A Large West Antarctic Ice Sheet Explains Early Neogene Sea-Level Amplitude

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Early Neogene sea-level oscillations of approximately 40-60 m estimated from far-field records[1,2,3] have been interpreted as requiring the loss of virtually all Antarctic ice during peak interglacials[2]. This contrasts with ice-sheet model experiments suggesting most terrestrial ice in East Antarctica was retained even during the warmest intervals of the middle Miocene[4,5]. Data and model outputs can be reconciled if a large West Antarctic Ice Sheet (WAIS) expanded across the outer continental shelf during the early Miocene, accounting for the maximum ice-sheet volumes. Here, we provide geochemical and petrographic evidence from International Ocean Discovery Programme (IODP) Site U1521 showing that early Miocene glacimarine sediments (~17.72-17.40 Ma) in the central Ross Sea were clearly derived from West Antarctica. Complimentary seismic, lithological and palynological data reveal that grounded ice was intermittently proximal to the site. This is the earliest geological evidence for WAIS expansion across most of the Ross Sea shelf. Rapid deposition of nearly 190 m of sediment at Site U1521 in ~320 kyr implies unusually fast glacial erosion of West Antarctica. This interval therefore represents a key step in the genesis of a marine-based WAIS and a tipping point in Antarctic ice-sheet evolution.

Introduction

Reconstructing past changes to Antarctica's ice sheets helps inform predictions of the continent's future contribution to sea-level rise[6,7]. Drilling efforts around Antarctica since the 1970s have begun to reveal the Cenozoic evolution of Antarctic glaciation[8,9,10,11], but fundamental steps in the development of the ice sheets remain poorly constrained. One key uncertainty is the timing of West Antarctic Ice Sheet (WAIS) expansion across the outer continental shelf. Early work on benthic oxygen isotope records and Antarctic abyssal plain sedimentary records suggested WAIS formation did not occur until the late Miocene or early Pliocene[12,13]. However, more recent drilling from the Antarctic margin[11,14,15] and ice-sheet modelling studies[4,5,16] have raised the possibility that ice-sheet expansions into the marine realm could have occurred in the early Miocene or even earlier, facilitated by a subaerial West Antarctic topography[17,18].

Without widespread WAIS expansions across the continental shelf in the Early Neogene, maximum ice volumes are low enough that global sea-level fluctuations of ~40-60 m seen in far-field stratigraphic records[1] and oxygen isotope-derived ice volume estimates[2,3] require the near complete loss of the East Antarctic Ice Sheet (EAIS) during the warmest middle Miocene periods[2]. This is incompatible with current ice-sheet model outputs, which show retention of most terrestrial East Antarctic ice even during the warmest feasible middle Miocene environmental conditions[4]. This is mainly due to hysteresis effects driven by height-mass balance feedbacks, where the presence of the ice sheet means ice can be retained following warming beyond the point which the ice sheet would be able to form in[4,19].

Marine sediments, deposited on the continental shelf of the Ross Sea, can reveal whether the WAIS expanded across the continental shelf, but existing geological records are hampered by poor recovery, unconformities and/or close proximity to East Antarctica[9,10,11]. Seismic data show significant volumes of early Miocene glacimarine sediment deposited around the West Antarctic margin[20,21,22,23], but these data require age and physical property constraints from drilling. They also lack the resolution to conclusively differentiate between sediment supply from continental-scale ice-sheet expansion and local ice caps on (paleo)topographic highs[22,23]. Consequently, WAIS grounding across the shelf is only clear in seismic data after the cooling of the Miocene Climate Transition (~14 Ma)[24,25]; it remains uncertain whether there were earlier WAIS expansions across the Ross Sea shelf.

