the lowest being 20 on 6 April 1993 in the early morning hours between 0442 and 0459.

(iv) It was observed that the fading rate of scintillation is lower than that of GHz scintillation. The average value of VHF scintillation rate was 37 fades/min and that of GHz scintillation, 42 fades/min. On 17 April 1993, the lowest fading rate for VHF and GHz scintillation was 26 fades/min and 28 fades/min respectively. The highest value of VHF scintillation rate recorded was 48 fades/min and that of GHz scintillation, 52 fades/min.

It is clear that the fading rates at VHF and GHz scintillation are of similar magnitude within 10%. This implies that the electron density irregularities in the ionosphere causing scintillations at VHF and GHz are the same and they are drifting with the same velocity.

The exceptionally high values of mean scintillation index at GHz frequencies indicate that the refractive irregularities with scale sizes very much greater than the Fresnel scale[10, 11] are responsible for the observed strong and intense GHz scintillations at Kolhapur.

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Magma mixing in plutonic environment: Geochemical and isotopic evidence from the Closepet Batholith, Southern India

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The Closepet Batholith in southern India contains two groups of magmatic intrusions: (i) mantle-derived quartz monzonites and monzogranites (SiO_2-poor clinopyroxene bearing and porphyritic facies) display a narrow range of initial $^{87}Sr/^{86}Sr$ ratios (0.7017–0.7029 at 2.5 Ga) and ε Nd (–0.9 to –4.7 at 2.5 Ga). (ii) crustal-derived granites (SiO_2-rich equigranular grey and pink granites) show wide range of initial $^{87}Sr/^{86}Sr$ ratios (0.7028–0.7366 at 2.5 Ga) and ε Nd (–2.7 to –8.91 at 2.5 Ga). Field data and single zircon $^{207}Pb/^{206}Pb$ ages demonstrate that the two groups are broadly contemporanous and mechanically mixed. This observation is supported by geochemical and isotopic data that show well-defined mixing trends in both Harker binary diagrams and I_{Sr} vs ε Nd plots. The continuous chemical variation in the two magmatic bodies is interpreted in terms of interaction and mixing of two unrelated end-members derived from different source regions (enriched mantle vs Peninsular gneisses). The proposed model involves intrusion of mantle-derived magmas into anatectic zone in the mid-continental crust: where they supply additional heat and fluids and promote large-scale melting of surrounding crust. During this event occurred mixing between mantle derived magma and anatectic melts.

GRANITIC rocks are major components of continental crust occurring throughout the whole Earth history. The origin of stable and permanent crust is inextricably linked to granitoid genesis[1]. Hence knowledge about granitoid genesis is fundamental to our understanding of

