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THE AGE DISTRIBUTION OF DETRITAL ZIRCONS IN QUARTZITES FROM THE TOODYAY-LAKE GRACE DOMAIN, WESTERN AUSTRALIA: IMPLICATIONS FOR THE EARLY EVOLUTION OF THE YILGARN CRATON

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ABSTRACT. **Evidence for the early history of the Archean Yilgarn Craton has been largely obliterated by the craton-wide emplacement of granitic rocks at c. 2650 Ma. However, detrital zircons from rare, c. 3.1 Ga quartz-rich metasediments preserved in the Yilgarn Craton provide an opportunity to investigate the age structure and composition of the pre-existing basement and therefore provide a valuable record of the early history of crustal components that combined to form the Yilgarn Craton. In this report we present the results of an ion microprobe (SHRIMP) U–Pb geochronological study of detrital zircons from six samples of quartzites from the Toodyay-Lake Grace Domain (TLGD) in the South West Terrane of the Yilgarn Craton. Consistent features in the detrital zircon age spectra in all samples demonstrate a basic uniformity in the composition of the source rocks. The results suggest a provenance dominated by c. 3350 to 3200 Ma granitic rocks with an age peak at c. 3265 Ma. No granites of this age have so far been identified in the south-western part of the Yilgarn Craton, although c. 3280 Ma granites occur in the Narryer Terrane in the northwestern corner of the craton. A second consistent zircon age component suggests an earlier episode of granite emplacement at c. 3500 to 3400 Ma. A minor component of material contributed zircons as old as 3850 Ma to the pre-2650 Ma basement of the proto-Yilgarn Craton. Our zircon age results suggest that the provenance of the TLGD was different from that of the c. 3.1 Ga quartzites and metaconglomerates from Mt Narryer and the Jack Hills in the Narryer Terrane and from the Maynard Hills greenstone belt in the Southern Cross Domain. Although the zircon age spectra are not consistent with an origin from presently exposed gneisses from the Narryer Terrane, the presence of granite and pegmatite in the Narryer Terrane close in age to the main zircon age peak in the TLGD sediments suggests a possible connection. Some detrital zircons in the TLGD have been altered hydrothermally or overgrown by zircon rims during the c. 2650 Ma sillimanite-grade metamorphism that affected the southern part of the TLGD.**

Key words: Detrital zircon, geochronology, Provenance studies, Yilgarn Craton

INTRODUCTION

There have been several conflicting views on the early history of the Yilgarn Craton. Gee and others (1981) commented that "events in the interval 2800 to 2600 Ma (dominated by craton-wide granite emplacement) are seen as a unique episode that considerably modified the crust, but which added little new sialic material. The actual crust-building processes considerably preceded this event and in the Yilgarn block we know very little of their timing and nature." Alternatively, Myers (1990) proposed that the Yilgarn Craton can be divided into a number of tectonostratigraphic terranes that comprise distinct rock units with different geological histories that were

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amalgamated into a super-craton, of which the Yilgarn Craton is a part, during a major episode of plate tectonic activity from 2.7 to 2.6 Ga (Myers, 1990,1995).

To test these models and to further understand the early evolution of the Yilgarn Craton, it is necessary to determine the nature of the basement rocks of the constituent terranes. However, this is a difficult task, firstly because almost all evidence of the early history has been obliterated by the craton-wide, c. 2650 Ma emplacement of granitoids (for example Nemchin and Pidgeon, 1997), and secondly, because there is no consensus on the number and configuration of component terranes making up the craton. Following Gee (1979), there have been a number of proposals for the subdivision of the Yilgarn Craton into domains, terranes, and superterranes based on different criteria (Gee and others, 1981; Myers, 1990, 1995; Wilde and others, 1996, 2001; Whitaker, 2001; Tyler and Hocking, 2001; Cassidy and others, 2006). Of the various craton subdivisions, the scheme of Whitaker (2001) is the only one to define the gneisses and metasediments of the Jimperding-Berkshire Valley belt as a separate entity, the Toodyay-Lake Grace Domain (TLGD, fig. 1A). In this paper, although we follow the scheme of Cassidy and others (2006), we retain the TLGD because it contains the quartzitic metasedimentary rocks that are the subject of the present study. Within the Yilgarn Craton (fig. 1A), only the TLGD, the Narryer Terrane (NT), and the Southern Cross Domain (SCD) of the Youanmi Terrane, contain c. 3.1 Ga quartzitic metasedimentary rocks. The age distributions of their detrital zircon suites provide direct evidence on the ages of early components of the craton and the independence or otherwise of individual domains or terranes. F1

Similarities between the TLGD and the NT (fig. 1A) were pointed out by Whitaker (2001), who noted that both areas are dominated by regionally aligned, compositionally banded gneisses. These two regions also contain similar metasedimentary units, including quartzite, banded iron-formation, and pelitic metasedimentary rocks, and were considered to be equivalent by early workers (Gee and others, 1981). There are numerous papers reporting on the ages of detrital zircons in metaconglomerates from Mt Narryer and the Jack Hills in the NT (Froude and others, 1983; Compston and Pidgeon, 1986; Maas and McCulloch, 1991; Wilde and others, 2001; Cavosie and others, 2004; Pidgeon and Nemchin, 2006 and many others), and a lesser number of reports on detrital zircon ages from the SCD (Wyche and others, 2004; Wyche, 2007, and references therein).

However, there are only a few reports on U–Pb ages of detrital zircon suites from the TLGD. Nieuwland and Compston (1981) reported TIMS U–Pb concordia intercept ages of c. 3341 Ma and c. 3267 Ma for discordant zircon size-fractions from two quartzite units from the Jimperding metamorphic belt in the southern TLGD and an intercept age of c. 3246 Ma for zircons from an interlayered orthogneiss, which they interpreted as the age of crystallization of the igneous protolith. In a later study, Bosch and others (1996) reported sensitive high-resolution ion microprobe (SHRIMP) U–Pb ages of detrital zircons from a pelitic schist from the Katrine area in the Jimperding Metamorphic Belt, and interpreted the youngest result as a maximum age of deposition. Kinny (1990) summarized the results of SHRIMP U–Pb measurements of 50 detrital zircon grains from a quartzite at Windmill Hill (fig. 1C) in the Jimperding belt. Two-thirds of the zircons had ^{207}Pb/^{206}Pb ages of c. 3350 to 3177 Ma (median 3270 Ma), whereas the remaining third were older, with ages up to 3500 Ma including one grain with an exceptionally old age of 3735 ± 10 Ma. Kinny (1990) suggested that the provenance of the Jimperding quartzite was probably an originally extensive block of early Archean crust which was the precursor to the Yilgarn Craton, and of which the NT may be a remnant. Wyche and others (2004) and Wyche (2007) extended the comparison of detrital zircon ages to include zircon age spectra from samples of quartz-rich metasediments from the SCD in the central Yilgarn Craton. On the basis of the detrital zircon ages these authors concluded that the quartz-rich metasedimentary rocks from Mt Narryer and the Jack Hills in the NT, the Illaara and Maynard Hills

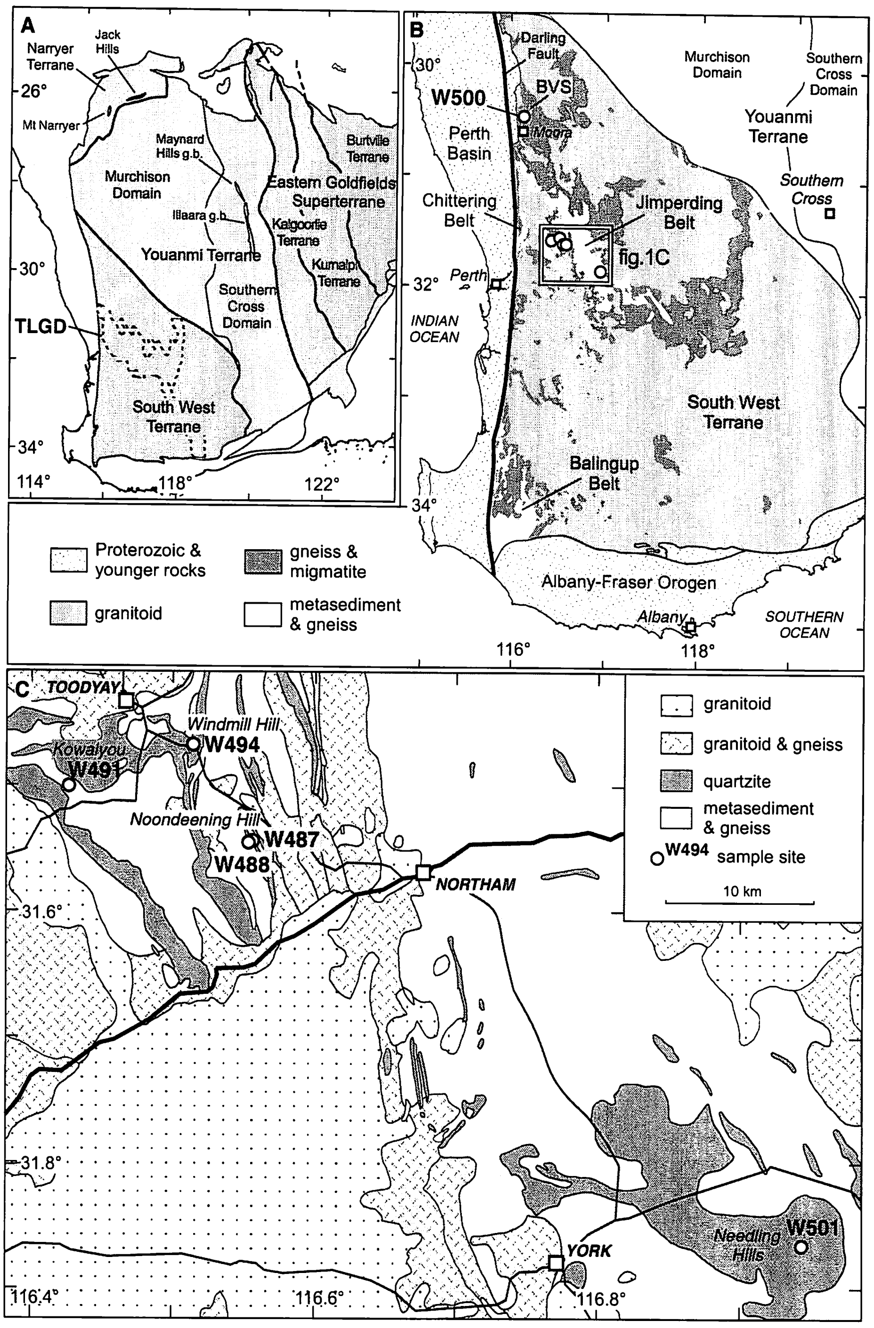

Fig. 1. (A) Tectonic subdivisions of the Yilgarn Craton (Cassidy and others, 2006), showing the Toodyay-Lake Grace Domain (TLGD) as defined geophysically by Whitaker (2001). (B) Simplified geological map of Archean rocks of the South West Terrane, showing the location of the Jimperding metamorphic belt. The location of sample W500 is shown. BVS, Berkshire Valley Succession. (C) Geological map of the central Jimperding belt in the Toodyay area, showing the locations of sampled quartzites.

greenstone belts in the SCD, and in the TLGD, had similar source rocks and probably shared a common history prior to the proposed accretion of the NT to the Youanmi Terrane after c. 2680 Ma.

