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The U-Pb detrital zircon signature of West Antarctic ice stream tills in the Ross embayment, with implications for Last Glacial Maximum ice flow reconstructions

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Abstract: Glacial till samples collected from beneath the Bindschadler and Kamb ice streams have a distinct U-Pb detrital zircon signature that allows them to be identified in Ross Sea tills. These two sites contain a population of Cretaceous grains 100–110 Ma that have not been found in East Antarctic tills. Additionally, Bindschadler and Kamb ice streams have an abundance of Ordovician grains (450–475 Ma) and a cluster of ages 330–370 Ma, which are much less common in the remainder of the sample set. These tracers of a West Antarctic provenance are also found east of 180° longitude in eastern Ross Sea tills deposited during the last glacial maximum (LGM). Whillans Ice Stream (WIS), considered part of the West Antarctic Ice Sheet but partially originating in East Antarctica, lacks these distinctive signatures. Its U-Pb zircon age population is dominated by grains 500–550 Ma indicating derivation from Granite Harbour Intrusive rocks common along the Transantarctic Mountains, making it indistinguishable from East Antarctic tills. The U-Pb zircon age distribution found in WIS till is most similar to tills from the west-central Ross Sea. These data provide new specific targets for ice sheet models and can be applied to pre-LGM deposits in the Ross Sea.

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Key words: provenance, Siple Coast, WAIS, Whillans Ice Stream

Introduction

Understanding local landscape modifications by glaciers and the global impacts of dynamic changes in ice sheets have occupied efforts of earth scientists for centuries. The West Antarctic Ice Sheet (WAIS), in particular, has long been considered susceptible to changes in sea level and ocean temperature variations resulting in more dynamic behaviour than the East Antarctic Ice Sheet (EAIS), which has a smaller proportion of its basal area below sea level (e.g. Joughin & Alley 2011). A new analysis of the past several decades of data shows that central West Antarctica has become one of the fastest warming areas of the planet (Bromwich *et al.* 2013). On longer timescales, the geological record provides an important archive of the ice sheet's response to warming over the past several hundred thousand to millions of years. Various studies have suggested that the WAIS fluctuated in synchrony with orbital forcings and even 'collapsed' at various times throughout its history (e.g. Naish *et al.* 2009, Pollard & DeConto 2009). Higher global sea levels during previous late Quaternary interglacials found in geological records from Australia to Bermuda are often attributed a smaller WAIS (e.g. O'Leary *et al.* 2013). Reconstructions of EAIS and WAIS extent, based on direct geological evidence, come from sediment cores and geophysical surveys on the Antarctic continental margin where the ice sheets have left their imprints (e.g. Anderson *et al.* in press).

A variety of challenges hinder the interpretation of ice sheet history from sedimentary records. In Antarctica, determining the chronology of offshore glacial deposits has been a particularly persistent problem (e.g. Andrews *et al.* 1999), but advances in analytical techniques have provided new opportunities to more accurately map out past ice extent and flow directions. Shipboard and satellite remote sensing techniques have revealed paradigm changing geomorphic features. For example, multibeam swath bathymetry surveys show that the continental shelf around Antarctica has been sculpted into a complex mosaic of linear ridges and troughs, drumlins, and moraines once thought absent from Antarctica (e.g. Shipp *et al.* 1999). Similarly, provenance studies that reveal the path of past ice sheet flow and the source of ice-rafted debris to the Southern Ocean have advanced from studies of sand and pebble petrography to isotopic (Sm-Nd, Pb-Pb) and geochronological tools (U-Pb, Ar-Ar) (e.g. Farmer *et al.* 2006, Pierce *et al.* 2011, Flowerdew *et al.* 2013, Licht & Palmer 2013). These tools are particularly useful for fingerprinting debris from parts of the ice sheet whose

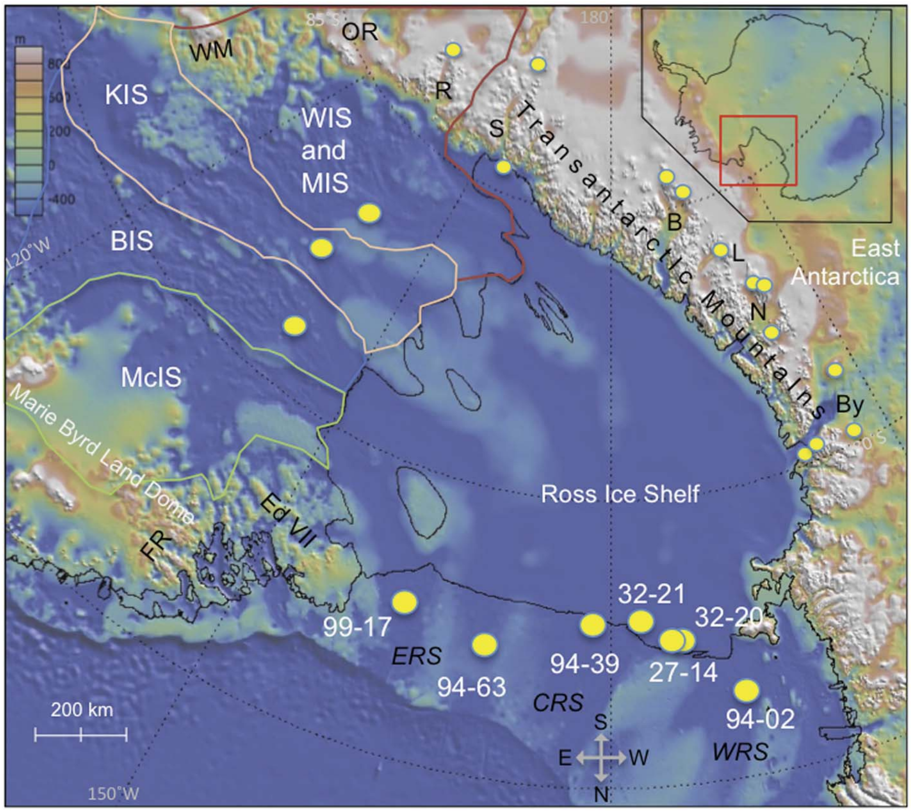

Fig. 1. Relief map of Ross embayment area of study from GeoMapApp. Yellow dots show sample locations. B = Beardmore Glacier, BIS = Bindschadler Ice Stream, By = Byrd Glacier, CRS = central Ross Sea, Ed VII = Edward VII Peninsula, ERS = eastern Ross Sea, FR = Ford Ranges, KIS = Kamb Ice Stream, L = Law Glacier, McIS = MacAyeal Ice Stream, MIS = Mercer Ice Stream, N = Nimrod Glacier, OR = Ohio Range, R = Reedy Glacier, S = Scott Glacier, WIS = Whillans Ice Stream, WM = Whitmore Mountains, WRS = western Ross Sea.

