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U–Th–Pb detrital zircon geochronology from the southern Prince Charles Mountains, East Antarctica—Defining the Archaean to Neoproterozoic Ruker Province

G. Phillips [a,*], C.J.L. Wilson [a], I.H. Campbell [b], C.M. Allen [b]

[a] *School of Earth Sciences, The University of Melbourne, Parkville, Vic. 3010, Australia*
[b] *Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia*

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Abstract

Laser ablation inductively coupled mass spectrometry (LA-ICPMS) dating of detrital zircon has been employed to tighten geochronological constraints from the southern Prince Charles Mountains, East Antarctica. The grains of detrital zircon are from extensive metasedimentary units that define different stratigraphic levels. Provenance information from this study has identified three lithostratigraphic units that range in age from Archaean to Neoproterozoic times. The newly defined Tingey Complex contains the oldest known strata, and consists of an Archaean felsic basement overlain by three stratigraphic layers, distinguished by *ca.* 3200 Ma, *ca.* 2800 Ma and *ca.* 2500 Ma detrital zircon grains. The Lambert Complex consists of a metasedimentary package, characterised by *ca.* 2100 Ma, *ca.* 1900–1800 Ma and *ca.* 2600 Ma detrital zircon grains that possibly overlies late Palaeoproterozoic orthogneiss. The Neoproterozoic Sodruzhestvo Group comprises the youngest exposed unit and consists of a thick, clastic-dominated sequence that is distinguished by *ca.* 1170–970 Ma grains. This study suggests that the isotopic differences reported from the southern Prince Charles Mountains are a result of stratigraphic stacking, rather than due to juxtaposition via collision and accretion tectonics. The discovery of *ca.* 2500 Ma detrital zircon grains within the Palaeoproterozoic metasedimentary rocks of the Tingey Complex strengthens correlations with Archaean fragments exposed in neighbouring regions of East Antarctica. Constraining the deposition of the Sodruzhestvo Group to the mid-Neoproterozoic period suggests a prominent period of basin development occurred within the southern Prince Charles Mountains at this time.

Keywords: Detrital zircon; East Antarctica; Laser ablation inductively coupled mass spectrometry (LA-ICPMS); Neoproterozoic; Provenance; Ruker Province; Stratigraphy

1. Introduction

Rocks exposed within the Prince Charles Mountains represent exhumed segments of continental basement that underlies the ice-covered East Antarctic Shield (Fig. 1). Initial studies of thick packages of metasedimentary rocks within the Ruker Terrane of the southern Prince Charles Mountains (Fig. 1; Grew, 1982; Kamenev et al., 1993; Phillips et al., 2005) have indicated a complex geologic evolution that was associated with periods of orogenic activity and sediment deposition. The age of deposition of these rocks is currently unconstrained, which creates difficulties when attempting to chronologically order key events that shaped the region. For example, a current model that explains the crustal architecture of the Prince Charles Mountains suggests that an

* Corresponding author. Tel.: +61 38344 9596; fax: +61 38344 7761.
E-mail address: g.phillips2@pgrad.unimelb.edu.au (G. Phillips).

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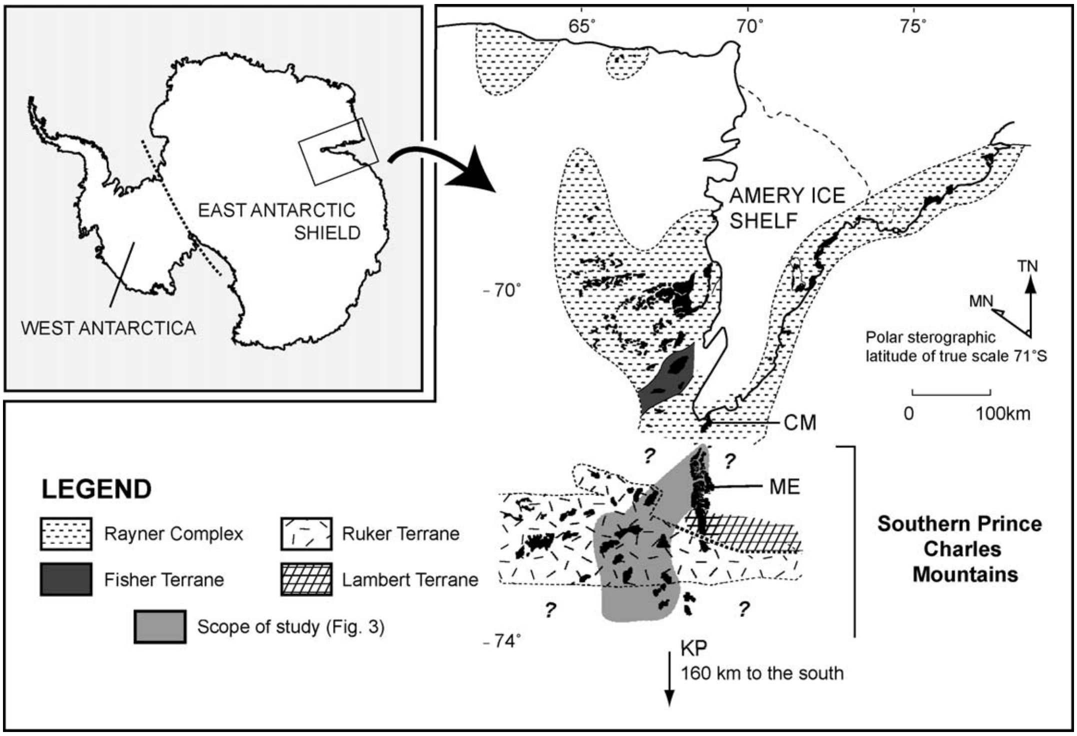

Fig. 1. Location of the Prince Charles Mountains within the Lambert Glacier-Amery basin, distribution of terranes and definition of the study area. *Abbreviations*: CM, Clemence Massif; ME, Mawson Escarpment; KP, Komsomolsky Peak.

Early Palaeozoic collision between Antarctica and India caused the accretion of the Early Neoproterozoic Rayner Complex (Fig. 1) onto the Archaean Ruker Terrane during the formation of East Gondwana (Fig. 2; Fitzsimons, 2000; Boger et al., 2001). This event is also suggested to be responsible for the accretion of the isotopically distinct Lambert and Ruker Terranes, now exposed within the southern Prince Charles Mountains (Figs. 1 and 3).

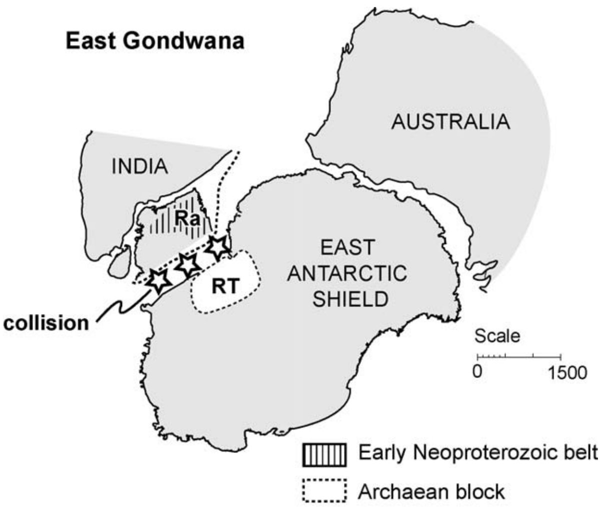

Fig. 2. Current tectonic model that explains the Early Palaeozoic crustal evolution of the Prince Charles Mountains (after Boger et al., 2001). Model involves the Early Palaeozoic collision and accretion of the Rayner Complex (Ra) and attached India to the Ruker Terrane (RT).

In this paper, the timing of deposition of sedimentary rocks (now metasedimentary rocks) exposed in the southern Prince Charles Mountains is constrained through U–Th–Pb dating of detrital zircon using laser ablation inductively coupled mass spectrometry (LA-ICPMS). Analyses of large numbers of zircon grains allow construction of detailed age-histograms that uniquely characterise source terranes. Moreover, performing large numbers of analyses increases the probability of defining the youngest concordant age population, which gives the maximum possible age of sediment deposition. With this age information, the aforementioned tectonic model will be evaluated. Combining this information with palaeocurrent data, inferences on the geomorphology of the region during periods of sediment transport can also be made. Finally, in a region where much of the bedrock exposure is ice-covered, this technique can act as a reconnaissance tool to determine the ages of unexposed basement rocks.

