any perceptible bio-deterioration of fired clay brick during the course of its existence in the altar structure.

Investigations on a fired brick sample from an ancient altar structure reveal that technology of making fired clay building-material was adequately known during the period. Further, physical and mineralogical examination of briquette samples revealed that partial deterioration of fired body resulted due to physical factors like river flow, seismic activity, temperature fluctuations, etc. and partly due to chemical factors involving rain-water leaching, wetting and drying cycles during its existence in the altar structure.

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^{207}Pb–^{206}Pb ages of zircons from the Nuggihalli schist belt, Dharwar craton, southern India

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^{207}Pb/^{206}Pb ages of individual zircon grains from metasediments and tonalite trondhjemitic and granitic gneisses in the Nuggihalli schist belt, Dharwar craton are determined by an ion microprobe. Zircons identified in a metasedimentary rock have ages up to ~3.2 Ga, suggesting an upper limit age of 3.3 Ga for the onset of sedimentation in this region. The ages of the gneissic protoliths are ~3.1 Ga and they appear to be nearly contemporaneous with the metasedimentary protoliths. Our data and those reported previously are indicative of multiple emplacement of the gneissic precursors, and suggest an episodic evolution of the Dharwar craton over an extended period during the early Archean.

THE Dharwar craton forms a major part of the southern Indian shield. The supracrustal association of this craton is divided into two groups, the older Sargur group and the younger Dharwar Supergroup on the basis of lithological, metamorphic and structural characteristics[1]. The craton is comprised of two blocks, the western and the eastern, with the eastern margin of Chitradurga schist belt acting as a notional boundary between them[2]. The western block is made up of orthogneisses and granodiorites, interspersed with older tracts of metasedimentary and metamorphosed igneous suites. A variety of mafic and ultramafic rocks, many having affinities with komatiites, high-magnesian basalts and tholeiites that are regarded as some of the early recognized greenstone rocks, are exposed in the western block. Nuggihalli schist belt in the southern part of the craton is one such unit. It is surrounded by older granitoid suites that include dioritic, tonalitic and trondhjemitic gneisses and migmatites. Some of the granitoid units in the western block are reported to be intrusive into the supracrustal mafic and ultramafic rocks[3]. However, in the absence of clearly-defined field evidence it is difficult to infer the exact relationship between the supracrustals and the surrounding gneisses. We have determined ^{207}Pb–^{206}Pb ages of zircons from four samples, a metasediment, two closely spaced tonalite trondhjemitic gneisses (TTG) and one granitic gneiss, surrounding the Nuggihalli schist belt to further our understanding of the early Archean evolution of the Dharwar craton.

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The metasedimentary sample (quartz–mica–chlorite schist) analysed in this study was from the northern bank of the Arsikere tank. Two of the gneissic (TTG) samples were collected from the area around Tagadur mines and a third one from the Kodihalli village on the eastern bank of the Arsikere tank. Gneisses from the Tagadur area are grey coloured with quartz and plagioclase as the dominant phases; K-feldspars occur as phenocryst and biotite forms the ferromagnesian phase. Accessory mineral includes apatite and zircon. In the granitic gneiss sample from the Kodihalli area, quartz and K-feldpsar are the primary phases, phenocryst plagioclase are partially altered. Biotite is present as secondary mineral, while apatite, zircon and magnetite occur as accessory minerals.

The samples were processed using standard technique[4] to obtain zircon grains. Each sample was crushed into centimetre-sized chips and was thoroughly washed after eliminating the weathered portions. The clean chips from each sample were then pulverized to $< 250\,\mu$m in a clean environment using a stainless steel piston and cylinder. Non-magnetic, high-density mineral grains were concentrated by density separation using aqueous Na-polytungstate solution (density = $3\ \mathrm{g\ cm^{-3}}$) followed by magnetic separation using a Frenz isodynamic separator. Zircon grains were handpicked from this fraction using a binocular microscope. Individual clear, unfractured and least intensely coloured zircons were selected and mounted on a double-sided tape, cast in epoxy and sectioned by polishing. Transparent zircons with simple internal structure were documented in detail. The grains recovered from the metasediment are subrounded to subhedral, transparent, and colourless to brownish in transmitted light. The zircons obtained from the gneissic samples are generally transparent, colourless to pale brown, euhedral in shape and mostly inclusion-free. A few zircons show fine zoning, while a few others have distinct core-overgrowth features. The grain mounts were thoroughly cleaned in ethanol using ultrasonic method and coated with a 100 nm thick, high-purity gold film for isotopic measurement using an ion microprobe.

