U-Pb zircon geochronology in the western part of the Rayner Complex, East Antarctica

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U-Pb zircon geochronology was applied to nine metasedimentary samples collected from Mt. Yuzhnaya, Condon Hills, and Mt. Lira in the inland region of the Rayner Complex of western Enderby Land, East Antarctica, in order to define the eastern limits of the western Rayner Complex that underwent the Pan–African metamorphism and to evaluate potential source areas of metasedimentary rocks. Condon Hills and Mt. Lira revealed metamorphic ages of ~ 894 and ~ 934 Ma, respectively, which are consistent with previously reported metamorphism in association with Rayner Structural Episode (RSE). Mt. Yuzhnaya samples affected by the RSE contain zircon grains rejuvenated during 590–570 Ma, which indicates that the Pan–African reworking can be extended up to Mt. Yuzhnaya. On the other hand, the Condon Hills samples include Archean detritus, and the age peaks from 3850 to 2491 Ma are the oldest components in the Rayner Complex of western Enderby Land. There is no evidence of reworked Napier Complex rocks in the studied Rayner samples.

Keywords: Rayner Complex, East Antarctica, SHRIMP U-Pb zircon dating, Metamorphism

INTRODUCTION

East Antarctica has been recognized as a critical location within Rodinia, the early Neoproterozoic supercontinent assumed to have assembled along late Mesoproterozoic to early Neoproterozoic mobile belts. The Rayner Complex, East Antarctica is considered to belong to the Circum–Antarctic Mobile Belt, which is one of the major pieces of evidence for the Rodinia reconstruction. The Rayner Complex includes coastal outcrops and minor inland nunataks in western Enderby Land and Kemp Land, adjacent to the Napier Complex and further east into MacRobertson Land (Fig. 1). The rocks were affected by amphibolite– to granulite–facies metamorphism during the early Neoproterozoic (e.g., Sheraton et al., 1987; Harley and Hensen, 1990; Harley et al., 1990; Shiraishi et al., 1997; Harley, 2003), in contrast to the Napier Complex, which is characterized by Neoarchean ultrahigh temperature (UHT) granulite–facies metamorphism (e.g., Harley and Motoyoshi, 2000, and references therein). The transition zone between the Rayner Complex and the Napier Complex is obscured in western Enderby Land, but the Rayner Complex in Kemp Land has been thought to represent reworked Napier Complex rocks (Ellis, 1983; Sheraton and Black, 1983). However, previously reported zircon inheritance and depleted mantle model ages ($T_{DM}$) of Sm–Nd system indicate a minor contribution of Archean crust to the Rayner Complex in western Enderby Land (Black et al., 1987; Shiraishi et al., 1997).

Recent geochronological works in the Rayner Complex using secondary ion mass spectrometry (SIMS) dating of zircon and electron microprobe (EMP) dating of monazite revealed that the western coastal region adjacent to the Lützow–Holm Complex also shows evidence for younger events (537–522 Ma zircon ages: Shiraishi et al., 1997; 533–517 Ma monazite ages: Asami et al., 2005; Motoyoshi et al., 2006) compared to the inland region (~1320–760 Ma: Shiraishi et al., 1997). These age distributions may suggest that the western coastal region (the western Rayner Complex) was overprinted by high-grade metamorphism during the Cambrian (Pan–African).
However, there is ambiguity of expanse of the Cambrian overprinting to the inland region of the Rayner Complex (Shiraishi et al., 2008).

In this study, U–Pb zircon geochronology was applied to samples from Mt. Yuzhnaya, Condon Hills, and Mt. Lira in the inland region of the Rayner Complex (Fig. 1), with the aim of better defining the eastern limits of the western Rayner Complex that underwent Cambrian (Pan–African) metamorphism. Also, through U–Pb analysis of detrital zircon cores, potential source areas of metasedimentary rocks in the Rayner Complex of western Enderby Land are evaluated.

