreat of the East Antarctic Ice Sheet. While the smallest estimate (3m) is unlikely to accurately represent the response of the ice margin to the warmest range of Pliocene climate conditions²⁷, larger estimates (10 to 16m)^{6,7} are influenced by initial ice sheet configurations used within climate modelling frameworks. Our new data, as well as maximum modelled erosion for the northern part of the Wilkes Subglacial Basin²⁷ are in agreement with retreat of the ice margin several hundred kilometres inland. Such retreat could have contributed between 3 and 10m of global sea level rise from the East Antarctic Ice Sheet, providing a new and crucial target for future ice sheet modelling. Irrespective of the extent of ice retreat, our data document a dynamic response of the East Antarctic Ice Sheet to varying Pliocene climatic conditions, revealing that low-lying areas of Antarctica's ice sheets are vulnerable to change under warmer than modern conditions, with important implications for the future behaviour and sensitivity of the East Antarctic Ice Sheet.

Supplementary Information is linked to the online version of the paper at xxxxx

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FIGURE LEGENDS

Figure 1. Regional map of study area, including geology of outcrops and inferred subglacial geology. Coloured shading represents the simplified geographical extent of four geological terranes differentiated according to their neodymium isotopic characteristics (expressed as ϵ_{Nd}) (see Supplementary **Section 1** for detailed geological context). **Areas above sea level are shown as pale grey with grey outlines, and ice shelves are shown in white**²⁴. Outline of the Central Basin (CB) denotes its location within the Wilkes Subglacial Basin²³. Red lines denote the spatial extent of modelled maximum East Antarctic Ice Sheet retreat for the Pliocene: Line A - 3m²⁸, line B - 10m⁶, line C - 16m⁷. The inset map illustrates the westward flowing Antarctic coastal current (arrows). EAIS: East Antarctic Ice Sheet; WAIS: West Antarctic Ice Sheet.

Figure 2. Pliocene records from IODP Site U1361 in comparison to other circum-Antarctic and global records. From left to right: (a) Paleomagnetic chron boundaries based on inclination measurements¹⁷ (red data points); grey shading indicates intervals with no data; (b) lithostratigraphy¹⁸; (c-f) **new records of natural gamma radiation, Ba/Al, opal wt.% and Nd and Sr isotopic compositions**; pink shading: high productivity intervals based on Ba/Al; vertical black stippled lines: Holocene Nd and Sr isotopic compositions (core-tops); (g) **global benthic oxygen isotope stack (LR04)**²⁹; (h) **circum-Antarctic indicators for warm temperatures**; pink: Pliocene high-productivity intervals at IODP Site U1361; dark blue: diatom and silicoflagellate assemblages from the Kerguelen Plateau²⁰ and Prydz Bay¹⁹; light blue: silicoflagellate assemblages from Prydz Bay²¹; lilac: diatomite deposits from ANDRILL cores in the Ross Sea²⁵; (i): paleomagnetic timescale³⁰.

Figure 3. Neodymium and strontium isotopic composition of Pliocene detrital sediments from IODP Site U1361 and East Antarctic geological terranes proximal to the study area. Fields for the isotopic composition of various terranes are based on literature values (see Supplementary **Section 1**). Data corresponding to the Adélie Land Craton primarily plot outside of the neodymium and strontium isotopic space shown (ϵ_{Nd} : -20 to -28; $^{87}Sr/^{86}Sr$: 0.750 to 0.780).