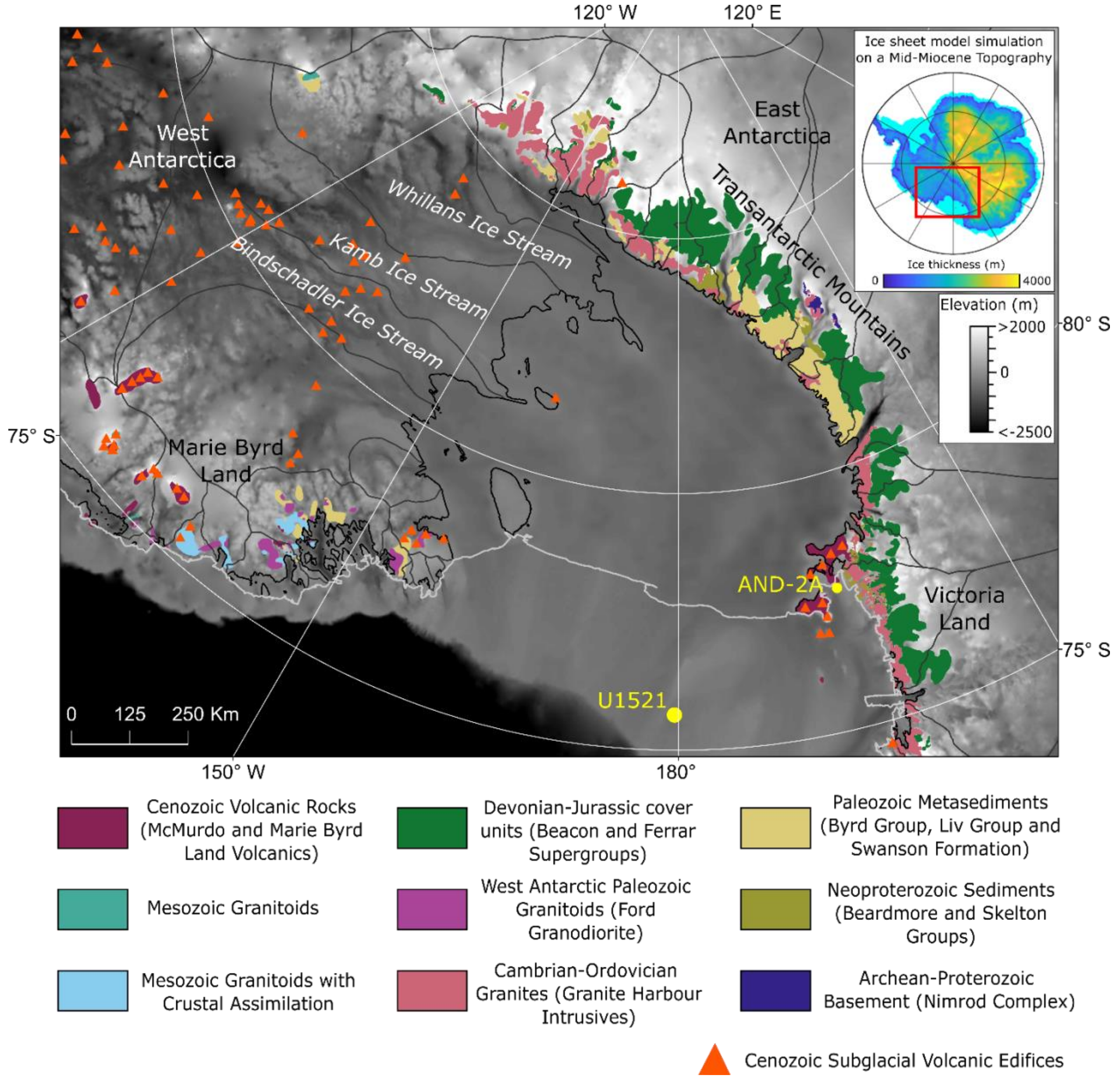

Figure 1. *Map of the Ross Sea region showing the outcropping regional geology[26] overlain on the BedMachine Antarctica V1 modern bed topography[27]. IODP Site U1521 is located on the outer continental shelf of the central Ross Sea. Key locations referenced in the text are labelled, including the ANDRILL 2A (AND-2A) drill site. The white dashed line indicates the boundary between East and West Antarctic lithosphere[28]. Orange triangles show Cenozoic subglacial volcanic edifices detected based on morphological characteristics, gravity anomalies and magnetic anomalies[29]. The inset shows an ice-sheet model run using a 'cold' climate and a mid-Miocene topography. Provenance indicators from Sequence 2 sediments at Site U1521 are broadly consistent with an ice sheet similar to or exceeding the extent of the model output pictured, which was simulated on a Mid-Miocene topography with a 'cold' orbit and 280 ppm CO_2 climate[4].*

IODP Site U1521 and Provenance Approach

IODP Site U1521 (75°41.0' S, 179°40.3' W) was drilled to 650.1 metres below sea floor (mbsf) in the Pennell Basin on the outer continental shelf of the Ross Sea in 562 m water depth (Fig. 1). The site was strategically located in a region that ice-sheet models indicate is one of the last sectors in Antarctica where ice grounds during glacial maxima, making it an ideal location to assess the timing of past maxima in ice-sheet extent and WAIS expansions onto the outer continental shelf[4,16,30]. The sediments from base of the hole up to 209.17 mbsf constitute an expanded early Miocene sequence (~18 to ~16.3 Ma; see Supplement for details on the age model) with 73% recovery. Individual sequences (1-4) are differentiated based on unconformities in the chronostratigraphic framework and divided further (A/B) based on major lithological boundaries. These sediments provide a unique window for detailed analysis of ice-sheet behaviour immediately before the Miocene Climate Optimum (MCO, ~17-15 Ma; Fig. 2; Fig. S1; Table S1).

The sediments below 209.17 mbsf at Site U1521 are predominantly muddy to sandy diamictites, often interbedded with thin laminae and beds of mudstone (see detailed lithological descriptions in the Supplement)[30]. Palynological counts on 23 samples (see Supplement and Table S3) revealed sparse palynomorphs in Sequence 1 and 4A, common reworked dinoflagellate cysts in Sequence 2 and evidence for high biological productivity in Sequence 3B (Fig. S8). Thus, the lithological and palaeontological data from Sequences 1, 2, 3A and 4A suggest a predominantly ice-proximal glacimarine (and potentially subglacial) setting, while data from Sequence 3B suggest an ice-distal setting. Notably, the ~190 m Sequence 2 succession, containing a high proportion of reworked dinoflagellate cysts, was deposited rapidly (~0.6 mm $year^{-1}$) within a ~320 kyr interval spanning ~17.72-17.40 Ma (Fig. S1).

Through comparison to terrestrial rock outcrops, the marine sediments at Site U1521 were traced back to their source region. A differing geological history of the rocks beneath the EAIS and WAIS (Fig. 1) gives the sediment eroded by each ice sheet a distinct geochemical, petrological and mineralogical composition, allowing expansions from each ice sheet to be distinguished. We applied multiple sediment provenance proxies to avoid bias towards, or omission of, any lithologies[31]. Specifically, we analysed the detrital fine fraction of 37 samples for neodymium (Nd) and strontium (Sr) isotope compositions (<63 µm) and 23 samples for clay mineralogy (<2 µm). Eight of these samples were processed for U-Pb dating of detrital zircons (<300 µm) and five for $^{40}Ar/^{39}Ar$ dating of detrital hornblende grains (150-300 µm). Additionally, the petrography of 15,740 clasts >2 mm was identified continuously down-core (Fig. S7).