The purpose of the present contribution is to report SHRIMP U–Pb ages of detrital zircon suites from six samples of quartzite taken along the length of the TLGD. These data provide new information on the early provenance of this part of the Yilgarn Craton and answer questions concerning the possible occurrence of >3.9 Ga zircons in metasedimentary rocks of the TLGD. We also review and reassess the detrital zircon age spectra from the NT and SCD, compare these with the new results from the TLGD, and draw conclusions on the relationships between the provenances of the sediments and the nature of the early Yilgarn Craton.

ANALYTICAL METHODS

SHRIMP U–Pb results for zircons from four samples (W487, W488, W491, and W494) of quartzites from the Jimperding Metamorphic Belt in the TLGD (fig. 1C) were published by the Geological Survey of Western Australia (Wingate and others, 2008a-d). In this paper we report results for an additional two samples from quartzites from the northern (W500) and southern (W501) part of the TLGD.

Zircons were separated from quartzite samples W500 and W501 using a Wilfley table, followed by conventional density and magnetic techniques, and hand-picking. The other four samples were separated using density and magnetic techniques described in Wingate and others (2008e). Zircon grains were mounted in epoxy together with chips of the CZ3 standard zircon (^{206}Pb/^{238}U = 0.09142 [564 Ma]; Pidgeon and others, 1994; Nelson, 1997), polished to expose the interiors of the grains, cleaned and gold-coated, and then analyzed on the SHRIMP II ion microprobes in the John de Laeter Centre at Curtin University (Kennedy and de Laeter, 1994). The common-Pb correction employed non-radiogenic ^{204}Pb and an average crustal common-Pb composition (Stacey and Kramers, 1975) appropriate to the age of the mineral. Data were processed using recent updates of the SQUID and Isoplot software of Ludwig (2001, 2003), and ages were calculated using the decay constants recommended by Steiger and Jäger (1977).

Except where zircon overgrowths were targeted deliberately, analyses of samples W500 and W501 were made in the centers of grains without taking into account internal structural complexities. Grains were selected progressively across the mount, and the only grains excluded were those with extensive cracking and dense clouding due to alteration. Most analyses consisted of sets of four scans, and an analysis of the zircon standard was made after each five analyses of unknown zircons. Uncertainties assigned to isotopic ratios and dates for individual analyses reflect uncertainties arising from counting statistics and common-Pb correction. Ratios and dates based on ^{238}U/^{206}Pb also include a calibration uncertainty and an external "spot-to-spot" uncertainty, related to the reproducibility of the standard ^{238}U/^{206}Pb measurements. We consider as reliable only those data that are less than 5 percent discordant and indicate <1 percent common ^{206}Pb.

ZIRCON SAMPLES AND SHRIMP U–Pb RESULTS

The locations of the six quartzite samples (fig. 1) are listed below with both Geological Survey of Western Australia (GSWA) and Curtin University sample numbers. Samples were collected over a distance of approximately 170 km along the length of the TLGD (fig. 1). Note that the outcrop is not continuous and the sampled quartzite bands cannot be shown to be the same unit. One sample (W500) is from a massive quartzite from the Berkshire Valley Succession in the far north of the TLGD. Four quartzite samples were collected from fuchsite-bearing flaggy quartzite from the Jimperding metamorphic belt in the vicinity of Toodyay. Two samples from Noondeening Hill were taken to examine variations in the zircon age distributions on the scale of a few hundred meters. The sixth sample (W501) is from a fuchsite-bearing quartzite from the Needling Hills in the southeasternmost part of the Jimperding belt.

SHRIMP U–Pb isotopic analyses of zircons from W500 and W501 are presented in tables 1 and 2. Data from other samples are contained in reports published by the Geological Survey of Western Australia (Wingate and others, 2008a-d). The zircon age spectra for all samples are shown in the stacked profiles in figure 2. In the following, the samples are described from north to south along the TLGD. **T2c** **F2**

W500, Moora

Sample W500 (MGA zone 50, 417311E, 6626592N) was taken from a low outcrop of quartzite at the junction of the old Geraldton Road and Miling West Road (fig. 1B). The zircon population consists of irregularly shaped to subrounded grains with no evidence of rims. Fifty-seven analyses of 57 zircon grains were made over two SHRIMP sessions (table 1). The first session showed consistently higher common Pb and instability in the total secondary beam monitor. The sample was cleaned and re-coated with Au, and a second session resulted in much lower common Pb and very stable run conditions. After excluding eight analyses >5 percent discordant, 48 of the remaining 49 analyses fall within the range c. 3490 to c. 3190 Ma, with one at c. 3695 Ma. Distinct age peaks occur at c. 3300 Ma and c. 3250 Ma, with smaller peaks at c. 3430 and c. 3385 Ma (fig. 2). Two zircons have ages of c. 3485 Ma.

W494 (GSWA 177904), Windmill Hill Railway Cutting

Sample W494 (MGA zone 50, 453921E, 6506567N) was taken from a coarse-grained quartzite unit about 20 m west of a contact with amphibolite, on the north side of the Windmill Hill railway cutting (fig. 1C). This is in the vicinity of, but may not be exactly, the unit previously sampled by Kinny (1990). The quartzite in the cutting was derived from sands with silty layers and shows weak cross-bedding. Zircons are clear and colorless to pale brown, and range from subhedral to strongly rounded. Most zircons display concentric growth zoning and a number of grains have a thin overgrowth of younger zircon. Details of 155 analyses of 121 zircons are given in Wingate and others (2008b). Five analyses were >5 percent discordant and are not considered further. The remaining 150 analyses have $^{207}Pb/^{206}Pb$ ages of 3695 to 3005 Ma, and the age spectrum (fig. 2) has a strong symmetrical age peak between c. 3350 and 3200 Ma, with a median of c. 3270 Ma. Several small, poorly resolved peaks occur between 3700 and 3400 Ma, and include possible components at c. 3430 Ma and c. 3580 Ma.

W491 (GSWA 177901), Kowalyou Farm

Sample W491 (MGA zone 50, 445610E, 6503813N) was collected from a quarry in the Jimperding quartzite on the southern slope of a low hill, about 3 km southeast of Kowalyou Farm, and 10 km west of the town of Toodyay (fig. 1C). The sample is a coarse-grained, pale pinkish-gray, recrystallized quartzite, which exhibits a subhorizontal foliation and a lineation defined by muscovite and fuchsite in the foliation plane. Micas developed on foliation planes give the rock a flaggy character and it has been quarried as a building stone. Zircons from this sample are clear and colorless to pale brown. Grains are 100 to 300 mm in length with aspect ratios up to 6:1. Most grains display concentric growth zoning. Surface pitting and rounding are consistent with mechanical abrasion during sedimentary transport. Some grains have thin zircon overgrowths. U–Pb analyses of 69 zircons were reported by Wingate and others (2008a). The spectrum of $^{207}Pb/^{206}Pb$ ages (fig. 2), rejecting two analyses that are >5 percent discordant, shows major symmetrical peak between 3380 and 3180 Ma, with a median of c. 3270 Ma. A few older grains are present in the population, with ages up to 3676 Ma, and minor components at c. 3550 Ma and c. 3460 Ma.

W487 (GSWA 177907), Noondeening Hill

Sample W487 (MGA zone 50, 457913E, 6500201N) was obtained from a band of massive, coarse-grained, recrystallized quartzite on the southern end of Noondeening

