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Dynamic Behaviour of the East Antarctic Ice Sheet during Pliocene Warmth

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Warm intervals within the Pliocene Epoch (5.33 to 2.58 million years ago) were characterised by global temperatures comparable to those predicted for the end of this century[1] and atmospheric CO_2 concentrations similar to today[2,3,4]. Estimates for global sea level highstands during these times[5] imply possible retreat of the East Antarctic Ice Sheet, but ice-proximal evidence from the Antarctic margin is scarce. Here we present

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

Recent satellite observations reveal that the Greenland and West Antarctic ice sheets are losing mass in response to climatic warming[8]. Basal melting of ice shelves by warmer ocean temperatures is proposed as one of the key mechanisms facilitating mass loss of the marine-based West Antarctic Ice Sheet[9]. While thinning of ice shelves and acceleration of glaciers has been described for some areas of the East Antarctic margin[9], the mass balance of the predominantly land-based East Antarctic Ice Sheet is less clear[10]. Its vulnerability to warmer-than-present temperatures may be particularly significant in low-lying regions, such as the Wilkes Subglacial Basin (Fig. 1).

This hypothesis can be tested by studying intervals from geological records deposited under similar environmental conditions to those predicted for the near future. Warm intervals within the Pliocene Epoch are such analogues, with mean annual global temperatures between 2 and 3°C higher than today[1] and atmospheric CO_2 concentrations between 350 and 450ppm, 25 to 60% higher than pre-industrial values[2,3,4]. Estimates for eustatic sea level highstands during these times, reconstructed from benthic foraminiferal oxygen isotopes[5] and paleoshoreline reconstructions[11], are variable but indicate 22 ± 10 meters of sea level rise, although estimates derived from paleoshoreline reconstructions may need corrections for glacio-isostatic adjustments[12]. Complete melting of Greenland and West Antarctica's ice sheets could account for around 12 meters[13] of eustatic sea level rise, indicating that most estimates for Pliocene sea level require a contribution from the East Antarctic Ice Sheet. While ice sheet modelling suggests that low-lying areas of the East Antarctic continent may be candidates for Pliocene ice sheet loss[6,7], direct evidence from ice-proximal records on locations of ice margin retreat are limited[14-16].

To improve our understanding of the response of the East Antarctica Ice Sheet to past warm climates, Integrated Ocean Drilling Program Site U1361 (64°24.5°S 143°53.1°E; 3465m water depth) was drilled during Expedition 318 into a submarine levee bank, 310 kilometres offshore of the Adélie Land margin, East Antarctica (Fig. 1). Approximately 50 meters of continuous Pliocene marine sediments, within the resolution of current biostratigraphic and magnetostratigraphic data[17], were recovered. Available physical property[18], sedimentology[18], and paleomagnetic and micropaleontology data[17] are here combined with new opal (%) data, bulk geochemistry data, and radiogenic isotope data from analyses of detrital sediments.

The Pliocene study section at IODP Site U1361 spans an interval between 5.3 and 3.3 million years ago and contains a sedimentary sequence alternating between eight diatom-rich silty clay layers, and eight diatom-poor clay layers with silt laminations (Fig. 2). Diatom-rich sediments have higher diatom valve and bulk-sediment biogenic opal concentrations and distinctively lower signals in natural gamma radiation (Fig. 2), indicating lower clay content. The diatom-rich units are also characterised by higher Ba/Al ratios (Fig. 2), pointing to multiple extended periods of increased biological productivity related to less sea ice, and warmer spring and summer sea surface temperatures. This inference is supported by diatom and silicoflagellate assemblage and TEX_{86} paleothermometry data from marine and land-based records from the Antarctic Peninsula margin[19], the Kerguelen Plateau[20], Prydz Bay[15,19,21] and the Ross Sea[22]. These reconstructions identify elevated mean annual Pliocene sea surface temperatures[15,19-21] , spring and summer sea surface temperatures between 2 to 6°C above modern levels[22], and prolonged warm intervals spanning up to 200,000 years in duration, superimposed on a baseline of warmer-than-present temperatures.

In order to constrain the effects of prolonged warming on the dynamics of the East Antarctic Ice Sheet, we produced a Pliocene record of continental erosion patterns based on detrital marine sediment provenance (<63µm grain-size fraction) from IODP Site U1361. We used the radiogenic isotope compositions of neodymium ($^{143}Nd/^{144}Nd$, expressed as ε_{Nd}, which describes the deviation of measured $^{143}Nd/^{144}Nd$ ratios from the Chondritic Uniform Reservoir in parts per 10,000) and strontium ($^{87}Sr/^{86}Sr$), both of which vary in continental rocks based on the age and lithology of geological terranes. In IODP Site U1361 sediments, both ratios show significant variations throughout the studied Pliocene interval, with ε_{Nd} 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; $^{87}Sr/^{86}Sr$: 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; $^{87}Sr/^{86}Sr$: 0.709 to 0.719), and Early Palaeozoic bedrock ($\varepsilon_{Nd:}$ -11.2 to -19.8; $^{87}Sr/^{86}Sr$: 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 ~70°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-basins[23] (Fig. 1). Recent subglacial topographic data compilations[22] 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 origin[23] (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 level[9], such as the mouth of the Wilkes Subglacial Basin[24] (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 Sea[25].

