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Mid to late Archaean (3.3–2.5 Ga) tonalitic crustal formation and high-grade metamorphism at Mt. Riiser-Larsen, Napier Complex, East Antarctica

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Abstract

The Archaean Napier Complex consists of felsic orthogneiss, mafic granulite and a variety of paragneisses metamorphosed in the granulite facies, in part at ultrahigh-temperature (UHT, >900 °C). Orthopyroxene-bearing felsic orthogneiss of tonalitic-granodioritic composition, the highly recrystallized Archaean tonalite-trondhjemite-granodiorite (TTG) crust, is a major constituent of the complex, especially at Mt. Riiser-Larsen, which is located within the UHT region. Sensitive high-resolution ion microprobe (SHRIMP) U–Pb analyses of zircon grains from three different layers of orthopyroxene-bearing felsic orthogneiss were carried out. Two of the analyzed orthogneiss samples yield 3270 ± 12 Ma and 3267 ± 5 Ma concordia ages from igneous zircon cores. Another sample shows slightly scattered and discordant ages (∼3350 Ma) with a concordia age of 3073 ± 12 Ma. These data suggest that the initial TTG crust of the Mt. Riiser-Larsen was formed at ∼3270 Ma, and perhaps at 3070 Ma. These ages are considerably younger than the formation of tonalitic crust at Mt. Sones, Gage Ridge, and at Fyfe Hills (3840–3770 Ma), but older than that at Proclamation Island (2980 Ma) and several other areas at ∼2840 Ma. Two of the orthogneiss samples yield subordinate 2850–2790 Ma zircon concordia ages that are considered to result from a high-grade metamorphic event, which may also relate to 2830 Ma granitic magmatism recorded in the area. Zircon grains from the three analyzed orthogneiss samples yield an intense 2520–2450 Ma age cluster that probably reflect the UHT metamorphic event in the area. The ca. 3300 Ma age for TTG magmatism and ca. 2500 Ma age for high-grade metamorphism are comparable to the events in South India, which is thought by some authors to have been continuous with the Napier Complex from the Mid Proterozoic until Gondwana break up.

Keywords: Archaean; Granulite; Napier Complex; SHRIMP; TTG; Ultrahigh-temperature (UHT) metamorphism

1. Introduction

The Napier Complex is an Archaean granulite terrane covering a coastal area of 400 km^2 × 200 km^2 between longitudes 46 and 57°E in Antarctica (Fig. 1). It consists of tonalitic-trondhjemitic-granodioritic (TTG) orthogneisses, granitic gneiss, mafic granulite and a variety of paragneisses, and was affected by multiple thermal events, including ultrahigh-temperature (UHT, >900 °C) metamorphism in the Late Archaean (Sheraton et al., 1987; Harley and Black, 1997). The Complex has attracted interest since Dallwitz (1968) discovered the UHT mineral assemblage sapphirine

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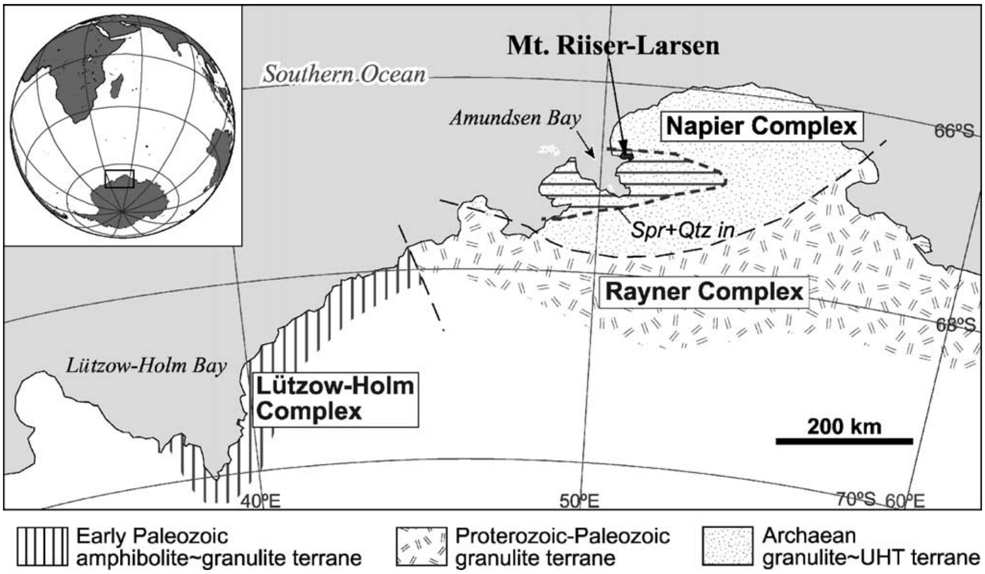

Fig. 1. Geological outline of the Napier Complex and surrounding area in East Antarctica (after Harley and Hensen, 1990). The UHT region of the Napier Complex is adopted by the sapphirine + quartz (Spr + Qtz) in isograd taken from Harley and Hensen (1990).

+ quartz, which Hensen and Green (1973) estimated to be stable only at temperatures above 1040 °C at mid to lower crustal levels. Subsequent studies showed that UHT conditions were achieved on a regional scale of 200 km × 100 km (Harley and Hensen, 1990) and that the peak metamorphic temperatures exceeded 1100 °C (Harley and Motoyoshi, 2000; Hokada, 2001).

A number of geochronological studies have been carried out on granulites, UHT gneisses and related igneous rocks in the Napier Complex during the last two decades. The results can be roughly classified into four age clusters: 4000–3700, 3100–2800, 2600–2300 Ma (e.g. Sheraton et al., 1987; Harley and Black, 1997; Grew, 1998; Asami et al., 2002; Carson et al., 2002; and references cited therein) and minor 2200 Ma ages (Grew et al., 2001; Owada et al., 2001; Suzuki et al., 2001). Ages of ca. 4000 Ma were first reported for tonalitic gneiss from Fyfe Hills by Sobotovich and others in 1976 (Sheraton et al., 1987), and subsequent studies suggested 4000–3800 Ma tonalitic igneous activity occurred in at least three localities in the complex (Fyfe Hills, Mt. Sones and Gage Ridge: e.g. Black et al., 1986a; Harley and Black, 1997). Harley and Black (1997) concluded based on sensitive high-resolution ion microprobe (SHRIMP) U–Pb zircon analyses that the initial tonalitic magmatism of the Napier Complex occurred at 3840–3770 Ma. However, most of the other areas and lithologies are thought to have formed, or been metamorphosed, during the Late Archaean (3100–2450 Ma: e.g. Sheraton et al., 1987; Harley and Black, 1997; Grew, 1998). The age of the UHT event is still the subject of debate: two contrasting interpretations are proposed, which are 2500–2450 Ma (Grew and Manton, 1979; De Paolo et al., 1982; Grew, 1998; Asami et al., 1998, 2002; Carson et al., 2002), or 3100–2820 Ma (Black and James, 1983; Sheraton et al., 1987; Harley and Black, 1997). In the latter scenario, the rocks are interpreted to have been overprinted by an amphibolite lower-granulite facies grade event at ∼2450 Ma, after isobaric cooling from the UHT metamorphism at ∼2820 Ma.