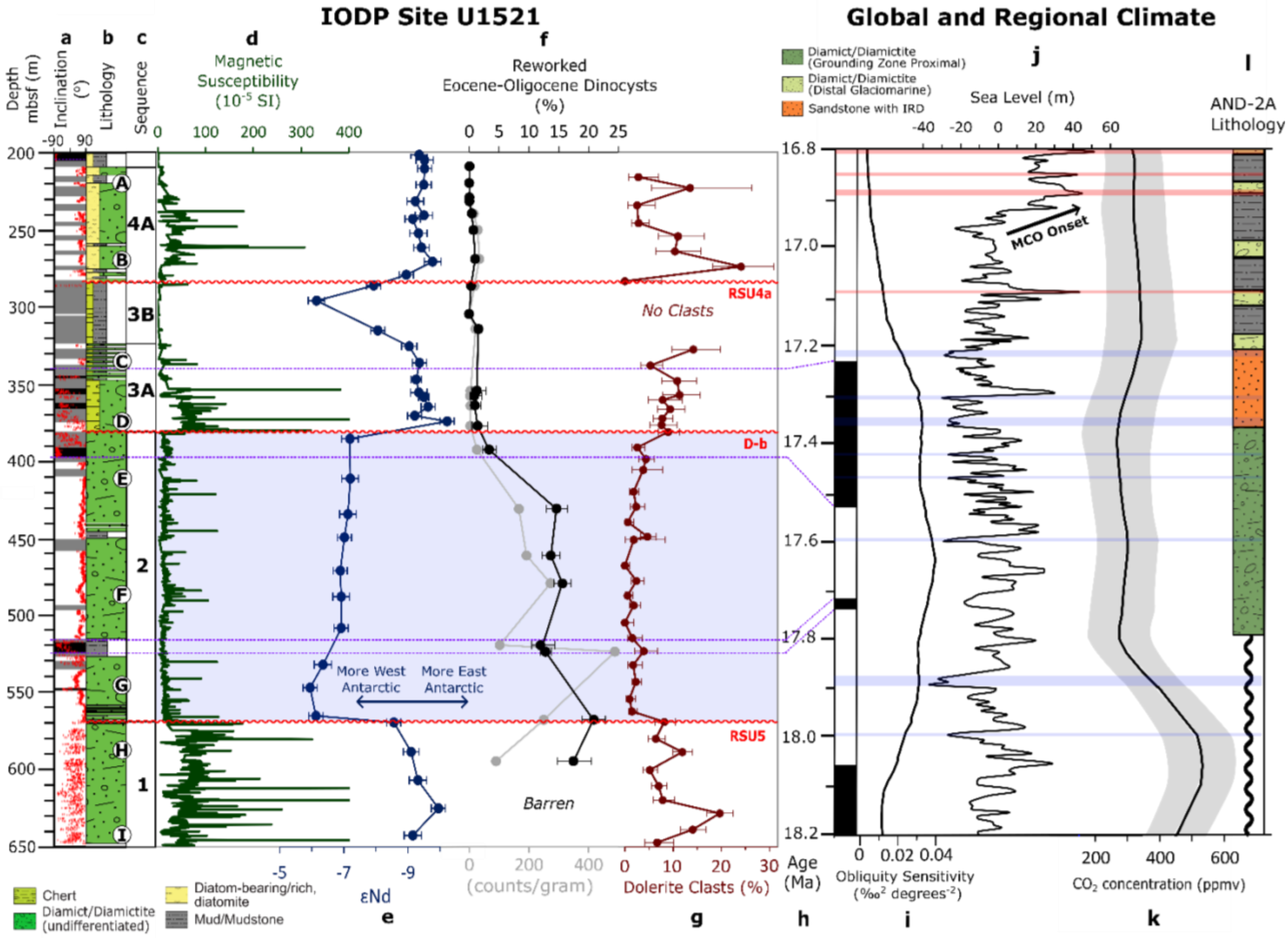

Figure 2. *Selected provenance proxies from IODP Site U1521 compared to early Miocene climate records. The blue shaded section (Sequence 2) highlights the interval with sediments of predominantly West Antarctic provenance. The depth of Ross Sea Unconformity (RSU) 4a and 5 and seismic surface D-b are indicated in red[23]. a) Site U1521 inclination data after 20 nT demagnetisation (red points)[30] and polarity interpretation*

(white = reverse polarity, black = normal polarity, grey = no interpretation). b) Site U1521 lithostratigraphy. c) Chronostratigraphic sequences. The circled letters between b) and c) show the depths of the zircon U-Pb samples shown in Figure 3. d) Magnetic susceptibility measured on the whole core[30]. e) Neodymium isotope data (error bars are 2 S.D. external reproducibility). f) Abundance of Eocene-Oligocene dinocysts as a percentage (black) and concentration (grey). g) Dolerite clast abundance. Errors shown in f) and g) are 95% confidence intervals[32]. Magnetostratigraphic tie points between the polarity interpretations from shipboard data (a)[30] and geomagnetic polarity timescale (h)[33] are marked by purple dashed lines. i) Obliquity sensitivity, indicating the strength of obliquity in the $\delta^{18}O$ record relative to the theoretical strength of obliquity forcing. This has been interpreted as representing the presence of marine-based Antarctic ice [15]. j) Sea-level record based on an oxygen isotope splice[2]. Red and blue shaded intervals indicate pronounced sea-level highstands (>40 m) and lowstands (<-20 m), respectively. MCO = Miocene Climatic Optimum. k) Compilation of CO_2 proxy records with a LOESS smoothing (shaded region indicates 1 sigma error), including all available proxies (phytoplankton, paleosols, boron isotopes, leaf gas exchange, stomatal frequencies and the $\delta^{13}C$ value of terrestrial C3 plant remains). References for the CO_2 compilation are provided in the methods section. k) Simplified lithological log from the AND-2A record, with diamictites differentiated based on a grounding-zone proximal vs distal glacimarine depositional setting[11,15].

