Late Archaean (2550–2520 Ma) juvenile magmatism in the Eastern Dharwar craton, southern India: constraints from
geochronology, Nd–Sr isotopes and whole rock geochemistry

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Abstract

The results of field, geochronologic, geochemical and isotopic studies are presented for the granitoids that occur east of the Closepet batholith up to the Kolar schist belt (KSB). Field data, such as common foliation, strong shear deformation occasionally leading to mylonitization, together with petrographic data, including reduction in grain size with corroded borders, show characteristics of the syn-kinematic emplacement of the granitoids. Single zircon evaporation ages define a minimum age of 3127 Ma for the tonalitic–trondhjemitic–granodioritic (TTG) basement and 2552–2534 Ma plateau ages for the emplacement of the granitoids, which slightly predate (20–30 Ma) the emplacement of the 2518 Ma Closepet batholith. Major and trace element data, together with isotopic data, suggest at least four magmatic suites from Closepet batholith to the east, which have independent magmatic evolution histories. The observed data are compatible with magma mixing for the Closepet batholith, melting of TTG and assimilation–fractional crystallization processes for Bangalore granites, either melting of heterogeneous source or different degree of melting of the same source for the granitoids of Hoskote–Kolar and fractional crystallization for the western margin of the KSB. Isotopic (Nd–Sr) and geochemical data (LREE and LIL elements) suggest highly enriched mantle and ancient TTG crust for the Closepet batholith, enriched mantle and TTG crust for the Bangalore granites, c.a. chondritic mantle source for the granitoids of Hoskote–Kolar and the quartz monzonites of the western margin of the KSB and slightly depleted mantle for granodiorites of the eastern margin of the KSB. We interpret all these geochronologic, geochemical and isotopic characteristics of granitoids from the Closepet batholith to the east up to the KSB in terms of a plume model. The centre of the plume would be an enriched 'hot spot' in the mantle that lies below the present exposure level of the Closepet batholith. Melting of such an enriched mantle hot spot produces high temperature magmas (Closepet) that penetrate overlying ancient crust, where they strongly interact and induce partial melting of the surrounding crust. These magmas cool very slowly, as the hot spot maintains high temperatures for a long time; thus they appear younger (2518 Ma). On the contrary, to the east the plume induces melting of c.a. chondritic or slightly depleted mantle that produces relatively colder and less enriched magmas, which show less or no interactions with the surrounding crust and cool rapidly and appear slightly older (2552–2534 Ma).

This plume model can also account for late Archaean geodynamic evolution, including juvenile magmatism, heat source for reworking, inverse diapirism and granulite metamorphism in the Dharwar craton. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Eastern Dharwar craton; Juvenile granitoids; Late Archaean; Plume; Sr–Nd isotopes; Zircon geochronology

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1. Introduction

The first half of our planet’s history corresponds mainly to juvenile crustal accretion. Because of the greater Earth heat production, the petrogenetic processes that operated were different from modern ones (e.g. Condie, 1981; Martin, 1986, 1994). The transition between archaic and modern petrogenetic mechanisms took place at the Archaean-Proterozoic transition, about 2500 Ma ago. In fact, the typical Archaean tonalitic–trondhjemitic–granodioritic (TTG) juvenile crust accretion continued up to 2700 Ma, whereas high-Mg plutonism took place in all Archaean cratons between 2600 and 2500 Ma. These plutons, generally referred to as late granodioritic or granitic plutons, were recently termed ‘sanukitoids’ by Stern and Hanson (1991). These rocks, initially described in north America (Stern, 1989; Stern and Hanson, 1991; Sutcliffe, 1989), possess both modern (classical calc-alkaline differentiation, mafic-felsic association, high Mg, Ni and Cr) and archaic (low HREE contents, strongly fractionated REE patterns, etc.) characteristics. Consequently, because of their transitional composition and their emplacement at a hinge period, they appear to be very important to our understanding of accretionary processes of the Archaean-Proterozoic transition.

The study of this late Archaean juvenile magmatism is complicated by the fact that these mainly mantle-derived magmas strongly interacted with the crust in which they intruded. Their mantle characters were often obliterated and altered by a superimposed crustal signature, such that they were considered as having a mixed, if not pure, crustal origin (e.g. Quéré, 1985; Jahn et al., 1988; Stern and Hanson, 1991; Jayananda et al., 1995a). Consequently, in order to discuss the change in juvenile petrogenetic processes at the Archaean-Proterozoic boundary, it appears necessary to separate clearly the mantle and crustal signatures; in other words, it is essential, first, to quantify and, subsequently, to quantify the interaction between the primary juvenile magmas and the crust in which they transited and emplaced. The changes in magma production at the Archaean-Proterozoic transition can be discussed only after an accurate determination of both the source and the conditions of melting and differentiation of their juvenile component.