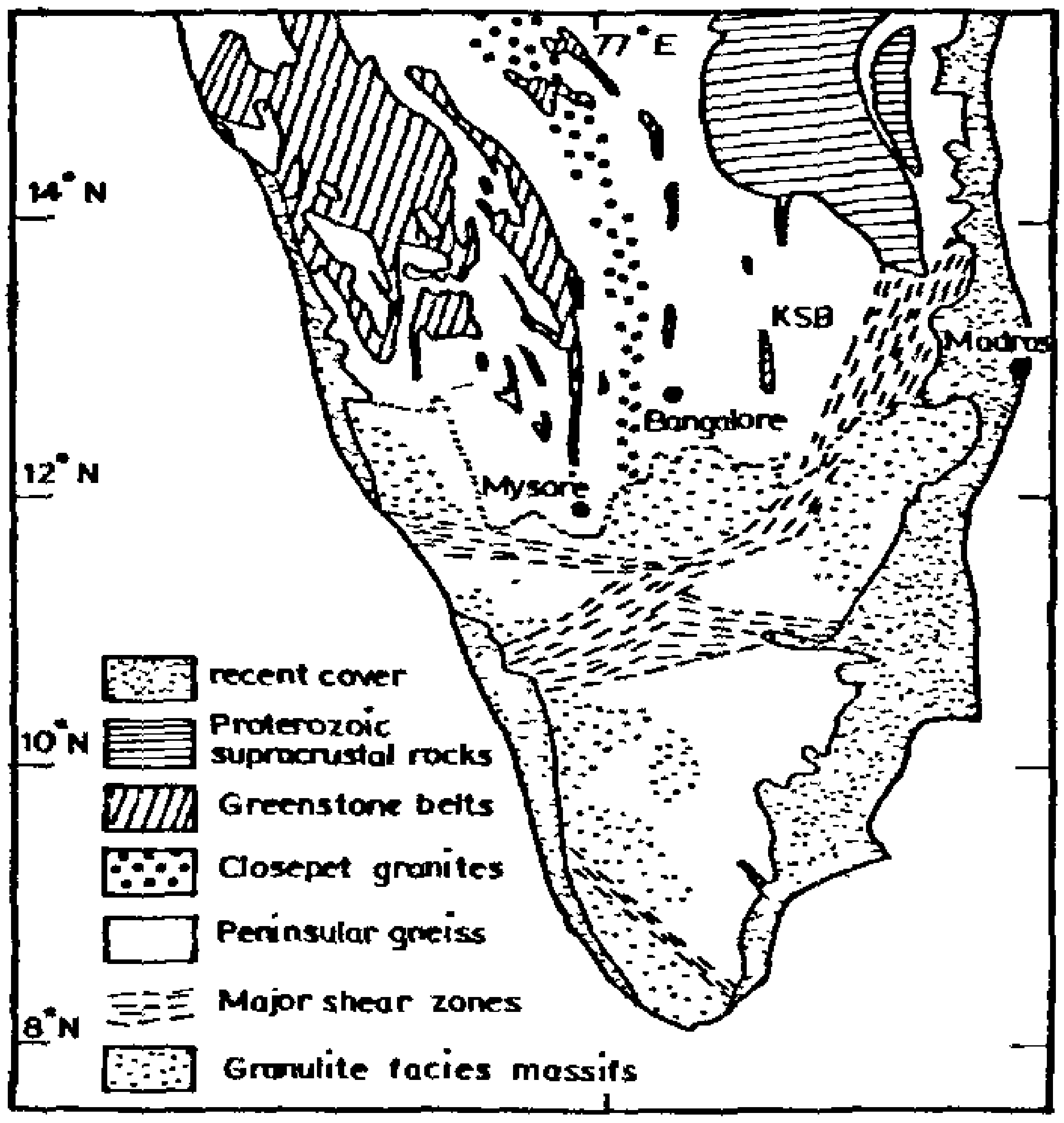

Figure 1. Geological sketch map of southern India (after Friend and Nutman[11]).