subglacial geology is distinctive. For example, the differing geological histories of Marie Byrd Land and the Transantarctic Mountains (TAM), which flank the West Antarctic rift basin over which the WAIS flows, should provide erosional products that can be used to identify and trace ice sheet flow over each area. This paper reports the results from a study of detrital zircons from Ross embayment tills and shows that grains from West Antarctica have characteristic age populations, providing an important new tracer of the WAIS. Such tracers provide an essential tool to help discriminate between sediments deposited beneath ice flowing from East and West Antarctica.

Setting and background

East and West Antarctica are divided by the 3500 km long TAM. In the Ross embayment, the majority of the EAIS flows toward the coast via outlet glaciers cutting through the TAM, whereas most ice draining into the Ross Sea from West Antarctica flows via fast moving ice streams unconstrained by exposed bedrock. Some ice streams, such as Kamb (KIS) and Bindschadler (BIS), originate entirely in West Antarctica, whereas the Mercer and Whillans ice stream catchments extend into East Antarctica (Fig. 1), but are considered key dynamic features of the WAIS.

The history of ice sheet development and fluctuations can be challenging to reconstruct where repeated ice advances erase, rework and/or bury the record from previous advances. Glacial deposits from the last glacial maximum (LGM) are well characterized in the Ross embayment and show that grounded ice reached the outer continental shelf in the eastern and central Ross Sea, but not in the western Ross Sea (see summary in Anderson *et al.* in press). Till deposited on the continental shelf has been shaped into mega-scale glacial lineations that typically parallel the sea floor troughs and are interpreted to represent substrate deformation associated with streaming ice (e.g. Shipp *et al.* 1999). Such lineations reflect ice flow direction and some cross-cutting patterns are observed in eastern Ross Sea floor troughs (Mosola & Anderson 2006).

The modern WAIS occupies a portion of the West Antarctic rift basin, which is characterized by muted basin-parallel ridges and troughs that contain sediment up to 400–800 m thick (Peters *et al.* 2006). The subglacial sediments are interpreted to have varying water content over space and time, and thus have dynamic interactions with the ice sheet base that impact ice stream flow into the Ross Sea (e.g. Christoffersen *et al.* 2010). The West Antarctic basin formed in the mid-Cretaceous through the Cenozoic with horizontal displacement totalling several hundred kilometres between Marie Byrd Land and East Antarctica (Fig. 1) (Winberry & Anandakrishnan 2004). Major extension began in the Cretaceous *c.* 105 Ma and continued throughout the Cenozoic, with 150 km of

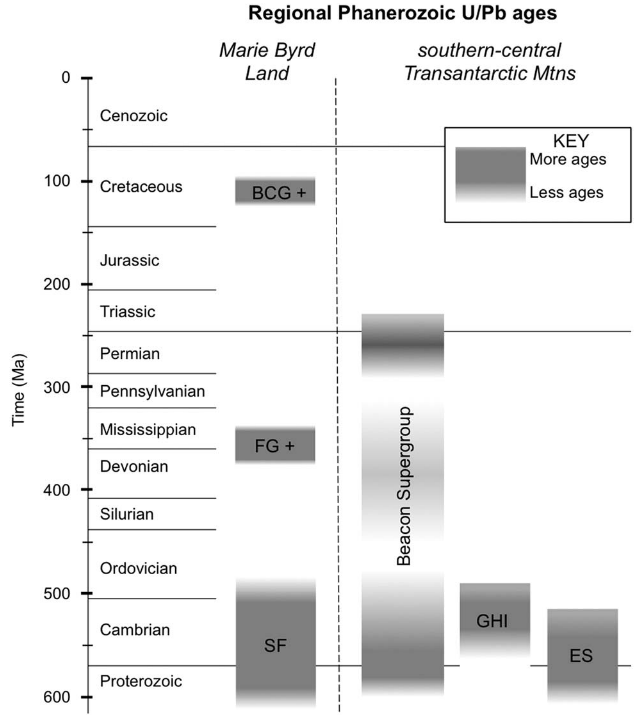

Fig. 2. Diagram shows the relative frequency of Phanerozoic U-Pb zircon ages from dominant bedrock types surrounding the study area. Darker shades of grey indicate a higher frequency of grains relative to the total distribution from that rock type. BCG + = Byrd Coast Granite plus others described in text, ES = Eocene sandstone, FG + = Ford Granodiorite plus others described in text, GHI = Granite Harbour Intrusives, SF = Swanson Formation.

extension recorded in the Eocene–Oligocene (e.g. Siddoway 2008). During the Eocene, the TAM were being uplifted relative to West Antarctica and shed sediments into the West Antarctic basin (e.g. Siddoway 2008).

The major rock outcrop exposures of West Antarctica are in Marie Byrd Land and consist of the Palaeozoic Swanson Formation, magmatic rocks spanning the Devonian to mid-Cretaceous, and Cenozoic volcanic rocks (Tingey 1991). Late Cretaceous erosion produced the Marie Byrd Land dome (LeMasurier & Landis 1996). This feature trends east–west, roughly parallel to the Marie Byrd Land coast (Fig. 1) (LeMasurier & Landis 1996, Winberry & Anandakrishnan 2004) and probably shed sediment southward into the initial lowlands of the forming West Antarctic basin. Most of the pre-Cenozoic rock units contain zircons that have been dated using U-Pb and these units are briefly described below to characterize possible sources of detrital zircons in West Antarctic glacial till.