Felsic orthogneisses with TTG compositions form an abundant lithology in the complex from which ∼3800 Ma igneous zircon ages were reported, and are suggested to form the earliest igneous crust in the complex (Harley and Black, 1997). This study presents SHRIMP U–Pb zircon analyses of such felsic orthogneisses from Mt. Riiser-Larsen in order to evaluate the timing of initial tonalitic magmatism in the area, and discuss their regional significance on the evolution of the Napier Complex and the surrounding area.

2. Geological setting and samples

Mt. Riiser-Larsen is located on the northeast coast of Amundsen Bay within the UHT region of the Napier Complex (Fig. 1). The study area (Fig. 2) is composed of orthopyroxene-bearing felsic orthogneiss, garnet-bearing felsic gneiss and two-pyroxene-bearing mafic granulite with subordinate pelitic, psammitic, siliceous, aluminous and ferruginous paragneisses, pyroxenite and ultramafic granulite (Ishizuka et al., 1998). These Archaean gneisses are intensely deformed and display layer parallel foliations with tight, intrafolial folds (D1-D2; Black and James, 1983). A relatively massive and thick tonalitic orthogneiss unit concordantly overlies the layered gneisses in the eastern part of Mt. Riiser-Larsen. All gneisses are deformed by gentle and open folding to produce a weak dome structure (D3; Black and James, 1983). Mineral assemblages are nearly anhydrous, consistent with recrystallization under UHT metamorphic conditions, and a minor abundance of high-F phlogopite is occasionally included (Motoyoshi and Hensen, 2001). Secondary hydrous biotite also rarely occurs. D1-D2 layering is locally cut by Proterozoic dolerite dikes (∼1.2 Ga: Sheraton and Black, 1981).

Major and rare earth element (REE) compositions of orthopyroxene-bearing felsic orthogneisses in the study area are comparable with typical Archaean TTG (Suzuki et al., 1999). We have dated zircon grains from three orthogneiss samples using SHRIMP. The analyzed samples were collected from both the massive orthogneiss unit and layered gneisses (Fig. 2). Sample TH97011302 (hereafter shortened to 11302) was collected from the thick and massive orthogneiss unit (Fig. 3A). Sample TH97012401 (hereafter shortened to 12401) was collected from a felsic orthogneiss layer interlayered with mafic granulite. Sample TH97012816 (hereafter shortened to 12816)

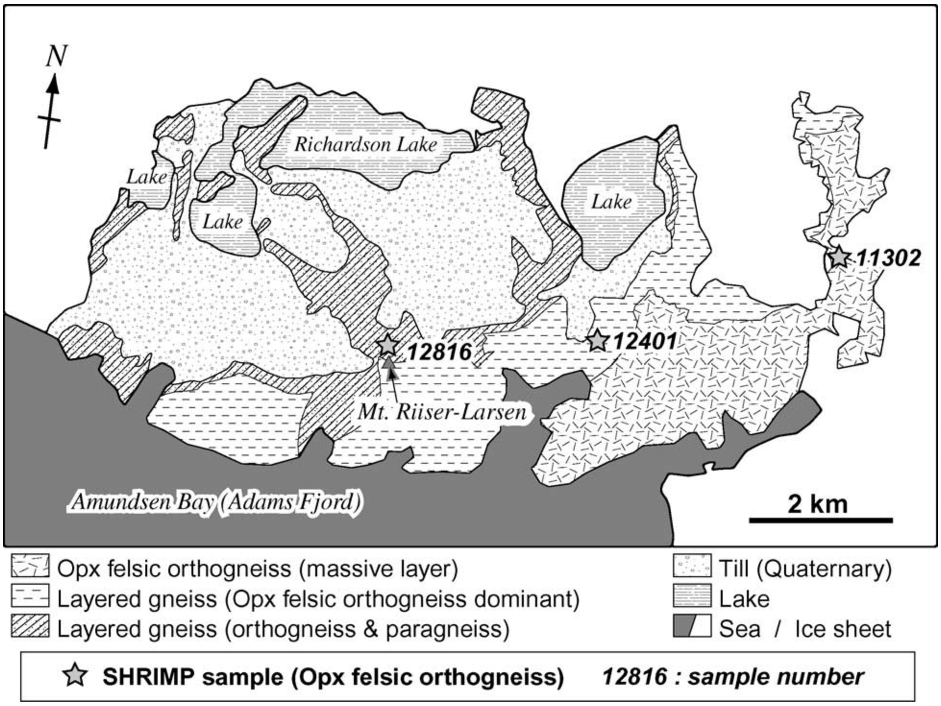

Fig. 2. Simplified geological sketch map of the Mt. Riiser-Larsen area in the Napier Complex along with the sample localities of tonalitic-granodioritic gneisses analyzed by SHRIMP.