Table 1

U–Pb analytical data for zircons from sample W500: quartzite, Moora

Grain Area	^{238}U (ppm)	^{232}Th (ppm)	Th/U	*f*204 (%)	^{238}U/^{206}Pb	(±1σ)	^{207}Pb/^{206}Pb	(±1σ)	^{238}U/^{206}Pb*	(±1σ)	^{207}Pb*/^{206}Pb*	(±1σ)	^{238}U/^{206}Pb* age (Ma)	(±1σ)	^{207}Pb*/^{206}Pb* age (Ma)	(±1σ)	Disc. (%)
18.1	1360	3	0.00	0.035	0.866	0.032	0.18795	0.00146	0.866	0.032	0.18764	0.00149	4949	272	2722	13	-81.8
53.1	329	363	1.14	0.031	1.622	0.028	0.25203	0.00060	1.623	0.048	0.25176	0.00061	3095	115	3196	4	3.2
10.1	331	206	0.64	0.180	1.470	0.019	0.25880	0.00103	1.473	0.020	0.25723	0.00110	3341	58	3230	7	-3.4
14.1	286	608	2.20	0.136	1.474	0.015	0.25917	0.00083	1.476	0.016	0.25799	0.00087	3336	47	3234	5	-3.1
2.1	218	304	1.44	0.254	1.537	0.016	0.26039	0.00079	1.541	0.017	0.25817	0.00088	3225	45	3236	5	0.3
36.1	143	126	0.91	-0.010	1.533	0.030	0.25816	0.00091	1.533	0.047	0.25825	0.00091	3237	128	3236	6	0.0
44.1	322	468	1.50	0.008	1.540	0.027	0.25876	0.00060	1.540	0.045	0.25868	0.00061	3226	122	3239	4	0.4
54.1	211	124	0.61	0.006	1.538	0.028	0.25882	0.00073	1.538	0.046	0.25876	0.00073	3230	124	3239	4	0.3
19.1	168	107	0.66	0.189	1.497	0.017	0.26050	0.00090	1.500	0.018	0.25886	0.00097	3293	50	3240	6	-1.7
57.1	233	143	0.64	-0.013	1.531	0.028	0.25902	0.00074	1.531	0.046	0.25913	0.00074	3240	124	3241	4	0.0
48.1	275	105	0.40	0.000	1.525	0.027	0.25915	0.00064	1.525	0.045	0.25915	0.00064	3251	124	3242	4	-0.3
58.1	188	244	1.34	0.007	1.552	0.029	0.25997	0.00078	1.552	0.047	0.25991	0.00078	3206	124	3246	5	1.2
43.1	187	122	0.68	0.030	1.512	0.028	0.26017	0.00079	1.513	0.046	0.25992	0.00080	3272	127	3246	5	-0.8
62.1	74	16	0.22	0.018	1.368	0.032	0.26080	0.00124	1.368	0.046	0.26064	0.00125	3537	156	3251	8	-8.8
50.1	177	48	0.28	0.035	1.526	0.029	0.26101	0.00087	1.527	0.046	0.26070	0.00088	3247	127	3251	5	0.1
31.1	170	143	0.87	0.016	1.525	0.029	0.26113	0.00083	1.526	0.046	0.26099	0.00084	3250	127	3253	5	0.1
39.1	375	488	1.35	-0.014	1.486	0.026	0.26089	0.00056	1.486	0.043	0.26101	0.00056	3317	125	3253	3	-2.0
45.1	190	292	1.58	-0.007	1.510	0.028	0.26104	0.00079	1.509	0.045	0.26110	0.00079	3277	127	3253	5	-0.7
37.1	122	82	0.70	0.011	1.462	0.029	0.26120	0.00098	1.462	0.045	0.26110	0.00098	3360	135	3253	6	-3.3
22.1	89	30	0.35	0.485	1.477	0.022	0.26554	0.00131	1.484	0.023	0.26131	0.00153	3320	66	3255	9	-2.0
42.1	131	45	0.35	0.000	1.544	0.032	0.26228	0.00096	1.544	0.048	0.26228	0.00096	3219	129	3260	6	1.3
15.1	86	61	0.73	0.516	1.425	0.021	0.26786	0.00133	1.432	0.022	0.26336	0.00157	3414	69	3267	9	-4.5
4.1	313	147	0.48	0.103	1.512	0.014	0.26445	0.00068	1.513	0.015	0.26355	0.00070	3270	41	3268	4	-0.1
23.1	371	333	0.93	0.213	1.788	0.022	0.26649	0.00286	1.792	0.023	0.26463	0.00292	2858	47	3274	17	12.7
17.1	45	45	1.03	0.356	1.447	0.028	0.26784	0.00177	1.452	0.029	0.26474	0.00199	3377	87	3275	12	-3.1
55.1	148	64	0.45	0.000	1.509	0.029	0.26492	0.00089	1.509	0.046	0.26492	0.00089	3277	129	3276	5	0.0
47.1	275	390	1.47	0.024	1.553	0.027	0.26537	0.00065	1.554	0.046	0.26516	0.00066	3203	121	3278	4	2.3
13.1	56	27	0.49	0.460	1.444	0.028	0.26963	0.00181	1.451	0.028	0.26562	0.00210	3380	86	3280	12	-3.0
59.1	148	50	0.35	0.019	1.508	0.029	0.26598	0.00109	1.509	0.046	0.26582	0.00110	3278	129	3282	6	0.1
35.1	99	97	1.02	0.055	1.524	0.032	0.26910	0.00110	1.525	0.048	0.26862	0.00113	3251	133	3298	7	1.4
38.1	54	26	0.49	0.128	1.477	0.036	0.27010	0.00151	1.479	0.050	0.26899	0.00159	3329	147	3300	9	-0.9
49.1	121	71	0.60	0.044	1.477	0.030	0.26958	0.00099	1.478	0.046	0.26920	0.00101	3331	134	3301	6	-0.9
30.1	402	198	0.51	0.007	1.525	0.026	0.26973	0.00056	1.525	0.045	0.26967	0.00056	3250	122	3304	3	1.6

TABLE 1

(continued)

Grain Area	^{238}U (ppm)	^{232}Th (ppm)	Th/U	*f*204 (%)	^{238}U/^{206}Pb	(±1σ)	^{207}Pb/^{206}Pb	(±1σ)	^{238}U/^{206}Pb*	(±1σ)	^{207}Pb*/^{206}Pb*	(±1σ)	^{238}U/^{206}Pb* age (Ma)	(±1σ)	^{207}Pb*/^{206}Pb* age (Ma)	(±1σ)	Disc. (%)
8.1	105	77	0.76	0.350	1.409	0.020	0.27370	0.00125	1.414	0.021	0.27067	0.00140	3448	67	3310	8	-4.2
61.1	382	610	1.65	0.008	1.547	0.027	0.27078	0.00061	1.547	0.045	0.27071	0.00061	3213	121	3310	4	2.9
11.1	332	383	1.19	0.119	1.477	0.015	0.27180	0.00107	1.479	0.016	0.27077	0.00110	3329	47	3310	6	-0.6
12.1	110	125	1.17	1.146	1.583	0.044	0.28338	0.00407	1.602	0.046	0.27344	0.00544	3127	115	3326	31	6.0
16.1	40	42	1.09	1.015	1.338	0.030	0.28746	0.00205	1.352	0.031	0.27869	0.00265	3569	107	3356	15	-6.4
21.1	182	191	1.08	0.315	1.730	0.018	0.28168	0.00096	1.735	0.019	0.27896	0.00106	2934	41	3357	6	12.6
24.1	117	63	0.55	0.355	1.727	0.079	0.28204	0.00223	1.734	0.079	0.27897	0.00244	2936	168	3357	14	12.6
33.1	129	90	0.72	0.030	1.472	0.029	0.28132	0.00098	1.473	0.046	0.28106	0.00099	3341	134	3369	6	0.8
7.1	94	113	1.23	0.477	1.424	0.020	0.28762	0.00128	1.431	0.021	0.28351	0.00149	3416	66	3382	8	-1.0
32.1	70	32	0.47	0.017	1.459	0.033	0.28421	0.00131	1.459	0.048	0.28406	0.00132	3364	144	3385	7	0.6
25.1	55	29	0.55	0.552	1.354	0.026	0.28960	0.00174	1.361	0.027	0.28485	0.00202	3550	92	3390	11	-4.7
9.1	250	305	1.26	0.161	1.715	0.016	0.28735	0.00087	1.718	0.018	0.28597	0.00091	2957	38	3396	5	12.9
20.1	78	70	0.92	0.501	1.384	0.021	0.29240	0.00140	1.391	0.022	0.28810	0.00164	3493	72	3407	9	-2.5
46.1	98	51	0.54	0.093	1.381	0.030	0.28985	0.00116	1.382	0.044	0.28905	0.00120	3509	147	3413	6	-2.8
40.1	126	45	0.37	0.026	1.449	0.029	0.28993	0.00094	1.450	0.045	0.28970	0.00095	3382	135	3416	5	1.0
60.1	104	105	1.05	0.039	1.425	0.030	0.29099	0.00114	1.426	0.045	0.29066	0.00116	3426	141	3421	6	-0.1
52.1	132	172	1.34	0.000	1.421	0.028	0.29181	0.00101	1.421	0.044	0.29181	0.00101	3434	138	3427	5	-0.2
51.1	302	393	1.34	0.030	1.465	0.026	0.29305	0.00063	1.466	0.043	0.29280	0.00064	3353	128	3433	3	2.3
34.1	53	57	1.11	0.094	1.443	0.036	0.29369	0.00155	1.444	0.049	0.29288	0.00160	3392	151	3433	9	1.2
5.1	188	87	0.48	0.135	1.402	0.015	0.29684	0.00091	1.404	0.016	0.29568	0.00094	3467	52	3448	5	-0.6
3.1	220	97	0.46	0.187	1.413	0.016	0.29777	0.00085	1.415	0.017	0.29617	0.00091	3445	55	3450	5	0.1
41.1	229	165	0.74	0.019	1.387	0.025	0.30226	0.00073	1.387	0.041	0.30210	0.00074	3500	137	3481	4	-0.5
6.1	234	269	1.18	0.124	1.387	0.014	0.30465	0.00101	1.389	0.015	0.30359	0.00103	3496	49	3489	5	-0.2
1.1	101	48	0.50	0.332	1.289	0.018	0.34993	0.00135	1.294	0.019	0.34721	0.00144	3691	71	3695	6	0.1

Notes: Analyses are listed in order of increasing ^{207}Pb*/^{206}Pb* age. *f*204 is the proportion of common ^{206}Pb in measured ^{206}Pb, as estimated using measured ^{204}Pb/^{206}Pb. Pb*, radiogenic Pb. U/Pb ratios and ages include calibration and reproducibility uncertainties (1 sigma), respectively, of 0.36% and 0.50% (analyses 1.1-25.1) and 0.47% and 1.54% (analyses 26.1-57.1). Disc., discordance, calculated as 100 × [1 − (^{238}U/^{206}Pb* age)/(^{207}Pb*/^{206}Pb* age)].

