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New U–Pb zircon ages from Paleo–Mesoarchean TTG gneisses of the Singhbhum Craton, Eastern India

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Two new U–Pb ages of 3448 ± 19 Ma and 3527 ± 17 Ma were obtained on zircons from the Older Metamorphic Tonalite Gneisses (OMTG), Singhbhum North Orissa Craton, Eastern India. These dated TTG-type OMTG gneisses are from the least studied northern area of the Singhbhum Craton. They occur as enclaves in the Singhbhum granite batholith (SBG), emplaced during two distinct periods: from 3440 to 3330 Ma (SBG-A) and from 3200 to 3050 Ma (SBG-B). The U–Pb age of 3448 ± 19 Ma age is close to the older SBG-A phase. The U–Pb age of 3527 ± 17 Ma could corresponds to an older intrusive or inherited from a xenocryst population. Dacitic lava from the southern BIF-bearing Iron Ore Group (IOG) greenstone belt has been recently dated at 3506 ± 2.3 Ma suggesting that it is older than both phases of the SBG. It is thus possible that the metasedimentary rocks of the Older Metamorphic Group (OMG), occurring as enclaves in both OMTG and SBG suites, might be partly derived from the IOG rocks.

Keywords: U–Pb geochronology, zircon, Paleoarchean, Singhbhum granite batholith, Singhbhum Craton

INTRODUCTION

The eastern segment of the Indian Precambrian shield includes one of India's older records of Paleoarchean crust, known as the Singhbhum North Orissa Craton or simply the Singhbhum Craton (Fig. 1). The craton is composed primarily of the Singhbhum granite batholith (SBG; Fig. 1) and narrow greenstone belts associated with Banded Iron Formations called the Iron Ore Group (IOG; Fig. 1). The SBG was emplaced during two distinct phases: from 3440 to 3330 Ma (older phase: SBG-A) and from 3200 to 3050 Ma (younger phase: SBG-B). The SBG contains enclaves of metasedimentary rocks (referred to as the Older Metamorphic Group or OMG) and TTG gneisses (referred to as the Older Metamorphic Tonalite Gneiss or OMTG; Saha, 1994). Acid volcanics from the southern IOG belt have been dated at 3507 ± 2.3 Ma (U–Pb on zircon by SHRIMP; Mukhopadhyay *et al.*, 2008), which is older than the two SBG phases, as well as, the major and younger component of the OMTG. Therefore, OMG enclaves, considered as the oldest supracrustal rocks in the region might be derived from IOG rocks. The OMTG and SBG-A rocks are petrographically and geochemically similar but OMTG is known to contain components as old as 3660 ± 79 Ma (Ghosh *et al.*, 1996; Fig. 1).

This paper reports two new U–Pb zircon ages of 3448 ± 19 Ma and 3527 ± 17 Ma for the TTG gneisses of the OMTG. These gneisses are from the previously undated northern part of the craton (Figs. 1 and 2).

GEOLOGICAL BACKGROUND

The oldest supracrustal enclaves of the SBG (OMG), consist of amphibolite grade pelitic schists, arenites, calc-magnesian metasediments, para- and ortho-amphibolites, synkinetically intruded and partially digested by a suite of biotite (hornblende) tonalite gneisses grading into trondhjemite-granodiorite (OMTG; Sarkar and Saha, 1977, 1983; Saha, 1994). The majority of the OMTG rocks fall in the trondhjemite field. Geochemically, OMTG shows remarkable similarity with Paleoarchean TTGs from different parts of the world, except for having conspicuously low Ti V, Y, Zr, Ba and Rb, and higher Sr and Mn (Saha, 1994). To the south of Holudpukur, Saha (1994) mapped extensive exposures of supracrustal rocks as OMG, which are of lower metamorphic grade and comprise pillow basalts, gabbros, ultramafic rocks, ferruginous arenites and tuffaceous rocks. These closely resemble the IOG assemblage (Fig. 2).

The OMG and OMTG rocks from the Champua and Onlajori areas (Fig. 1) range in age from 3660 to 3330