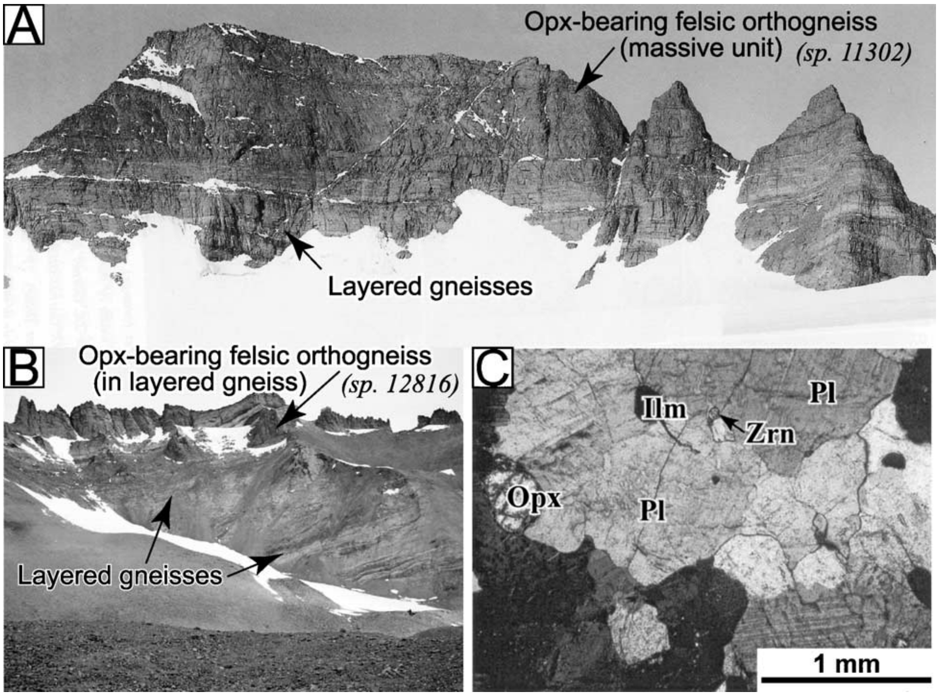

Fig. 3. (A) Field photo of thick (>100 m) and relatively massive orthopyroxene-bearing felsic (tonalitic) orthogneiss unit overlying the layered gneisses composed mainly of felsic orthogneiss. The height of the cliff is 300–400 m from the top of the ice sheet. (B) Field photo of a relatively thin layer (<10 m) of orthopyroxene-bearing felsic (tonalitic) orthogneiss intercalated with layered gneisses composed of both orthogneiss and paragneiss in the mountain peak of Mt. Riiser-Larsen (868 m height). (C) Photomicrograph of orthopyroxene-bearing felsic orthogneiss sample (sp. 11302). Crossed Nicols.

occurs as a ~10 m thick layer in the layered gneisses composed of orthogneiss and paragneiss (Fig. 3B). These orthogneiss samples are composed of orthopyroxene, antiperthitic plagioclase (in 11302 and 12816) or mesoperthitic ternary feldspar (in 12401), quartz and minor ilmenite, apatite and zircon (Table 1 and Fig. 3C). Biotite rarely occurs around orthopyroxene or ilmenite as a secondary phase.

Table 1
Mineral assemblages of the analyzed orthogneisses

Sample number	Qtz	Pl	Meso	Opx	Ilm	Ap	Zrn	Bt
11302	−	+		+	−	−	−	−
12401	−		+	+	−	−	−	−
12816	−	+		+	−	−	−	−

Mineral abbreviations essentially follow Kretz (1983) except ‘Meso.’ Qtz: quartz, Pl: plagioclase, Meso: mesoperthitic ternary feldspar, Opx: orthopyroxene, Ilm: ilmenite, Ap: apatite, Bt: biotite, Zrn: zircon, +: present, −: minor.

3. Analytical techniques

The rock specimens were ground in a tungsten-carbide mortar, and zircon grains were separated by using a sieve, magnet and heavy liquid. Zircon grains with small fragments of a standard zircon (SL13 and FC1) were mounted in epoxy, and the mount was polished and gold-coated. Zircon grains were imaged using cathodoluminescence (CL) to assess internal zircon structure prior to ion microprobe analysis.

Zircon grains were analyzed for U, Th and Pb using SHRIMP II at the National Institute of Polar Research, Tokyo, Japan. The analytical techniques for SHRIMP analysis essentially follow Compston et al. (1984) and Williams et al. (1984). A ~30 μm diameter analytical spot was used, and secondary ions were measured at a mass resolution of 5500. Standard zircon SL13 (U = 238 ppm; ^{206}Pb/^{238}U age of 572 Ma) provided by the Australian National University was used for the reference value of U concentration in