The immature meta-sediments of the Swanson Formation, which outcrop in the Ford Ranges and Edward VII Peninsula (Fig. 1), have U-Pb ages of *c.* 500–600 Ma (Fig. 2) and a smaller population 800–1000 Ma (Pankhurst *et al.* 1998). The Swanson Formation was intruded by the Ford Granodiorite which was emplaced *c.* 375 Ma; ages from associated granites and migmatites span *c.* 335–375 Ma (Fig. 2) (Pankhurst *et al.* 1998, Siddoway & Fanning 2009, Korhonen *et al.* 2010). The Byrd Coast Granite was emplaced following the Ford Granodiorite, with ages of 95–124 Ma (Pankhurst *et al.* 1998, Siddoway 2008). Igneous activity in the mid-Cretaceous continued with granite emplacement along the Ruppert and Hobbs coasts 101–110 Ma (Mukasa & Dalziel 2000) and the Ford Ranges to Edward VII Peninsula 95–120 Ma (e.g. Weaver *et al.* 1992, Korhonen *et al.* 2010) (Fig. 2).

On the southern margin of the West Antarctic rift basin, exposed rocks of the TAM have also been dated using U-Pb of zircons. Those described here are the most widespread rock units along the southern TAM. The Granite Harbour Intrusives extend along much of the mountain front and U-Pb ages for this complex group of rocks are typically 485–545 Ma (Fig. 2) (e.g. Goodge *et al.* 2012, Paulsen *et al.* 2013). The other Cambrian–Neoproterozoic rocks in the region (LaGorce and Wyatt formations) are limited to outcrops in the upper reaches of Scott Glacier (Stump *et al.* 2007). Following the Ross orogeny, exhumation and erosion of the granitic and metamorphic basement of East Antarctica produced the Kukri Peneplain on which the Beacon Supergroup clastic sediments were deposited and intruded by the Ferrar dolerite at *c.* 180 Ma. In the southern TAM, along the Shackleton Glacier, Elliott & Fanning (2008) describe U-Pb zircon ages in the Buckley and Fremouw formations that shift from almost exclusively Permian–Early Triassic (245–260 Ma) to increasing numbers Ross/Pan-African grains (480–600 Ma; Fig. 2). Ross/Pan-African U-Pb zircon ages are also common in Eocene sandstones inferred to occur in sedimentary basins along the TAM front (e.g. Paulsen *et al.* 2011). An additional potential source of zircons to the upper reaches of Whillans Ice Stream (WIS) is from the Whitmore Mountains (Fig. 1). Flowerdew *et al.* (2007) report U-Pb detrital zircon ages from sedimentary rocks there with a dominant population 500–550 Ma.

Little is known about the composition, age and extent of rocks inland of the southern TAM, which are buried by the EAIS. Previous work has shown that many nunatak moraines at the head of East Antarctic outlet glaciers in this region contain subglacially-derived sediments, providing a window into the unexposed bedrock that lies beneath the EAIS (e.g. Palmer *et al.* 2012). In contrast, till samples collected from lateral moraines along the valley sides are dominated by input from adjacent wall rock (Palmer *et al.* 2012). U-Pb dating of detrital zircons from nunatak moraines has been completed along the TAM (Schilling 2010, Palmer *et al.* 2012, Welke 2013) and provide U-Pb age constraints that represent an integration of geochronological information

Table I. Site and sample information.

Site name	Site label	Latitude	Longitude	Depth in core (cm)	Local bedrock
West Antarctic ice streams					
Bindschadler 98-2-1	BIS	-81.074	-140.005	NA	NA
Kamb 96-3-1	KIS	-82.446	-135.959	30–40, 40–50, 140–150, 180–190	NA
Whillans 89-1-4	WIS	-83.478	-138.246	10–20, 130–140, 160–170	NA
East Antarctic moraines					
Reedy Glacier	R	-86.486	-124.718	NA	Unknown metamorphic
Scott Glacier	S	-87.350	-149.922	NA	Buckley Formation*
		-85.467	-154.454	NA	Granite Harbour Intrusives
Beardmore Glacier	B	-85.625	167.295	NA	Victoria Group*
		-85.305	164.693	NA	Victoria Group*
Law Glacier	L	-84.130	160.980	NA	Victoria Group*
Nimrod Glacier	N	-83.283	156.037	NA	Nimrod Group & Granite Harbour Intrusives
		-83.295	156.741	NA	Nimrod Group & Granite Harbour Intrusives
		-82.432	158.121	NA	Beacon Supergroup
Byrd Glacier^	By	-81.341	152.679	NA	Devonian Beacon Supergroup
		-80.262	153.653	NA	Devonian Beacon Supergroup
		-80.402	157.134	NA	Granite Harbour Intrusives
		-80.209	159.143	NA	Granite Harbour Intrusives
Ross Sea cores					
NBP94-01-02^	94-02	-76.284	169.704	111–126	NA
ELT32-20^	32-20	-77.585	174.918	64–69, 132–137	NA
ELT27-14^	27-14	-77.627	175.377	47–50, 63–66, 105–109, 164–170	NA
ELT32-21^	32-21	-77.933	178.013	54–58, 104–108	NA
NBP94-07-39^	94-39	-77.924	-177.982	52–54, 100–102	NA
NBP94-07-63	94-63	-77.327	-169.180	52–54, 112–114	NA
NBP99-02-17	99-17	-77.716	-161.862	104–106	NA

NA = not applicable.
^Most U-Pb ages previously published in Licht & Palmer (2013).
*Part of Beacon Supergroup.

from East Antarctic outlet glacier catchment areas. In summary, the U-Pb zircon ages from till and bedrock exposures provide the context for understanding the origin of grains found beneath the West Antarctic ice streams and identifying distinctive populations that can be used to trace ice emanating from different parts of the continent.

Materials and methods

Till samples were collected from East and West Antarctic sites in the Ross embayment in order to define the distinguishing characteristics of each source area for comparison with LGM-age Ross Sea tills. Nine samples, comprising 2–5 cm thick intervals, were taken from sediment cores collected beneath WIS, KIS and BIS (Fig. 1, Table I) during the 1992–99 field seasons by researchers at the California Institute of Technology (Kamb & Engelhardt). East Antarctic till samples, collected by Indiana University-Purdue University Indianapolis researchers during field seasons from 2005–11, were selected from moraines found at the base of nunataks near the head of each major outlet glacier, as well as along the length of several of these same glaciers (Fig. 1, Table I). All East Antarctic till collection sites were modern ice-cored moraines, with till thickness ranging from < 2 cm to > 40 cm. At each site, material was collected 1–3 cm beneath the surface to minimize the effects of wind deflation. Till samples from seven Ross Sea cores collected in sea floor troughs along a transect near the Ross Ice Shelf front (Fig. 1) were obtained from the Antarctic Research Facility at Florida State University. Each of these sample integrated material over a 2–5 cm interval.