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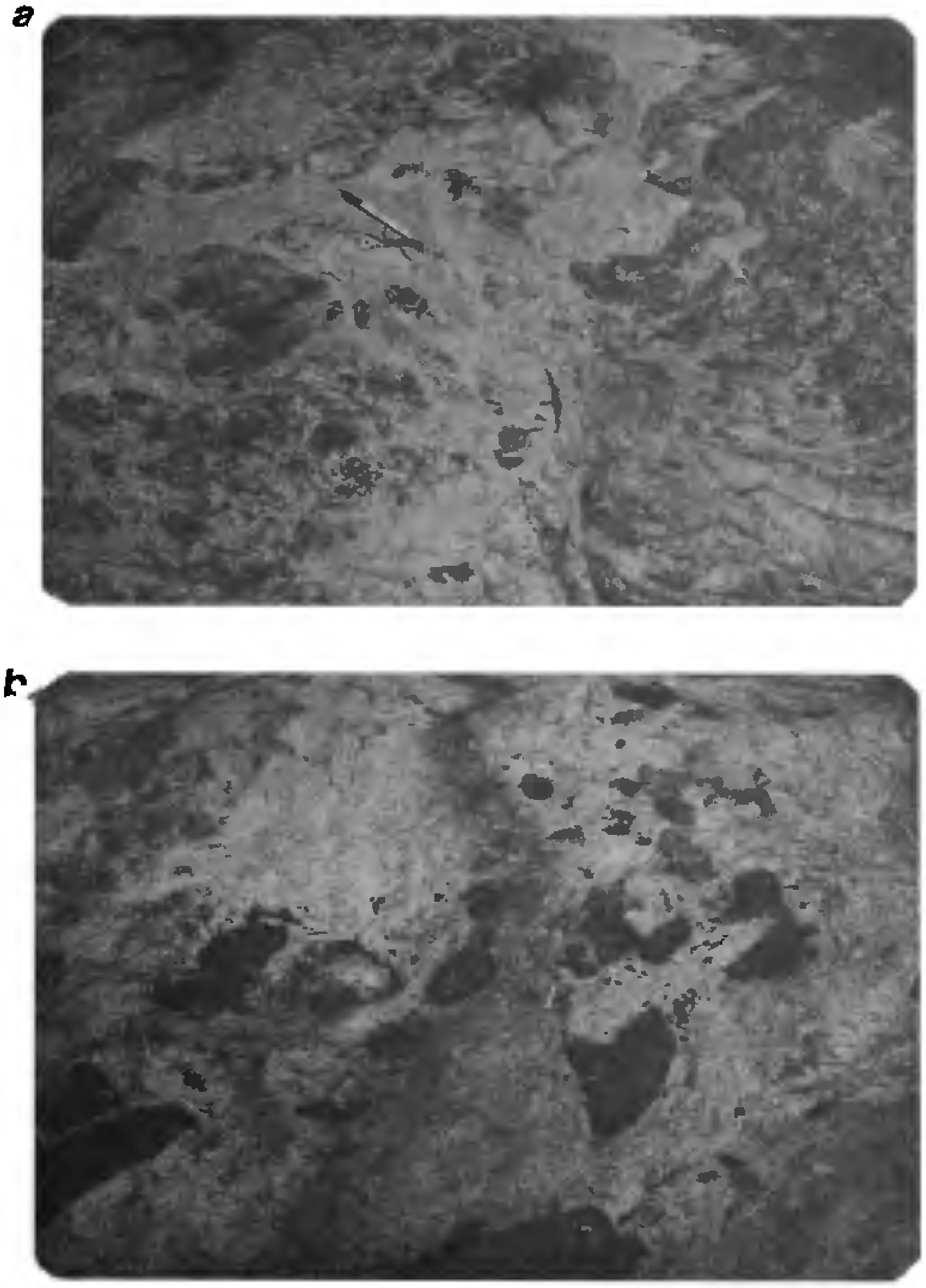

Figure 2. *a*, Mixing of intrusive (clinopyroxene bearing grey facies) and anatectic granites (equigranular pink facies) at Ammayyanahalli quarry (about 2 km NNW of Ramanagaram) *b*, Angular to rounded microgranular enclaves of intrusive facies in anatectic granite at about 4 km west of Bidadi in Bangalore–Mysore road.

continental evolution. Several models were proposed to explain the chemical composition of the granitic rocks such as restite unmixing[2], fractional crystallization[3,4] and magma mixing[5–8]. Crustal and mantle sources have been proposed; however, more recent studies suggest variable contributions from both mantle and crust[9]. In this regard the Closepet Batholith of southern India is particularly interesting[9]. Recent field, geochemical and isotopic data suggest both crustal and mantle input in its genesis[10]. The main purpose of this paper is to discuss the continuous chemical variation of two magmatic bodies in the Closepet Batholith in the light of new data.