The Archaean terrains of southern India are exposed over large areas in the Dharwar craton, because of Earth heat production, the petrogenetic processes that operated were different from and consist of: (1) TTG gneiss basement, (2) greenschist belts and (3) late calc-alkaline to K-rich granite plutons. This craton corresponds to a N-S cross-section of the Archaean continental crust; its northern part is affected by low-grade greenschist metamorphism (upper crust), whereas its southern part intruded into the upper crust, whereas its roots are exposed in the granulitic zone (Jayananda et al., 1995a). The sanukitoid character of its parental magma has recently demonstrated by Moyen (1996). Consequently, it corresponds to an exceptional object for studying the crust–mantle magma interactions at all the crustal levels (Jayananda et al., 1995a; Moyen et al., 1997c).

East of the Closepet batholith, Balakrishnan and Rajamani (1987), Reddy (1990) and Krogstad et al. (1991, 1995) studied small plutons around the Kolar schist belt (KSB) and proposed distinct petrogenetic models. On the one hand, Martin et al. (1995), Krogstad et al. (1991) and Moyen et al. (1997b) reported that the late plutons are not restricted only to the Closepet batholith, but extend at least 100 km to the east, corresponding to more or less parallel bodies. Moyen et al. (1997b) pointed out that all these late plutons do not display the same degree of interaction with the surrounding crust. On the other hand, Jayananda et al. (1995a) showed that the crust–mantle interactions are more widespread and intense in the deeper crustal levels.

Based on the structural, petrological, geochemical and isotopic data, several geodynamical models (reviewed in Section 7) have been proposed to explain late Archaean magmatism, metamorphism and structural patterns of the Dharwar craton. In short, two main groups of models are described.

- Active margin models have been proposed by Chadwick et al. (1997). Krogstad et al. (1989,
2. Geological setting

The southern Indian Precambrian shield is divided into two blocks, Archaean to the north and Proterozoic to the south (Fig. 1). These two domains are separated by an east-west-running Palghat–Cauvery shear zone. The Archaean domain is classically termed as 'Dharwar craton' that exposes a large section of the continental crust through an exceptional transition from upper to lower crust (Pichamuthu, 1965; Janardhan et al., 1982; Raase et al., 1986; Bouhallier et al., 1995).

Like most Archaean cratons (Condie, 1994; Windley, 1995) the Dharwar craton is also made up of classical 'trilogy' of Archaean terrains.

- Early to middle Archaean (3400–3000 Ma) TTG basement regionally known as 'Peninsular gneisses' (Buhl, 1987; Bhaskar Rao et al., 1991; Friend and Nutman, 1992; Meen et al., 1992; Peucat et al., 1993a, 1995; Mahabaleswar et al., 1995a).
- Two generations of volcano-sedimentary greenstone belts (Viswanatha and Ramakrishnan, 1975; Chadwick et al., 1981; Swaminath and Ramakrishnan, 1981): an older 3580–3200 Ma Sargur Group (Nutman et al., 1992; Ramakrishnan et al., 1994; Peucat et al., 1995) and a younger 3000–2500 Ma Dharwar Supergroup (Drury et al., 1983; Taylor et al., 1984; Bhaskar Rao et al., 1992; Anil Kumar et al., 1996; Nutman et al., 1996).
- Late Archaean (2600–2500 Ma) calc-alkaline to K-rich granitic intrusions form the latest magmatic event in the craton (Drury and Holt, 1980; Friend, 1984; Condie et al., 1985; Rogers, 1988; Newton, 1990; Friend and Nutman, 1991; Jayananda and Mahabaleswar, 1991; Kroghstad et al., 1991, 1995; Jayananda et al., 1995a).

The most spectacular of these late magmatic bodies is the N-S-trending Closepet batholith, which cuts across the regional metamorphic isograds. Further, the Dharwar craton is subdivided into the western and eastern blocks (Swaminath et al., 1976) that are separated by a mylonitic zone along the eastern margin of the Chitradurga schist belt. The western Dharwar craton is dominated by TTG Peninsular gneisses and volcano-sedimentary greenstone belts, whereas the eastern Dharwar craton is dominated by late Archaean granitic rocks with minor TTG and thin narrow elongated greenstone belts.

