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Age of younger tonalitic magmatism and granulitic metamorphism in the South Indian transition zone (Krishnagiri area); comparison with older Peninsular gneisses from the Gorur–Hassan area

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ABSTRACT A major episode of continental crust formation, associated with granulite facies metamorphism, occurred at 2.55–2.51 Ga and was related to accretional processes of juvenile crust. Dating of tonalitic–trondhjemitic, granitic gneisses and charnockites from the Krishnagiri area of South India indicates that magmatic protoliths are 2550–2530 ± 5 Ma, as shown by both U–Pb and ^{207}Pb/^{206}Pb single zircon methods. Monazite ages indicate high temperatures of cooling corresponding to conditions close to granulite facies metamorphism at 2510 ± 10 Ma. These data provide precise time constraints and Sr–Nd isotopes confirm the existence of late tonalitic–granodioritic juvenile gneisses at 2550 Ma. Pb single zircon ages from the older Peninsular gneisses (Gorur–Hassan area) are in agreement with some previous Sr ages and range between 3200 ± 20 and 3328 ± 10 Ma. These gneisses were derived from a 3.3–3.5-Ga mantle source as indicated from Nd isotopes. They did not participate significantly in the genesis of the 2.55-Ga juvenile magmas. All these data, together with previous work, suggest that the 2.51-Ga granulite facies metamorphism occurred near the contact of the ancient Peninsular gneisses and the 2.55–2.52-Ga 'juvenile' tonalitic–trondhjemitic terranes during synaccretional processes (subduction, mantle plume?). Rb–Sr biotite ages between 2060 and 2340 Ma indicate late cooling probably related to the dextral major east–west shearing which displaced the 2.5-Ga juvenile terranes toward the west.

Key words: juvenile tonalitic magmas; syn- to post-accretional granulites; 2550–2510 Ma; U-Pb, Sr, Nd isotopes.

INTRODUCTION

South Indian granulites, in the vicinity of the Transition Zone of the southern Karnataka craton, are known to be derived from metamorphism of older Archaean gneisses, close to 2.5 Ga. In fact, geochronological and isotope data suggest the occurrence of two types of granulites (Peucat *et al.*, 1987, 1989). One type results from the metamorphism of 3.0-Ga or older Peninsular gneisses (BR Hills-type charnockites), and the second was derived from the metamorphism of a younger tonalitic–granodioritic suite. The latter was emplaced shortly before the development of the granulite facies metamorphism (Nilgiris, Krishnagiri, Salem-type charnockites). The tonalitic–granodioritic magmatism may be of importance in constraining the genesis of the granulite facies metamorphism since it may be related to accretional processes of juvenile crust in subduction or mantle-plume environments.

Previous investigations of the Krishnagiri area (south of Kolar, Fig. 1; Peucat *et al.*, 1987, 1989) have shown that the ages of the magmatic precursors to the tonalitic gneisses and granites, as well as of the granulite facies metamorphic event, are similar and close to 2.5 Ga. This contrasts with some charnockites further west that were derived from 3.0-Ga protoliths. These ages were calculated from Rb–Sr and Sm–Nd whole-rock isochrons, which provided relatively high errors on the ages, in particular when based on different rock types.

The aims of the present study are: (i) to date more precisely these rocks using U–Pb zircon and monazite techniques, in order to constrain the timing of plutonism and metamorphism; (ii) to compare the initial Sr and Nd isotopic signatures of these gneisses with those of the 3.3-Ga Gorur–Hassan gneisses, an example of Peninsular gneisses, to determine whether the latter are possible source rocks; (iii) to elucidate the low-temperature cooling history from Rb–Sr systematics of micas.

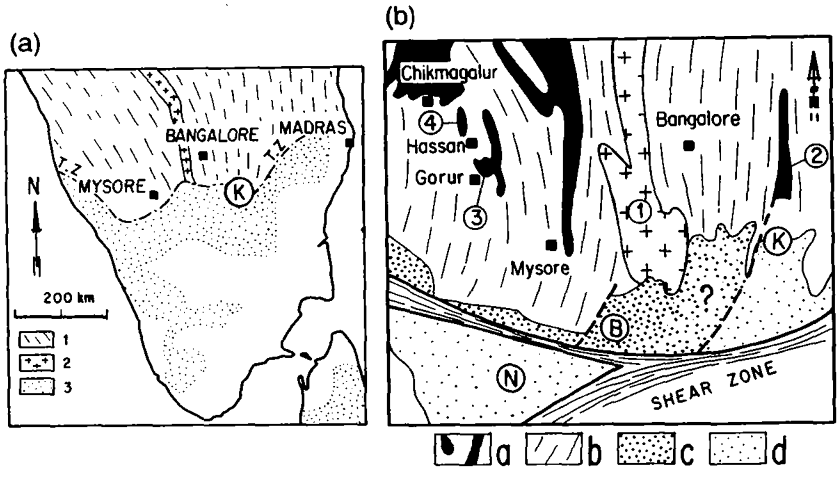

Fig. 1.. (a) South India Peninsula: 1, Archaean greenstone belts and low-grade Peninsular gneisses; 2, Closepet Granites; 3, high-grade Peninsular gneiss; T–Z, transition zone; K, Krishnagiri. (b) Geological sketch map of Dharwar craton: 1, Closepet batholith; 2, Kolar schist belt; 3, Holenarsipur schist belt; 4, Segegudda schist belt; a, supracrustal belts; b, Peninsular gneisses; c, granulitic old Peninsular gneisses; d, 2.5-Ga charnockites; N, Nilgiri Hills; B, Biligirirangan Hills (BR Hills), K, Krishnagiri.