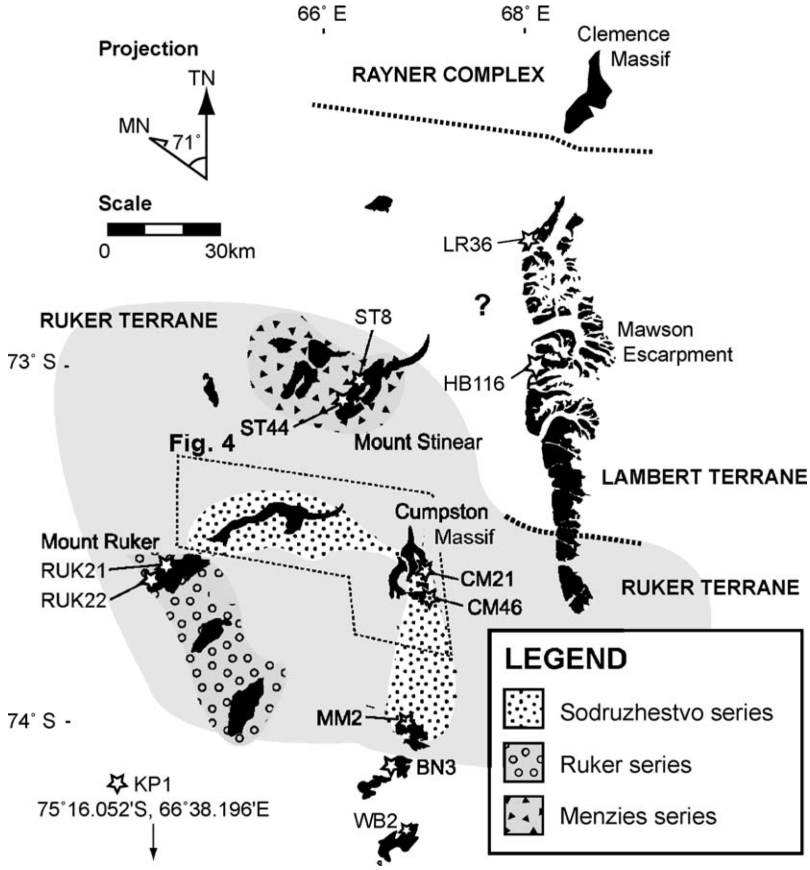

Fig. 3. Outcrop map of the southern Prince Charles Mountains. Sample localities represented by stars. *Abbreviations* (from the north): LR, Lines Ridge; ST, Mount Stinear; HB, Harbour Bluff; CM, Cumpston Massif; RUK, Mount Ruker; MM, Mount Maguire; BN, Blake Nunataks; WB, Wilson Bluff; KP, Komsomolsky Peak. Location of Fig. 4 is indicated by dashed polygon. Light grey shade represents the extent of the Archaean Ruker Terrane. Nomenclature of units is taken from Kamenev et al. (1993).

2. Geological framework

The Prince Charles Mountains are isolated nunataks and ranges within the Lambert Glacier-Amery basin of East Antarctica (Harrowfield et al., 2005). The basin is divided into four main tectonic domains, which are from north to south: Rayner Complex, Fisher Terrane, Lambert Terrane and the Ruker Terrane (Fig. 1). These domains are defined primarily on U–Pb geochronology (Young and Black, 1991; Mikhalsky et al., 1996, 2001; Boger et al., 2001).

The Rayner Complex is composed of orthogneiss and paragneiss units that are characterised by an Early Neoproterozoic (*ca.* 990–900 Ma) U–Pb isotopic age signature (Young and Black, 1991; Manton et al., 1992; Kinny et al., 1997; Carson et al., 2000; Boger et al., 2000). These rocks have been deformed and metamorphosed to granulite facies, commonly attributed to the *ca.* 990–900 Ma event (Thost and Hensen, 1992; Fitzsimons and Thost, 1992). At present, the southern extent of the Rayner Complex (and thus contact with the Ruker Terrane) is unresolved. Reported U–Pb zircon ages of *ca.* 910 Ma (Corvino et al., 2005) from Clemence Massif are taken to indicate that this Complex extends into the central Prince Charles Mountains (Fig. 1).

The Fisher Terrane is characterised by bimodal mafic and felsic intrusive rocks that preserve greenschist to amphibolite facies mineral assemblages (Mikhalsky et al., 1996). U–Pb zircon geochronology indicates crystallisation of the basic to intermediate rocks occurred between *ca.* 1300 Ma and 1200 Ma (Beliatsky et al., 1994; Kinny et al., 1997; Mikhalsky et al., 1999). A second stage of magmatism is associated with felsic intrusions between *ca.* 1050 Ma and 1020 Ma (Kinny et al., 1997; Mikhalsky et al., 2001).

Rocks of the Lambert Terrane consist of voluminous sheets of felsic orthogneiss that are interleaved with packages of siliceous, and minor calcareous metasedimentary rock (Boger and Wilson, 2005). The orthogneiss is characterised by Early Palaeozoic (*ca.* 550 Ma and *ca.* 490 Ma) metamorphic zircon that grew as rims around Archaean–Palaeoproterozoic cores (*ca.* 2120 Ma and *ca.* 2800 Ma; Boger et al., 2001). An emplacement age for the orthogneiss, and a depositional age for the metasedimentary units are unresolved. The final phase of tectonothermal reworking of the Lambert Terrane occurred during the Early Palaeozoic (*ca.* 550–490 Ma) and was associated with amphibolite facies metamorphism and the intrusion of pegmatite (Boger and Wilson, 2005).

The Ruker Terrane is distinguished by an Archaean protolith and a complex geologic history (Grew, 1982; Boger et al., 2001; Mikhalsky et al., 2001). Detailed mapping of the terrane were undertaken on Prince Charles Mountains Expedition of Germany and Australia (PCMEGA), with the results published by Phillips et al. (2005). The oldest exposed rocks of the Terrane are characterised by voluminous, Archaean (*ca.* 3190–3170 Ma; Boger et al., 2006) felsic gneiss, termed the "Mawson orthogneiss" (Mikhalsky et al., 2001). An orogenic event is interpreted to have affected the basement at *ca.* 2800 Ma, constrained through U–Pb dating of zircon from partial melts and leucosomes (Boger et al., 2006). Metasedimentary rocks overlie the basement and are separated into the following series: Menzies, Ruker and Sodruzhestvo, after Kamenev et al. (1993; Fig. 3). The discrimination of units is based on the occurrence of intruding mafic dykes, sills, metamorphic grade (Kamenev et al., 1993), and structural complexity (Phillips et al., 2005).

Limited geochronology creates difficulties when determining the age of the metasedimentary units of the Ruker Terrane. A Rb/Sr muscovite age of *ca.* 2580 Ma for emplacement of a pegmatite that cuts the rocks of the Menzies series supports an Archaean depositional age for the unit (Tingey, 1991). A Palaeoproterozoic age of deposition for the Ruker series has been suggested due to the occurrence of banded iron formation (Thost et al., 1998). Deposition of the clastic-dominated Sodruzhestvo series has been reported to occur during the Palaeoproterozoic to Neoproterozoic times, and is therefore poorly constrained (Halpern and Grikurov, 1975; Mikhalsky et al., 2001). Rocks of the Sodruzhestvo series are distinguished by the preservation of original sedimentary structures such as ripple marks and crossbeds (Phillips et al., 2005). Palaeocurrent measurements indicate sediment transport during deposition was directed away from the interior of the continent (Fig. 4; Phillips et al., 2005). Evidence for a single phase of Early Palaeozoic folding and low-grade metamorphism constrains the termination of tectonothermal reworking of the Sodruzhestvo series (Phillips et al., 2005).

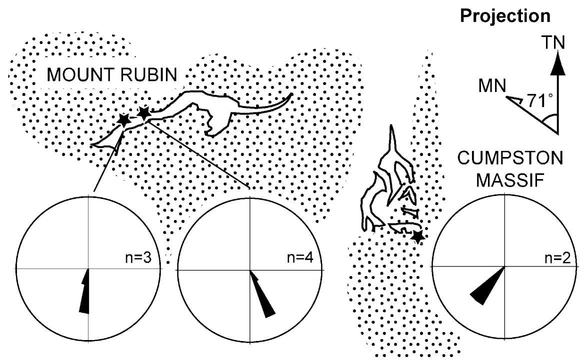

Fig. 4. Palaeocurrent data from rocks of the Sodruzhestvo series. Rose diagrams were calculated from ripple mark data measured at Mount Rubin and Cumpston Massif. Unfolding of bedding to reconstruct the initial current direction was carried out using standard stereographic techniques.

3. Methods

Geochronological analyses were preformed on individual detrital zircon grains using LA-ICPMS. Samples were collected on PCMEGA during the Austral summer (December–February) of 2002–2003. For all thirteen samples, between 73 and 149 detrital zircon grains were extracted for analysis (Table 1). Results that are >5% discordant were excluded from the dataset. Of the total analysed detrital zircon grains, 50% are concordant (736/1480). These concordant results were incorporated into the age spectra (Fig. 5). Age populations for the concordant grains are quoted as ranges (*i.e.* 3200–3100 Ma), unless the MSWD for a population approaches 1 and judged to be a single age population. Analyses of zircon from a single age event, for example, crystallisation of an igneous rock, routinely give low MSWD results. An age population with a low MSWD (*i.e.* <1) that also shows similarities in zircon chemistry (*i.e.* U/Th) or structure/morphology (*i.e.* colour, weathering) has been interpreted to reflect zircon incorporation from a single igneous source. We have quoted a single age plus a 2σ uncertainty for events that have an MSWD < 2. Analytical and data reduction techniques are described in Appendix A.