TABLE 2

U–Pb analytical data for zircons from sample W501: quartzite, Needling Hills

Grain Area	^{238}U (ppm)	^{232}Th (ppm)	Th/U	*f*204 (%)	^{238}U/^{206}Pb	(±1σ)	^{207}Pb/^{206}Pb	(±1σ)	^{238}U/^{206}Pb*	(±1σ)	^{207}Pb*/^{206}Pb*	(±1σ)	^{238}U/^{206}Pb* age (Ma)	(±1σ)	^{207}Pb*/^{206}Pb* age (Ma)	(±1σ)	Disc. (%)
38.1	733	53	0.07	0.041	1.983	0.150	0.17604	0.00032	1.984	0.160	0.17567	0.00033	2631	257	2612	3	-0.7
80.1	720	79	0.11	0.160	2.080	0.074	0.17779	0.00112	2.084	0.077	0.17637	0.00121	2527	113	2619	11	3.5
63.1	957	38	0.04	0.008	1.759	0.060	0.18098	0.00089	1.760	0.062	0.18091	0.00089	2901	128	2661	8	-9.0
29.1	846	17	0.02	0.045	1.826	0.134	0.18170	0.00029	1.827	0.144	0.18129	0.00030	2814	272	2665	3	-5.6
87.1	815	168	0.21	0.191	2.026	0.073	0.18490	0.00095	2.030	0.076	0.18320	0.00098	2582	118	2682	9	3.7
93.1	1134	14	0.01	0.014	1.969	0.069	0.18441	0.00192	1.969	0.072	0.18428	0.00192	2647	118	2692	17	1.7
64.1	746	184	0.25	0.011	1.772	0.061	0.19077	0.00097	1.772	0.063	0.19067	0.00098	2884	129	2748	8	-5.0
48.1	1072	57	0.06	0.008	2.001	0.063	0.19236	0.00071	2.001	0.066	0.19229	0.00071	2613	105	2762	6	5.4
22.1	696	436	0.65	0.167	1.963	0.033	0.20370	0.00041	1.966	0.057	0.20222	0.00048	2651	94	2844	4	6.8
46.1	817	419	0.53	0.047	2.010	0.070	0.20619	0.00077	2.011	0.073	0.20577	0.00078	2602	115	2873	6	9.4
73.1	366	107	0.30	0.354	1.663	0.073	0.21332	0.00166	1.669	0.075	0.21017	0.00173	3027	171	2907	13	-4.1
92.1	678	443	0.67	0.245	1.948	0.072	0.21577	0.00141	1.953	0.075	0.21358	0.00146	2666	125	2933	11	9.1
23.1	532	116	0.23	0.000	1.811	0.031	0.21380	0.00060	1.811	0.053	0.21380	0.00060	2834	102	2935	5	3.4
19.2	586	23	0.04	0.012	1.737	0.129	0.21496	0.00046	1.737	0.139	0.21486	0.00046	2932	290	2943	3	0.4
13.1	758	218	0.30	0.053	1.869	0.031	0.22145	0.00038	1.870	0.054	0.22098	0.00040	2762	98	2988	3	7.6
88.1	392	55	0.15	0.022	1.683	0.060	0.23323	0.00148	1.683	0.062	0.23303	0.00148	3006	139	3073	10	2.2
14.1	728	92	0.13	0.015	1.353	0.022	0.23561	0.00036	1.353	0.039	0.23548	0.00036	3567	136	3090	2	-15.4
94.1	142	196	1.43	0.225	1.792	0.071	0.23755	0.00200	1.796	0.073	0.23556	0.00207	2854	145	3090	14	7.6
16.1	485	100	0.21	0.003	1.670	0.028	0.23728	0.00184	1.670	0.048	0.23725	0.00184	3024	111	3102	12	2.5
54.1	72	38	0.54	0.068	1.536	0.052	0.24027	0.00183	1.537	0.054	0.23967	0.00186	3231	147	3118	12	-3.6
67.1	888	268	0.31	0.279	1.959	0.067	0.24302	0.00134	1.965	0.070	0.24056	0.00137	2652	116	3124	9	15.1
5.1	585	1018	1.80	0.020	2.053	0.034	0.24111	0.00102	2.053	0.059	0.24094	0.00102	2558	90	3126	7	18.2
27.1	182	169	0.96	0.026	1.632	0.044	0.24123	0.00098	1.633	0.059	0.24099	0.00099	3080	141	3127	7	1.5
55.1	726	234	0.33	0.036	1.611	0.059	0.24146	0.00134	1.611	0.061	0.24114	0.00134	3112	151	3128	9	0.5
41.1	594	103	0.18	0.008	1.695	0.125	0.24434	0.00039	1.695	0.134	0.24427	0.00039	2989	294	3148	3	5.1
79.1	820	55	0.07	0.016	1.786	0.061	0.24937	0.00115	1.786	0.063	0.24923	0.00115	2866	127	3180	7	9.9
84.1	439	249	0.59	0.009	1.533	0.053	0.25244	0.00123	1.533	0.055	0.25236	0.00123	3237	149	3200	8	-1.2
4.1	640	347	0.56	0.005	1.576	0.026	0.25280	0.00053	1.576	0.045	0.25276	0.00053	3167	117	3202	3	1.1
70.1	396	245	0.64	0.175	1.581	0.054	0.25526	0.00126	1.584	0.057	0.25373	0.00129	3156	144	3208	8	1.6
61.1	219	136	0.64	0.063	1.445	0.050	0.25518	0.00139	1.445	0.052	0.25463	0.00140	3389	159	3214	9	-5.5
35.1	176	122	0.72	0.056	1.486	0.106	0.25694	0.00242	1.487	0.115	0.25645	0.00243	3315	325	3225	15	-2.8
1.1	306	204	0.69	0.020	1.545	0.027	0.25665	0.00178	1.545	0.045	0.25648	0.00178	3217	122	3225	11	0.3
68.1	630	91	0.15	0.103	1.784	0.060	0.25785	0.00118	1.785	0.063	0.25695	0.00120	2867	126	3228	7	11.2
33.1	515	339	0.68	0.020	1.384	0.098	0.25936	0.00077	1.385	0.106	0.25919	0.00078	3505	347	3242	5	-8.1
28.2	39	40	1.04	0.058	1.456	0.121	0.25971	0.00162	1.457	0.128	0.25920	0.00166	3368	377	3242	10	-3.9

TABLE 2

(continued)

Grain Area	^{238}U (ppm)	^{232}Th (ppm)	Th/U	*f*204 (%)	^{238}U/^{206}Pb	(±1σ)	^{207}Pb/^{206}Pb	(±1σ)	^{238}U/^{206}Pb*	(±1σ)	^{207}Pb*/^{206}Pb*	(±1σ)	^{238}U/^{206}Pb* age (Ma)	(±1σ)	^{207}Pb*/^{206}Pb* age (Ma)	(±1σ)	Disc. (%)
98.1	842	541	0.66	0.024	1.602	0.058	0.25985	0.00267	1.602	0.061	0.25964	0.00268	3127	150	3245	16	3.6
53.1	636	52	0.08	0.025	1.623	0.051	0.26024	0.00120	1.624	0.054	0.26001	0.00121	3094	130	3247	7	4.7
78.1	89	67	0.77	0.043	1.487	0.052	0.26144	0.00170	1.488	0.054	0.26107	0.00172	3314	157	3253	10	-1.9
12.1	920	84	0.09	-0.003	1.568	0.026	0.26104	0.00037	1.568	0.045	0.26107	0.00037	3180	117	3253	2	2.3
89.1	90	60	0.69	0.112	1.578	0.061	0.26218	0.00179	1.580	0.063	0.26120	0.00183	3162	160	3254	11	2.8
76.1	101	74	0.75	0.052	1.454	0.051	0.26174	0.00161	1.455	0.053	0.26129	0.00163	3373	160	3254	10	-3.6
86.1	64	37	0.60	0.000	1.484	0.056	0.26134	0.00392	1.484	0.057	0.26134	0.00392	3321	166	3255	24	-2.0
75.1	201	135	0.69	0.090	1.433	0.050	0.26404	0.00141	1.434	0.052	0.26325	0.00143	3411	162	3266	9	-4.4
26.1	340	112	0.34	0.000	1.547	0.028	0.26391	0.00285	1.547	0.046	0.26391	0.00285	3215	123	3270	17	1.7
91.1	137	79	0.60	0.040	1.517	0.056	0.26478	0.00200	1.517	0.058	0.26444	0.00201	3264	162	3273	12	0.3
28.3	133	60	0.47	0.023	1.415	0.108	0.26500	0.00395	1.415	0.116	0.26479	0.00396	3446	362	3275	23	-5.2
66.1	194	98	0.52	0.025	1.433	0.048	0.26534	0.00135	1.433	0.050	0.26512	0.00135	3413	157	3277	8	-4.1
7.1	98	48	0.51	0.000	1.536	0.032	0.26512	0.00774	1.536	0.048	0.26512	0.00774	3232	131	3277	46	1.4
31.1	144	42	0.30	0.020	1.372	0.100	0.26571	0.00178	1.373	0.107	0.26554	0.00178	3528	357	3280	11	-7.6
52.1	768	149	0.20	0.015	1.546	0.049	0.26586	0.00097	1.547	0.051	0.26572	0.00097	3215	136	3281	6	2.0
34.1	511	262	0.53	0.156	1.682	0.120	0.26776	0.00376	1.685	0.129	0.26641	0.00377	3004	287	3285	22	8.6
15.1	333	52	0.16	0.022	1.530	0.027	0.26665	0.00063	1.530	0.045	0.26645	0.00064	3242	123	3285	4	1.3
10.1	464	364	0.81	0.000	1.540	0.026	0.26666	0.00134	1.540	0.045	0.26666	0.00134	3225	120	3286	8	1.9
49.1	54	22	0.42	0.113	1.426	0.049	0.26792	0.00179	1.428	0.051	0.26693	0.00186	3422	160	3288	11	-4.1
74.1	192	69	0.37	0.041	1.435	0.054	0.26744	0.00283	1.435	0.056	0.26709	0.00283	3408	172	3289	17	-3.6
57.1	790	42	0.06	0.002	1.410	0.049	0.26787	0.00437	1.410	0.051	0.26785	0.00437	3455	163	3293	26	-4.9
30.1	113	37	0.34	-0.018	1.382	0.099	0.26853	0.00091	1.382	0.107	0.26869	0.00091	3509	351	3298	5	-6.4
32.1	203	153	0.78	0.020	1.336	0.095	0.26902	0.00238	1.336	0.103	0.26885	0.00238	3602	361	3299	14	-9.2
36.1	114	58	0.52	0.000	1.339	0.096	0.26937	0.00105	1.339	0.103	0.26937	0.00105	3596	362	3302	6	-8.9
25.1	118	172	1.50	0.000	1.482	0.030	0.26987	0.00188	1.482	0.046	0.26987	0.00188	3324	134	3305	11	-0.6
24.1	496	257	0.53	0.101	1.635	0.028	0.27085	0.00063	1.637	0.047	0.26998	0.00065	3074	113	3306	4	7.0
60.1	136	92	0.70	0.025	1.380	0.047	0.27091	0.00186	1.381	0.049	0.27069	0.00186	3512	165	3310	11	-6.1
21.1	674	451	0.69	0.083	1.635	0.027	0.27283	0.00105	1.636	0.047	0.27211	0.00106	3075	113	3318	6	7.3
45.1	511	278	0.56	0.255	1.464	0.115	0.27482	0.00050	1.468	0.123	0.27261	0.00055	3349	358	3321	3	-0.8
47.1	409	236	0.59	0.126	1.716	0.054	0.27425	0.00206	1.718	0.057	0.27315	0.00207	2957	122	3324	12	11.0
97.1	662	429	0.67	0.020	1.688	0.062	0.27383	0.00146	1.689	0.064	0.27366	0.00146	2998	144	3327	8	9.9
40.1	394	146	0.38	0.000	1.303	0.106	0.27532	0.00058	1.303	0.112	0.27532	0.00058	3672	413	3337	3	-10.0
51.1	111	102	0.94	0.026	1.423	0.047	0.27562	0.00142	1.423	0.049	0.27540	0.00143	3430	154	3337	8	-2.8
65.1	145	98	0.70	0.064	1.350	0.049	0.27825	0.00466	1.351	0.051	0.27770	0.00467	3571	177	3350	26	-6.6
62.1	280	263	0.97	0.000	1.329	0.046	0.27996	0.00612	1.329	0.048	0.27996	0.00612	3616	173	3363	34	-7.5