GEOLOGICAL SETTING OF THE KRISHNAGIRI AREA

South Indian granulites have been described extensively in previous studies (e.g. Pichamuthu, 1961; Friend, 1981; Janardhan *et al.*, 1982; and see the Special Issue of *Journal of Geology*, **94**, 1986, the *Lunar and Planetary Institute Technical Report*, **88-06**, 1988, and the *Memoir of the Geological Society of India*, **17**, 1990). The geology of the transition zone near Krishnagiri was described in detail by Condie *et al.* (1982) where tonalitic, trondhjemitic and granodioritic–granitic gneisses were partially to completely transformed into charnockites (Fig. 2). Granitic gneisses were probably developed from tonalitic gneisses at the beginning of granulite facies metamorphism. Rb–Sr isochron ages are 2457 ± 174, 2529 ± 114 and 2490 ± 171 Ma for the tonalitic, granitic gneisses and charnockites, respectively (2463 ± 65 Ma for a composite isochron; Peucat *et al.*, 1987, 1989); an Sm–Nd isochron age of 2455 ± 121 Ma was obtained using all rock types. In addition to the problem of precision, the age of the tonalitic gneisses was younger than expected (3 Ga) and, in spite of Nd and Sr systems being in agreement, it was not possible to rule out isotopic resetting during the granulitic metamorphism.

Samples

Condie *et al.* (1982) described the tonalitic gneisses as being composed of 40–50% sodic plagioclase, 30–40% quartz and 5–10% microcline. Accessory minerals are hornblende, apatite, magnetite, hypersthene, titanite, allanite and zircon. The granitic gneisses, which range from granodioritic to granitic in composition, have similar assemblages except that microcline increases to 10–30% and other minerals decrease proportionally. The charnockites exhibit the same proportions of feldspar and quartz as the tonalitic gneisses, but they contain 5–10% hypersthene. The chemical compositions of samples used in this study are reported in Table 1. On a $CaO–Na_2O–K_2O$ diagram (Fig. 3), most samples are transitional between tonalite and granodiorite. Sample 1 is a tonalite and sample 2 is a granodioritic–granitic gneiss; no true granite nor monzogranite samples were at our disposal.

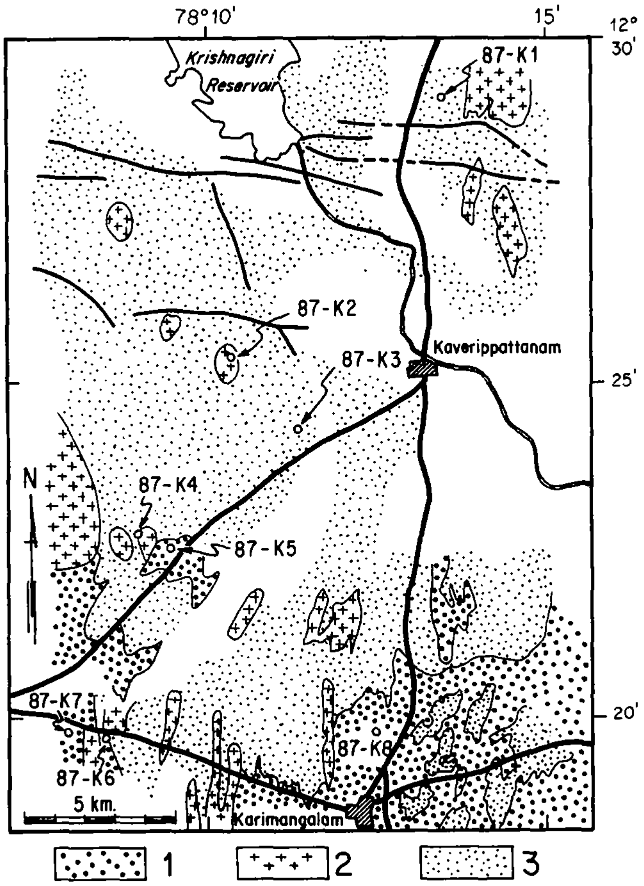

Fig. 2. Simplified geological map of Krishnagiri area (K on Fig. 1) from Condie *et al.* (1982) showing location of samples: 1, charnockitic gneisses; 2, granitic gneisses; 3, tonalitic gneisses.

Table 1. Major element contents, determined by XRF, of tonalitic gneisses (87K1, K3, K4), granitic gneiss (87K2) and charnockitic gneisses (87K5, K6, K7, K8).

	87K1 9158	87K2 9159	87K3 9160	87K4 9161	87K5 9162	87K6 9163	87K7 9164	87K8 9165
SiO_2	69.21	65.96	58.42	59.34	65.76	62.41	69.07	63.78
TiO_2	0.34	0.45	1.26	0.77	0.66	0.68	0.29	0.56
Al_2O_3	15.78	16.1	15.97	16.01	14.42	15.65	15.74	15.57
Fe_2O_3	3.04	3.94	7.86	6.68	6.66	5.53	2.88	5.15
MnO	0.04	0.05	0.11	0.11	0.11	0.11	0.03	0.07
MgO	0.98	1.38	2.87	3.44	2.29	3.02	0.97	2.34
CaO	3.58	3.58	5.48	5.48	3.49	5.24	3.45	4.53
Na_2O	5.01	4.50	4.43	4.35	3.63	4.17	4.32	4.14
K_2O	1.34	2.92	2.16	2.09	2.02	1.72	2.18	2.44
P_2O_5	0.12	0.23	0.45	0.27	0.15	0.2	0.12	0.25
LOI	0.48	0.41	0.39	0.58	0.71	0.99	0.77	0.52
Total	99.92	99.52	99.4	99.12	99.9	99.72	99.82	99.35

U–Pb AND Rb–Sr RESULTS OF THE KRISHNAGIRI AREA

Zircon dating

Zircons were dated using two methods. Conventional dating was performed following the dissolution method of Krogh (1973) using 2–5 mg of zircon. These results are presented on standard U–Pb concordia diagrams. A discordia was obtained from each of three rocks analysed. The samples were also dated by the single-crystal evaporation method (Kober, 1986, 1987). This yields only $^{207}Pb/^{206}Pb$ ages as U and Pb contents cannot be determined. If the zircons have not experienced significant disturbance, this age should correspond to the upper intercept of the discordia. Zircons from seven samples were analysed by this technique.