4. Results and data review

Descriptions of detrital zircon grains according to chemistry and grain structure are presented in Table 1. The table contains the percentage of grains that comprise the dominant populations defined according to U content, Th/U ratio and distinguishing physical features.

Table 1
Characterisation of detrital zircon grains through crystal morphology, colour, U content and Th/U ratios

Sample(s)	Grains	Pop'n (%)	Size (μm)	U (ppm)	Th/U ratio	Features
CM46	127	65	450–200	1000–50	0.8–0.5	Colourless, rounded
CM21	131	65	450–200	1000–50	0.8–0.5	Colourless, rounded
MM2	94	70	300–200	200–100	1.0–0.2	Colourless, rounded, moderately fractured
KP1	106	70	300–100	500–250	0.9–0.2	Colourless, rounded, moderately fractured
BN3	73	100	450–150	5000–2500	0.3–0.1	Brown, platy, highly metamict, extreme U contents
WB2	128	50	300–150	700–300	0.9–0.1	Colourless, rounded, moderately fractured
HB116	104	Very mixed provenance with no dominant populations				
LR36	135	60	400–150	600–200	1.0–0.3	Colourless, rounded, moderately fractured
RUK21	149	60	300–200	300–200	1.1–0.5	Red-brown, rounded
		15	300–100	80–70	0.8–0.7	Clear, unweathered
RUK22	103	60	300–200	300–200	1.1–0.5	Red-brown, rounded
		15	300–100	80–70	0.8–0.7	Clear, unweathered
ST8	93	90	500–100	700–50	0.9–0.2	Colourless, highly fractured
ST44wr	100	90	300–100	400–50	0.7–0.1	Colourless, rounded, highly fractured
ST44qc	137	90	300–100	400–50	0.7–0.1	Colourless, rounded, moderately fractured

Pop'n (%) refers to percentage of grains from the zircon separate that define the population.

Table 2
Summary table of U–Th–Pb data

Stratigraphic unit	Sample	Main age populations	Maximum age of deposition	Population size	MSWD	Conc. grains
Sodruzhestvo Group	CM46	1130–970	1038	41		69/127
		2150–2000		10		
		2800–2600		7		
	CM21	1170–1020	1070	38		85/131
		2130–2020		24		
	MM2	1140–1040	1090	8		24/94
		2200–2000		6		
		2800–2600		4		
Lambert Group	KP1	2160–2000	1862	40		69/106
		1862 ± 12		15	0.46	
		2618 ± 29	12	1.55		
	BN3	2108 ± 06	2108	21	0.25	25/73
	WB2	2660–1830	1830	40		47/128
Ruker Group	HB116	2502 ± 09	2500	20	0.40	57/104
		2670–2600		10		
	LR36	2470 ± 14	2470	24	1.12	27/135
	RUK21	2486 ± 8	2486	69	1.16	118/149
		2800–2700		8		
		3280–3135		8		
	RUK22	2650–2450	2500	40		62/103
		2850–2750		12		
		3200–3100		9		
Stinear Group	ST8	2778 ± 11	2778	18	0.48	21/93
Menzies Group	ST44wr	3210–3100	3150	38		56/100
	ST44qc	3260–3100	3145	51		76/137

Main populations are indicated as a range of ages when MSWDs are >2. The 'conc. grains' column represents concordant results/total grains analysed.

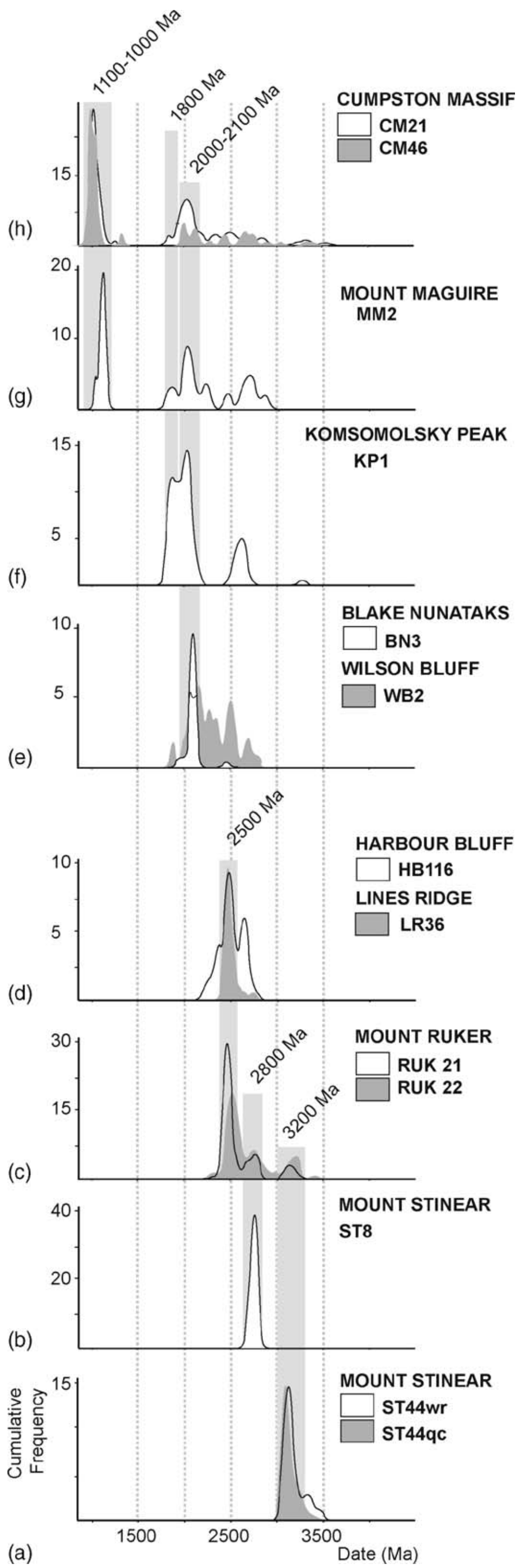

Fig. 5. (a–h) Frequency age spectra for concordant detrital zircon analyses from all samples. See Fig. 3 for sample locations.

The total LA-ICPMS U–Th–Pb dataset is available on request to the corresponding author. A summary of these data is presented in Table 2.

4.1. *Mount Stinear—Menzies series*

Two packages of metasedimentary rock are exposed along the western flank of Mount Stinear (Fig. 3; Phillips et al., 2005). These packages are separated by a 3 km wide, structurally bound block of felsic orthogneiss. Both metasedimentary units have been interpreted as components of the Menzies series as outlined in Mikhalsky et al. (2001). Detrital zircon from a conglomerate (ST44) representing one of the packages, and a quartzite from the other (ST8) was analysed.

The conglomerate sample was divided into two parts for detrital zircon age analysis. The detrital zircon spectrum for the quartz-rich clast only sample (ST44qc) is dominated by Archaean (*ca.* 3260–3100 Ma) ages (Fig. 5a; Table 2). Detrital zircon analyses from the whole rock separate (ST44wr) also show a prominence of Archaean ages (*ca.* 3210–3100 Ma; Fig. 5a). A significant component of older detrital zircon aged between *ca.* 3400 Ma and 3200 Ma distinguishes this age spectrum from that of the quartz-rich clast separate. Both age spectra constrain the depositional age of the conglomerate to post-date *ca.* 3150 Ma. Analyses that define a relatively tight discordia indicate the dominance of Pb loss during Early Neoproterozoic times (Fig. 6a; Table 2).

The detrital zircon spectrum from sample ST8 is also dominated by Archaean-aged grains, albeit *ca.* 400 Ma younger (Fig. 5b). Concordant analyses show a prominent age population at 2778 ± 11 Ma (18 grains; MSWD = 0.48). This age is interpreted as the maximum depositional age for the sandstone (now quartzite).

4.2. *Mount Ruker—Ruker series*

An agglomerate (RUK21) and quartzite (RUK22) were sampled from the Ruker series for detrital zircon analysis (Fig. 3). Three age populations were obtained from the agglomerate sample (RUK21; Fig. 5c). Early Palaeoproterozoic analyses dominate the age spectrum and define a population mean of 2486 ± 9 Ma (69 grains; MSWD = 1.16) (Table 2). Emplacement of the agglomerate must have occurred after this age. Two smaller age groupings between *ca.* 2800 Ma and 2700 Ma, and *ca.* 3280 Ma and 3125 Ma characterise the remainder of the detrital zircon analyses. A similar age spectrum is identified from the overlying quartzite (RUK22; Fig. 5c). The main population ranges between *ca.* 2650 Ma and

2450 Ma, is associated with red-brown and rounded detrital zircon crystals (Table 1) and constrains the maximum depositional age. The two older populations range between *ca.* 2850 Ma and 2750 Ma, and *ca.* 3200 Ma and 3100 Ma age intervals.