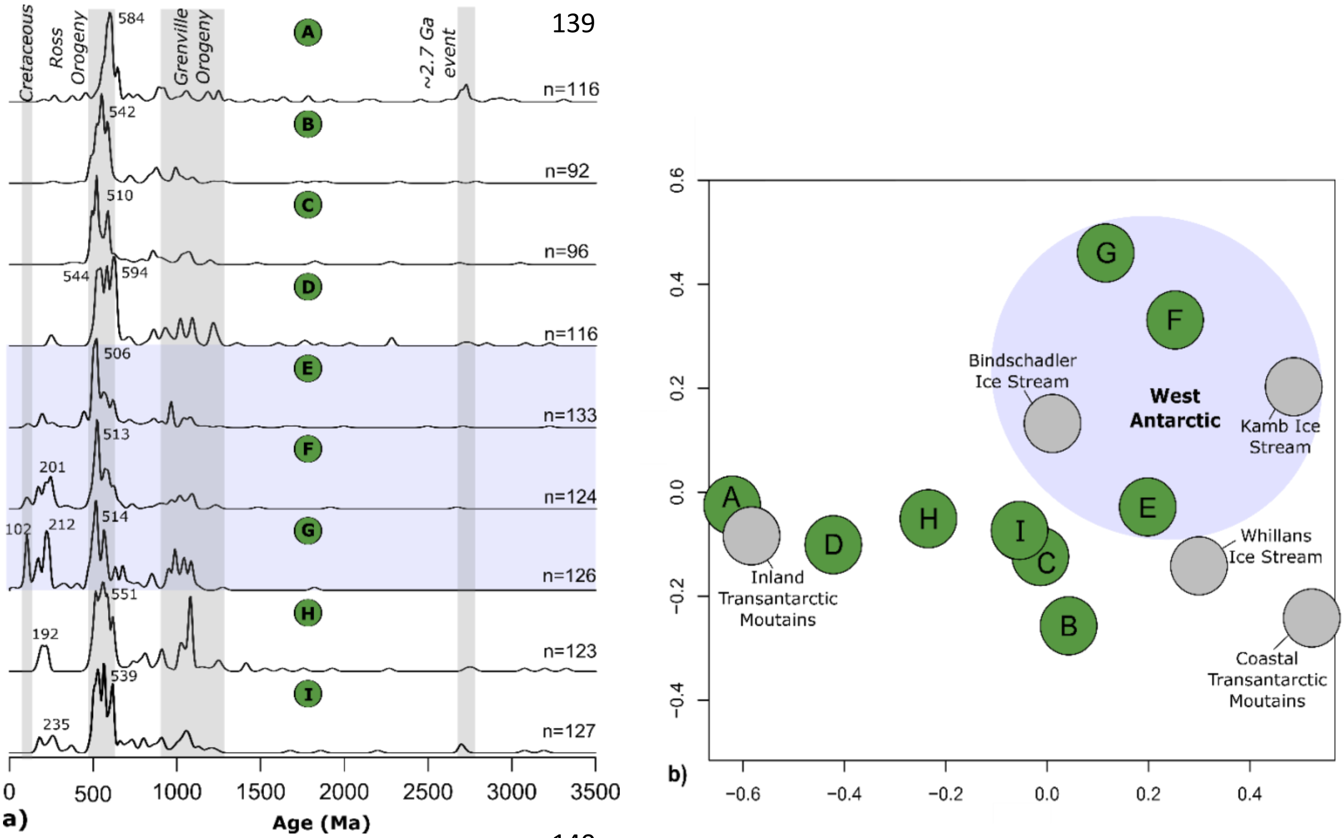

Figure 3. a) Detrital zircon U-Pb ages displayed as kernel density estimates (KDEs). When present, large Ross Orogeny (~600-500 Ma), Triassic (~240-190 Ma) and Cretaceous (~100 Ma) age peaks are labelled. The age ranges of the Ross Orogeny, Grenville Orogeny and a ~2.7 Ga event recorded in Ross Sea sedimentary strata are illustrated using grey-shaded bars. Descending in depth, the samples midpoints are 220.23, 270.03, 335.72, 373.58, 410.82, 487.40, 546.55, 588.00 and 642.21 mbsf, as shown on the lithological log in Figure 2. The same data are displayed in b) as a multi-dimensional scaling (MDS) plot calculated using the Kolmogorov–Smirnov statistic[34]. Stress (a measurement of the goodness of fit between the disparities and the fitted distances[34]) = 0.072. A MDS plot visualises the degree of similarity between each sample, with any two points plotting closer if they are more similar. The axis scales are dimensionless and have no physical meaning. Samples from Site U1521 (shaded green) are compared to previously published zircon U-Pb data (shaded grey) from Kamb, Whillans and Bindschadler ice streams in West Antarctica, as well as Transantarctic Mountain moraines from more inland and more coastal regions[35,36,37]. The KDEs and region of the MDS plot interpreted as having a West Antarctic provenance are shaded in blue, consistent with Figure 2.

Note that although Whillans Ice Stream drains the WAIS, it is excluded from the blue shaded area as its close proximity to the Transantarctic Mountains leads to a provenance indistinguishable from East Antarctica[36].

