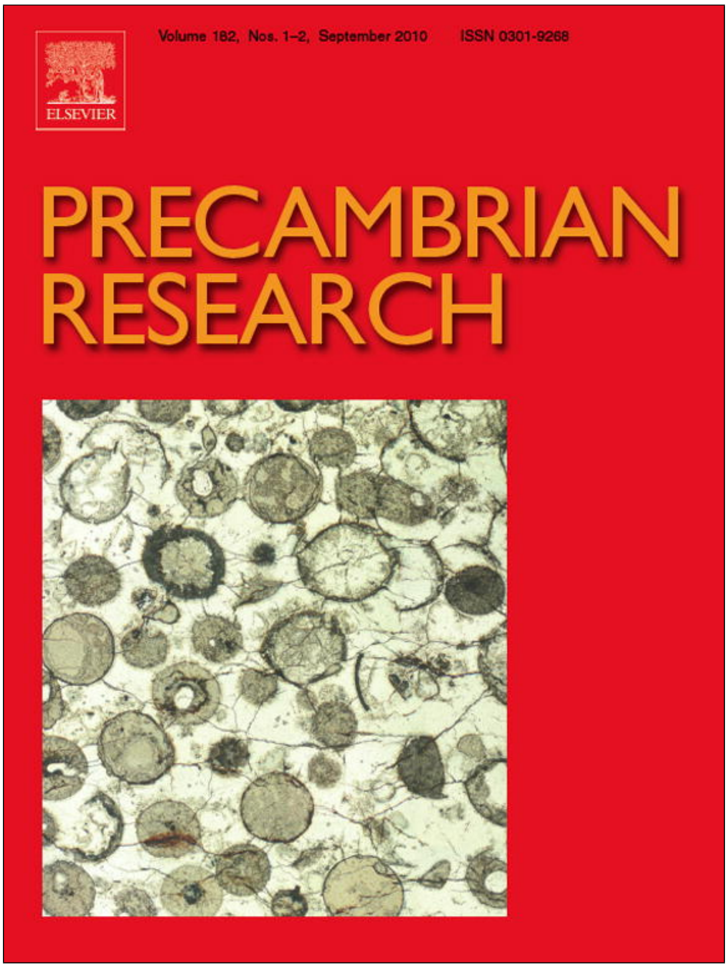
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New Sm–Nd, Rb–Sr, U–Pb and Hf isotope systematics for the southern Prince Charles Mountains (East Antarctica) and its tectonic implications

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ABSTRACT

We report isotopic (Sm–Nd, Rb–Sr and zircon Hf and U–Pb SIMS SHRIMP) data on rocks collected from various localities throughout the southern Prince Charles Mountains known as the Ruker Province. The area is made up of a high-grade metamorphic basement, overlain by variably deformed and metamorphosed supracrustal associations of Proterozoic age. The area comprises two distinct tectonic terranes, experienced major tectonothermal processes in the Archaean (ca. 3400–2800 Ma: the Ruker Terrane) or in the Palaeoproterozoic (ca. 2500–2100 Ma: the Lambert Terrane). New zircon U–Pb ages of ca. 3180–3150 Ma, ca. 2800, and ca. 2500 Ma were obtained for various orthometamorphic rocks from the Ruker Terrane and ca. 2200 Ma, ca. 1740 Ma, and ca. 920 Ma for syn-tectonic granitic veins and leucosomes from the Lambert Terrane. The Sm–Nd data provide evidence for the initial separation of the continental crust of the Ruker Terrane from the mantle mainly between ca. 3.2 and 3.4 Ga, but up to 3.8 Ga, and indicate the presence of two mantle reservoirs which correspond to (1) depleted to slightly enriched, and (2) ultra-depleted mantle. Some material was also derived from the mantle at ca. 2.7–3.0 Ga; the crust of this age apparently underlies the central part of the Ruker Terrane (the Cumpston Massif–Mt Newton block), which is also distinguished by younger (ca. 2.5–2.1 Ga) zircon ages. The Lambert Terrane contains subordinate ca. 3.6–3.8 Ga protoliths, and the bulk of the crust seems to have originated between 2.6–2.9 Ga from various mantle sources and it may represent an accretional complex onto the Archaean Ruker Terrane.

We also summarize published isotopic data and propose an integrated geological evolution for both terranes of the Ruker Province, discuss its relationships with the bordering Rayner Province, and compare its isotopic features with other Precambrian cratons of Gondwana. The key geological features of the Ruker Terrane suggest a similarity to the Yilgarn Craton, which would imply considerable mineral resource potential of the Prince Charles Mountains.

1. Introduction

The structure of the Prince Charles Mountains (PCM, Fig. 1) was initially described as a tectonic integrity built up of presumed Archaean high-grade metamorphic rocks of the crystalline basement and Proterozoic to lower Palaeozoic supracrustal formations in an intracratonic fold system located in the southern PCM (Ravich et al., 1978; Fedorov et al., 1982). Based on whole-rock isochron and muscovite Rb–Sr ages, Tingey (1982a, 1991) distinguished two major tectonic provinces: Meso–early Neoproterozoic (ca. 1100–800 Ma) in the north and Archaean (ca. 2800–2600 Ma) in the south.

Kamenev et al. (1993) proposed a threefold subdivision of the area on structural and lithological grounds and distinguished the Ruker, Beaver, and Lambert metamorphic complexes in the southern, northern, and central PCM, respectively. These authors considered the sPCM to be an Archaean (ca. 3.2–2.5 Ga) granite–greenstone terrane, although many other investigators eventually did not maintain this interpretation (e.g., Harley, 2003). The northern PCM was distinguished by Kamenev (1993) as a "charnockite–granulite" mobile belt, termed the Beaver Complex. The Ruker and the Beaver complexes were thought to be separated by the Lambert Complex representing a tectonic mixture of variously reworked rocks of these complexes in the central PCM (northern Mawson Escarpment, Shaw Massif, Mts Izabelle, Lanyon, and Meredith, and a few other outcrops). Ivanov and Kamenev (1990) also distinguished a lithologically distinct Fisher belt within the Lambert Complex, and Mikhalsky et al. (1996) proposed that this belt originated in the Mesoproterozoic (ca. 1.3 Ga) in convergent tectonic settings.

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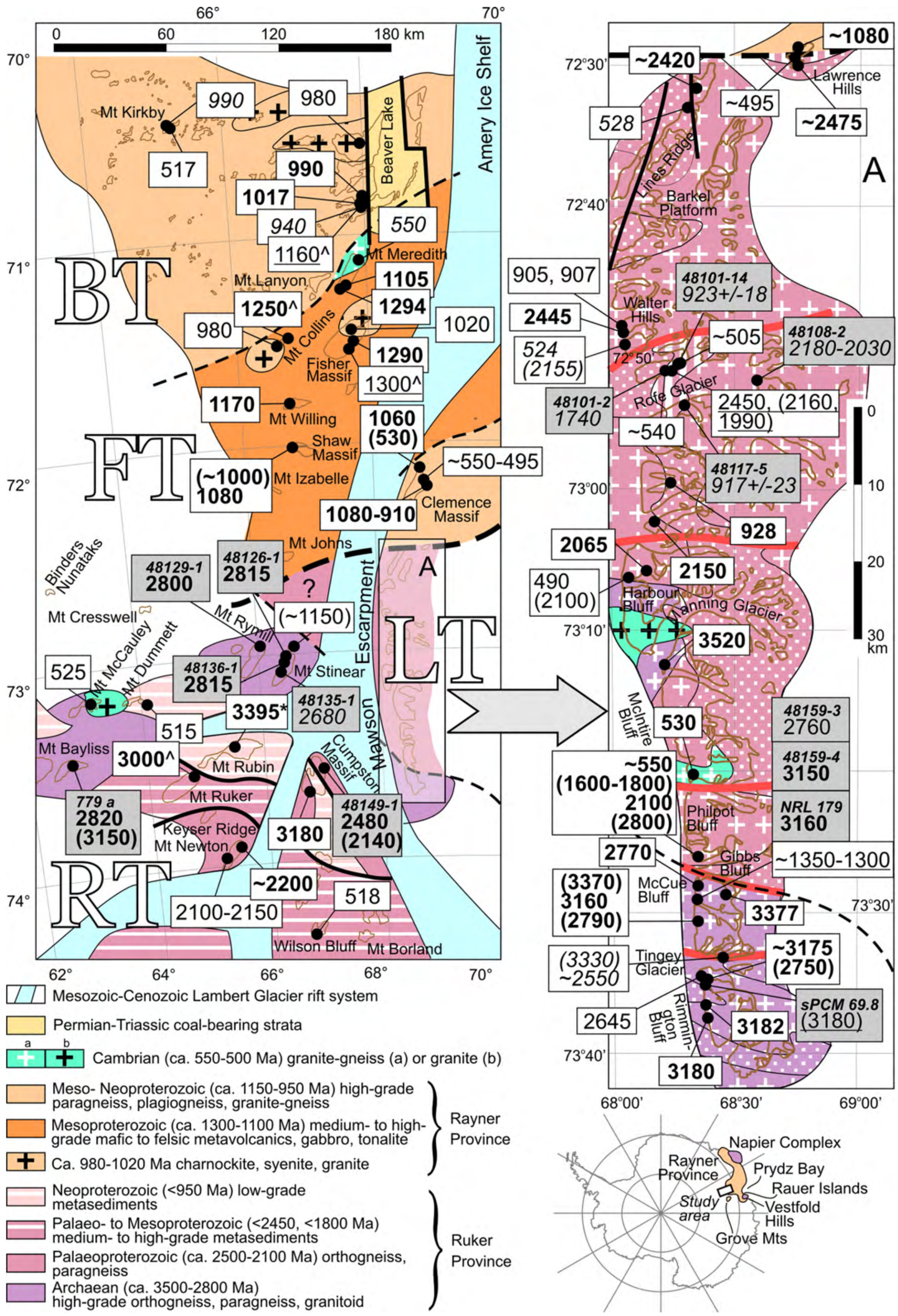

Fig. 1. Zircon U–Pb dates in the main lithotectonic units in the Prince Charles Mountains. Inset A, a geological sketch of the Mawson Escarpment, enlarged on right-hand side. Geological features for the Mawson Escarpment modified from Phillips et al. (2005b, 2009) and Boger et al. (2008). Rayner Province after Fitzsimons (2000). Dates were obtained by SIMS SHRIMP or TIMS (labeled ^), and are shown in Ma in framed boxes. Font style: bold = crystalline basement pre-tectonic granite or granite-gneiss (emplacement or metamorphic ages); italics = syn-tectonic granite; underlined = mafic rocks (metagabbro, metabasalt, mafic dyke); normal = post-tectonic granite. Values given in brackets indicate either inheritance (when older than the emplacement age) or overprint (when younger). Grey fill box – this study, other dates from Beliatsky et al. (1994), Kinny et al. (1997), Carson et al. (2000), Boger et al. (2000, 2006, 2008), Mikhalsky et al. (2001, 2006a, 2007c, 2008), Mikhalsky and Roland (2007), Maslov et al. (2007), Corvino and Henjes-Kunst (2007), Corvino et al. (2008). * – an age of a tonalite cobble in low-grade sediments. BT – the Beaver Terrane, FT – the Fisher Terrane, LT – the Lambert Terrane, RT – the Ruker Terrane. Outcrop areas are shown in light brown line. Black lines: thick dashed line – the boundary between the Ruker Province and the Rayner Province, thin dashed line – the boundaries between Fisher/Beaver terranes and Ruker/Lambert terranes, solid line – fault or thrust. Thick red lines – high-strain shear zone. Black cross indicates post-tectonic granitoid. White textures in inset A indicate: dots – largely sedimentary protolith, cross – largely granitoid protolith (pre- to syn-tectonic granitoid), thick vertical ruling – mafic and ultramafic rocks.

Based mostly on geochemistry, published Rb–Sr ages (Tingey, 1982a) and imprecise zircon thermal ionization ages, Mikhalsky et al. (2001) also described the structure of the PCM in terms of three tectonic units: the Ruker Terrane in the sPCM, the Beaver–Lambert Terrane in the central and northern PCM, and the Fisher Terrane in the central PCM, although the latter was tentatively considered to be an internal sub-terrane enclosed within the Beaver–Lambert Terrane. Mikhalsky et al. (2006a) distinguished a separate, spatially minor, Palaeoproterozoic (ca. 2.4–2.1 Ga) Lambert Terrane in the central–northern Mawson Escarpment on the basis of lithology and isotopic U–Pb zircon SHRIMP age data. Thus, the number of distinguished tectonic terranes came to four (Beaver, Fisher, Lambert, and Ruker terranes), although their relationships and tectonic origin remained largely unclear. Other authors considered the central and northern PCM as part of much larger Rayner Province (inset in Fig. 1), characterized by ca. 1000 Ma metamorphism and deformation (e.g., Fitzsimons, 2000), a notion also followed in the present study.

Phillips et al. (2006) included both the Lambert and Ruker terranes within a single Ruker Province on the basis of a detrital zircon U–Th–Pb study. Thus, the available data indicate a complex, heterogeneous geological structure and evolution of the PCM, especially in its southern part, which is quite remarkable for good outcrops of ancient (>3.0 Ga) rocks, relatively rare in Antarctica. So far the tectonic evolution of the sPCM remains controversial.

Published geochronological dates for the wide area of the sPCM were mostly obtained either by Rb–Sr or U–Pb zircon thermoemission methods, precise SHRIMP dates being restricted to the better-exposed and geologically complex Mawson Escarpment (Fig. 1). Given the strong lithological, chemical, and metamorphic grade variations in the Ruker Terrane (e.g., Tingey, 1991; Mikhalsky et al., 2001, 2006b), geological and tectonic correlations throughout the area are impossible unless more geochronological and geochemical data are obtained.

In this study we present new isotopic data (whole-rock and mineral Sm–Nd and zircon Hf and U–Pb SIMS SHRIMP) on rocks from various localities throughout the sPCM, and address the currently enigmatic relationships between the different terranes in the PCM. Another goal of our study is to summarize the geological and isotopic data available for the sPCM and use them to produce a regional timetable. This will enable a better correlation of tectonothermal events throughout the sPCM and a comparison with other Precambrian cratons of Gondwana and will elucidate its role in the composition of the early Precambrian supercontinents. These data also shed additional light on the geological relationships between the Archaean lower-grade southern PCM and Proterozoic higher-grade northern PCM (nPCM).

The geological data and samples were mostly collected during the Prince Charles Mountains Expedition of Germany and Australia (PCMEGA) in 2002–2003. We also present new data on a specimen collected in the early 1970s by D.S. Solov'ev, a pioneer of the geology of the PCM, from the remote and the so far poorly studied westernmost part of the Ruker Terrane (Mt Bayliss).

2. Regional geological setting

In the sPCM (outcrops south of 72°30′S), thick metasedimentary and orthogneiss sequences occur. The Ruker Terrane occupies the area west of the Lambert Glacier and the southern part of the Mawson Escarpment (Fig. 1) and comprises metasedimentary rocks, minor metavolcanics, and abundant granite gneiss and granite. The Lambert Terrane occupies the central and northern parts of the Mawson Escarpment (Fig. 1) and is largely built up of metasedimentary rocks and grey gneiss with mafic schist. Ion-microprobe studies by Boger et al. (2001, 2006, 2008), Mikhalsky et al. (2006a) and Corvino et al. (2008) showed distinctive isotopic features for rocks cropping out in the southern and central–northern Mawson Escarpment. These authors showed the distinctive significance of Palaeoproterozoic (2500–2100 Ma) and locally also Early Palaeozoic (530–490 Ma) tectonics within the latter area.

In the Ruker Terrane a number of variably metamorphosed lithotectonic units have been described: the Mawson Orthogneiss, the Menzies Series, the Ruker Series, and the Sodruzhestva Series (Ravich et al., 1978; Mikhalsky et al., 2001 and references therein). Tingey (1982a) distinguished three metamorphic events in the sPCM. However, recent isotopic studies suggest a more complex metamorphic history for the Ruker Terrane.

The Mawson Orthogneiss commonly has a marked compositional layering and a wide range of composition, from tonalite and trondhjemite (plagiogranite) to granite. Both biotite–quartz–feldspar gneiss and hornblende–biotite–quartz–feldspar gneiss are common, and the latter contains relatively abundant allanite, zircon and titanite. Garnet-bearing felsic gneiss occurs locally. Although the gneiss is largely recrystallised (granoblastic–polygonal or interlobate texture) and generally strongly foliated, locally it has massive homogeneous texture and contains zoned plagioclase phenocrysts indicative of an intrusive origin. Most gneiss were metamorphosed under middle to upper amphibolite-facies conditions, as migmatitic structures are common, but greenschist or lower amphibolite-facies retrogression is widespread. Relict granulite-facies assemblage is present in orthogneiss in the southern Mawson Escarpment. Larger, variably deformed granite plutons crop out at Mounts Ruker, Rymill, Stinear, and Bayliss. The Mawson Orthogneiss comprises two major rock suites (Mikhalsky et al., 2006a): (a) minor Y-depleted tonalitic to trondhjemitic orthogneiss, similar to tonalite–trondhjemite–granodiorite (TTG) associations, thought to represent new sialic crust; and (b) spatially widespread Y-undepleted granite gneiss similar to A-type granites.

The presumed Archaean granitic basement appears to be overlain by medium- to high-grade metasedimentary rocks (the Menzies Series of Ravich et al., 1978). The Menzies Series forms highly heterogeneous members consisting predominantly of mica–quartz schist and quartzite, biotite–hornblende–quartz ± garnet schist and pelitic (high-Al) staurolite–mica–quartz schist, kyanite–staurolite–buiotite–muscovite schist and kyanite–garnet–muscovite–quartzite. Local development of cordierite–sillimanite-bearing assemblages may be due to contact metamorphism associated with emplacement of abundant Cambrian granite (ca. 525–515 Ma, Mikhalsky and Roland, 2007). Prominent thick units of white to greenish quartzite, associated with pelitic rocks, as well as amphibolite units are widespread. Minor marble and other calcareous rocks, metaconglomerate, and metagreywacke occur locally.

The Ruker Series consists of green schist facies mafic (rarely ultramafic) to felsic schists (probably metavolcanic rocks) and associated metapelitic schist, slate, phyllite, diamictite (tillite?), and banded ironstone. Secondary chlorite, carbonate, quartz, sericite, biotite, and actinolite are the major constituents; these phases occur in widely varying amounts. The Sodruzhestva Series is also of green schist facies, but of more calcareous composition (metapelitic and calcareous schist, phyllite, and slate, with minor marble, quartzite, and diamictite). Its metamorphism was prograde, and original sedimentary features (cross-bedding, ripple marks) are locally preserved.

In many localities most rock types are cut by variably deformed and metamorphosed mafic dykes of several generations and (in Cumpston Massif) mafic sills. Early Palaeozoic activity (granitic magmatism, local metamorphism, folding and thrust tectonics) is an important component of the geology of the sPCM.

Early studies (Tingey, 1982a,b, 1991 and references therein) reported Rb–Sr ages, which showed that the presumed granitic basement and at least some of the overlying metasediments in the sPCM were of Archaean age (similar whole-rock Rb–Sr isochrones, ca. 2700 Ma, 2750 Ma and 2760 Ma, for both the Lambert and Ruker terranes). These contrasted with Meso- to Neoproterozoic ages (whole-rock Rb–Sr isochrons from ca. 770 to 1030 Ma) for the granulite-facies rocks of the northern PCM.