We have used a Cameca ims-4f ion microprobe for measuring ^{207}Pb/^{206}Pb isotopic ratio in the zircons using procedures described elsewhere[4]. The instrument was operated at a high-mass resolution ($M/\Delta M \sim 4600$) that can resolve all the significant isobaric molecular interferences in the Pb isotope mass spectrum. A 7 nA focused primary beam of ^{16}O$^-$ was used to sputter $\sim 20\,\mu$m domains of individual zircon grains. Each analysis consisted of 15 blocks of data and each block comprised of five scans through the mass sequence ^{204}(Zr$_2$O), ^{204}Pb, ^{206}Pb, ^{207}Pb, ^{208}(HfO$_2$) and ^{208}Pb in peak jumping mode. The age for a given analysis was inferred from the weighted mean ^{207}Pb/^{206}Pb ratio obtained from the data of the 15 quasi-independent blocks that were corrected for common Pb following the method of Cumming and Richards[5]. The exclusion of uranium isotopes in our measurement routine rules out the possibility of having specific information on Pb-loss as well as presence of multiple age components within our dataset. Several objective criteria (see refs 4 and 6) were used for identifying analyses belonging to the magmatic component and the age of a sample was derived from the mean radiogenic ^{207}Pb/^{206}Pb ratio obtained by pooling the data (at block level) for all these analyses. The inferred age may be considered as the 'minimum' age of the sample. However, for samples that show a sharp cut-off in higher radiogenic ^{207}Pb/^{206}Pb ratios, the minimum age closely approximates the true age of the sample. Details of the procedure adopted for data acquisition and assessment are reported elsewhere[4,6].

Eighteen analyses were conducted on ten zircons from the metasediment (quartz–mica–chlorite schist, Z-81) and the Pb-isotopic data for these analyses are presented in Table 1. All the analyses have low common Pb component (<3%) and they yielded ages in the range of ~ 2.4 to 3.2 Ga. Two analyses conducted in a single zircon have nearly identical ages of 3184 ± 26 Ma (1A; 1σ error) and 3160 ± 34 Ma (1B). Three zircons with distinct core-overgrowth morphology (2, 4 and 9) were analysed. The core region in one grain yielded an age of 3202 ± 25 Ma (2A), while the ages determined for the overgrowth were lower, 2845 ± 73 (2B) and 2746 ± 44 Ma (2C). In the other cases, the core regions yielded ages of ~ 3.0 to 3.1 Ga (4A, 4B, 9A and 9C), while the ages of the overgrowths are much lower. The younger ages for the overgrowths represent secondary events responsible for their formation. Although it is not possible to uniquely identify such events, we note here that some of these ages are similar to those of metavolcanics from the Bababudan group[7] located to the north of the Nuggihalli schist belt. Our zircon age data for the metasediment suggest the presence of sedimentary protoliths of 3.05 to 3.2 Ga and also imprints of younger events at ~ 2.8 to 2.9 Ga. An upper limit age of ~ 3.3 Ga may be inferred for the onset of deposition of the sedimentary protoliths in this region of the Dharwar craton.

Nine analyses conducted on eight zircons in the TTG sample Z-93 have low common Pb component. Five of these analyses conducted on four zircons yielded ages of ~ 3.1 Ga, while the ages for the other analyses are much lower (Table 1). We identify the five analyses with higher ages as belonging to the magmatic group and obtain a weighted mean radiogenic ^{207}Pb/^{206}Pb value of 0.2357 ± 0.001, corresponding to an age of 3091 ± 8 Ma for this sample. The lower ages appear to be an overprint of younger events at 2.8–2.9 Ga, whose signatures are also present in our zircon data for the metasediment.

We have performed eighteen analyses in eight zircons from the other TTG sample (Z-85) from the Tagadur area. Uranium content in the analysed domains of most of the zircons is found to be high, and ages obtained for analyses characterized by high uranium content (> 1000 ppm)

