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Late Archaean crust-mantle interactions: geochemistry of LREE-enriched mantle derived magmas. Example of the Closepet batholith, southern India

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Abstract The Closepet batholith in South India is generally considered as a typical crustal granite emplaced 2.5 Ga ago and derived through partial melting of the surrounding Peninsular Gneisses (3.3 to 3.0 Ga). In the field, it appears as a composite batholith made up of at least two groups of intrusions. (a) An early SiO_2-poor group (clinopyroxene quartz-monzonite and porphyritic monzogranite) is located in the central part of the batholith. These rocks display a narrow range in both initial $^{87}Sr/^{86}Sr$ (0.7017–0.7035) and ε_{Nd} ($-$ 0.9 to $-$ 4.1). (b) A later SiO_2-rich group (equigranular grey and pink granites) is located along the interface between the SiO_2-poor group and the Peninsular Gneisses. They progressively grade into migmatised Peninsular Gneisses, thus indicating their anatectic derivation. Their isotopic characteristics vary over a wide range ($^{87}Sr/^{86}Sr$ ratios = 0.7028–0.7336 and ε_{Nd} values from $-$ 2.7 to $-$ 8.3, at 2.52 Ga). Field and geochronological evidence shows that the two groups are broadly contemporaneous (2.518–2.513 Ga) and mechanically mixed. This observation is supported by the chemical data that display well defined mixing trends in the ε_{Sr} vs ε_{Nd} and elemental variation diagrams. The continuous chemical variation of the two magmatic bodies is interpreted in terms of interaction and mixing of two unrelated end-members derived from different source regions (enriched peridotitic mantle and Peninsular Gneisses). It is proposed that the intrusion of mantle-derived magmas into mid-crustal levels occurred along a transcurrent shear zone; these magmas supplied additional heat and fluids that initiated anatexis of the surrounding crust. During this event, large-scale mixing occurred between mantle and crustal melts, thus generating the composite Closepet batholith. The mantle-derived magmatism is clearly associated with granulite facies metamorphism 2.51 $\pm$ 0.01 Ga ago. Both are interpreted as resulting from a major crustal accretion event, possibly related to mantle plume activity.

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Introduction

A large part of most Archaean cratons is made up of a huge amount of trondhjemitic-tonalitic-granodioritic (TTG) gneisses, volcanic-dominated greenstone belts, deep crustal granulite sections and subordinate calc-alkaline to K-rich granites. Extensive research carried out over the last two decades on Archaean cratonic areas has improved our understanding of early continental evolution. However, most of these studies focused on mineralised greenstone belts, TTG and granulites, while little attention has been paid to the less widely developed calc-alkaline and K-rich granites. These granites are generally syn-to late-tectonic and both their modal and chemical characteristics are clearly distinct from those of typical Archaean TTG. Their petrogenesis remains a matter of debate; mantle as well as lower or upper continental crust sources have been proposed, assuming different kinds of interaction between these materials (Querré 1985; Condie et al. 1985; Allen et al. 1986; Sutcliffe 1989; Newton 1990a; Stern and Hanson, 1991; Evans and Hanson 1992). These rocks are crucial to our understanding of the end-Archaean events, since they have recorded mantle evolution and crustal growth processes as well as stabilisation of cratons and mantle-crust interactions.

The late Archaean Closepet batholith in southern India has a ribbon shape and cross-cuts the Dharwar craton (Fig. 1); it forms the latest Archaean event in this area (Newton 1990a). Because of its exceptional fresh exposures and its close association with different tectono-metamorphic domains, the Closepet batholith has been investigated in many studies (Radhakrishna 1956; Suryanarayana 1960; Divakara Rao et al. 1972, 1990; Friend 1983, 1985; Allen et al. 1986; Jayananda 1988; Newton 1990b; Jayananda et al. 1992). However, most of these studies concentrate on field and petrological descriptions, whereas detailed geochemical and isotopic studies are generally lacking. The purpose of the present paper is: (1) to present detailed new field, geochemical (major, trace, REE and isotopes) and geochronological (U-Pb zircon dating) data for the southern part of the Closepet batholith, (2) to constrain the composition of its source as well as its petrogenesis, and (3) to discuss the geodynamic mechanisms that controlled its genesis and emplacement.

Geological setting

The oldest components of the Dharwar craton, southern India (Fig. 1) are the 3.3–3.0 Ga Peninsular Gneisses associated with supracrustal belts (Sargur Group); both are overlain by extensive volcano-sedimentary sequences (Dharwar Super Group), (Chadwick et al. 1981; Radhakrishna, 1983; Drury 1983; Newton 1990a, b). The youngest components are: (1) calc-alkaline to K-rich granitoids (Closepet type), which intruded the Peninsular Gneisses at 2.6 to 2.5 Ga, and (2) associated greenstones (Chitradurga and Bababudan belts). In the southern part of the craton, greenstone belts are N-S striking, whereas the metamorphic zonation is roughly perpendicular to this direction (Fig. 1). Metamorphism evolves from low-grade greenschist-facies in the North to high-grade granulite-facies in the South (Pichamuthu 1965; Janardhan et al. 1979, 1982; Condie 1981a; Condie et al. 1982; Hanson et al. 1988; Raase et al. 1986; Newton 1990a, b).

The Closepet batholith is a N-S elongated composite intrusive body that runs nearly 400 km across the Dharwar craton from Kabbaldurga in the South up to Deccan plateau in the North (Fig. 1). At its southern extremity, it occurs as a network of veins and as small plutons; towards the North it forms high-level intrusions cutting across the Peninsular Gneisses and greenstone belts. The parallelism of batholith contacts with the strike of the surrounding greenstone belts indicates that the deformation which caused the elongate structure of the greenstones also guided the emplacement of the Closepet batholith (Newton 1990a).

The general geology of the southern Karnataka has already been described in detail by Rama Rao (1940), Suryanarayana (1960), Pichamuthu (1965), Janardhan et al. (1982), Friend (1981, 1983, 1984, 1985), Jayananda (1988) and Newton (1990b). The Peninsular Gneisses, together with minor supracrustal enclaves, form the so-called "old Archaean basement" of this area and are affected by

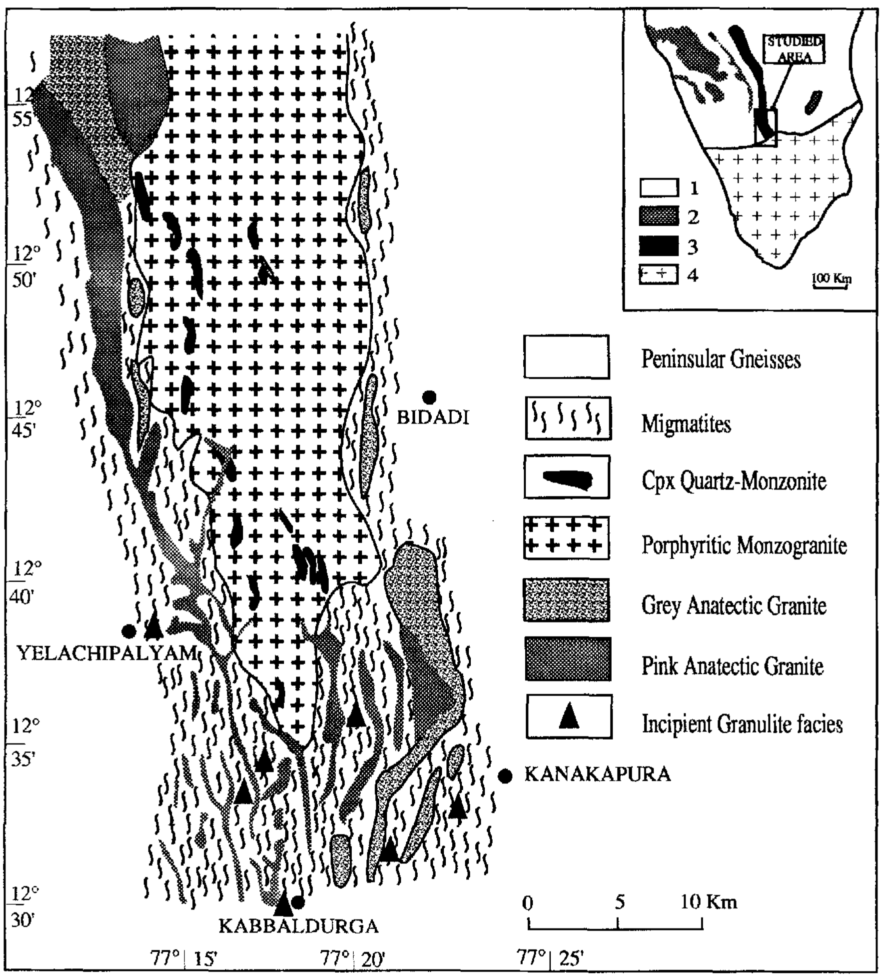

Fig. 1 Geological sketch map of the south Closepet area, showing sampling localities and relationships between the different components of the batholith. The inset shows a general geological map of southern India. *1* Peninsular Gneisses, *2* greenstone belts, *3* Closepet batholith, *4* granulites

granulite metamorphism. They are trondhjemitic-tonalitic-granodioritic (TTG) in composition and show a general N-S striking vertical foliation. They were emplaced over a long time-span, from 3.4 to 2.96 Ga (Buhl 1987; Friend and Nutman 1991, 1992; Peucat et al. 1993a).