Table 2
SHRIMP U–Pb zircon analyses of orthogneisses from the Mt. Riiser-Larsen

Spot	U (ppm)	Th (ppm)	Th/U ratio	Comm. ^{206}Pb%	^{238}U/^{206}Pb ratio	^{207}Pb/^{206}Pb ratio	^{207}Pb/^{206}Pb age (Ma)	Disc (%)
11302 Opx-bearing felsic orthogneiss (in massive layer)								
1.1	824	550	0.67	0.03	1.9026 ± 0.054	0.2210 ± 0.0006	2988 ± 5	9
2.1	309	321	1.04	0.03	1.5021 ± 0.039	0.2625 ± 0.0012	3262 ± 7	−1
2.2	3214	323	0.10	0.01	2.1933 ± 0.052	0.1647 ± 0.0003	2505 ± 3	3
3.1	1671	149	0.09	0.00	2.2245 ± 0.068	0.1670 ± 0.0011	2528 ± 11	5
3.2	441	556	1.26	0.11	2.1977 ± 0.063	0.1645 ± 0.0017	2503 ± 17	3
4.1	49	169	3.44	−0.04	2.1642 ± 0.072	0.1633 ± 0.0024	2490 ± 24	2
5.1	159	124	0.78	0.16	1.8859 ± 0.058	0.1876 ± 0.0038	2721 ± 33	−1
6.1	370	359	0.97	0.04	1.4401 ± 0.043	0.2738 ± 0.0019	3328 ± 11	−2
6.2	554	167	0.30	0.01	1.8423 ± 0.047	0.1951 ± 0.0011	2785 ± 9	0
7.1	56	227	4.04	0.20	2.1766 ± 0.073	0.1658 ± 0.0029	2515 ± 29	3
11.1	1177	251	0.21	0.01	1.8837 ± 0.047	0.2012 ± 0.0022	2836 ± 18	3
11.2	541	368	0.68	0.02	1.6532 ± 0.040	0.2435 ± 0.0017	3143 ± 11	3
12.1	49	156	3.20	0.37	2.1721 ± 0.057	0.1607 ± 0.0018	2463 ± 19	1
13.1	39	109	2.83	0.31	2.1787 ± 0.059	0.1606 ± 0.0021	2462 ± 22	1
14.1	105	429	4.07	0.03	2.1690 ± 0.062	0.1632 ± 0.0011	2489 ± 12	2
15.1	936	773	0.83	0.01	1.7936 ± 0.043	0.2293 ± 0.0016	3047 ± 11	6
16.1	359	307	0.86	0.02	1.4577 ± 0.037	0.2684 ± 0.0018	3296 ± 11	−2
17.1	549	447	0.81	0.00	2.1862 ± 0.059	0.1649 ± 0.0004	2506 ± 4	3
18.1	41	133	3.29	0.05	2.1476 ± 0.058	0.1622 ± 0.0024	2479 ± 25	1
19.1	177	384	2.17	0.21	2.1264 ± 0.051	0.1668 ± 0.0009	2526 ± 9	2
20.1	735	631	0.86	0.03	1.4477 ± 0.034	0.2601 ± 0.0025	3247 ± 15	−4
21.1	415	369	0.89	0.02	1.6779 ± 0.044	0.2541 ± 0.0036	3211 ± 23	6
22.1	169	139	0.82	0.08	1.4531 ± 0.038	0.2748 ± 0.0028	3333 ± 16	−1
23.1	850	618	0.73	0.01	1.5093 ± 0.037	0.2642 ± 0.0013	3272 ± 8	0
24.1	340	271	0.80	0.03	1.5680 ± 0.037	0.2662 ± 0.0015	3284 ± 9	3
25.1	311	178	0.57	0.17	2.3046 ± 0.054	0.1630 ± 0.0009	2487 ± 9	7
26.1	1532	1200	0.78	0.00	1.8093 ± 0.042	0.2165 ± 0.0018	2955 ± 14	4
27.1	36	108	3.02	0.06	2.1869 ± 0.059	0.1657 ± 0.0018	2514 ± 18	3
12401 Opx-bearing felsic orthogneiss (interlayered with mafic granulite)								
5.2	1251	65	0.05	0.01	1.9047 ± 0.044	0.2043 ± 0.0008	2861 ± 6	5
9.1	228	214	0.94	0.03	1.5186 ± 0.046	0.2633 ± 0.0008	3267 ± 5	0
9.2	137	330	2.42	0.05	2.1760 ± 0.057	0.1656 ± 0.0015	2514 ± 15	3
10.1	464	416	0.90	0.02	2.2097 ± 0.057	0.1620 ± 0.0005	2476 ± 5	3
11.1	67	390	5.80	0.19	2.2171 ± 0.056	0.1614 ± 0.0016	2471 ± 17	3
12.1	570	257	0.45	0.01	1.6296 ± 0.040	0.2496 ± 0.0019	3182 ± 12	3
23.1	375	274	0.73	0.02	1.5970 ± 0.042	0.2531 ± 0.0020	3204 ± 13	2
24.1	47	153	3.25	0.29	2.1213 ± 0.058	0.1610 ± 0.0023	2466 ± 24	−1
25.1	39	134	3.39	0.24	2.3128 ± 0.067	0.1583 ± 0.0020	2438 ± 21	5
26.1	3995	496	0.12	0.00	2.1575 ± 0.050	0.1620 ± 0.0002	2477 ± 2	1
27.1	499	517	1.04	0.01	1.6282 ± 0.039	0.2642 ± 0.0015	3272 ± 9	6
28.1	474	281	0.59	0.01	1.5608 ± 0.039	0.2757 ± 0.0036	3339 ± 21	4
29.1	38	136	3.55	−0.10	2.4377 ± 0.075	0.1615 ± 0.0018	2471 ± 18	10
30.1	561	326	0.58	0.02	2.1057 ± 0.049	0.1593 ± 0.0007	2448 ± 8	−2
12816 Opx-bearing felsic orthogneiss (in layered gneiss)								
11.1	1759	813	0.46	0.01	2.0799 ± 0.068	0.1796 ± 0.0007	2649 ± 7	4
12.1	1257	679	0.54	0.01	1.6528 ± 0.039	0.2427 ± 0.0010	3138 ± 7	3
13.1	667	319	0.48	0.02	1.6874 ± 0.039	0.2309 ± 0.0032	3059 ± 22	2
14.1	624	386	0.62	0.01	1.7498 ± 0.049	0.2385 ± 0.0007	3110 ± 5	6
15.1	242	161	0.66	0.07	2.1207 ± 0.051	0.1721 ± 0.0009	2579 ± 9	3
16.1	842	344	0.41	0.01	1.8079 ± 0.042	0.2039 ± 0.0011	2857 ± 9	1

Table 2 (*Continued*)

Spot	U (ppm)	Th (ppm)	Th/U ratio	Comm. ^{206}Pb%	^{238}U/^{206}Pb ratio	^{207}Pb/^{206}Pb ratio	^{207}Pb/^{206}Pb age (Ma)	Disc (%)
17.1	53	96	1.82	0.12	2.2143 ± 0.057	0.1614 ± 0.0015	2470 ± 16	3
18.1	1335	340	0.25	0.01	1.9248 ± 0.046	0.1986 ± 0.0033	2815 ± 27	4
19.1	3080	1414	0.46	0.00	1.7937 ± 0.042	0.2026 ± 0.0008	2847 ± 7	0
20.1	258	154	0.60	0.02	1.6251 ± 0.039	0.2332 ± 0.0007	3074 ± 5	−1
20.2	899	61	0.07	0.02	1.7952 ± 0.044	0.2041 ± 0.0006	2859 ± 5	0
21.1	879	407	0.46	0.01	1.9285 ± 0.047	0.1938 ± 0.0004	2775 ± 3	3
22.1	581	341	0.59	0.01	1.5322 ± 0.038	0.2778 ± 0.0057	3351 ± 32	3
23.1	61	122	2.00	0.05	2.1624 ± 0.055	0.1586 ± 0.0013	2441 ± 14	0
24.1	520	1244	2.39	0.01	1.8048 ± 0.044	0.2017 ± 0.0005	2840 ± 4	0
25.1	1069	199	0.19	0.02	2.1784 ± 0.051	0.1679 ± 0.0005	2537 ± 5	4
25.2	1055	190	0.18	0.02	2.1796 ± 0.051	0.1668 ± 0.0006	2526 ± 6	4
26.1	2065	403	0.19	0.00	2.1910 ± 0.056	0.1659 ± 0.0004	2516 ± 4	4
27.1	183	236	1.29	0.07	2.1262 ± 0.055	0.1648 ± 0.0008	2505 ± 8	1
27.2	1323	145	0.11	0.00	2.1117 ± 0.051	0.1663 ± 0.0004	2521 ± 4	1
28.1	282	331	1.17	0.05	1.9425 ± 0.054	0.1937 ± 0.0014	2774 ± 12	3