Table 1. Pb isotopic data of zircons from the Nuggihalli schist belt

Analysis no.[a]	Measured $^{204}Pb/^{206}Pb$	Measured $^{207}Pb/^{206}Pb$	Total ^{206}Pb (counts)	^{206}Pb[b] (ppm)	U[c] (ppm)	$^{207}Pb/^{206}Pb$[b]	Obs./Exp.[d]	Age[e] (Ma)
Quartz–mica–chlorite schist (Z-81)								
1A	0.00032	0.2535	42320	99	180	0.2500 ± 41	1.3	3184 ± 26
1B	0.00062	0.2531	25080	77	142	0.2462 ± 53	1.0	3160 ± 34
2A	0.00036	0.2568	44530	222	401	0.2528 ± 41	1.3	3202 ± 25
2B	0.00179	0.2234	16820	99	202	0.2169 ± 91	1.2	2845 ± 73
2C	0.00162	0.2100	25750	172	369	0.1906 ± 52	0.98	2746 ± 44
4A	0.00086	0.2522	42835	148	274	0.2426 ± 40	1.2	3137 ± 26
4B	0.00057	0.2380	104980	703	1335	0.2314 ± 25	1.55	3062 ± 17
4C	0.00180	0.2330	43430	234	464	0.2120 ± 42	1.10	2921 ± 32
5	0.00103	0.2159	20080	131	271	0.2038 ± 72	1.12	2857 ± 57
6	0.00126	0.2449	14455	81	154	0.2305 ± 86	0.97	3055 ± 60
7A	0.00134	0.2597	10940	64	116	0.2446 ± 113	1.01	3150 ± 72
7B	0.00027	0.2201	38110	204	406	0.2169 ± 37	1.04	2958 ± 28
8	0.00025	0.2183	10745	72	145	0.2154 ± 81	1.05	2946 ± 61
9A	0.00123	0.2447	10210	88	167	0.2307 ± 125	1.05	3057 ± 86
9B	0.00081	0.1672	20840	219	553	0.1571 ± 75	1.19	2425 ± 81
9C	0.00156	0.2378	8430	112	217	0.2198 ± 163	1.13	2979 ± 120
9D	0.00117	0.1970	28610	280	623	0.1829 ± 55	1.17	2679 ± 49
10	0.00091	0.2090	57100	488	1025	0.1983 ± 28	1.1	2812 ± 23
TTG-Tag 2 (Z-93)								
1B	0.00113	0.2412	130245	604	1166	0.2283 ± 32	1.7	3040 ± 22
2A	0.0019	0.2529	76035	350	671	0.2310 ± 31	1.1	3059 ± 22
3B	0.00075	0.2458	183430	867	1633	0.2375 ± 14	1.0	3103 ± 09
4A	0.00063	0.2562	43215	188	343	0.2492 ± 48	1.5	3180 ± 30
4B	0.00040	0.2444	79720	322	602	0.2399 ± 29	1.5	3119 ± 19
5	0.00163	0.2196	89560	462	955	0.2006 ± 26	1.05	2831 ± 21
6	0.00140	0.2028	74995	287	628	0.1862 ± 29	1.09	2708 ± 25
7	0.00026	0.2182	160255	548	1097	0.2152 ± 32	2.88	2945 ± 23
8	0.00026	0.2048	196695	642	1345	0.2018 ± 19	2.14	2840 ± 15
TTG-Tag1 (Z-85)								
1A	0.0016	0.2408	74505	537	1054	0.2224 ± 30	1.1	2998 ± 22
1B	0.00234	0.2537	55190	450	873	0.2269 ± 44	1.2	3030 ± 31
2A	0.00147	0.2381	52655	441	870	0.2211 ± 36	1.1	2989 ± 26
2C	0.00083	0.2490	41320	457	855	0.2398 ± 33	1.0	3118 ± 22
2D	0.00083	0.2503	35065	357	665	0.2410 ± 42	1.1	3127 ± 28
3A	0.00088	0.2362	49955	647	1257	0.2261 ± 43	1.6	3024 ± 31
3C	0.00044	0.2507	43595	498	917	0.2458 ± 38	1.2	3158 ± 24
5A	0.00070	0.2491	42860	687	1280	0.2413 ± 34	1.1	3128 ± 22
5C	0.00078	0.2393	80380	604	1159	0.2304 ± 32	1.6	3055 ± 22
Granitic gneiss, Koha (Z-83)								
1	0.00136	0.2287	234920	873	1767	0.2128 ± 16	1.1	2927 ± 12
2A	0.00024	0.2482	222905	933	1719	0.2455 ± 15	1.5	3156 ± 09
3	0.00268	0.2694	39515	110	206	0.2393 ± 50	1.0	3115 ± 33
4	0.00104	0.2484	243485	637	1201	0.2367 ± 29	2.1	3098 ± 19
5A	0.00062	0.2617	29675	90	163	0.2549 ± 44	1.0	3215 ± 27
5B	0.00034	0.2584	49135	98	176	0.2546 ± 28	1.0	3214 ± 17
5C	0.00051	0.2468	51305	120	223	0.2411 ±55	2.0	3127 ± 36
6	0.00122	0.2501	89020	601	1118	0.2364 ±27	1.20	3096 ± 18
7	0.00152	0.2493	73870	478	896	0.2321 ±33	1.21	3066 ± 23
8	0.00109	0.2285	92250	511	1009	0.2160 ±24	1.13	2951 ± 18
9	0.00152	0.2406	74215	355	682	0.2232 ±45	1.68	3004 ± 32
10	0.00151	0.2715	19305	137	242	0.2548 ±89	1.38	3215 ± 55
11	0.00034	0.2471	44200	173	320	0.2433 ±32	1.00	3141 ± 20