The Closepet batholith is clearly younger than the Peninsular Gneisses; an allanite from the granite in Kabbaldurga quarry yields a concordant U-Pb age of 2.52 Ga (Grew and Manton 1984), whereas recent zircon U-Pb data give an age of 2.513 $\pm$ 0.004 Ga for the anatectic granite and 2.528 $\pm$ 0.005 Ga for the associated migmatites (Friend and Nutman 1991). The age of granulite-facies metamorphism is younger than 2.528 $\pm$ 0.005 Ga (Friend and Nutman 1992) and determined at 2.510 $\pm$ 0.010 Ga from U-Pb data on monazites (Peucat et al. 1993a). It is broadly contemporaneous with the age of the Closepet batholith emplacement (Friend 1983).

In its southern part, the Closepet batholith is heterogeneous and four major rock-types are recognised:

(1) Clinopyroxene-bearing dark grey quartz-monzonite.
(2) Porphyritic monzogranite.
(3) Equigranular grey granite.
(4) Equigranular pink granite.

The four rock-types show different field relationships with the surrounding basement. The clinopyroxene quartz-monzonite and the porphyritic monzogranite are intrusive into the basement and occupy the central part of the complex (Fig. 1); they are referred to as intrusive monzogranites. These early intrusive facies contain angular enclaves of gneisses and metabasic rocks. By contrast, the equigranular grey and pink granites grade progressively into the surrounding basement through a zone of migmatites which are referred to as anatectic granites in the present study.

Intrusive monzogranites

The intrusive monzogranites show sharp intrusive contacts with the Peninsular Gneisses. The clinopyroxene-bearing dark grey quartz-monzonite occurs as discontinuous sheets displaying a north-striking foliation which contains an alignment of mafic minerals. The porphyritic monzogranite is volumetrically the most important; it is rich in K-feldspar phenocrysts (average 30–40%) and contains small microgranular enclaves elongated parallel to the N-S foliation. Phenocrysts are commonly segregated along the sheets, where they show strong deformation in places, such evidence indicates that shear deformation was active throughout the crystallisation of the granite (Jayananda and Mahabaleswar 1991b; Martin et al. 1993).

The contact between the clinopyroxene quartz-monzonite and porphyritic monzogranite is gradational. Lobate and pillow-shaped fragments of clinopyroxene-bearing facies are included within the porphyritic monzogranite, whereas K-feldspar megacrysts of the later can be found in the former. These relationships are indicative of sub-contemporaneous emplacement of the two magmas and also illustrate their mechanical mixing. Both are cut by a network of equigranular grey and pink granite veins.

Anatectic granites

At the southern end of the Closepet batholith, both pink and grey equigranular granites grade into the Peninsular Gneisses through a large migmatized zone (Friend 1983). The alternating leucosome, melanosome and mesosome layers give a banded aspect to the Peninsular Gneisses, which are thus transformed into metatexites. Towards the intrusive monzogranites, metatexites progressively grade into diatexites and to nebulitic granites with heterogeneous chaotic textures underlain by biotitic schlieren. The progressive and continuous gradation from gneisses to grey and pink equigranular granites indicates that the later rock-types were formed through anatexis of the Peninsular Gneisses. Anatectic granites occur as veins and sheets in the Kanakapura-Kabbaldurga area (Fig. 1); their volume gradually increases towards the North where they are located systematically on the margins of the intrusive monzogranites. In many cases, anatectic granites contain enclaves of the earlier intrusive bodies. Lobate contacts between equigranular grey and pink granites are common together with mechanical mixing. These structures are indicative of the synchronous emplacement of the two anatectic magmas.

Petrography

Detailed petrographic descriptions have already been presented elsewhere (Jayananda 1988; Jayananda et al. 1992) and can be summarised as follows.

(1) The clinopyroxene quartz-monzonite is a dark grey medium-grained rock that contains quartz, plagioclase (An_{20-30}), K-feldspar, clinopyroxene, hornblende and biotite. The accessory minerals include zircon, apatite, allanite, sphene and magnetite. The clinopyroxene is unstable and replaced to varying degrees by a hornblende-biotite association.

(2) The porphyritic monzogranite contains large (3–5 cm) pink coloured K-feldspar phenocrysts in a coarse-grained grey to dark-grey matrix. Hornblende and biotite are the major mafic minerals, microcline is found as large anhedral perthitic grains when plagioclase (An_{15-25}) is confined to the matrix. Both replacive and intergranular myrmekites are common. The accessories are zircon, apatite, allanite, sphene, ilmenite and magnetite.

(3) The equigranular grey granites are biotite-rich but in very rare instances they also contain hornblende. K-feldspar and plagioclase (An_{15-20}) are variably perthitic and antiperthitic with myrmekitic textures. Zircon, allanite, apatite and sphene are usually present.

(4) The equigranular pink granites are similar to the grey granites but contain more microcline and less plagioclase (An_{10-20}), biotite is the major ferromagnesian mineral. The common accessory minerals are zircon and allanite with rare apatite.

Geochronology

The age of the Closepet batholith has been established at about 2.50 Ga (Buhl et al. 1983; Grew and Manton; 1984). Recent SHRIMP U-Pb dating from zircon by Friend and Nutman (1991) from anatectic granite provided an age of 2.513 $\pm$ 0.005 Ga. As intrusive monzogranites are found as enclaves in the anatectic granites, and in order to check the time span between emplacement of both groups, clinopyroxene quartz-monzonite and porphyritic monzogranite were dated by the single grain evaporation zircon method of Kober (1986). The results are presented in Table 1 and in Fig. 2.

Zircons from the clinopyroxene quartz-monzonite (sample CG 9b) are subhedral to euhedral, elongated, clear to slightly brown, with fine zoning structures and no visible cores. Zircons from the porphyritic monzogranite (sample CG 23b) are euhedral, elongated to stubby, brown and strongly zoned, without any visible inherited core. Both intrusive monzogranites define common patterns: a first step-heating age of 2.513 $\pm$ 0.005 Ga and a second one of 2.518 $\pm$ 0.005 Ga. the age of 2.518 Ga is taken as the magmatic event; the age of 2.513 Ga, which is not significantly different from the previous one, may be related to the anatectic stage as inferred from SHRIMP data (Friend and Nutman 1991). These ages indicate that both clinopyroxene quartz-monzonite and the porphyritic monzogranite are contemporaneous as suggested by field relationships. They are also broadly synchronous with the adjacent granulite metamorphism as established from U-Pb monazite dating at 2.51 $\pm$ 0.01 Ga (Peucat et al. 1993a).

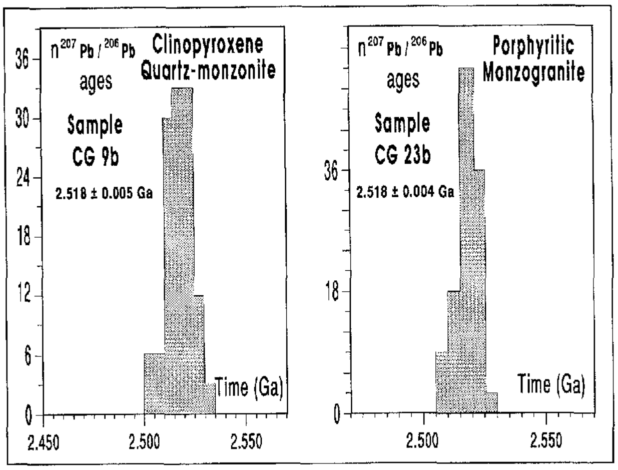

Fig. 2 Single-zircon $^{207}Pb/^{206}Pb$ data for clinopyroxene quartz-monzonite (sample CG 9b) and porphyritic monzogranite (sample CG 23b) showing that they were emplaced contemporaneously at 2.518 Ga

Geochemistry

Analytical methods

Major and trace elements were analysed by XRF at Rennes and Liverpool Universities. Analytical precision for major elements is within 2% but it may reach 10% for elements of low abundance (e.g. MnO or P_2O_5). For trace elements, precision is better than 5%; for contents less than 30 ppm, the uncertainties are within 10%. Rare earth elements were determined using an ARL 1510 Inductively Coupled Plasma Spectrometer at Oxford Brookes University. Details of the analytical methods have been given elsewhere (Jayananda 1988).