The whole craton displays a strong N-S-trending fabric interpreted as the consequence of late Archaean transcurrent shear deformation (Drury and Holt, 1980; Chadwick et al., 1989) and this deformation also guided the emplacement of the Closepet batholith (Jayananda and Mahabaleswar, 1991).

The study area is located slightly north of the amphibolite-granulite facies transitional domains (Fig. 2), from Closepet batholith in the west, up to the KSB to the east. This area exposes old Archaean basement, the KSB and several north-south-trending granitoid bodies.
(1) The Archaean basement is made up of Peninsular gneisses together with subordinate interlayered high-grade supracrustal rocks. Numerous intrusive veins, dykes and sheets of granites are found along the foliation of the gneisses. A progressive decrease in the abundance of basement outcrops and increase of granitoids can be observed from the Closepet batholith to
the east up to the KSB. Furthermore, to the east of the KSB the TTG basement gneiss outcrops are rarely observed as enclaves in granodiorites. The basement gneisses show a general foliation of N10–15°E with sub-vertical dip and are affected by strong shear deformation.

Near the southern end of the Closepet batholith, SHRIMP U–Pb zircon data together with single zircon evaporation ages show that the protoliths of the Peninsular gneisses emplaced at 2960 ± 5 Ma (Friend and Nutman, 1992; Mahabaleswar et al., 1995a) with a minor 3400 Ma component (Buhl, 1997). These basement gneisses involved in a reworking event lead to extensive migmatization close to 2528 Ma and are partially overprinted by granulite assemblages during 2528–2510 Ma (Friend and Nutman, 1992; Peucat et al., 1993a; Mahabaleswar et al., 1995a), which is sub-contemporaneous with the emplacement of the Closepet batholith (Friend and Nutman, 1991; Jayananda et al., 1995a). In the western margin of the KSB, 207Pb/206Pb zircon data provide a minimum age of 3140 Ma for the TTG basement (Krogstad et al., 1991).

(2) The KSB is a north-south-trending 80 km long and 4–8 km wide volcanic-dominated belt comprising komatiitic to tholeiitic amphibolites, intermediate to felsic volcanic rocks and iron formations. Its western margin is bounded by a shear zone characterized by quartz-muscovite-bearing mylonites. 40Ar/39Ar dating of muscovite from the shear zone indicates an age of ca. 2400 Ma (Krogstad et al., 1991).

Balakrishnan et al. (1990) presented a Pb-Pb whole-rock isochron age of 2732 ± 155 Ma for metabasalts from the western part of the KSB,
which is comparable to the Rb-Sr whole-rock isochron age of ca. 2700 ± 40 Ma for amphibolites from the eastern part of the KSB (Walker et al., 1989). Based on distinct isotope and trace elemental characteristics of the surrounding gneiss terrains, Krogstad et al. (1995) proposed the KSB as an oceanic feature.

(3) The whole study area was affected by late Archaean metamorphism. P-T conditions deduced from co-existing mineral phases in the high-grade supracrustal rocks occurring within the TTG basement in the south Closepet batholith and Bangalore areas indicate 670–730°C and 5–6 kb (Harris and Jayaram, 1982), whereas at the western boundary of the KSB metamorphic conditions reach 550–600°C (Mahabaleswar et al., 1995b).

(4) Late Archaean granitoid intrusions are the object of this work. Based on field distribution, five groups of magmatic intrusions have been recognized from west to east.

(a) The Closepet batholith comprises two magmatic suites, a widespread intrusive component is quartz-monzonitic to monzogranite, with frequent pillowed co-magmatic mafic-ultramafic enclaves and occasional cumulate enclaves and a minor anatectic granitic component grading progressively to the surrounding Peninsular gneisses through a 10 km thick migmatitic zone (Friend, 1983; Jayananda et al., 1995a). Both the intrusive and anatectic facies display magma mixing. The intrusive mantle-derived component shows chemical characteristics similar to the Archaean sanukitoids (Martin et al., 1993; Jayananda et al., 1995a; Moyen, 1996; Moyen et al., 1997a,c).