Table 2

(continued)

Grain Area	^{238}U (ppm)	^{232}Th (ppm)	Th/U	f204 (%)	^{238}U/^{206}Pb	(±1σ)	^{207}Pb/^{206}Pb	(±1σ)	^{238}U/^{206}Pb*	(±1σ)	^{207}Pb*/^{206}Pb*	(±1σ)	^{238}U/^{206}Pb* age (Ma)	(±1σ)	^{207}Pb*/^{206}Pb* age (Ma)	(±1σ)	Disc. (%)
28.1	44	42	0.98	0.025	1.228	0.090	0.28023	0.00176	1.228	0.097	0.28002	0.00177	3839	400	3363	10	-14.2
82.1	427	210	0.51	0.224	1.408	0.048	0.28209	0.00261	1.411	0.050	0.28015	0.00263	3454	161	3364	15	-2.7
50.1	641	64	0.10	0.094	1.508	0.047	0.28361	0.00417	1.510	0.050	0.28280	0.00418	3276	139	3378	23	3.0
72.1	118	39	0.34	0.024	1.365	0.048	0.29014	0.00528	1.366	0.050	0.28993	0.00528	3542	170	3417	28	-3.6
95.1	214	114	0.55	0.047	1.494	0.054	0.29154	0.00338	1.494	0.056	0.29114	0.00338	3303	160	3424	18	3.5
19.3	340	58	0.18	0.017	1.541	0.113	0.29156	0.00079	1.541	0.121	0.29142	0.00080	3224	321	3425	4	5.9
11.1	662	232	0.36	0.008	1.390	0.023	0.29161	0.00301	1.390	0.040	0.29154	0.00301	3495	132	3426	16	-2.0
81.1	147	60	0.42	0.053	1.341	0.047	0.29276	0.00466	1.342	0.049	0.29231	0.00467	3590	173	3430	25	-4.7
43.1	125	93	0.77	1.056	1.360	0.102	0.30223	0.00204	1.374	0.111	0.29319	0.00220	3525	368	3435	12	-2.6
3.1	558	491	0.91	0.047	1.576	0.026	0.29396	0.00051	1.577	0.046	0.29356	0.00052	3166	117	3437	3	7.9
19.1	365	53	0.15	-0.010	1.434	0.025	0.29383	0.00061	1.434	0.042	0.29391	0.00061	3411	130	3438	3	0.8
42.1	120	58	0.49	0.000	1.354	0.097	0.29507	0.00285	1.354	0.104	0.29507	0.00285	3565	357	3445	15	-3.5
44.1	278	191	0.71	0.012	1.292	0.092	0.29571	0.00056	1.292	0.099	0.29561	0.00056	3695	372	3447	3	-7.2
39.1	433	153	0.37	0.080	1.300	0.092	0.29708	0.00046	1.301	0.100	0.29640	0.00051	3676	369	3452	3	-6.5
96.1	126	103	0.85	0.014	1.485	0.055	0.29785	0.00225	1.485	0.057	0.29773	0.00225	3319	165	3458	12	4.0
8.1	88	52	0.61	0.054	1.392	0.030	0.29998	0.00121	1.393	0.045	0.29952	0.00123	3489	147	3468	6	-0.6
59.1	229	161	0.73	0.038	1.279	0.043	0.30210	0.00147	1.279	0.045	0.30178	0.00148	3724	174	3479	8	-7.0
56.1	187	88	0.48	0.007	1.289	0.042	0.30340	0.00139	1.289	0.044	0.30335	0.00139	3701	169	3487	7	-6.1
9.1	458	174	0.39	0.005	1.387	0.024	0.30884	0.00819	1.387	0.040	0.30880	0.00819	3500	134	3515	41	0.4
83.1	258	126	0.50	0.141	1.480	0.053	0.31124	0.00200	1.482	0.055	0.31005	0.00202	3325	160	3521	10	5.6
6.1	454	27	0.06	-0.006	1.419	0.031	0.31452	0.00059	1.419	0.046	0.31457	0.00059	3439	145	3543	3	3.0
37.1	289	249	0.89	-0.013	1.306	0.109	0.31562	0.00260	1.306	0.116	0.31573	0.00260	3665	423	3549	13	-3.3
85.1	207	122	0.61	0.020	1.333	0.048	0.32138	0.00174	1.333	0.050	0.32121	0.00175	3608	178	3576	8	-0.9
99.1	98	59	0.62	0.076	1.427	0.054	0.32357	0.00214	1.428	0.056	0.32294	0.00217	3422	175	3584	10	4.5
2.1	544	210	0.40	0.035	1.412	0.024	0.33332	0.00052	1.413	0.041	0.33303	0.00052	3451	131	3631	2	5.0
58.1	240	111	0.48	0.006	1.191	0.040	0.33449	0.00194	1.191	0.042	0.33444	0.00195	3929	187	3638	9	-8.0
17.1	291	81	0.29	0.029	1.322	0.023	0.33922	0.00071	1.322	0.039	0.33898	0.00071	3631	142	3658	3	0.7
77.1	108	63	0.61	0.000	1.329	0.047	0.35077	0.00199	1.329	0.049	0.35077	0.00199	3618	177	3710	9	2.5
71.1	102	67	0.68	0.000	1.217	0.043	0.35530	0.00413	1.217	0.044	0.35530	0.00413	3866	190	3730	18	-3.7
18.1	276	112	0.42	0.007	1.238	0.022	0.36380	0.00294	1.238	0.037	0.36374	0.00294	3816	152	3766	12	-1.4
69.1	373	323	0.90	0.014	1.184	0.039	0.36548	0.00160	1.184	0.041	0.36537	0.00160	3946	186	3772	7	-4.6

Notes: Analyses are listed in order of increasing ^{207}Pb*/^{206}Pb* age. *f*204 is the proportion of common ^{206}Pb in measured ^{206}Pb, as estimated using measured ^{204}Pb/^{206}Pb. Pb*, radiogenic Pb. U/Pb ratios and ages include calibration and reproducibility uncertainties (1 sigma), respectively, of 0.47% and 1.54% (analyses 1.1-24.1), 2.87 and 7.10% (analyses 25.1-45.1), and 0.99% and 2.70% (analyses 46.1-99.1). Disc., discordance, calculated as 100 × [1 − (^{238}U/^{206}Pb* age)/(^{206}Pb*/^{206}Pb* age)].

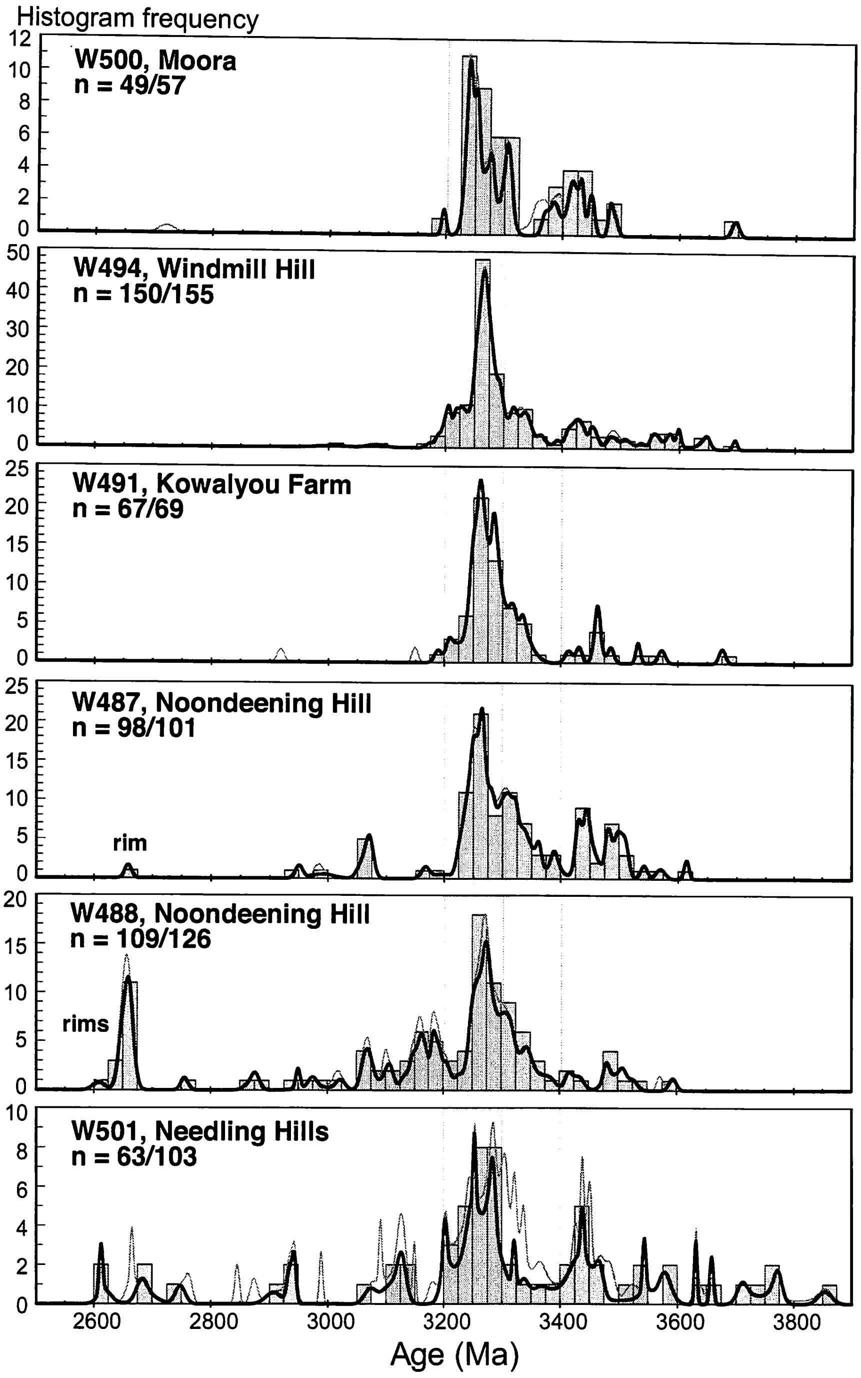

Fig. 2. Probability density diagrams and histograms of $^{207}Pb/^{206}Pb$ ages obtained for zircons from six TLGD quartzite samples. Thick curves and frequency histograms (bin width 25 Ma) include only data <5% discordant, thin curves include all data. n = ages < 5% discordant/total number of ages.