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 ~3m[28] (line A, Fig. 1) and ~16m[7] (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 conditions[27], 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 Basin[27] 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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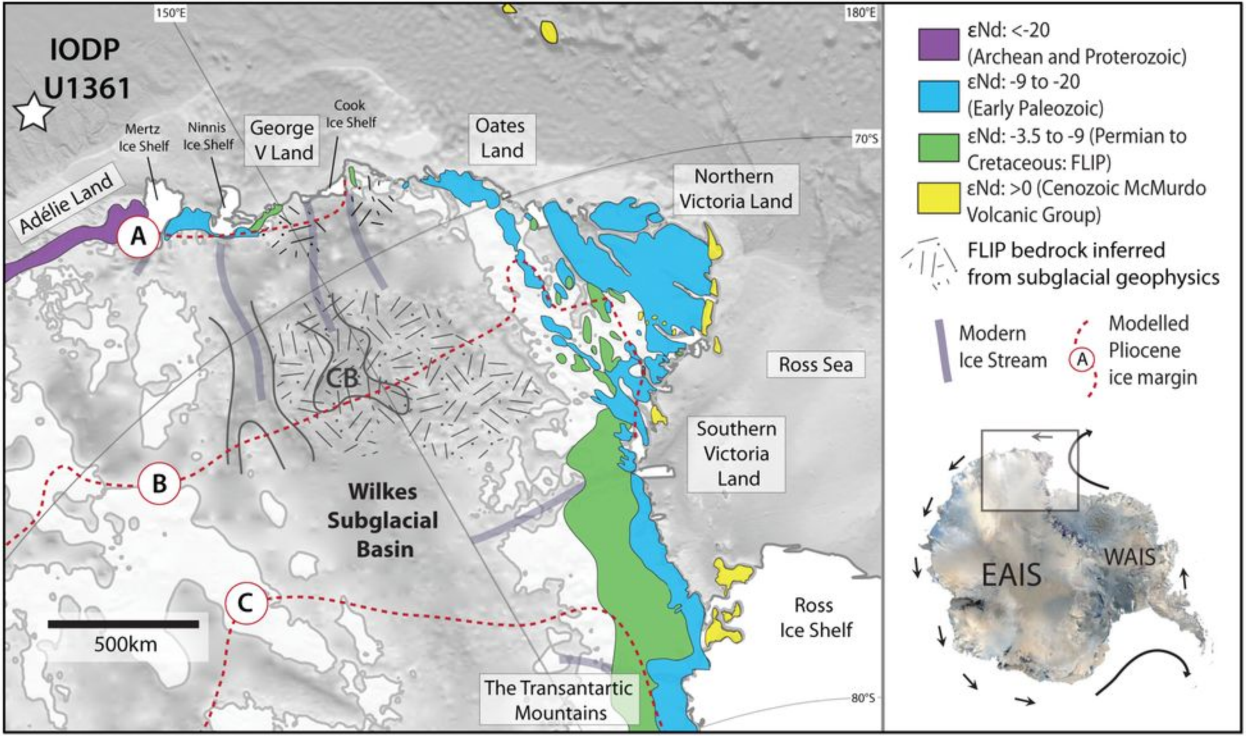
FIGURE LEGENDS

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 Basin[23]. Red lines denote the spatial extent of modelled maximum East Antarctic Ice Sheet retreat for the Pliocene: Line A - 3m[28], line B - 10m[6], line C - 16m[7]. 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 measurements[17] (red data points); grey shading indicates intervals with no data; (b) lithostratigraphy[18]; (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 Plateau[20] and Prydz Bay[19]; light blue: silicoflagellate assemblages from Prydz Bay[21]; lilac: diatomite deposits from ANDRILL cores in the Ross Sea[25]; (i): paleomagnetic timescale[30].

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).