REGIONAL GEOLOGY

The Rayner Complex consists of hornblende-bearing metamorphic rocks, and was initially defined and distinguished from the anhydrous granulite facies Napier Complex by Kamenev (1972) on the basis of metamorphic grade. Metamorphosed and deformed mafic dykes in the Rayner Complex were thought to be equivalents of undeformed ~ 1200 Ma dykes in the Napier Complex (e.g., Sheraton et al. 1980; Sheraton and Black, 1982; Clarke, 1988). The Napier Complex contains felsic igneous precursors to orthogneisses as old as ~ 3800 Ma, and most lithologies were formed or metamorphosed during the late Archean, but the timing of peak UHT metamorphism is controversial (Horie et al., 2012, and references therein). Some geochronological works suggested that the UHT metamorphism occurred no earlier than 2840 Ma, and possibly from 2590 to 2550 Ma (e.g., Harley et al., 2001; Crowe et al., 2002; Kelly and Harley, 2005), whereas other researchers interpret the younger ~ 2500–2450 Ma age to represent the UHT event (e.g., Grew, 1998; Carson et al., 2002; Hokada et al., 2003; Hokada and Harley, 2004). The Rayner Complex was affected by amphibolite- to granulite–facies metamorphism between ~ 990 and ~ 900 Ma (e.g., Sheraton et al., 1987; Harley and
The RSE has been relatively well interpreted to be composed predominantly of Archean Hensen, 1990; Harley et al., 1990; Shiraishi et al., 1997; Harley, 2003. The Rayner Complex in Kemp Land is interpreted to be composed predominantly of Archean Hensen, 1990; Harley et al., 1990; Shiraishi et al., 1997; Harley, 2003. The RSE has been relatively well defined on the Mawson Coast in MacRobertson Land and the northern Prince Charles Mountains. Kelly et al. (2002) suggested that the RSE could be divided into an east-directed sub-horizontal thrusting, and a regional scale south-dipping extensional shear zoning at the Øygarden Group, Kemp Land. The amphibolite– granulite-facies metamorphism was accompanied by the RSE. The geochronological data of the Rayner Complex in western Enderby Land, Kemp Land, the Mawson Coast, and the northern Prince Charles Mountains are well summarized in Halpin et al. (2005). There is little geochronological data for western Enderby Land. Black et al. (1987) reported U–Pb ages of 923 ± 7 Ma (zircon, granitic gneiss, Mt. Flett) and 892 ± 90 Ma from (monazite, paragneiss, Mt. Underwood). SHRIMP U–Pb zircon analysis of charnockitic gneiss in Sandercock Nunataks yielded 977 ± 11 Ma (Shiraishi et al., 1997). The western coastal region of the Rayner Complex adjacent to the Lützow–Holm Complex shows evidence for younger events. Shiraishi et al. (1997) reported younger SHRIMP U–Pb zircon ages of 522 ± 8 and 537 ± 8 Ma from pelitic gneiss and charnockitic gneiss in Mt. Vechernyaya. Pelitic gneiss at Forefinger Point also yielded younger SHRIMP U–Pb zircon ages of 530 ± 8 Ma. EMP monazite dating of Mt. Vechernyaya and Forefinger Point show the Pan–African ages of 523 ± 12 and 533 ± 9 Ma (Asami et al., 2005), and 517 ± 22 and 528 ± 14 Ma (Motoyoshi et al., 2006), respectively.

SAMPLES AND ANALYTICAL METHODS

Sample description

U–Pb isotopic analyses of zircon were performed for nine metasedimentary samples from Mt. Yuzhnaya, Condon Hills, and Mt. Lira (Fig. 1) which belongs to the inland region of the western Rayner Complex, collected during the 2004–2005 Japanese Antarctic Research Expedition.

Mt. Yuzhnaya samples. Metapelitic gneisses at Mt. Yuzhnaya are characterized by garnet-bearing mineral assemblages, with or without sillimanite. In addition, felsic to intermediate orthogneisses located in the sampling area contain orthopyroxene and hornblende. These assemblages are interpreted to suggest lower-granulite–facies metamorphism. No obvious reaction textures indicating post-peak decompression are observed.

Three metapelitic gneiss samples were collected. Sample MY05021501 is characterized by a mineral assemblage consisting of garnet, biotite, sillimanite, quartz, plagioclase, and K–feldspar, with accessory zircon, and monazite. Orthopyroxene occurs locally but is not in contact with sillimanite. Sample MY05021503 contains the mineral assemblage of garnet, biotite, quartz, plagioclase, and K–feldspar, with accessory zircon. The sampling site contains localized lenses of orthopyroxene–hornblende–bearing gneiss, which also contains biotite + plagioclase + quartz. Sample MY05021504 is composed of garnet, biotite, quartz, plagioclase, and K–feldspar, with accessory spinel, zircon, and monazite.

Condon Hills. Metapelitic gneisses at Condon Hills are characterized by garnet- and sillimanite–bearing mineral assemblages. In addition, quartzo–feldspathic gneisses located in the sampling area contain orthopyroxene and biotite. These assemblages are interpreted to suggest peak metamorphism at granulite–facies condition. Cordierite occurs rimming and embaying sillimanite, which is interpreted to suggest decompression following peak metamorphism, or potentially, a later, lower-pressure overprint.