On the basis of detrital zircon U–Th–Pb study of the metasediments, Phillips et al. (2006) distinguished five separate lithostratigraphic units within their Ruker Province: the Menzies Group (Mesoarchaean, <3200 Ma), the Stinear Group (Neoarchaean, <2800 Ma), the Ruker Group (Early Palaeoproterozoic, <2500 Ma, >2100 Ma), the Lambert Group (Palaeo–Mesoproterozoic <1800–2100 Ma), and the Sodruzhestva Group (<950 Ma). Each of these has distinct metamorphic and deformational features. These authors defined the Ruker Province to include the earlier recognised Ruker and Lambert terranes (Fig. 1).

The Lambert Terrane largely consists of high-grade orthogneiss and supracrustal rocks (garnet paragneiss and marble). Grey biotite and garnet–biotite ± hornblende gneiss, granite-gneiss, plagiogneiss and mafic granulite or amphibolite, are the most common rock types. Orthopyroxene-bearing variety occurs in the northern part of the Lambert Terrane. Metagabbro and ultramafic rocks form tectonic slabs and blocks in Rofe Glacier area and Lawrence Hills. Ages between ca. 3520 Ma and 2120 Ma (Boger and Wilson, 2005; Mikhalsky et al., 2006a; Boger et al., 2008; Corvino et al., 2008) were obtained for granite gneiss. Sedimentation in a wide time frame (2400–1000 Ma) was suggested (Corvino et al., 2008). Essentially undeformed granite and pegmatite veins were dated at ca. 500 Ma (Mikhalsky and Roland, 2007).

3. U–Pb data

Zircon was recovered and analysed for U–Pb isotopic composition in a total of 14 samples. These include pre- or syn-tectonic granite gneisses, undeformed granites, and one metagabbro. Essential petrographic and chemical data for the studied samples are given in Table 1. The analyses were carried out with a SIMS SHRIMP-II ion microprobe at the Centre of Isotopic Research (CIR, VSEGEI, St.-Petersburg, Russia). Six to 12 representative zircon grains from each sample were studied. Each analysis consisted of five scans through the mass range; the spot diameter was about 18 μm and the primary beam intensity about 4 nA. The Pb/U ratios were normalized relative to a value of 0.0668 for the $^{206}Pb/^{238}U$ ratio of the TEMORA reference zircon, equivalent to an age of 416.75 Ma (Black et al., 2003). The results are presented in the Supplement files and the samples localities are shown in Fig. 1. In this figure are also indicated the zircon U–Pb (SHRIMP) ages published by Mikhalsky et al. (2006a), Boger et al. (2000, 2001, 2006, 2008), Corvino and Henjes-Kunst (2007), and Corvino et al. (2008) and a few bulk U–Pb zircon TIMS data published elsewhere.

3.1. The Ruker Terrane

Samples from a number of localities were studied (Figs. 1 and 2) and the data are presented in geographic order from east to west (and north to south within a given area). McCue Bluff in the southern Mawson Escarpment is an area where a spectacular unmetamorphosed mafic dyke swarm crops out and also where unique (for the Ruker Terrane) orthopyroxene-bearing rocks occur (Fig. 2a) (see Roland and Mikhalsky, 2007 for detailed description). Orthopyroxene-bearing pegmatite bodies locally occur within two-pyroxene metagabbro (Fig. 2b) in a nearby locality, which indicates high-grade metamorphic conditions.

Table 1
Petrographic and chemical data for the studied samples.

Sample	Qtz	Pl	Ksp	Cpx + Opx	Minor	Trace (<5 total)	Rock	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5
NRL179	10–15	45–50	30–35	5		Bt	Granite gneiss	69.22	0.18	15.49	0.43	2.13	0.03	0.83	1.75	3.87	5.75	0.03
48159-4	10	30–35		35–40	Hbl 20		Metagabbro	51.44	0.74	14.74	2.85	7.12	0.17	6.84	10.52	3.37	0.67	0.16
48159-3	5-10	–	90–95				Mc-phyric aplite											
sPCM69.8	~20	~70			Hbl ~10	Bt	Microtonalite											
48149-1	20–25	40–45	30–35			Bt, Ms, All	Granite gneiss	68.98	0.40	15.96	0.96	1.72	0.05	0.57	2.44	5.20	2.52	0.30
48126-1	10–15	55–60	25–30			Hbl, Ttn, Bt, OM	Qtz diorite-gneiss	70.09	0.82	11.79	1.81	3.61	0.08	0.86	2.14	3.08	3.42	0.32
48136-1	20–25	40–45	25–30			Hbl, Bt, Ttn, Mbz, OM	Granite-gneiss	74.23	0.54	12.04	1.31	2.08	0.08	0.75	1.37	3.20	3.64	0.29
48135-1	35–40	~50	10–15			Chl (Bt)	Qtz-phyric aplite	70.78	0.10	15.98	0.24	0.65	0.01	0.12	1.32	5.03	4.01	0.10
48129-1	10–15	50–60	20–25		Hbl 10–15		Px(?) granite	71.59	0.82	11.94	0.82	3.81	0.07	0.78	2.06	2.82	4.49	0.43
779a	35–40	10–15	~40			Ep, Ttn, Bt	Qtz–Fsp gneiss	75.6	0.20	12.5	1.67*	nd	0.03	0.25	1.28	2.90	5.12	0.05
48101-2	25–30	70–75				Bt	Microtonalite	74.15	0.18	14.60	0.25	0.65	0.01	0.97	3.92	2.95	1.92	0.20
48101-14	15–20	5-10	~75			Bt	Granite	72.90	0.18	13.80	1.63*	nd	0.01	0.36	1.06	1.66	7.19	<0.05
48108-2	25–30	~40	~20		Bt 10–15		Granite	74.88	0.28	12.39	bdl	2.12	0.01	0.44	1.63	2.60	4.89	0.12
48117-5	20–25	~70			Bt 5–10		Tonalite	67.30	0.36	17.66	bdl	2.70	0.02	1.22	4.51	4.01	1.46	0.11

Mineral content in volume %. Abbreviations after Kretz (1983), OM – opaque mineral. bdl – below determination level, nd – no data.

* Total FeO as Fe_2O_3 (by XRF).

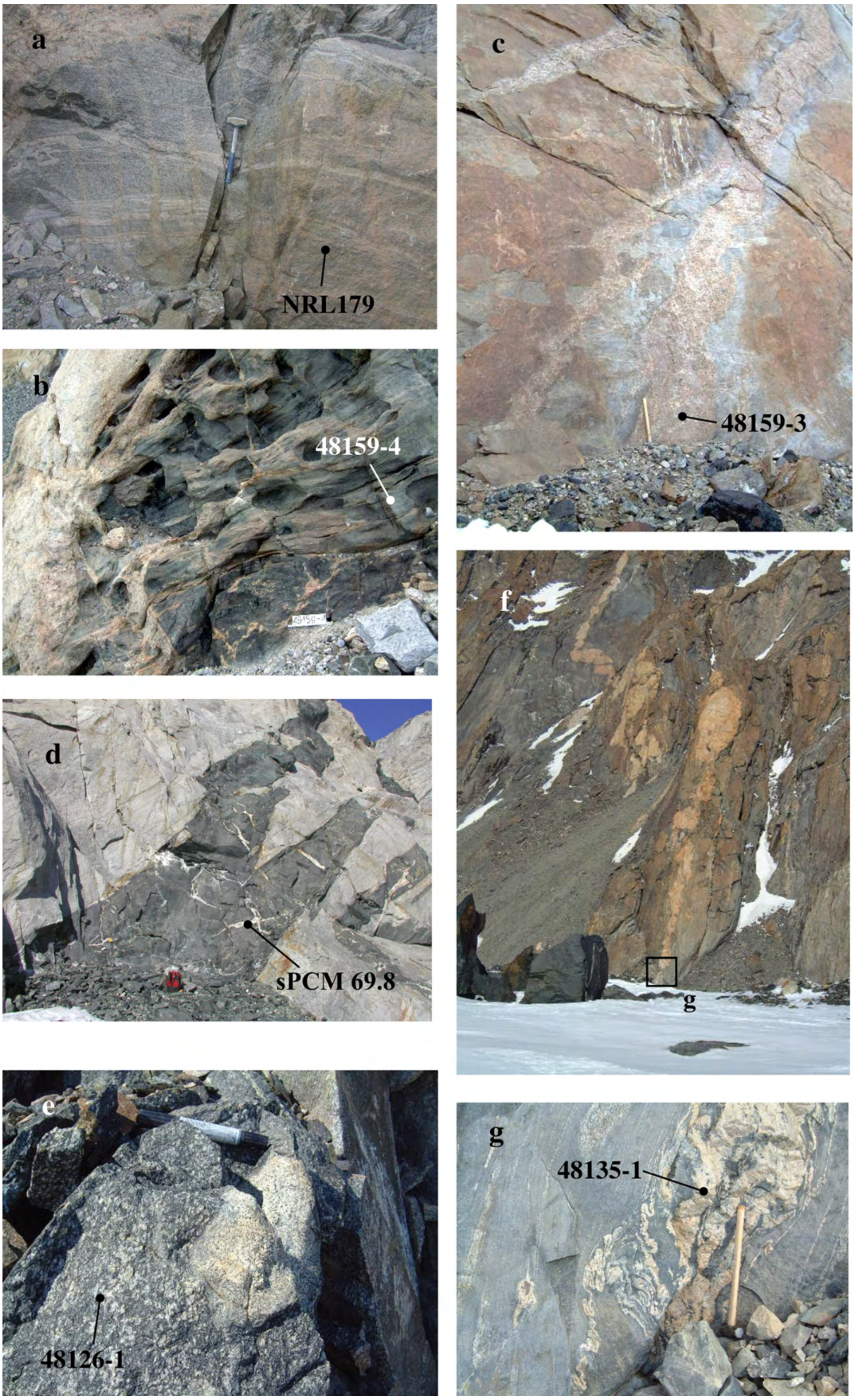

Fig. 2. Sampled outcrops in the Ruker Terrane: a) Opx-bearing gneiss NRL179, McCue Bluff; b) mafic granulite 48159-4 cut by Opx-bearing pegmatite, McCue Bluff; c) post-tectonic pegmatite 48159-3, McCue Bluff; d) thin felsic veinlets (sample sPCM 69.8) within a metamorphosed mafic dyke, Rimmington Bluff; e) metapsammite xenolith in granite-gneiss 48126-1, Mt Stinear, north; f, g) a syn-tectonic pegmatite 48135-1, Mt Stinear, center.

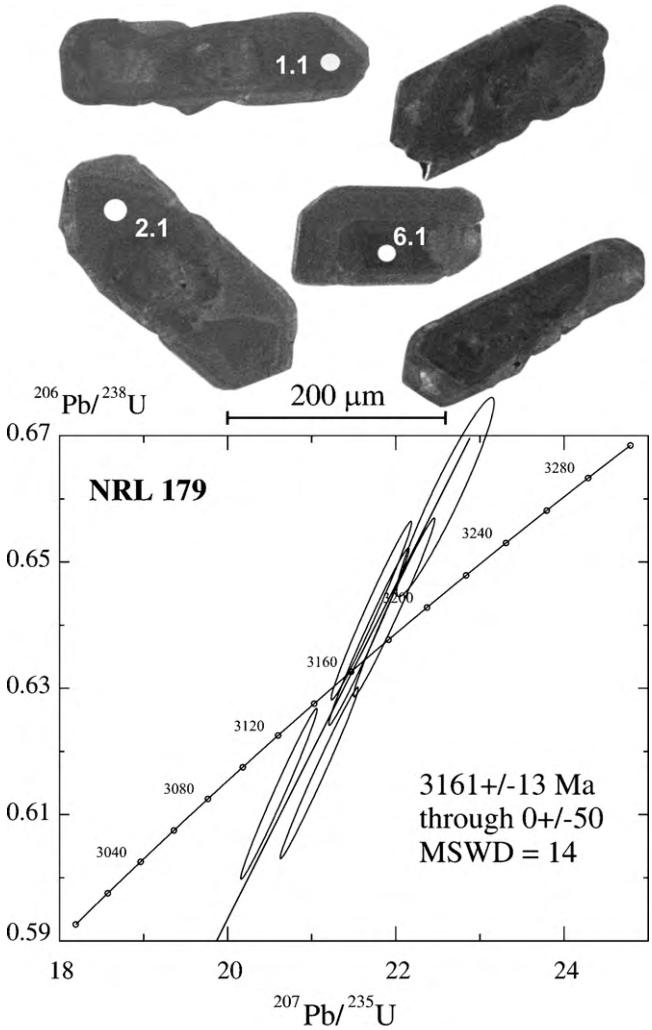

Fig. 3. U–Pb Concordia plot and the cathodoluminescent images (CL) of zircons from sample NRL 179.

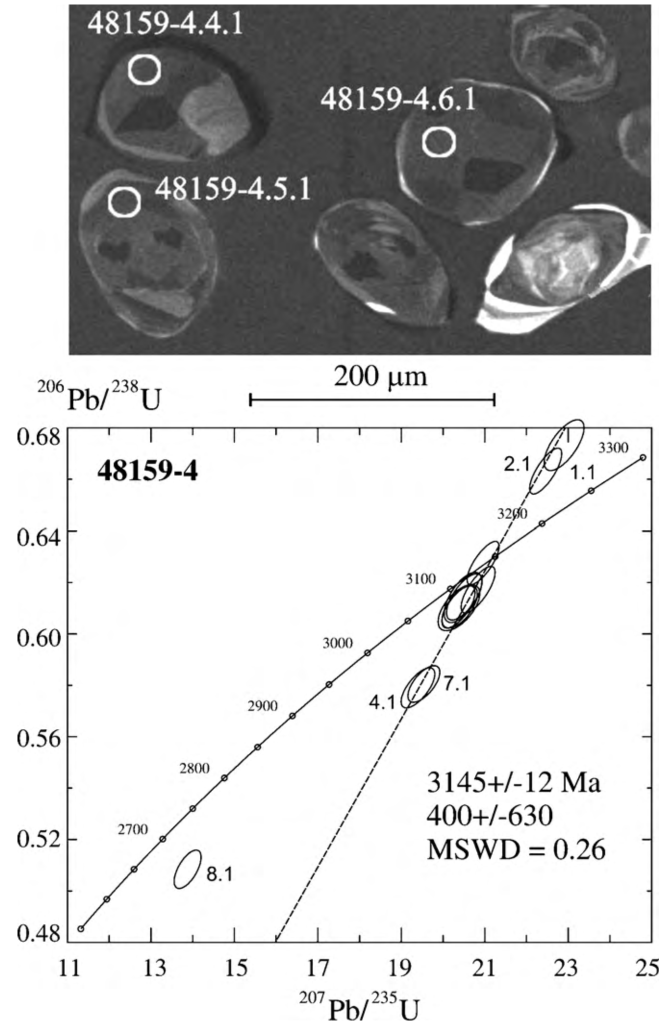

Fig. 4. U–Pb Concordia plot and the CL of zircons from sample 48159-4.

A "charnockitic" gneiss (Opx-bearing felsic gneiss; sample **NRL 179**) from McCue Bluff contains large (200–400 μm) short- to long-prismatic, partly corroded grains with length/width ratio (*l*) of 1.7–4 (Fig. 3). Under cathodoluminescence (CL), many grains show an inhomogeneous structure, with darker high-U zones. Six analyses of six high-U areas were obtained and yielded a concordant weighted mean $^{207}Pb/^{206}Pb$ age of 3160 ± 15 Ma (Fig. 3). In spite of low-Th/U (0.04–0.09), this age is interpreted to be an igneous crystallisation age. This interpretation is supported by the grain morphology. No outer lower-U areas could be analysed due to fracturing.

A metagabbro (hornblende-bearing two-pyroxene mafic rock of granoblastic texture; sample **48159-4**) was collected about 50 m from the Opx-bearing felsic gneiss sample described above. It contains strongly rounded or isometric zircon grains, 100–150 μm large. Under CL, zircon grains show an inhomogeneous irregular structure and some grains display thin highly reflective rims or facets (Fig. 4). Twelve analyses on 12 grains were obtained on grain interiors. All have high Th/U (mostly 0.4–0.5), which may suggest a magmatic origin, but the grain shape rather argues for a metamorphic origin. Most of the analyses are only slightly discordant, and form a regression line with an upper intercept at 3145 ± 12 Ma and a lower intercept at ca. 400 Ma (Fig. 4). A group of seven, nearly concordant analyses gives a weighted mean $^{206}Pb/^{238}U$ age of 3120 ± 13 Ma. Analysis 8.1 is also discordant and shows the lowest U and Th and a much lower $^{206}Pb/^{238}U$ age of 2650 Ma. The age of ca. 3150 Ma may be the best estimate of zircon crystallisation, but it is difficult to distinguish between a metamorphic, inherited, or cognate origin for these grains. However, the Hf isotopic composition (see below) of grains which yielded the most concordant analyses support a cognate origin. A metamorphic overprint in this rock is most likely reflected by a ca. 2750 Ma mineral Sm–Nd isochron (see below), and the only manifestation of this event in the U–Pb zircon systematics may be analysis 8.1, which falls off the regression line and represents a mixture of ca. 3150 Ma and younger components. Other grains escaped this ca. 2750 Ma isotopic disturbance, possibly due to solid-state zircon recrystallization which maintained the U–Pb isotopic compositions as closed systems.

A post-tectonic pegmatite vein (Fig. 2c; microcline-phyric aplite of blastocataclastic texture, sample **48159-3**), which post-dates the "charnockite" colour front (Fig. 2a) but pre-dates the mafic dykes, contains a few short-prismatic corroded zircon grains 100–200 μm large, as well as fragmented zircons (Fig. 5). Under CL, zircon shows an irregular structure, but no zoning or cores could be detected. Six analyses on six grains were obtained. All analyses were high-U and mostly also high-Th; Th/U is high (0.1–0.3). All the analyses are discordant, three having 20–30% discordance. A regression line through 5 analyses gives an upper intercept at 2765 ± 17 Ma, which is interpreted as crystallisation age. The analyses show high-U content and low discordance, which rules out an inherited nature of these zircon grains. Three less discordant

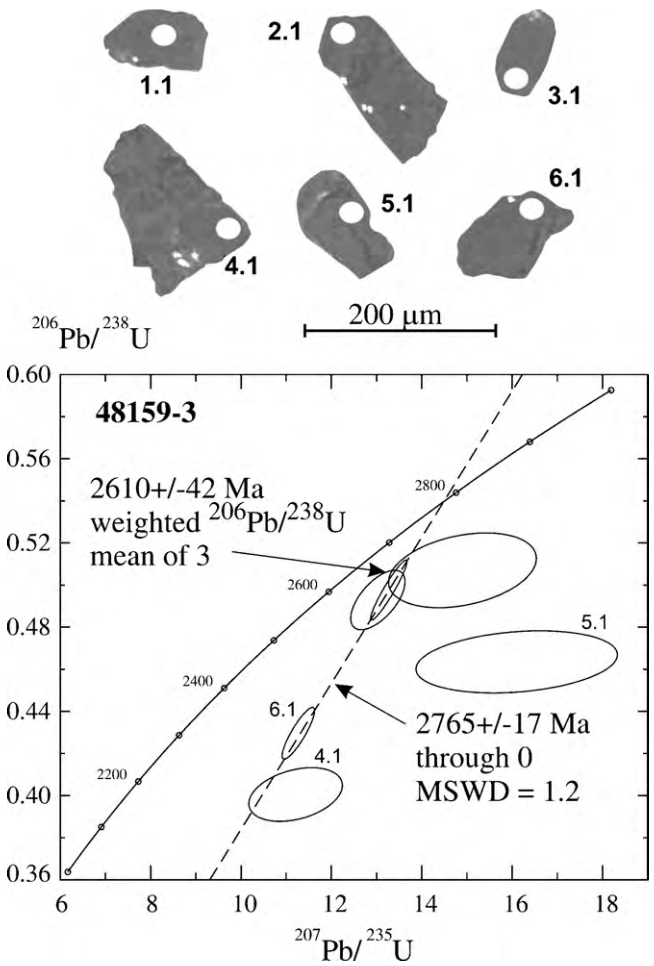

Fig. 5. U–Pb Concordia plot and the CL of zircons from sample 48159-3.