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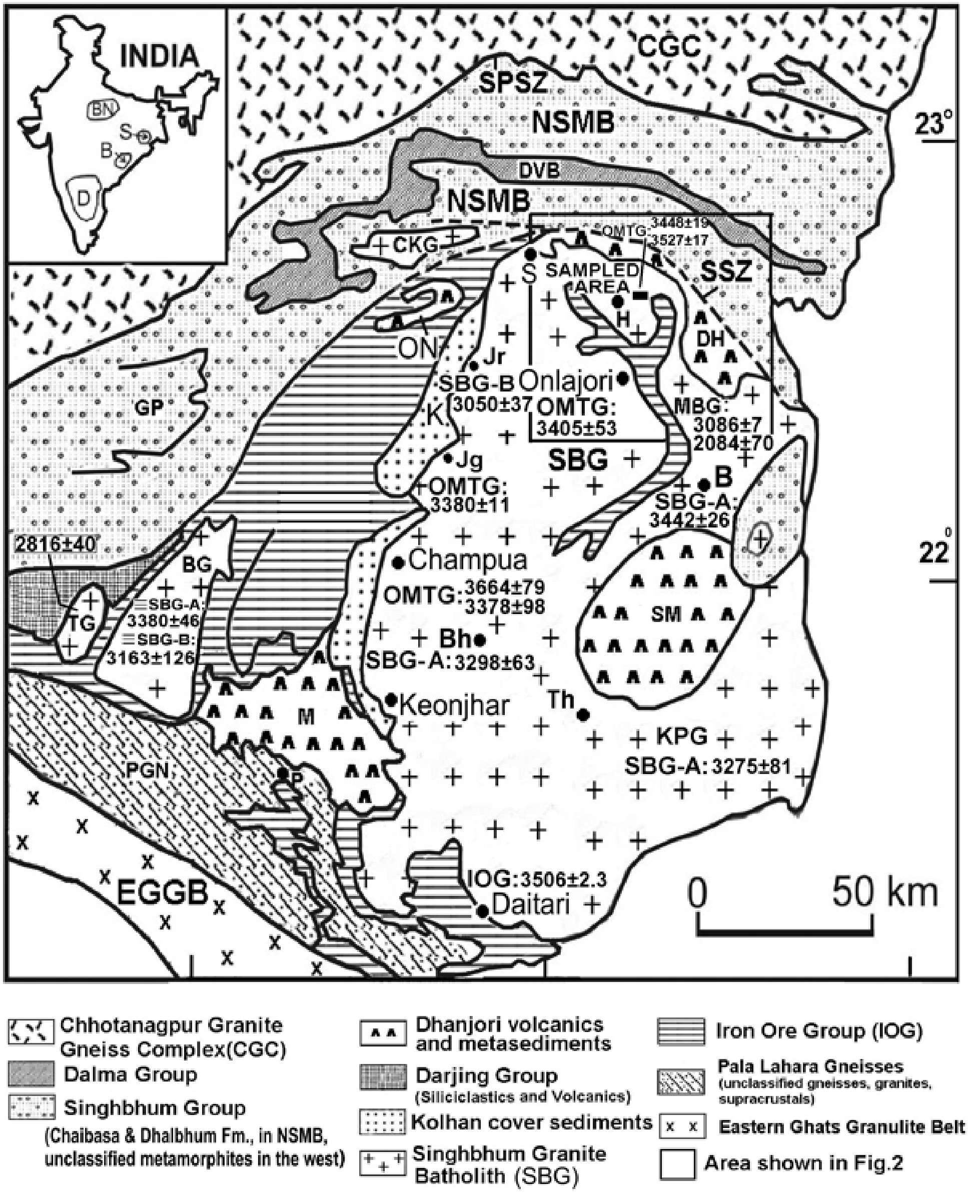

Fig. 1. Simplified geological map of the Singhbhum North Orissa Craton and the surrounding Proterozoic mobile belts, Eastern India (modified after Saha, 1994). Abbreviations for geologic units: DVB, Dalma Volcanic Belt; DH, Dhanjori Basin; ON, Ongarbira volcanics; IOG, Iron Ore Group; M, Malangtoli volcanics; SM, Simlipal volcanics; Singhbhum Granite, (SBG) and adjacently located granite plutons e.g., BG, Bonai Granite; CKG, Chakradharpur Granite; KPG, Kaptipada Granite; MBG, Mayurbhanj Granite; TG, Tamperkola Granite; remnants of older supracrustal rocks Older Metamorphic Group (OMG) and Older Metamorphic Tonalite Gneiss (OMTG) not shown; GP, Gangpur Basin; K, Kolhan cover sediments; EGGB, Eastern Ghats Granulite Belt; NSMB, North Singhbhum Mobile Belt; PGN, Pala Lahara Gneiss; SSZ, Singhbhum Shear Zone. Localities: B, Besoi; Bh, Bhaunra; H, Hata/Haludpukur; Jg, Jagannathpur; Jr, Jorapokhar; S, Saraikela; Th, Thakurmunda. Ages in Ma are shown for OMTG, SGB-A, SGB-B and IOG. Index for inset map: B, Bastar craton; BN, Bundelkhand craton; D, Dharwar craton; S, Singhbhum craton.

Ma (Pb–Pb on WR, Moorbath *et al*., 1986; Sm–Nd on WR, Sharma *et al*., 1994; Pb–Pb on zircon, Goswami *et al*., 1995; Pb–Pb on WR, Ghosh *et al*., 1996; Pb–Pb on zircon, Misra *et al*., 1999). The SBG-A and SBG-B from different areas yielded 3440–3300 Ma and 3200–3050 Ma ages, respectively (Fig. 1; Saha, 1988, 1994; Pb–Pb on WR, U–Pb on zircon and Sm–Nd on WR, Sengupta *et al*., 1991, 1996; Pb–Pb on WR, Ghosh *et al*., 1996). Therefore, the older phase of SBG-A corresponds to the younger and major components of the OMTG (Fig. 1). The rocks