Errors are 1σ uncertainties.

zircon. Pb/U ratios were corrected for instrumental mass fractionation using ratios measured on the standard zircon FC1 (1099 Ma; Paces and Miller, 1993). Common Pb corrections were based on the measured ^{204}Pb. Data reduction and processing were conducted using the computer programs SQUID ver. 1 and ISOPLOT ver. 2 provided by K.R. Ludwig at the Berkeley Geochronology Center of the University of California (Ludwig, 2001a,b). Analytical results are shown in Table 2 and Figs. 4 and 5, with errors at 1σ (ca. 68% confidence level), whereas those for average concordant ages, which include U decay constant uncertainties, calculated by using ISOPLOT shown in Fig. 4 and in the text are at 2σ (ca. 95% confidence level).

4. Results of SHRIMP zircon analyses

4.1. Orthopyroxene-bearing felsic orthogneiss from massive unit (11302)

The oldest age population, ranging from 3330 to 3260 Ma, is obtained from oscillatory-zoned igneous zircon cores (Figs. 4A, B and 5), which plot either on concordia or in the slightly discordant field. Three concordant analyses (dark gray symbols in Fig. 4A) give an average age of 3270 ± 12 Ma (Th/U = 0.7–1.0). Six concordant analyses (dark gray symbols in Fig. 4B), which are mainly from overgrowth rims or structureless zircon grains, indicate a younger age population with an average age of 2479 ± 15 Ma (Th/U = 1.3–4.1). Relatively scattered, nearly concordant ages of 2840–2720 Ma (average age of 2789 ± 35 Ma from three analyses shown as pale gray symbols in Fig. 4A; Th/U ratios <0.2) are obtained from both oscillatory-zoned and recrystallized zircon domains.

4.2. Orthopyroxene-bearing felsic orthogneiss interlayered with mafic granulite (12401)

Oscillatory-zoned igneous zircons yield a relatively scattered and discordant age population of 3339–3182 Ma (Th/U = 0.5–1.0). One concordant analysis has an ^{207}Pb/^{206}Pb age of 3267 ± 5 Ma with Th/U = 0.9 (dark gray symbol in Fig. 4C). Five analyses, mainly from overgrowth rims and structureless zircon grains (dark gray symbols in Fig. 4D), yield an average age of 2474 ± 12 Ma (Th/U = 0.1–5.8).

4.3. Orthopyroxene-bearing felsic orthogneiss in layered gneisses (12816)

U–Pb ages of oscillatory-zoned igneous zircons from this sample are concordant to weakly discordant and scattered. The oldest age of 3351 ± 32 Ma (Th/U = 0.59) with 97% concordance is obtained