Evidence for Early Miocene WAIS Growth

At Site U1521, detrital ε_{Nd} values are consistently more radiogenic (higher) in Sequence 2 compared to the sediments above and below (Fig. 2), implying a contribution from a more radiogenic end member. This end member can be traced to beneath the WAIS; the ε_{Nd} values, ranging between -7.2 and -5.9, are in good agreement with measurements of late quaternary diamicts from the eastern Ross Sea shelf, adjacent to West Antarctica[38]. Here, the radiogenic end member is hypothesised to be the Cenozoic alkali volcanic rocks of Marie Byrd Land in West Antarctica[38] (Fig. S3). Subaerial outcrops of the Marie Byrd Land volcanic province are limited, but magnetic and gravity anomalies associated with subglacial cone-shaped structures indicate the presence of numerous subglacial volcanoes (Fig. 1)[29]. These are likely to be the more radiogenic end member contributing to Sequence 2. Conversely, the less radiogenic (lower) ε_{Nd} values seen in adjacent sediments, ranging between -10.2 and -8.6, reflect a mixture of lithologies present in the (East Antarctic) Transantarctic Mountains and fall within the range of late quaternary Ross Sea tills of Transantarctic Mountain provenance (Fig. S3, S6)[38,39]. These less radiogenic sediments also show higher and more variable magnetic susceptibility (Fig. 2)[30]. The patterns seen in the ε_{Nd} data are broadly mirrored by detrital Sr isotope compositions (Fig. S8).

Single-grain geochronology/thermochronology and clast petrography can provide more detailed insights into specific source terranes. In the Transantarctic Mountains, Precambrian rocks were affected by the pervasive Ross Orogeny (615-470 Ma), which was accompanied by extensive intrusive felsic magmatism (see Supplementary Information)[40]. Zircon age populations from Sequences 1, 3A and 4A show a strong peak towards the earlier part of the Ross Orogeny (595 to 535 Ma) and a 6 to 21% population of Archaean and Paleoproterozoic (>1600 Ma) zircon grains

(Figs. 1, 3). These features, together with a lack of grains younger than 250 Ma, resemble moraines in the Transantarctic Mountains[35,36,37]. Clasts in sequences 1, 3A and 4A also correlate with rocks in the Transantarctic Mountains, with lithologies including common felsic granitoids and meta-greywackes alongside rarer limestones, marbles and sandstones (Fig. S7)[40]. Although a relatively minor component, dolerite clasts are found throughout Sequences 1, 3A and 4A (Fig. 2g) and these are unique to the Jurassic Ferrar Group, which outcrops in the Transantarctic Mountains (Fig. 1). Furthermore, rare *Protohaploxypinus* pollen, a distinctive component of the Permian Beacon Supergroup sediments from the Transantarctic Mountains, are observed in Sequence 3A[41]. Overall, the sediments comprising Sequences 1, 3A and 4A at Site U1521 are predominantly sourced from erosion of the Transantarctic Mountains in East Antarctica.

In contrast, Sequence 2, characterized by the highest ε_{Nd} values, contains Cretaceous (~100 Ma) zircon U-Pb ages (n = 16; Fig. S5, Fig. 3a). Such ages are indicative of a West Antarctic provenance, as they are presently only found beneath modern Siple Coast ice streams including Kamb Ice Stream and those closer to Marie Byrd Land[36,42]. The age spectra from Sequence 2 share many other features with data from the Siple Coast ice streams, including a broad Triassic (~240-190 Ma) age peak, few pre-Mesoproterozoic zircons (<5 % of grains) and a young (~515-505 Ma) Ross Orogeny peak (Fig. 3)[36]. Detrital hornblende $^{40}Ar/^{39}Ar$ ages from Sequence 2 further corroborate a West Antarctic provenance. Unlike zircon grains, which can survive multiple sedimentary cycles, hornblende grains are less resistant to weathering. The absence of Grenvillian (~1100-900 Ma) ages in the Sequence 2 hornblende sample (Fig. S5) suggests a West Antarctic provenance, as Grenville-age rocks are absent there[43]. The scarcity of Ferrar Group dolerite clasts, common in the Transantarctic Mountains, is also consistent with a West Antarctic provenance (Figs. 1, 2). Additionally, Sequence 2 contains evidence for recycling of older marine detritus, most likely from the Early Cenozoic rift-fill strata that exist in the eastern Ross Sea region of the West Antarctic Rift System[21]. This is inferred from the dominance of reworked Eocene-Oligocene species in the diatom and spore-pollen assemblages[29], alongside the common (13-21%) reworked Eocene-Oligocene marine dinocysts, which are rare (<1.5%) in younger sediments (Fig. S8).

Finally, the high abundance of smectite - up to 58% at the bottom of Sequence 2 (Fig. S7, S9) – provides further evidence of a West Antarctic provenance; Quaternary sediments in the eastern Ross Sea (adjacent to West Antarctica) have a similarly high smectite content[44]. In addition to this evidence for a provenance shift, smectite content significantly declines up-section within Sequence 2. This falling contribution is accompanied by a rise in basalt clast abundance (Fig. S9), which is unexpected given that smectite is considered a weathering product of basalt and volcanic rocks. This trend of increasing basalt clast abundances and falling basalt weathering product (i.e. smectite) is consistent with the removal of a more weathered regolith layer, followed by erosion of progressively more pristine, less weathered, continental detritus. The ~17.72 to 17.40 Ma Sequence 2 interval could therefore have seen the first advance of grounded ice over these areas of West Antarctica for an extended period.

Further evidence for WAIS expansion across the shelf can be found in seismic data[23]. The sediment package deposited at Site U1521 between ~17.72 and 17.40 Ma can be traced across the Ross Sea continental shelf and contains widespread progradational wedges and high relief morainal banks[20,21,23]. Given the abundant occurrence of diamictites at Site U1521 and the glacial features distinguished in the seismic dataset, marine-terminating ice was clearly present during this interval. The seismic package is also thicker towards the eastern Ross Sea (i.e. West Antarctica)[23]. Taken together, the seismic data, high deposition rate, common reworked marine microfossils and provenance data revealing transport of large volumes of West Antarctic detritus as far west as the Pennell Basin in the central Ross Sea, all indicate that the early Miocene WAIS must have intermittently extended across most of the outer continental shelf.