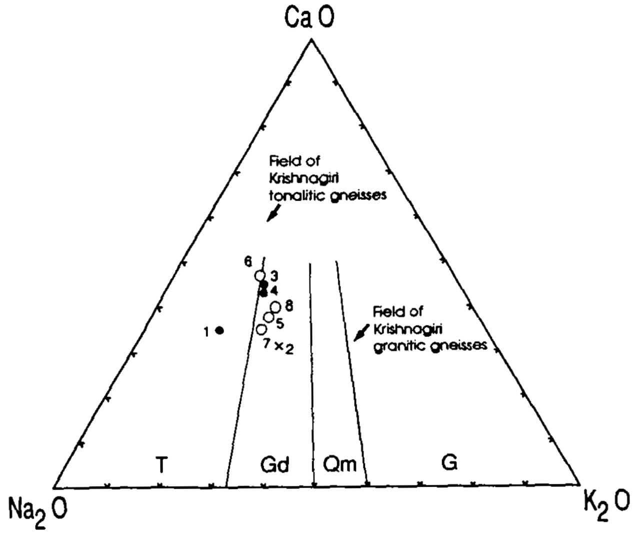

Fig. 3. CaO–Na_2O–K_2O (wt%) diagram. Sample position shown by 87K1, 1; 87K2, 2; etc. Black circles, tonalitic gneisses; open circles, charnockitic gneisses; cross, granitic sample 87K2. T, tonalite–trondhjemite; Gd, granodiorite; Qm, quartz monzonite; G, granite. Fields of Krishnagiri tonalitic and granitic gneisses are reported from Condie *et al.* (1982).

Tonalitic samples

Three samples from the tonalite suite were analysed, one by both techniques (87K3) and two additional samples by the single-grain method (87K1, 87K4). Zircons are euhedral to subhedral and elongate in shape and are transparent; zoning is seen in some samples, tips are often rounded and overgrowths and cores are not visible (Fig. 4).

Sample 87K3. U–Pb data are reported in Table 2 and Fig. 4. The four size fractions analysed define an upper intercept on the concordia of 2532 ± 15 Ma. They are only slightly discordant so it is unlikely that the lower intercept is of significance. A single grain was evaporated in three steps and similar ages of 2530 Ma were obtained (Table 3; Fig. 5b). These agree with the discordia age.

Sample 87K1. A single grain provides a $^{207}Pb/^{206}Pb$ age of 2552 ± 14 Ma (Table 3).

Sample 87K4. One grain provides a $^{207}Pb/^{206}Pb$ age of 2533 ± 3 Ma (Table 3) and the second 2539 ± 1 Ma.

These ages, which range between 2530 and 2550 Ma, are considered to be crystallization ages corresponding to the emplacement of the tonalitic magmas because: (1) zircons do not show overgrowth which would suggest resetting of the U–Pb system; (2) the data have only a restricted range in ages; and (3) the $^{207}Pb/^{206}Pb$ ages are similar to the upper intercept of the discordia.

Granitic sample

Zircons are euhedral, elongate and strongly zoned, with rounded tips. No cores or overgrowths are visible, but a

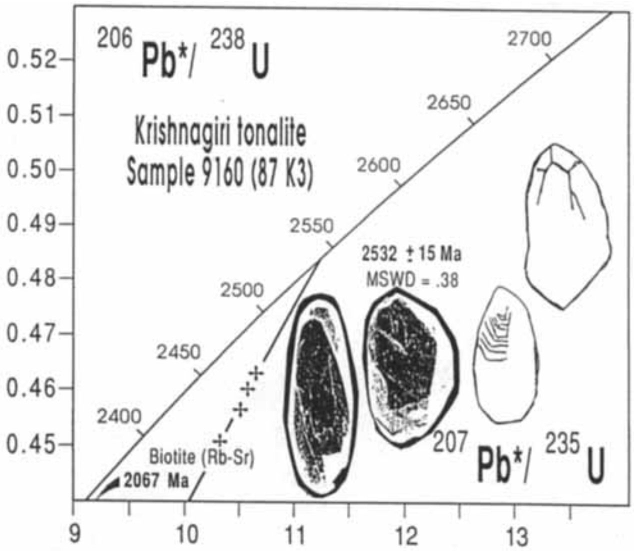

Fig. 4. Zircon U–Pb concordia plot of the tonalitic sample 87K3. Morphology of zircons as observed from SEM pictures, two crystals on left. Crystals on right correspond to internal structures under optical microscope.

Table 2. U–Pb zircon and monazite data from Krishnagiri gneisses (dissolution method).