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Northern
Victoria Land
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εNd: -9 to -20
(Early Paleozoic)
εNd: -3.5 to -9 (Permian to
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εNd: >0 (Cenozoic McMurdo
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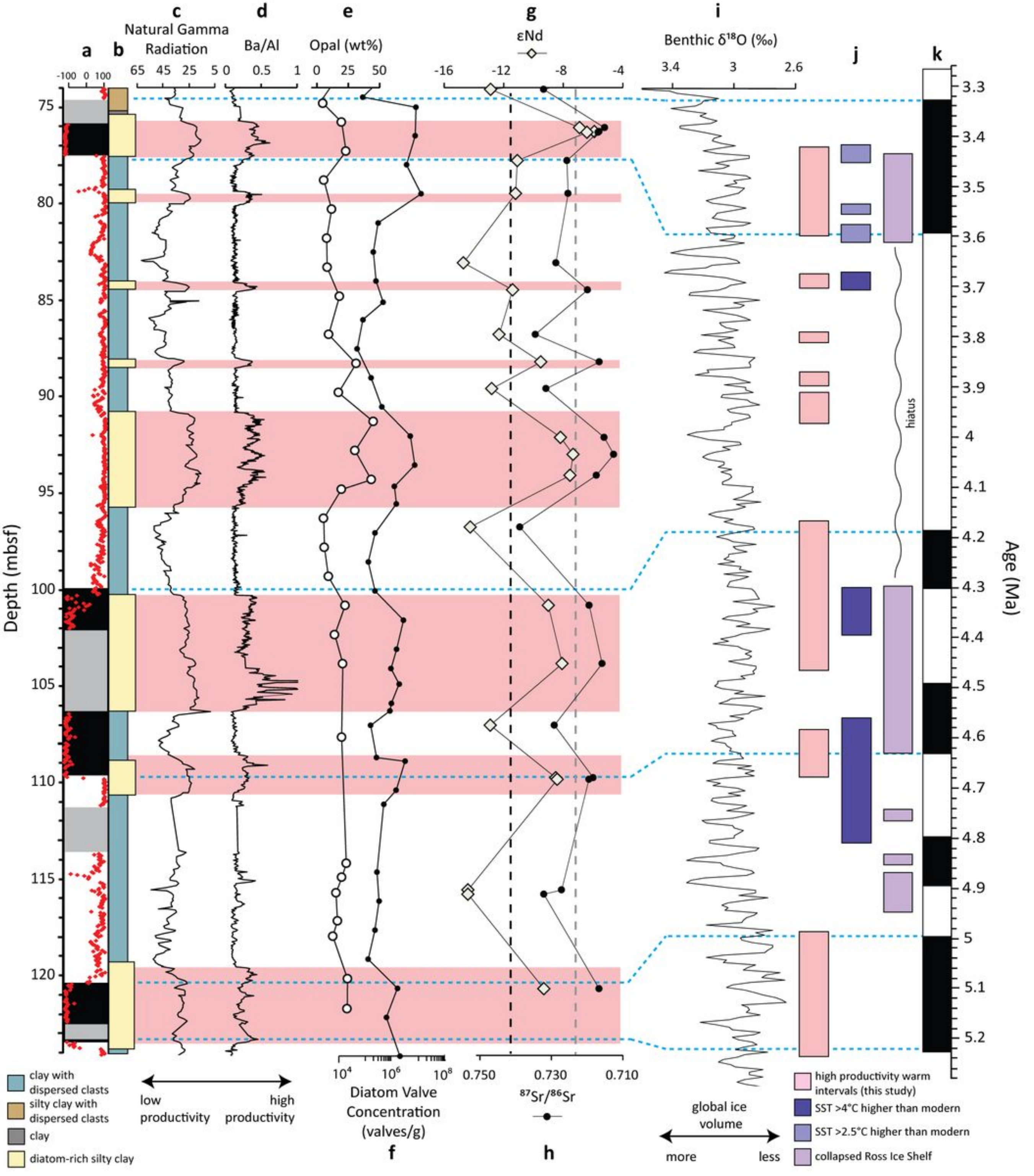

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f
87Sr/86Sr
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low productivity
high productivity
global ice volume
more
less
clay with dispersed clasts
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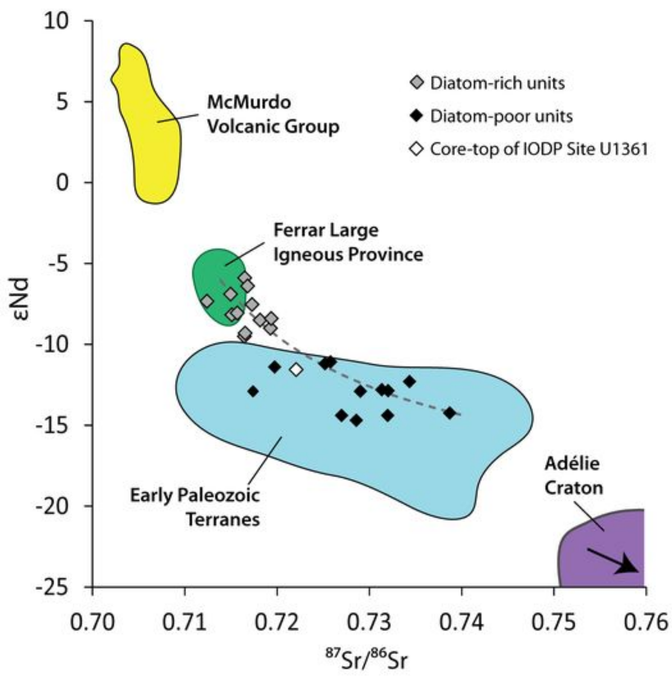
clay
diatom-rich silty clay
high productivity warm intervals (this study)
SST >4°C higher than modern
SST >2.5°C higher than modern
collapsed Ross Ice Shelf


McMurdo Volcanic Group
Ferrar Large Igneous Province
Early Paleozoic Terranes
Adélie Craton
Diatom-rich units
Diatom-poor units
Core-top of IODP Site U1361
εNd
87Sr/86Sr
10
5
0
-5
-10
-15
-20
-25
0.70
0.71
0.72
0.73
0.74
0.75
0.76