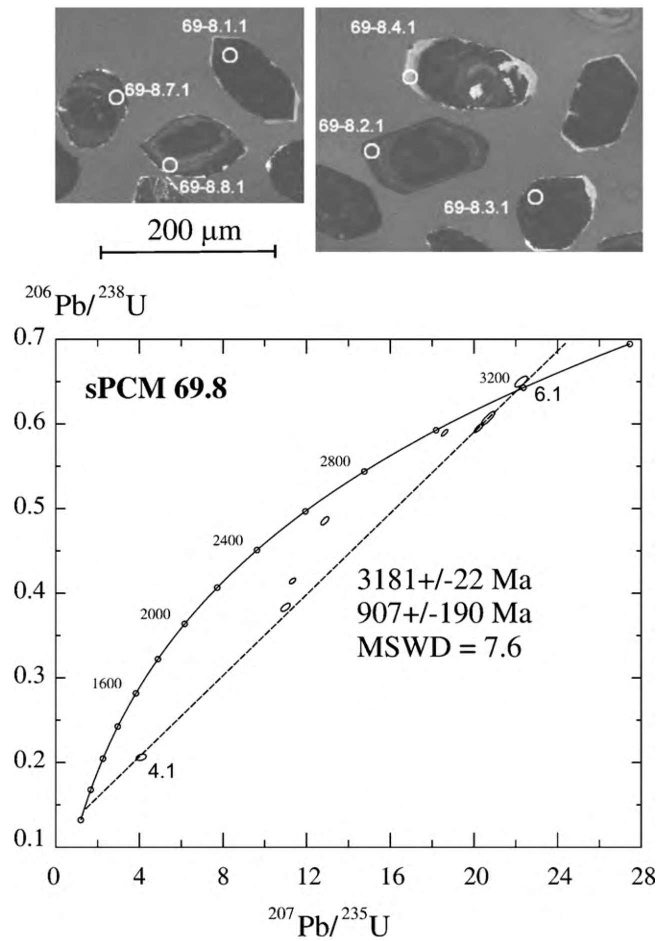

Fig. 6. U–Pb Concordia plot and the CL of zircons from sample sPCM 69.8.

analyses gave a $^{206}Pb/^{238}U$ weighted mean of 2610 ± 42 Ma, which may be considered to approximate the minimum age of pegmatite emplacement, which is in a good agreement with an age of ca. 2645 Ma for a post-tectonic pegmatite in Rimmington Bluff (Boger et al., 2006).

Mafic dykes in Rimmington Bluff to the south of Tingey Glacier commonly display considerable ductile deformation effect and locally contain thin and short quartz–plagioclase veinlets (sample **sPCM 69.8**, microtonalite) confined to the dyke interiors (Fig. 2d). Zircon forms mostly small (100–150 μm), short-prismatic to pseudo-octagonal crystals. Under CL, they display a homogenous structure, and a few grains contain vaguely developed high-U cores. A few zircon grains have very thin low-U rims (Fig. 6). Eight analyses on eight grains have been obtained. Concentrations of U, Th and Th/U vary widely. Most analyses are highly discordant. A regression line through five analyses yielded an upper intercept at 3181 ± 22 Ma and a lower intercept at 907 ± 190 Ma (MSWD = 7.6). The highest $^{206}Pb/^{238}U$ age (ca. 3230 Ma) was obtained for a core (analysis 6.1), and the lowest $^{206}Pb/^{238}U$ age (ca. 1200 Ma) for a low-U rim (analysis 4.1). The other three analyses show a wide spread of isotopic ratios indicative of additional thermal events at ca. 3200–2800 Ma. The age of ca. 3180 Ma corresponds well with the dates obtained from the same area (Boger et al., 2006; Mikhalsky et al., 2006a), which indicate the inherited nature of these grains. It is possible that the low-U rims were formed at the expense of inherited crystals during the veinlet crystallisation. Thus, the time of dyke deformation (and likely metamorphism) may be tentatively ascribed to a ca. 1000 Ma event.

A muscovite-biotite bearing granite gneiss (**48149-1**) was sampled from a thick orthogneiss sequence in the north-eastern Cumpston Massif. This orthogneiss contains a syn-tectonic pegmatite vein (sample 48149-5) dated by Mikhalsky et al. (2008) at ca. 2500 Ma (an upper intercept). Sample 48149-1 contains abundant well-shaped short-prismatic (l = 2.5–3) zircon crystals mostly 200–350 μm large (Fig. 7). Oscillatory zoning can be observed under the CL. Some grains have thin and bright rims. Ten analyses (five rims and five inner areas) on nine grains were obtained. Most analyses are low-U, but show varying concentrations of Th. The rim analyses tend to lower U, Th concentrations and lower Th/U (0.01–0.29), while analyses from the inner areas show higher U, Th and Th/U = 0.25–1.10. Two rims (7.1, 9.1) and three inner zone analyses (1.1, 3.1, 8.1) were nearly concordant, and the others – essentially discordant (Fig. 7). The three concordant core analyses gave a weighted $^{206}Pb/^{238}U$ mean age of 2484 ± 14 Ma, and a regression line drawn through all analyses except 7.1, and 9.1 gave an upper intercept at 2484 ± 14 Ma and a lower intercept at 849 ± 14 Ma (MSWD = 2.1). In Fig. 7 the isotopic data for pegmatite sample 49149-5 are shown for a comparison. Zircon grains of that sample also had mantles which are represented by three analyses with lowermost $^{206}Pb/^{238}U$. It is noteworthy that these mantles are very U-rich (3500–3800 ppm) and Th/U low (<0.01). The core analyses of that sample showed isotopic Pb/U ratios quite similar to sample reported here. This indicates that zircon grains in the pegmatite were inherited from the host granite gneiss. On the other hand, the concordant rim analyses of granite gneiss 48149-1 (7.1, 9.1) and the three rim analyses of the pegmatite 48149-5 define a regression line with an upper

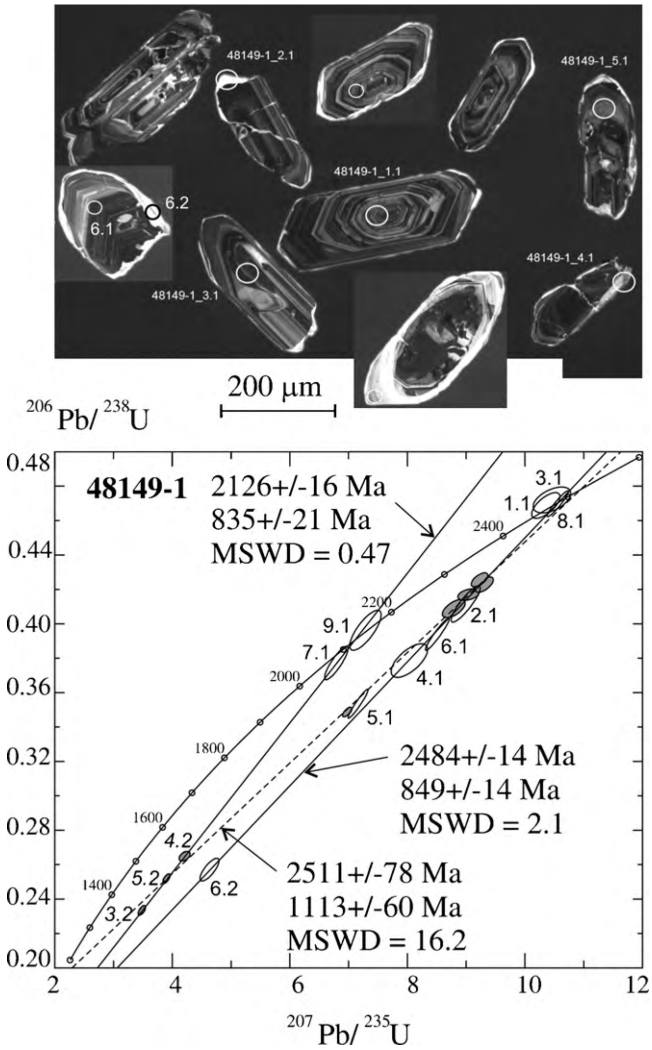

Fig. 7. U–Pb Concordia plot and the CL of zircons from sample 48149-1. The analyses of sample 48149-5 (syn-tectonic pegmatite, Mikhalsky et al., 2008) are shown in grey and labeled italic, of those analyses 3.2, 4.2, 5.2 representing rims.

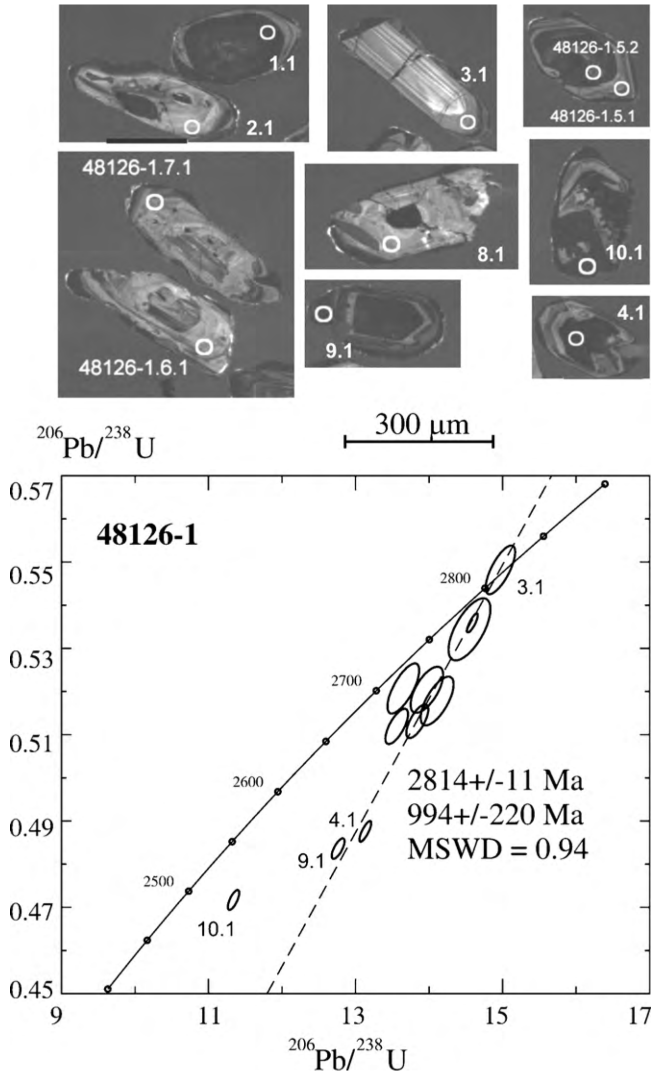

Fig. 8. U–Pb Concordia plot and the CL of zircons from sample 48126-1.

intercept at 2126 ± 16 Ma with low MSWD = 0.47, which coincides with a concordant analysis 9.1 (2143 ± 20 Ma). This clearly reflects a zircon growth (or recrystallization) event at ca. 2120 Ma. This event probably was accompanied by partial melting and pegmatite emplacement which led to the inherited zircon recrystallization under high-U fluid activity conditions. However, the precise age of the pegmatite emplacement can not be determined due to the lack of cognate zircon material found, and can only be estimated by the concordant rim analyses of zircons from the host granite gneiss. We interpret the ca. 2485 Ma date as the age of granite gneiss protolith emplacement and ca. 2120 Ma – as a metamorphic age. Subsequent thermal overprint and Pb-loss occurred at ca. 850 Ma. A lower intercept at ca. 1100 Ma reported by Mikhalsky et al. (2008) thus seems to be an errorchron.

Two granite gneiss, and one syn-tectonic aplite samples from the western escarpment of Mt Stinear were studied. Sample **48126-1** is a gneissic biotite–hornblende quartz diorite of ferroan calc-alkalic composition (classification of Frost et al., 2001). It contains small xenoliths of metasedimentary rocks (Fig. 2e) and represents a prominent lithotectonic unit, distinguished by Phillips et al. (2005a) as the Northern Granite. Abundant zircon grains recovered from this sample are mostly large (200–300 μm) and have short- to long-prismatic shape (l = 1.5–3.5) with well developed pyramidal facets. Under CL, they show mosaic or oscillatory structures (Fig. 8) and some have large high-U inner domains. Eleven analyses on 10 grains were obtained. Most of the analyses plot close to the Concordia and form a coherent cluster which comprises the inner high-U and outer low-U areas. A regression line drawn through nine analyses gives an upper intercept at 2814 ± 11 Ma and a lower intercept at ca. 1000 Ma (Fig. 8). Most grains have high Th/U ratios (0.4–0.6) suggestive of a magmatic origin, but the strongly discordant analysis 10.1 (Th/U = 0.04) indicates considerable Pb loss at 1000 ± 200 Ma.

Sample **48136-1** is a foliated schistose biotite–hornblende granite gneiss of calc-alkalic ferroan composition, quite similar to sample 48126-1. It represents the Central Felsic Gneiss lithotectonic unit of Phillips et al. (2005a) in Mt Stinear. Zircon grains from this sample are large (200–400 μm), non-transparent, greyish, and of short-prismatic (l = 1–2) to pseudo-octagonal shape. Under CL, thin oscillatory zoning can be observed (Fig. 9). Eight analyses on eight grains show a large range of Th/U ratio (0.1–0.8). High-Th/U analyses are concordant and reflect granite crystallisation at 2815 ± 60 Ma (Fig. 9). The low-Th/U analyses form a regression line with a lower intercept at ca. 700 Ma, probably due to a thermal overprint or a series of overprinting events which caused isotopic disturbance reflected in the relatively high MSWD (1.5).

A highly deformed syn-tectonic vein from the same area (sample **48135-1**; Fig. 2f, g) consists of quartz-phyric retrogressed aplite.

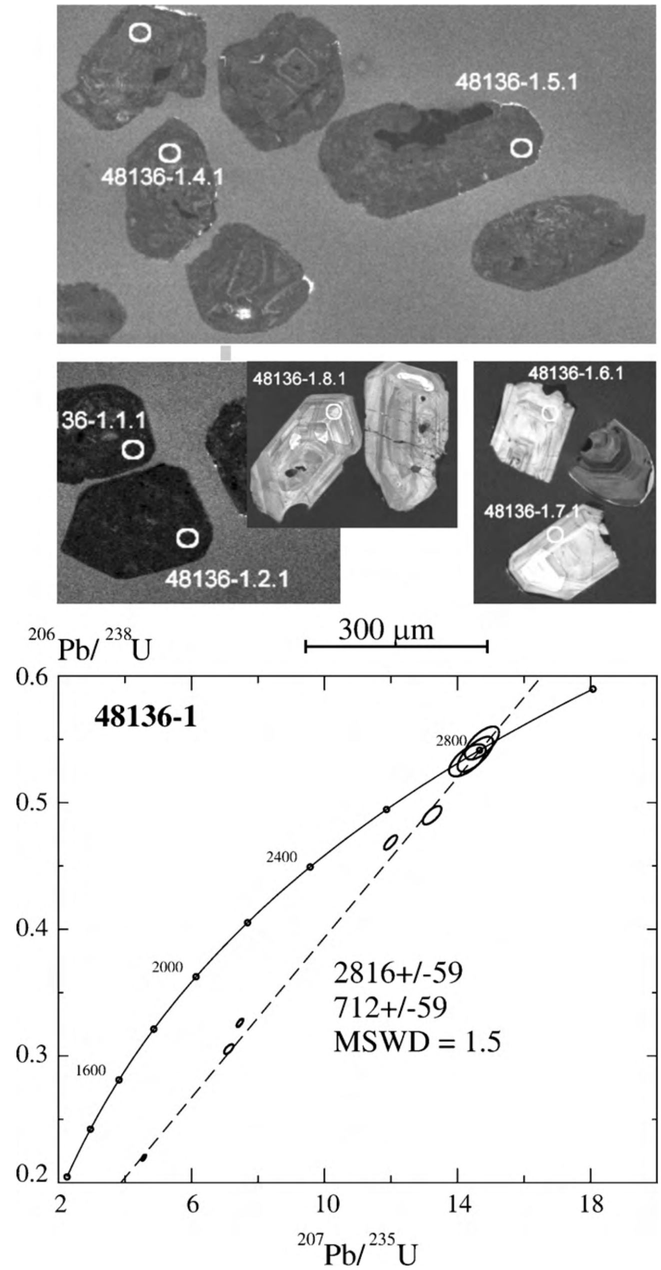

Fig. 9. U–Pb Concordia plot and the CL of zircons from sample 48136-1.

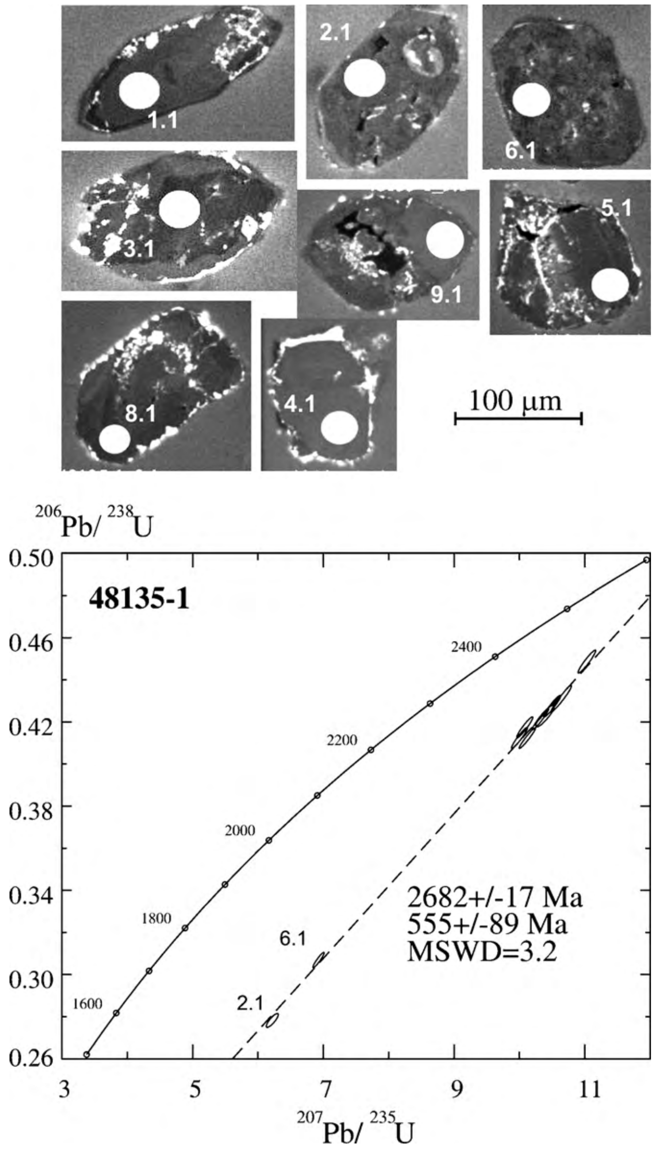

Fig. 10. U–Pb Concordia plot and the CL of zircons from sample 48135-1.