Three metapelitic gneiss samples were collected. Sample CH05021503 is characterized by a mineral assemblage consisting of garnet, biotite, cordierite, and quartz. Sillimanite, K–feldspar, zircon, and monazite are accessories. Garnet and cordierite include fine needles of sillimanite (less than 100 µm in diameter) and quartz with minor biotite. Sample CH05021505 contains the mineral assemblage of garnet, biotite, cordierite, sillimanite, quartz, and plagioclase, with accessory K–feldspar, zircon, and monazite. Sillimanite occurs commonly as inclusions in garnet and cordierite, and also as prismatic grain (up to 200–300 µm) in matrix. Sample CH05021508 is composed of garnet, biotite, plagioclase, and quartz with minor amounts of K–feldspar, zircon, and monazite. Rounded and sometimes irregular–shaped porphyroblastic garnet grains, up to 2–3 mm in diameter, are contained. Plagioclase sometimes shows antiperthite texture.

Mt. Lira. Metapelitic gneisses at Mt. Lira are characterized by the presence of cordierite and/or cordierite + orthopyroxene corona developed around the garnet. Spinel (not directly in contact with quartz) is common in garnet–bearing gneisses. Felsic to intermediate rocks located in the sampling area include orthopyroxene-bearing (Opx + Cpx and/or Opx + Grt) mineral assemblages. These assemblages are interpreted to suggest peak metamorphism at upper-granulite–facies conditions followed by decompression to relatively lower-pressure conditions.

Three metapelitic gneiss samples were collected. Sample ML05021503 is characterized by a mineral as-
semble consisting of garnet, orthopyroxene, biotite, plagioclase, K-feldspar, and quartz with minor amounts of sillimanite, spinel, and zircon. Sillimanite and spinel are commonly included in garnet porphyroblast, whereas cordierite occurs around garnet. Sample ML05021508 contains the mineral assemblage of garnet, biotite, plagioclase, K-feldspar, and quartz, with accessory orthopyroxene, cordierite, sillimanite, spinel, and zircon. Sillimanite and spinel occur commonly as inclusions in garnet porphyroblast. Orthopyroxene + cordierite corona is developed around garnet. Sample ML05021509 is composed of garnet, biotite, and quartz with minor amounts of orthopyroxene, cordierite, spinel, and zircon. Orthopyroxene and cordierite form corona around garnet porphyroblast. Fine needles of rutile are included in garnet and quartz.

**Analytical methods**

Zircon grains in the samples were concentrated using conventional mineral-separation techniques, including crushing and pulverizing, followed by heavy liquid separation with methylene iodide, and magnetic separation. The procedures were designed to prevent inter-sample cross contamination. Final purification was done by hand picking, taking care to ensure that the grains selected for analysis represent the zircon population as a whole. Approximately 100 grains of each sample were selected and mounted in an epoxy resin disc, with each mount containing only those samples from a single region, together with reference materials. After curing, these discs were polished to reveal cross sections through the grain centers. In order to investigate internal zoning patterns within individual zircon grains, backscattered electron (BSE) and cathodoluminescence (CL) images were obtained using a scanning electron microscope (SEM; JEOL JSM-S5900LV) equipped with a Gatan mini CL detector at the National Institute of Polar Research (NIPR), Japan. Fine needles of rutile are included in garnet and quartz. They may contain mineral inclusions such as feldspar, quartz, and sillimanite. In CL images, zircon grains show weak to moderate concentric zoning and faint sector zoning. They contain a mix of concordant to discordant data. Only concordant data, defined as less than 10% discordance (discordance = [1−(206Pb/238U age)/(207Pb/206Pb age)] × 100; e.g., Song et al., 1996), were considered in age evaluation and calculation of pooled ages. When reporting ages, for those more than 1300 Ma, 207Pb/206Pb ages are used, whereas for those less than 1300 Ma, 206Pb/238U ages are used. This cut-off was used due to low count-rates on the 207Pb peak in young zircons, thus increasing uncertainties (Black et al., 2004).

**RESULTS**

U-Pb zircon analyses of the Rayner Complex samples contain a mix of concordant to discordant data. Only concordant data, defined as less than 10% discordance (discordance = [1−(206Pb/238U age)/(207Pb/206Pb age)] × 100; e.g., Song et al., 1996), were considered in age evaluation and calculation of pooled ages. When reporting ages, for those more than 1300 Ma, 207Pb/206Pb ages are used, whereas for those less than 1300 Ma, 206Pb/238U ages are used. This cut-off was used due to low count-rates on the 207Pb peak in young zircons, thus increasing uncertainties (Black et al., 2004).