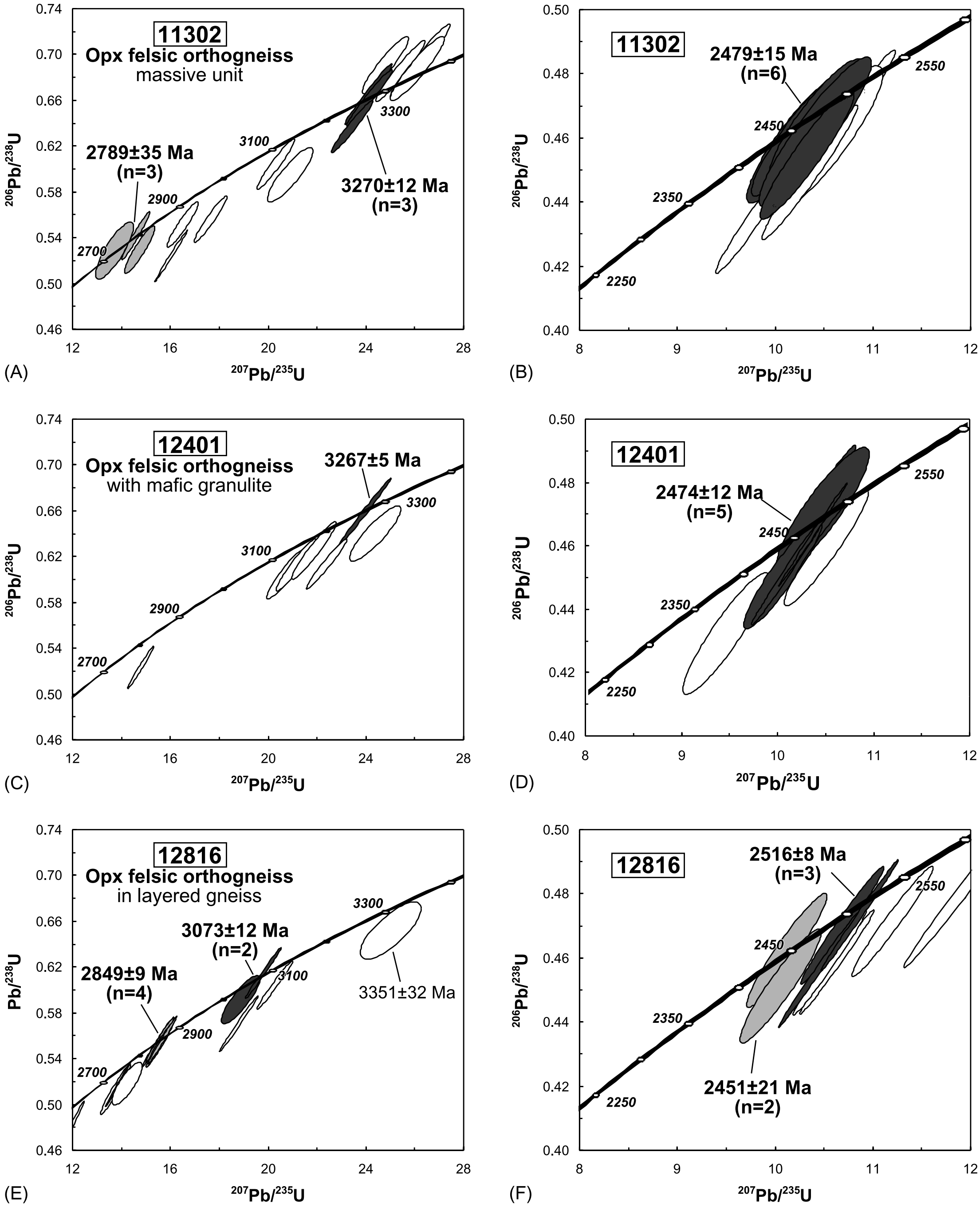

Fig. 4. $^{207}Pb/^{206}Pb$–$^{238}U/^{206}Pb$ concordia plots for zircons from tonalitic-granodioritic orthogneisses in the Mt. Riiser-Larsen area. Error ellipses are reported with 1σ uncertainties. Calculated average concordant ages are of 2σ confidence. See text for details. (A) and (B) Sp. 11302 from massive orthopyroxene-bearing felsic orthogneiss. (C) and (D) Sp. 12401 from orthopyroxene felsic gneiss interlayered with mafic granulite. (E) and (F) Sp. 12816 from orthopyroxene felsic gneiss intercalated with layered gneisses.

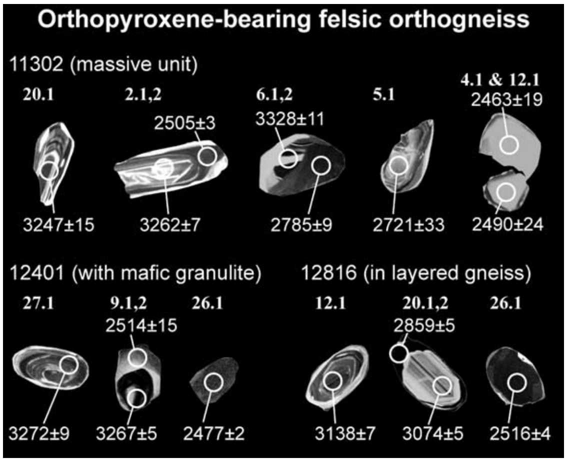

Fig. 5. Cathodoluminescence images and $^{207}Pb/^{206}Pb$ ages of selected zircon grains from orthopyroxene-bearing felsic orthogneiss samples analyzed by SHRIMP.

from an oscillatory-zoned core, and two concordant analyses (dark gray symbols in Fig. 4E) have an average age of 3073±12 Ma (Th/U = 0.5–0.6). A younger age population from overgrowth rims and structureless or zoned zircon grains is also scattered. We have calculated average ages of 2849 ± 9 Ma from four analyses (open symbols in Fig. 4E, Th/U = 0.1–2.4) and 2516 ± 8 Ma from three analyses (dark gray symbols in Fig. 4F, Th/U = 0.1–1.3). Two younger concordant analyses yield an average age of 2451 ± 1 Ma (pale gray symbols in Fig. 4F, Th/U = 1.8–2.0).

5. Discussion

5.1. Interpretation of zircon ages and thermal history of the Mt. Riiser-Larsen

The ca. 3270 Ma age obtained from oscillatory-zoned zircon cores of two orthogneiss samples (11302 and 12401) is interpreted to represent the age of magmatism to form the tonalitic protolith of these samples (Table 3). The other orthogneiss (12816) preserves one zircon remnant near this age (3350 Ma) but is somewhat younger in terms of its definitive concordant zircon population (3070 Ma). There appear to be two possible interpretations of the data: either it is a 3300 Ma igneous rock that experienced extensive remelting or modification at 3070 Ma, or it is a 3070 Ma igneous rock with some minor inheritance of 3300 Ma xenocrystic zircon. In either case, the 3270 Ma is considered to be the oldest magmatic event to form initial TTG crust in the Mt. Riiser-Larsen followed by a ∼3070 Ma event.

Two of the analyzed orthogneiss samples (11302 and 12816) yield 2850–2790 Ma zircon ages, which are interpreted to reflect a metamorphic event on the basis of their textures (Fig. 5). The presence of zoned zircon grains of this age suggests either zircon growth associated with partial melting during high-grade metamorphism, or local isotopic resetting of pre-existing zoned zircon grains. There is an isotopic record of an event within the same age bracket as defined by Harley and Black (1997) from Dallwitz Nunatak, Casey Bay and the Napier Mountains (2840–2820 Ma). However, whereas those authors interpreted this age to reflect UHT metamorphism, we do not consider our age data to correspond to this event because ca. 2800 Ma zircon ages area are less abundant than ca. 2500 Ma age populations (11302 and 12816) or are lacking (12401). Hokada et al. (2001; in review) also reported ca. 2800 Ma ages from igneous cores preserved in zircons from sapphirine-quartz and osumilite-bearing magnesian paragneisses, suggesting that magmatic zircons of this age sourced the protolith of these paragneisses and that the deposition of the sedimentary precursors of the paragneisses and the UHT event should be younger than this age in the Mt. Riiser-Larsen. A similar ∼2830 Ma SHRIMP age was obtained from igneous zircon cores of garnet-bearing granitic gneiss in the same area (Suzuki, 2000), who suggested that. Suzuki (2000) also suggested that widespread felsic and mafic magmatism took place at ca. 3000–2700 Ma based on Sm–Nd whole rock isochron ages. High-grade metamorphism, not always at UHT conditions and associated with extensive magmatism at this age, may have caused recrystallization or local isotopic resetting of zircons in the pre-existing 3270–3070 Ma TTG crust.

The 2520–2470 Ma zircon ages clearly correspond to a metamorphic event on the basis of their textures (Fig. 5). Hokada et al. (2001; in review) reported similar 2520–2460 Ma SHRIMP zircon ages from garnet-orthopyroxene-bearing paragneisses in the same area, and they concluded that the peak UHT event occurred at 2481 ± 3 Ma. 2500–2400 Ma was also interpreted as the time of metamorphism for granitic gneiss (Suzuki, 2000), quartzo-feldspathic gneiss (Asami et al., 1998, 2002) and sapphirine-osumilite-bearing paragneisses (Asami et al., 2002; Hokada et al., 2001; in review) in the same area. The ∼2450 Ma event was considered by some authors (Black and James, 1983; Sheraton et al., 1987; Harley and Black, 1997) as a relatively lower-grade (amphibolite to lower-granulite facies) event. However, the orthogneiss samples analyzed here preserve anhydrous mineral assemblages consistent with UHT metamorphic conditions, and we have found very limited abundances of secondary biotite formation in the orthogneiss samples; only a few tiny biotite grains occur around orthopyroxene or ilmenite in thin section, and no other petrographical evidence of amphibolite-granulite facies overprinting to cause pervasive zircon recrystallization can be seen. For these reasons, we conclude that the 2520–2470 Ma ages reflect the UHT metamorphic event.