Our data therefore show that WAIS expansions across the Ross Sea continental shelf date back to at least ~17.72 Ma, prior to the Miocene Climatic Transition (~14 Ma) and significantly earlier than previously suggested[12,13,23,24,45]. This ~17.72 to 17.40 Ma WAIS advance coincides with an interval of high obliquity sensitivity (Fig. 2i), supporting the use of this metric as a proxy for enhanced ice-sheet sensitivity to ocean dynamics and thus marine-based ice advance[15].

Birth of a Marine-Based WAIS

The mean erosion rate for the Ross Sea sector of the WAIS between ~17.72 and 17.40 Ma can be estimated using the volume of the corresponding seismic package east of Site U1521 (see supplementary methods)[23]. Assuming that, at the time of deposition, the area of the Ross Sea drainage sector of the WAIS was approximately the same as today, the inferred sediment volume requires a mean catchment erosion of approximately 90 (-30/+50) m in ~320 kyr (Table S2). The erosion rate in this interval (~0.275 mm a^{-1}) exceeds the long-term mean rate calculated for this part of the WAIS between 23 and 14 Ma (0.012 mm a^{-1})[18] by a factor of more than 20. This highlights the ~17.72 to 17.40 Ma period as one of unusually rapid erosion, with erosion rates comparable to modern subpolar to temperate glacial catchments[46]. Transporting this large volume of subglacially eroded debris quickly to the WAIS margin required abundant meltwater at the ice-sheet bed[47], as well as fast-flowing ice streams that extended into marine settings where broad deposition could take place. This required sufficiently cool ocean temperatures permitting the advance of marine-based ice, yet warm enough atmospheric conditions to provide sufficient precipitation to drive dynamic ice flow and enhanced basal erosion[4].

Since most of West Antarctica, apart from Marie Byrd Land, was thermally subsiding throughout the Miocene[18], the high erosion rate at ~17.72 to 17.40 Ma is unlikely to have been driven by tectonic uplift. The eroded sediments therefore reflect a rapid lowering of the terrestrial West Antarctic hinterland and infilling of the Ross Sea basins, although we acknowledge our data cannot directly constrain topographic change. This erosive event occurred at a time when topographic reconstructions show there was a transition from a terrestrial West Antarctica (at 23 Ma) to a largely sub-marine West Antarctica (at 14 Ma)[18]. The timing and large volume of sediment deposited in Sequence 2 suggests this interval must therefore record a critical step in this transition of the WAIS from a largely terrestrial ice-sheet to one that was primarily marine-based (i.e. mainly grounded below sea level). This critical change to West Antarctic topography occurred almost immediately prior to the significant changes to Antarctic cryosphere and climate seen during the MCO[2,11]. This suggests subglacial erosion drove changes in ice-sheet behaviour as, after ~17.40 Ma, a greater submarine area in central West Antarctica would have made the mass-balance control of the WAIS more sensitive to external drivers such as sea-level and oceanic forcing[5,16]. We propose that ice retreat at the onset of the MCO may be partially attributable to the crossing of this topographic tipping point and that Sequence 2 records the birth of a marine-based WAIS. We date this event to well before 14 Ma, the time slice at which topographic reconstructions first show a largely sub-marine West Antarctica[18].

Sea-Level Reconciliation

Grounded ice flowing from West Antarctica was close to Site U1521 towards the end of the early Miocene. We therefore validate recent modelling studies suggesting that an ice-sheet nucleating on a partially terrestrial West Antarctica could expand extensively into the marine realm under early Miocene climatic and paleotopographic conditions[4,5,16]. Our data are consistent with an ice extent similar to, or exceeding, the largest modelled early to middle Miocene Antarctic ice sheets (Fig. 1), equivalent to up to ~80 m of global average sea level depending on the reconstructed topography used[4,5,16]. This evidence for an expanded WAIS, containing approximately 14-15 m SLE[4,16], implies the loss of nearly all terrestrial East Antarctic ice during the warmest periods of the Miocene is not required; far-field sea-level amplitudes of ~40-60 m[1,2,3] allow for terrestrial ice to remain, consistent with modelled hysteresis effects[4]. By providing the earliest conclusive evidence for a large marine-based WAIS, our data also dispel the long-held notion that a WAIS, able to impact global eustacy and climate, was not present until ~14 Ma, or even later[12,13,45].

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Methods

Neodymium and Strontium Isotopes

Samples were disaggregated and wet sieved to isolate the <63 µm fraction, which was then dried down at 60°C. This size fraction represents the bulk composition, as samarium and neodymium are incorporated in equal proportions into most rock-forming minerals meaning grain-size sorting is not likely to impact results[48,49]. However, the Rb-Sr system is subject to elemental fractionation during weathering and grain-size sorting, which can influence $^{87}Sr/^{86}Sr$ ratios (see 'Provenance Changes within Sequence 2' section in supplement). To remove authigenic Fe-Mn oxyhydroxide phases, samples were leached in a mixture of 0.05 M hydroxylamine hydrochloride, 15% acetic acid, and 0.03 M EDTA at a pH of 450. A carbonate removal step was not included due to the very low carbonate content[30]. Leached sediment was dried, homogenised, and 50 mg aliquots were digested on a hotplate in concentrated HF (2 mL), $HClO_4$ (0.8 mL) and HNO_3 (1 mL) for three to five days, with a subsequent 6 M HCl step. The Nd was isolated from the sample matrix using a cation exchange resin (AG50W-X8, 200-400 µm mesh) and HCl in increasing molarity, followed by a low molarity HCl Ln-Spec resin procedure (50–100 µm mesh). The sample matrix from the cation exchange step was dried down, taken up in HNO_3, then loaded onto Eichrom Sr Spec resin to wash down the matrix and elute the Sr[51].