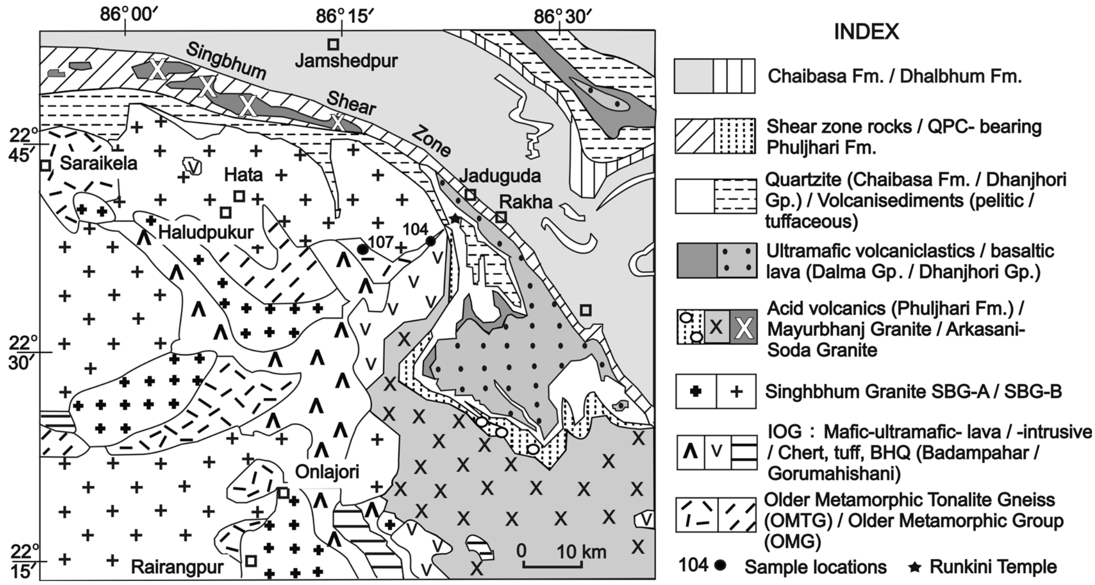

Fig. 2. Geological map of the studied area showing sample locations (modified after Saha, 1994; Sarkar and Saha, 1962). Abbreviations: Gp., Group; Fm., Formation.

belonging to the SBG-A phase are also geochemically similar to the OMTG rocks, as they are both K_2O-poor (1.5–2.5%) granodiorite to tonalite and also showing comparable REE pattern (Saha, 1994). On the other hand, the SBG-B is more granitic in affinity (K_2O up to 4–5% and SiO_2 up to 75–76%; Saha, 1994). The presence of the Tamperkola and the Mayurbhanj Granite Pluton close to the western and eastern margins of the Singhbhum Craton are a clear evidence of Neoarchean (3.0–2.8 Ga) magmatic activity (Saha *et al*., 1977; Misra *et al*., 1999; Bandyopadhyay *et al*., 2001).

The Singhbhum Granite massif is flanked to the north by a volcano-sedimentary fold belt of Neoarchean–Paleoproterozoic age (North Singhbhum Mobile Belt or NSMB; Fig. 1), whereas the Singhbhum Shear Zone (SSZ) occurs close to the northern margin of the craton.

Samples and Methods

The studied area is located in the northern region of the SBG complex. A crescent shaped OMTG body (Kalikapur body in Saha, 1994) is exposed intermittently for about 15 km. The mafic-ultramafic rocks of the IOG Badampahar–Gorumahisani belt are exposed in the southwest and the SBG-B rocks in the north, up to the boundary with the NSMB (Figs. 1 and 2).

Two samples of moderately foliated TTG gneisses from the SBG-A suite were collected from the two ends of the OMTG body: sample no. 03122104, west of the Runkini Temple (22°37′43″:86°18′33″) and sample no. 03122107, south of the Potka Police Station (22°37′11″:86°24′39″) (Fig. 2; Table 1). These samples are hereafter referred to as sample 104 and sample 107, respectively.

SBG-A gneisses are composed primarily of plagioclase, rather than K-feldspar. Chlorite and biotite are common, while accessory minerals include hornblende, epidote, sphene, apatite, zircon, tourmaline and sometimes garnet. The An–Ab–Or plots mostly fall in the trondhjemite field. They display a LREE-enriched to steeply sloping REE pattern, without Eu-anomaly, a characteristic feature comparable with that observed in the Ancient Gneissic Complex of Barberton, South Africa (Saha, 1994).

In order to identify and discriminate primary magmatic zircons from recycled populations, the morphological criteria from Pupin (1980) were applied. Zircon crystals selected for U–Pb dating display euhedral habits, without overgrowth and abrasion effects.

U–Pb isotopic analyses of the zircons were carried out at the Earthquake Research Institute, The University of Tokyo, using a Thermo Elemental VG 3 UV-Laser Ablation Inductively Coupled Plasma-Mass Spectrometer (LA-ICP-MS). The CHICANE ion lens optics system was applied to the LA-ICP-MS to obtain enhanced (2–3 times higher) sensitivity, compared to the ordinary setting (Orihashi *et al*., 2003; Iizuka and Hirata, 2004). A 213-nm Nd-YAG UV laser (UP-213) produced an ablation pit of 30 μm with *ca*. 20 μm depth, under ablation energy of 11–13 mJ/cm^2, with a pulse repetition rate of 10 Hz and 20 ns duration. For enhancing the elemental sensitivity of the heavy mass range a small, amount of N_2 gas (1.0