Hill, about 1.7 km southeast of the Noondeening Hill survey marker (fig. 1C). The sample site is in the westernmost of three bands of quartzite that strike north-northwest along the length of Noondeening Hill, located halfway between the towns of Toodyay and Northam. Zircons are mainly clear, colorless to pale brown, and up to 250 μm long. Some grains show complex oscillatory zoning, whereas others are broken fragments with linear zoning. Some grains have thin euhedral overgrowths concentrated at the grain terminations. Details of 101 analyses of 88 grains are given in Wingate and others (2008c). Excluding three analyses >5 percent discordant, the results show a large skewed peak between 3220 and 3400 Ma, with a median at c. 3275 Ma (fig. 2). The shoulder on this peak at c. 3380 Ma could indicate the presence of a second age component. Small, well-defined peaks occur at c. 3440 and c. 3490 Ma, and the oldest grain is c. 3614 Ma. A few grains are younger than 3200 Ma, and the peak at 3070 Ma (five analyses) may be significant. A single analysis of a low-Th/U (0.03) zircon overgrowth has a ^{207}Pb/^{206}Pb age of c. 2660 Ma.

W488 (GSWA 177908), Noondeening Hill

Sample W488 (MGA zone 50, 457624E, 6500083N) is a gray-white, coarse-grained, recrystallized quartzite, collected on Noondeening Hill, about 300 m southwest of W487 (fig. 1C). The zircons resemble those from W487, and consist of subhedral to subspherical detrital cores with thin subhedral to euhedral zircon overgrowths concentrated at grain terminations. Cathodoluminescence (CL) images of typical grains are shown in figure 3A. Results of 126 analyses on 91 zircons from this population are reported by Wingate and others (2008c). Most analyses are concordant to slightly discordant, and their distribution is consistent with episodes of ancient, and probably some recent, loss of radiogenic Pb. Excluding seventeen analyses >5 percent discordant analyses, the age spectrum exhibits a strong, asymmetrical peak between c. 3220 and 3390 Ma, with a median at c. 3280 Ma (fig. 2). In addition, there are smaller components at c. 3500 and c. 3420 Ma, and the oldest grain is c. 3593 Ma. A strong peak at c. 2660 Ma represents 14 analyses deliberately targeted on low-Th/U zircon overgrowths (fig. 3A). Additional results between 2750 and 3200 Ma include peaks at c. 3170 and c. 3070 Ma. F3

W501, Needling Hills

Sample W501 (MGA zone 50, 494761E, 6473421N) was taken from an outcrop of foliated quartzite from the eastern end of the Needling Hills, about 20 km east of the town of York (fig. 1C). Zircons were generally small (<100 μm in length), with irregular to rounded forms. A total of 103 analyses of 99 grains were made over two sessions (table 2). Excluding 40 analyses >5 percent discordant, the remaining 65 analyses range mainly between 2900 and 3850 Ma, with prominent age peaks at c. 3440 Ma, c. 3250 Ma and a minor peak at c. 3125 Ma. The age of 3854 ± 12 Ma (1σ) is the oldest found in the present study. Five analyses younger than 2800 Ma were obtained from variably metamict, high-U zircon (figs. 3B and C).

DISCUSSION

Apparent Ages Younger than 3000 Ma

SHRIMP U–Pb ages as young as c. 2650 Ma were obtained for euhedral rims and alteration patches in grains from samples W487, W488, and W501 from the southern part of the TLGD (table 2, fig. 2). These younger zircon components could have formed from penetrating hydrothermal solutions associated with high-grade metamorphism of the Jimperding metamorphic belt or possibly with the emplacement of surrounding granitic rocks.

Fourteen analyses of euhedral zircon rims (fig. 3A) in sample W488 (177908) yield ages between 2666 and 2643 Ma (fig. 4). These overlap with the c. 2649 to 2640 Ma ages F4

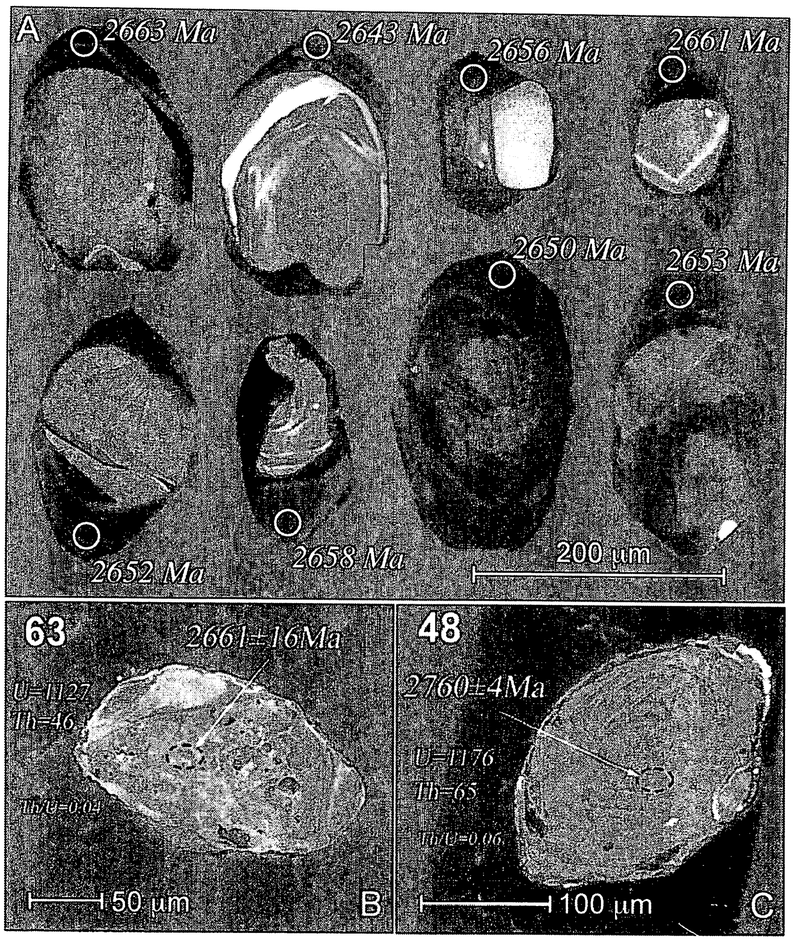

Fig. 3. Cathodoluminescence (CL) images of selected zircons. (A) Typical zircon rims in sample W488, showing the approximate locations of analysis sites and ^{207}Pb/^{206}Pb dates obtained. (B) and (C) examples of zircons in sample W501 that yield ^{207}Pb/^{206}Pb ages between 2700 and 2600 Ma. These analyses are located on areas of altered zircon, typified by spongy, featureless, irregular-shaped patches overprinting the original euhedrally zoned zircon.

of zircons from mafic granulites in the TLGD reported by Nemchin and others (1994), and support a metamorphic origin for the overgrowths. However, the ages of the zircon rims can also be compared with the history of formation of the surrounding Darling Range granites. Nemchin and Pidgeon (1997) proposed the following history of granite emplacement: "initial granite magma formation between 2690 Ma and 2650 Ma, crystallization and emplacement of granite magma at 2648 to 2626 Ma, and slow cooling, indicated by marginal re-crystallization and continued Pb loss from the zircons until 2628 to 2616 Ma."

Although the age of zircon rims is within that of granite emplacement we favor a metamorphism-related hydrothermal origin, because the rims occur only on zircons from samples in zones of high metamorphic grade. Several results that fall between the age of the rims and c. 3050 Ma, the age of deposition of the quartz-rich sediments, are attributed to analysis of mixtures of rim and core material or to analysis of alteration patches observed in some zircons. Hydrothermally altered zircons are most common in sample W501 from the Needling Hills. We have not studied the alteration in detail,

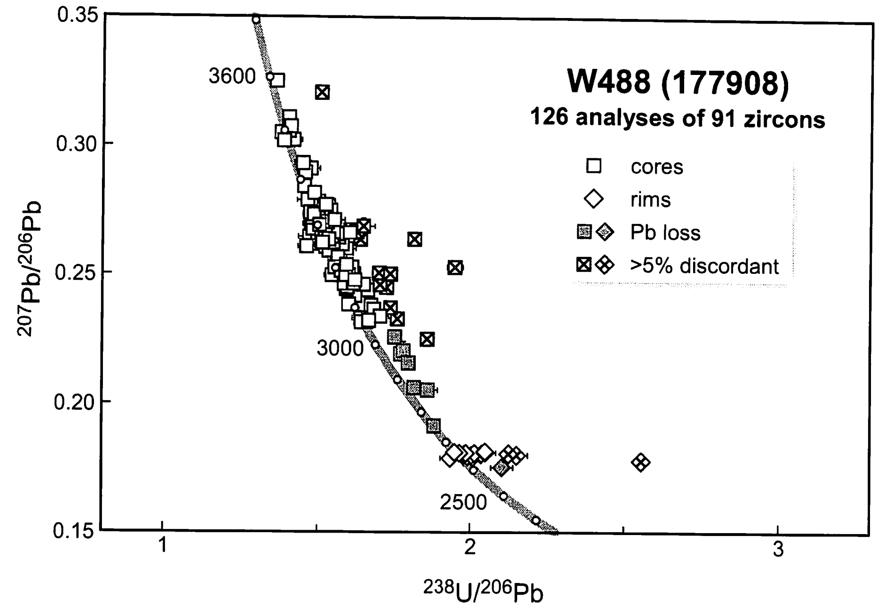

Fig. 4. Concordia diagram showing U–Pb data for sample W488, indicating analyses of detrital zircon cores (square symbols) and c. 2660 Ma metamorphic zircon rims (diamonds). All data are corrected for common Pb.

because this is beyond the scope of the present "provenance" study. However, the alteration patches typically occur as irregular-shaped, featureless to granular areas exhibiting vestiges of primary igneous zoning (figs. 3B and C). Analyses conducted entirely or partially of these areas invariably produce intermediate ages, reflecting the interaction of hydrothermal fluids with radiation-damaged zircon, resulting in partial loss of radiogenic Pb and possibly the addition of other trace elements, as demonstrated experimentally (Geisler and others, 2001). In view of the above, zircon ages between c. 3050 Ma, the age of sedimentation, and c. 2650 Ma, the age of metamorphism, are disregarded below in assessing the significance of the detrital zircon age spectra from the TLGD.