It contains a few small (<100 μm) zircon grains of short-prismatic shape (l = 1–1.5), some of which have well developed pyramidal facets (Fig. 10). Ten analyses on 10 grains were obtained. All are highly discordant and have very low-Th/U (<0.04). Nevertheless, they form a well-constrained regression line with an upper intercept at 2682 ± 17 Ma and a lower intercept at 550 ± 90 Ma (Fig. 10). The upper intercept age probably reflects the time of the aplite injection and contemporaneous ductile deformation, and the lower intercept reflects a thermal overprint.

A pluton in the northern part of Mt Rymill consists of coarse-grained granitic rocks. We studied a metamorphosed quartz monzonite (sample **48129-1**) of calc-alkalic ferroan composition, quite similar, in terms of major elements, to the analysed Mt Stinear rocks. The Mt Rymill sample contains sieve-like quartz-hornblende aggregates, probably replacing pyroxene. Zircon grains recovered from this sample are very short-prismatic (l = 1.3–2.0, rarely up to 2.5) and 200–400 μm large. Under CL, they show irregular inner zoning indicating a magmatic origin (Fig. 11), but no distinctive cores or rims can be seen. Six analyses on six grains were performed. All analyses show consistent high Th/U (0.6–0.9), although both U and Th contents vary widely (100–1600 ppm U, and 80–1000 ppm Th). Five out of six analyses plot relatively close to the Concordia curve (Fig. 11), but analysis 6.1 (high-U) is strongly discordant. A regression line drawn through it and three near-concordant analyses gives an upper intercept at 2800 ± 7 Ma, and a lower intercept at 75 ± 400 Ma (MSWD = 0.25). We interpret the ca. 2800 Ma age as the best estimate of the granitoid crystallization age. The remaining two, somewhat discordant, analyses reflect inheritance, but the inherited material cannot have been very much older.

A sample (**779a**) of thinly foliated titanite–epidote–biotite-bearing quartz–feldspar gneiss containing large potassium feldspar porphyroblasts was collected by S.D. Solov'ev from the eastern part of Mt Bayliss in the early 1970s. Like the granitic rocks described above, this sample is a calc-alkalic ferroan acidic rock, but can be distinguished for its higher SiO_2 and lower FeO, MgO, TiO_2 and P_2O_5 contents. The rock contains abundant short- to long-prismatic (l = 1.5–3) corroded zircon crystals, mostly 150–250 μm long (Fig. 12). Under CL, thin oscillatory zoning can commonly be observed. Ten analyses on 10 grains were obtained. All analyses

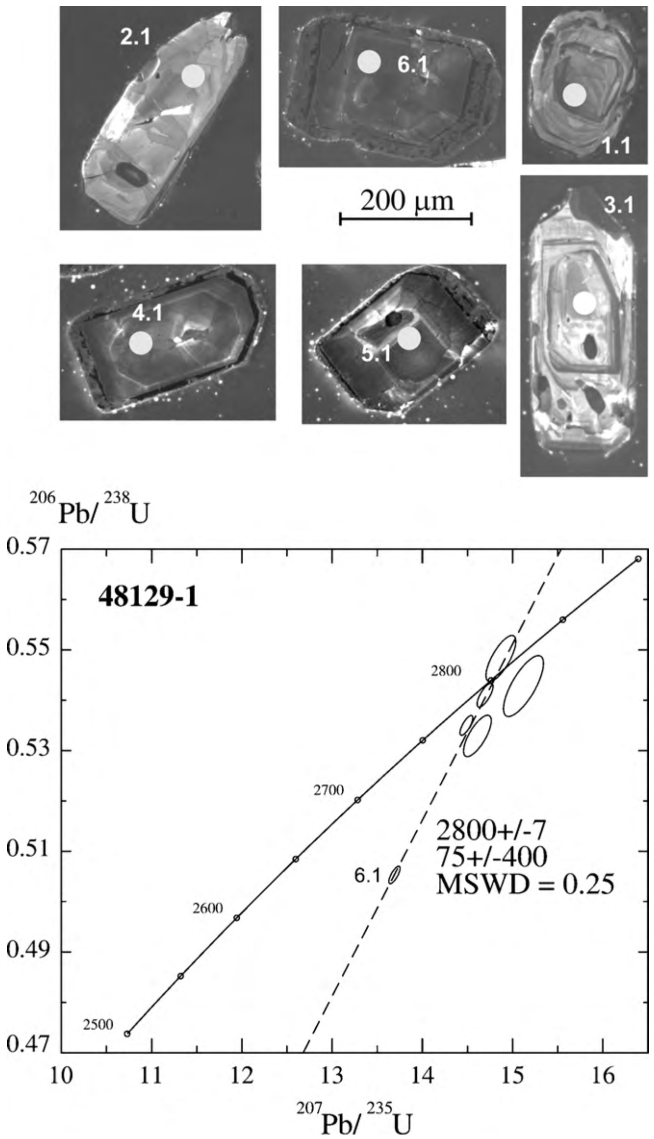

Fig. 11. U–Pb Concordia plot and the CL of zircons from sample 48129-1.

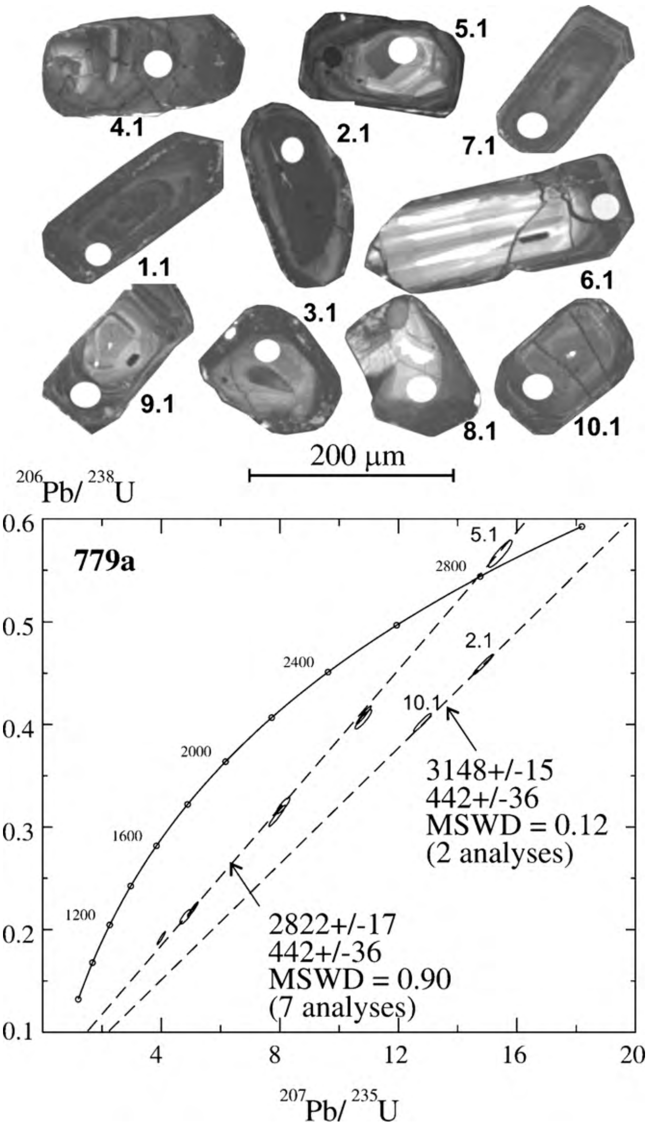

Fig. 12. U–Pb Concordia plot and the CL of zircons from sample 779a.

show high Th/U (0.3–1.0) and are highly discordant (except analysis 5.1). Eight analyses form a regression line with an upper intercept at 2822 ± 17 Ma and a lower intercept at 442 ± 36 Ma (Fig. 12). These ages may reflect magmatic crystallisation and thermal overprinting, respectively. Two other analyses suggest the presence of an older, ca. 3150 Ma, component, as defined by a two point regression line forced through 442 Ma.

3.2. The Lambert Terrane

Four granitic samples from the Rofe Glacier area of the northern Mawson Escarpment were analysed (Figs. 1 and 13). On the northern flank of the Rofe Glacier a thick mafic two-pyroxene granulite sequence crops out. The sequence contains thin late-tectonic (injected) leucocratic quartz–plagioclase leucosome veins (sample 48101-2), which are concordant with the foliation, some are deformed into small rootless isoclinal folds, but may cut through the main metamorphic fabric of the country rock. These features suggest roughly co-eval leucosome emplacement, metamorphism, and folding events at this locality. The rocks are cut by thicker, pinkish gneissose granitoid sheet- or dyke-like bodies (sample 48101-14), as well as post-tectonic sub-vertical white Bt granite dykes (Fig. 13a) dated at ca. 500 Ma (sample 48101-3 in Mikhalsky and Roland, 2007).

A sample from a leucosome (**48101-2**, microtonalite) contains abundant angular zircon fragments, irregular, short-prismatic and a few very long-prismatic grains (l = 5–8, Fig. 14) up to 500 μm large. Nine analyses on nine grains were obtained. The analyses of fragments show low-Th/U = 0.03–0.05, whereas analysis 9.1 has Th/U = 0.80. All analyses are to some degree discordant, with eight low-Th/U analyses giving a poorly constrained regression line (MSWD = 13.0) with an upper intercept at ca. 1740 Ma (Fig. 14), which is believed to reflect the syn-metamorphic leucosome emplacement age. The high-Th/U analysis suggests the presence of inherited material of ca. 2250 Ma, which may reflect the emplacement age of the source mafic protolith. Two analyses indicate prominent Pb loss at ca. 850 ± 50 Ma.

Sample **48101-14** is a medium-grained biotite-bearing potassium-rich granite dyke which cuts through the main rock foliation at a low angle. The zircon grains recovered from this sample are small (100–150 μm, rarely 300 μm). Most are fragments of larger crystals, but some small grains are of very short-prismatic shape (l = 1.2–1.5, Fig. 15). Coarse inner oscillatory zoning is present. Eight analyses on eight grains were obtained. All

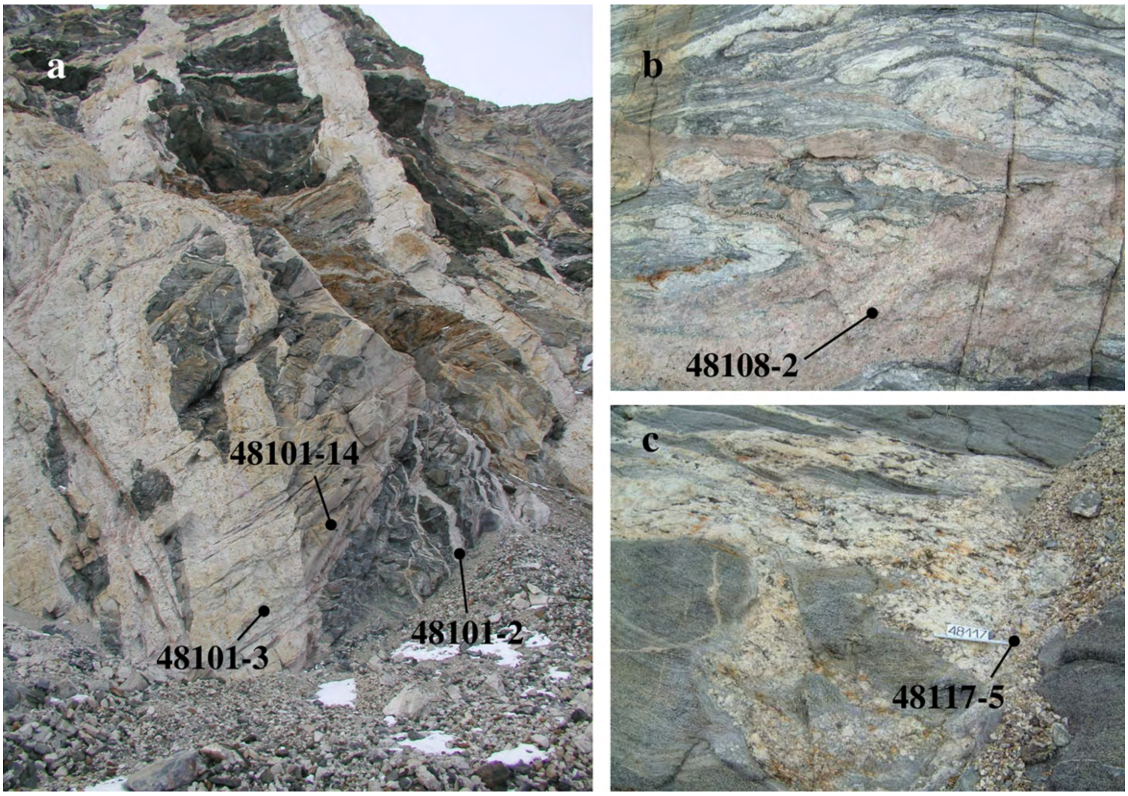

Fig. 13. Sampled outcrops in the Lambert Terrane (the Rofe Glacier area): a) mafic granulite crosscut by three generations of felsic veins 48101-2, 48101-3, 48101-14 (cliff height about 30 m); b) syn-tectonic felsic vein 48108-2 (view area about 0.5 × 0.5 m); c) late-tectonic felsic vein 48117-5 (view area about 2 × 2 m).

analyses show moderately high Th/U (0.09–0.23), consistent with a magmatic origin. All are concordant (Fig. 15), with a $^{207}Pb/^{206}Pb$ weighted mean age of 923 ± 18 Ma (MSWD = 0.73), interpreted as the time of crystallisation of the granite dyke.

Sample **48108-2** represents a corrugated (tightly folded) syn-tectonic coarse-grained biotite granite vein within grey banded migmatitic fine-grained biotite-rich gneiss in the upper Rofe Glacier area (Fig. 13b). This rock contains rounded or oval grains 150–200 μm large (Fig. 16). The grain shape suggests a detrital origin and hence a sedimentary source for this rock. Under CL, zircon grains display an inhomogeneous, often mosaic structure. Ten analyses on 10 grains were obtained. Th/U ratio is either <0.05 (four analyses with lower $^{206}Pb/^{238}U$ ages in the range 1500–1800 Ma) or 0.3–0.6 (six analyses with higher $^{206}Pb/^{238}U$ ages in the range 1800–2200 Ma). Eight of the analyses form a regression line (Fig. 16), with an upper intercept at 2217 ± 61 Ma and a lower intercept at ca. 1250 Ma (MSWD = 1.6). We interpret the age of ca. 2200 Ma as inherited and an upper limit for the emplacement age. These data probably indicate a ca. 2200 Ma tectonothermal episode, which was followed by weathering and sedimentation, and subsequent melting not later than the mid-Mesoproterozoic (possibly at ca. 1250 Ma).

Sample **48117-5** represents a thin, slightly schistose biotite tonalite vein intruded into mafic schist in the southern fringe of the Rofe Glacier (Fig. 13 c). The rock contains abundant large (300–500 μm) corroded short- to long-prismatic (l = 2.5–4) zircon grains. Under CL, only faint inner darker areas could be distinguished in few grains. Six analyses on six grains (light and dark areas) were obtained. All analyses show high-U and low-Th/U (<0.05) and all but one are somewhat discordant (Fig. 17) and form a regression line with an upper intercept at 917 ± 23 Ma forced through the zero point. This date reflects the vein crystallisation age.

4. Zircon Hf isotopic data

Zircons from two samples (three grains each) were analysed for Hf isotopes (see the Supplement files) at the CIR (VSEGEI, St.-Petersburg) by laser ablation for dated zircon grains on a 193 nm ArF Excimer laser coupled with a multi-collector ICP-MS (Neptune, FinniganMAT). Parameters ε_{Hf} and T^{Hf} were calculated assuming a negligible Lu/Hf ratio of 0.0002. Zircons from sample 48159-4 (metagabbro from McCue Bluff dated at ca. 3150 Ma, this study) have high ε_{Hf} (t = 3150 Ma) values between 0 and 3 and T^{Hf} model ages 3060–3190 Ma. These model ages closely correspond with the U–Pb zircon age. This supports a cognate origin for these grains, which crystallised from a mafic melt, and is thus consistent with the 3150 Ma emplacement age of the gabbro.

Zircons from sample 48148-6 (a felsic gneiss from Mt Newton dated at ca. 2200 Ma, Mikhalsky et al., 2008) have widely varying, but consistently high ε_{Hf} (t = 2200 Ma) values between −3 and 22 and T^{Hf} model ages of ca. 1300–2400 Ma. Provided the measured grains represent a coherent generation in terms of ages and yielded concordant U/Pb analyses, the observed diversity in ε_{Hf} is most likely caused by exceeding Lu concentration (maybe due to inclusions of apatite in zircon). The Sm–Nd model T_{CHUR} age of this rock is 2.56 Ga, which is similar to T^{Hf} model age of 2.40 Ga. This value was obtained for a grain (3.1) with the highest concordant $^{206}Pb/^{238}U$ age of 2257 Ma, and we believe this analysis represent the most "pristine" zircon matter containing less Lu and was not modified by subsequent events. Adjustment of Lu/Hf ratio to 0.0024 would produce T^{Hf} model age equal to T^{Nd}; $\varepsilon_{Hf}(t)$ would than recalculate to −7.0. A similar procedure for the other two analyses (11.1, 9.1) would change $\varepsilon_{Hf}(t)$ to −5.3 (Lu/Hf = 0.0087) and −3.2 (Lu/Hf = 0.0168), respectively. Thus, zircon from sample 48148-6 probably crystallised from a within-crust melt, although the crustal residence time did not exceed 300–400 Ma (assuming derivation

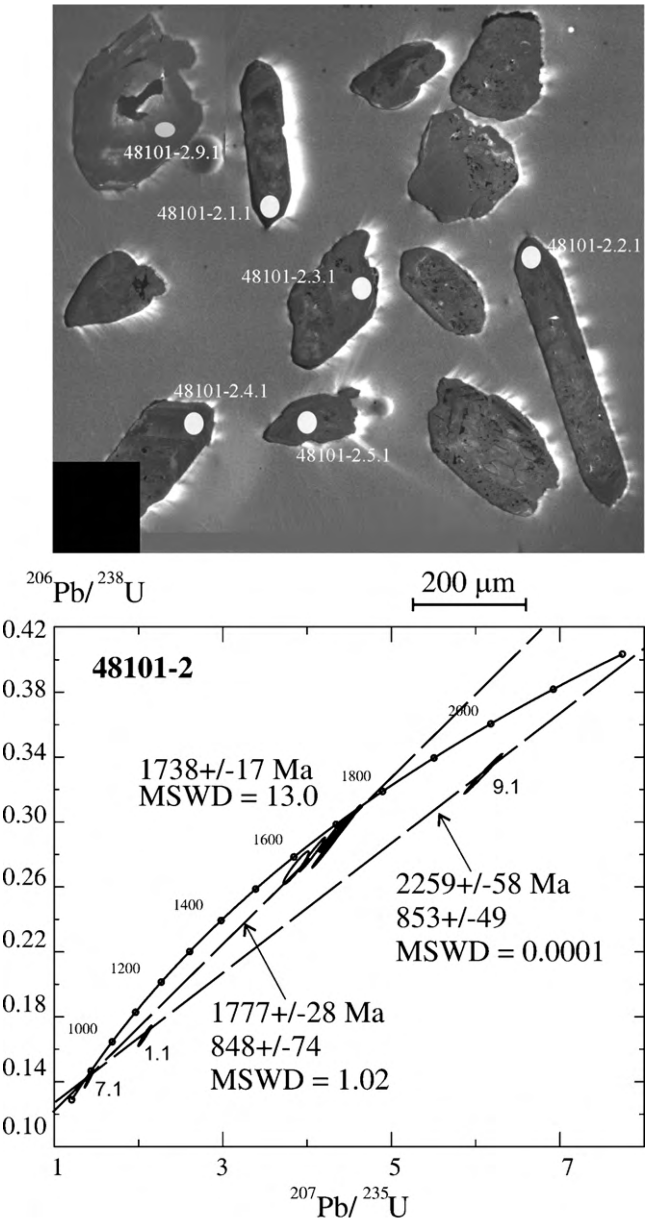

Fig. 14. U–Pb Concordia plot and the CL of zircons from sample 48101-2.