Sample (μm)	Analysis	U (ppm)	Pb (ppm)	^{206}Pb/^{204}Pb meas.	^{207}Pb/^{206}Pb meas.	^{208}Pb/^{206}Pb meas.	^{206}Pb/^{238}U calc.	^{207}Pb/^{235}U calc.	^{207}Pb/^{206}Pb corr.	^{206}Pb/^{238}U (Ma)	^{207}Pb/^{235}U (Ma)	^{207}Pb/^{206}Pb (Ma)
Zircon 87K2	9159											
<37		361	174	10902	0.16973	0.15202	0.42485	9.8756	0.16859	2282	2423	2544
<37				9704	0.16914	0.15056						2536
80–100		410	204	10077	0.17004	0.14732	0.43917	10.2215	0.16880	2347	2455	2546
80–100				17543	0.16987	0.14770						2549
105–120		401	201	12209	0.17013	0.14530	0.44396	10.3518	0.16911	2368	2467	2549
105–120				23327	0.16940	0.14437						2547
>149		373	186	15802	0.16983	0.13947	0.44435	10.3567	0.16904	2370	2467	2548
>149				14927	0.16973	0.13868						2547
Monazite 87K2	9159	125	4235	1977	0.17113	84.42	0.4576	10.398	0.1648	2429	2471	2506
Zircon 87K3	9160											
<37		244	132	16363	0.16743	0.20170	0.46049	10.5821	0.16666	2442	2487	2525
<37				8553	0.16789	0.10324			0.16643			2522
37–55		218	117	15856	0.16730	0.18459	0.46338	10.6387	0.16651	2454	2492	2523
37–55				10095	0.16737	0.09927			0.16614			2519
55–69		179	87.7	15479	0.16685	0.09712	0.45112	10.3282	0.16605	2400	2465	2518
>69		171	84.7	16644	0.16695	0.09775	0.45627	10.4559	0.16620	2423	2476	2520
Zircon 87K8	9165											
<37		279	157	23912	0.16943	0.2139	0.47361	11.0301	0.16891	2499	2526	2547
<37				14189	0.16937	0.2127			0.16849			2543
80–100		250	139	24885	0.16963	0.2090	0.47008	10.9621	0.16913	2484	2520	2549
80–100				1992	0.17471	0.2210			0.16845			2542
100–105		210	119	30683	0.16980	0.2121	0.47638	11.1264	0.16940	2511	2534	2552
100–105				37997	0.16965	0.2021			0.16932			2551
120–149		191	106	27888	0.16949	0.1976	0.47318	11.0288	0.16904	2497	2526	2548
120–149				30927	0.16987	0.1980			0.16947			2552
Monazite 87K3	9165	70	5125	1419	0.17471	190.7	0.4359	9.9714	0.1659	2332	2432	2517

Table 3. ^{207}Pb/^{206}Pb single zircon data from *Krishnagiri* and Gorur–Hassan-type gneisses (evaporation method). e., estimated.

Sample	Analysis	Step current (A)	^{206}Pb/^{204}Pb meas.	^{207}Pb/^{206}Pb meas.	Error ($2\sigma_m \times 10^{-4}$)	^{207}Pb/^{206}Pb corr.	Age ^{207}Pb/^{206}Pb (Ma)	Error (1σ) (Ma)
Krishnagiri								
87K1	9158	2.9	25,287	0.1698	14	0.1695	2552	30
87K2	9159	2.7	45,258	0.1696	1	0.1695	2552	3
87K3	9160	2.6	100,000e.	0.1673	3	0.1670	2528	8
		2.8	100,000e.	0.1672	1	0.1671	2529	3
		3.1	100,000e.	0.1675	1	0.1673	2531	3
87K4	9161	3.2	24,768	0.1680	3	0.1675	2533	7
87K4(2)		2.6	175,693	0.1682	1	0.1681	2539	5
87K5	9162	3.2	46,697	0.1674	2	0.1671	2529	7
87K5(2)		2.6	8989	0.1701	1	0.1689	2546	7
		3.2	8989	0.1702	6	0.1690	2548	8
87K6	9163	2.8	37,853	0.1699	5	0.1695	2553	11
87K8	9165	2.6	100,000e.	0.1692	2	0.1691	2548	7
		3.2	100,000e.	0.1684	7	0.1683	2541	13
Gorur								
Ind 55c	10446	2.6	1609	0.2618	28	0.2546	3212	76
		2.8	2891	0.2739	10	0.2705	3309	7
Ind 55d	10447	2.6	5400	0.2567	12	0.2540	3210	5
		2.8	16,280	0.2600	2	0.2591	3242	15
Segegudda								
Ind 56a	10448	2.6	4018	0.2602	5	0.2579	3234	8
		2.9	13,043	0.2744	4	0.2737	3328	10
Halekote								
HL5a	11209	2.6	5000e.	0.2548	12	0.2529	3203	19
Chikmagalur								
Ind 57a	10449	2.6	1244	0.2694	16	0.2607	3251	33