Till samples were sieved to isolate the 63–150 µm fraction and sent to the University of Arizona LaserChron Center for zircon separation using a Frantz magnetic separator combined with heavy liquids following standard methods. Both the unknown zircons and zircons standards (SL = 564 ± 4 Ma and R33 = 419.3 ± 0.4 Ma; Gehrels *et al.* 2008) were mounted in the middle of 1-inch diameter epoxy pucks and polished to expose the interior of the grains.

The U-Pb analysis on zircon crystals was conducted using a laser ablation multicollector inductively coupled plasma mass spectrometry (LA-MC-ICPMS) (Gehrels *et al.* 2008). Data were collected over several years from the same lab; initial was work done on a GVI isoprobe, which was upgraded to a Nu HR ICPMS with a photon machines analyte G2 excimer laser. In all cases, a 30 µm

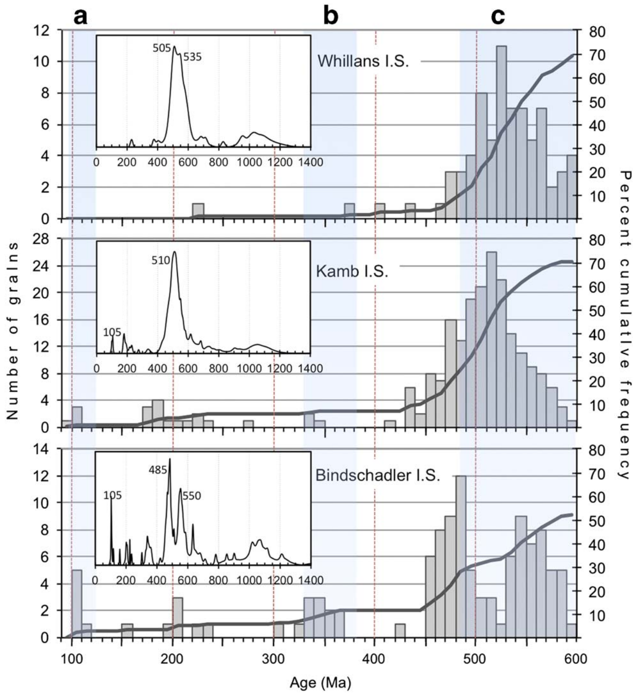

Fig. 3. Histogram and cumulative frequency (black line) of detrital zircons younger than 600 Ma from West Antarctic ice stream tills. Inset probability diagram shows age distributions to 1400 Ma and the y-axis shows relative probability. Shaded regions highlight ages of common detrital zircon populations in rocks from the region. **a** = constraints from Edward VII Peninsula Granites 95–100 Ma (Weaver *et al.* 1992), Ford Ranges 102–119 Ma (Korhonen *et al.* 2010, Siddoway 2008), and Ruppert and Hobbs coasts Mount Prince Granite *c.* 110–100 Ma (Mukasa & Dalziel 2000), **b** = Ford Granodiorite and related rocks, **c** = Ross orogeny and Swanson Formation detrital zircons 500–600 Ma.

diameter pit was ablated into each zircon with the laser. The ablated material was carried by He into the ICPMS where U, Th and Pb isotopes were measured simultaneously. Each measurement was made in static mode for ^{238}U, ^{232}Th, ^{208}Pb, ^{206}Pb, and a discrete dynode ion counter for ^{204}Pb and ^{202}Hg. Each analysis involved one 15 second integration for backgrounds, fifteen 1 second integrations with the laser firing continuously, followed by a 30 second delay to prepare for the next sample. Errors in determining U and P isotopic ratios result in a measurement error of 1–2% (2σ) (Gehrels *et al.* 2008). Common Pb correction was made using Hg-corrected ^{204}Pb, assuming an initial Pb composition from Stacey & Kramers (1975). Isotopic data collected from the LA-MC-ICPMS was reduced using an Excel macro (‘Agecalc’). The data were filtered for discordance using 30% cut-off in order to retain more Archean ages. The ^{206}Pb/^{238}U age was selected for < 1000 Ma zircons, and ^{206}Pb/^{207}Pb age for > 1000 Ma grains.

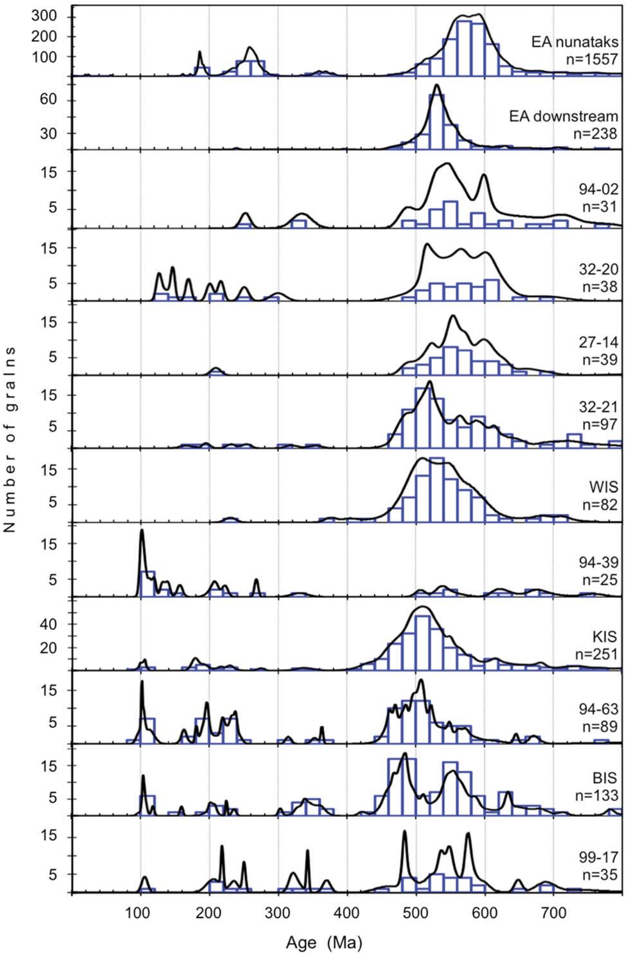

Fig. 4. Distribution of U-Pb zircon ages from West Antarctica, the Ross Sea and East Antarctic outlet glaciers shown by histograms of the number of ages and probability density (black curve). Note the presence of U-Pb ages 100–110 Ma is limited to Ross Sea core sites east of 180°. Number of grains refers only to ages < 800 Ma shown, not the total number measured; see Supplemental data table for complete list of ages. The histogram y-axes values are necessarily variable.