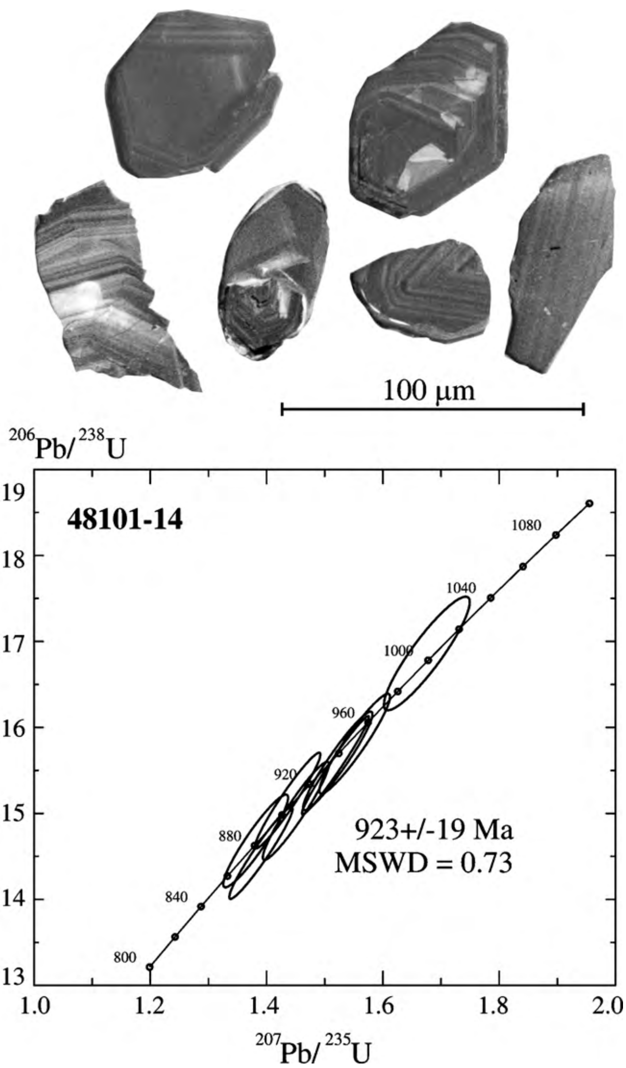

Fig. 15. U–Pb Concordia plot and the CL of zircons from sample 48101-14.

from primitive mantle at ca. 2.5–2.6 Ga) or 700 Ma (assuming derivation from depleted mantle at ca. 2.9 Ga, see below).

5. Sm–Nd data

Forty-two whole-rock samples, as well as three mineral separates from a metagabbro in McCue Bluff, were analysed to obtain Sm–Nd model ages. They mostly include felsic orthogneisses, granites, and a few mafic rocks from the Mawson Escarpment and many other localities in the sPCM. The Sm–Nd studies were conducted at BGR (Hannover) and at the CIR (VSEGEI, St.-Petersburg) on similar equipment: thermo-ion multi-collector solid-source mass-spectrometer THERMO Triton-TIMS in a static mode (BGR) or with simultaneous determination of the required isotopes (CIR). In both laboratories Nd isotopic ratios were normalized to $^{146}Nd/^{144}Nd = 0.7219$. Nd and Sm concentrations were determined by isotope-dilution techniques. Procedure blanks for Nd and Sm are less than 0.1% of the relevant sample concentration and are therefore negligible. The measured Nd isotopic compositions were adjusted to $^{143}Nd/^{144}Nd = 0.511860$ for the La Jolla standard (BGR) or to $^{143}Nd/^{144}Nd = 0.512104$ for the JNdi-1 standard (CIR). The results are presented in the Supplement files. Assuming that most of the area experienced thermal reworking at a subsequent stage of the geological evolution, a two-stage model was applied to calculate the depleted mantle (DM) extraction ages (Keto and Jacobsen, 1987), but the calculated T_{DM} and T_{DM2} values for basement rocks differ by only 100–200 Ma, which is not significant for the isotopic mapping discussed below. In contrast, post-tectonic granites have very different one- and two-stage model ages.

In the Ruker Terrane, T_{DM} model ages for the studied basement granite and felsic orthogneisses mostly fall within two time periods: Palaeoarchaean (3.2–3.4 Ga) and Neo- to Mesoarchaean (2.7–3.0 Ga). The rocks dated at ca. 3100–3200 Ma or collected from the same localities yielded the T_{DM} model ages in the range 3.2–3.4 Ga with $\varepsilon_{Nd}(t) = -1$ to +2.5, and the rocks dated at ca. 2800 Ma have relatively low $\varepsilon_{Nd}(t)$ in the range −1 to −4, indicating remelting of ca. 3.2–3.4 Ga crust (Fig. 18). Samples with T_{DM} model ages in the range 2.7–3.0 Ga were collected from Cumpston Massif (except 48140-1), Mt Newton, and Mt Borland, which points to the presence of relatively young continental crust in this area. Two rocks dated at ca. 2500 Ma (48149-1, Cumpston Massif, this study), and ca. 2200 Ma (48148-6, Mt Newton, Mikhalsky et al., 2008) also yielded relatively low T_{DM} ages (2.68 Ga and 2.90 Ga, respectively), but different $\varepsilon_{Nd}(t)$ values of 1.8, and −3.4, respectively. Sample

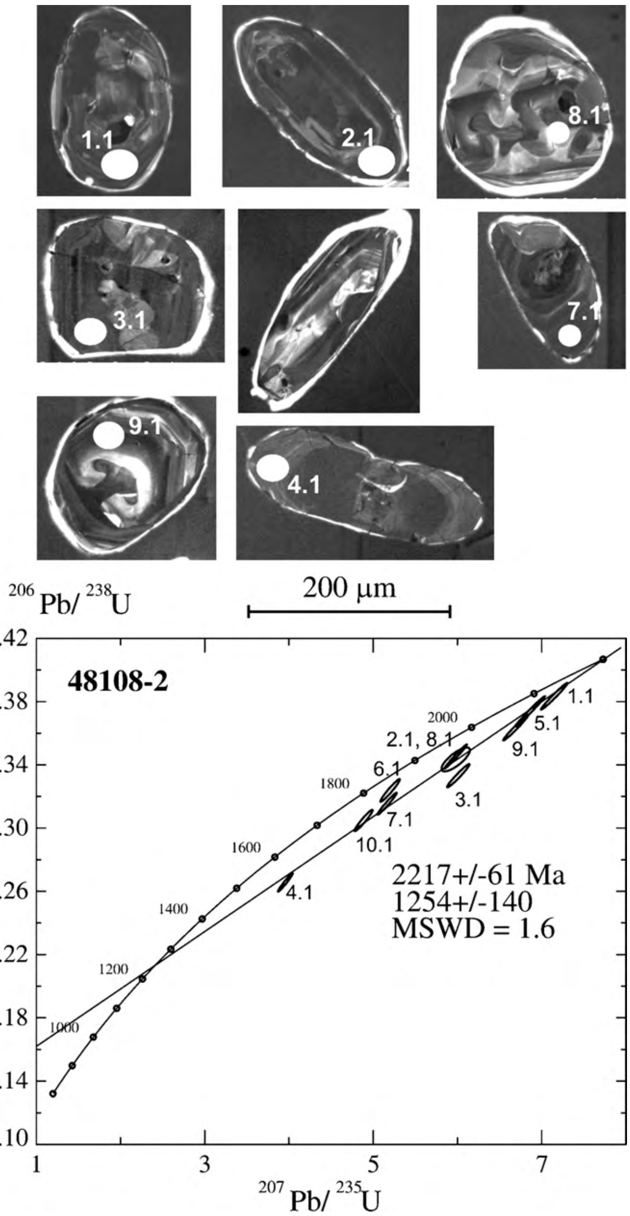

Fig. 16. U–Pb Concordia plot and the CL of zircons from sample 48108-2.

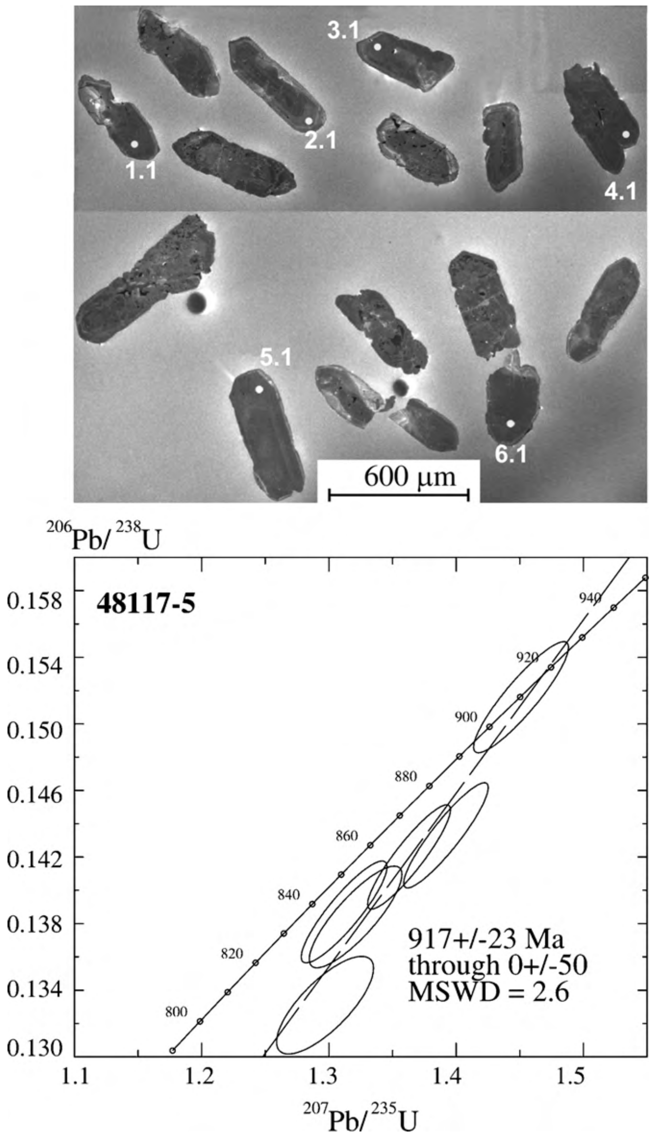

Fig. 17. U–Pb Concordia plot and the CL of zircons from sample 48117-5.

48140-1 (southern Cumpston Massif, ca. 3180 Ma, Mikhalsky et al., 2008) has much older T_{DM} of ca. 3.54 Ga indicating the presence of an ancient crustal component within this area as well.

Two of the studied samples (48168-6, a tonalite cobble in Mt Rubin metasediments and NRL179, an orthogneiss from McCue Bluff) have T_{DM} ages significantly lower than the U–Pb crystallisation ages (Fig. 18). The initial $\varepsilon_{Nd}(t)$ of these rocks is +10 and +5, respectively, and both analyses plot on the same Sm–Nd evolution line. This indicates derivation from a source of ultra-depleted, rather than "normal" depleted, character.

The Early Palaeozoic (ca. 520 Ma, Mikhalsky and Roland, 2007) post-tectonic granitic rocks yielded a wide spectrum of isotopic Sm/Nd ratios (see the Supplement files) which may reflect various degrees of partial melting of different crustal sources. The highest Sm/Nd ratio [$f = (^{147}Sm/^{144}Nd_{sam})/(^{147}Sm/^{144}Nd_{CHUR}) - 1$] of 0.75 was obtained for a granite (sample 48132-1) which has high HREE contents and an unusual negative slope of its chondrite-normalized REE pattern (Mikhalsky and Roland, 2007). This feature suggests a high degree of melting of a garnet-bearing source, probably under high-pressure conditions. In spite of large variations of f and T_{DM} ages, initial $\varepsilon_{Nd}(t = 500\ \text{Ma})$ values for most (five out of six) granites fall within a relatively narrow interval of −20 to −23, which may be the best estimate of the isotopic composition of the crustal source region. The two-stage T_{DM2} model ages (assuming a common upper crust Sm/Nd ratio of 0.12) for these rocks are 2.9–3.0 Ga, which may suggest that the younger, ca. 2.7–3.0 Ga crust underlies the area sampled by the granites. However, the Ruker Terrane basement rocks mostly have Sm/Nd around 0.11, and the T_{DM2} ages calculated with this value are 2.95–3.15 Ga, broadly similar to the majority of the basement rocks and thus pointing to the same, rather than a younger, source.

A metagabbro from McCue Bluff, dated at ca. 3150 Ma (this study), was studied for its whole rock and mineral Sm–Nd systematics. This rock has a granoblastic texture and is composed of clino- and orthopyroxene, plagioclase, quartz, and texturally equilibrated hornblende. A whole-rock and mineral Sm–Nd isochron was obtained for this sample. Four points (WR, Pl, Opx, Cpx) yielded a nearly perfect isochron age of 2755 ± 54 Ma (MSWD = 0.096), which we interpret as a metamorphic age. The rock has T_{DM} = 3.38 Ga, $\varepsilon_{Nd}(t = 2.75\ \text{Ga})$ = +1, and $\varepsilon_{Nd}(t = 3.15\ \text{Ga})$ = +1.6. This indicates that the composition of the mantle source is within the normal mantle

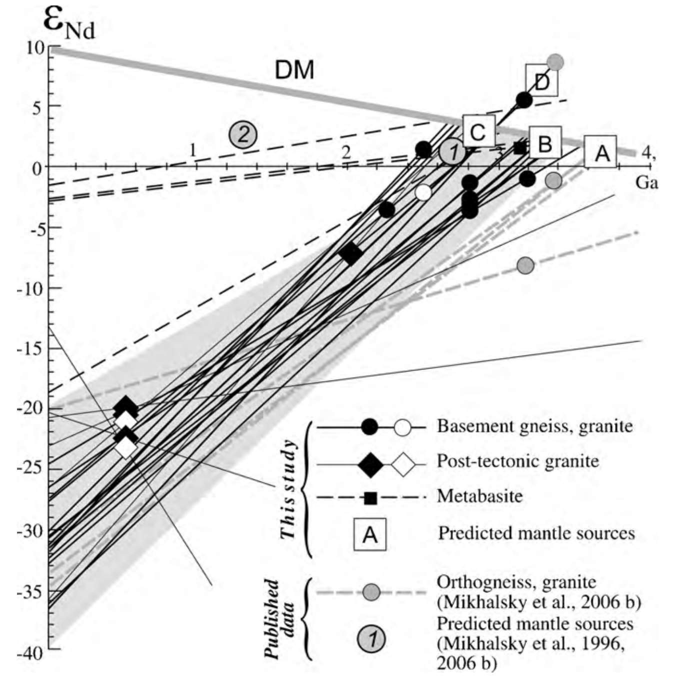

Fig. 18. Nd isotope evolution diagram for the Ruker Terrane rocks. The initial $\varepsilon_{Nd}(T)$ values are indicated by symbols: filled – dated samples (black – this study, grey – published), white – predicted ages (this study). The grey area is the field of most orthogneiss samples (common $f_{Sm/Nd}$) from the Ruker Terrane reported by Mikhalsky et al. (2006a), while a few rocks with lower f are shown as thicker grey dashed lines. DM – depleted mantle (after DePaolo, 1988).

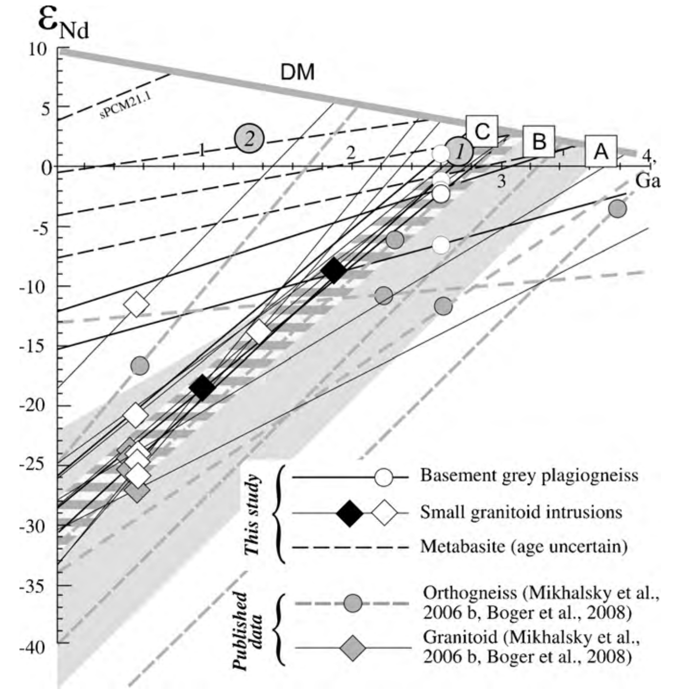

Fig. 19. Nd isotope evolution diagram for the Lambert Terrane rocks. Grey field is same as in (a), horizontal hatched field corresponds to the Ruker Terrane 2.7–3.0 Ga crust; other symbolization as in Fig. 18.

array. A few other analysed mafic rocks have similar $\varepsilon_{Nd}(t = 3.15\text{ Ga})$ values in the range 2–5 (Fig. 18). Thus we believe that partial melts from the normal mantle (mafic samples) or from crust derived from such a mantle source (granitic samples) played an important role in the observed composition of the sPCM (maybe with admixture of other mantle sources, such as enriched or ultra-depleted mantle).