4.3. Northern Mawson Escarpment—unclassified rock units

Two samples were analysed from the Mawson Escarpment in an attempt to determine the deposition age of the narrow metasedimentary horizons that are interlayered with the dominant gneissic lithology (Fig. 3). The detrital age spectrum from sample LR36 is dominated by Early Palaeoproterozoic analyses that define a mean population at 2470 ± 14 Ma (24 grains; MSWD = 1.12) (Fig. 5d; Table 2) and a lower intercept of Late Proterozoic age (Fig. 6b). Based on the single population mean, the maximum depositional age of sample LR36 is constrained to *ca.* 2470 Ma. In contrast, HB116 has a broader spread of Archaean–Palaeoproterozoic ages (Fig. 5d; Table 2). The dominant age population is between *ca.* 2550 Ma and 2450 Ma with the remaining concordant grains defining a population between *ca.* 2670 Ma and 2600 Ma. Deposition of sample HB116 must post-date *ca.* 2500 Ma, based on the mean of the youngest age peak.

4.4. Southern-most Prince Charles Mountains—unclassified rock units

Wilson Bluff, Blake Nunataks and Komsomolsky Peak are located within the southern-most expanses of the Prince Charles Mountains (Fig. 3). Analysis of these samples provides some of the most inland U–Th–Pb zircon age data from the East Antarctic Shield. Prior to this study there were no geochronological constraints to classify these units.

Detrital zircon grains were sampled from a quartzite at Wilson Bluff (WB2; Fig. 3). The detrital age spectrum has weakly defined age populations; essentially a broad spread of analyses from *ca.* 1830 Ma to 2660 Ma (Fig. 5e; Table 2). A maximum depositional age for the sandstone (now quartzite) is taken to be *ca.* 1830 Ma, based on the youngest population of detrital zircon grains.

Detrital zircon grains were extracted from a siliceous layer within a package of interlayered biotite-rich metapelite and metapsammite at Blake Nunataks (BN3;

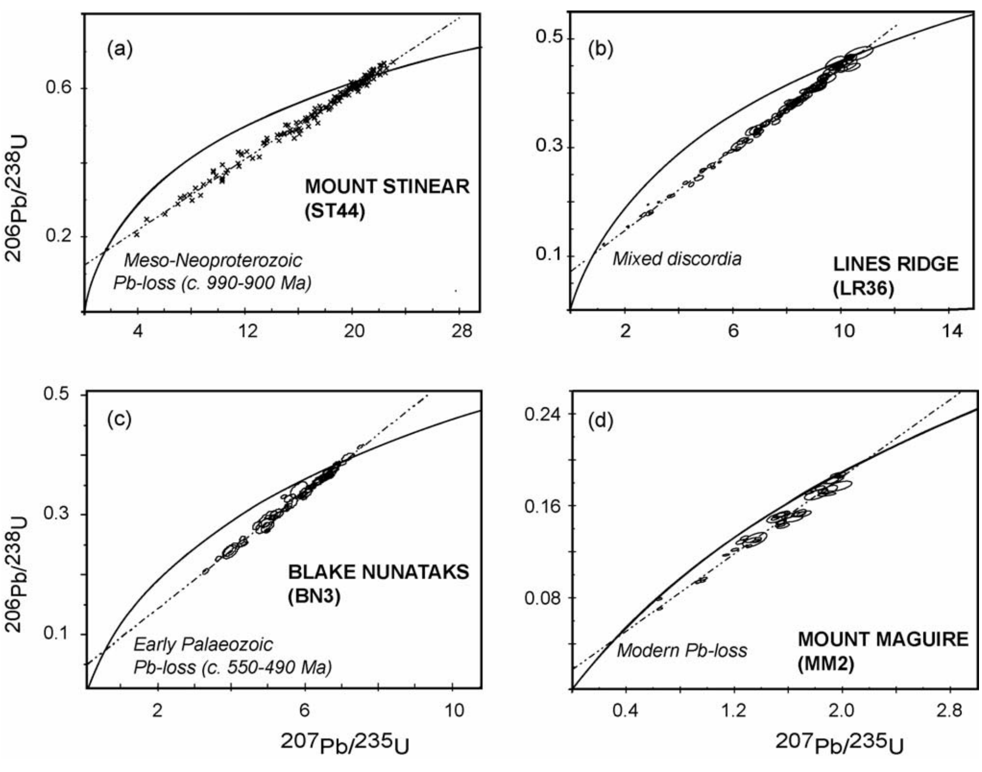

Fig. 6. (a–d) Concordia plots for samples that show prominent discordia due to Pb loss.

Fig. 3). These grains are distinguished by extremely high U-levels (2500–5000 ppm) and metamict morphologies (Table 1). Concordant analyses produced a mean age of 2108 ± 6 Ma (21 grains; MSWD = 0.25; Fig. 5e). Discordant grains define a chord that indicates a Cambrian-age lower intercept (Fig. 6c). Based on the single age population, the depositional age of the psammite at Blake Nunataks must post-date *ca.* 2108 Ma.

Grains of detrital zircon were sampled from a 1 m thick package of quartzite at Komsomolsky Peak (KP1; Fig. 3). The largest population of detrital ages (Fig. 5f; Table 2) are in the age range of *ca.* 2160–2000 Ma. The two smaller, albeit more statistically sound populations at 1862 ± 12 Ma (15 grains; MSWD = 0.46) and 2618 ± 29 Ma (12 grains; MSWD = 1.55) define the remainder of the spectrum. The youngest mean age population of *ca.* 1862 Ma is interpreted to constrain a maximum depositional age for the metasedimentary lenses at Komsomolsky Peak.

4.5. Mount Maguire and Cumpston Massif—Sodruzhestvo series

Detrital zircon grains from Mount Maguire (MM2; Fig. 3) were extracted from a garnet-bearing quartzite. The detrital age spectrum is characterised by a dominant age peak between *ca.* 1140 Ma and 1040 Ma (Fig. 5g; Table 2). Of the remaining concordant analyses, populations at *ca.* 2200–2000 Ma, *ca.* 2800–2600 Ma and *ca.* 1800 Ma are conspicuous. Concordant analyses of two grains also show Cambro-Ordovician ages (not shown in Fig. 5g). As it is recognised that metamorphism of the Sodruzhestvo series occurred just prior to these ages (*ca.* 550–490 Ma), these analyses are interpreted to be a result of Pb loss, rather than of detrital origin. Therefore, the youngest age grouping at *ca.* 1090 Ma constrains a maximum depositional age for the quartzite. Discordia from this Mesoproterozoic population defines modern Pb loss (Fig. 6d; Table 2).

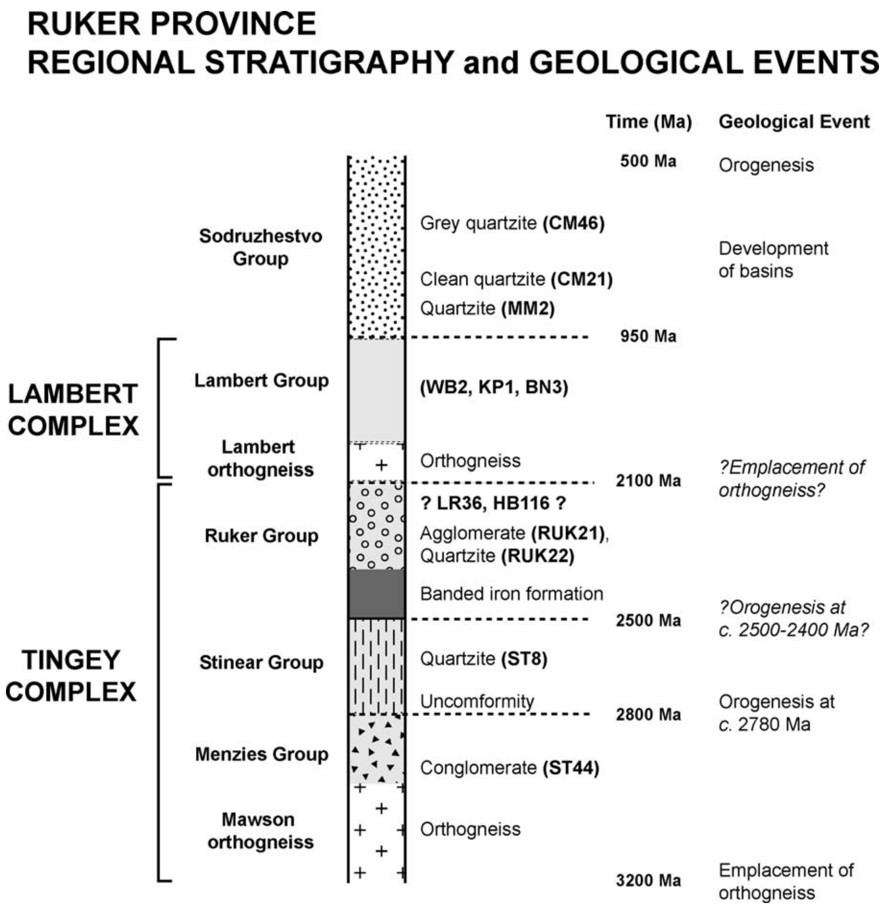

Fig. 7. New regional chronostratigraphic division for the southern Prince Charles Mountains. Note that key geological events can also be constrained employing this division.