Neodymium isotopes were measured in the MAGIC laboratories at Imperial College London on a Nu high resolution multi-collector inductively coupled plasma mass spectrometer (HR MC-ICP-MS). To account for instrumental mass bias, isotope ratios were corrected using an exponential law and a $^{146}Nd/^{144}Nd$ ratio of 0.7219. Although negligible, interference of ^{144}Sm on ^{144}Nd was corrected for. Bracketing standards were used to correct measured $^{143}Nd/^{144}Nd$ ratios to the commonly used JNdi-1 value of 0.512115[52]. USGS BCR-2 rock standard was processed alongside all samples and yielded $^{143}Nd/^{144}Nd$ ratios consistently within error of the published ratio of 0.512638 ± 0.000015[53]. Full procedural blanks for Nd ranged from 7 to 30 pg (n = 6). $^{143}Nd/^{144}Nd$ ratios are expressed using epsilon notation (ε_{Nd}), which denotes the deviation of a measured ratio from the modern Chondritic Uniform Reservoir (0.512638)[54] in parts per 10,000.

Strontium isotopes were measured in the MAGIC laboratories at Imperial College London on a TIMS (Thermal Ionisation Mass Spectrometer). 10% of the sample was loaded in 1 µL of 6M HCl onto degassed tungsten filaments with 1 µL of $TaCl_5$ activator. The measured $^{87}Sr/^{86}Sr$ ratios were corrected for instrumental mass bias using an exponential law and an $^{88}Sr/^{86}Sr$ ratio of 8.375. Interference of ^{87}Rb was corrected for using an $^{87}Rb/^{85}Rb$ ratio of 0.386. Analyses of the NIST 987 standard reference material were completed every four unknowns, yielding a mean of 0.710290 ± 0.000041 (2SD, n = 36). Samples were corrected to the published value of 0.710252 ± 0.000013[53]. The relatively poor reproducibility for our NIST 987 runs was due to technical issues, but is still more than sufficient for interpreting sample results, which change in the 3rd to 4th digit. Accuracy of results was confirmed using rock standard USGS BCR-2, processed with every batch of samples, which yielded $^{87}Sr/^{86}Sr$ ratios of 0.705010 ± 0.00029 (2SD, n = 18). This is well within error of the published value of 0.705013 ± 0.00010[53].

Detrital Zircon U-Pb Dating

To ensure there were enough grains for statistical analysis, samples were taken over 40 cm of core. Samples were disaggregated, dried and sieved at 300 µm. Zircons from the <300 µm fraction were concentrated using standard gravity settling and magnetic separation techniques. Samples were then mounted in resin, polished and analysed using an Agilent 7900 laser ablation inductively-coupled plasma mass spectrometer (LA-ICP-MS) with a 25-35 µm pit diameter in the London Geochronology Centre at University College London. Approximately 150 grains resembling zircons were randomly selected for analysis from each sample. Plešovice zircon[55] was used as a primary standard to correct for instrumental mass bias and depth-dependent inter-element fractionation. Approximate U and Th concentrations were calculated by comparison with NIST 612 glass[56].

Data reduction of the time-resolved mass spectrometer data was performed using GLITTER 4.5[(57)]. Ages younger than 1100 Ma were calculated using the $^{206}Pb/^{238}U$ ratio whilst older grains used the $^{207}Pb/^{206}Pb$ ratio. Data were filtered to exclude non-zircons based on zirconium concentrations (>10^6 counts per second) and a -5/+15% discordance threshold was applied. This yielded at least 92 grains per sample, giving a 95% confidence that any age populations comprising more than 7% of the sample will be measured[58]. GJ1 zircon[59] was used as a secondary standard to verify accuracy of the data. Repeat analyses using zircons with and without existing ablation pits were made to check sample reproducibility; these agreed within the uncertainties associated with random sampling. Final data were processed and visualised using the R package IsoplotR[60].

Clast Petrography

The gravel fraction (>2 mm) was characterized in continuum along the core, between 648.17 and 209.17 mbsf. Clasts exposed in the cut surface of the archive half core were measured, logged and described on the basis of macroscopic features (e.g. shape, colour, texture). Logging aimed to identify the distribution and variation of the gravel-size clasts along the core length. Clast logging followed the methodologies applied to the ANDRILL and CRP records; on the basis of macroscopic features, clasts were grouped into seven main lithological groups: igneous rocks, quartz fragments, dolerites, volcanic rocks, metamorphic rocks, sedimentary rocks and sedimentary intraclasts[61,62,63,64]. Data processing involved counting the occurrence of each lithological group over each 10 cm core interval. The total number of clasts in each core was then divided by the core length to normalize the clast abundance, and the number of clasts for each lithological group was summarized for each core (Fig. S7). To highlight the along-core variation in dolerite and volcanic clasts - two of the most indicative lithologies for provenance constraint - the number of these clasts was divided by the total number of clasts in each core (Fig. S7). A total of 73 pebble to cobble-sized clasts were sampled for petrographic analysis, of which the most representative of each lithological group were analysed using standard petrographic methods with polarized light microscopy.

Palynology

Sample processing was performed at Utrecht University, following standard techniques of the Laboratory of Palaeobotany and Palynology. Samples were oven-dried and weighed (~15 g dry weight sediment each). One *Lycopodium clavatum* tablet with a known amount of marker spores was added for quantification of palynomorph abundances[65].