The 2.52-Ga-old Closepet Batholith is a major intrusive complex in southern India, it runs about 400 km in N–S direction across the Dharwar craton (Figure 1). The apparent parallelism of the Closepet Batholith with the surrounding Dharwar greenstone belts indicates that the deformation which caused elongate structure of the greenstone basins also guided its emplacement[12]. In its southern end, the Closepet Batholith cut-across the amphibolite-granulite transition zone where it is spatially associated with migmatites and incipient charnockites. Geochronologic data in the transition zone demonstrate that granulite facies metamorphism and emplacement of the Closepet Batholith are broadly contemporaneous[10, 11].

Recent field work in the south Closepet area indicates that the Batholith is made up of at least two magmatic bodies[10]: an intrusive group divided into a clinopyroxene bearing and a porphyritic facies and an anatectic group constituting equigranular grey and pink granites. U-Pb SHRIMP dating of zircons indicates an age of 2513 ± 5 Ma for the anatectic granites[11] and

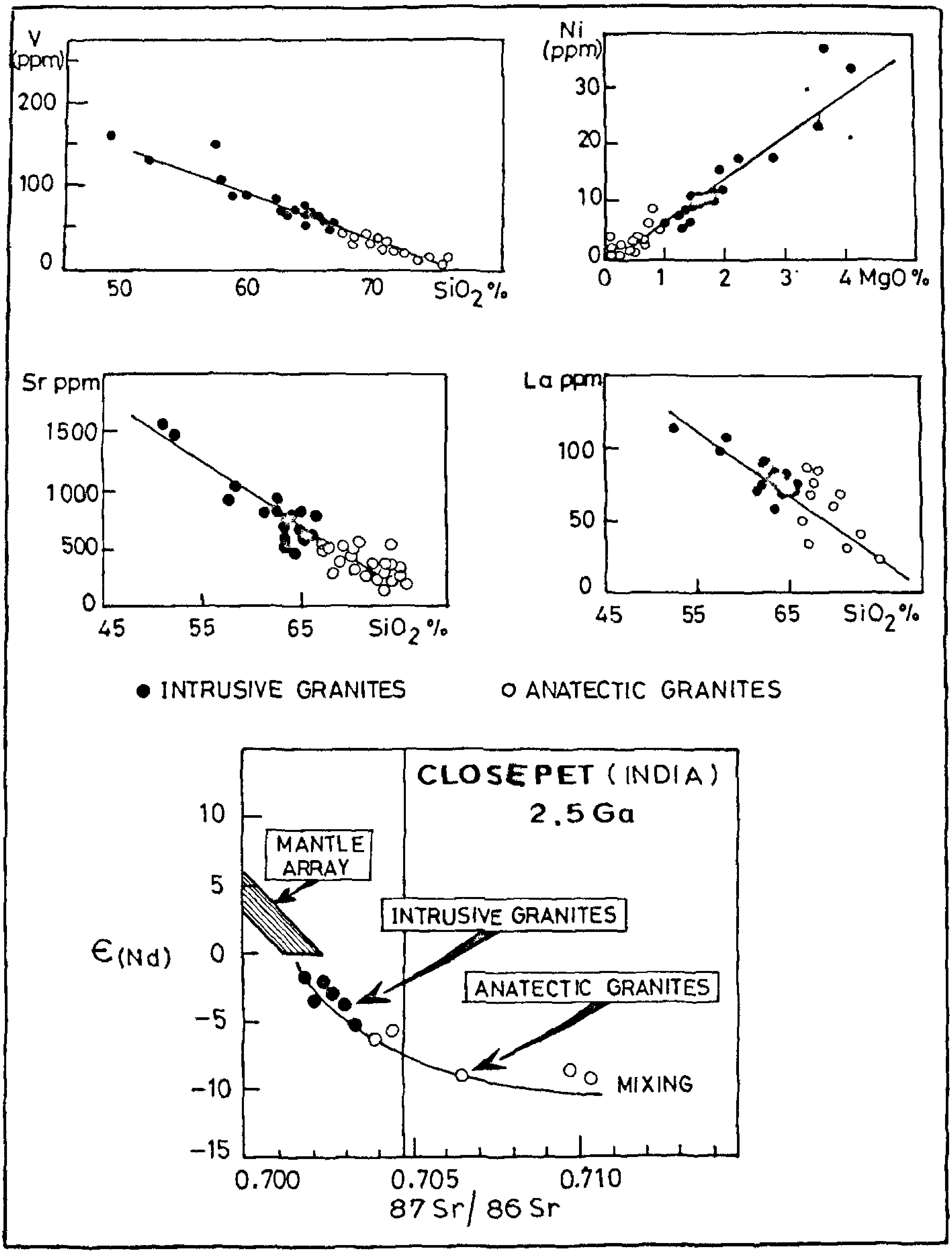

Figure 3. Trace element and ε Nd vs I_{Sr} isotopic diagram

$^{207}Pb/^{206}Pb$ single zircon dating of intrusive facies gave an age of 2518 ± 5 Ma[10] (sample CG 9 is a cpx bearing quartz-monzonite collected at about 4 km south of Ramanagaram; CG 23 is a porphyritic monzogranite collected at about 6 km north of Kabbaldurga). The clinopyroxene bearing and porphyritic facies are intrusive into the basement (Peninsular gneisses with minor supracrustal enclaves) and occupy the central part of the batholith. The equigranular grey and pink granites progressively grade to the surrounding basement through a zone of migmatites. In the field both intrusive and anatectic groups display mechanical mixing features (Figure 2). Along the marginal zones anatectic granites frequently contain enclaves of intrusive facies (Figure 2*a*). Field evidence together with geochronological data indicate their co-magmatic evolution.