Suzuki et al. (2001) reported ca. 2200 Ma Sm–Nd mineral isochron ages from sapphirine-orthopyroxene-quartz-bearing magnesian paragneiss in the same area. They suggested that this younger age may represent either prolonged high-grade (UHT?) event, or isotopic disturbance by an unspecified local thermal event.

5.2. TTG crustal formation and UHT metamorphism in the Napier Complex

The thermal history of the Mt. Riiser-Larsen area discussed in the previous section, and that proposed from the other areas in the Napier Complex, are summarized in Table 4. Few ca. 3300 Ma magmatic ages have previously been reported from the Napier Complex; two ∼3300 Ma zircon analyses by SHRIMP were obtained from quartzo-feldspathic gneiss in Tonagh Island (Shiraishi et al., 1997) where most other zircon analyses were between 2550 and 2450 Ma. Although there is insufficient geochronological data to discuss the entire Archaean crustal evolution of the Napier Complex in view of its large areal extent, at least three generations of crustal formation are identified in different parts of the complex (∼3800, 3300, 3000 Ma; Fig. 6). ∼3800 Ma TTG gneisses are reported at one locality in Casey Bay (Fyfe Hills) and at two localities in the inland region of Tula Mountains (Mt. Sones and Gage Ridge). The 3300 Ma TTG igneous rocks in the Mt. Riiser-Larsen area (and Tonagh Island?) are located in the coastal region of Tula Mountains—Amundsen Bay area (Fig. 6). Several other ca. 3000 Ma or younger rocks have been reported at several localities including Mt. Riiser-Larsen, and the youngest 2630 Ma felsic

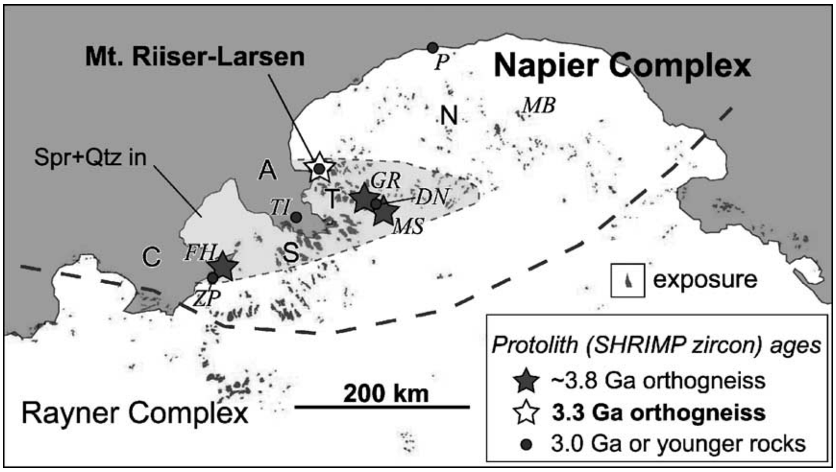

Fig. 6. Distributions of the reported protolith ages by SHRIMP zircon analyses. A: Amundsen Bay; C: Casey Bay; DN: Dallwitz Nunataks; FH: Fyfe Hills; GR: Gage Ridge; MB: Mt. Bride; MS: Mt. Sones; N: Napier Mountains; P: Proclamation Island; S: Scott Mountains; T: Tula Mountains; TI: Tonagh Island; ZP: Zircon Point. Data sources: Black et al. (1986a); Harley and Black (1997); Shiraishi et al. (1997); Carson et al. (2002).

Table 3
Summary of geochronological data from Mt. Riiser-Larsen

Rock type	Method	Protolith age (Ma)	Metamorphic age (Ma)			Reference
			Pre-2600	2600–2400	Post-2400	
Orthogneiss						
Opx-bearing felsic gneiss (11302)	SHRIMP/Zrn	3270 ± 12	2789 ± 35	2479 ± 15		This study
Opx-bearing felsic gneiss (12401)	SHRIMP/Zrn	3267 ± 5		2474 ± 12		This study
Opx-bearing felsic gneiss (12816)	SHRIMP/Zrn	ca. 3350, 3073 ± 12	2849 ± 9	2516 ± 8, 2451 ± 21		This study
Grt-bearing felsic gneiss	SHRIMP/Zrn	2830		2480		Suzuki (2000)
Felsic gneiss/mafic granulite	Sm–Nd/WR	3000–2700				Suzuki (2000)
Opx-Qtz-Kfs gneiss	EMP/Zrn, Mnz			2440–2400		Asami et al. (1998, 2002)
Paragneiss						
(lithology not shown)	SHRIMP/Zrn		2900			Black and James (1983)
Grt-Opx gneisses	SHRIMP/Zrn			2520, 2480, 2460		Hokada et al. (2001; in review)
Spr-Qtz/Os-bearing paragneisses	EMP/Zrn, Mnz	3000–2700		2500–2450		Hokada et al. (2001; in review)
Spr-Os-bearing paragneiss	EMP/Zrn			2420		Asami et al. (1998, 2002)
Spr-Opx-Os-Qtz-Pl gneiss	Sm–Nd/MI				2200	Suzuki et al. (2001)

SHRIMP: ion microprobe (SHRIMP) U–Pb age, EMP: electron microprobe U-Th-Pb chemical age, Sm–Nd: Sm–Nd isochron age, Zrn: zircon, Mnz: monazite, WR: whole-rock isochron, MI: mineral internal isochron. Mineral abbreviations are as same as in Table 1, except Spr: sapphirine, Os: osumilite.