Two quartzite samples from separate stratigraphic levels at Cumpston Massif have also been used to constrain the depositional age of the Sodruzhestvo series (CM21 and CM46; Fig. 3). The lower level sample (CM21) has an age spectrum dominated by Late Mesoproterozoic analyses between *ca.* 1170 Ma and 1020 Ma (Fig. 5h; Table 2), and a second population between *ca.* 2130 Ma and 2020 Ma. Based on a mean age of *ca.* 1070 Ma, deposition of this stratum must have occurred during the Neoproterozoic period. A similar sized population of Late Mesoproterozoic to Early Neoproterozoic (*ca.* 1130–970 Ma) detrital zircon analyses also dominates the age spectrum of sample CM46 (Fig. 5f; Table 1). Two other populations at *ca.* 2150–2000 Ma and *ca.* 2800–2600 Ma characterise the remainder of the spectrum. A mean age of *ca.* 1038 Ma for the youngest population constrains the maximum depositional age for this strata.

5. Discussion

5.1. New stratigraphic division

Data presented in this paper have led to improvements in the stratigraphic divisions of the southern Prince Charles Mountains. These improvements are required due to the poor control on the crustal architecture of the region on the basis of limited geochronology. Moreover, provenance information suggests that the individual components of the southern Prince Charles Mountains represent an Archaean to Neoproterozoic tectonostratigraphic pile (*cf.* Boger et al., 2001). The new stratigraphic division (Fig. 7) temporally orders individual crustal components of the newly defined Ruker Province on the basis of depositional age and provenance. Employing the terminology from the International Stratigraphic Guide (1976), packages of metasedimentary rock that have similar provenance are classified as 'groups' (rather then 'series'). Secondly, 'terranes' are termed 'complexes', which define a lithostratigraphic unit composed of different rock types, yet comprises similar isotopic characteristics.

The newly defined Tingey Complex consists of at least four regional stratigraphic units: (1) the Archaean (*ca.* 3190–3170 Ma) Mawson orthogneiss (Mikhalsky et al., 2001; Boger et al., 2006); (2) the Menzies Group, deposited after *ca.* 3150 Ma; (3) the Stinear Group, deposited after *ca.* 2800 Ma; (4) the Ruker Group, deposited after *ca.* 2500 Ma. The Tingey Complex is a renaming of the Ruker Terrane as termed by Kamenev et al. (1993). Renaming removes any confusion that arises due to: (1) the original name, the 'Ruker Terrane', refers to a distinct tectonic entity that has preserved a unique geologic history with reference to the other units in the region—it actually represents the continental basement; (2) the initial division had the Ruker Group as a metasedimentary component of the Ruker Terrane, which is confusing; (3) the region is primarily known in the literature as the Ruker Terrane, thus it would be better to rename an individual component, and refer to the Archaean to Neoproterozoic rocks of the southern Prince Charles Mountains as the Ruker Province.

Provenance of the Menzies and Stinear Groups indicates good correlation with igneous and metamorphic zircon ages from the underlying Mawson orthogneiss. Detrital zircon provenance from the Menzies Group correlates with emplacement ages of the orthogneiss (Fig. 8a; Boger et al., 2006). Moreover, orogenesis at

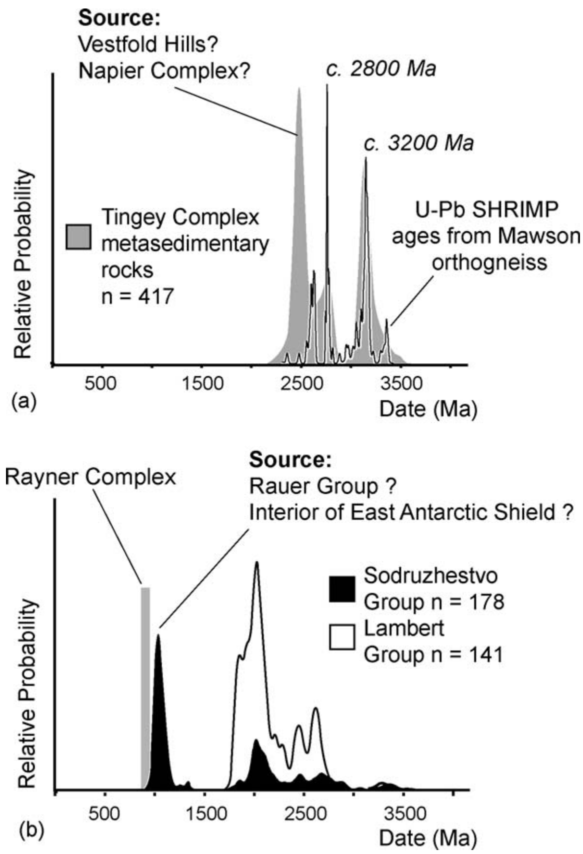

Fig. 8. A U–Pb isotopic comparison between provenance of units from this study and U–Pb SHRIMP ages from the crystalline basement. (a) Total provenance information from metasedimentary rocks of the Tingey Complex (shaded; this study) and U–Pb SHRIMP ages from magmatic/metamorphic zircon from the Mawson orthogneiss (Boger et al., 2001, 2006). (b) Total provenance data from metasedimentary rocks of the Lambert Group and Sodruzhestvo Group.

ca. 2800 Ma, as also suggested by Boger et al. (2006) correlates with the provenance of the Stinear Group. However, the inference that all of the metasedimentary units of the Tingey Complex were locally derived from the underlying Mawson orthogneiss is problematic when explaining the provenance of the Ruker Group. The Ruker Group is characterised by limited *ca.* 2800 Ma and *ca.* 3200 Ma detrital zircon grains (Fig. 5c) that correlate with the underlying Mawson orthogneiss, Menzies and Stinear Groups, and a dominant population of detrital zircon grains that range in age between *ca.* 2450 Ma and 2500 Ma (Fig. 5c and d). The tectonic implications of this age signature are discussed in the following section. The classification of the limited metasedimentary rocks exposed along the northern Mawson Escarpment as Ruker Group (LR36 and HB116) also extends the northern boundary of rocks that display Late Archaean–Early Palaeoproterozoic precursors to the northern-most Mawson Escarpment (Fig. 9; *cf.* Fig. 3).

Boger et al. (2001) have reported a discrepancy in U–Pb zircon ages between the orthogneiss units of the Tingey and Lambert Complexes. Orthogneiss units from the central Mawson Escarpment (Fig. 3) contain *ca.* 2790 Ma, 2120 Ma, 1800 Ma and 550–490 Ma zircon ages. These ages are absent from any rocks analysed from the Tingey Complex. There are, however, similarities between these zircon ages, and detrital ages from sedimentary rocks at Wilson Bluff, Blake Nunataks and Komsomolsky Peak. These exposures

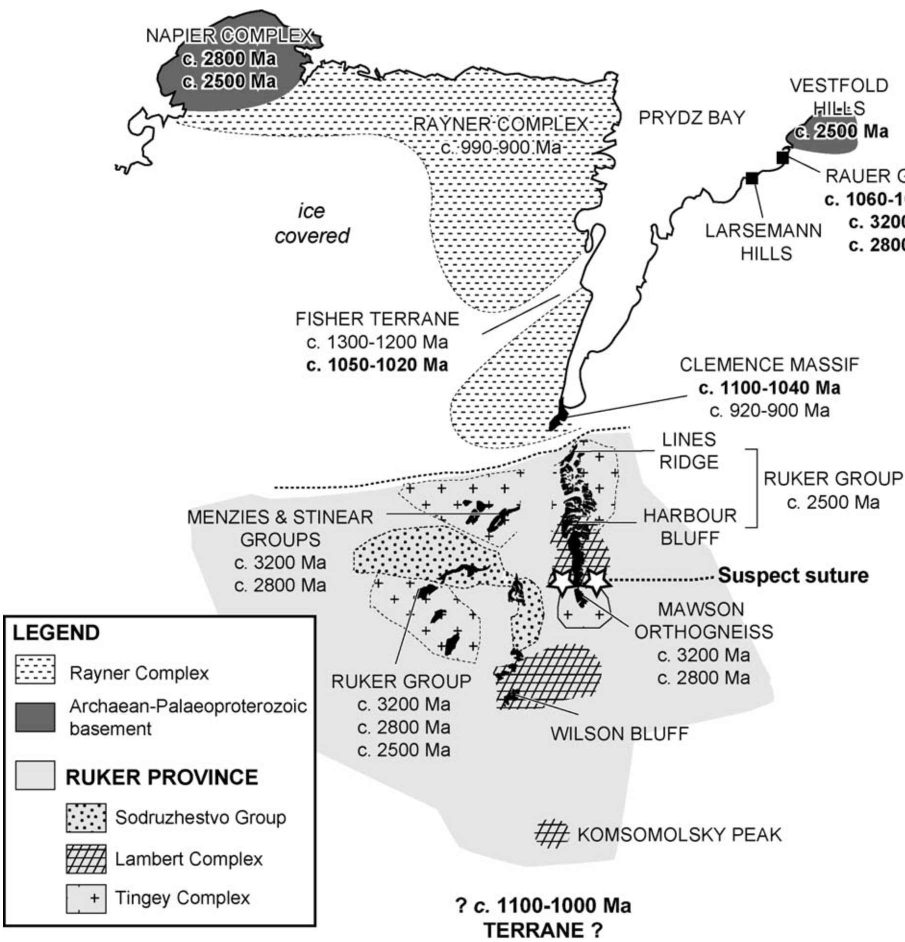

Fig. 9. Summary figure showing main tectonic units of the Lambert Glacier-Amery basin, distinguished by U–Pb isotope studies. Location of Early Palaeozoic suture between rocks of the Tingey and Lambert Complexes as suggested by Boger et al. (2001) is represented by stars. U–Pb zircon ages from tectonic units exposed in the northern Lambert Glacier-Amery basin region that correlate with detrital zircon ages from the Ruker Province are in bold font.