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 $^{87}Rb/^{86}Sr$ and $^{147}Sm/^{144}Nd$ ratios are 2% and 0.5% respectively. A Finnigan Mat 262 mass spectrometer was used to determine the Sr and Nd isotopic ratios of the whole-rocks. Replicate analyses of NBS 987 yield mean $^{87}Sr/^{86}Sr$ and $^{143}/^{144}Nd$ ratios of 0.71020 ± 0.00008 and 0.511835 ± 0.000005, respectively for the La Jolla standard. Samples were normalised to 0.511860; T_{DM}Nd ages were calculated using the values of present depleted mantle as: $^{143}Nd/^{144}Nd = 0.51315$ ($\varepsilon o = +10$) and $^{147}Sm/^{144}Nd = 0.2137$, following a radiogenic linear growth for the mantle with $\varepsilon_{Nd} = 0$ at 4.54 Ga.

Single zircon analyses were performed following the procedure proposed by Kober (1986). Decay constants and isotopic abundance ratios are those listed by Steiger and Jäger (1977).

Major elements

Representative whole-rock analyses are given in Table 2. The distinction between intrusive and anatectic bodies is also supported by major-element data: the intrusive monzogranites are SiO_2-poor (50.30%–67.97%), whereas the pink and grey anatectic granites are SiO_2-rich (67.33%–76.52%). The intrusive monzogranites have high Mg number (Mg# = 0.46–0.32) when compared to anatectic granites (0.36–0.02); both display high $Na_2O + K_2O$ (7.83% and 8.34% in intrusive monzogranites and anatectic granites, respectively). The An–Ab–Or triangle of O'Connor (1965) can only be used with rocks containing more than 10% of normative quartz. This is not the case for some of the intrusive monzogranites. Nevertheless, in order to compare Closepet batholith composition with typical TTG, low SiO_2 monzogranites were reported in this diagram, but as they do not have the required quartz content, the field where they plot does not correspond with the name appropriate for their modal composition (which is adopted here). In this An–Ab–Or triangle the intrusive monzogranites plot in the granodiorite field extending towards the granite domain, where most of the anatectic granites fall (Fig. 3). The grey patch on Fig. 3 represents the compositional field of anatectic liquids generated from migmatised Peninsular Gneisses (metatexites). The composition of metatexites is closely similar to that of the pink and grey equigranular granites, thus supporting an anatectic origin. Both intrusive monzogranites and anatectic granites are clearly distinct from the Archaean grey gneisses (Peninsular Gneisses), which are typical TTG rocks mostly plotting in the trondhjemite field (Fig. 3). This difference is also reflected in the K–Na–Ca triangle (Fig. 4), (Barker and Arth 1976) where all the Closepet components define a classical calc-alkaline differentiation trend, showing no affinity with the Peninsular Gneisses which plot along the trondhjemitic line. Here also, both metatectic liquids and anatectic granites show the same composition.

All the major elements are negatively correlated with SiO_2 on Harker diagrams (Fig. 5), except for K_2O which shows a positive correlation. Only alkalis (Na_2O and K_2O) displays a slight scattering of points around the regression line. It should also be noted that the field

Table 1 Single zircon Pb isotopic data

Sample	Step Ampere	$^{206}Pb/^{204}Pb$ Measured	$^{207}Pb/^{206}Pb$ Measured	Error 2 σ	$^{206}Pb/^{204}Pb$ Corrected	$^{207}Pb/^{206}Pb$ Age (Ga)	Error 1 σ	Error 2 σ
				Cpx Quartz-monzonite				
CG 9b	2.9	23134	0.1663	2	0.1657	2.514	5	2
	3.2	38254	0.1664	2	0.1660	2.518	5	2
				Porphyritic Monzogranite				
CG 23b	2.8	3522	0.1690	3	0.1654	2.512	13	5
	3.2	5976	0.1681	1	0.1661	2.518	4	1

Table 2 Average composition (x), standard deviation (σ) and representative analyses of the Closepet batholith and Peninsular gneisses Mg# = mol. MgO/(MgO + FeO*)

	Cpx QZ-Monzonite				Porph. Monzogranite				Grey granite				Pinkgranite				Migmat.		Gneisses	
%	x	σ	CG 9	CG 40	x	σ	CG 5	J 39	x	σ	J 15	J 29	x	σ	J 2	J 57	x	σ	x	σ
SiO_2	55.12	3.2	50.30	60.55	64.80	2.2	62.03	67.97	70.93	2.5	67.33	74.27	73.83	2.0	70.51	76.52	74.03	2.2	73.15	1.5
Al_2O_3	16.28	1.3	13.84	15.70	15.75	0.7	16.51	14.85	15.00	0.8	16.21	13.99	14.20	0.6	15.03	13.53	13.31	1.0	14.71	1.2
Fe_2O_3	9.64	2.0	14.20	6.98	5.34	0.8	5.94	4.17	2.96	1.0	4.12	1.02	1.65	0.7	2.70	1.06	2.57	1.3	2.31	0.7
MnO	0.13	0.0	0.14	0.14	0.07	0.0	0.10	0.06	0.04	0.0	0.03	0.02	0.02	0.0	0.02	0.01	0.04	0.0	0.07	0.0
MgO	3.42	0.8	4.05	3.06	1.51	0.3	1.92	1.00	0.54	0.2	0.81	0.16	0.22	0.2	0.11	0.17	0.42	0.2	0.64	0.3
CaO	5.79	0.9	7.70	4.60	3.34	0.3	3.93	2.81	1.96	0.5	2.91	1.56	1.45	0.4	1.69	1.16	1.70	0.4	2.26	0.3
Na_2O	3.99	0.6	3.08	3.97	4.20	0.4	4.16	4.24	3.93	0.6	4.76	3.65	3.54	0.5	3.72	2.80	3.50	0.5	5.02	0.5
K_2O	3.27	0.6	1.80	3.42	3.93	0.5	4.15	3.95	4.39	0.8	3.19	5.01	4.82	0.6	5.79	4.63	3.99	0.6	1.52	0.4
TiO_2	1.40	0.5	2.87	1.02	0.70	0.1	0.80	0.69	0.40	0.2	0.52	0.26	0.20	0.1	0.26	0.08	0.35	0.2	0.25	0.2
P_2O_5	0.97	0.4	2.01	0.56	0.36	0.1	0.47	0.26	0.11	0.0	0.13	0.07	0.07	0.0	0.17	0.04	0.09	0.1	0.21	0.2
Mg#	0.41	0.04	0.36	0.46	0.36	0.03	0.39	0.32	0.28	0.04	0.28	0.24	0.20	0.10	0.07	0.24	0.06	0.03	0.06	0.02
ppm																				
Zr	319	72	510	257	265	46	294	306	263	157	304	127	131	43	145	59				
Ba	1485	645	812	884	986	221	1202	970	751	235	1135	923	873	446	1512	795				
Sr	1161	301	840	654	684	127	882	527	355	182	766	391	321	166	504	254				
Rb	94	20	50	110	106	19	98	119	144	37	117	134	129	28	124	140				
V	138	39	223	103	64	10	80	45	30	14	46	15	15	10	26					
Ni	26	9	46	20	11	3	15	7	5	3	3	3	3	1	3					
Cr	239	31			127	18		119	101	21	115	72	82	30	109					

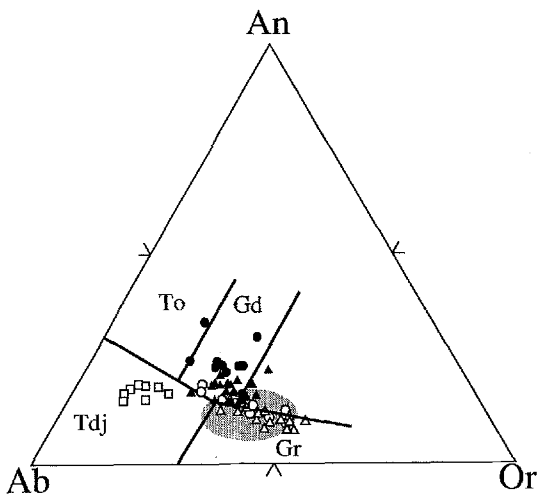

Fig. 3 Normative An–Ab–Or triangle (O'Connor 1965); with fields from Barker (1979). The intrusive monzogranites plot mainly in the granodioritic field whereas the anatectic grey and pink granites extend into the granitic domain. They do not show any affinity with typical Archaean TTG, which normally plot in the tonalitic and trondhjemitic fields. ●: clinopyroxene quartz-monzonite, ▲: porphyritic monzogranite, ○: equigranular grey anatectic granite, △: equigranular pink anatectic granite, □: 3.4-Ga Peninsular Gneisses, *To* tonalite, *Tdj* trondhjemite, *Gd* granodiorite, *Gr* granite. The *grey stippled area* represents the field of migmatised Peninsular Gneisses (metatexites)

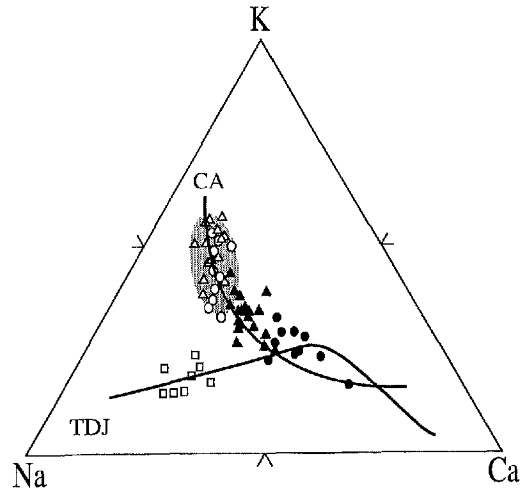

Fig. 4 K–Na–Ca triangle from Barker and Arth (1976). The rock-types of the Closepet batholith define a classical calc-alkaline trend (*CA*), being clearly distinct from the Peninsular Gneisses which follow a typical trondhjemitic trend (*TDJ*). Symbols as in Fig. 3

of metatexites always closely fits the field of the more silicic anatectic granites.