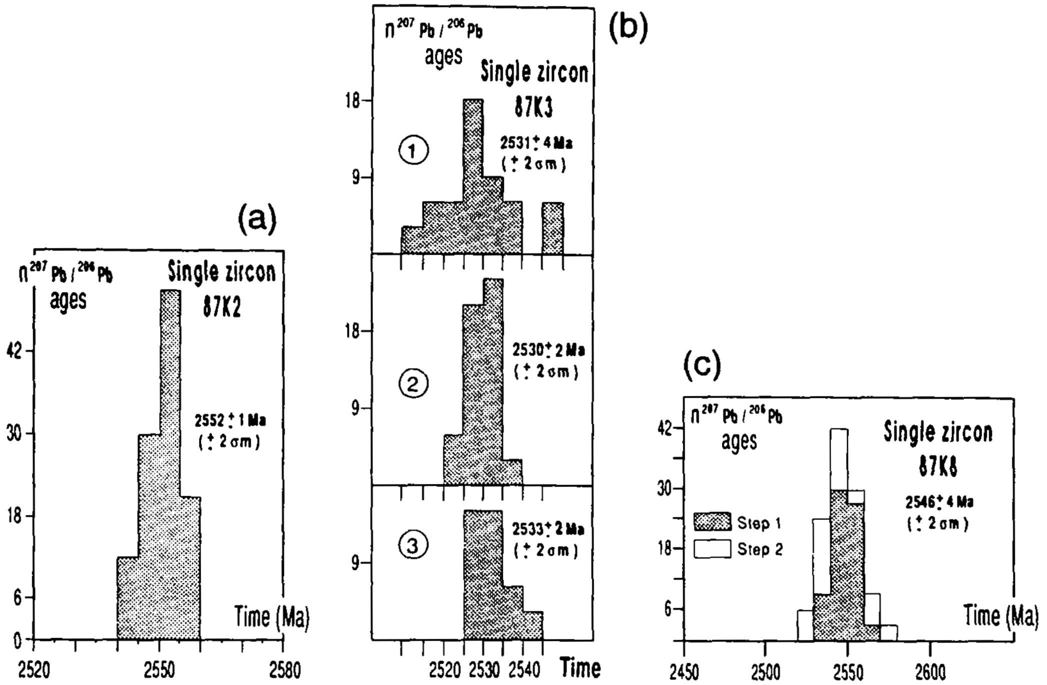

Fig. 5. Single zircon $^{207}Pb/^{206}Pb$ histogram ages from (a) the granitic gneiss 87K2, (b) the tonalitic gneiss 87K3 and (c) the charnockitic gneiss 87K8.

strongly zoned centre suggests several stages of growth during magmatic processes (Fig. 6).

Sample 87K2. Four size fractions define an upper intercept with the concordia at 2557 ± 16 Ma (Table 2, Fig. 6). A single grain analysed by the evaporation method provides a similar result of 2551 ± 1 Ma (Table 3, Fig. 5a).

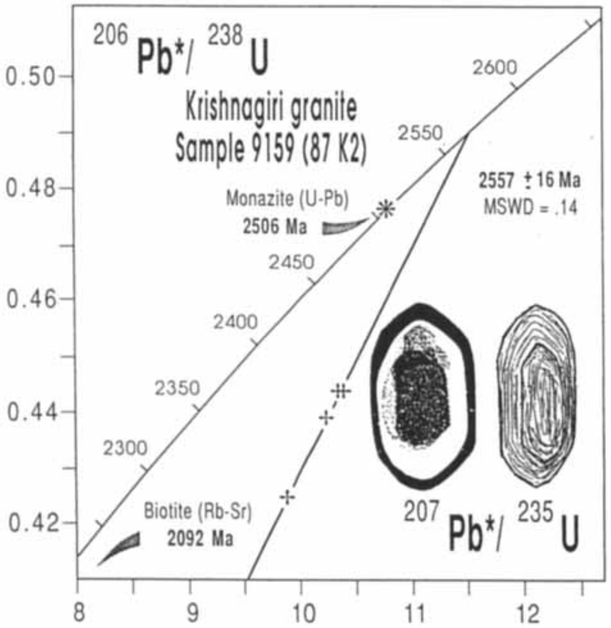

Fig. 6. Zircon U–Pb concordia plot for the granitic sample 87K2. The $^{207}Pb/^{206}Pb$ monazite age is reported on the concordia curve.

Charnockitic samples

Zircons are similar to those found in the granitic sample (Fig. 7).

Sample 87K8. Dissolution and evaporation methods provide the same result (Tables 2 & 3, Fig. 7); an upper intercept of 2557 ± 16 Ma and a $^{207}Pb/^{206}Pb$ age of 2548 ± 3 Ma. Samples 87K5 and K6 give similar $^{207}Pb/^{206}Pb$ ages of 2548 ± 5 Ma and 2553 ± 5 MA, respectively (Table 3).

All samples from tonalitic gneisses as well as those from the charnockites provide homogeneous results close to 2550 Ma.

Monazite dating

Monazite was found only in the samples of granitic gneiss (87K2) and charnockite (87K8). They are relatively poor in uranium (125 and 70 ppm); their high content of lead corresponds to more than 90% of the ^{208}Pb derived from ^{232}Th (Table 2). The points are slightly discordant, defining $^{207}Pb/^{206}Pb$ ages of 2506 ± 10 and 2517 ± 10 Ma, respectively.

Biotite dating

Rb–Sr whole-rock biotite pair ages were obtained from three samples (87K2, K3, K8). These ages are 2092, 2067 and 2337 ± 10 Ma, respectively (Table 4).

Table 4. Rb–Sr mica and corresponding whole-rock (WR) data from Krishnagiri gneisses

Sample (analysis)	Nature	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	Error ($2\sigma_m$)	Ages micas–WR pair (Ma)
87K2 (9159)	WR	64.5	627	0.21	0.71314	2	
	'muscovite'	50.1	1056	0.13	0.70798	3	
	biotite	433	76.1	17.28	1.21752	9	2092
87K3 (9160)	WR	61.9	451	0.40	0.71632	3	
	biotite	372	33.3	35.66	1.75114	9	2067
87K8 (9165)	WR	60.8	776	0.23	0.71025	2	
	biotite	398	69.2	17.57	1.28575	8	2337

COMPARISON WITH U–Pb ZIRCON AGES AND Sr–Nd SYSTEMATICS OF THE GORUR–HASSAN PENINSULAR GNEISSES

The Gorur–Hassan migmatitic gneisses (Fig. 1) are representative of the oldest Peninsular gneisses since Rb–Sr ages of 3300–3000 Ma were obtained by Beckinsale *et al.* (1982), Monrad (1983), Taylor *et al.* (1984) and Meen *et al.* (1992). Our aim is restricted here to a comparison of isotope systematics between these old gneisses and the 2500-Ma and Krishnagiri gneisses, to establish whether they are derived from different precursors.