Table 1. U–Pb isotope data for zircon crystals determined by LA-ICP-MS

Serial No.	Grain No.	Spot No.	Position[(a)]	Th/U	^{206}Pb[(b)] (%)	$^{207}Pb/^{206}Pb \pm 2\sigma$	$^{206}Pb/^{238}U \pm 2\sigma$	$^{207}Pb/^{235}U \pm 2\sigma$	^{238}U–^{206}Pb age (Ma)	^{235}U–^{207}Pb age (Ma)
Sample No. 03122104 (OMTG). Jaduguda–Hata road. Lat. 22°37′43″, Long. 86°18′33″										
1	1	1	R	0.73	0.78	0.3016 ± 0.0044	0.662 ± 0.019	27.51 ± 0.90	3273 ± 96	3402 ± 111
2	1	2	C	0.29	0.12	0.3045 ± 0.0046	0.702 ± 0.021	29.49 ± 0.98	3429 ± 101	3470 ± 115
3	2	3	R	0.26	0.26	0.3118 ± 0.0046	0.727 ± 0.021	31.23 ± 1.03	3520 ± 103	3526 ± 116
4	2	4	C	0.36	0.33	0.3097 ± 0.0048	0.697 ± 0.021	29.78 ± 1.00	3410 ± 101	3479 ± 116
5	3	5	R	0.55	0.29	0.3154 ± 0.0047	0.696 ± 0.020	30.27± 0.99	3405 ± 100	3495 ± 115
6	3	6	C	0.45	0.01	0.3062 ± 0.0045	0.615 ± 0.018	25.95 ± 0.85	3089 ± 90	3344 ± 110
7	4	7	C	0.72	1.07	0.2827 ± 0.0044	0.466 ± 0.014	18.15 ± 0.60	2465 ± 72	2998 ± 100
8	5	8	R	1.09	0.17	0.2946 ± 0.0040	0.566 ± 0.016	23.00 ± 0.74	2892 ± 84	3227 ± 104
9	6	9	C	0.79	0.63	0.2936 ± 0.0044	0.569 ± 0.017	23.04 ± 0.76	2903 ± 85	3228 ± 106
10	7	10	R	0.68	0.43	0.2781 ± 0.0042	0.475 ± 0.014	18.21 ± 0.60	2505 ± 73	3001 ± 99
11	7	11	C	0.64	0.30	0.3048 ± 0.0086	0.667 ± 0.021	28.02 ± 1.20	3293 ± 106	3420 ± 146
12	8	12	C	0.89	0.48	0.2646 ± 0.0074	0.469 ± 0.015	17.12 ± 0,73	2481 ± 79	2941 ± 125
13	9	13	R	0.64	0.07	0.3059 ± 0.0085	0.697 ± 0.022	29.38 ± 1.24	3408 ± 109	3466 ± 146
14	9	14	M	0.71	0.11	0.3030 ± 0.0084	0.716 ± 0.023	29.92 ± 1.26	3481 ± 111	3484 ± 147
15	9	15	C	0.58	0.25	0.3060 ± 0.9985	0.733 ± 0.023	30.94 ± 1.31	3546 ± 113	3517 ± 149
16	10	16	C	0.40	1.34	0.3109 ± 0.0089	0.743 ± 0.028	31.85 ± 1.37	3581 ± 116	3545 ± 153
17	11	17	C	1.18	0.04	0.2960 ± 0.0081	0.613 ± 0.020	25.02 ± 1.05	3082 ± 98	3309 ± 139
18	12	18	R	0.39	0.53	0.3085 ± 0.0087	0.687 ± 0.022	29.23 ± 1.25	3373 ± 108	3461 ± 148
19	12	19	C	0.70	0.25	0.3043 ± 0.0085	0.662 ± 0.021	27.79 ± 1.18	3276 ± 105	3412 ± 145
20	13	20	C	0.31	0.38	0.3083 ± 0.0087	0.693 ± 0.022	29.47 ± 1.26	3394 ± 109	3469 ± 149
Sample No. 03122107(OMTG) Jaduguda–Hata road (south to Potka Police Station). Lat. 22°37′11″, Long. 86°24′39″										
21	1	1	R	0.56	0.50	0.2964 ± 0.0059	0.6653 ± 0.0241	27.186 ± 1.120	3286 ± 119	3390 ± 140
22	2	2	R	0.57	1.15	0.2880 ± 0.0056	0.5896 ± 0.0213	23.409 ± 0.960	2988 ± 108	3244 ± 133
23	3	3	C	0.67	0.03	0.2748 ± 0.0053	0.5347 ± 0.0193	20.260 ± 0.828	2761 ± 99	3104 ± 127
24	4	4	R	0.60	n.d.	0.2854 ± 0.0056	0.6420 ± 0.0232	25.265 ± 1.039	3197 ± 115	3318 ± 136
25	4	5	M	0.82	0.05	0.2911 ± 0.0056	0.6714 ± 0.0242	26.951 ± 1.103	3311 ± 119	3382 ± 138
26	4	6	C	0.52	0.23	0.2734 ± 0.0053	0.5610 ± 0.0202	21.150 ± 0.867	2971 ± 103	3145 ± 129
27	5	7	R	0.57	n.d.	0.2872 ± 0.0056	0.6492 ± 0.0234	25.709 ± 1.055	3225 ± 116	3335 ± 137
28	5	8	C	0.55	0.11	0.2885 ± 0.0057	0.6997 ± 0.0253	27.829 ± 1.144	3419 ± 124	3413 ± 140
29	6	9	C	0.67	n.d.	0.2804 ± 0.0054	0.6122 ± 0.0220	23.671 ± 0.967	3079 ± 111	3255 ± 133
30	7	10	C	0.76	n.d.	0.2863 ± 0.0055	0.6622 ± 0.0239	26.143 ± 1.068	3276 ± 118	3352 ± 137
31	8	11	C	0.65	0.41	0.2907 ± 0.0031	0.5903 ± 0.0177	23.657 ± 0.754	2991 ± 90	3254 ± 104
32	9	12	C	0.58	n.d.	0.2877 ± 0.0032	0.6408 ± 0.0193	25.419 ± 0.816	3192 ± 96	3324 ± 107
33	10	13	C	0.55	0.51	0.2964 ± 0.0034	0.6593 ± 0.0199	26.943 ± 0.871	3265 ± 99	3381 ± 109
34	11	14	R	0.77	0.07	0.2855 ± 0.0030	0.6068 ± 0.0182	23.891 ± 0.761	3057 ± 92	3264 ± 104
35	11	15	C	0.85	n.d.	0.2918 ± 0.0031	0.6577 ± 0.0197	26.461 ± 0.843	3258 ± 98	3364 ± 107
36	12	16	R	0.62	n.d.	0.2820 ± 0.0030	0.5678 ± 0.0170	22.074 ± 0.704	2899 ± 87	3187 ± 102
37	13	17	R	0.66	n.d.	0.2822 ± 0.0031	0.5931 ± 0.0178	23.076 ± 0.739	3002 ± 90	3230 ± 103
38	13	18	C	0.60	0.33	0.2747 ± 0.0031	0.5018 ± 0.0151	19.007 ± 0.611	2622 ± 79	3042 ± 98
39	14	19	C	0.79	0.04	0.2773 ± 0.0029	0.5490 ± 0.0164	20.995 ± 0.666	2821 ± 85	3138 ± 100
40	15	20	C	0.64	1.02	0.2694 ± 0.0030	0.4956 ± 0.0149	18.411 ± 0.590	2595 ± 78	3011 ± 96