Felsic rocks in the Lambert Terrane have $\varepsilon_{Nd}(t = 2.4\text{ Ga})$ in the range −2 to +4 and T_{DM} ages of 2.3–2.9 Ga (Fig. 19). Other lithologies, such as mafic amphibolite, granulite, and metagabbro have much older model ages in the range 2.7–4.0 Ga (Lines Ridge, Harbour Bluff). However, there is no evidence for any of these rocks being older than 2.5 Ga, and their $\varepsilon_{Nd}(t = 2.4\text{ Ga})$ values vary widely between −6 and +4. Thus it is most likely that they originated from a highly heterogeneous mantle source or from a mixture of different sources, maybe similar to those envisaged for the Ruker Terrane, but with a more pronounced influence of an enriched mantle source. An amphibolite sample (sPCM21.1, tentatively dated at ca. 2.45 Ga by Corvino et al., 2008) has an unusually high $\varepsilon_{Nd}(0) = 4.1$ with $\varepsilon_{Nd}(t = 2.45\text{ Ga}) = 17$.

6. Rb–Sr data

We have analysed (with a THERMO Triton-TIMS at the CIR, VSEGEI, St.-Petersburg) five samples from localities representative of the younger events in the Ruker Terrane (four samples from Cumpston Massif and Mt Newton) and the Lambert Terrane (one sample, see the Supplement files). A dated sample (ca. 2500 Ma, 48149-1) from the north-eastern Cumpston Massif showed a very low initial $^{87}Sr/^{86}Sr$ (Sr_i) of 0.701, and its low Rb/Sr defines only minor variation of Sr_i in assumption of different age (t) of Rb–Sr fractionation: 0.699 at $t = 3.18$ or 0.706 Ga at $t = 0.5$ Ga. This indicates derivation of this rock protolith from a primitive mantle source at ca. 2.5 Ga. An undated sample (48141-1) from the south-western tip of Cumpston Massif yielded reasonable Sr_i values between 0.701–0.708 calculated for $t = 2.5$–2.4 Ga, quite similar to sample 48149-1. Sm–Nd T_{DM} values of these two samples (48141-1, 48149-1) also are similarly young (<3.0 Ga). A dated sample (48140-1, ca. 3180 Ma) from the south-western part of Cumpston Massif, located only 2 km eastward the sample 48141-1, showed much higher Rb/Sr, and high Sr_i of 0.736, which points to derivation of this rock from a metamorphic protolith. On the other hand, $Sr_i = 0.708$–0.703 was calculated for t of ca. 3.30–3.32 Ga, which shows that the protolith of this sample originated from a primitive mantle roughly at that time. Sm–Nd T_{CHUR} ages (ca. 3.2 Ga) from this locality also indicate a Palaeoarchaean age of separation from the mantle. The similarities between zircon crystallisation, Sm–Nd model ages and corresponding low calculated Sr_i values advocate for minor Rb/Sr fractionation during subsequent metamorphic and deformation events, maybe with the exception for sample 48140-1.

A dated sample (48146-1, ca. 2200 Ma) from Mt Newton showed high Sr_i of 0.713 suggestive of metamorphism; calculated $Sr_i(t = 2.5\text{ Ga}) = 0.707$ indicated derivation from a primitive source of late Archaean–early Palaeoproterozoic age.

An undated grey gneiss (48114-1) from Rofe Glacier area (the Lambert Terrane) showed calculated $Sr_i(t = 2.0\text{ Ga}) = 0.705$, indicating this age (2.0 Ga) of emplacement would be a reasonable suggestion.

7. The Precambrian (ca. 3.5–1.0 Ga) tectonic evolution of the southern Prince Charles Mountains

In this section we summarize the geological, geochemical and age data available for this region and emphasize some key features of the geological history and tectonic evolution of two terranes distinguished in the sPCM aimed at their comparison and correlation with other regions. The geological history is basically constrained by the U–Pb zircon studies, and the Sm–Nd isotopic data (new and published) are mainly utilized to assess the crustal residence time and to discern juvenile crust-formation episodes, although a few Sm–Nd isochron ages have also been obtained. A compilation of new and published elsewhere the U–Pb zircon (SHRIMP) ages for

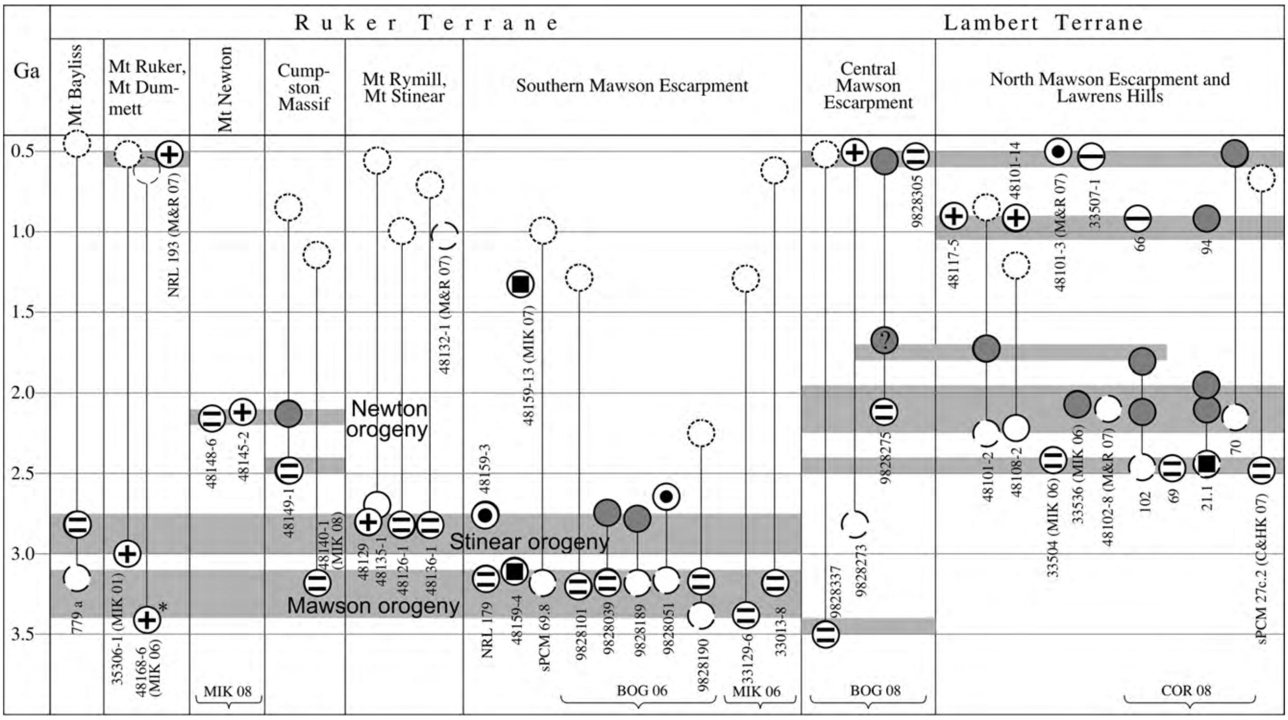

Fig. 20. Zircon SIMS SHRIMP U–Pb dates in a time–space diagram for the Ruker Province. Solid circle indicates concordant or upper intercept interpreted as a crystallisation age, long dashed circle – concordant or upper intercept interpreted as an inherited age, short dash circle – lower intercept interpreted as an overprint. The dated geological events are indicated by symbols: cross – granite intrusion (* – a cobble in low-grade sediments), double dash – felsic orthogneiss protolith intrusion, grey fill – high-grade metamorphism or migmatisation, black square – mafic intrusion (including dykes), dash – pre- to syn-tectonic small granite intrusion, thick dot – post-tectonic pegmatite or granite vein intrusion. Grey bar indicates a zircon producing time interval (orogeny). Data sources: MIK 01 – Mikhalsky et al. (2001), MIK 06 – Mikhalsky et al. (2006a), M&R 07 – Mikhalsky and Roland (2007), MIK 08 – Mikhalsky et al. (2008), MIK 07 – Mikhalsky et al. (2007b), BOG 06 – Boger et al. (2006), BOG 08 – Boger et al. (2008), COR 08 – Corvino et al. (2008), C&HK 07 – Corvino and Henjes-Kunst (2007).

various areas of the sPCM is presented in Fig. 20. Below we concentrate on the Precambrian ca. 3.5–1.0 Ga (pre-Grenville age) history, and the Neoproterozoic to Cambrian ca. 1.0–0.5 Ga evolution has been described in reasonable details elsewhere (e.g., Phillips et al., 2007, 2009; Boger and Wilson, 2005; Boger et al., 2008; Corvino et al., 2008).

7.1. The Ruker Terrane

The geological history of the Ruker Terrane can be traced back to the Early Archaean, with the first recorded tectonomagmatic event initiated at ca. 3.4 Ga (Mikhalsky et al., 2006a) and the separation of continental crust from the mantle beginning at about 3.8 Ga. The available Sm–Nd data (Mikhalsky et al., 2006b and this study) show that the Ruker Terrane has a heterogeneous isotopic structure. T_{DM} model ages for the basement granitic rocks fall within three time intervals: Eoarchean (3.6–3.8 Ga), Palaeoarchaen (3.2–3.4 Ga), and Neo- to Mesoarchaean (2.7–3.0 Ga). This isotopic diversity could theoretically be explained in terms of varying protolith crustal residence times, and thus three separate crust-formation events may be distinguished. On the other hand, there are indications of the presence of continental crust derived from an ultra-depleted mantle source: two granitic samples with $\varepsilon_{Nd}(t = 3.2–3.4\,Ga)$ of +10 and +5. Such a source was envisaged by Mikhalsky et al. (2007a), who reported an ultramafic rock from the southern Mawson Escarpment with high f, T_{CHUR} model age of ca 4.2 Ga, and $\varepsilon_{Nd}(t = 3.4\,Ga) = +7$. These authors noted that the data closely matched the composition of the presumed early Archaean (3.4–3.8 Ga) ultra-depleted mantle reported by Bennett et al. (1993) from the Australian and Greenland cratons. The rocks with relatively low T_{DM} (ca. 2.7–3.0 Ga) may also have been derived from a similar source, as their Nd isotopic evolution lines are very similar (Fig. 18). However, voluminous production of such crust would require specific and unusual petrogenetic conditions and tectonic environments, questions beyond the scope of the present study and clearly needing further investigation. On the other hand, felsic volcanic and volcano-sedimentary rocks from Mt Ruker were reported (Mikhalsky et al., 2001, 2006b) to have initial $\varepsilon_{Nd}(t = 2.8–2.9\,Ga)$ of +2 to +5 (source number 1 in Fig. 18), thus indicating a mantle source corresponding to a normal mantle array. A few metabasite rocks (metagabbro, amphibolite layers, deformed dyke) analyses here also showed "normal" mantle $\varepsilon_{Nd}(t = 2.8\,Ga) = +1$ to $+4$. So it is most likely that the Mesoarchaean (2.7–3.0 Ga) event was of crust-forming character, and "normal" (depleted to slightly enriched) mantle was the principal source region, although the actual extent of mantle-derived rocks of this age cannot be evaluated at present.

Thus we suggest that three distinct components derived from the "normal" mantle (Fig. 18) contributed to the continental crust of the Ruker Terrane: (A) Eoarchaean at ca. 3.6–3.8 Ga, (B) Palaeoarchaean at 3.2–3.4 Ga, and (C) Mesoarchaean at 2.7–3.0 Ga. Some contribution from an ultra-depleted mantle (D in Fig. 18) is also indicated by a few samples. The bulk of the crust in the Ruker Terrane was apparently derived from the mantle at, or prior to, ca. 3.2–3.4 Ga. The Mesoarchaean (ca. 2.7–3.0 Ga) crust seems to underlie the area of Cumpston Massif–Mt Newton–Mt Borland. The Rb–Sr and Hf isotopic data presented above suggest that juvenile mantle additions occurred until or at ca. 2.5 Ga.

As shown above, the Palaeoarchaean (3400–3100 Ma) tectonomagmatic activity in the Ruker Terrane embraced two separate episodes. Emplacement of pre-tectonic trondhjemite was dated at 3390–3380 Ma and of granite at 3180–3160 Ma (U–Pb zircon SHRIMP data, Boger et al., 2006; Mikhalsky et al., 2006a). The former event was identified only in the southern Mawson Escarpment by concordant U–Pb zircon ages. Mikhalsky et al. (2007c) also obtained an upper intercept age of 3330 ± 60 Ma for a syntectonic granitoid vein and interpreted it as an inherited age. The voluminous pre-tectonic TTG-like tonalite and trondhjemite were likely derived by partial melting of mafic material such as lower continental crust or subducted oceanic crust (Mikhalsky et al., 2006a), and were indications of the Orogenic event 1. Compositionally similar (but not yet dated) TTG-like rocks have also been found elsewhere in the south-eastern part of the Ruker Terrane (Mikhalsky et al., 2001, 2006a). The ca. 3180–3160 Ma event was determined by U–Pb zircon ages (upper intercept to concordant) for rocks from the southern Mawson Escarpment and Mt Bayliss. Gabbro emplacement dated at ca. 3150 Ma (this study) is very close to this interval. Mikhalsky et al. (2006b) reported a Sm–Nd whole-rock isochron age of 3230 ± 130 Ma (MSWD = 1.74) for 10 orthogneisses from the southern Mawson Escarpment. These data most likely reflect high-grade metamorphic reworking which may be better estimated by ca. 3100 Ma single zircon concordant analysis for an orthogneiss (Mikhalsky et al., 2006a). Pre-tectonic granite and gabbro were emplaced at this stage and manifested the Orogenic event 2. The latter event was accompanied by high-grade metamorphism (M_1, ca. 3145–3100 Ma). This metamorphism has been recorded in the Mawson Orthogneiss and the Menzies Series rocks (after Ravich et al., 1978), assigned to the basement of the Ruker Terrane.

So far there is no evidence for an extensional event (e.g., sedimentation or mafic dyke emplacement) separating the ca. 3400 Ma and 3100 Ma events. Thus, we tentatively suggest that all the tectonomagmatic events between ca. 3400 and 3100 Ma represent a single prolonged orogeny (which we propose to name the Palaeoarchaean ca. 3.1–3.4 Ga **Mawson Orogeny**), terminated by coarse-grained clastic sediment deposition of the Menzies Group of Phillips et al. (2006). Detrital zircons dated at 3260–3100 Ma were recovered from younger metasediments by Phillips et al. (2006).

Subsequent Mesoarchaean (ca. 3000–2750 Ma) tectonomagmatic episode (a newly proposed **Stinear Orogeny**) appears to include various geological events. Zircon U–Pb data yielded ages in the range of 2800–2750 Ma (Boger et al., 2006 and this study) interpreted either as emplacement or metamorphic ages. Nearly identical ca. 2800 Ma ages were obtained for granite gneisses (protolith emplacement) from Mts Stinear and Bayliss, and for an apparently undeformed (post-tectonic?) granitoid from Mt Rymill (this study). Biotite granite emplacement at Mt Ruker was dated at ca. 3000 Ma by conventional zircon studies (Mikhalsky et al., 2001). The Stinear Orogeny included pre-tectonic granitoid emplacement, high-grade metamorphism M_2, and pervasive ductile deformation. Metamorphism at ca. 2750 Ma was also established by dating zircon rims in granitic orthogneiss in Rimmington Bluff (Boger et al., 2006). Furthermore, dated (ca. 3150 Ma) metagabbro is of two-pyroxene–plagioclase composition and has a granoblastic–polygonal texture, suggestive of granulite-facies conditions. We tentatively ascribe an age of ca. 2750 Ma to this high-grade event as evidenced by mineral separate Sm–Nd data (this study).

Belyatsky et al. (2003) reported ca. 2800–2900 Ma whole rock and mineral separate Sm–Nd isochron ages for green schist mafic rocks from a volcanic pile of apparently bimodal composition (mafic–felsic with a minor ultramafic component) in Mt Ruker. However, those data revealed unusual low $\varepsilon_{Nd}(t)$ of about −8 to −10. This may either reflect derivation from an extremely enriched mantle source or may be due to the REE fractionation during the low-grade recrystallization (e.g., Ma et al., 2010). Thus the ages reported by Belyatsky et al. (2003) may have been deduced from mixing lines rather than meaningful isochrones and must be treated with caution.

The Mesoarchaean (ca. 3000–2750 Ma) tectonomagmatic episode apparently began with deposition of conglomerates in Mt Stinear, assigned to the Menzies Group by Phillips et al. (2006), which implies within-continent subsidence. The ca. 2800 Ma orthogneiss contains xenoliths composed of metapsammite (hornblende or biotite-bearing quartz–plagioclase schist and quartzite), which represent other pre-orogenic lithologies. Thus, the sedimentary record, albeit not yet well documented, provides little evidence for a marginal sedimentary platform or deep-water basin. Such environments would argue for a subduction-related tectonic regime capable of producing juvenile additions to the crust. Taking into consideration the Sm–Nd model ages of 2.7–3.0 Ga, it can reasonably be suggested that the ca. 3000–2750 Ma Stinear Orogeny included production of new continental crust. However, until the geochemical composition of ca. 2800 and younger felsic orthogneisses is better studied, it is difficult to distinguish lithologies suggestive of subduction-related settings. Nevertheless we favour for a considerable portion of the Ruker Terrane crust formed during this episode.

The time between ca. 2750 Ma and ca. 2200 Ma was characterized by undeformed muscovite pegmatite, syn-kinematic granitoid vein injection or locally orthogneiss protolith emplacement in a syn- or pre-tectonic setting (Rb–Sr muscovite and U–Pb zircon ages of 2645 Ma, 2580 Ma, 2540 Ma, 2500 Ma: Boger et al., 2006; Tingey, 1982a; Mikhalsky et al., 2007c, 2008, and this study), which reflects localised, rather than regionally pervasive, deformation. Phillips et al. (2006) suggested that the Stinear Group now metamorphosed sediments (predominantly quartzite and muscovite–kyanite metapelite) were deposited between 2780 and 2500 Ma ago, and the Ruker Group sediments (low-grade agglomerate, quartzite – the supposedly upper part of the Ruker Series of Mikhalsky et al., 2001) between 2500 and 2100 Ma. These authors also suggested that the two depositional episodes were separated by an orogenic event at ca. 2500–2400 Ma. Our new zircon U–Pb isotopic data confirm pre-tectonic granitoid emplacement at ca. 2500 Ma at Cumpston Massif, and new Rb–Sr and Sm–Nd data indicate an input of juvenile material of this age. High-strain shear zones in the southern Mawson Escarpment were probably formed in the latest Archaean time (>2540 Ma and <2645 Ma) indicating collisional tectonics and maybe suturing as these zones contain mafic and ultramafic mantle derivates. This event probably marked final amalgamation and general stabilisation of the crust in the sPCM.

Subsequent tectonomagmatic activity has been detected in Mt Newton and Cumpston Massif. In this area, Mikhalsky et al. (2008) recognised a new tectonothermal episode at ca. 2200–2100 Ma (the **Newton Orogeny**), on the basis of the U–Pb zircon data. This episode includes pre-tectonic felsic magmatism, possibly metamorphism (M_3), folding, and granite and pegmatite emplacement. A post-tectonic granite from Mt Newton was dated at 2117 ± 11 Ma (Mikhalsky and Roland, 2007). This episode is also reflected by detrital zircon ages of 2200–2000 Ma obtained from younger sediments (Phillips et al., 2006), as well as in a single U–Pb zircon lower intercept age for a granite gneiss in the southern Mawson Escarpment (Boger et al., 2006). Detrital zircon populations of ca. 1850 Ma suggest that the Palaeoproterozoic tectonothermal activity may have lasted until that time (Phillips et al., 2006).