**Mt. Yuzhnaya**

**Sample MY05021501.** Zircon grains from this sample have rounded habits and are typically <150 µm in size. They may contain mineral inclusions such as feldspar, quartz, and sillimanite. In CL images, zircon grains show weak to moderate concentric zoning and faint sector zoning (Figs. 2a and 2b). Some grains have inherited cores (Fig. 2a). Seventy-one U-Pb zircon analyses of sample MY05021501 were performed on 63 grains. All analyses are characterized by low Th/U ratios (0.003–0.089), excluding analysis MY501–20.1 (0.13; 858 ± 3 Ma) (Sup-
Figure 2. Cathodoluminescence (CL) images of zircon in Mt. Yuzhnaya (a)-(f), Condon Hills (g)-(i), and Mt. Lira (j)-(l). Ages of more than 1300 Ma are calculated from $^{207}\text{Pb}/^{206}\text{Pb}$, whereas those less than 1300 Ma are calculated from $^{206}\text{Pb}/^{238}\text{U}$. 

Age data fall into 4 age clusters (Figs. 3a and 3b). The first group is composed of Paleoproterozoic components (2245–1944 Ma) obtained from moderately zoned and faintly sector zoned grains. Five age peaks are centered at ~2247, 2181, 2129, 2069, and 1943 Ma. The second group has continuous age distribution from late Mesoproterozoic to early Neoproterozoic (1049–854 Ma). This group is characterized by weakly to moderately zoned grains and consists of around 8 age peaks. Half of the data (38 spots) belongs to this group. The third and fourth groups show narrow age distribution, with middle (784–755 Ma) and late Neoproterozoic (589–570 Ma) ages, respectively. These
Figure 3. Concordia diagrams (a), (c), and (e) and probability density diagrams (b), (d), and (f) of Mt. Yuzhnaya. (a) and (b) MY05021501, (c) and (d) MY05021503, (e) and (f) MY05021504. Only concordant data, defined as being less than 10% discordant, were considered in age evaluation and calculation of pooled ages.
groups were obtained from weakly zoned rim (Figs. 2a and 2b).

Sample MY05021503. Zircon grains from this sample have round habits and are typically <150 µm in size. They may contain mineral inclusions such as feldspar and quartz. In CL images, most zircon grains are characterized by sector- and oscillatory-zoned core and broad-zoned rim (Figs. 2c and 2d). Some grains show weak to moderate zoning. The thin, medium–gray CL rim has a thickness of less than 5 µm, which is smaller than the spatial resolution of SHRIMP-II. Eighty-seven U–Pb zircon analyses of sample MY05021503 were performed on 73 grains. The Th/U ratios of MY05021503 zircons vary (0.049–0.34) and those of most zircons are >0.1 (Supplementary Table S1). Age data fall into 4 age clusters (Figs. 3a and 3b). The first group is composed of Paleoproterozoic components (2368–1916 Ma) obtained from sector- and oscillatory-zoned cores and 6 age peaks centered at ~2356, 2212, 2182, 2128, 2088, and 1939 Ma. About 78% of the grains (68 spots on 57 grains) belong to this group. The second group obtained from dark CL grains is composed of two components, of 1838 and 1764 Ma. The third group has continuous age distribution from late Mesoproterozoic to early Neoproterozoic (1035–888 Ma) and is obtained from weakly to moderately zoned grains and broad–zoned rim.

Sample MY05021504. Zircon grains from this sample have rounded habits and are typically <150 µm in size. They may contain mineral inclusions such as feldspar, quartz, and sillimanite. In CL images, zircon grains are weakly to moderately zoned and some grains show faint sector zoning with fir-tree structures (Figs. 2e and 2f). Some zircon grains have sector- and oscillatory-zoned core and broad-zoned rim. Seventy-eight U–Pb zircon analyses of sample MY05021504 were performed on 67 grains. All analyses are characterized by low Th/U ratios (0.003–0.064), excluding analysis MY504–35.1 (0.25; 2185 ± 5 Ma) and MY504–46.2 (0.15; 1940 ± 5 Ma) (Supplementary Table S1). Age data fall into 4 age clusters (Figs. 3e and 3f). The first group is composed of Paleoproterozoic components (2464–1928 Ma) obtained from sector and oscillatory zoned cores, and 6 age peaks centered at ~2464, 2203, 2182, 2157, 2054, and 1940 Ma. The second group was obtained from weakly to moderately zoned grains, and the broad-zoned rim and has continuous age distribution from late Mesoproterozoic to early Neoproterozoic (1072–857 Ma). This group consists of around 8 age peaks and contains about 67% of the data (52 spots). The third and fourth groups show narrow age distribution of middle (653–650 Ma) and late Neoproterozoic (590–577 Ma) ages, respectively. The third group is found in the broad–zoned rim (MY504–55.2) and in the weakly zoned grains. The fourth group is obtained from the weakly zoned grains.