Results

West Antarctica

A total of 630 detrital zircons were analysed from WIS, KIS and BIS (Fig. 3 and Supplemental data found at http://dx.doi.org/10.1017/S0954102014000315). Multiple samples were analysed from each ice stream and combined to produce a single age distribution and provide an integrated dataset representing the till from each site. With only one exception from KIS where one small sample lacked an age of *c.* 100 Ma, U-Pb age distributions from samples within each ice stream were statistically indistinguishable from each other using the Kolmogorov-Smirnoff test (Schilling 2010). Grain yields from some samples were very low because of the small sample sizes; additional samples and analyses would be required to robustly assess time-transgressive changes in zircon age populations.

The age distributions for WIS and KIS are similar, with a dominant single Cambrian peak, a smaller but significant Mesoproterozoic population and few older grains (Fig. 3 insets). The Cambrian peak overlaps with the timing of the Ross orogeny and this age population from both sites extends into the late Neoproterozoic. In contrast, BIS till shows a strongly bimodal distribution across this time interval, with peaks at 485 and 550 Ma (Fig. 3 inset). The till from this site also has a larger number of Mesoproterozoic and older grains compared to the other two sites.

At all sites, the Devonian- to Jurassic-age zircons are much lower in abundance than older grains and show the number of ages in this range increasing toward Marie Byrd Land. Some peaks in the probability curves represent only one or two grains (Fig. 3); probability peaks are typically considered geologically meaningful when three or more concordant ages overlap (Gehrels *et al.* 2008). Based on this criterion, WIS till lacks any significant peaks in this range, KIS till has one at 170–190 Ma, and BIS till has age clusters of interest at 330–350 Ma and 200–210 Ma. Significantly, only KIS and BIS contain a mid-Cretaceous peak *c.* 100–110 Ma (Fig. 3).

Ross Sea

A total of 501 detrital zircons were analysed from seven cores in the Ross Sea (Fig. 4 and Supplemental data found at http://dx.doi.org/10.1017/S0954102014000315). All of the Ross Sea samples, except 94-39, are dominated by Cambrian–late Neoproterozoic U-Pb ages. The proportion of grains in the younger part of this range, 480–550 Ma, increases eastward toward West Antarctica. Core 99-17 has a bimodal distribution across this interval, similar to the peaks in BIS tills. Generally, the cores show east–west spatial variability in the content of Mesozoic grains. Cores collected east of 180° longitude have a higher proportion of Mesozoic grains and also contain a *c.* 100–110 Ma age population, consistent with the ages from KIS and BIS. This peak is absent in the cores west of the 180° longitude. Several of the probability peaks in the Mesozoic, including all peaks in core 32-20, are not considered geologically meaningful based on these data because they are the product of fewer than three concordant ages.

East Antarctica

A total of 2796 detrital zircons were analysed from 13 East Antarctic sample sites and the 1795 ages that are 800 Ma and younger are shown in Fig. 4. For the purposes of this study, the East Antarctic tills have been amalgamated into two groups, sites from nunatak moraines at the head of outlet glaciers and downstream sites from the valley sides to the mouth. Ten sites from Byrd Glacier to Reedy Glacier (Fig. 1) represent the nunatak moraines and they show three main populations. Around 30% of the grains are Mesoproterozoic and older, 29% of ages are 550–610 Ma, and 5% are 240–270 Ma (Fig. 4). In contrast, three downstream sites from Byrd and Scott glaciers have a single dominant peak 530–540 Ma, with a small proportion of grains 550–610 Ma.

Discussion

The response of the WAIS to climatic and oceanographic forcings is of primary interest to the scientific community and identifying a distinctive tracer that can be used to constrain ice flow in both proximal and distal glacial sediments is key to placing limits on past fluctuations of the WAIS. Subglacial till samples were available for three of the Siple Coast ice streams and these allow us to directly fingerprint the ice streams and understand better the origin of West Antarctic basin fill. Whereas traditional sand petrological studies have been successfully used to link onshore and offshore tills (Licht *et al.* 2005, Licht & Palmer 2013), the methodology can be more difficult in distal glacial marine deposits where the number of sand grains is too small to develop reliable statistical sampling, and common minerals such as quartz are not easily traced back to their source. Detrital minerals, such as zircon and amphibole, can be more useful in these cases by providing both composition and geochronological data to more easily tie grains to their region of origin (e.g. Pierce *et al.* 2011, Licht & Palmer 2013). The focus here is on the geographical variability in U-Pb detrital zircon ages in WAIS tills that can be applied to ice sheet reconstructions over a variety of temporal and spatial scales, with emphasis on the LGM.

U-Pb ages in West Antarctic tills and their origin

The U-Pb ages from WIS till are predominantly late Neoproterozoic–Cambrian and over 50% of grains have ages between 500–600 Ma (Fig. 3). Peaks in the probability plot at 505 Ma and 535 Ma, commonly called the Ross-age peak, are consistent with the age of the Granite Harbour Intrusives formed during the Ross orogeny. The Granite Harbour Intrusives are mapped along much of the length of the TAM front and outcrop in areas closest to the catchments of the Whillans/Mercer ice streams, including the Ohio Range to Reedy Glacier (Fig. 1) (Mirsky 1969). As noted earlier, U-Pb zircon ages from bedrock samples of the Granite Harbour Intrusives are typically 485–545 Ma and moraines along the TAM outlet glacier valleys flanked by the Granite Harbour Intrusives produce U-Pb zircon ages that are predominantly 500–550 Ma (‘downstream moraines’ in Fig. 4) (Schilling 2010, Licht & Palmer 2013). The moraine closest to WIS for which there are detrital zircon U-Pb ages is at the base of the Scott Glacier, where 64% of grains have U-Pb ages 500–550 Ma, with the highest probability peak at 530 Ma (Schilling 2010). From these observations, combined with information about current ice flow paths, it is probable that the bulk of detrital zircons, and by association the remainder of sediment beneath the WIS, has accumulated over time from erosion of coastal outcrops of the TAM and/or basement highs in West Antarctica.