The intrusive facies contain quartz, plagioclase (An 20–30), K-feldspar (microcline), clinopyroxene, hornblende and biotite. Clinopyroxene is unstable being replaced to varying degrees by hornblende-biotite association. In porphyritic facies the K-feldspar megacrysts contain euhedral plagioclase inclusions which contain anorthitic calcic (resorbed) cores. The anatectic facies contain quartz, plagioclase (An 8–14), K-feldspar and biotite. The common accessory phases in both groups are zircon, apatite, allanite, sphene and magnetite.

Geochemical and isotopic data are presented elsewhere[10]. Details of geochemical and isotopic data together with analytical procedures can be obtained from the first author.

The Closepet Batholith displays SiO_2-contents ranging continuously from 49.38 to 77.30%. The anatectic granites have high silica (70–77%) and intrusive facies have low silica (49.38–64%). The intermediates between anatectic and intrusive facies have SiO_2 compositions from 64–70%. In terms of major element chemistry the intrusive facies are quartz-monzonite to monzogranite in composition. The anatectic granites have Q-Ab-Or normative compositions similar to eutectic melts produced by experimental anatexis[13]. On the other hand it must be noticed that the intrusive facies are SiO_2-poor than the surrounding Peninsular gneisses[14, 15]. Consequently they cannot be derived from these gneisses by simple anatectic process.

The intrusive clinopyroxene-bearing monzodiorites and porphyritic monzogranites are characterized by high abundances of Sr (414–1600 ppm), Ni (7–36 ppm), V (45–135 ppm) and Sc (10–15 ppm). In contrast, the anatectic granites have low Sr (70–400 ppm), Ni (2–8 ppm), V (14–20 ppm) and Sc (2–6 ppm).

The most remarkable feature of major and trace element data is that both intrusive and anatectic bodies display strong linear trends in element–element binary diagrams (Figure 3).