Trace elements

As with the major elements, trace elements show good negative correlation with SiO_2 (Fig. 6), except for Rb which, instead of scattering, displays a positive correlation. In the intrusive monzogranites, Sr and Ba concentrations can reach 1,591 ppm and 3,007 ppm, respectively; whereas they can be as low as 70 ppm, and 277 ppm, respectively, in the SiO_2-rich anatectic granites. Ni and V never exceed 46 ppm and 223 ppm respectively, even in the low-SiO_2 rocks.

Rare earth elements (REE, Table 3) show different patterns. (1) The intrusive monzogranites (Fig. 7) have high LREE contents ($La_N = 334 - 182$) and moderately low HREE ($Yb_N = 16 - 5.2$) without any significant Eu anomaly. (2) The anatectic granites (Fig. 7) display

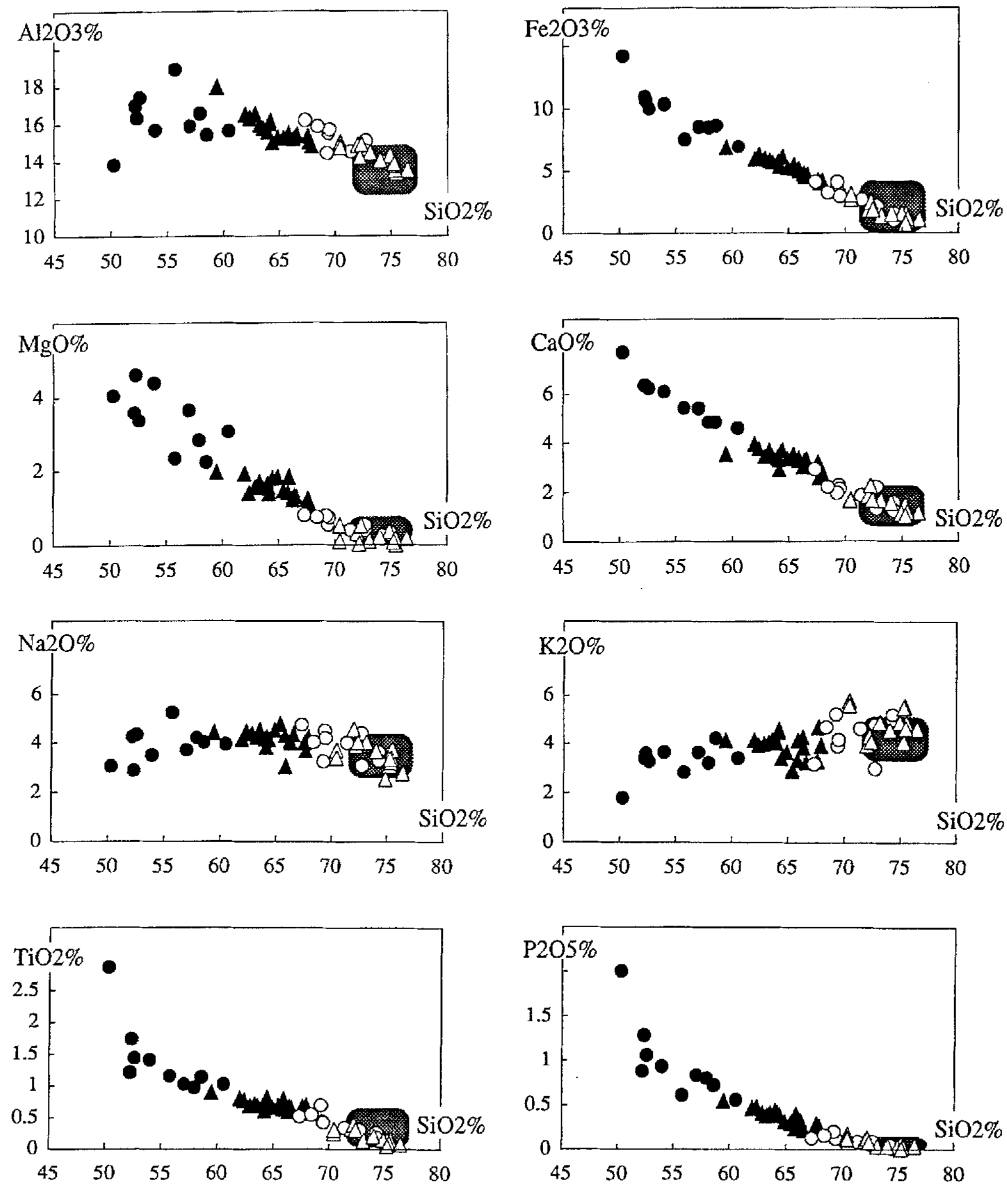

Fig. 5 Harker plot for Closepet batholith showing good negative correlation of all major-elements with SiO_2, except for K_2O which is positively correlated. The correlation trends are interpreted in term of mixing between intrusive monzogranites and anatectic granites. Symbols as in Fig. 3.

lower LREE abundances ($La_N = 228–73$) and rather similar heavy REE patterns with a slight negative Eu anomaly. On a binary diagram (Fig. 6), LREE (e.g. Ce) are negatively correlated with SiO_2; this behaviour is the same as for major and other trace elements.

Isotopic data

Both the clinopyroxene quartz-monzonite and porphyritic monzogranite exhibit the same restricted range of initial Sr composition (I_{Sr}) at 2.52 Ga, 0.7017–0.7029 and 0.7024–0.7035, respectively (Table 4). These values are slightly higher than those generally expected for the contemporaneous depleted mantle. By contrast, the anatectic granites display a larger range of I_{Sr}; the grey anatectic granites are heterogeneous in composition, showing a range of 0.7040–0.7066 for the less radiogenic samples up to 0.7336 for one sample. A similar granite (sample CHT2), farther west in the Chitradurga belt, had an I_{Sr} of 0.7169 at 2.52 Ga. Pink granites also appear to be heterogeneous, with I_{Sr} ranging from 0.7028 to 0.7119. In conclusion, these data clearly indicate that an old crustal component was involved in the anatectic granite genesis. Nevertheless, in some cases, the data also suggest either a mantle input or the participation of a short-lived crustal component.

The clinopyroxene quartz-monzonite is characterised by low negative initial ε_{Nd} values (-0.9 to -2.6) and fairly uniform T_{DM} ages (2.9 Ga). Likewise, the porphyritic monzogranite yields slightly negative ε_{Nd}