[(a)]Pit position in zircon crystal: C, Core; M, Mantle; R, Rim.
[(b)]Percentage of ^{206}Pb contributed by common Pb on the basis of ^{204}Pb.
Common Pb value from Stacey and Kramers (1975).
n.d. = not determined.

ml/min) was added to the He carrier gas. Detailed procedure and analytical precision are described in Orihashi *et al*. (2008).

In order to assess the accuracy of U–Pb age of the zircon samples, the U–Pb age of FC1 zircon standard was also measured (Fig. 3; Table 2). The ^{238}U–^{206}Pb and ^{235}U–^{207}Pb ages obtained for FC1 ($N = 6$) were 1098 ± 25 Ma (2σ) and 1108 ± 26 Ma (2σ), respectively. The Concordia age of 1117 ± 14 Ma was calculated using ISOPLOT® (Ludwig, 2001) (2σ, MSWD = 4.1, Probability = 0.043) and it is in agreement with values reported by Paces and Miller (1993).

RESULTS

The analytical data and the U–Pb isotope ages calculated from 40 ablation spots on 28 zircon grains selected from the samples 104 and 107 (Table 1) are shown in the Tera-Wasserburg diagrams (Figs. 4a and b). Both diagrams show significant discordant lines. The upper intercept ages obtained from these plots for each rock sample yield ages of 3527 ± 17 Ma (2σ; MSWD = 2.3) and 3448 ± 19 Ma (2σ; MSWD = 2.3), respectively. The discordant lines are apparently due to Pb loss, but the points plotted are located either on the Concordia curve or close to the curve. Therefore, the upper intercept ages may be close to the primary age of zircon crystallization in OMTG. Although the two rock samples were collected from the same granite body, there is a difference in age of *ca*. 80 Ma. The lower intercept ages of both diagrams yield roughly 900–1000 Ma, suggesting a possible thermal event at *ca*. 1 Ga.

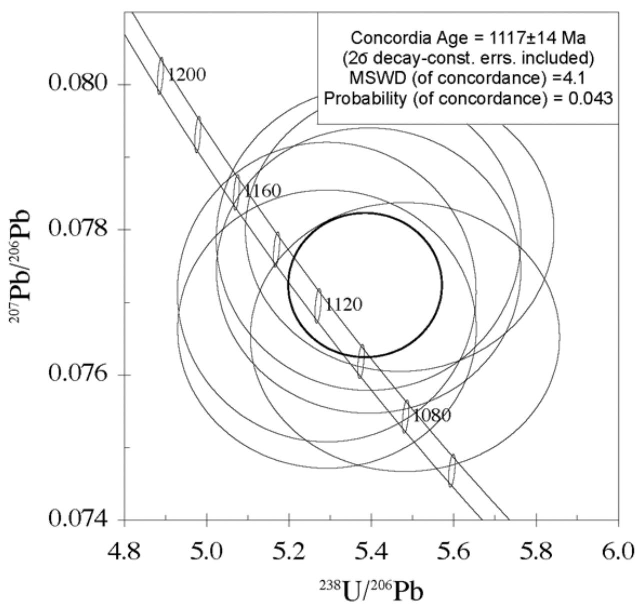

Fig. 3. Tera-Wasserburg diagram for FC1 zircon standard.

U–Pb spot analyses on the same zircon grain gave U–Pb ages of cores older than those of the mantles and rims and/or older or equivalent to those of rims, within the range of the analytical error. However, in some grains (no. 3 in sample no. 104 and no. 4 and 13 in sample no. 107; Table 1), U–Pb ages of cores are apparently younger than those of mantles and rims, beyond their analytical error. This suggests that the zircon rims for those grains might be less affected by Pb loss than the cores or mantles. Such cases are known in zircons from Archean gneisses (Gerdes and Zeh, 2009) and also from Pleistocene volcanic fields (Miller and Wooden, 2004).

DISCUSSION AND CONCLUSIONS

Zircon grains recovered from OMG metasediments of the Champua area yielded Pb–Pb ages of *ca*. 3550, 3400 and 3200 Ma (Goswami *et al*., 1995; Misra *et al*., 1999). Moorbath *et al*. (1986) reported a Pb–Pb WR isochron age of 3378 ± 98 Ma, for seven Champua area OMTG samples. Sharma *et al*. (1994) obtained a 3305 ± 60 Ma (Sm–Nd WR) age for OMG amphibolites from the same area. Four samples of biotite tonalite gneisses from the largest remnant of the Champua area OMTG defined a Pb–Pb WR isochron age of 3664 ± 79 Ma (MSWD = 1.66; Ghosh *et al*., 1996), while five biotite-bearing tonalitic granodiorite gneisses from the Onlajori area defined a