The Closepet Batholith is characterized by high abundances in REE compared to the surrounding basement[10, 14]. The intrusive facies display highly fractionated REE patterns with $(La/Yb)_N$ ratios ranging from 19 to 39 without significant Eu anomalies (Figure 4 *a*). On the other hand the anatectic granites generally contain moderate total REE but few samples show strong REE and LILE enrichment; the REE patterns are moderate to strongly fractionated and show negative Eu anomalies (Figure 4 *b*). The high total REE and other incompatible elements (e.g. $K_2O = 3.26\%$; Rb = 87 ppm) in intrusive facies compared to their low SiO_2 levels (average 54.56%) imply derivation from enriched mantle source[10]. Although field evidences suggest the derivation of anatectic granites by melting of

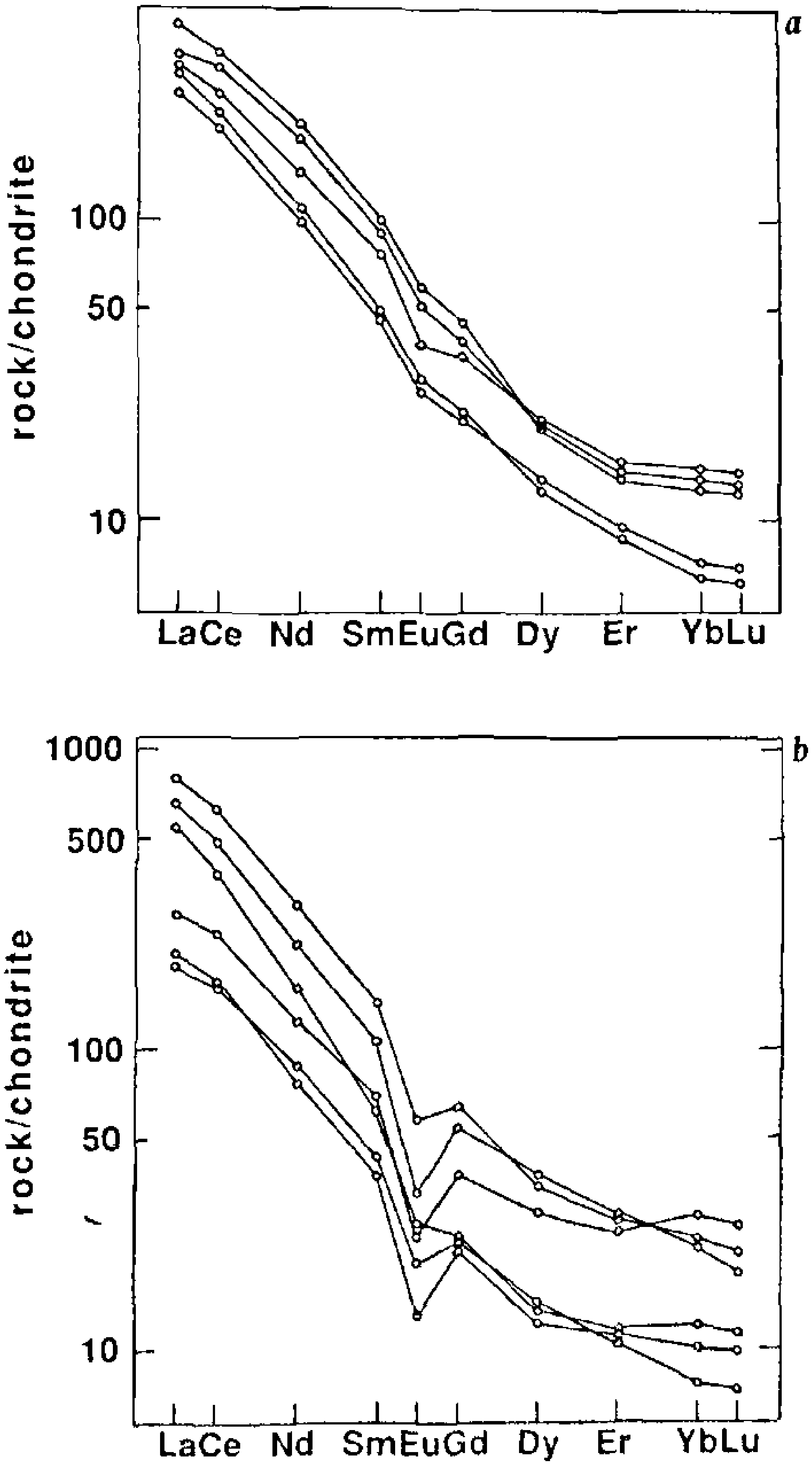

Figure 4. *a* REE patterns of intrusive quartz monzonites and monzogranites, *b*, REE patterns of anatectic granites.