(b) Bangalore granites generally occur as large sheets, dykes and veins intruding the Peninsular gneiss basement. They contain large migmatized gneissic enclaves, co-magmatic mafic enclaves and also disrupted elongated angular mafic boudins. Occasionally, late brittle shears filled with epidote traverse the granites. The volume of these granite bodies progressively increases further north and they occur as large plutons in the Nandidurg area.

(c) East of Hoskote up to the Kolar area the granitoids occur as large granodioritic to granitic plutons, which occasionally contain migmatized TTG enclaves, co-magmatic mafic enclaves and also boudins of elongated mafic rocks. A number of N40°E-trending ductile–brittle dextral shear bands cut across the granitoids. Occasionally, high strain zones characterized by strong shear deformation leading to mylonitization can be observed. At places late brittle shears filled with epidote can also be observed.

(d) Near the western margin of the KSB, our study is confined to south of Bangarpet up to the KSB itself. In this area, dark grey quartz-monzonites are the most abundant lithology and occur as large sheets and elongated bodies. They frequently contain large pillowed co-magmatic mafic enclaves, as well as migmatized TTG enclaves. These quartz monzonites are cut by dykes and veins of grey granite. They do not show any intrusive relationship with the KSB and are bounded by a shear zone. Further, about 10 km north of the present study area, Balakrishnan and Rajamani (1987) studied the granitoids and termed them Dod and Dosa gneisses and suggested their derivation from primitive mantle-derived sanukitoid magmas. On the other hand, Krogstad et al. (1991) presented a U-Pb zircon age of 2631 ± 6 Ma for the Dod gneiss, 2610 ± 10 Ma for the Dosa gneiss and 2533 ± 3 Ma for the Patna granite. Based on elemental and isotopic data, Krogstad et al. (1995) proposed an Andean continental magmatic arc setting for their origin.

(e) Along the eastern margin of the KSB, dark grey granodiorite and grey granite are the dominant lithologies; they show a clear intrusive relationship with the KSB. They are also involved in a shear deformation that affected the KSB. Occasionally, the granodiorites are migmatized and exhibit a banded structure. At places, rotated angular mafic enclaves are abundant and, occasionally, pillowed mafic enclaves are also observed. In rare instances, small (30 cm diameter) banded gneiss enclaves are found in granite. Immediately north, Krogstad et al. (1991, 1995) presented a U-Pb zircon age of 2532 ± 3 Ma for the Kumbha gneiss and, based on isotopic characteristics, a Phanerozoic arc setting has been proposed.

All these granitoids display penetrative N10-15°E sub-vertical foliation, concordant with the regional fabric. They are affected by strong shear
deformation with occasional high strain zones depicting C–S fabric and even mylonitization, implying that the deformation has been active throughout the emplacement and cooling.

3. Petrography and geochemistry

Representative analyses of the various granitoids in the area studied are given in Tables 1 and 2. Details of analytical techniques are presented in Appendix A. The observed petrographic and chemical variations, together with a comparison of the various suites, are presented below.

3.1. The Closepet batholith

Petrographic descriptions of the Closepet batholith have already been presented by Jayananda et al. (1992, 1995a), and are only summarized here. It consists of intrusive and anatectic suites.

(a) The intrusive suite comprises:
- a clinopyroxene quartz monzonite [quartz + plagioclase (An20–30)+ K-feldspar + clinopyroxene + hornblende and biotite with accessory zircon, allanite, sphene, apatite and magnetite];
- a porphyritic monzogranite [quartz + plagioclase (An15–25)+ K-feldspar + hornblende + biotite with accessory zircon, allanite, apatite, sphene and magnetite] with 3–5 cm K-feldspar phenocrysts, which corresponds to the main facies of the massif.

(b) The anatectic suite contains both pink and grey granites [quartz + K-feldspar + plagioclase (An10–15)+ biotite with accessory zircon and sphene].

The intrusive facies are SiO$_2$ poor (50–68%) and have high Mg# (0.46–0.32) when compared with anatectic granites (SiO$_2$, 68–76%; Mg#, 0.36–0.02); both suites display high alkali contents (Na$_2$O + K$_2$O up to 7.83% in intrusive rocks and 8.34 in anatectic facies). In the Ab–An–Or triangular diagram they plot in the granodiorite field and extend into the granite field where most of the anatectic samples fall (Jayananda et al., 1995a) (Fig. 3), whilst in the K–Na–Ca triangle of Barker and Arth (1976) they define a classical calc-alkaline differentiation trend (Jayananda et al., 1995a) (Fig. 4). In Harker’s binary plots all major elements exhibit a strong linear correlation with SiO$_2$ (Jayananda et al., 1995a) (Fig. 5).