Zircon Age Spectra for the Toodyay-Lake Grace Domain (TLGD)

The most striking feature of the detrital zircon age spectra of the TLGD is the major age component between c. 3350 and 3200 Ma, present in all six samples (fig. 2). The age spectrum for all six samples combined (fig. 5) shows that this peak is F5 asymmetric and may represent two or more generations of zircon too close in age to resolve, but is dominated by a peak at c. 3265 Ma. Most zircons included in this age component have U and Th contents of 50 to 800 ppm and 50 to 300 ppm, respectively, and Th/U ratios of 0.1 to 1.0 (tables 1 and 2). These parameters, together with the euhedral, concentric growth zoning in many zircons, as seen in CL images (fig. 3A), suggest that most of the zircons were derived from a 3300 to 3200 Ma generation of granitic rocks. Granites of this age are not known in the southern Yilgarn Craton, with the possible exception of a c. 3250 Ma orthogneiss from the Jimperding metamorphic belt reported by Nieuwland and Compston (1981).

Also present in the zircon age spectrum is a smaller component between 3500 and 3400 Ma (fig. 2). Based on zoning in the zircons and their U and Th contents we similarly interpret this generation of zircons to represent an earlier episode of

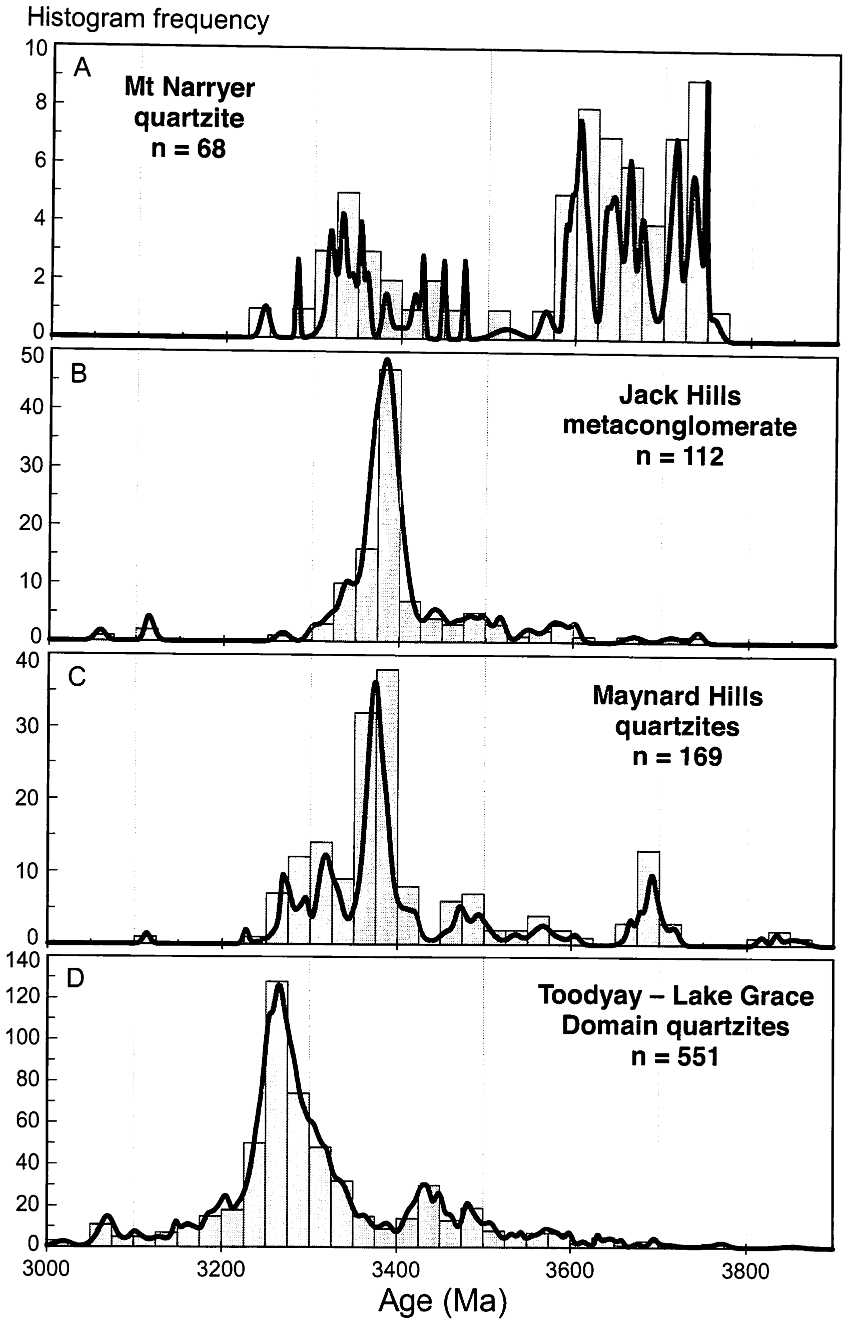

Fig. 5. Probability density diagrams and histograms for detrital zircon ages between 3.0 and 3.9 Ga. (A) Quartzite from Mt Narryer (Pidgeon and Nemchin, 2006) in the Narryer Terrane (NT), (B) metaconglomerate from the Jack Hills greenstone belt (Pidgeon and Nemchin, 2006) in the NT, (C) quartzites from the Maynard Hills greenstone belt (Wyche, 2007, and references therein) in the Southern Cross Domain (SCD), and (D) quartzites from the Toodyay-Lake Grace Domain (TLGD) of the South West Terrane (this study). All data are <10% discordant; ages from duplicate analyses of the same zircons are averaged.

granitoid emplacement. Small peaks at c. 3000 Ma in the southernmost samples (W487, W488, and W501) might represent a minor contribution of zircons from c. 3000 Ma granites or greenstones which are known in the Yilgarn Craton (for example Pidgeon and Wilde, 1990).

Zircons older than 3500 Ma are present in all six TLGD samples and vary in amount and age, but apparently not systematically (fig. 2). Only a single >3500 Ma grain was detected in the northernmost sample (W500). Zircons of this age are most common in the sample from Windmill Hill (W494, 16 zircons), and in the southernmost sample, from the Needling Hills (W501, 12 zircons). No detrital zircons in the TLGD samples yielded ages >4.0 Ga. This represents a major difference between the detrital zircon age spectra in the TLGD quartzites compared to similar rocks in the NT and SCD. The oldest zircon in the TLGD samples (W501), with an age of c. 3854 ± 24 Ma (2σ), is older than any zircon age reported for gneisses in the NT (Kinny and others, 1988; Nutman and others, 1991).

The 3500 to 3400 and 3350 to 3200 Ma age components, as well as a few >3500 Ma zircons, vary in proportion from one sample to another, which may reflect differences in the local abundances of different generations of granites or to vagaries of the local weathering and transport systems. Despite these minor variations, the characteristic features of the TLGD detrital zircon age spectra form a basis for comparison with zircon ages from quartzitic metasediments in c. 3.1 Ga quartzites and conglomerates in the NT and the SCD to the north and east.

Comparison of Detrital Zircon Age Profiles from the Narryer Terrane (NT) and Southern Cross Domain (SCD)

Nelson (2001) and Wyche and others (2004) argued that the similarity of the age profiles of detrital zircons from quartzites from the Maynard Hills and Illaara greenstone belts in the SCD, Windmill Hill (Kinny 1990) in the TLGD, and the Jack Hills in the NT, suggests they were derived from a similarly aged continental source. Wyche (2007) reached the same conclusion based on analyses of detrital zircons from additional samples from the Maynard Hills and the Illaara greenstone belts.

The most intensely studied detrital zircon suites in the Yilgarn Craton are from c. 3.1 Ga metaconglomerates from the Jack Hills in the NT (fig. 1A) (for example Compston and Pidgeon, 1986; Maas and McCulloch, 1991; Cavosie and others, 2004; Crowley and others, 2005; Dunn and others, 2005; Pidgeon and Nemchin, 2006; Kemp and others, 2010). The Jack Hills zircons form two main age components, those older and those younger than 3.9 Ga. Because we have found no >3.9 Ga zircons in the TLGD samples, and only one such grain has been reported for samples from the Maynard Hills greenstone belt (Wyche and others, 2004) (fig. 1A), we have restricted the present discussion to the age distributions of the 3900 to 3100 Ma detrital zircon populations (fig. 5).

Several studies are in agreement (for example Crowley and others, 2005; Pidgeon and Nemchin, 2006) that the U–Pb ages of the younger group of detrital zircons, from the original "old zircon" locality in the Jack Hills (Compston and Pidgeon, 1986), are characterized by a broad age component from c. 3400 to c. 3300 Ma, with a well-defined maximum at c. 3380 Ma and a low shoulder extending to 3600 Ma (fig. 5B). Crowley and others (2005) referred to these zircons as "Group 1" and Pidgeon and Nemchin (2006) referred to them as the "Jack Hills type." Crowley and others (2005) reported more complex zircon age profiles for samples from elsewhere in the Jack Hills belt that they referred to as their "Group 2." These contained few grains coeval with the 3380 Ma "Group 1" peak, and are generally evenly spread from 3650 to 3200 Ma. This "Group 2" distribution is also observed in results for other Jack Hills samples dated by GSWA (Nelson, 2004; Wingate and others, in preparation). It is clear that more variation exists in the age spectra of the Jack Hills detrital zircons than is evident in the zircon ages from the original old zircon site of Compston and Pidgeon (1986). Also, it appears that some Jack Hills quartzite bands may contain Proterozoic zircons, suggesting that at least some of the sediments have been reworked in the Proterozoic (Cavosie and others, 2004; Grange and others, 2010), and caution must be exercised in assessing the significance of detrital zircon age spectra from Jack Hills samples.