(and further inland?) are interpreted as cover rocks of the Lambert orthogneiss, and henceforth termed the "Lambert Group". Therefore, both orthogneiss and metasedimentary units constitute a second lithostratigraphic unit within the region, called the "Lambert Complex" (Fig. 7). The emplacement of the orthogneiss is suggested to have occurred at *ca.* 2100 Ma on the basis of reported thermal activity from the region (Tingey, 1991). Secondly, the exclusivity of *ca.* 2100 Ma detrital zircons from sample BN3 (and low MSWD) provides a strong argument for a significant local crustal melting event or the emplacement of juvenile crust at this time.

A stratigraphic relationship between the Lambert and Tingey Complexes differs from previous interpretations (see Boger et al., 2001). Isotopic differences have been explained through the juxtaposition of the two complexes during an Early Palaeozoic collision (location of suspect suture represented by stars in Fig. 9). It is speculated that this collision was also responsible for the emplacement of the Lambert orthogneiss during this time (Boger and Wilson, 2005). However, support for a Proterozoic stratigraphic relationship between the two Complexes is convincing: (1) rocks of the Tingey and Lambert Complexes are exposed on both sides of the suspect suture (Fig. 9), (2) Zircon ages that define the Lambert Complex are also reported from the Sodruzhestvo Group, which was deposited during the Neoproterozoic period (*ca.* 900–550 Ma; see below) and (3) if the Lambert orthogneiss was the source for the detrital zircon within the Lambert Group then it would have had to be emplaced prior to sediment deposition (at least >*ca.* 900 Ma). Further work is required to determine the emplacement age and geochemistry of the orthogneiss and its relationship with the Lambert Group metasedimentary units.

The detrital age spectrum from Cumpston Massif and Mount Maguire show a dominant input of Meso- to Early Neoproterozoic zircon that constrains the deposition of the Sodruzhestvo Group and basin development within the Ruker Province during Neoproterozoic times (*ca.* 900–550 Ma; Fig. 7). Correlation between the Palaeo- and Mesoproterozoic detrital zircon ages from the Sodruzhestvo Group and those of the Lambert Complex indicate the likeliness of a localised source for the Neoproterozoic rocks (Fig. 8b). A dearth of detrital ages similar to those from the older Tingey Complex also suggests burial of this unit during the deposition of the Sodruzhestvo Group. The latter package was folded and metamorphosed during closure of the basin during the Early Palaeozoic (Phillips et al., 2005). This event was also likely to be associated with exhumation of the now exposed Tingey Complex.

5.2. Tectonic implications regarding the ca. 2500 Ma provenance signature

The depositional history of the metasedimentary rocks of the Archaean Tingey Complex is best explained through the localised erosion of an underlying basement. The identification of *ca.* 3200 Ma, *ca.* 2800 Ma and *ca.* 2500 Ma detrital zircon within rocks of the Ruker Group suggests a strong correlation with the Archaean–Palaeoproterozoic basement blocks of the Lambert Glacier-Amery basin (Fig. 9). Similarities in zircon provenance between the cover rocks of the Tingey Complex and U–Pb magmatic/metamorphic ages from the Napier Complex, Rauer Group and Vestfold Hills, propose a longer geological history for these Archaean fragments than the Early Palaeozoic collision and accretion model has suggested (*cf.* Fitzsimons, 2000; Boger et al., 2001).

U–Pb geochronology from the Napier Complex indicates two dominant periods of significant zircon growth (Carson et al., 2002). These events are orthogneiss crystallisation (*ca.* 2626 Ma) and ultra-high temperature metamorphism between *ca.* 2480 Ma and 2450 Ma. Evidence for orogenesis at *ca.* 2840–2820 Ma (Harley and Black, 1997) adds further support for any correlation between the Napier Complex basement and detrital zircon provenance of the Ruker Group. Secondly, the Vestfold Hills also preserve evidence for a prominent tectonothermal overprint at *ca.* 2500 Ma (Black et al., 1991), which could be interpreted as another source region for the detrital zircon. Finally, emplacement of orthogneiss and metamorphism at *ca.* 3200 Ma and 2800 Ma, respectively, is reported from the basement of the Rauer Group (Kinny et al., 1993). These correlations suggest that the Napier Complex, Vestfold Hills Block and/or Rauer Group were exposed, and likely juxtaposed with the Tingey Complex during the Late Archaean to Early Palaeoproterozoic deposition of the Ruker Group. It has been suggested by Sims et al. (1994) that rocks of the Vestfold Hills Block and neighbouring Rauer Group (Fig. 9) were likely juxtaposed during Archaean times, based on correlation between mafic dykes—adding further support for a regional Archaean–Palaeoproterozoic relationship between the basement blocks.

The detection of *ca.* 3200 Ma, *ca.* 2800 Ma and *ca.* 2500 Ma isotopic ages within the detrital zircon record of the Ruker Group is the first instance of these three age groupings being within a single lithostratigraphic unit. In other areas, evidence for only one or two of the age groupings have been reported from the individual crustal blocks (*i.e.* only *ca.* 2500 Ma from the

Vestfold Block, only *ca.* 2800 Ma and *ca.* 2500 Ma from the Napier Complex, and only *ca.* 3200 Ma and *ca.* 2800 Ma from the Rauer Group). This raised significant doubt as to the affinities between the different Archaean–Palaeoproterozoic blocks. However, the identification of all three age signatures within the Ruker Group suggest the Vestfold Hills, Rauer Group and Napier Complex were possibly juxtaposed with the Tingey Complex during the Late Archaean–Early Palaeoproterozoic. If this is the case, collision and accretion tectonic models that have been pursued to explain the construction of this segment of the East Antarctic Shield are not required.

5.3. Tectonic implications regarding the ca. 1100–1000 Ma provenance signature

Thick packages of Sodruzhestvo Group sediment were deposited onto the continental crust of the Ruker Province during Neoproterozoic times. Provenance data from these metasedimentary rocks indicate a dominant input of *ca.* 1100–1000 Ma aged detrital zircon grains. The neighbouring Rayner Complex that is distinguished by U–Pb zircon ages between *ca.* 990 Ma and 900 Ma is too young to be a source terrane (Fig. 8b). However, limited evidence of *ca.* 1060–1000 Ma zircon growth within the Rauer Group (Kinny et al., 1993), Fisher Terrane (Kinny et al., 1997; Mikhalsky et al., 2001), Larsemann Hills (Zhao et al., 1995) and Clemence Massif (Corvino et al., 2005) do not preclude a local, northern source terrane (Fig. 9). These regions do show correlative isotopic ages with the detrital zircon from the Sodruzhestvo Group, however, the lack of *ca.* 990–900 Ma zircon grains that should have also been deposited into the basins as sediment was transported over the Rayner Complex remains problematic (Fig. 9). A relationship between *ca.* 1060–1000 Ma orthogneiss that underlie *ca.* 990–900 Ma paragneiss units as reported at Clemence Massif provides an analogy (Corvino et al., 2005). If sediment was eroded and transported from the underlying orthogneiss, then transportation of the *ca.* 990–900 Ma component would also be assumed. This is not supported by the zircon ages that distinguish the rocks of Sodruzhestvo Group. A similar argument can be put forward for the Fisher Terrane (*ca.* 1050–1020 Ma and *ca.* 1300–1200 Ma signatures) and the Rauer Group (*ca.* 1060–1000 Ma, *ca.* 2800 Ma and *ca.* 3200 Ma signatures), where *ca.* 1300–1200 Ma, *ca.* 2800 Ma or *ca.* 3200 Ma isotopic ages are absent from the provenance record of the Sodruzhestvo Group.