The Newton Orogeny must to some extent have affected all the pre-2100 Ma lithotectonic units, i.e., the Mawson Orthogneiss, and the Menzies, Stinear, and Ruker Groups of Phillips et al. (2006). The late metamorphic event (M_3?) in the southern Mawson Escarpment, manifested by orthopyroxene decomposition and garnet growth (Roland and Mikhalsky, 2007) due to pressure increase and poorly dated at ca. 1900 Ma (the Sm–Nd whole-rock mineral separate data, Mikhalsky et al., 2006b), roughly correlates with this orogeny. The increase of pressure in the basement rocks presumably reflected considerable subsidence, which resulted in the accumulation of sediments and some magmatic activity. It is noteworthy that no mafic magmatism associated with the Newton episode has been recognised. Hence, the Newton Orogeny was apparently an intra-continental phenomenon and did not produce voluminous mantle-derived additions to the crust. Pegmatite vein emplacement in Keyser Ridge, close to Mt Newton, was dated by Rb–Sr study at ca. 1700 Ma and ca. 2000 Ma by Tingey (1982b), and probably occurred during the waning stage of the Newton Orogeny.

Phillips et al. (2006) reported detrital zircon ages in the ranges of ca. 2700–2600 Ma, 2160–2000 Ma, and 1860–1830 Ma from the medium- to high-grade metasediments from the southernmost part of the Ruker Terrane and distinguished these metasediments as the Lambert Group. There is only relatively slight isotopic evidence for the age of this metamorphism, which also overprinted the presumably Mesoproterozoic (ca. 1350–1300 Ma, Mikhalsky et al., 2007b) mafic dykes elsewhere in the Ruker Terrane. A number of poorly constrained U–Pb zircon lower or rarely upper intercept ages in the range of ca. 1400–900 Ma have been obtained (Boger et al., 2006; Mikhalsky et al., 2006a; Mikhalsky and Roland, 2007). Rb–Sr whole-rock isochrons of ca. 1400 and 1170 Ma from Mt Ruker and southern Mt Rymill, respectively, have been reported by Tingey (1982a) and interpreted as reset ages for very high Sr_i. These data indicate Pb loss and Rb–Sr resetting due to a thermal overprint. Nevertheless, Tingey (1991) and Mikhalsky et al. (2001) suggested that most of metamorphic recrystallization (M_2 of Tingey, 1991 or M_4 in this study) was confined to a ca. 1000 Ma event, but an Early Palaeozoic (ca. 530 Ma) age of metamorphism (M_5) may be reasonably suggested taking into consideration the data from the neighbouring Lambert Terrane.

7.2. The Lambert Terrane

The geological history of the Lambert Terrane, like that of the Ruker Terrane, goes back to the Eoarchaean, with the initial separation of continental crust from the mantle at ca. 3.8 Ga. Available Sm–Nd data indicate two episodes of continental crust generation/mobilisation in the Lambert Terrane (ca. 3.6–3.8 Ga and ca. 2.6–2.9 Ga) and also suggest the involvement of different mantle sources, basically similar to those distinguished in the Ruker Terrane (Fig. 19). Interestingly, the Neo- to Mesoarchaean (ca. 2.6–2.9 Ga) crustal material was recurrently sampled in the Lambert Terrane by various granites during at least four separate events (ca. 2400 Ma, 1740 Ma, 920 Ma, and 500 Ma). A few rocks showed the Sm–Nd T_{DM} model ages as low as 1.8 Ga, and most rocks have T_{DM} model ages in the range 2.6–2.9 Ga, basically similar to a group of ca. 2.7–3.0 Ga model ages in the Ruker Terrane. The Lambert Terrane apparently has an even more heterogeneous isotopic composition, than the Ruker Terrane, which is clearly reflected in the highly varying $\varepsilon_{Nd}(t)$ values obtained in this study and published elsewhere (Fig. 19). Most granitic rocks have coherent isotopic features ($\varepsilon_{Nd}(t = 2.4\,Ga) = -2$ to +4 and T_{DM} 2.6–2.9 Ga), but some have significantly lower (ca. 1.8 Ga, 2.3 Ga) or higher (ca. 3.2–3.8 Ga) T_{DM} model ages. The oldest model ages have been reported from the northernmost (Lines Ridge) and central (Harbour Bluff–Manning Glacier) areas of the Mawson Escarpment (Mikhalsky et al., 2006b), which thus may represent older crust domains. Some rocks have even higher T_{DM} ages up to 4.2 Ga. However, they have markedly higher *f*, which reflects rare-earth element fractionation, possibly at ca. 2.4 and/or 0.5 Ga, thus making these T_{DM} ages meaningless. Both mafic and felsic rocks in the Lambert Terrane have similar $\varepsilon_{Nd}(t = 2.4\,Ga)$ of −2 to +4, which indicates a roughly co-genetic origin of their protoliths from broadly similar mantle source(s). Variations in the isotopic composition (ε_{Nd}) may be explained by derivation from two end members: depleted and enriched mantle. The bulk of the Lambert Terrane crust originated at about 2.6–2.9 Ga, or possibly somewhat later (at ca. 2.4 Ga) if an enriched mantle reservoir contributed significantly to protolith compositions. Such an influence may be reflected by a few samples with low $\varepsilon_{Nd}(t = 2.0–2.4\,Ga)$ of −5 to −10.

The earliest tectonomagmatic episode in the Lambert Terrane was dated at ca. 3500 Ma in the Manning Glacier area (Boger et al., 2008) for a sodium-rich, TTG-like orthogneiss. These authors suggested that this rock represented either a sialic basement onto which the metasediments of the Lambert Terrane were deposited, or a tectonically intercalated sliver of old crust within younger material. At present there is no convincing evidence for any option. However, Corvino et al. (2008) showed that some orthogneisses in the northern portion of the Lambert Terrane may form an infrastructural domain (basement composed of early Archaean crust, ca. 3.6–3.8 Ga) tectonically overlain by the Palaeoproterozoic (<2400 Ma) metasediments and roughly co-eval felsic magmatic rocks, derived from ca. 2.6–2.9 Ga crust.

The early Palaeoproterozoic (ca. 2.4–2.5 Ga) tectonomagmatic episode has been constrained by a number of ages. A 2470 ± 10 Ma age was obtained for a felsic (supposedly volcanic) orthogneiss in the Lawrence Hills (Corvino and Henjes-Kunst, 2007), and pretectonic granitoid (now grey gneiss) emplacement was dated at 2423 ± 18 Ma in (Lines Ridge; Mikhalsky et al., 2006a) and 2445 ± 9 Ma (north of the Rofe Glacier; Corvino et al., 2008). Single concordant ages of 2446 ± 3 Ma and 2422 ± 13 Ma obtained for magmatic zircon cores in amphibolite (metagabbro) and augengneiss, respectively, provide further evidence for this episode (Corvino et al., 2008). The ages of ca. 2490–2420 Ma were obtained for grey gneissose two-feldspar–quartz rocks of granitic to granodioritic composition (Mikhalsky et al., 2006a; Corvino and Henjes-Kunst, 2007; Corvino et al., 2008). These authors showed that at least some of these rocks represent a calk-alkalic association of juvenile nature. A Rb–Sr whole-rock isochron of ca. 2700 Ma ($Sr_i = 0.721$) obtained for rocks from McIntyre Bluff was interpreted as a metamorphic age (M_1, Tingey, 1982a). Concordant U–Pb ages of ca. 2670–2450 Ma for detrital zircons from gneissose meta-psammite (Corvino and Henjes-Kunst, 2007) indicate that this tectonothermal episode could have started at ca. 2650 Ma.

The northernmost part of the Lambert Terrane (the Rofe Glacier to Lawrence Hills) contains mafic metamorphic piles at least some 100 m thick, composed of mafic granulite, hornblende schist, and metagabbro, spatially associated with paragneiss and marble, and locally containing slabs or tectonically dismembered blocks composed of ultramafic rocks (Mikhalsky et al., 2007a). High-grade grey plagiogneiss crops out along with the mafic rocks. The emplacement age of this ultramafic–mafic complex is unknown, but zircon ages between 2450 and 2000 Ma were obtained for an amphibolite (metagabbro, Corvino et al., 2008). These authors suggested an emplacement age of ca. 2450 Ma. Thus the early Palaeoproterozoic (ca. 2.4–2.5 Ga) episode contributed mantle-derived material to the crust.

U–Pb detrital zircon studies for paragneisses from the Lambert Terrane produced ages in the range of 2670–2450 Ma (Corvino and Henjes-Kunst, 2007; Phillips et al., 2006; Corvino et al., 2008). However, the source of these zircons (local or distal) is not known, and Corvino and Henjes-Kunst (2007) correlated these ages with ca. 2650 Ma detrital zircon ages obtained from clastic sedimentary protoliths (now quartzite) in the Ruker Terrane. An age of ca. 2450 Ma was accepted as the upper age limit for sedimentation in the Lambert Terrane. The lower limit was suggested to be a ca. 940 Ma age of metamorphic zircon (Corvino et al., 2008). It must be noted that these paragneisses lack ca. 2250–1950 Ma zircons, which should be anticipated from our study. Structural data (Corvino et al., 2008 and unpublished data of the authors) do not provide evidence for any tectonic discrepancy between the supracrustal rocks (mainly psammitic paragneiss and marble) and the basement grey gneisses, which experienced an overprint at ca. 2250 Ma. Thus, at least some of the supracrustal rocks could have been deposited during the early Palaeoproterozoic prior to ca. 2250–1950 Ma tectonism.

In mid-Palaeoproterozoic time (ca. 2250–1950 Ma) the Lambert Terrane experienced considerable thermal (M_2) and structural reworking, as evidenced from U–Pb zircon upper intercept ages. A few U–Pb zircon upper and lower intercept ages in the range 2200–2100 Ma were obtained for various rock types: presumed inherited 2217 ± 61 Ma zircons within a syn-tectonic felsic vein, inherited ca. 2250 Ma zircons in leucosome, ca. 2150–2130 Ma concordant ages for an amphibolite, 2155 ± 70 Ma upper intercept for an inter-boudin leucosome, 2152 ± 10 Ma concordant rim analyses for an augen gneiss, and 2104 ± 6 Ma for a folded pegmatitic granite (Corvino et al., 2008, and this study). The protoliths of some granitic orthogneisses may have been emplaced at this stage as suggested by Boger et al. (2008) and Corvino et al. (2008). High-grade metamorphism (M_2) has been dated at ca. 2065 Ma by Mikhalsky et al. (2006a), and Corvino et al. (2008) suggested metamorphism at ca. 1990–1960 Ma. The Sm–Nd data indicate remelting of the older crust in the area at that time.

A late Palaeoproterozoic event at ca. 1740 Ma is reflected by a swarm of slightly deformed late-tectonic leucocratic felsic veins (leucosome) within mafic granulite in the Rofe Glacier area (this study). These veins were roughly co-eval with a metamorphic and deformational episode in this locality and reflected high-grade (granulite-facies) metamorphism (M_3). However, this event is only hinted at in other analysed samples. A few very imprecise U–Pb zircon upper intercept and single concordant ages of ca. 1800–1600 Ma (Boger et al., 2008; Corvino et al., 2008) were obtained for zircon rims, providing some indirect evidence for their interpretation as a metamorphic event.

Late Mesoproterozoic to Early Neoproterozoic (1250–900 Ma) activities are manifested by a few lower intercepts at about ca. 1250–1000 Ma and by a 1081 ± 6 Ma zircon age obtained for a leucocratic gneiss in Lawrence Hills (Corvino and Henjes-Kunst, 2007). Corvino et al. (2008) reported a metamorphic age of 928 ± 29 Ma obtained for a high-grade paragneiss and an emplacement age of ca. 905 ± 10 Ma for a post-tectonic leucogranite dyke. These authors distinguished the waning stages of the Rayner Orogeny in the northern Mawson Escarpment and noted a transition from upper amphibolite to lower granulite facies metamorphism (M_4) and formation of nappe-like structures in deep levels of an E–W to NE–SW trending fold–thrust system. Our new data confirm the ca. 920 Ma age of syn-tectonic granite vein emplacement, consistent with partial melting, which was enhanced within sedimentary protoliths but was not developed within mafic granulites. Thus, the available data indicate that the early Neoproterozoic (ca. 1000–900 Ma) activity was apparently much stronger than the late Mesoproterozoic (ca. 1250–1000 Ma), being much better reflected by the U–Pb zircon data. A prominent feature of the Lambert Terrane is widespread, but apparently strongly localised, Early Palaeozoic (ca. 530 Ma) deformation and associated, but not commonly identified, metamorphism (M_5), in much details described in Boger and Wilson (2005), Corvino et al. (2008), and Phillips et al. (2009).

It must be noted that some mafic rocks within the Lambert Terrane have similar isotopic compositions to rocks in the Mesoproterozoic (ca. 1300–1100 Ma) Fisher Terrane (source 2 in Fig. 19), exposed to the north (Mikhalsky et al., 2006b). Similar amphibolites crop out at Lawrence Hills, Mt Cresswell, Mt Johns, and Shaw Massif (unpublished data of FHK). These rocks suggest possible mantle additions to the crust during the Mesoproterozoic, maybe co-eval with the prominent Mesoproterozoic crust-forming "Fisher Episode" (1300–1100 Ma, Mikhalsky et al., 1996, 2001).

8. The Ruker Province in a comparison with surrounding terranes and possible correlations with other Precambrian cratons

An important issue of the geology of the Prince Charles Mountains is nature and origin of the two tectonic provinces distinguished in the northern and southern segments of the mountain belt: the Rayner and the Ruker provinces, respectively (Fig. 1). Our new isotopic analyses, combined with data published elsewhere (Zhao et al., 1997; Mikhalsky et al., 1996, 1999, 2006b; Corvino and Henjes-Kunst, 2007; Boger et al., 2008), provide a substantial background for a comparison between them. A wide range of T_{DM} model ages is observed in the Ruker Province (predominantly 3.8–2.6 Ga), while a range of 2.4–1.4 Ga is typical for the Rayner Province (Mikhalsky et al., 2006b; Mikhalsky, 2008 and unpublished data of FHK). This fact defines a fundamental distinction between the two provinces in terms of crustal residence times, which is further enhanced by their contrasting geological histories (Fig. 21). It must be noted, that the Sm–Nd model ages show a heterogeneity of the Ruker Province: the Lambert Terrane rocks have basically younger T_{DM} model ages than those in the Ruker Terrane (albeit essentially overlapping in the range 2.7–2.9 Ga), but anyway they are much older than those calculated for the Rayner Province. The latter has been reported to comprise two terranes as well (the Fisher and the Beaver terranes, Fig. 1) differing in both lithology and geochronology (Mikhalsky et al., 2001 and references therein, Fig. 21), although some basic similarities between them may be discerned (overlapping T_{DM} model ages, ca. 1.1–1.0 Ga tonalitic intrusions and ca. 1.0–0.93 Ga major tectonothermal overprint: Carson et al., 2000; Boger et al., 2000; Mikhalsky et al., 2001; Maslov et al., 2007). Within the frame of the present study it should be also noted, that both the Fisher and the Beaver terranes contain detrital or inherited zircons of ca. 1.7–1.9 Ga, ca. 2.1–2.2 Ga or ca. 2.5–2.8 Ga (Kinny et al., 1997; Beliatsky et al., 1994; Kamenev et al., 2009), corresponding well with the U–Pb zircon ranges in the Lambert Terrane.

The Grove Mountains and the Prydz Bay Coast (inset in Fig. 1) reveal basically similar composition to the northern PCM, although in these areas the Early Palaeozoic (ca. 0.55–0.50 Ga) tectonism played a much stronger role and was responsible for the formation of pervasive structures and metamorphic assemblages (e.g., Harley, 2003; Liu et al., 2009a,b and references therein). These data provide evidence that ca. 2.1–2.5 Ga Lambert Terrane or similar Palaeoproterozoic crustal blocks partly served source areas for the Rayner Province. At the same time, the Rayner Province protoliths have a much shorter crustal history than, and cannot be correlated with or represent reworked or remelted derivates from, the "Lambert-age" (ca. 2.5–2.1 Ga) terranes.

Irrespectively of the exact mantle separation age (which strongly depends on the mantle composition in terms of Sm–Nd systematics), the Ruker Province represents one of only a few pre-3.4 Ga known crustal entities on Earth. Amongst others are the Kaapvaal Craton with maximum Sm–Nd T_{DM} ages in the range 3.4–3.7 Ga (Jahn and Condie, 1995; Cloutier et al., 2005 and references therein), the Zimbabwe Craton 3.2–3.7 Ga, the Pilbara Craton 3.4–3.6 Ga, the Yilgarn Craton 2.7–3.7 Ga (Champion and Sheraton, 1997 among many others), and the Napier Complex of Enderby Land 3.6–4.0 Ga (DePaolo et al., 1982).