The presence of grains > 550 Ma in WIS till suggests that this part of the West Antarctic basin also contains some material derived from sources other than the Granite Harbour Intrusives. Such ages are associated with an early phase of the Ross orogeny, the Pan-African orogeny, and the Grenville orogeny (1300–1000 Ma). Zircon ages 500–1200 Ma can be found in siliciclastic rocks from the Beacon Supergroup (Elliott & Fanning 2008) which outcrop in the southern TAM, the Swanson Formation, a pre-Devonian accretionary complex on Edward VII Peninsula in Marie Byrd Land (Pankhurst *et al.* 1998) and Eocene sandstone erratics found near McMurdo Sound (e.g. Paulsen *et al.* 2011). Considering the distance of the known Swanson Formation outcrops from the WIS and the subglacial topography, this seems a less likely source than the TAM for sediments found beneath WIS. It is highly probable that the populations > 550 Ma have been recycled and do not represent erosion of primary bedrock sources.

The detrital zircon age distribution from KIS till is similar to that of WIS till, with the highest proportion of grains falling in the Cambrian accompanied by a much smaller fraction of Mesozoic and Proterozoic grains (Fig. 3). The maximum probability peak is at 510 Ma. Similar to WIS, we infer a TAM source for these 'Ross-age' grains. Differences from WIS include a higher number of ages Ordovician (488 Ma) and younger. In particular, the relatively large number of grains *c.* 450–480 Ma is more similar to BIS till than WIS till, and is younger than most known Granite Harbour Intrusives. The youngest U-Pb age reported from an igneous intrusion in the southern TAM is 484.7 ± 8.4 Ma; samples were from the coastal Fallone Nunataks between the Reedy and Scott glaciers (Paulsen *et al.* 2013). If such ages were common along coastal outcrops, then WIS tills would be expected to contain a higher fraction of this population than KIS tills. However, the fraction of grains 450–480 Ma in tills increases toward Marie Byrd Land, not toward the TAM. The outcrop source of these grains is not known but may be related to a late plutonic phase of the Ross orogeny seaward of the TAM and currently located within the West Antarctic basin.

The KIS till contains a U-Pb age peak at *c.* 100–110 Ma. The number of grains is small, but such young ages are not known from East Antarctic outcrops and have not been found in thousands of analyses from East Antarctic tills (Schilling 2010, Licht & Palmer 2013, Welke 2013). Several sources from Marie Byrd Land are consistent with this age and could have contributed grains into the West Antarctic basin prior to glaciation. Leucogranites from the Fosdick Mountains in the Ford Ranges have U-Pb ages 100–120 Ma (Siddoway 2008, Korhonen *et al.* 2010), and K-Ar age of biotites within the nearby Edward VII granites yield a similar range (95–100 Ma) (Weaver *et al.* 1992). Granitoids and felsic and intermediate dike swarms with U-Pb ages of 101–110 Ma have also been reported along the Ruppert and Hobbs coasts of western Marie Byrd Land (Mukasa & Dalziel 2000). Additional analyses would be required to further refine the source of these grains, but the source must be limited to Marie Byrd Land.

The U-Pb age distribution of BIS has several distinctive features, including a strong bimodal distribution of Cambrian–Ordovician grains (Fig. 3) rather than the more typical single Ross-age peak. Furthermore, BIS has a higher proportion of grains > 600 Ma as indicated by the cumulative frequency curve in Fig. 3. Almost 50% of grains are > 600 Ma, with the majority of these having ages 1000–1100 Ma (Fig. 3 inset). A small number of ages are scattered across the Proterozoic and even extend back to the Archean (Schilling 2010). The BIS till contains the highest proportion of grains younger than 400 Ma, with at least three significant discrete populations.

In BIS till, the typical Ross-age peak is replaced by two U-Pb age populations centred at 485 Ma and 550 Ma. As noted earlier, the source of zircons 450–475 Ma is unknown, but their absence from the TAM where the geology is better exposed and the number of grains in this age range increases toward Marie Byrd Land, thus zircons 450–475 Ma are considered to be a signal of ice originating in West Antarctica, north of *c.* 83°S. Further studies beyond the scope of this project would be required to determine the specific geological origin of these grains.

Zircon ages 540–590 Ma and 1000–1100 Ma overlap with ages known from outcrops in the TAM (Fig. 2), as well as till from East Antarctic nunataks. However, the relatively high numbers in BIS till but lower proportion in KIS till suggest a different origin. Because the BIS catchment is completely within the West Antarctic basin and lies closer to Marie Byrd Land than the TAM, these grains probably originated from the Swanson Formation of Marie Byrd Land from which Pankhurst *et al.* (1998) reported grains with similar ages. The material may have been shed south-westward into the West Antarctic basin from the Marie Byrd Land dome during a period of mid-Cretaceous erosion (LeMasurier & Landis 1996) with subsequent incorporation into sub-ice stream tills. Alternatively, they could have been derived from unknown subglacial outcrops within the basin. These data highlight the challenge of identifying the source of ubiquitous U-Pb ages without other discriminating information.