Condon Hills

Sample CH05021503. Zircon grains from this sample have round habits and are typically <250 µm in size. They contain mineral inclusions such as feldspar and quartz, with minor apatite, sillimanite, and monazite. Oscillatory-zoned cores are truncated by mantles and rims (Fig. 2g), which is interpreted as indicating that protolith of sample CH05021503 contained magmatic detritus. Most of the grains show medium–gray rims of variable widths (10–50 µm). The overgrowth rims define irregular boundaries with the oscillatory-zoned cores. Eighty-seven U–Pb zircon analyses of sample CH05021503 were performed on 77 grains (Supplementary Table S2 is available online from http://doi.org/10.2465/jmps.150811). The inherited cores with the magmatic oscillatory zoning show wide range age distribution from Neoarchean to Paleoproterozoic (3645–1863 Ma), and 8 age peaks centered at ~3645, 2783, 2582, 2490, 2142, 2068, 1942, and 1881 Ma (Figs. 4a and 4b). Th/U ratios of the inherited cores are relatively high (0.097–1.28). The overgrowing medium–gray rims are characterized by lower Th contents (3–33 ppm) and lower Th/U ratios (0.009–0.062). All 17 analytical spots yielded a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 893 ± 6 Ma (95% confidence level, mean square weighted deviation (MSWD) = 0.36) (Fig. 4b).

Sample CH05021505. Zircon grains from this sample have rounded habits and are typically <250 µm in size. They contain mineral inclusions such as feldspar and quartz, with minor apatite, sillimanite, and monazite. Broad-zoned and oscillatory-zoned cores are truncated by mantles and rims (Fig. 2h), which is taken to indicate that protolith of sample CH05021505 contained magmatic detritus. Most of the grains show dark CL rims of variable widths (20–50 µm). The overgrowth rims define irregular boundaries between the cores. Sixty-six U–Pb zircon analyses of sample CH05021505 were performed on 62 grains (Supplementary Table S2). The inherited cores with the broad zoning and oscillatory zoning show wide range of age distribution, from Neoarchean to Paleoproterozoic (3070–1864 Ma). Eight age peaks are centered at ca. 3070, 3018, 2704, 2580, 2492, 2077, 1937, and 1878 Ma (Figs. 4c and 4d). The Th/U ratios of the inherited cores are relatively high (0.13–1.44). The overgrowth rims are characterized by lower Th contents (7–35 ppm) and lower Th/U ratios (0.011–0.063). All 11 analytical spots yielded a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 894 ± 6 Ma (95% confidence level, MSWD = 0.93) (Fig. 4d).
Figure 4. Concordia diagrams (a), (c), and (e), weighted mean diagrams, and probability density diagrams (b), (d), and (f) of Condon Hills. (a) and (b) CH05021503, (c) and (d) CH05021505, (e) and (f) CH05021508. Only concordant data, defined as being less than 10% discordant, were considered in age evaluation and calculation of pooled ages.
Sample CH05021508. Zircon grains from this sample have round habits and are typically <250 µm in size. They contain mineral inclusions such as feldspar and quartz, with minor apatite, sillimanite, and monazite. Weakly zoned and oscillatory-zoned cores are truncated by mantles and rims (Fig. 2i), which is taken to indicate that protolith of sample CH05021508 contained magmatic detritus. Most of the grains show dark CL rims of variable widths (20-50 µm). The overgrowth rims define irregular boundaries with the cores. One-hundred-five U-Pb zircon analyses of sample CH05021508 were performed on 91 grains (Supplementary Table S2). The inherited cores with the broad zoning and oscillatory zoning show wide range of age distribution, from Neoarchean to Paleoproterozoic (3850-1766 Ma). Fifteen age peaks are centered at ~ 3850, 3650, 3524, 3129, 2873, 2782, 2684, 2581, 2490, 2142, 2070, 1988, 1939, 1880, and 1767 Ma (Figs. 4e and 4f). Th/U ratios of the inherited cores are relatively high (0.13-1.55) except for CH508-77.1 (4.88; 2136 ± 13 Ma), CH508-43.2 (2.81; 3850 ± 6 Ma), and CH508-13.1 (2.00; 1766 ± 6 Ma). The overgrowth rims are characterized by lower Th contents (2-71 ppm) and lower Th/U ratios (0.005-0.056). All 10 analytical spots yielded a weighted mean 206Pb*/238U age of 893 ± 6 Ma (95% confidence level, MSWD = 0.35) (Fig. 4f).