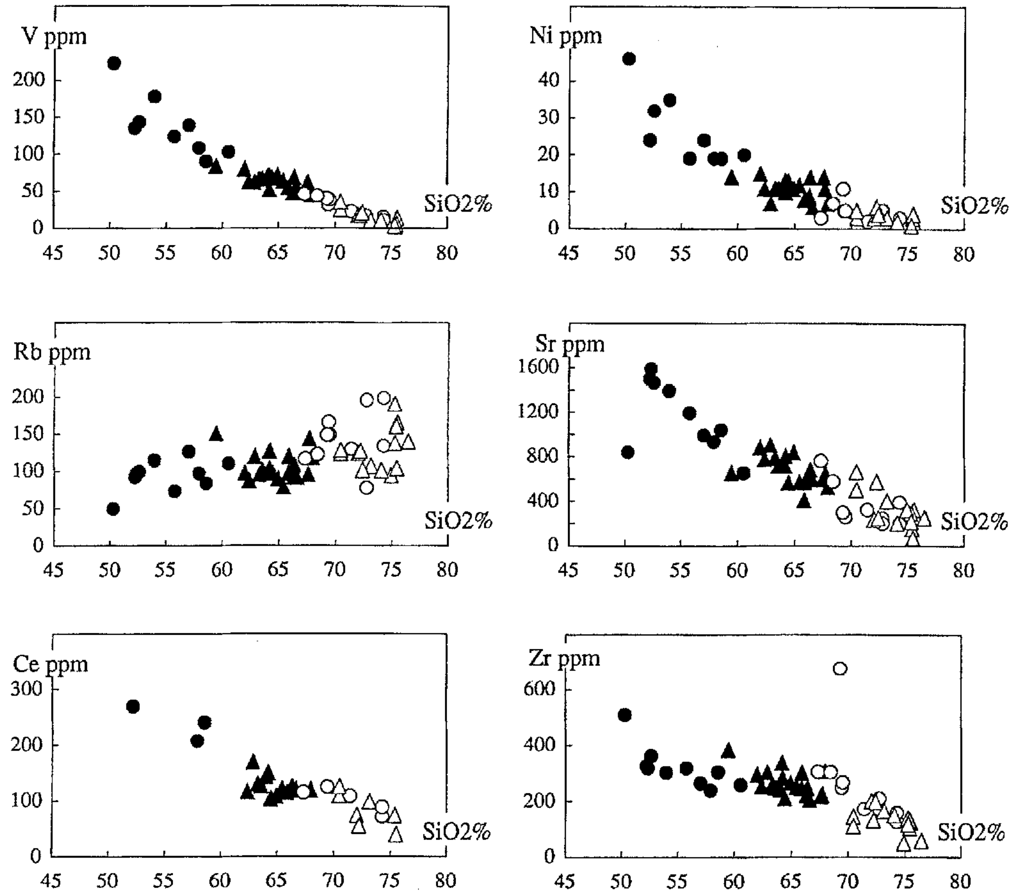

Fig. 6 Harker plot for trace-elements in Closepet batholith; as with the major elements, all trace elements, except Rb, are negatively correlated with SiO_2, thus supporting the mixing model between intrusive monzogranites and anatectic granites. Symbols as in Fig. 3

values (− 2.4 to − 4.1) and clustered T_{DM} ages (3.0 Ga). The anatectic granites show lower ε_{Nd} values (− 2.7 to − 8.3) and some higher T_{DM} ages (3.0 to 3.4 Ga). Both samples of pink granite exhibit similar ε_{Nd} values (− 4.7) which are not correlated with initial I_{Sr} (0.7028 and 0.7119). This apparent paradox suggests a mixing between two components, one being depleted in Nd and enriched in Sr (basic), while the other displays the opposite characteristics (Peucat et al. 1988).

The ε_{Nd} values of the intrusive monzogranites (− 0.9 to − 4.1) are correlated with the chemical composition (SiO_2-poor), suggesting that they are derived from the mixing of a mantle component (juvenile or not) with an older continental crust rather than from direct melting of old Peninsular Gneisses (T > 3.0 Ga) which would have a more negative ε_{Nd} at 2.52 Ga (Peucat et al. 1993a, and Fig. 8). On the other hand, no sample had a positive ε_{Nd} at that time, so, even the clinopyroxene quartz- monzonite may not be totally devoid of crustal involvement. This result is in agreement with field data that show at least some mechanical mixing between all the magmatic bodies.

Petrogenesis

Several theories have been proposed for the origin of the Closepet batholith, including metasomatism of gneisses and schists (Radhakrishna 1956; Suryanarayana 1960; Divakara Rao et al. 1972, 1990), in situ partial melting of Peninsular Gneisses (Friend 1983; Jayananda 1988; Newton 1990a; Jayananda and Mahabaleswar 1991a) or batch melting of gneisses followed by fractional crystallisation (Allen et al. 1986). Although most of these models can account for anatectic granite genesis, they appear inappropriate for intrusive monzogranites. The purpose of the present discussion is to place constraints on the mechanisms and source involved in Closepet batholith petrogenesis.

Two groups of granites

The distinction between anatectic and intrusive bodies, based on field relationships, appears to be not only structural, but also genetic in nature.

Table 3 Rare Earth Element abundances in Closepet batholith rock-types

	Cpx Quartz-Monzonite			Porph. Monzogranite		Grey Granite		Pink Granite	
ppm	J 1	J 9	J 11	J 3	J 10	J 36	CG 3	CG 21	CG 29
La	103	110	141	97	82	66	52	43	75
Ce	224	260	292	184	163	135	88	74	125
Nd	94	111	123	65	59	45	30	26	44
Sm	14.87	17.07	18.68	9.38	9.11	7.37	5.39	4.99	6.7
Eu	2.9	3.78	4.21	2.03	1.81	1.01	1.07	1.18	2.07
Gd	9.34	10.08	11.85	5.93	5.79	5.52	3.7	3.95	4.28
Dy	6.63	7.22	7.03	4.2	4.12	4.11	1.82	2.78	1.91
Er	3.48	3.37	3.19	2	1.83	2.48	0.92	1.48	0.9
Yb	3.27	3.04	2.69	1.51	1.34	2.15	0.85	1.25	0.61
Lu	0.5	0.43	0.42	0.23	0.18	0.33	0.18	0.23	0.12

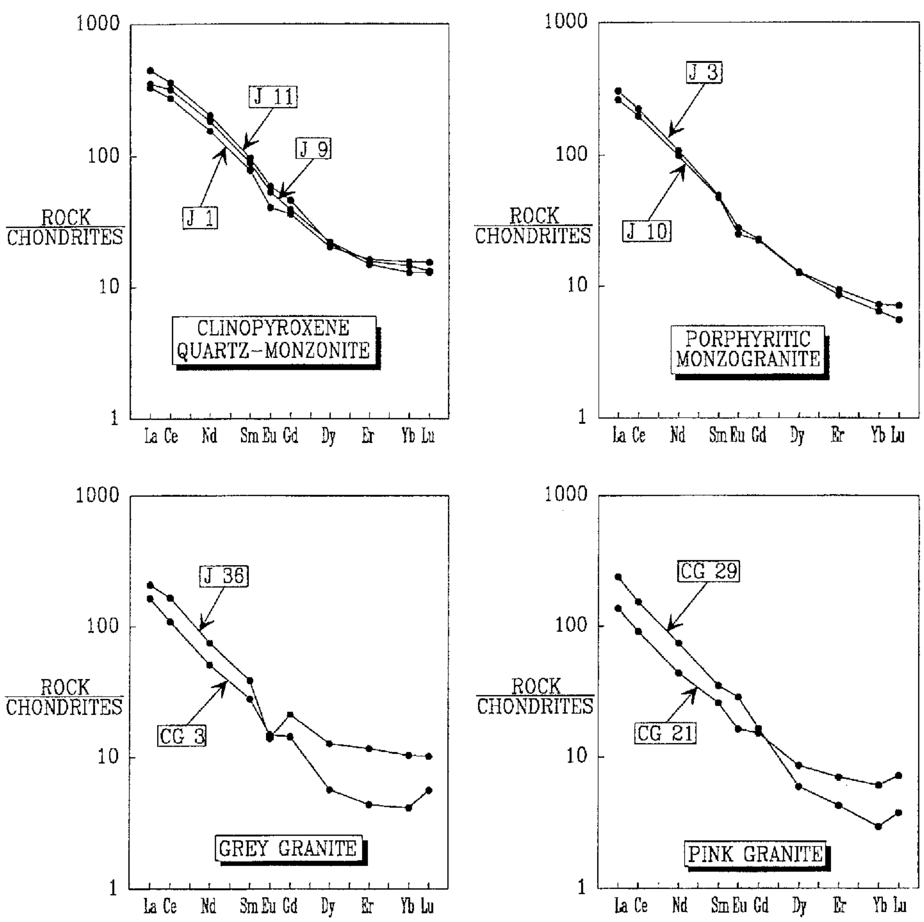

Fig. 7 Rare Earth Element chondrite-normalised patterns for different constituents of the Closepet batholith

Anatectic granites

As mentioned by several authors (Friend 1983; Jayananda 1988; Allen et al. 1986; Newton 1990a), the anatectic origin of both pink and grey equigranular granites is well documented.

(a) In the field, in the southern part of the Closepet area (Fig. 1), the Peninsular Gneisses grade up progressively into anatectic granites through metatexites, diatexites and nebulites. Near their margins, both pink and grey granites contain large amounts of mafic schlieren and strongly migmatized gneissic enclaves.