The distributions of U–Pb ages of detrital zircons from quartzites from Mt Narryer have been described by Froude and others (1983), Maas and McCulloch (1991), Crowley and others (2005), and Pidgeon and Nemchin (2006). Crowley and others (2005) reported age spectra for nine samples from old to young sedimentary units in the Mt Narryer quartzite. They found that the zircon ages range from c. 3750 to c. 3300 Ma, with peaks at 3650, 3600, and 3500 Ma, and noted that the age components tended to be younger in the higher (younger) units. Nemchin and Pidgeon (2006) reported a similar zircon age distribution for a sample taken from lithostratigraphic unit C, in which the <3.9 Ga zircons are dominated by two main age components, one at 3750 to 3600 Ma and a second at 3450 to 3250 Ma (fig. 5A). This contrasts with the detrital zircon age spectrum (fig. 5B) from the original discovery outcrop in the Jack Hills, which is dominated by a single 3500 to 3350 Ma component, with a strong peak at 3380 Ma (Crowley and others, 2005; Pidgeon and Nemchin, 2006). This difference was noted previously by Nutman and others (1991), based on the measurements of Froude and others (1983) and Compston and Pidgeon (1986), and strongly suggests that the Mt Narryer sediments were derived from a different source to that which provided type 1 zircons in the Jack Hills conglomerate.

Results of SHRIMP U-Pb analyses of detrital zircons from six quartzite samples from the Maynard Hills greenstone belt of the SCD are given in Wyche, 2007, and references therein). One grain with an age of c. 4350 Ma was found in sample 169075 (Nelson, 2005a). Otherwise, zircon ages in the six samples range from 3920 to 3131 Ma. Minor age differences within and between the zircon components of the different samples may indicate local variations in the composition of the provenance, although the overall similarity of the age distributions suggests that, within the limitations of the relatively small data sets, the provenance of the quartzites is consistent over the length of the greenstone belt. The age spectrum of the combined results (fig. 5C) is therefore a reliable estimate of the age distribution of detrital zircons in the Maynard Hills quartzites.

It is evident that the prominent peak at c. 3380 Ma and the spread of minor peaks to older ages in the spectra for the Jack Hills and the Maynard Hills detrital zircons are almost identical (fig. 5). On this basis, we agree with Wyche (2007), that the detrital zircons in the Maynard Hills in the SCD and Group 1 zircons from the Jack Hills in the NT were derived from a similarly aged continental source. Further support for a common source for detrital zircons in metasediments from the Jack Hills and Maynard Hills is the presence in these samples of >4.1 Ga zircons. Very old zircons are also present in one (178064; Nelson, 2005) of the two quartzite samples from the Illaara greenstone belt, and the <3.9 Ga age spectrum for the second Illaara sample (142999; Nelson, 2000) is very similar to those for the Jack Hills and Maynard Hills samples, and we tentatively propose that the Illaara quartzites had the same source rocks as those in the Jack Hills and the Maynard Hills. As concluded by Wyche (2007), it is unlikely that the provenance of the Jack Hills quartzites in the NT and the Maynard Hills and Illaara quartzites in the SCD were separate entities prior to the deposition of the quartz-rich clastic sedimentary rocks at c. 3.1 Ga. On this evidence alone, there is no basis for dividing this part of the Yilgarn Craton into separate terranes.

Neither the Jack Hills nor the Maynard Hills detrital zircon age spectra contain the prominent age component between c. 3600 and 3800 Ma, which is evident in the spectrum for the Mt Narryer quartzite (fig. 5).

Comparison of Detrital Zircon Age Profiles from the Jack Hills, Mt Narryer, and the Toodyay-Lake Grace Domain (TLGD)

As shown in figure 5, the detrital zircon age spectrum of the TLGD is different from those of both the Mt Narryer and Jack Hills samples. The dominant age component at c. 3265 Ma in the TLGD profile is not present in age profiles for the Mt Narryer or the Jack Hills and, similarly, the prominent age components in the Mt Narryer and Jack Hills spectra are not present in age distributions for the TLGD. This is taken as convincing evidence that the source rocks for the quartz-rich sediments of the TLGD were different from those of Mt Narryer and the Jack Hills. It is interesting that the detrital zircon age spectra from the Jack Hills and Maynard Hills and the TLGD are dominated by single age components interpreted to represent granite-generation events separated in time by just over 100 Ma.

The Presently Exposed Narryer Terrane as a Possible Source of the Detrital Zircon Suites

The question of whether the Mt Narryer and the Jack Hills detrital zircons were derived from presently exposed gneisses in the NT has been addressed by Myers and Williams (1985), Crowley and others (2005), and Amelin (1998). The prominent 3750 to 3600 Ma component in zircon ages from the Meeberrie gneiss (Kinny and others, 1988; Kinny and Nutman, 1996; Pidgeon and Wilde, 1998; Crowley and others, 2005) is present in the detrital zircon profile of the Mt Narryer quartzite (fig. 5A), suggesting that the Meeberrie gneiss was a source of detrital zircons for the quartzite. However, the 3750 to 3600 Ma age component is not represented in the type 1 zircon age spectrum for the Jack Hills metaconglomerate. Amelin (1998) stated that "a direct comparison between the ages of the detrital zircons (Jack Hills) and the dated gneisses in the Narryer Gneiss Complex indicates that the sediment provenance, or at least a considerable part of it, is distinct from the rocks presently exposed in the area."

The age distributions of zircons in gneisses and granites of the Meeberrie gneiss are extremely complex, with zircons in most samples ranging in age from 3.7 to 3.3 Ga, and including significant age components at c. 3.75 to 3.6 and c. 3.3 Ga (fig. 7 of Kinny and Nutman, 1996). This inhomogeneity also extends to individual zircons (Pidgeon and Wilde, 1998). The detrital zircon age spectra from the TLGD (figs. 2 and 5D) do not exhibit age components similar to those summarized by Kinny and Nutman (1996) and we discount the possibility that zircons, characteristic of the Meeberrie gneiss, were a significant component of the source rocks of the TLGD.

However, the Meeberrie gneiss (Myers and Williams, 1985), which surrounds the Jack Hills, includes granites and pegmatites with zircon U–Pb ages of c. 3290 Ma and without inherited grains (Nutman and others 1991; Kinny and Nutman, 1996; Pidgeon and Wilde, 1998). This result is within the range of ages, and close to the main peak age of c. 3265 Ma, for detrital zircons from the TLGD. This may be a coincidence and the small age difference between the ages may be real. Also, these rocks are a minor component of the exposed NT and do not influence our conclusion that the presently exposed NT was not a provenance for the zircons in the quartzitic metasediments of the TLGD. However, it remains possible that the c. 3290 Ma granites were extensively developed in a missing part of the proto-Yilgarn Craton that formed the provenance for sediments of the TLGD. The minor component of >3.4 Ga zircons in the age spectra of the TLGD (fig. 5D) could also be explained by the incorporation of zircons from remnant fragments of Meeberrie gneiss. Although not conclusive this can be taken as support for the conclusion of Wyche (2007) that "it is unlikely the areas now occupied by the Youanmi, South West, and Narryer Terranes were separate entities prior to the deposition of quartz-rich clastic sedimentary rocks at c. 3100 Ma."

CONCLUSIONS

Evidence for the early evolution of the Yilgarn Craton has been largely obliterated by the extensive and widespread emplacement of granites at c. 2650 Ma. Apart from the old gneisses in the Narryer Terrane (NT), the only surviving fragments of the early Yilgarn Craton are detrital minerals in c. 3.1 Ga quartz-rich metasediments in the NT, the Southern Cross Domain (SCD) and the South West Terrane (fig. 1). Comparison of the age distributions of zircons from these metasediments holds the key to clarifying the early history of the craton. Our determinations, reported in this contribution, of the age profiles of detrital zircons from quartzites of the Toodyay-Lake Grace Domain (TLGD) provide new data aimed at answering some of the major questions.

We show that the provenance of the TLGD was dominated by granitic rocks emplaced at c. 3265 Ma, and included a lesser component of 3500 to 3350 Ma granites, and a minor component of rocks or inherited zircons with ages up to c. 3850 Ma. The detrital zircon age spectra from the TLGD quartzites are very consistent, and do not match those from Mt Narryer or the Jack Hills in the NT or the Maynard Hills in the SCD, indicating that these sediments were derived from separate provenances in the proto-Yilgarn Craton. The absence of zircons with ages >3.9 Ga also distinguishes the age spectra of the TLGD from those of Mt Narryer and the Jack Hills in the NT and the Maynard Hills and Illaara greenstone belts in the SCD. The TLGD zircon age spectra are also not compatible with the ages of gneisses presently exposed in the NT, demonstrating that the gneisses were not a source of sediment in the TLGD. However, the age of c. 3290 Ma for a minor suite of granites within the NT is within the range of detrital zircon ages in the TLGD, and it is therefore possible that these granites formed part of the provenance of the TLGD.

The age spectrum of detrital zircons from the Jack Hills metaconglomerate is similar to those from Maynard Hills quartzites, indicating that these sediments shared a common provenance at the time of sedimentation, questioning the concept that the two terranes followed a separate history prior to the amalgamation of the Yilgarn Craton at c. 2.65 Ga (Myers, 1990, 1995). However, the age spectra for detrital zircons from the Mt Narryer quartzites and the Jack Hills metaconglomerate are significantly different, indicating that they were derived from different source areas, prompting questions about the early coherence of the NT.

Although considerable progress has been made, the present detrital zircon age database is not sufficient to underpin a general model for the evolution of the Yilgarn Craton. Available results raise doubts about the model of accretion of independent terranes at c. 2.65 Ga. However, additional studies of the ages of detrital zircon suites from other c. 3.1 Ga quartzitic metasediments are needed to further address outstanding questions regarding the early history of the Yilgarn Craton.

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