As noted above, BIS tills show three clusters of zircon ages < 400 Ma. The oldest of these is *c.* 330–370 Ma, which is consistent with derivation from the Ford Granodiorite and related rocks from Edward VII Peninsula, the Fosdick Mountains and/or the Ruppert and Hobbs coasts (Fig. 2) (Pankhurst *et al.* 1998, Mukasa & Dalziel 2000, Siddoway & Fanning 2009). The second age cluster spans the Triassic–Jurassic boundary and has fewer grains. Similar ages are seen in KIS till, but across a wider range. No clear source of these grains has been identified; a few grains with slightly older ages (220–250 Ma) have been identified from the Cretaceous Alexandra Mountains metamorphic complex, which outcrops on Edward VII Peninsula (Pankhurst *et al.* 1998), and in sandstones of the Section Peak Formation in north Victoria Land (Elsner *et al.* 2013). The broad distribution of ages makes this a less reliable West Antarctic tracer than others discussed. The youngest and sharpest peak is 100–110 Ma, which is similar in age to, but more abundant than in, KIS tills. As discussed above, there are several possible Marie Byrd Land sources for these zircons and it is considered to be a key fingerprint of the WAIS.

Summary of West Antarctic U-Pb tracers

The distinctive U-Pb age populations among detrital zircons from BIS and KIS tills provide an important tracer for the northern two-thirds of the WAIS catchment in the Ross embayment, including ice adjacent to the catchment of Thwaites Glacier. Overall, the most distinctive signature of West Antarctic-derived ice is the 100–110 Ma U-Pb age population. This tracer applies to ice emanating from Marie Byrd Land to KIS. These findings are consistent with Ar-Ar ages of ice-rafted hornblende grains found in surface sediments offshore West Antarctica (Roy *et al.* 2007). In contrast, the absence of 100–110 Ma grains from WIS till, combined with nearly complete overlap with ages from East Antarctic sources means that U-Pb ages cannot be used to uniquely trace the WIS flow path. Detrital zircons associated with the Ross/Pan-African orogeny (480–625 Ma) are widespread in sediment and rocks from the Ross embayment East and West Antarctic tills, Permian Beacon Supergroup sandstones, the Swanson Formation and in offshore sediments (Fig. 2) (Pankhurst *et al.* 1998, Elliott & Fanning 2008, Schilling 2010, Palmer *et al.* 2012, Licht & Palmer 2013), and thus must be interpreted with caution. The results from this study indicate that zircon grains 450–475 Ma are supplied by West Antarctic ice north of *c.* 83°S, as their abundance increases with proximity to Marie Byrd Land and the TAM lack zircons of these ages. Interestingly, the West Antarctic tills lack a cluster of ages 240–270 Ma reported by Elliott & Fanning (2008) to be abundant in Permo–Triassic sandstones of the Buckley and Fremouw formations (Beacon Supergroup) and interpreted to have originated from arc-volcanism in West Antarctica.

West Antarctica/Ross Sea till comparison

The U-Pb ages from tills deposited on the Ross Sea continental shelf during the LGM were analysed to compare with West and East Antarctic tills in order to determine whether distinctive age populations were identifiable in downstream subglacial deposits. Histograms and probability plots were created for ages < 800 Ma, showing zircon age distributions from each ice stream, an east–west transect of Ross Sea cores, as well as East Antarctic tills collected along the TAM. Samples from the TAM were combined into two groups: i) till from moraines along valley sides to the mouth (downstream moraines), and ii) nunatak moraines from the head of major East Antarctic outlets (Fig. 4). Here the focus is on the presence or absence of unique grain populations to trace flow paths rather than relying on statistical tests of population similarity. This approach highlights age populations that may be made up of a relatively small number of ages, but having critical provenance information.

The two characteristic features of BIS till, a narrow age peak at 100–110 Ma and the double Ross-age peak, are present in core 99-17, the easternmost Ross Sea sample analysed (Fig. 4). Core 94-63, located one trough westward, also shows a 100–110 Ma peak, but lacks the characteristic bimodal peaks at 485 Ma and 550 Ma. The signature of KIS till is a single Ross-age population, peaking at 510 Ma, and a small number of grains 100–110 Ma. Core 94-63 shows both these populations (Fig. 4), though the core has a higher proportion of grains 100–110 Ma. Relative to KIS, the till in 94-63 has a higher fraction of grains 460–480 Ma, more similar to ages found in BIS till, suggesting some input of ice from areas now within the BIS catchment. Core 94-39 has the highest proportion of grains 100–110 Ma and a muted Ross-age peak, unlike any other West or East Antarctic tills analysed. Unfortunately, the zircon yields in this core were quite small ($n = 30$) reducing the likelihood that the age distribution fully represents the populations in the till. However, the presence of the 100–110 Ma population is interpreted as a clear signal that West Antarctic-derived ice flowed over this site during the LGM. We speculate that mid-Cretaceous bedrock provinces extend offshore of the Edward VII Peninsula into the Ross Sea and outcrop on subglacial high points, such as Roosevelt Island or Siple Dome, providing a local source of zircons with this distinctive age. Geophysical surveys of Siple Dome indicate that the associated subglacial topographical high is essentially devoid of a till cover (Gades *et al.* 2000), allowing subglacial erosion to readily access this bedrock.

West of 180° longitude, the 100–110 Ma zircons are absent from Ross Sea tills and the probability of finding