surrounding Peninsular gneisses, it is not possible to account for very high REE and other trace elements (Zr, Hf, Nb and Y) in few samples. The very high REE and trace element content in these samples requires an external source, probably it could be due to circulation and interaction of fluid phase associated with intrusive magmas. Fluid inclusion study[16] also indicates that the intrusive facies are potential carriers of juvenile CO_2-rich fluids. The large negative Eu anomalies in the anatectic granites reflect a major crustal contribution in their genesis.

The quartz-monzonitic to monzogranitic intrusive facies show consistently low initial $^{87}Sr/^{86}Sr$ ratios (0.7017–0.7029 at 2.5 Ga) and plot just above the predicted mantle values at the same period indicating a major juvenile input in their genesis[10]. In contrast the anatectic granites show low to high initial $^{87}Sr/^{86}Sr$ ratios (0.7028–7366 at 2.5 Ga) suggesting their derivation from a source with different pre-crustal history[10, 11, 17, 18]. The intrusive facies show high $^{143}Nd/^{144}Nd$ ratios with low negative ε Nd values (–0.9 to –4.7 at 2.5 Ga) and fairly uniform model ages (2.9 Ga). On the other hand the anatectic granites have low $^{143}Nd/^{144}Nd$ ratios with high negative ε Nd values (–2.7 to –8.91 at 2.5 Ga) and variable model ages (3.0 to 3.4 Ga).

The isotopic 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 shortlived crustal component. On the other hand the intrusive facies cannot be derived by direct melting of Peninsular gneisses which had ε Nd values –8 to –15 at 2.5 Ga[18] (Jayananda and Peucat unpublished data). However, the intrusive facies show slight negative ε Nd values despite a major juvenile input in their genesis. This apparent paradox could be attributed to their derivation from an enriched mantle reservoir. Nevertheless, the intrusive facies even at lowest SiO_2 levels may not be totally devoid of crustal involvement, as field evidences suggest some mechanical mixing between the two magmatic bodies.

Field, geochemical and isotopic data suggest that the Closepet Batholith contains two magmatic bodies derived from distinct source regions. Field evidences together with geochronologic data[10, 11] demonstrate that both the magmatic bodies are broadly contemporaneous. However, these two magmatic bodies display strong linear trends on the element–element binary diagrams (Figure 3). Such linear trends cannot be explained by fractional crystallization of a single parental magma either derived from mantle or crustal source. Alternatively interaction and mixing of two unrelated end members can be considered in order to explain the continuous chemical variation of the two magmatic bodies of the Closepet Batholith. These end members should be anatectic melts derived from Peninsular gneisses and a magma derived from enriched mantle source. The evidences in support of this approach are presented below.

In the southern Closepet area several exposures display spectacular small scale evidences of mixing of intrusive magma and *in situ* anatectic melts. Mechanical mixing features such as diffused margins, elongated fragments and boudins of intrusive facies in anatectic granites are common. Frequently anatectic granites form net-vein complexes in the intrusive facies. Petrographic evidences particularly presence of plagioclase inclusions with calcic cores in K-feldspar megacrysts imply mixing and hybridization process[4, 8]. The fluids associated with mantle-derived intrusive magmas were potential carriers of trace elements, which could have enriched anatectic granites in the hybrid zones.