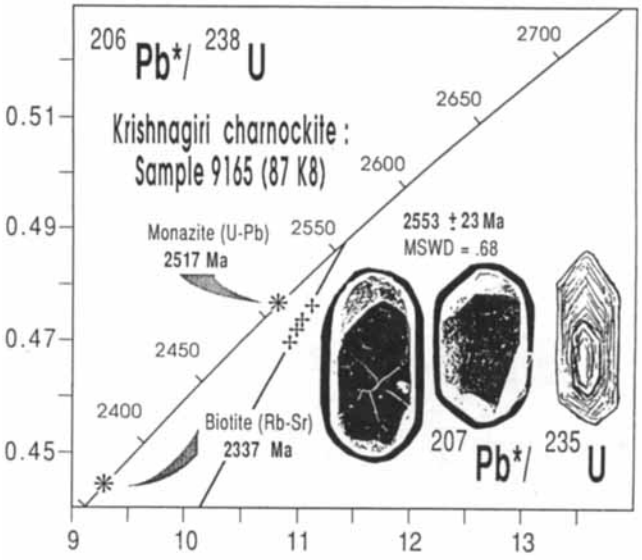

Fig. 7. Zircon U–Pb concordia plot for the charnockite, sample 87K8. The $^{207}Pb/^{206}Pb$ monazite age is reported on the concordia curve.

Furthermore, we have recently obtained some preliminary single-zircon dates from two granodioritic samples (collected to the west of the Holenarsipur belt). Another sample from the Halekote trondhjemite (close to the nothern contact with the Holenarsipur schist belt) and two granodioritic gneiss from north of Hassan (south-west of

Table 5. Sm–Nd and Rb–Sr data of whole-rocks from the Gorur–Hassan-type gneisses.

Sample	Analysis	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	Error ($\times 10^{-6}$)	T_{DM} (Ma)	Epsilon (2.5 Ga)	(3.3 Ga)
Gorur									
Ind 55b	10445	1.44	5.98	0.1456	0.511591	5	3460	−4.15	1.06
Ind 55d	10447	13.95	53.99	0.1562	0.511835	4	3458	−2.79	1.35
Gor 3a2	11203	11.98	43.83	0.1653	0.512028	4	3504	−1.92	1.29
Gor 3b	11204	4.86	27.59	0.1065	0.510783	4	3340	−7.45	1.76
HL1a	11205	4.29	19.99	0.1297	0.511253	4	3414	−5.68	1.16
Halekote									
HL5a	11209	1.90	8.50	0.1348	0.511393	3	3368	−4.58	1.74
Segegudda									
Ind 56a	10448	9.92	44.08	0.1360	0.511441	5	3327	−4.03	2.17

Sample	Analysis	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$		Io Sr (2.5 Ga)	(3.3 Ga)
Gorur								
Ind 55b	10445	67.8	634	0.310	0.714876	5	0.70367	0.70000
Ind 55d	10447	62.5	129	1.41	0.764650	5	0.71370	0.69701
Gor 3a2	*11203	77	59	3.8	0.865441	27	0.72688	0.68149
Gor 3b	*11204	77	474	0.5	0.718915	10	0.70191	0.69634
HL1a	*11205	62	723	0.2	0.711660	9	0.70269	0.69975
Halekote								
HL5a	*11209	68	835	0.236	0.711513	11	0.70300	0.70020
Segegudda								
Ind 56a	10448	70.7	727	0.281	0.714060	6	0.70391	0.70058

*XRF Rb and Sr data.

the Segegudda belt and west of Chikmagalur) were also investigated. The data are given in Table 3; various step-heating ages from two Gorur gneiss samples (Ind55) provide ages of 3210 ± 5 and 3309 ± 7 Ma. The north Hassan gneiss (Ind56) provides ages of 3234 ± 8 and 3328 ± 10 Ma; the trondhjemite sample (HL5a) gives an age of 3203 ± 19 Ma. A gneiss from the west of Chikmagalur (Ind57) provides an age of 3251 ± 33 Ma (Table 3).

Sr and Nd data are reported in Table 5. The T_{DM} (Nd) model ages of the six gneiss samples range from 3.5 to 3.3 Ga, close to the zircon ages. The εNd values, for 3.3 Ga, range from +1 to +2, whereas ^{87}Sr/^{86}Sr ratios vary between 0.681 and 0.701. Calculated back to 2.5 Ga, the εNd values range between −2 and −7 and the ^{87}Sr/^{86}Sr ratios between 0.702 and 0.727. Similar values are obtained from one sample of the Halekote trondhjemite (Table 5).

DISCUSSION

Magmatism and metamorphism

The Gorur–Hassan-type gneisses

The oldest ^{207}Pb/^{206}Pb ages, close to 3.3 Ga, confirm those obtained for similar gneisses using Rb–Sr (3315 ± 54 Ma) and Pb–Pb (3305 ± 13 Ma) systems (Beckinsale *et al.*, 1982); they are interpreted as magmatic ages. Step ages close to 3200 Ma may be related to migmatitic processes and/or later trondhjemite emplacement. The similar U–Pb zircon and Nd model ages of the gneisses and the trondhjemite suggest they were derived within a short period of time from similar mantle sources (Fig. 8). The individual initial Sr ratios calculated back to 3.3 Ga are very low and sometimes lower than the initial value assumed for the primitive Earth, thus suggesting an opening of the Rb–Sr system and probable resetting during migmatization.

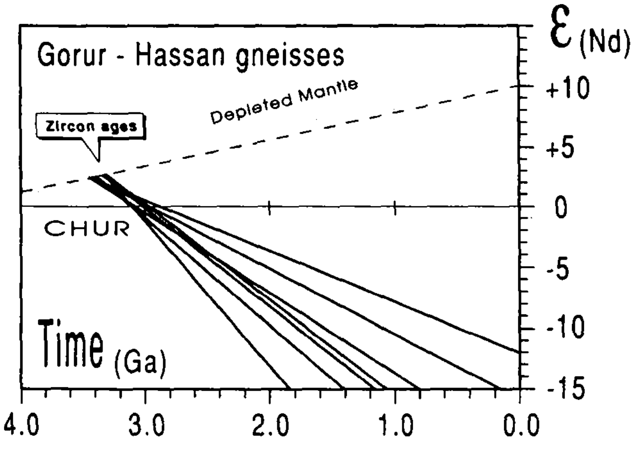

Fig. 8. εNd CHUR vs. time diagram for the Gorur–Hassan gneisses. Nd isotopic growth lines are drawn using data of Table 5.