Table 4
Summary of thermal history of the Mt. Riiser-Larsen, and comparison to the other areas in the Napier Complex

Age (Ma)	Mt. Riiser-Larsen (this study)		Age (Ma)	Other areas (Harley and Black, 1997)	
			3840–3770	Tonalitic magmatism (Fyfe Hills, Mt. Sones, Gage Ridge)	
3270	Tonalitic magmatism				
				Deposition of supracrustal rocks	
$\sim$3070	Tonalitic magmatism?				
3000–2700	Felsic and mafic magmatism		2980	Charnockitic magmatism (Proclamation Is). (D1 metamorphism in Napier Mountains)	
2850–2790	Metamorphism and granitic magmatism	Pre-D1	2840–2820	Granitic magmatism (Napier Mountains) and metamorphism at UHT conditions (Tula and Scott Mountains)	D1-D2
	Exhumation of igneous rocks and deposition of supracrustal rocks			Near isobaric cooling at 0.5–0.8 GPa	[a]
2520–2450	Metamorphism at UHT conditions	D1-D2, D3	2480–2450	Metamorphism[b] at amphibolite to lower-granulite facies conditions	D3[b]
2200	Local thermal event?		2410	Granitic magmatism (Napier Mountains)	

[a] 2630 Ma magmatism was reported for felsic orthogneiss at Tonagh Island (Carson et al., 2002).

[b] 2480–2450 Ma ages were proposed for the UHT and D1-D2 deformation events (e.g. Grew, 1998; Carson et al., 2002).

orthogneiss was dated from Tonagh Island (Carson et al., 2002). These presumably imply that different TTG crustal segments formed, and were juxtaposed, during the Early-Mid Archaean, or that multiple periods of igneous intrusions occurred prior to the UHT metamorphic events in the Late Archaean–Early Proterozoic.

Based on Gondwana and Rodinia reconstructions (e.g. Hoffman, 1991; Fitzsimons, 2000), the Archaean Napier Complex and surrounding Proterozoic Rayner Complex in Antarctica are considered to form a conjugate margin with the Archaean and Proterozoic amphibolite-granulite terranes of South India (e.g. Dharwar Craton, Nilgiri-Madras Blocks and Eastern Ghats Belt). However, there is less evidence for when these two Archaean-Proterozoic cratons were juxtaposed, or whether they were originally part of the same Archaean cratonic terrane that was fragmented at the break up of Gondwana. Asami et al. (2002) implied that the Napier Complex was continuous with Archaean granulite terranes of Nilgiri-Madras Blocks in South India based on the ca. 2500 Ma metamorphic ages in both these areas, which expanded the idea proposed by Grew and Manton (1979). However, lithologic and metamorphic conditions of these two terranes are not always consistent with each other; 2550–2520 Ma juvenile granitic magmatism and associated metamorphism is widespread in South India (e.g. Peucat et al., 1993; Jayananda et al., 2000), whereas such magmatism is typically lacking and slightly younger granitic magmatic ages of limited abundance at ∼2450 Ma are reported locally together with somewhat younger metamorphic ages (∼2480 Ma) in the Napier Complex. In addition, metamorphic conditions of the Archaean regions of the South India have been estimated to be amphibolite-granulite facies, which is different from the granulite-UHT estimated for the Napier Complex. In spite of the discrepancy between these two terranes, similarities are also present with respect to their thermal history; ca. 3000–2700 Ma igneous and metamorphic ages are also reported from amphibolite-granulite terranes of South India (e.g. Friend and Nutman, 1992; Meen et al., 1992; Kumar et al., 1996). In addition, 3330–3200 Ma TTG magmatism has been reported from the Peninsular Gneiss in South India (Peucat et al., 1993), which is comparable with the ca. 3300 Ma ages reported here for TTG magmatic ages at Mt. Riiser-Larsen. These ages might imply more similarities between the Archaean history of the Napier Complex and high-grade gneiss region of South India than previously thought: nevertheless further geochronological and geochemical studies are needed.

The first to propose a deformation-metamorphism history of the Napier Complex was Black and James (1983), who recognized two intense ductile deformation events (D1-D2) at granulite facies (UHT) conditions, followed by a relatively lower-grade upright folding event (D3). D1-D2 were proposed to have occurred at 3100–2900 Ma and D3 at 2480–2450 Ma (Black and James, 1983). Harley and Black (1997) noted that UHT metamorphism could be no older than 2840 Ma, and went on to suggest that the D1-D2 events occurred between 2840 and 2820 Ma on the basis of SHRIMP zircon data from an orthogneiss at Dallwitz Nunatak. Syn-tectonic granites emplaced in Mt. Bride, the relatively lower-grade Napier Mountains, were also used to support this 2840–2820 Ma age (Black et al., 1986b; Table 4 and Fig. 6). All of these studies concluded that 2480–2450 Ma zircon ages occurred under upper-amphibolite to lower-granulite facies conditions during the D3 event. Contrary to this interpretation, the 2500–2450 Ma ages were ascribed to the UHT event in several other geochronological studies (e.g. Grew and Manton, 1979; De Paolo et al., 1982; Grew, 1998; Asami et al., 1998, 2002; Carson et al., 2002; Hokada et al., in review). Grew (1998) discussed that Be pegmatites were emplaced during the prograde stage and recrystallized under UHT conditions during a single deformation-metamorphism episode at 2475 ± 25 Ma. Carson et al. (2002) concluded that the 2630 Ma magmatic age from Tonagh Island predated peak UHT metamorphism and that the UHT event occurred at 2480–2450 Ma. Our data is consistent with the 2480–2475 Ma UHT metamorphism associated with the D1-D2 events as summarized by these authors. As discussed in the previous section, few of the available geochronological data from Mt. Riiser-Larsen suggest the older 2840–2820 Ma UHT event, nevertheless, we do not exclude the possibility that another high-grade (UHT?) event of this age affected the Napier Complex. As the Napier Complex comprises an area of 400 km × 200 km, more age data are needed from each of the isolated localities divided by the ice sheet in order to better evaluate their mutual relationships.

6. Conclusions

(1) Initial TTG crust of the Mt. Riiser-Larsen was formed at 3270 Ma, and perhaps at 3070 Ma. These are considerably younger than the formation of tonalitic crust at Mt. Sones, Gage Ridge, and Fyfe Hills (3840–3770 Ma), but older than that at Proclamation Island (2980 Ma) and several and other (∼2800 Ma).

(2) A subsequent event areas at 280–2790 Ma is considered more likely to be related to high-grade metamorphism and magmatism than to the regional UHT event in the Napier Complex as proposed by Harley and Black (1997).

(3) A major thermal event at 2520–2470 Ma is recognized and is interpreted to reflect the UHT event rather than a post-UHT, medium-grade overprint. The data support a 2480–2475 Ma age for the UHT event as summarized by Grew (1998).

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