(b) In a Q–Ab–Or CIPW normative plot (Fig. 9), the anatectic granites plot near the eutectic composition of the granitic system (Winkler 1974) for pressures ranging from 2 to 7 kbar and Ab/An ratios similar to those of Peninsular Gneisses. Consequently, their

Table 4 Sm-Nd and Rb-Sr isotopic data

Sample	Analysis	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	Error $\times 10^{-6}$	T DM Ga	Eplison 2.52 Ga
			Cpx Quartz-Monzonite					
CG9	10998	25.606	152.84	0.1013	0.5111021	3	2.869	− 0.9
CG 37	11425	20.746	133.24	0.0941	0.510814	3	2.958	− 2.6
CG 27	11016	15.921	100.16	0.0961	0.510874	13	2.931	− 2.1
CG 27 (2)	11016	15.826	98.218	0.0974	0.510891	3	2.942	− 2.2
			Porphyritic Monzogranite					
CG 23	11012	14.219	88.340	0.0973	0.510853	4	2.988	− 2.9
CG 28	11017	13.475	96.759	0.0842	0.510573	5	3.013	− 4.1
CG 5	10994	15.259	93.996	0.0981	0.510890	5	2.962	− 2.4
			Grey Anatectic Granites					
CG 3	10992	4.594	31.727	0.0875	0.510647	4	3.004	− 3.8
CG 12	11001	24.552	135.6	0.1095	0.510774	4	3.446	− 8.3
CG 42	11430	10.852	70.867	0.0926	0.510787	5	2.954	− 2.7
			Pink Anatectic Granites					
CG 29	11018	5.555	42.849	0.0784	0.510451	6	3.020	− 4.7
CG 31	11020	0.693	5.249	0.0798	0.510470	5	3.030	− 4.7
CHT2	*	8.083	49.975	0.0978	0.510663	4	3.246	− 6.8

Sample	Analysis	Rb (ppm)	Sr (ppm)	87Rb/86Sr	87Sr/86Sr	Error $\times 10^{-6}$	Initial Sr 2.52 Ga
			Cpx Quartz-Monzonite				
CG 9	10998	50	840	0.172	0.707977	8	0.7017
CG 37	11425	99	591	0.485	0.720469	7	0.7028
CG 27	11016	125	992	0.365	0.715930	7	0.7026
CG 27 (2)	11016	125	992	0.365	0.716154	12	0.7029
			Porphyritic Monzogranite				
CG 23	11012	104	720	0.418	0.718037	8	0.7028
CG 28	11017	151	656	0.667	0.727818	11	0.7035
CG 5	10994	98	882	0.322	0.714155	8	0.7024
			Grey Anatectic Granites				
CG 3	10992	199	196	2.967	0.81208	9	0.7040
CG 12	11001	149	298	1.454	0.759527	8	0.7066
CG 42	11430	108	685	0.458	0.750207	10	0.7336
			Pink Anatectic Granites				
CG 29	11018	128	668	0.555	0.723044	6	0.7028
CG 29 (2)	11018	128	668	0.555	0.723012	8	0.7028
CG 31	11020	138	220	1.827	0.778450	13	0.7119
CHT2	*	122	232	1.531	0.772718	8	0.7169

composition is consistent with partial melting of the surrounding gneisses.

(c) In triangular plots (Fig. 3 and 4), as well as in Harker diagrams (Fig. 5), the composition of the more silicic anatectic granites closely fits the composition of the liquids generated by in situ partial melting of Peninsular Gneisses (metatexites).

(d) The isotopic data also indicate a crustal origin for these anatectic granites; I_{Sr} are variable but always high (Fig. 8), ranging from 0.7028 to 0.7336, with ε_{Nd} varying from − 2.7 to − 8.3. Even if some values are not purely crustal, they imply a dominantly crustal origin for the anatectic granites and are consistent with the Peninsular Gneisses as a source.

All these characteristics: (1) poorly differentiated suite (67.33% < SiO_2 < 76.52%), (2) close association with migmatites, (3) lack of hornblende and clinopyroxene, (4) absence of magnetite, (5) presence of micaceous enclaves or schlieren, (6) normative corundum > 0.5%, (7) molecular $Al_2O_3/(CaO + Na_2O + K_2O) > 1.1$, and (8) high I_{Sr}, are identical to those of S-type granitoids of Chappell and White (1974) or more precisely to the CI-type of Didier et al. (1982).

Intrusive monzogranites

Field, petrographic and geochemical data indicate that neither the clinopyroxene quartz-monzonites nor the

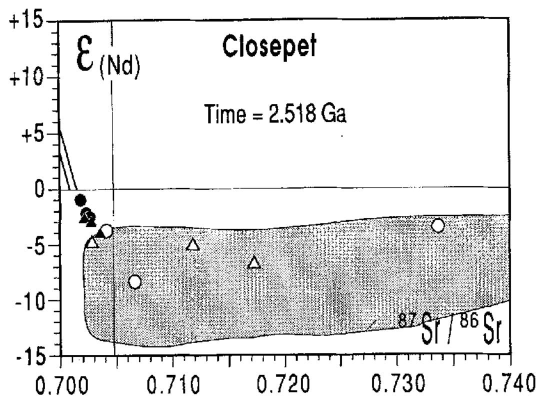

Fig. 8 εNd versus $^{87}Sr/^{86}Sr$ diagram. The ε_{Nd} values of the intrusive monzogranites (− 0.9 to − 4.1), correlated with their chemical composition (SiO_2-poor), suggest that they are derived from the mixing of a mantle component with and older continental crust rather than from direct melting of old Peninsular Gneisses (*stippled field*). On the contrary, the composition of anatectic granites is compatible with direct melting of Peninsular Gneisses. Symbols as in Fig. 3. ▤ field of 3.2 old basement

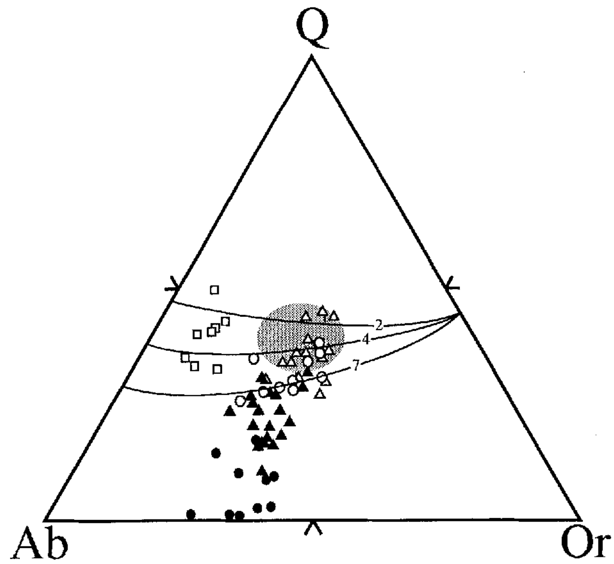

Fig. 9 Q–Ab–Or normative triangle showing the experimental cotectic lines and minima values as measured by Winkler (1974) between 2.4 and 7 kbar. Both grey and pink equigranular granites plot close to the eutectic values. By contrast, the position of the intrusive granites precludes their genesis from partial melting of the Peninsular Gneisses. Symbols as in Fig. 3

porphyritic monzogranites are generated through partial melting of Peninsular Gneisses, so they cannot be cogenetic with the anatectic granites.

(a) In contrast to the pink and grey equigranular granites, the intrusive bodies never show gradual transitions towards the gneisses through progressive migmatisation; they always display sharp contacts and contain angular enclaves of migmatised gneisses. The intrusive monzogranites are rich in microgranular mafic enclaves, but do not contain any micaceous remnants or schlieren. The microgranular enclaves show lobate contacts and contain K-feldspar phenocrysts from the host porphyritic monzogranite, thus indicating that the two magmas were emplaced and crystallised at the same time.

(b) The intrusive monzogranites have high clinopyroxene and/or hornblende modal abundances (with minor biotite), but these two mafic minerals are completely absent from the anatectic granites and associated migmatites. On the other hand Peninsular Gneisses are mainly biotite-bearing rocks with subordinate hornblende in places, which never contain clinopyroxene. It is not possible to generate clinopyroxene- and hornblende-rich magmatic rocks through the partial melting of felsic rocks where these minerals are lacking; consequently, monzogranitic magmas cannot be produced by anatexis of the surrounding Peninsular Gneisses.

(c) In the Q–Ab–Or CIPW normative triangle (Fig. 9), the anatectic granites plot near the eutectic of the granitic system. In contrast, some members of the intrusive monzogranite suite extend up to the Ab–Or join; their composition is clearly distinct from that of experimental anatectic melts. Although this may be explained by higher degrees of partial melting, in such a case the melts should define a horizontal trend and plot between the eutectic points and the Peninsular gneiss composition. However, this is not observed and, since the intrusive monzogranites rather display a perpendicular trend, an anatectic origin is ruled out.

(d) Since the Peninsular Gneisses are SiO_2-rich (68–72%), their partial melting should produce magmas with similar or slightly higher SiO_2 contents. The intrusive monzogranites show SiO_2 ranging from 50.30% to 68.18%, contents which are inconsistent with a gneissic source.

(e) The intrusive monzogranites have low I_{Sr} (0.7017–0.7035) plotting along or just above the mantle array; on this evidence, they are clearly distinct from the pink and grey equigranular granites. Neodymium isotopes (ε_{Nd} = − 0.9 to − 4.1) lead to similar conclusions, suggesting a dominant mantle or lower crustal influence on the petrogenesis of both the clinopyroxene quartz-monzonites and the porphyritic monzogranites (Fig. 8).