Trace elements, except Y, also show good linear correlation with SiO$_2$ contents (Fig. 6), which have...
Table 1

Average composition, x, standard deviation (S.D.) of representative major and trace element analyses of the granitoids from the western margin of the KSB, Hoskote–Kolar and Bangalore area

<table>
<thead>
<tr>
<th></th>
<th>Bangalore area</th>
<th>Hoskote-Kolar area</th>
<th>Western margin of KSB</th>
<th>Quarite hornfels</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Granite</td>
<td>Granodiorite</td>
<td>Granite</td>
<td>Quartz–monzonites</td>
</tr>
<tr>
<td>SiO₂</td>
<td>73.3 ± 0.5</td>
<td>68.9 ± 0.2</td>
<td>71.1 ± 0.6</td>
<td>72.1 ± 0.5</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>14.9 ± 0.9</td>
<td>15.1 ± 0.6</td>
<td>15.1 ± 0.9</td>
<td>15.0 ± 0.6</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>1.6 ± 0.1</td>
<td>3.4 ± 0.2</td>
<td>2.5 ± 0.1</td>
<td>6.5 ± 0.2</td>
</tr>
<tr>
<td>MnO</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
</tr>
<tr>
<td>Na₂O</td>
<td>3.8 ± 0.2</td>
<td>3.4 ± 0.2</td>
<td>3.0 ± 0.2</td>
<td>2.9 ± 0.2</td>
</tr>
<tr>
<td>K₂O</td>
<td>4.3 ± 0.3</td>
<td>3.7 ± 0.2</td>
<td>3.4 ± 0.2</td>
<td>3.3 ± 0.2</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.2 ± 0.1</td>
<td>0.3 ± 0.1</td>
<td>0.3 ± 0.1</td>
<td>0.3 ± 0.1</td>
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<tr>
<td>P₂O₅</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
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</tr>
<tr>
<td>LOI</td>
<td>0.2 ± 0.1</td>
<td>0.2 ± 0.1</td>
<td>0.2 ± 0.1</td>
<td>0.2 ± 0.1</td>
</tr>
<tr>
<td>Total</td>
<td>99.6 ± 0.4</td>
<td>99.0 ± 0.4</td>
<td>99.2 ± 0.4</td>
<td>99.3 ± 0.4</td>
</tr>
</tbody>
</table>