Mt. Lira

Zircon grains from the Mt. Lira show similar features among three samples: they have round habits and are typically <200 µm in size; and contain mineral inclusions such as feldspar and quartz. In CL images, zircon grains are irregularly broad-zoned (Fig. 2j), weakly concentric-zoned (Fig. 2k), and sector-zoned with fir-tree structures (Fig. 2l), and core-rim structure is not obvious. The zoning textures are common features of zircon in granulite facies rocks (Corfu et al., 2003), which suggests that all zircon crystallized under granulite-facies peak metamorphic conditions.

Sample ML05021503. U-Pb zircon analyses of this sample were performed on 46 grains (Supplementary Table S3) is available online from http://doi.org/10.2465/jmps.150811). The U-Pb data show a weighted mean 206Pb*/238U age of 937 ± 6 Ma (95% confidence level, MSWD = 0.95) (Figs. 5a and 5b). The Th/U ratios of the zircon grains are scattered widely (0.043-5.23) regardless of the internal texture.

Sample ML05021508. The U-Pb zircon analyses of this sample were performed on 41 grains (Supplementary Table S3). The U-Pb data show a weighted mean 206Pb*/238U age of 932 ± 6 Ma (95% confidence level, MSWD = 1.19) (Figs. 5c and 5d). The Th/U ratios of the zircon grains are scattered widely (0.026-4.33) regardless of the internal texture.

Sample ML05021509. The U-Pb zircon analyses of this sample were performed on 41 grains (Supplementary Table S3). The U-Pb data show a weighted mean 206Pb*/238U age of 931 ± 6 Ma (95% confidence level, MSWD = 1.3) (Figs. 5e and 5f). The Th/U ratios of the zircon grains are scattered widely (0.043-5.23) regardless of the internal texture.

DISCUSSION

Timing of metamorphism in association with the RSE

The results of U-Pb zircon dating of Mt. Yuzhnaya, Condon Hills, and Mt. Lira in this study are summarized in Figure 6. Zircon grains in the Mt. Lira samples show rounded external morphology and internal morphological features of irregular, broad zoning (Fig. 2j), weak concentric zoning (Fig. 2k), and sector zoning with fir-tree structures (Fig. 2l), suggesting that the zircons crystallized during high-grade metamorphism, probably in the presence of anatectic melt (Corfu et al., 2003). Therefore, the weighted mean 206Pb*/238U age of ~ 934 Ma in 3 samples (Fig. 5) indicates the timing of the metamorphism. Zircon grains from the Condon Hills samples have overgrowths that show low Th/U ratios (<0.011; Supplementary Table S2), which suggests formation during high-grade metamorphism (Williams and Claesson, 1987; Schiette et al., 1989; Kinny et al., 1990; Maas et al., 1992). These metamorphic overgrowths also have near equivalent ages, at ~ 894 Ma (Fig. 4).

The metamorphic age of the Mt. Lira samples is consistent with those at Mt. Underwood (980-920 Ma: Black et al., 1987) and the Øygarden Group in Kemp Land (930-900 Ma: Kelly et al., 2002), which indicates that the metamorphism occurred in association with deformation events of the RSE (Kelly et al., 2002, and references therein). The wide range of Th/U ratios in the Mt. Lira zircons suggests that coexisting accessory minerals such as apatite and monazite had consumed and concentrated amounts of Th during the zircon crystallization (Vavra et al., 1999). On the other hand, the metamorphic age of the Condon Hills samples is obviously younger than that of Mt. Lira (~ 934 Ma), which is common in other parts of the Rayner Complex (≥900 Ma: e.g., Sheraton et al., 1987; Black et al., 1987; Harley and Hensen, 1990; Harley et al., 1990; Shiraishi et al., 1997; Kelly et al., 2002; Harley, 2003; Halpin et al., 2005). However, some previous studies have reported ages younger than ~ 900 Ma. For example, Black et al. (1987) reported an upper intercept age of 892 ± 90 Ma from U-Pb monazite
Figure 5. Concordia diagrams (a), (c), and (e) and weighted mean diagrams (b), (d), and (f) of Mt. Lira. (a) and (b) ML05021503, (c) and (d) ML05021508, (e) and (f) ML05021509. Only concordant data, defined as being less than 10% discordant, were considered in age evaluation and calculation of pooled ages.
Kelly et al. (2002) reported the U–Pb zircon ages from metamorphic rims in samples of migmatite and pegmatite in the Øygarden Group of Kemp Land are 884 ± 24 and 844 ± 24 Ma, respectively. In addition, Kelly et al. (2012) reported electron microprobe ages of ≥880 Ma from monazite, interpreted to have formed through growth and/or recrystallization during post–peak garnet breakdown under high-temperature conditions.