Both petrographic and chemical characters of the intrusive monzogranites: (1) large range of differentiation ($50.30\% < SiO_2 < 67.97\%$), (2) presence of hornblende and clinopyroxene, (3) presence of ilmenite and magnetite, (4) relative abundance of microgranular enclaves, (5) normative diopside or normative corundum < 0.5%, (6) molecular $Al_2O_3/(CaO + Na_2O + K_2O) \leq 1.1$, and (7) low I_{Sr}, indicate that these rocks belong to the I-type granitoids of Chappell and White (1974) or to the M-type of Didier et al. (1982).

Correlations

The above discussion points out that the Closepet batholith is made up of at least two contrasted magmas: (1) a SiO_2-rich one, produced by anatexis of Peninsular Gneisses, and (2) a SiO_2-poor one, which probably has a deeper and more mafic source. Nevertheless, on Harker plots (Fig. 5 and 6) as well as in triangular diagrams (Fig. 3 and 4), both the intrusive and anatectic bodies show a well defined single variation trend that seems to be in contradiction against a two-source hypothesis. The trends could be artefacts resulting from a sum effect, but in element vs. SiO_2 diagrams the sum effect should always produce negative correlation. This is not the case here, where K_2O, Na_2O and Rb are positively correlated. On the other hand this artefact should not significantly influence the trace elements. Consequently, this trend indicates that some genetic link exists between the two magmatic types. In magmatic rocks, such linear trends are assumed to be produced by fractional crystallisation or by mixing processes. A single partial melting process may be excluded since it can be shown that at least two contrasted sources were involved.

Fractional crystallisation

A fractional crystallisation process from magmas which contain more than 55% SiO_2 implies that the low-SiO_2 (50–55%) rocks are cumulates or mixture between liquid and cumulate, a conclusion which is not supported by the field evidence. The clinopyroxene quartz- monzonites show magmatic structures (lobate or pillowed contacts with the porphyritic monzogranite) and contain K-feldspar xenocrysts derived from the monzogranites. Thus the low-SiO_2 rocks represent magmas rather than cumulates. This is corroborated by thin-section studies which show that the intrusive monzogranites exhibit typical magmatic textures without any evidence of cumulate formation.

On the other hand, cumulates with less than 50% SiO_2 could have been totally segregated and extracted at depth, so that they remain unknown at the present day exposure level. The trends on Harker diagrams (Fig. 5 and 6), are straight lines without any break. If this resulted from fractional crystallisation from the less differentiated magmas, it follows that the composition of the cumulate remained strictly constant throughout the process. This is unrealistic considering that the liquid composition varies over a very wide range (50.30%–76.57% SiO_2). Moreover, fractional crystallisation of anatectic magmas whose composition is close to the eutectic of the granitic system, cannot lead to a wide range of products. Even if were able to proceed, it would produce small volumes of cumulate with respect to felsic magma; in the Closepet batholith, SiO_2-poor intrusive rocks are far more widespread than SiO_2-rich liquids.

Magma mixing

Although fractional crystallisation is not able to account for the linear variation trends on Harker plots, magma mixing provides a better explanation. Mixing is here assumed to occur between anatectic and intrusive magmas.

Mixing structures are widely observed in the field, not only between clinopyroxene quartz-monzonites and porphyritic monzogranites (or between pink and grey equigranular granites), but also between intrusive and anatectic magmas. Spectacular small-scale mixing structures are well exposed in the Closepet batholith; i.e. diffuse margins and elongated fragments and boudins of intrusive bodies in the anatectic granites. Very often in the contact zone, the anatectic granites form an intimate diffuse net-vein complex which extends into the intrusive facies.

A mixing hypothesis is also supported by major as well as trace element data, which show linear correlation with SiO_2. In trace-element vs. SiO_2 diagrams (Fig. 6), single linear regressions can be observed for all elements including the REE. Such correlations over such a large range of SiO_2 are incompatible with partial melting or fractional crystallisation, but are consistent with mixing-like mechanisms. Nevertheless, the selective scattering of data in Na_2O, K_2O, Rb diagrams may indicate that other additional processes (i.e. magmatic fractionation or fluid circulation and interaction) could have been superimposed onto the mixing.

Nd and Sr isotopic compositions show a covariance in nature that is best expressed on a plot of initial ε_{Nd} versus I_{Sr}. On a such diagram (Fig. 8) isotopic mixing between two end-members generates intermediate compositions whose representative points lie along a hyperbola (De Paolo and Wasserburg 1979; Gray 1984). The initial Nd and Sr isotopic compositions of intrusive monzogranites at 2.52 Ga define a continuous linear array located between the field of the anatectic granites (which is itself superimposed on that of 3.3-Ga Peninsular Gneisses) and the field of single stage depleted mantle-derived rocks at 2.52 Ga, this being in agreement with a magma mixing process.

Mixing end-members

Anatectic granites

Field evidence and all geochemical data clearly indicate that the anatectic granites were derived from Peninsular Gneisses through partial fusion. Nevertheless, both grey and pink granites have high K_2O/Na_2O ratios (1.12 and 1.36 respectively) when compared with

Peninsular Gneisses (0.33). The derivation of high K_2O/Na_2O rocks from a low K_2O/Na_2O source implies very low degrees of partial melting with a residue made up of K_2O-free minerals. This is not the case on the Closepet area, where melanosomes in the metatexites and mafic schlieren in anatectic granites contain hornblende and biotite. By contrast, the high silica content of TTG (69–73%), requires degrees of partial melting ranging from 30 to 90% in order to account for anatectic granite composition; this conclusion is consistent with the apparent degree of partial melting inferred from field observations. Consequently, a single partial melting of Peninsular Gneisses, cannot produce the K_2O and LILE enrichment of the anatectic liquids. The leucosomes, generated by anatexis of the surrounding Peninsular Gneisses, have an average K_2O/Na_2O ratio of 1.14, similar to that of the anatectic granites, but inconsistent with single partial melting process. This shows that an additional mechanism of selective alkali-enrichment, located in the source of anatectic granites, operated.

Intrusive monzogranites

The other end-member of the mixing could be represented by some of the SiO_2-poor clinopyroxene quartz-monzonites, which exhibit magmatic liquid textures. Their low-SiO_2 content implies derivation from a mafic or an ultramafic source, while their isotopic composition indicates that they originate mainly from a deep-seated source such as the mantle or the lower crust. Nevertheless, it should be noted that: (a) in the ε_{Nd} vs I_{Sr} diagram (Fig. 8), the clinopyroxene quartz-monzonites do not plot within the DM field, and (2) with respect to their low SiO_2 content (55.12%) they are enriched in K_2O (3.27%), Rb (94 ppm) and LREE ($La_N = 375$).

Several processes could account for this enrichment.

(1) The magmas were contaminated by the upper continental crust. A model based on Sr and Nd isotopes was calculated assuming the contamination by continental crust (TTG in composition) of a magma generated through partial melting of a depleted mantle. Only 15–20% of crustal contamination is required to account for the isotopic characteristics of the clinopyroxene quartz-monzonites. However, the basement TTG are poorer in K_2O (1.52%), Rb (55 ppm) and LREE ($La_N = 100$) than the contaminated magma. Consequently, the clinopyroxene quartz-monzonite composition cannot be produced by crustal contamination alone, but necessitates an already enriched source.

(2) The enriched source could have been the mantle or the base of the continental crust. The I_{Sr} and ε_{Nd} values agree rather with a lower crust model, since the clinopyroxene quartz-monzonites do not plot in the depleted mantle (DM) field (Fig. 8). However, it should be pointed out that the lower crust has SiO_2 contents greater than 50% (Taylor and McLennan 1985), so its partial melting cannot generate quartz-monzonitic magmas with about 50% SiO_2. Similar arguments, supported by geochemical modelling, also preclude an Archaean tholeiite as a source (Barker 1979; Tarney and Saunders 1979; Jahn et al. 1981; Condie 1981b; Martin 1986, 1987). On the other hand, experimental melting of basalt at different pressures (from 8 to 32 kbar), in water over- and under-saturated conditions, generates more felsic magmas ($SiO_2 \cong 65\%$) which are similar to TTG in composition (Holloway and Burnham 1972; Helz 1976; Wolf and Wyllie 1989; Rapp et al. 1991; Winther and Newton 1991; Beard and Lofgren 1991). Thus, a mantle source appears the more likely because it accounts for the SiO_2 contents of the clinopyroxene quartz-monzonites. Since this mantle source was LILE and LREE-enriched, the source of the intrusive monzogranites could have been previously enriched over a long period of time (3.0 Ga). In this case, the Nd-depleted mantle model is inappropriate and the calculated degree of crustal contamination should be much lower than that predicted from DM calculations. Alternatively, the mantle source may also have been enriched or chondritic at about 2.5 Ga, more or less contemporaneously with the melting events, this could be indicated from $T_{CHUR_{Nd}}$ model ages of clinopyroxene quartz-monzonite samples which range from 2.57 to 2.70 Ga and increase up to 2.8 Ga in the more contaminated porphyritic monzogranite. But, in order to account for the low degree of contamination inferred from major-element geochemistry, Nd-contamination of a chondritic or depleted source should have occurred before the metasomatic enrichment processes, as observed in some alkali-basaltic and carbonatitic magmas (Bernard-Griffiths et al. 1988).