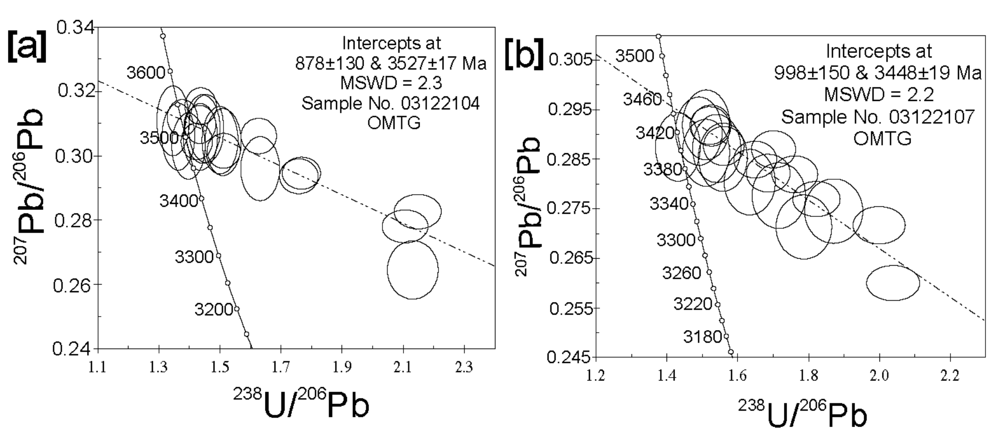

Fig. 4. Tera-Wasserburg diagrams of zircon recovered from samples 104 and 107. Discordia upper intercept ages are calculated using ISOPLOT® program (Ludwig, 2001).

Table 2. U–Pb isotopic data for FC1 zircon standard, determined by LA-ICP-MS

Group No.	Spot No.	Position[a]	Th/U	$^{206}Pb^{(b)}$ (%)	$^{207}Pb/^{206}Pb \pm 2\sigma$	$^{206}Pb/^{238}U \pm 2\sigma$	$^{207}Pb/^{235}U \pm 2\sigma$	$^{238}U–^{206}Pb$ age (Ma)	$^{235}U–^{207}Pb$ age (Ma)
1	1	R	0.69	n.d.	0.0766 ± 0.0016	0.189 ± 0.011	2.00 ± 0.12	1116 ± 62	1114 ± 66
1	2	M	0.64	n.d.	0.0779 ± 0.0017	0.185 ± 0.010	1.99 ± 0.12	1097 ± 61	1112 ± 67
1	3	C	0.69	n.d.	0.0774 ± 0.0016	0.185 ± 0.010	1.98 ± 0.12	1097 ± 61	1109 ± 66
1	4	C	0.67	n.d.	0.0780 ± 0.0016	0.183 ± 0.010	1.97 ± 0.12	1083 ± 61	1104 ± 66
1	5	M	0.69	0.13	0.0765 ± 0.0015	0.182 ± 0.010	1.92 ± 0.11	1080 ± 60	1090 ± 65
1	6	R	0.66	n.d.	0.0771 ± 0.0017	0.189 ± 0.011	2.01 ± 0.12	1116 ± 66	1119 ± 67
Average ± 2SD								1098 ± 31	1108 ± 21
Weighted average ± 95% conf.								1098 ± 25	1108 ± 26

[a]Pit position in zircon crystal: C, Core; M, Mantle; R, Rim.
[b]Percentage of ^{206}Pb contributed by common Pb on the basis of ^{204}Pb.
Common Pb value from Stacey and Kramers (1975).
n.d. = not determined.

younger Pb–Pb (WR) isochron age of 3405 ± 53 Ma (MSDW = 1.30; Ghosh *et al.*, 1996). Misra *et al.* (1999) reported zircon Pb–Pb ages of *ca.* 3440 Ma for the Champua area OMTG. Nelson *et al.* (2007) reported an OMTG zircon crystallization age of 3380 ± 11 Ma (U–Pb, SHRIMP zircon) from the Jagannathpur area (Fig. 1). Therefore, OMTG sample sets from the Champua region yielded a 3664 ± 79 Ma Pb–Pb WR isochron age (Ghosh *et al.*, 1996) and *ca.* 3440 Pb–Pb zircon ages (Misra *et al.*, 1999). This suggests coexisting remnants of polymetamorphosed granitoid gneisses of 3664 Ma and 3440 Ma within the OMTG bodies, in which younger component appears to be better preserved.

The SGB-A from the Bisoi and Bhaunra granite yielded Pb–Pb (WR) isochron ages of 3442 ± 26 Ma and 3298 ± 63 Ma, respectively (Fig. 1; Ghosh *et al.*, 1996). These ages give possible dates for the emplacement of the SBG-A phases. Trondhjemitic xenoliths from Bonai granite (equivalent of SBG-A component) yielded an age of 3380 ± 46 Ma (U–Pb, Sm–Nd WR) for a magmatic zircon and a minimum age of 3448 Ma for xenocrystic zircon (Sengupta *et al.*, 1996).

The age of major and younger component of OMTG (3405 ± 26 Ma, Pb–Pb isochron age on WR, Ghosh *et al.*, 1996; and *ca.* 3440 Ma, Pb–Pb age on zircon, Misra *et al.*, 1999) and the age of the older component of SBG-A (3442 ± 26 Ma, Pb–Pb on WR isochron age, Ghosh *et al.*, 1996) recorded from different parts of the Singhbhum Craton (Fig. 1), are close to the OMTG age of 3448 ± 19 Ma reported in this study. Furthermore, SBG-A and OMTG rocks are also geochemically very similar, as previously mentioned. It is thus possible that the OMTG dated here at 3448 ± 19 Ma represents an older phase of SBG-A. The older OMTG age of 3527 ± 17 Ma might come from an older intrusive or inherited xenocryst population.