Nevertheless, significant Rb–Sr isochron relationships are preserved (Beckinsale *et al.*, 1982), suggesting that the opening was not very important on the scale of sampling (10 kg each sample). The age of 3203 ± 19 Ma obtained from the Halekote trondhjemite is slightly older than those from the Sr and Pb systems which give ages between 3.1 and 3.0 Ga (Beckinsale *et al.*, 1982; Stroh *et al.*, 1983; Meen *et al.*, 1992). Is the zircon age therefore inherited from the surrounding gneisses or were the Sr and Pb systems slightly reset during late metamorphism? This is a question beyond the scope of this paper, which should be debated in relation to the numerous Pb and Sr ages close to 3.0 Ga which have been obtained from the gneisses near Holenarsipur and Chikmagalur (Monrad, 1983; Taylor *et al.*, 1984; Meen *et al.*, 1992) and apparently are younger than our zircon ages.

The Krishnagiri gneisses

The emplacement age of the tonalitic gneisses, obtained from U–Pb upper intercepts as well as from ^{207}Pb/^{206}Pb evaporation of single zircons, is in the range 2550–2530 Ma. Ages from charnockitic gneisses are similar. Due to the magmatic origin of these zircons and the lack of inherited structure, we consider these ages as being those of the tonalitic and granodioritic magmatic intrusion. A similar age from the granitic gneiss (2550 Ma) confirms this interpretation in terms of a magmatic event. Nevertheless, there is some question regarding one point: the granites are considered by Condie *et al.* (1982) to have been melted from tonalitic precursors during the granulitic event which is dated close to 2510 Ma. However, sample 87K2 is granodioritic in composition; plotting in the field of the granitic gneisses as defined by Condie *et al.* (1982), it is not a true granite. We presently believe that the U–Pb age close to 2550 Ma corresponds to the general tonalitic event; the true anatectic granites remain to be dated.

The timing of the granulitic event is better constrained from the U–Pb monazite ages of 2517 and 2506 Ma. At 2510 ± 10 Ma, they fall in the range of average monazite dates obtained from several charnockite massifs along the transition zone (Buhl, 1987; in Peucat *et al.*, unpubl. data). Monazite ages are known to record cooling above 600° C and are sometimes estimated up to 700–750° C (Parrish, 1990). These conditions are close to those defined for granulite metamorphism in the transition zone (e.g. Janardhan *et al.*, 1982; Raith *et al.*, 1983; Hansen *et al.*, 1984); thus we consider the age of 2510 ± 10 Ma as the best estimate of the granulitic event in the Krishnagiri area as well as along the South Indian transition zone. This result is in agreement with recent data from the Closepet Batholith, where anatectic granites are dated at 2513 ± 5 Ma (Friend & Nutman, 1991) and the intrusive granites are dated at 2518 ± 5 Ma (Jayananda *et al.*, unpubl. data). This batholith was affected by and probably related to the granulitic event (Friend, 1983).

Nature of the 2.5-Ga magmas from Sr and Nd systematics

On Fig. 9, the isotopic signatures of Sr and Nd systems (recalculated at 2.5 Ga) in Krishnagiri gneisses (Peucat *et al.*, 1989) are compared with those of the 2.52-Ga Closepet granites (Jayananda *et al.*, unpubl. data), the 3.3-Ga gneisses from the Gorur–Hassan region (Table 5) and the ancient massive charnockites (Peucat *et al.*, 1989). The Krishnagiri gneisses have positive or zero εNd and initial ^{87}Sr/^{86}Sr close to 0.702. This clearly indicates that they were not derived by melting of the 3.3-Ga gneisses which had εNd (2.5 Ga) values of -4 to -15 and initial ^{87}Sr/^{86}Sr ratios of 0.702–0.750. They also differ from the Closepet granites, which contain anatectic granites derived from the ancient Peninsular gneisses. They also contrast with the intrusive granites which exhibit negative εNd values despite clear major juvenile input during their petrogenesis (Jayananda *et al.*, 1993).

Assuming an εNd value close to $+5$ for the mantle at this time, we can calculate that an ancient crustal contamination may have occurred in the source. According to the model of Martin (1987), where tonalitic magmas are melted from enriched tholeiite, 10% of older gneisses can be mixed with 90% of enriched tholeiite to produce tonalitic magmas with an εNd value close to zero. Consequently, the Krishnagiri gneisses are at present the most juvenile magmas recognized close to 2.5 Ga in this region.

Just to the north of the Krishnagiri area is the amphibolite facies Kolar schist belt (Fig. 1b). Krogstad *et al.* (1989, 1991) have shown that this lower grade belt corresponds to a possible suture which joins eastern terranes *c.* 2.5 Ga old with older western terranes. It is also possible to recognize two main blocks involved in the 2.5-Ga granulite metamorphism (Peucat *et al.*, 1989). One block may correspond to a 'western' craton involving 3-Ga or older gneisses and another more 'eastern' block containing 2.5-Ga juvenile crust, which possibly runs from the Madras area (Bernard-Griffiths *et al.*, 1987) to Krishnagiri and the Nilgiri Hills; it represents a major period of accretion (2.5 Ga ago) probably at the boundary of the older craton. These blocks could have been joined in suture zones close to the Kolar and Closepet areas 2.5 Ga ago and probably dislocated during major dextral shearing before 2.3 Ga ago (as suggested by mica cooling ages).