In recent years Nd-Sr isotopic compositions are considered as powerful tools to evaluate assimilation/magma-mixing process[19]. Nd-Sr isotopic compositions show co-variance in nature that is best expressed on the plot of ε Nd vs $^{87}Sr/^{86}Sr$ ratio (see Figure 3). Isotopic mixing between two end members generates intermediates which lie along an hyperbola[19]. The Nd and initial Sr isotopic compositions of intrusive and anatectic granites form a continuous line which indicate mixing of two unrelated end members that are isotopically discrete. However, the absence of consistent correlation between Nd isotopic compositions versus Nd concentration rules out simple mixing[20]; fractional crystallization and/or assimilation appears to be apparent along with or prior to magma mixing.

Magma mixing model has been proposed to explain the chemical variation of granitic rocks from Phanerozoic terrains such as Cordillaran and Hercynian orogenic belts. Nd-Sr isotopic correlation for the Andean granites from northern Chile and Antarctic Peninsula is consistent with magma-mixing model, involving mixing of variable proportions of mantle-derived magmas and crustal melts derived from older basement[21]. Magma-mixing model is also consistent with the model proposed by De Paolo[21, 22] for the granitoids of the Sierra Nevada batholiths of California. In this model the granitoids of Sierra Nevada were interpreted as products of magma mixing between depleted mantle-derived magmas and crustal melts. A similar model involving mixing of mantle-derived magmas and anatectic melts from metasedimentary source has been suggested by Gray[5] to explain Sr and Nd variations of Lachlan fold belt of southeastern Australia. Consequently it is clear that magma mixing is an important process that could account for chemical variation of many granitoids in the Archaean and Phanerozoic terrains.

Field, geochemical and isotopic data suggest that mixing of intrusive magmas and anatectic melts can produce a great variety of hybrid rocks depending upon each proportion in the mixing. In southern India, the 2.5

Ga magmatism and metamorphism appears to be related to a major thermal and accretional event possibly associated with the uprise of a mega-plume[23, 24]. The mega-plume caused the ascent of heat and fluids along with mantle-derived material into the continental crust, which induced large-scale melting of crust, mixing and hybridization of magmas.

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Extraordinary helium anomaly over surface rupture of September 1993 Killari earthquake, India

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An interesting helium field associated with the surface rupture of the September 1993 Killari earthquake has been discovered. Extensive soil-gas helium measurements over a 300 × 200 m area covering the rupture zone brought forth helium peaks, sharp and very high (reaching several tens of ppm as against 'regional' of 0.2 ppm), restricted to the features marking the rupture. Measurements in the immediate vicinity showed two helium 'spots' revealing concealed segments. The helium release is a clear signature of the faulting associated with the earthquake.

IMMEDIATELY following the 29 September 1993 Killari earthquake in India (also called Latur earthquake, magnitude: 6.3), a trace of surface rupture was recognized[1-3]. This trace, about 2 km from Killari, is marked by a set of gentle scarps in discontinuous segments, their cumulative length not exceeding one kilometer. Ground conditions being favourable over this trace for meaningful overburden-gas sampling, we carried out a few preliminary helium analyses during the third week of October 1993. Surprisingly high helium levels were observed which persisted even a month later. This prompted us to undertake a detailed survey (313 sites in a 300 × 200 m area). We report here the extraordinary helium anomaly which is highly restricted to the trace and its immediate vicinity (Figure 1). Helium excesses were also detected over two barely visible features few hundred metres away from this area (Figure 3), indicating that they also form part of the surface rupture. We believe helium survey provides a significant new tool in earthquake studies.

The faulting associated with an earthquake, initiated at depth, rarely penetrates to the surface and leave a significant expression. When it does, the characteristics of the surface rupture can give valuable geological insights into the regional seismogenic processes[4-6]. Johnston and Bullard[7] anticipated a surface rupture for the 1989 Ungava (Canada) earthquake because of its occurrence in Precambrian shield crust, absence of thick sediment cover, shallow focus, thrust mechanism and adequate size. All these factors also apply to the Killari earthquake and hence the occurrence of a surface rupture is not surprising. This rupture joins a very select