It could be suggested that the oldest event resulting in the formation of continental crust in eastern India started around 3600 Ma. The OMG enclaves are partially similar to the IOG supracrustal rocks that were intruded by OMTG, Within SBG, these remnants are preserved as both OMG and OMTG. The zircon grains from OMG metasediments were either of granitoid provenance with ages of 3.6–3.5 Ga (Goswami *et al.*, 1995) or from acid-intermediate volcanics, that are frequently associated with the Paleoarchean greenstone, similar to the southern belt of IOG, which has been dated at a minimum age of 3506 ± 2.3 Ma (U–Pb on zircon by SHRIMP; Mukhpadhyay *et al.*, 2008). This IOG is thus older than the major component of OMTG (3405 ± 53 Ma, Ghosh *et al.*, 1996; *ca.* 3440 Ma, Misra *et al.*, 1999) and older phase of the Singhbhum granite batholith (SBG-A; 3440 to 3330 Ga; Saha, 1994; Ghosh *et al.*, 1996; Fig. 1). Rb–Sr ages of 3.1–3.2 Ga (Saha, 1994; Mukhopadhyay, 2001) obtained from SBG and other suites of rocks record a widespread thermal event possibly coinciding with the emplacement of the SBG-B. Zircon ages also indicate a widespread metamorphic event at 3.2 Ga. The younger and major phase of SBG-B intrudes the IOG at many sections.

There are a few records of gneisses older than 3500 Ma, from other cratons in India (Fig. 1 inset). An U–Pb zircon age of 3566 ± 11 Ma was recorded on a tonalite from the central part of the Bastar Craton (Ghosh, 2004). The oldest granite from the Dalli–Rajhara area, also from the central part of the Bastar Craton, was dated at 3583 ± 6 Ma (U–Pb on zircon by SHRIMP; Rajesh *et al.*, 2009). In the Bundelkhand Craton, a Rb–Sr WR age of 3503 ± 99 Ma was reported for the Baghora trondhjemite (Sarkar *et al.*, 1996). The Dharwar Craton and Western Indian gneissic complex did not yield ages older than 3.3 Ga.

Supracrustal rocks or enclaves within TTG like gneisses have often recorded ages older than 3.5 Ga

(Bowring and Williams, 1999; Böhm *et al*., 2000; Dalrymple, 2004; Condie, 2005). These enclaves are broadly similar in character to those of the OMG and OMTG from the Singhbhum Craton. Island arc remnants are generally regarded as major components of Paleoarchean crust and are possibly preserved as roots in the OMTG component. OMTG in the Singhbhum Craton retains 3664 ± 79 Ma old remnants. The southern belt IOG, with typical oceanic greenstone affinity, has a minimum age of 3506 ± 2.3 Ma (Mukhopadhyay *et al*., 2008), older than SBG-A and -B, as well as of the major body of the OMTG. Therefore, we conclude that OMG enclaves in OMTG and SBG correspond, at least partially, to the IOG supracrustal rocks.

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References

Bandyopadhyay, P. K., Chakrabarti, A. K., Deomurari, M. P. and Misra, S. (2001) 2.8 Ga old anorogenic granite-acid volcanic association from western margin of Singhbhum–Orissa craton, eastern India. *Gondwana Res*. **4**, 465–475.

Böhm, C. O., Heaman, L. M., Creaser, R. A. and Corkery, M. T. (2000) Discovery of pre-3.5 Ga exotic crust at the northwestern Superior Province margin, Manitoba. *Geology* **28**, 75–78.

Bowring, S. A. and Williams, I. S. (1999) Priscoan (4.00–4.03 Ga) orthogneisses from northwestern Canada. *Contrib. Mineral. Petrol*. **134**, 3–16.

Condie, K. C. (2005) *Earth as Evolving Planetary System*. Elsevier, 447 pp.

Dalrymple, G. B. (2004) *Ancient Earth, Ancient Skies: The Age of Earth and Its Cosmic Surroundings*. Stanford Univ. Press, 247 pp.

Gerdes, A. and Zeh, A. (2009) Zircon formation versus zircon alteration—New insights from combined U–Pb and Lu–Hf in-situ LA-ICP-MS analyses, and consequences for the interpretation of Archean zircon from the Central Zone of the Limpopo Belt. *Chem. Geol*. **261**, 230–243.

Ghosh, D. K., Sarkar, S. N., Saha, A. K. and Ray, S. L. (1996) New insights on the early Archaean crustal evolution in eastern India: re-evaluation of Pb–Pb, Sm–Nd and Rb–Sr geochemistry. *Ind. Miner*. **50**, 175–188.

Ghosh, J. G. (2004) 3.56 Ga tonalite in the central part of the Bastar Craton, India: oldest Indian date. *J. Asian Earth Sci*. **23**, 359–364.

Goswami, J. N., Misra, S., Wiedenbeck, M., Ray, S. L. and Saha, A. K. (1995) $^{207/206}$Pb ages from the OMG, the oldest recognised rock unit from Singhbhum–Orissa Iron Ore craton, E. India. *Curr. Sci*. **69**, 1008–1012.

Iizuka, T. and Hirata, T. (2004) Simultaneous determinations of U–Pb age and REE abundances for zircons using ArF excimer laser ablation-ICP-MS. *Geochem. J*. **38**, 229–242.

Ludwig, R. K. (2001) User Manual for ISOPLOT® rev. 2.49. Berkeley Geochronology Center, Special Publication 1a, 55 pp.

Miller, J. S. and Wooden, J. L. (2004) Residence, Resorption and recycling of zircons in Devils Kitchen Rhyolite, Coso volcanic field, California. *J. Petrol*. **45**, 2155–2170.