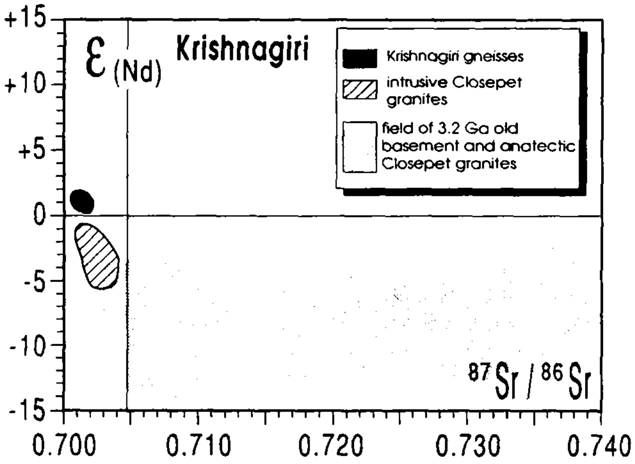

Fig. 9. εNd vs. ^{87}Sr/^{86}Sr diagram for the Krishnagiri gneisses, Closepet granites and 3.3-Ga gneisses at 2.50 Ga.

CONCLUSIONS

The 3.3-Ga Peninsular gneisses in the vicinity of Holenarsipur constitute an early episode of continental crust formation from the mantle; this gneiss did not participate in the genesis of the 2.5-Ga magmas close to the transition zone. A second major episode of continental crust formation, associated with the granulite facies metamorphism, occurred at 2.55–2.51 Ga and was related to accretional processes of juvenile crust in subduction or mantle-plume environments.

The sequence of events around 2.5 Ga in the transition zone can be summarized as follows (references in the text):

1 2550–2530 ± 5 Ma corresponds to the accretion of a juvenile crust of tonalitic–granodioritic composition with positive or zero initial εNd and low initial strontium ratios;

2 2518–2513 ± 5 Ma corresponds to the emplacement of juvenile intrusive granitoids and the melting of 3.0-Ga gneisses to produce anatectic granites in the southern part of the Closepet batholith.

3 2510 ± 10 Ma corresponds to the age of the granulite facies metamorphism which occurred 10–30 Ma later than the accretion event;

4 2300–2100 Ma corresponds to late cooling close to 300–350° C, representing the limit in the main high-temperature (Raith *et al.*, 1990) shear zones along the transition zone.

The transition zone is mainly localized at the boundary of ancient Peninsular gneisses with newly formed 2.5-Ga tonalite–trondhjemitic terranes to the south.

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APPENDIX

Analytical procedures

The major element contents were determined by XRF, using a sequential Phillips PW 1404 spectrometer. The analytical precisions are as follows: SiO_2 1%, Al_2O_3 1.5–3%, Fe_2O_3 2–3%, MnO 10%, MgO 1–3%, CaO 2–5%, Na_2O 1.5–3%, K_2O 2.5%, TiO_2 2–5%, P_2O_5%.

Rb, Sr, Sm and Nd contents were determined by isotope dilution using a Cameca THN-206 mass spectrometer. Total blanks were: Rb 0.1 ng, Sr = 1 ng, Sm = 0.2 ng, Nd < 0.5 ng. Uncertainties for $^{87}Rb/^{86}Sr$ ratios are 2% and for $^{147}Sm/^{144}Nd$ ratios 0.5%. Isotope Sr analyses of micas were performed using the Cameca THN-206 mass spectrometer and a Finnigan Mat 262 was used to determine Sr and Nd isotopic ratios of whole rocks. Replicate analyses of NBS 987 yield a mean $^{87}Sr/^{86}Sr$ ratio of 0.71020 ± 8 and $^{143}Nd/^{144}Nd$ mean ratio of 0.511835 ± 5 for the La Jolla standard, samples were normalized to 0.511860. T_{DM}Nd ages were calculated using values of the present depleted mantle as: $^{143}Nd/^{144}Nd = 0.51315(\varepsilon_0 = +10)$ and $^{147}Sm/^{144}Nd = 0.2137$, following a radiogenic linear growth for the mantle with εNd tending to zero at 4.54 Ga.

U–Pb analyses were performed on the Finnigan Mat 262 on 2–5 mg of zircon separate, following Krogh (1973). Total blanks were lower than 0.5 ng and common lead assumed to have the following isotopic composition: $^{206}Pb/^{204}Pb$ 18.0, $^{207}Pb/^{204}Pb$ 15.5, $^{208}Pb/^{204}Pb$ 37.0. Uncertainties used are as follows: when $^{206}Pb/^{204}Pb > 6000$: $^{207}Pb/^{235}U = 0.7\%$, $^{206}Pb/^{238}U = 0.5\%$,

$^{207}Pb/^{206}Pb = 0.1\%$; when $1000 < {}^{206}Pb/^{204}Pb < 6000$: $^{207}Pb/^{235}U = 0.9\%$, $^{206}Pb/^{238}U = 0.6\%$, $^{207}Pb/^{206} = 0.4\%$. Correction for mass fractionation was 0.10% AMU. NBS 983, using Faraday cups provided $^{206}Pb/^{204}Pb = 2763 \pm 7$, $^{207}Pb/^{206}Pb = 0.071309 \pm 3$, $^{208}Pb/^{204}Pb = 0.013645 \pm 1$; $^{206}Pb/^{204}Pb$ ratios, when ^{204}Pb is recorded from the ion counting system (ICT), range between 2708 and 2780. Calculation of the concordia intercept ages is from Ludwig's (1980) program and errors (2σ) using the regression of York (1969).

Single zircon analyses were performed following the procedure proposed by Kober (1986, 1987), using both mass spectrometers. Use of ICT on the Finnigan Mat allows measurement of very high $^{206}Pb/^{204}Pb$ ratios, which sometimes had to be estimated from the Cameca measurements when the run was not of an adequate intensity.

Decay constants and isotopic abundance ratios are those listed by Steiger & Jäger (1977).