Post-Rayner Structural Episode overprints

The garnet–biotite gneisses of Mt. Yuzhnaya contain early Neoproterozoic zircon grains and overgrowths (~1000-850 Ma, Figs. 3 and 6), which indicates that the Mt. Yuzhnaya samples were affected by the metamorphism in association with the RSE. On the other hand, two garnet–biotite–sillimanite gneisses, MY05021501 and MY05021504, contain zircon grains and overgrowths younger than the RSE (Fig. 3: 784–755, ~650, and 590–570 Ma). Some previous studies have reported middle Neoproterozoic ages in the Rayner Complex of western Enderby Land. Black et al. (1987) reported an upper intercept ages of 761 ± 8 and 766 ± 15 Ma from U–Pb zircon dating of a pegmatite from Mt. Underwood and a granite from Condon Hills (ID–TIMS), respectively. Asami et al. (2005) also reported zircon core ages of 800–700 Ma from EMP dating of an orthopyroxene–biotite gneiss from Mt. Vechernyaya. The middle Neoproterozoic ages are found in the broad–zoned rim and the weakly zoned grains with low Th/U ratios. Therefore, the Mt. Yuzhnaya samples were affected by post-tectonic igneous events in the Rayner Complex of western Enderby Land.

The youngest zircon ages of 590–570 Ma are similar to previously reported ages at Vechernyaya and Forefinger Point in the western coastal region of the Rayner Complex (SHRIMP U–Pb zircon 537–522 Ma: Shiraishi et al., 1997; EMP monazite 528–517 Ma: Motoyoshi et al., 2006; EMP monazite 533–523 Ma: Asami et al., 2005). Shiraishi et al. (1997) suggest that the high–grade metamorphism in the western coastal region occurred at ~520 Ma. The youngest zircon ages of the Mt. Yuzhnaya samples are ~50 Ma older than the previous data. Dunkley et al. (2014) reported metamorphic ages of >600–570 Ma, which are similar to the youngest zircon ages of the Mt. Yuzhnaya samples from the neighboring Lützow–Holm Complex. Black et al. (1987) reported that granite in Condon Hills was overprinted by ~540 Ma green-schist–facies metamorphism through comparison between Rb–Sr whole rock isochron (574 ± 32 Ma) and lower intercept age of ID–TIMS U–Pb zircon dating (766 ± 15 Ma). As shown in Figures 2a and 2c, the youngest zircon ages were obtained from weakly zoned overgrowths and weakly zoned grains, which suggest that some zircon grains in the Mt. Yuzhnaya samples were affected by Pan–African overprint.

Although Black et al. (1987) reported 574 Ma metamorphism from granite in Condon Hills by Rb–Sr whole rock isochron, the U–Pb zircon dating of the Condon Hills samples used in this study never show ages younger than the metamorphic age of ~894 Ma. Black et al. (1987) also reported U–Pb zircon age of 766 ± 15 Ma from the same sample. The younger Rb-Sr whole rock isochron age indicates either relative loss of radiogenic Sr or, more probably, gain of Rb over sampling distance during the low-grade metamorphism. The zircon grains in Condon Hills had sustained U–Pb system and had not been overgrown and recrystallized during the low–grade metamorphism, because the closure temperature of zircon is >900 °C (Cherniak, 2010) and zirconium is commonly immobile under lower–temperature conditions (Rasmussen, 2005, and references therein).

Implication of detrital zircons

Most of the Rayner Complex has been thought to repre-
sent reworked Napier Complex rocks (Ellis, 1983; Sheraton and Black, 1983). However, previously reported zircon inheritance and \( T_{DM} \) of Sm-Nd system indicate a minor contribution of Archean crust to the Rayner Complex (Black et al., 1987; Shiraishi et al., 1997). Kelly (2001) presented Eoarchean zircon inheritance from the Øygarden Group in Kemp Land. Other Archean components were reported from Edward VIII Gulf (Rb–Sr whole rock isochron, Sheraton and Black, 1983), Fold Island (U–Pb zircon, Clarke, 1987), and Stillwell Hills (Rb–Sr whole rock isochron, Clarke, 1987) in Kemp Land, and from Mt. Meredith (U–Pb zircon, Kinny et al., 1997) in northern Prince Charles Mountains. On the other hand, there has been no report on the signature of the Archean crusts in the Rayner Complex of western Enderby Land.