A time-space diagram for the Precambrian terranes in the central section of the East Antarctic margin and some East Gondwana cratons is presented in Fig. 22. The Napier Complex of the Enderby Land (inset in Fig. 1) includes the oldest known crustal rocks of East Antarctica (ca. 3950 Ma, Black et al., 1992), but its tectonothermal evolution was most intense between ca. 2650 and 2480 Ma (Harley, 2003), when the Ruker Province was more-or-less stable. The Vestfold Block (inset in Fig. 1) had a peculiar geological evolu-

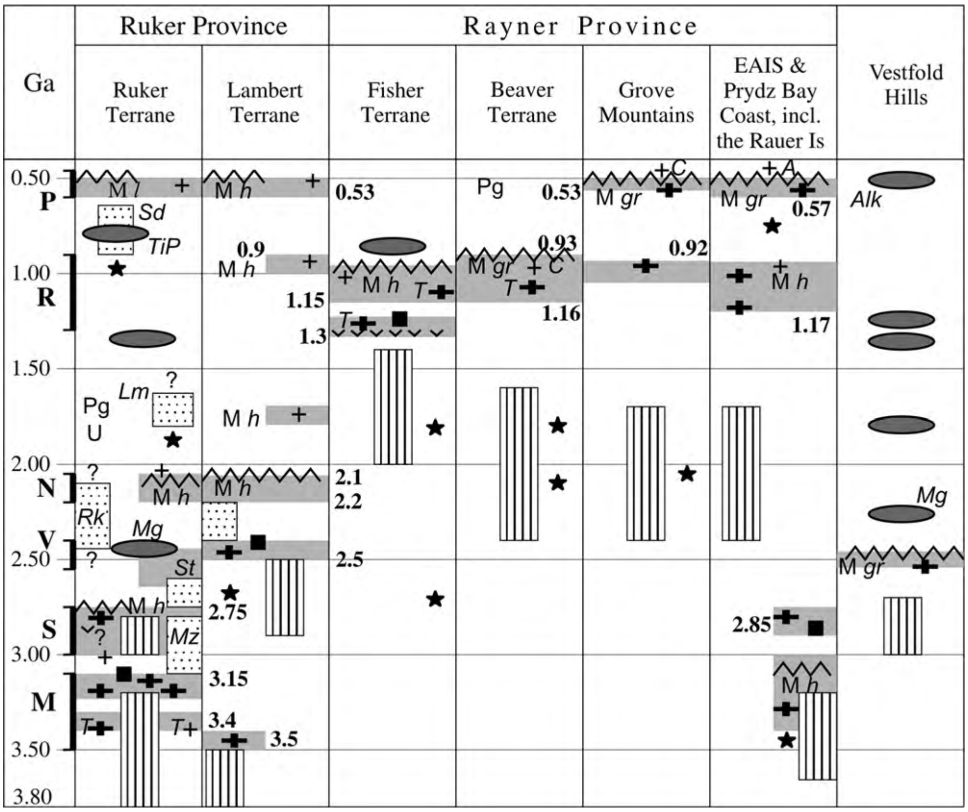

Fig. 21. Time–space diagram for the PCM and surrounding areas. Grey bar – zircon-producing epochs (from U–Pb data), vertical ruled rectangle – the Sm–Nd T_{DM} model age range, stippled rectangle – approximate sedimentation interval, stretched thick cross – orthogneiss protolith intrusion, cross – granite intrusion, black square – gabbro intrusion, grey lens – mafic dyke intrusion, "v"s – volcanic activity, wiggly line – deformation, star – detrital on inherited zircon. M – metamorphism (*h* – high-grade, *l* – low-grade, *gr* – granulite-facies). Pg – pegmatite intrusion. U – uplift. *A* – A-type granite. *T* – tonalite. C – charnockite. Mafic dyke composition: *TiP* – high-Ti, P, *Mg* – high-Mg, *Alk* – alkaline. In the Ruker Terrane: *Sd* – Sodruzhestva Group, *Lm* – Lambert Group, *Rk* – Ruker Group, *St* – Stinear Group, *Mz* – Menzies Group (Phillips et al., 2006). EAIS – east Amery Ice Shelf coast. Orogenic episodes outlined as black bars on the time axe: M – Mawson, S – Stinear, V – Vestfold, N – Newton, R – Rayner, P – Prydz.

tion with relatively short crustal residence time of ca. 3.0–2.7 Ga, only one prominent tectonomagmatic episode at ca. 2500–2475 Ma (inherited zircon of ca. 2800 Ma has also been reported) and a number of post-tectonic mafic dyke injection events at ca. 2240 Ma, 1750–1830 Ma, 1380 Ma, 1250 Ma, 500 Ma (Collerson et al., 1983; Lanyon et al., 1993; Zulbati and Harley, 2007 and references therein). The early Palaeoproterozoic (ca. 2.5 Ga) tectonomagmatic event distinguished in the Lambert Terrane and partly in the Ruker

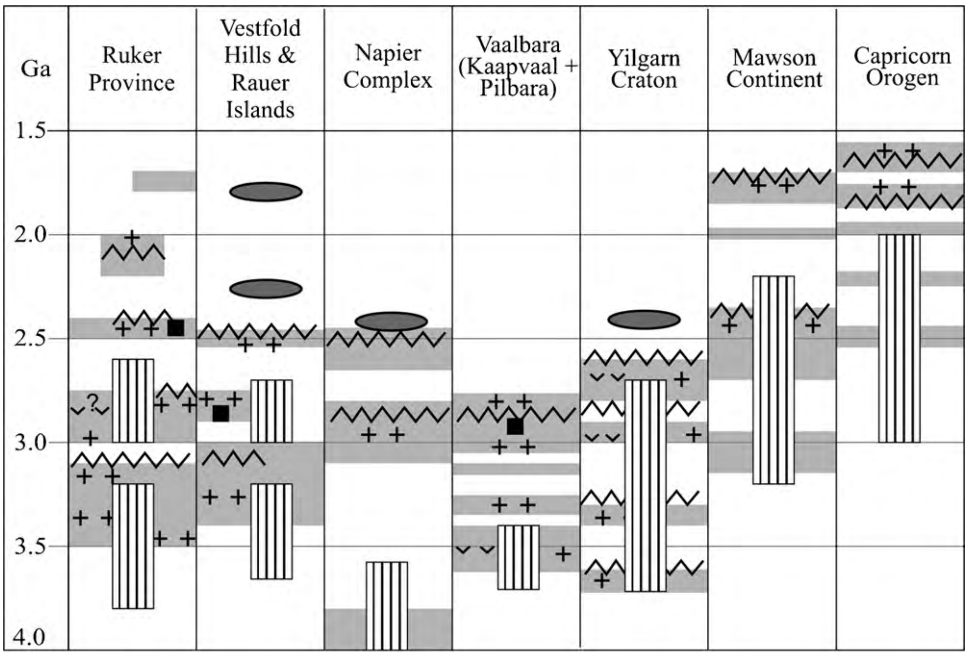

Fig. 22. Generalized time–space diagram (the Archaean–Palaeoproterozoic) for the Precambrian blocks in Antarctica and selected terranes of Gondwana. Cross stands for felsic magmatism, other symbols as in Fig. 21.

Terrane of the sPCM was roughly co-eval with high-grade metamorphism and pervasive deformation in the Vestfold Hills block (the **Vestfold Orogeny**, ca. 2500–2475 Ma). Nevertheless, the rocks in the Lambert Terrane are somewhat younger in terms of crustal residence time and, on the contrary to the Vestfold Hills injected by post-tectonic mafic dyke swarms, did not remain stable since the early Palaeoproterozoic (ca. 2400 Ma). Phillips et al. (2009) suggested that the Vestfold block was the source region for the Proterozoic (<2.5 Ga) sediments in the Ruker Province.

Another Archaean terrane crops out in the Rauer Islands adjacent to the Vestfold Hills. This block occurs strongly reworked within ca. 550–500 Ma Prydz Bay metamorphic complex (Harley, 2003 and references therein), but nevertheless preserves geological features resembling some of the Ruker Terrane (Fig. 21): orthogneiss protolith emplacement ages of >3.3 Ga and 2.85–2.8 Ga and similar Sm–Nd T_{DM} model ages. Thus the combined early geological history of the Vestfold Hills–Rauer Islands crustal segment (Fig. 22) reveals striking similarities with the Lambert–Ruker segment (i.e., the Ruker Province). This provisional observation, however, implies a conjugate evolution of the Vestfold Hills and the Rauer Islands, as well as the Lambert and the Ruker terranes since ca. 2.5 Ga, which contradicts the common assumption, based on prominent geological distinctions between these areas, of their separate evolution until the ca. 530 Ma continent collision (e.g., Boger et al., 2001; Zulbati and Harley, 2007 and discussions therein). However, this notion presupposes an accidental conjugation of relatively small the Archaean terranes as a result of ca. 530 Ma continent collision. Thus, the geological meaning of the abovementioned distinctions may need re-evaluation.

Among ancient Gondwanian blocks, the Kaapvaal and Pilbara cratons are believed to have once comprised the earliest supercontinent Vaalbara (e.g., Zegers et al., 1998). A worthwhile detailed comparison of the geological composition and tectonic history of the Ruker Terrane, which is hinted at by very old zircon ages, and the Vaalbara Supercontinent is beyond the scope of the present study, but some corresponding major tectonomagmatic episodes may be found. Thus, Vaalbara U–Pb ages in the ranges of 3600–3400 Ma, 3350–3250 Ma, 3120–3100 Ma, 3050–2900 Ma, and 2780–2700 Ma (Fig. 3 in Zegers et al., 1998) are not dissimilar to those found in the Ruker Terrane. However, the Vaalbara Supercontinent is thought to have amalgamated by 3.1 Ga and rifted between 2.7 and 2.0 Ga behaving as a relatively stable block between these events. The Ruker Terrane, in contrast, is apparently younger in terms of predominant T_{DM} ages and experienced a prominent tectonomagmatic episode at ca. 2800 Ma and became stable only after ca. 2500 Ma or even after 2100 Ma. Moreover, the Ruker Terrane apparently lacks ca. 3.5–3.6 Ga greenstones and ca. 2.9 Ga ultramafic layered magmatic complexes, and its basement experienced a complex history of high-grade metamorphic reworking, unlike the Pilbara and Kaapvaal cratons. Thus the Ruker Terrane apparently reveals a different geological record.

A better correlation can be found between the Ruker Terrane and the Yilgarn Craton, which was assembled between 2.8 and 2.6 Ga by the accretion of a multitude of older blocks or terranes of existing continental crust, most of which formed between 3.7 and 2.6 Ga (Myers, 1990, 1993). The Yilgarn Craton consists mainly of ca. 2.8 Ga granite–gneiss metamorphic terranes (the Southern Province and Western Gneiss Belt) and some granite–greenstone terranes as old as 3.0–2.75 Ga or 2.75–2.65 Ga. The Western Gneiss Terrane is a composite of polydeformed metagranite and amphibolite-facies metasedimentary gneisses and migmatites, dated at 3.3 and up to 3.7 Ga. The period between 2.78 Ga and 2.63 Ga is thought to have been one of intense tectonic, volcanic, plutonic, and metamorphic activity. This was interpreted as a major episode of plate tectonic activity which brought together and amalgamated a number of diverse crustal fragments (including volcanic arcs, etc.) to form the Yilgarn Craton (Myers, 1993). Taking into account a mantle input to the crust in the sPCM between ca. 3.0–2.7–2.5 Ga (this study), it can be concluded that the Ruker Terrane experienced similar processes. However, most of the area in the sPCM was eventually covered by Neoarchaean (<2780 Ma), Palaeoproterozoic (<2470 Ma), Mesoproterozoic (<1800–2100 Ma), and Neoproterozoic (<950 Ma, Phillips et al., 2006) supracrustal rocks obscuring much of the basement geology. Nevertheless, the Stinear and possibly lower Ruker groups of the Ruker Terrane can find correlations with the Neoarchaean metasedimentary sequences of the Yilgarn Craton, e.g., the Jumperding Gneiss Complex, composed of quartzite, high-Al schist, and banded iron formation, among other lithologies.

The Palaeoproterozoic (ca. 2.5–2.1 Ga) Lambert Terrane, forming the north-eastern part of the Ruker Province (modern coordinates), may also find analogous structures within ancient cratons. This should be a major target of future research, as Palaeoproterozoic tectonic activity is not well documented and not widely developed in Antarctica. An exception is the ca. 1.7 Ga Mawson Continent (Fanning et al., 1995), which is thought to comprise at least the Gawler Craton of South Australia and George V Land and Adélie Land in Antarctica. Other late Palaeoproterozoic (ca. 1700–1750 Ma) provinces in Antarctica are the Miller Range in the Transantarctic Mountains (Goodge et al., 2001) and the Shackleton Range (Zeh et al., 2004), although these areas experienced strong Cambrian (ca. 530–500 Ma) reworking. The combined geological history of the Mawson Continent (Fig. 22) included various events dated at ca. 3150–2950 Ma, 2700–2350 Ma, 2000 Ma, and 1850–1700 Ma (Fitzsimons, 2003 and references therein), and Sm–Nd T_{DM} model ages indicate separation from the mantle between 2.2 and 3.2 Ga (Turner et al., 1993; Peucat et al., 1999 among others). These ages roughly correspond to those obtained from the Lambert Terrane, suggesting a possible correlation. However, Fitzsimons (2003) concluded that one or more late Neoproterozoic–Early Cambrian (ca. 600–500 Ma) sutures may lie between the Mawson Continent and areas west of ∼100°E, thus separating Antarctica into at least two major lithospheric blocks. On the other hand, there is a large sub-glacial gap between the PCM and the Mawson Continent, so any correlation can only be speculative. Taking into account that the Ruker and Lambert terranes are bounded to the north by the Mesoproterozoic (ca. 1300–1100 Ma) Fisher Terrane, which may partly correlate with the Fraser Complex of the Albany–Fraser Orogen, their correlation with the Yilgarn Craton thus may be a better and reasonable suggestion.

The Lambert Terrane may be also compared with the Capricorn Orogen, which bounds the Yilgarn Craton to the north (modern coordinates). The Palaeoproterozoic Capricorn Orogen has yielded zircon ages of 2550–2450 Ma, 2200 Ma (Ophthalmian Orogeny), 2000–1960 Ma (Glenbourgh Orogeny), 1830–1780 Ma (Capricorn Orogeny), and 1670–1620 Ma (Cawood and Tyler, 2004; Occhipinti et al., 2004), generally similar to those from the Lambert Terrane. Thus, the isotopic data enables a tentative correlation of the Lambert Terrane with the Capricorn Orogen of Western Australia.

9. Summary and conclusions

The southern Prince Charles Mountains are underlain by a distinctive crustal block which experienced a prolonged geological evolution from the Palaeoarchaean (ca. 3500 Ma) to the Late Cambrian (ca. 500 Ma) and which can be distinguished as the Ruker Province as proposed by Phillips et al. (2006). It is made up of a high-grade metamorphic basement (upper amphibolite to granulite facies), which is structurally overlain by variously deformed and metamorphosed supracrustal associations of Palaeoproterozoic (<2470 Ma) to Neoproterozoic age (<950 Ma, Phillips et al., 2006). Most of the basement within the Ruker Province was formed during two major tectonomagmatic episodes at ca. 3500–3150 Ma (the Mawson Orogeny, comprising separate events at ca. 3500–3400 Ma and 3250–3150 Ma) and at ca. 3000–2750 Ma (the Stinear Orogeny confined to the Ruker Terrane). The first episode involved production of juvenile mafic to sodic felsic material derived from the mantle or lower crust. The second episode lacks direct indications of such processes, but they are implied by Sm–Nd T_{DM} model age data. The Stinear Orogeny produced a thick, now low-grade metamorphic, volcanic sequence. This sequence (the lower part of the Ruker Series of Mikhalsky et al., 2001) has been distinguished as a greenstone belt (Kamenev, 1993) and the published Sm–Nd data (Mikhalsky et al., 2006b) suggest it was late Mesoarchaean (ca. 2800–2900 Ma) in age. However, the upper part of the Ruker Series contains detrital zircons, which implies a Palaeoproterozoic age (<2470 Ma, Phillips et al., 2006). This discrepancy either may be due to the Sm–Nd fractionation during the low-grade metamorphic reworking or may reflect the occurrence of two separate supracrustal packages, and clearly needs further investigation.

The Palaeoproterozoic (ca. 2.5–2.1 Ga) tectonic evolution of the Ruker Province was largely confined to the Lambert Terrane (i.e., the north-eastern part of it) and to some areas within the Ruker Terrane (Cumpston Massif–Mt Newton, where low-Sr_i, high ε_{Nd} rocks occur). Our new zircon U–Pb, Lu–Hf and whole-rock Rb–Sr data indicate the presence of relatively young (ca. 2.9–2.5 Ga) crustal protoliths likely produced at this stage. The most significant additions to the crust occurred at ca. 2.4 Ga in the Lambert Terrane from a mixture of mantle sources involving depleted and enriched reservoirs. The Cumpston Massif–Mt Newton area experienced magmatism, metamorphism, and folding, followed by granite emplacement (ca. 2200–2100 Ma Newton Orogeny). These events probably reflect intraplate extension, subsidence, and basin inversion, and were probably related to co-eval orogenic events within the Lambert Terrane. The ca. 2100–2200 Ma ages from the Cumpston Massif–Mt Newton compare well with the U–Pb ages obtained from the Lambert Terrane. This might support a suggestion that the Cumpston Massif–Mt Newton block represents a tectonically displaced fragment of the Lambert Terrane. However, the magnetic anomaly field data (Damaske and McLean, 2005) do not confirm a separate crustal block in that area. Thus, it is likely that the tectonic structure of the southern Prince Charles Mountains is more complex than previously considered, and includes localised but significant mid-Palaeoproterozoic (ca. 2.1–2.2 Ga) intra-continent activity.

Many zircon growth events (ca. 2500–2400 Ma, 2250–1950 Ma, and 1800–1600 Ma) indicate a long and complex Palaeoproterozoic thermal history in the Lambert Terrane. Granite emplacement and high-grade metamorphism (ca. 1740 Ma leucosome) show that at least some of these events were of an orogenic nature. The calc-alkalic character of the Lambert Terrane orthogneisses indicates their derivation in convergent tectonic settings, so these rocks may represent an accretional complex onto the margin of the Ruker Terrane in the early Palaeoproterozoic (ca. 2450–2100 Ma).

The available geological and isotopic data support a suggestion that the tectonic evolution of the Lambert Terrane has many features in common with that of the Ruker Terrane (Fig. 20). These include: similar maximum crustal residence times indicated by the oldest Sm–Nd model T_{DM} ages; Palaeoarchaean U–Pb zircon ages of 3500–3380 Ma reflecting the earliest direct record of tectonomagmatic processes; comparable tectonothermal episodes at the Archaean–Proterozoic boundary (ca. 2500–2450 Ma) and in the Mid-Palaeoproterozoic at ca. 2200–2100 Ma; comparable overprinting episodes (although essentially distinct in terms of extent and intensity) in the late Meso- to early Neoproterozoic (ca. 1100–900 Ma) and in the Cambrian (ca. 530–500 Ma). Thus we believe that the Ruker and Lambert terranes experienced a common geological evolution since the Palaeoproterozoic (ca. 2450 Ma).

However, a direct correlation of the Lambert Terrane with the Ruker Terrane appears difficult. At the present stage of study the Lambert Terrane apparently includes a greater component of younger crustal protoliths (ca. 2.6–2.9 Ga) than the Ruker Terrane, and the Palaeoproterozoic (ca. 2.5–2.1 Ma) history of the former may include processes in convergent tectonic settings (similar ε_{Nd} values of felsic and mafic rocks, relative abundance of mafic and ultramafic rocks and calc-alkalic nature of felsic orthogneisses) which can be only subordinate and tentatively supposed in the latter. Thus the Lambert Terrane was apparently a Palaeoproterozoic (ca. 2.5–2.1 Ga) orogen, although much more work needs to be done to evaluate its origin and detailed geological history.

The nature of the apparent tectonic boundary between the Ruker and Lambert terranes (Gibbs Bluff in Mawson Escarpment) has been a subject of debate. Boger et al. (2001) first suggested a major continent–continent collision during the Early Palaeozoic (ca. 530 Ma). However, subsequent studies (Phillips et al., 2006, 2007, 2009; Mikhalsky et al., 2007b), along with the arguments presented above (such as the isotopic similarities between orthogneisses), allow an alternative suggestion that the Early Palaeozoic tectonothermal event was of intraplate rather than collisional nature.

The presented data support the distinction of two major tectonic provinces in the PCM: the Ruker Province in the southern PCM and the Rayner Province in the northern PCM (Tingey, 1991; Fitzsimons, 2000; Phillips et al., 2006), and argues against a three- or four-fold composition of the PCM (Kamenev et al., 1993; Mikhalsky et al., 2001). At the same time, it should be noted that each of the two provinces comprises separate terranes (or litho-tectonic zones) varying in lithology, metamorphic grade, and geological history.

The key geological features of the basement of the Ruker Province suggest a tentative correlation with (or at least resemblance to) the Yilgarn Craton–Capricorn Orogen of Western Australia, which would imply a considerable mineral resource potential of the sPCM. However, the available geological and isotopic data are insufficient for a more certain comparison and more work needed for proper understanding of the geological structure of the PCM.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.precamres.2010.07.004.

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