An alternate model suggests that the *ca.* 1100–1000 Ma detrital zircon originated from the interior of the East Antarctic Shield (Fig. 9; Wysoczanski and Allibone, 2004). North directed palaeocurrent data measured from the Neoproterozoic Sodruzhestvo Group supports this model (Fig. 4). Furthermore, identification of Lambert Complex rocks to the south of the Neoproterozoic basins (Fig. 9), suggests sediment transport directed away from the interior of East Antarctica would collect sediment sourced from the underlying Lambert Complex. We would therefore expect to see a Lambert Complex age component within the detrital zircon provenance of the Sodruzhestvo Group—which is demonstrated in thus study (Fig. 8b).

6. Conclusion

This study has revealed a complex stratigraphy within the continental crust now exposed in the southern Prince Charles Mountains. At least three regional, temporally distinct stratigraphic levels are evident. Deposition of the Menzies and Stinear Groups onto continental basement occurred during the Archaean, with sediment sourced from the basement. A large component of *ca.* 2500 Ma aged zircon within rocks of the Ruker Group suggests that there may be a possible Archaean correlation with other exposed blocks in the region (*i.e.* Napier Complex, Vestfold Block and Rauer Group). If this is the case, the tectonic model that suggests an Early Palaeozoic continent–continent collision between India and Antarctica was responsible for the crustal architecture of the region, needs revision. The Palaeo–Mesoproterozoic Lambert Complex, thought to comprise *ca.* 2100 Ma orthogneiss and overlying metasedimentary rocks, constitutes the next stratigraphic level in the pile, which covers the Tingey Complex. Sediment deposition during Neoproterozoic times (*ca.* 900–550 Ma) has been attributed to the development of basins throughout the region. A *ca.* 1100–1000 Ma provenance signature within these rocks may indicate an igneous or metamorphic terrane of this age within the interior of the East Antarctic Shield. Closure and reactivation of Neoproterozoic basins was associated with exhumation of the Tingey Complex that is constrained to the Early Palaeozoic.

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Appendix A. Methodology for high precision LA-ICPMS analyses

Samples were crushed and heavy mineral components separated using Wilfley table, heavy liquid and magnetic techniques at The University of Melbourne. Individual grains of detrital zircon were then hand picked, mounted in epoxy and polished for photography. Grain mounts were cleaned, gold coated and cathodoluminescence images used to assess the internal structure of the zircon grains. Coating was removed prior to ICP-MS analysis. Detrital zircon crystals were analysed at the Research School of Earth Sciences, Australian National University, employing a Lambda Physik LPX 120I ArF excimer laser (193 nm wavelength) and an Agilent 7500S quadrupole ICP-MS, using a 32 μm diameter laser spot size. Zircon standard 91500 was our primary standard and assumed a $^{207}Pb/^{206}Pb$ age of 1065 Ma, and $^{206}Pb/^{238}U$ age of 1062 Ma (Weidenbeck et al., 1995). Temora 2 was used as a secondary standard with an accepted concordant age of 416.78 ± 0.33 Ma (Black et al., 2004). The accuracy and precision of the dataset are reflected in the measurement of the 91500 standard in each analytical session.

Uncertainties in individual results are quoted at 1σ, and include a term that reflects uncertainty in measurement of the standard (last column—Table A). Typically, the reported uncertainty is about 1% for both $^{207}Pb/^{206}Pb$ and $^{206}Pb/^{238}U$ in individual Proterozoic and Archaean grains. MSWD for accurate measurements of the secondary standard (Temora 2), give an MSWD of about 1.5. If the MSWD is significantly larger than 1.5, it is interpreted to reflect data that are not from a single, simple age population. Our inability to precisely measure $^{207}Pb/^{206}Pb$ compared to $^{206}Pb/^{238}U$ ages in Temora 2 is a product of its relatively young age and low ^{207}Pb counts. This is why we vary concordance criteria for grains older ($^{206}Pb/^{238}U$ and $^{207}Pb/^{206}Pb$ versus $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$) as compared too younger than 800 Ma.

Our relative accuracy for Temora 2 using zircon 91500 had not previously been tested but there appears to be subtle matrix differences among zircon grains that typically result in a *ca.* 1% age difference among measured standards (Black et al., 2004). In this case, our reported average Temora 2 age for the six sessions is approximately 1.3% too old (Table A).

A.1. Data reduction

A zircon can be discordant for three reasons: (1) the presence of common Pb, (2) loss of Pb at some time after zircon crystallisation, (3) both or (4) measurement taken from two age domains in a single ablation. For the last point we use the MSWD relative to that expected from counting statistics to screen for age mixtures. This is an effective strategy unless the laser beam drills parallel to the domain boundary. Concerning points 1–3, we cannot measure common Pb directly because counts on systemic Hg (including ^{204}Hg) is many times that of ^{204}Pb, thus we must assume that a grain is discordant for reason 1 or 2. We cannot correct for both common Pb *and* Pb loss. Our strategy is as follows. First, we determine which analyses (employing no common Pb correction) are concordant at the 5% level. These analyses constitute reported ages used in constructing the frequency histograms shown in Fig. 5. We define a grain as concordant if ($^{207}Pb/^{206}Pb$ age $\pm 1\sigma$)/($^{206}Pb/^{238}U$ age $\pm 1\sigma$) = 0.95–1.05. Note that analyses older than 800 Ma dominate the dataset of unknowns and therefore the reported ages are $^{207}Pb/^{206}Pb$ as opposed to

Table A
Summary of Temora 2 zircon standard analyses

Day	$^{206}Pb/^{238}U$ age (Ma)	2σ	*N*	*n*	MSWD	$^{207}Pb/^{206}Pb$ age (Ma)	2σ	*n*	MSWD	1σ/average 91500 standard[a] (%)
1	413.1	2.3	23	23	0.95	417.7	8.1	13	1.52	1.2
2	419.9	2.1	26	26	0.65	427.5	8.1	15	2.05	1.5
3	422.9	1.9	38	36	1	421.4	8.9	13	1.44	1.2
4	422.5	3.2	29	27	1.71	424.1	13	14	5.2	1.4
5	420.4	2.7	20	20	1.21	414.3	16	6	3.29	1.2
6	425.6	3.4	24	24	1.53	432.4	14	12	4.23	1.4
Total	422.3	1.3	160	156	1.44	423.3	6	73	3.05	1.32

[a] Uncertainties in $^{206}Pb/^{238}U$. Similar to lesser values for $^{207}Pb/^{206}Pb$.

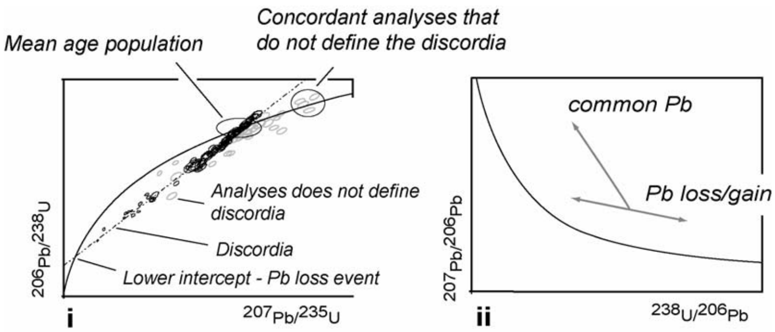

Fig. A.1. (i) Explanatory concordia plot showing interpretation of Pb loss events. (ii) Explanatory Terra-Wasserburg plot for determining discordia according to common Pb contamination, or Pb loss/gain.

^{206}Pb/^{238}U for the few grains <800 Ma (Bryan et al., 2004). Next, discordant grains (also employing no common Pb correction) are considered. If discordia is prominent from a population of concordant results (Fig. A.1i), and if these discordia also have low slopes on Terra-Wasserburg plots (ensuring that Pb loss and not common Pb dominates; Fig. A.1ii) the defined chord is modelled for lower age intercepts using Isoplot v.3 (Ludwig, 2003). Age estimates of a geological event that caused Pb loss are identified through this lower intercept (as in Fig. 6a–d). Pb loss in zircon is most likely a function of how much radiation damage accumulates in the crystal, which is a function of age and U concentration (Cherniak and Watson, 2003). This is supported by the strong discordance observed from detrital zircon analyses in sample BN3 (Fig. 6c; Table 2). Zircons self-heal at temperatures above *ca.* 360 °C, it is therefore assumed that Pb loss happens most readily in fluid-rich, moderately low temperature conditions. Moreover, discordia survive only if the zircon do not exceed this moderately low temperature for long periods of time.

Grains that lie near lower discordia intercepts could be either old zircon that has completely lost its Pb, or new zircon that has grown during the stimulus that also caused Pb loss from older zircon in the same rock. For the 42 (total grains 1449 analysed) grains <800 Ma, only 3 are concordant whereas if a 208-based common Pb correction is employed that number increases to 15. Whether a common Pb correction should be employed in these few cases is a matter of judgement based on what the grain and the analysis pattern look like. In this study, we have interpreted <800 Ma zircons as a function of Pb loss rather then new zircon growth.