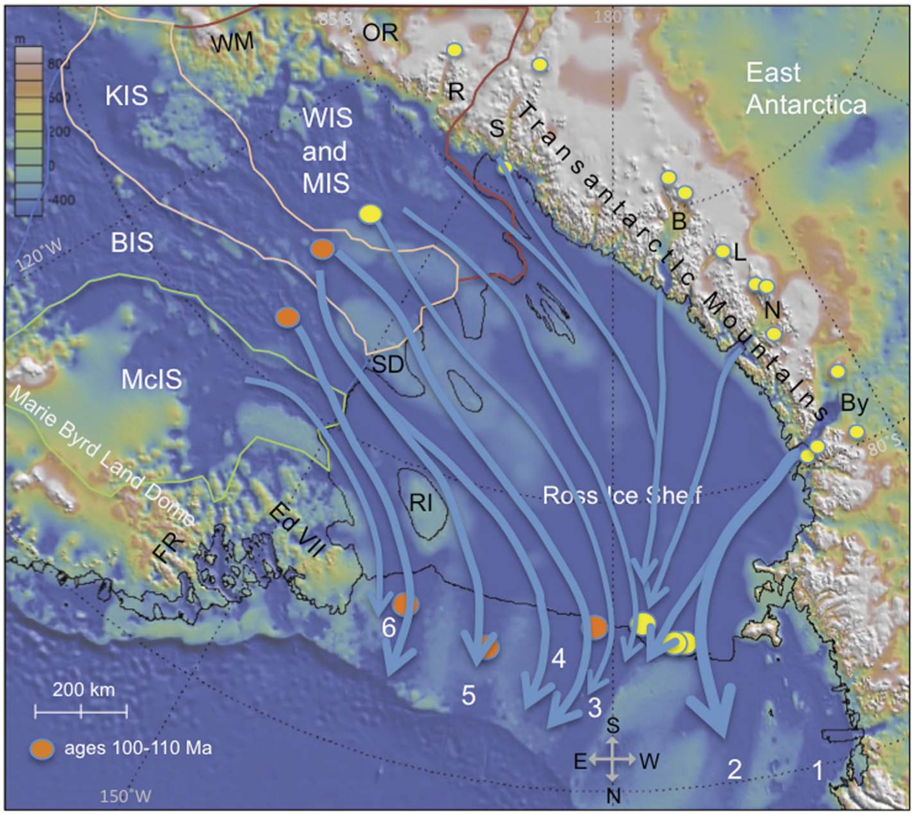

Fig. 5. Late Quaternary ice flow reconstruction for the Ross embayment. Orange dots highlight sample locations with U-Pb ages 100–110 Ma. Sea floor troughs are numbered following the convention in Mosola & Anderson (2006). RI = Roosevelt Island, SD = Siple Dome, other abbreviations are the same as in Fig. 1.

grains 550–610 Ma increases (Fig. 4). Almost 2800 zircon grains analysed from moraines distributed along the TAM are completely devoid of 100–110 Ma grains and tills from nunatak moraines are overwhelmingly 550–610 Ma grains. This combination indicates that cores in the western half of the Ross Sea contain sediment derived from East Antarctica. As noted above, the U-Pb ages in WIS till cannot be distinguished from 'downstream' East Antarctic tills eroded from outcrops of the TAM. Core 32-21 has the most similar age distribution to WIS till, with a Ross-age peak centred at 520 Ma. While most of the Ross Sea cores have a very small number of concordant ages that span the Cretaceous and Jurassic (Fig. 4), they cannot be considered geologically significant because they lack clusters of three or more overlapping ages and also lack a potential outcrop source.

The complex process of till accumulation and lack of high-resolution chronology within the Ross Sea tills means that it is not possible to determine whether all the LGM till represents the same snapshot in time even though all samples were collected in the upper 1.5 m of sediment. Previous analysis of seismic facies by Shipp *et al.* (1999) shows that the LGM till package in the inner Ross Sea is 0–5 m thick. Unfortunately, the strength of the till results in incomplete recovery of the full thickness, thus preventing measurement of provenance changes throughout the entire section. Where multiple samples from a single core (Ross Sea or ice stream) have been analysed, substantial variability with depth is not observed. However, the small core diameter means that the number of grains available for analysis is often less than optimal for robust statistical comparison. From this dataset, a time-transgressive analysis of possible flow direction changes within the LGM cannot be created.

Palaeoflow reconstruction

Model reconstructions of ice filling the Ross embayment during the LGM have shown a range of inputs from West and East Antarctica, with variable configurations of palaeo ice streams (e.g. Pollard & DeConto 2009, Golledge *et al.* 2013). The U-Pb ages reported here provide field data constraints on flow that can be used to place limits on modelling efforts and serve as an example of how such datasets can be useful in regions of convergent flow even when the subglacial bedrock geology is not well known. Sub-ice stream U-Pb fingerprints show a high level of similarity to offshore tills allowing refinement of flowlines described in Licht *et al.* (2005) and Farmer *et al.* (2006). The addition of a large number of new samples compared to previous studies allows us to fill in what were inferred flowlines. The new flowline reconstruction, built on this more robust dataset, is shown in Fig. 5. Ice flowlines are based on both the overall age population distribution and the presence of geologically significant peaks, such as 100–110 Ma.

These particular ages show that the boundary between the modern KIS and WIS was between troughs 3 and 4 during the LGM. This is largely consistent with previous reconstructions based on sand petrography and ε_{Nd}. That trough 3 was an area of convergent flow and high velocity ice is supported by both field observations of strong sea floor lineations (Shipp *et al.* 1999) and numerical model results from Golledge *et al.* (2013).

The closest model-data fit comes from a time-transgressive simulation described by Golledge *et al.* (2013, fig. 13B) where flow paths during ice advance, highlighted by a time-dependent particle tracking method, show a better match than ice flow under steady-state conditions during the LGM. Their model simulations suggest that till mobilization is most prevalent during transient glacial states, especially during initial ice advance. Field and modelling based studies provide support for the idea that grounded ice did not reside in the Ross Sea long enough during the LGM to achieve a steady-state (e.g. Licht & Andrews 2002). Compared to the results of this study, the models of the ice sheet maximum in Denton & Hughes (2002) and Golledge *et al.* (2013) tend to overpredict the input of ice derived from the southern TAM resulting in some mismatch with data in the area of trough 4; the rest of the flowlines are very similar. Although it is not possible to determine empirically whether the provenance information reported here relates to the ice flow configuration during advance, maximum or retreat, future studies and newer analytical techniques may be able to help resolve the temporal changes in flow path differences predicted by model simulations.

Conclusions

Detrital zircons contained within glacial till can be a valuable tracer of past ice flow, even in regions around Antarctica where the bedrock geology is not well known. In the Ross embayment, distinctive populations that show a limited spatial extent in interior regions of the continent are found in offshore glacial deposits. In particular, U-Pb zircon ages of 100–110 Ma, which are derived from rocks outcropping in Marie Byrd Land, occur in BIS and KIS tills and in LGM tills from the eastern Ross Sea. Such grains are absent from WIS tills, which do not have a U-Pb detrital zircon fingerprint that allows them to be distinguished from tills collected from the TAM. A comparison between zircon ages from East and West Antarctic source areas and LGM offshore tills allows us to trace ice originating in West Antarctica, north of *c.* 83°S, to the area east of 180° longitude.

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Supplemental material

A supplemental table will be found at http://dx.doi.org/10.1017/S0954102014000315.

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