As shown in Figure 5, protolith information of the Mt. Lira samples could not be obtained by U–Pb zircon dating. The garnet-biotite gneisses from Mt. Yuzhnaya contain the Paleoproterozoic components, but do not include the signature of the Archean crusts (Fig. 6). The Paleoproterozoic ages younger than 2180 Ma in the Rayner Complex of western Enderby Land were obtained by \( T_{DM} \) of Sm-Nd system at Mt. Flett (2180 Ma), Thala Hills (2170 Ma), Codon Hills (2020 Ma), and Underwood (1920–1650 Ma) (Black et al., 1987) and are consistent with those of the inherited zircon core ages of the Mt. Yuzhnaya samples. The ages older than 2180 Ma (such as 2464, 2356, and 2209 Ma) obtained in this study (Fig. 6) have not been reported previously, and represent newly identified Paleoproterozoic components in the Rayner Complex of western Enderby Land. The garnet-(cordierite)-biotite gneisses from Condon Hills contain the Eoarchean–Paleoproterozoic components of magmatic origin (Fig. 6). The Eoarchean signatures are only reported from Øygarden Group in Kemp Land (~3650 Ma, U–Pb zircon: Kelly, 2001; Kelly et al., 2004; Halpin et al., 2005), and the zircon inheritance of 3850 Ma is the first report of middle Eoarchean signature in the Rayner Complex. In addition, the age peaks at 3654, 3524, 3129, 3070, 3018, 2873, 2782, 2684, 2581, and 2491 Ma have not previously been reported in the Rayner Complex of western Enderby Land. In the Rayner Complex, similar ages can be found in limited locations such as the Øygarden Group (~3650 and ~2750 Ma, U–Pb zircon: Kelly, 2001; Kelly et al., 2004), Edward VIII Gulf (~3100 and ~2500 Ma, Rb–Sr whole rock isochron: Sheraton and Black, 1983), Fold Island (3080 ± 170 Ma, U–Pb zircon: Clarke, 1987), and Stillwell Hills (2692 ± 48 Ma, Rb–Sr whole rock isochron: Clarke, 1987) in Kemp Land. The Condon Hills area is therefore unusual in that Archean detritus remains.

On the other hand, the Archean age peaks of the Condon Hills samples are similar to those of Napier Complex. The age peaks mentioned above can be found in gneisses and quartzites of Fyfe Hills and Mt. Cronus as zircon inheritance (Horie et al., 2012). However, zircon grains that experienced the UHT metamorphism from late Neoarchean to early Paleoproterozoic (Horie et al., 2012, and references therein) are lacking in the Condon Hills samples. The age peaks of 2581 and 2491 Ma are identical to the timing of the UHT metamorphism in the Napier Complex (Horie et al., 2012, and references therein), but zircon that yielded these age peaks show magmatic oscillatory zoning with Th/U ratios of 0.15–1.3 (Fig. 2d), which indicates that the Condon Hills samples lack any signatures of the Napier Complex.

**CONCLUSIONS**

U–Pb zircon geochronology was applied to samples collected from Mt. Yuzhnaya, Condon Hills, and Mt. Lira in the inland region of the Rayner Complex of western Enderby Land. The Condon Hills samples and the Mt. Lira samples revealed that metamorphism occurred at ~894 and ~934 Ma, respectively. These metamorphic ages are consistent with previously reported timing of the metamorphism in association with the RSE. The Mt. Yuzhnaya samples contain early Neoproterozoic zircon grains and overgrowths (~1000–850 Ma), which indicates that these samples were affected by the RSE. On the other hand, the Mt. Yuzhnaya samples also contain zircon grains younger than the RSE (784–570 Ma). The middle and late Neoproterozoic zircon grains indicate that these samples were affected by post-tectonic igneous events and Pan-African reworking, respectively. Therefore, the western Rayner Complex that underwent the Cambrian metamorphism can be extended up to Mt. Yuzhnaya. The Condon Hills samples alone contain Archean detritus, and the age peaks from 3850 to 2491 Ma are the oldest components ever reported in the Rayner Complex of western Enderby Land. The ages of the Mt. Yuzhnaya samples older than 2180 such as 2464, 2356, and 2209 Ma have not been previously reported, and therefore represent newly identified Paleoproterozoic components in the Rayner Complex of western Enderby Land. There is no evidence of reworking of the Napier Complex in the studied Rayner samples.

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**SUPPLEMENTARY MATERIALS**

Supplementary Tables S1–S3 are available online from http://doi.org/10.2465/jmps.150811.

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