Discussion

The Closepet intrusive monzogranites show several similarities, but also some differences, with the Archaean sanukitoids (Archaean high-Mg granodiorites) as described by Stern et al. (1989) and Stern and Hanson (1991). In contrast to typical TTG, both sanukitoids and Closepet intrusive monzogranites show a wide range of differentiation from low-SiO_2 ($\cong 50\%$) to high-SiO_2 ($\cong 75\%$) magmatic rocks. Both were emplaced in ancient and already cratonised crustal segments; they never appear as early formed materials in continental crust differentiation and building. From a geochemical point of view, both are alkali-rich ($K_2O + Na_2O \cong 8\%$) with high contents of Sr (410–2,000 ppm) and Ba (550–3,000 ppm). However, the Closepet intrusive monzogranites have lower Mg# (0.31 to 0.46) and Ni contents (6–46 ppm) than

Archaean sanukitoids (Mg# = 0.36 to 0.62; Ni = 7 to 86 ppm; Stern and Hanson 1991). The REE patterns are similar, except for the HREE which appear slightly enriched in the Closepet monzogranites. Both are emplaced along a major crustal discontinuity (shear-zone at Closepet and greenstone-basement interface for sanukitoids). One of the main differences remains that the Closepet intrusive monzogranites strongly interact and mix with earlier crustal components, whereas such features are not described in typical Archaean sanukitoids. This crust-magma interaction could account for the chemical differences between the two kind of magma. Comparable late-Archaean suites with similar characteristics have already been described (with different names) in several places: "tonalitic and mafic rocks" in the Superior Province (Sutcliffe 1989), "phenocryst granodiorites" in eastern Finland (Martin et al. 1983; Querré 1985, "Taishan dioritic group" in China (Jahn et al. 1988). These occurrences indicate that Closepet-type petrogenetic process is not just a local phenomenon but rather a widespread mechanism.

In order to discuss the petrogenesis and emplacement of the Closepet batholith, several constraints may be fixed and summarised as follows:

(1) The Closepet batholith is made up of two magma types: one is crust-derived whereas the other has a deep-seated source (probably the mantle).

(2) A large degree of mixing is observed on all scales between the two kinds of magma.

(3) Both anatectic and intrusive magmas are LILE and LREE enriched.

(4) Field relationships indicate that the intrusive monzogranites were emplaced prior to the anatectic magmas.

(5) The anatectic granites are located on the margins of the intrusive bodies and they progressively grade to migmatised Peninsular Gneisses.

(6) The Closepet batholith was emplaced into a N–S major shear-zone that was active at that time (Newton 1990b).

(7) In the southern part of the Closepet area, migmatisation of the basement gneisses occurred slightly earlier or contemporaneously with the granulite-facies metamorphism between 2.52 and 2.51 Ga ago (Friend 1981, 1983, 1985; Peucat et al. 1989, 1993b). Moreover, fluid inclusion studies show that the intrusive monzogranites were major carriers of juvenile CO_2-rich volatiles (Santosh et al. 1991).

The anatexis of Peninsular Gneisses is widespread throughout southern India, but the apparent degree of fusion is generally low except in the immediate vicinity of the Closepet batholith, where melting can be almost total. Consequently, there is a geographical link between the degree of crustal melting and the emplacement of the Closepet intrusives. It is highly probable that this link is not only geographical but also genetic and that the emplacement of deeply-generated magmas induced the melting of the adjacent Peninsular Gneisses. In fact, in the whole southern part of the craton, the TTG are metamorphosed under high-grade amphibolite conditions, where incipient anatexis can occur. These gneisses needed only small amounts of heat and water to reach high degrees of partial melting: the intrusive monzogranites were able to provide both.

Since the intrusive monzogranitic magmas occupy a larger volume than the anatectic granites, their higher heat capacity provided the additional heat required to produce widespread melting. This is supported by the facts, that: (a) the anatectic magmas were generated and emplaced after the intrusive magmas, (b) the latter are separated from the gneisses by a screen of anatectic granites and migmatites, and (3) the degree of partial melting of the Peninsular Gneisses progressively increases towards the monzogranites.

The presence of water does not seem to be directly related to monzogranite intrusion. The whole Closepet batholith was emplaced into an active shear-zone and migmatisation immediately preceded granulite metamorphism (Newton 1990b). On the other hand, the intrusive monzogranites appear to be major carriers of CO_2-rich volatiles (Santosh et al. 1991). The role of fluids (H_2O vs CO_2) in anatexis is evident, explaining both the initiation of melting and the LILE/LREE enrichment. Newton (1989) considered that the CO_2-rich fluid phase destabilised biotite and amphibole in the Peninsular Gneisses, resulting in the liberation of H_2O. The liberated H_2O would also contain LILE and LREE elements, depending on their K_D mineral/fluid values (Mysen 1979). The uprising CO_2-front was preceded by a H_2O front that induced intense melting of the basement gneisses (Condie 1981a; Newton 1989, 1990a). The intrusive monzogranites were emplaced in a N-S active shear zone that controlled its shape and which could have acted as a drain, not only for magmas but also for the fluids whose ascent would have been facilitated by the major discontinuity. In southern India, the granulite-amphibolite transition zone has an E-W trending strike that shows a 100 km apophysis towards the North, running exactly along the Closepet shear-zone (Janardhan et al. 1982; Stähle et al. 1987). This clearly illustrates the role played by shear-zones and granites in fluid motion and granulite facies development. Santosh et al. (1991) demonstrated that the CO_2 from intrusive monzogranites is juvenile, thus showing that both shear-zones and granitoids can be major fluid carriers, and that deeply generated granites can control both heat and fluid transfer from the mantle to the upper crust.

Another unsolved problem is the physical mechanism of mixing. Mixing requires mechanical transport such as buoyant convection or tectonic shearing (Whalen and Currie 1984). Buoyant convection involves the mixing of hot dense magma such as basalt with cooler viscous magma such as rhyolite.

This process leads to the formation of plumes and spherical globules of hot material in the cooler magma but little exchange of material along the boundary (Huppert et al. 1983). Buoyant convection cannot explain the elongated fragments of intrusives within the anatectic granites and the lobed margins in the south Closepet area. Alternatively, tectonic shearing may be considered as an effective mechanism for magma mixing. Experimental studies also indicate that shearing stresses can rapidly and effectively homogenise viscous silicate melts (Kouchi and Sanagawa 1983). In the south Closepet area, field evidence suggests that shear deformation was active during the emplacement of the batholith (Newton 1990a; Jayananda and Mahabaleswar 1991b), indicating that shear stress mainly controlled the mixing process.

The main results of this study can be summarised as follows.

(1) The Closepet batholith is not a homogeneous body but rather a composite complex made up of two distinct magmas: (a) an intrusive SiO_2-poor magma, emplaced in an early stage into the central part of the massif (clinopyroxene quartz-monzonite and porphyritic monzogranite), and (b) an anatectic SiO_2-rich magma derived through partial melting of the surrounding Peninsular Gneisses and emplaced in between the intrusive monzogranites and the basement (pink and grey equigranular granites).

(2) Both magma types were generated and emplaced at about 2.513–2.518 Ga. They display features indicating inter-mixing. This magmatic mixing is clearly evident in the field and also in the geochemical data.

(3) One of the mixing end-members is a magma generated by hydrous partial fusion of the TTG basement, the other corresponds to a SiO_2-poor LILE-rich magma whose source could have been an enriched mantle rather than the lower crust.

(4) Both monzogranites and granites are enriched in LILE and LREE, thus reflecting the role of fluid metasomatism in their genesis.

(5) The intrusive monzogranites acted as carriers of heat and fluid from the mantle to the upper crust. They provided the additional energy and water that induced extensive melting of the TTG basement.

(6) The general shape of the Closepet batholith appears to be controlled by a major shear-zone that acted as a channel for the both magmas and fluids.

(7) It can be tentatively proposed that the petrogenetic conclusions drawn from Closepet batholith can be extended to the late Archaean high-Mg granodiorites (sanukitoids), that show similar field, petrological and chemical characteristics.

Finally, in southern India, magmatism and metamorphism at 2.5 Ga appear to have been related to a major thermal and accretional event. As proposed by Newton (1987) to explain the granulite-facies metamorphism, the huge heat flow is assumed to have been caused by the ascent of mantle materials possibly associated with the uprise of a mega-plume (Martin et al. 1993; Peucat et al. 1993b). The activity of a mega mantle plume could account for: (a) the regional low-pressure metamorphism, (b) the LILE and LREE enrichment of the mantle, (c) the genesis of Closepet-type magmas, and (d) the genesis and emplacement of the slightly depleted tonalitic magmas of Krishnagiri-Nilgiri type (Peucat et al. 1989, 1993a).

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