[a]Letters refer to multiple analyses of single zircons; [b]Radiogenic value corrected using model common Pb following Cumming and Richards[5]; [c]Calculated value based on the assumption that the sample has remained a closed system; [d]Ratio between the observed and expected (ion counting based) precision estimates; [e]Errors are 1σ

are significantly lower than analyses with lower uranium content. The lower ages most probably reflect Pb-loss from the analysed domains that are metamict, and we have excluded these analyses from our dataset. If we combine data from the analyses with U content < 1300 ppm (Table 1), we obtain a mean radiogenic ^{207}Pb/^{206}Pb value of 0.2312 ± 0.0011 (nine analyses, 121 blocks) corresponding to an age of 3060 ± 8 Ma. We consider this to be the minimum age of the gneissic protolith, as it is difficult to rule out possible Pb-loss in some of the analyses considered in our dataset. Two of the analyses conducted on a single grain (2C and D) yielded nearly concordant ages of ~ 3.1 Ga, and this may be close to the true age of the gneissic protolith.

Thirteen analyses were conducted in 11 zircons isolated from the granitic gneiss Z-83 (Table 1). In one of the grains with clearly discernable core-overgrowth morphology, we obtained similar ages (~ 3215 Ma) for two analyses conducted in the core region (5A and B), while one analysis conducted in the overgrowth (5C) yielded a distinctly younger age of ~ 3127 Ma. The lower age of the overgrowth is also close to the ages inferred from six other analyses (2A, 3, 4, 6, 7 and 11) on six additional zircons from this sample. Three other analyses yielded significantly lower ages that perhaps reflect Pb-loss in these cases. We identify the seven analyses with ages close to 3.1 Ga as belonging to the magmatic group and obtain a mean radiogenic ^{207}Pb/^{206}Pb ratio of 0.2397 ± 0.001 corresponding to an age of 3118 ± 7 Ma for this gneissic sample. The higher age of 3.2 Ga inferred for core regions in two grains (5 and 10) most probably represent an inherited component. The overgrowth in the latter case could not be dated because of the presence of a high common Pb component.

The zircon ages of the three gneissic samples from the Nuggihalli schist belt area analysed by us, cluster around 3.1 Ga. Although this age falls within the range of ages reported for gneisses from different neighbouring locations (Chitradurga, Hunasekatte, Chennarayapatna, Holenarasipur, Gorur–Hassan and Tiptur) obtained by whole-rock Pb–Pb and Rb–Sr methods[8-15], most of them have older ages in the range of 3.1–3.3 Ga. ^{207}Pb–^{206}Pb zircon ages for gneissic samples from the Holenarasipur area, obtained by single-grain evaporation technique, also yielded older ages of 3.2 to 3.3 Ga[10]. Some of the younger ages for gneissic rocks obtained in previous studies were interpreted as the timing of uranium metasomatism affecting these gneisses, rather than their crystallization age[11]. However, concordant ages seen in both individual zircons as well as in multiple analyses within single zircons and the well-preserved core-overgrowth age relationship led us to believe that identification of the magmatic component in our dataset for the three gneissic samples is appropriate, and the inferred ages are close to their true formation age. Overprint of a secondary event at ~ 2.8–2.9 Ga can also be inferred from the zircon data for both the gneissic samples and the metasediment.

The Pb–Pb zircon ages for the metasediment obtained in this study suggest an upper limit of 3.3 Ga for the time of onset of sediment deposition in the Nuggihalli region of the Dharwar craton. We could not find older components (cf ref. 16) and such relic, if present, appears to be extremely rare. The ages of some of the metasedimentary protoliths as well as the gneissic precursors in this region appear to be nearly contemporaneous. Zircon ages for magmatic as well as inherited components in the three gneissic samples from the Nuggihalli region obtained by us and the reported Pb–Pb and Rb–Sr ages for gneisses from Holenarasipur, Gorur–Hassan, Chikmagalur and Chitradurga regions of the Dharwar craton[8–15], are suggestive of a span of crystallization ages for the gneissic protoliths spreading from 3.0 to 3.3 Ga. This spread in age would imply episodic emplacement of the TTG suite in the Dharwar craton over a protracted period.

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