References

Beliatsky, B.V., Laiba, A.A., Mikhalsky, E.V., 1994. U–Pb zircon age of the metavolcanic rocks of the Fisher Massif (Prince Charles Mountains, East Antarctica). Antarct. Sci. 6, 355–358.

Black, L.P., Kinny, P.D., Sheraton, J.W., Delor, C.P., 1991. Rapid production and evolution of late Archaean felsic crust in the Vestfold Block of East Antarctica. Precambrian Res. 50, 283–310.

Black, L.P., Kamo, S.L., Allen, C.M., Davis, D.W., 2004. Towards more reliable U/Pb micro-probe geochronology: SHRIMP, ID-TIMS, ELA-ICP-MS and oxygen isotope documentation for a series of zircon standards. Chem. Geol. 205, 115–140.

Boger, S.D., Carson, C.J., Wilson, C.J.L., Fanning, C.M., 2000. Neoproterozoic deformation in the Radok Lake region of the northern Prince Charles Mountains, east Antarctica; evidence for a single protracted orogenic event. Precambrian Res. 104, 1–24.

Boger, S.D., Wilson, C.J.L., Fanning, C.M., 2001. Early Palaeozoic tectonism within the East Antarct. craton: the final suture between east and west Gondwana? Geology 29, 463–466.

Boger, S.D., Wilson, C.J.L., 2005. Early Cambrian crustal shortening and a clockwise *P–T–t* path from the southern Prince Charles Mountains, East Antarctica: implications for the formation of Gondwana. J. Metamorphic Geol. 23, 603–623.

Boger, S.D., Wilson, C.J.L., Fanning, C.M., 2006. An Archaean province in the southern Prince Charles Mountains, East Antarctica: U–Pb zircon evidence for *c.* 3170 granite plutonism and *c.* 2780 Ma partial melting and orogenesis. Precambrian Res. 145, 207–228.

Bryan, S.E., Allen, C.M., Holcombe, R.J., Fielding, C.R., 2004. U/Pb zircon geochronology of Late Devonian to Early Carboniferous extension-related silicic volcanism in the northern New England Fold Belt. Aust. J. Earth Sci. 51, 645–664.

Carson, C.J., Ague, J.J., Coath, C.D., 2002. U–Pb geochronology from Tonagh Island, East Antarctica: implications for the timing of ultra-high temperature metamorphism of the Napier Complex. Precambrian Res. 116, 237–263.

Carson, C.J., Boger, S.D., Fanning, C.M., Wilson, C.J.L., Thost, D.E., 2000. SHRIMP U–Pb geochronology from Mount Kirkby, northern Prince Charles Mountains, East Antarctica. Antarct. Sci. 12, 429–442.

Cherniak, D.J., Watson, E.B., 2003. Diffusion in zircon. In: Hanchar, J.M., Hoskin, P.W.O. (Eds.), Zircon: Reviews in Mineralogy and Geochemistry Mineral Society of America, vol. 53. Washington DC, pp. 113–143.

Corvino, A.F., Boger, S.D., Wilson, C.J.L., Fitzsimons, I.C.W., 2005. Geology and SHRIMP U–Pb chronology of the Clemence Massif, central Prince Charles Mountains, East Antarctica. Terra Antartica 12, 55–68.

Fitzsimons, I.C.W., Thost, D.E., 1992. Geological relationships in high-grade basement gneiss of the northern Prince Charles Mountains, East Antarctica. Aust. J. Earth Sci. 39, 173–193.

Fitzsimons, I.C.W., 2000. A review of tectonic events in the East Antarct. Shield and their implications for Gondwana and earlier supercontinents. J. Afr. Earth Sci. 31, 3–23.

Grew, E.S., 1982. Geology of the southern Prince Charles Mountains, East Antarctica. In: Craddock, C. (Ed.), Antarct. Geoscience. University of Wisconsin Press, Madison, pp. 473–478.

Halpern, M., Grikurov, G.E., 1975. Rubidium–strontium data from the southern Prince Charles Mountains. Antarct. J. US 10, 9–15.

Harley, S.L., Black, L.P., 1997. A revised Archaean chronology for the Napier Complex, from SHRIMP ion-microprobe studies. Antarct. Sci. 9, 74–91.

Harrowfield, M., Holdgate, G., Wilson, C.J.L., McLoughlin, S., 2005. Tectonic significance of the Lambert Graben, East Antarctica: reconstructing the Gondwanan rift. Geology 33, 197–200.

International Subcommission on Stratigraphic Classification (ISSC), 1976. In: Hedberg, H.D. (Ed.), International Stratigraphic Guide. John Wiley and Sons, New York, p. 200.

Kamenev, E.N., Andronikov, A.V., Mikhalsky, E.E., Krasnikov, N.N., Stüwe, K., 1993. Soviet geological maps of the Prince Charles Mountains, East Antarct. Shield. Aust. J. Earth Sci. 40, 501–517.

Kinny, P.D., Black, L.P., Sheraton, J.W., 1993. Zircon ages and the distribution of Archaean and Proterozoic rocks in the Rauer Islands. Antarct. Sci. 5, 193–206.

Kinny, P.D., Black, L.P., Sheraton, J.W., 1997. Zircon U–Pb ages and geochemistry of igneous and metamorphic rocks in the northern Prince Charles Mountains, Antarctica. AGSO J. Aust. Geol. Geophys. 16, 637–654.

Ludwig, K., 2003. User's Manual for Isoplot/Ex v3.0, a Geochronological Toolkit for Microsoft Excel. Berkeley Geochronological Centre Special Publication No. 4, pp. 25–31.

Manton, W.I., Grew, E.S., Hofmann, J., Sheraton, J.W., 1992. Granitic rocks of the Jetty Peninsula, Amery Ice Shelf area, east Antarctica. In: Yoshida, Y., Kaminuma, K., Shiraishi, K. (Eds.), Recent Progress in Antarct. Earth Science. Terra Scientific Publishing Company, Tokyo, pp. 179–189.

Mikhalsky, E.V., Sheraton, J.W., Laiba, A.A., Beliatsky, B.V., 1996. Geochemistry and origin of Mesoproterozoic metavolcanic rocks from the Fisher Massif, Prince Charles Mountains, East Antarctica. Antarct. Sci. 8, 85–104.

Mikhalsky, E.V., Laiba, A.A., Beliatsky, B.V., Stüwe, K., 1999. Geology, age and origin of the Mount Willing area (Prince Charles Mountains, East Antarctica). Antarct. Sci. 11, 338–352.

Mikhalsky, E.V., Sheraton, J.W., Labia, A.A., Tingey, R.J., Thost, D.E., Kamenev, E.N., Fedorov, L.V., 2001. Geology of the Prince Charles Mountain, Antarctica. AGSO Bull., 247.

Phillips, G., Wilson, C.J.L., Fitzsimons, I.C.W., 2005. Stratigraphy and structure of the southern Prince Charles Mountains, East Antarctica. Terra Antartica 12, 69–86.

Sims, J.P., Dirks, P.H.G.M., Carson, C.J., Wilson, C.J.L., 1994. The structural evolution of the Rauer Group, East Antarctica: mafic dykes as passive markers in a composite Proterozoic terrain. Antarct. Sci. 6, 379–394.

Thost, D.E., Hensen, B.J., 1992. Gneisses of the Porthos and Athos Ranges, northern Prince Charles Mountains, East Antarctica: constraints on the prograde and retrograde *P–T* path. In: Yoshida, Y., Kaminuma, K., Shiraishi, K. (Eds.), Recent Progress in Antarct. Earth Science. Terra Scientific Publishing Company, Tokyo, pp. 93–102.

Thost, D.E., Leitchenkov, G.L., O'Brien, P.E., Tingey, R.J., Wellman, P., Golynsky, A.V., 1998. Geology of the Lambert Glacier-Prydz Bay region, East Antarctica, 1:1 000 000 map. Australian Geological Survey Organisation, Canberra.

Tingey, R.J., 1991. The regional geology of Archaean and Proterozoic rocks in Antarctica. In: Tingey, R.J. (Ed.), The Geology of Antarctica. Oxford University Press, pp. 1–73.

Weidenbeck, M., Allé, P., Corfu, F., Griffin, W.L., 1995. Three natural zircon standards for U–Th–Pb, Lu–Hf, trace element and REE analyses. Geostandards Newslett. 19, 1–23.

Wysoczanski, R.J., Allibone, A.H., 2004. Age, correlation and provenance of the Neoproterozoic Skelton Group, Antarctica: Grenville age detritus on the margin of East Antarctica. J. Geol. 112, 401–416.

Young, D.N., Black, L.P., 1991. U–Pb zircon dating of Proterozoic igneous charnockites from the Mawson coast, East Antarctica. Antarct. Sci. 3, 205–216.

Zhao, Y., Liu, X., Song, B., Zhang, Z., Li, J., Yao, Y., Wang, Y., 1995. Constraints on the stratigraphic age of metasedimentary rocks from the Larsemann Hills, East Antarctica: possible implications for Neoproterozoic tectonics. Precambrian Res. 75, 175–188.