Misra, S., Deomurari, M. P., Wiedenbeck, M., Goswami, J. N., Ray, S. L. and Saha, A. K. (1999) ^{207}Pb/^{206}Pb zircon ages and the evolution of Singhbhum craton, eastern India: an ion microprobe study. *Precambrian Res*. **93**, 139–151.

Moorbath, S., Taylor, P. N. and Jones, N. W. (1986) Dating the oldest terrestrial rocks—fact and fiction. *Chem. Geol*. **57**, 63–86.

Mukhopadhyay, D. (2001) The Archaean nucleus of Singhbhum: The present state of knowledge. *Gondwana Res*. **4**, 307–318.

Mukhopdhyay, J., Beukes, N. J., Armstrong, R. A., Zimmermann, U., Ghosh, G. and Medda, R. A. (2008) Dating the Oldest Greenstone in India: A 3.51-Ga precise U–Pb SHRIMP zircon age for dacitic lava of the southern Iron Ore Group, Singhbhum craton. *J. Geol*. **116**, 449–461.

Nelson, D. R., Bhattacharya, H. N., Misra, S., Dasgupta, N. and Altermann, W. (2007) New Shrimp U–Pb dates from the Singhbhum Craton, Jharkhand–Orissa region, India (abstract). *International Conference on Precambrian Sedimentation and Tectonics and 2nd GPSS Meeting*, IIT-Bombay, A 47.

Orihashi, Y., Hirata, T., Tani, K. and Yoshida, H. (2003) Rapid and simultaneous determination of multi-element abundances and U–Pb age for zircon crystal using UV laser ablation ICP-MS technique: critical evaluation of the technique with 91500 zircon standard. *J. Mineral. Petrol. Sci*. **98**, 109–117.

Orihashi, Y., Nakai, S. and Hirata, T. (2008) U–Pb age determination for seven standard zircons using Inductively Coupled Plasma—Mass Spectrometry Coupled with frequency quintupled Nd-YAG (λ = 213 nm) laser ablation system: Comparison with LA-ICP-MS zircon analyses with a NIST glass reference material. *Resour. Geol*. **58**, 101–123.

Paces, J. B. and Miller, J. D. (1993) Precise U–Pb ages of Duluth Complex and related mafic inclusions, northeastern Minnesota: geochronological insights into physical, petrogenetic, paleomagnetic and tectonomagmatic processes associated with the 1.1 Ga mid-continental rift system. *J. Geophys. Res*. **98**, 13997–14013.

Pupin, J. (1980) Zircon and granite petrology. *Contrib. Mineral. Petrol*. **73**, 207–220.

Rajesh, H. M., Mukhopadhyay, J., Beukes, N. J., Gutzmer, J., Belyanin, G. A. and Armstrong, R. A. (2009) Evidence for an early Archaean granite from Bastar craton, India. *J. Geol. Soc. London* **166**, 193–196.

Saha, A. K. (1988) Some aspects of crustal growth of the Singhbhum–Orissa Iron Ore craton, eastern India. *Ind. J.*

Geol. **60**, 270–278.
Saha, A. K. (1994) Crustal evolution of Singhbhum–North Orissa, Eastern India. *Mem. Geol. Soc. Ind*. **27**, 341 pp.
Saha, A. K., Bose, R., Ghosh, S. N. and Roy, A. (1977) Petrology and emplacement of Mayurbhanj Granite batholith, eastern India. *Evolution of Orogenic Belts of India (Part 2), Bull. Geol. Min. Met. Soc. Ind*. **49**, 1–34.
Sarkar, A., Paul, D. K. and Potts, P. J. (1996) Geochronology and Geochemistry of Mid Archaean Trondhjemitic gneisses from Bundelkhand craton, Central India. *Recent Res. Geol*. **16**, 76–92.
Sarkar, S. N. and Saha, A. K. (1962) A revision of Precambrian stratigraphy and tectonics of Singhbhum and adjacent areas. *Quart. J. Geol. Min. Metal. Soc. Ind*. **34**, 99–136.
Sarkar, S. N. and Saha, A. K. (1977) The present status of Precambrian stratigraphy, tectonics and geochronology of Singhbhum–Mayurbhanj–Keonjhar region, eastern India. *Ind. J. Earth Sci*. **S. Ray Vol.**, 37–65.
Sarkar, S. N. and Saha, A. K. (1983) Structure and tectonics of the Singhbhum–Orissa Iron Ore craton, eastern India. *Structure and Tectonics of the Precambrian Rocks. Recent Res. in Geol*. **10**, 1–25, Hindusthan Pub., New Delhi.
Sengupta, S., Paul, D. K., deLaeter, J. R., Mc Naughten, N. J., Bandopadhyay, P. K. and de Smeth, J. B. (1991) Mid-Archean evolution of the eastern Indian craton: Geochemical and isotopic evidence from Bonai pluton. *Precambrian Res*. **49**, 23–37.
Sengupta, S., Corfu, F., Mc Nutt, R. H. and Paul, D. K. (1996) Mesoarchean crustal history of the Eastern Indian craton: Sm–Nd and U–Pb isotopic evidence. *Precambrian Res*. **77**, 17–22.
Sharma, M., Basu, A. R. and Ray, S. L. (1994) Sm–Nd isotopic and geochemical study of Archean tonalite-amphibolite association from the eastern Indian Craton. *Contrib. Mineral. Petrol*. **117**, 45–55.
Stacey, J. S. and Kramers, J. D. (1975) Approximation of terrestrial lead isotope evolution by a two-stage model. *Earth Planet. Sci. Lett*. **26**, 207–221.