Samples were treated with 10% HCl (Hydrochloric acid) and cold 38% HF (Hydrofluoric acid), then sieved over a 10 μm mesh with occasional mild ultrasonic treatment. To avoid any potential processing-related preservation bias, no oxidation or acetolysis was carried out. The processed residue was transferred to microscope slides using glycerine jelly as a mounting medium, and 2 slides were analysed per sample at 400× magnification. Slides were examined for detailed marine (dinoflagellate cysts, acritarchs and other aquatic palynomorphs) and screening-level terrestrial (pollen and spore) analysis at Utrecht University, with a subsequent detailed analysis for terrestrial palynomorphs on a sub-set of seven samples undertaken at GNS Science. Of the 23 palynological samples analysed for dinocysts, two contained < 60 dinocysts (Sequence 1; 594.48 mbsf and Sequence 2; 567.75 mbsf) and one was almost barren (yielding only 12 *in situ* dinocysts, Sequence 3A; 374.9 mbsf). The almost barren sample is excluded from all plots. The two low abundance samples are included in our dataset; however, because of the low dinocyst yield, careful interpretation is required. Samples between 594.48 and 567.75 mbsf and below 594.48 mbsf (cores 65R, 67R, 69R and 71R) were also checked, but yielded few dinocyst specimens. Those present comprised of fragments of mostly reworked dinocysts.

Pollen and spore identification followed taxonomic compilations[66,67], augmented by key Antarctic literature[68,69,70]. For pollen and spores, scanning continued until an entire cover slide was completed, or a 100 count reached. Results are presented as specimens/gram, and percentage of all terrestrial palynomorphs. Dinocysts were identified based on a taxonomical index[71] and informally and formally described species in the literature[72,73,74,75]. Dinocyst percentages were calculated based on the total *in situ* dinocysts counted, excluding reworked specimens (Table S3). The percentages of other palynomorph groups such as brackish and freshwater algae (*Cymatiosphaera* spp. and *Pediastrum* spp.) and reworked dinocysts were calculated using the total palynomorphs counted (Fig. 2; Fig. S8). *In situ* dinocyst and terrestrial palynomorph absolute abundance (specimens/g dry weight, Table S3) and the absolute abundance of the other palynomorph groups were calculated by counting the amount of *Lycopodium clavatum* spores encountered, following the equation of Benninghoff (1962)[76].

Protoperidinioid (P) dinocysts are mostly represented by the genera *Brigantedinium*, *Lejeunecysta*, and *Selenopemphix*. Gonyaulacoid (G) dinocysts mostly include *Batiacasphaera* spp., *Operculodinium* spp. and *Spiniferites* spp. Protoperidinioid cyst percentages (Heterotrophic % in Fig. S8; Table S3) and percentages of the most common species (*Brigantedinium* spp. *Lejeunecysta* spp., *Selenopemphix* spp. and *Selenopemphix antarctica*) were calculated to identify productivity trends and/or the presence of sea ice (see Supplementary Information). P dinocysts are likely produced by heterotrophic dinoflagellates[77] and, at present, dominate the assemblages in Antarctic sediments in areas with high nutrients and/or (year-round) sea-ice covered areas. At present, samples in quasi perennial sea-ice covered areas are dominated by *Selenopemphix antarctica* (~75%), with abundant *Brigantedinium* spp. and rare occurrence of other species[78,79,80]. G cysts are generally produced by phototrophic dinoflagellates. *Operculodinium* spp. is the most abundant, has species representatives among the extant cysts and has been selected to represent temperate-warm conditions. At present, it is almost exclusively found in temperate areas of the Southern Ocean, north of the Subantarctic Front[78] and never occurs in the circum-Antarctic sediments, while it was found common to abundant in other Antarctic warm Miocene records[81,82]. Reworked dinocysts include Eocene and Oligocene taxa (mostly *Vozzhennikovia* spp., but also few *Spinidinium* spp. and *Enneadocysta diktyostila*).

Paleo CO_2 Compilation

Proxy estimates of atmospheric CO_2 concentrations (Fig. 2) were obtained from the compilations on the websites paleo-co2.org and p-co2.org. Proxies include the $\delta^{13}C$ of marine phhtoplankton[83,84,85], the $\delta^{13}C$ of paleosols[86,87], boron isotope ($\delta^{11}B$) proxies[88,89,90,91], leaf gas-exchange[92], stomatal frequencies[93] and the $\delta^{13}C$ of terrestrial C3 plants[94]. An assessment of the validity of different proxies is beyond the scope of this paper, so all available proxies were included. The complied data are presented as a LOESS-smoothed curve through the data using the 'loess' function in R. The shaded region indicates 1 sigma error.

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Author Contributions

T.v.d.F., R.M.M, L.D.S and J.W.M. designed the research; J.W.M. conducted the Nd and Sr isotope analyses; L.Z., F.T. and M.P. performed the clast counts; J.W.M., P.V. and A.C. produced the zircon

U-Pb data; F.B. and V.B.R. collected the clay mineralogy data; F.S., J.P. and C.B. performed the palynological counts and interpretations; S.H. provided the hornblende $^{40}Ar/^{39}Ar$ data; L.F.P., F.C. and L.D.S. calculated the sediment volume estimate; R.L, R.M.M., T.E.v.P., D.H., D.K.K. and E.G., helped construct and improve the age model; N.B.S and S.R.M. conducted the astrochronlogical analyses; D.K.K. provided the XRF data; J.W.M. created the figures and wrote the text with assistance from all authors.

Data availability All data from this study can be found in the Supplementary Information and have been submitted to the British Geological Survey National Geoscience Data Centre.

Competing Interests The authors declare no competing interests.

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