| Nb             | 13 ± 1 | 12 ± 1 | 15 ± 1 | 14 ± 1 | 12 ± 1 | 10 ± 1 | 12 ± 1 | 9 ± 1 | 10 ± 1 |
| Zr             | 17 ± 1 | 17 ± 1 | 18 ± 1 | 19 ± 1 | 19 ± 1 | 20 ± 1 | 18 ± 1 | 17 ± 1 | 18 ± 1 |
| Nb             | 25 ± 2 | 21 ± 2 | 22 ± 2 | 21 ± 2 | 21 ± 2 | 20 ± 2 | 21 ± 2 | 20 ± 2 | 20 ± 2 |
| La             | 7 ± 0.5 | 5 ± 0.5 | 5 ± 0.5 | 5 ± 0.5 | 5 ± 0.5 | 5 ± 0.5 | 5 ± 0.5 | 5 ± 0.5 | 5 ± 0.5 |
| Ce             | 1.5 ± 0.5 | 1.5 ± 0.5 | 1.5 ± 0.5 | 1.5 ± 0.5 | 1.5 ± 0.5 | 1.5 ± 0.5 | 1.5 ± 0.5 | 1.5 ± 0.5 | 1.5 ± 0.5 |
| Nd             | 3 ± 0.5 | 3 ± 0.5 | 3 ± 0.5 | 3 ± 0.5 | 3 ± 0.5 | 3 ± 0.5 | 3 ± 0.5 | 3 ± 0.5 | 3 ± 0.5 |
| Sm             | 0.5 ± 0.3 | 0.5 ± 0.3 | 0.5 ± 0.3 | 0.5 ± 0.3 | 0.5 ± 0.3 | 0.5 ± 0.3 | 0.5 ± 0.3 | 0.5 ± 0.3 | 0.5 ± 0.3 |
| Eu             | 0.2 ± 0.1 | 0.2 ± 0.1 | 0.2 ± 0.1 | 0.2 ± 0.1 | 0.2 ± 0.1 | 0.2 ± 0.1 | 0.2 ± 0.1 | 0.2 ± 0.1 | 0.2 ± 0.1 |
| Gd             | 0.9 ± 0.5 | 0.9 ± 0.5 | 0.9 ± 0.5 | 0.9 ± 0.5 | 0.9 ± 0.5 | 0.9 ± 0.5 | 0.9 ± 0.5 | 0.9 ± 0.5 | 0.9 ± 0.5 |
| Dy             | 1.5 ± 0.5 | 1.5 ± 0.5 | 1.5 ± 0.5 | 1.5 ± 0.5 | 1.5 ± 0.5 | 1.5 ± 0.5 | 1.5 ± 0.5 | 1.5 ± 0.5 | 1.5 ± 0.5 |
| Ho             | 0.5 ± 0.3 | 0.5 ± 0.3 | 0.5 ± 0.3 | 0.5 ± 0.3 | 0.5 ± 0.3 | 0.5 ± 0.3 | 0.5 ± 0.3 | 0.5 ± 0.3 | 0.5 ± 0.3 |
| Er             | 0.5 ± 0.3 | 0.5 ± 0.3 | 0.5 ± 0.3 | 0.5 ± 0.3 | 0.5 ± 0.3 | 0.5 ± 0.3 | 0.5 ± 0.3 | 0.5 ± 0.3 | 0.5 ± 0.3 |
| Tm             | 0.2 ± 0.1 | 0.2 ± 0.1 | 0.2 ± 0.1 | 0.2 ± 0.1 | 0.2 ± 0.1 | 0.2 ± 0.1 | 0.2 ± 0.1 | 0.2 ± 0.1 | 0.2 ± 0.1 |
| Yb             | 0.5 ± 0.3 | 0.5 ± 0.3 | 0.5 ± 0.3 | 0.5 ± 0.3 | 0.5 ± 0.3 | 0.5 ± 0.3 | 0.5 ± 0.3 | 0.5 ± 0.3 | 0.5 ± 0.3 |
| Lu             | 0.2 ± 0.1 | 0.2 ± 0.1 | 0.2 ± 0.1 | 0.2 ± 0.1 | 0.2 ± 0.1 | 0.2 ± 0.1 | 0.2 ± 0.1 | 0.2 ± 0.1 | 0.2 ± 0.1 |
Table 2

Rare earth element abundances of representative analyses of granitoids from Closepet batholith, Bangalore, Hoskote-Kolar and the western margin of the KSB

<table>
<thead>
<tr>
<th>Intrusive facies</th>
<th>Anatectic facies</th>
<th>Granites</th>
<th>Granodiorite</th>
<th>Granites</th>
<th>Quartz-monzonites</th>
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</thead>
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<tr>
<td>Closepet</td>
<td>Bangalore</td>
<td>Hoskote-Kolar</td>
<td>W margin of KSB</td>
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<td></td>
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<tr>
<td>BH25a</td>
<td>BH27b</td>
<td>BH23a</td>
<td>BH26a</td>
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<tr>
<td>J8</td>
<td>J14</td>
<td>J20</td>
<td>J36</td>
<td>BH41b</td>
<td></td>
</tr>
<tr>
<td>La</td>
<td>25.79</td>
<td>87.42</td>
<td>86.49</td>
<td>87.86</td>
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</tr>
<tr>
<td>Ce</td>
<td>46.29</td>
<td>150.00</td>
<td>150.00</td>
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<tr>
<td>Pr</td>
<td>15.75</td>
<td>59.16</td>
<td>47.98</td>
<td>26.82</td>
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<tr>
<td>Nd</td>
<td>76.6</td>
<td>51.73</td>
<td>47.98</td>
<td>62.83</td>
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</tr>
<tr>
<td>Sm</td>
<td>13.2</td>
<td>8.57</td>
<td>1.11</td>
<td>8.72</td>
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<tr>
<td>Eu</td>
<td>1.74</td>
<td>1.06</td>
<td>0.67</td>
<td>1.34</td>
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<tr>
<td>Gd</td>
<td>10.16</td>
<td>8.17</td>
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<td>Tb</td>
<td>1.59</td>
<td>2.11</td>
<td>0.42</td>
<td>3.01</td>
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<tr>
<td>Dy</td>
<td>8.88</td>
<td>6.23</td>
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<tr>
<td>Ho</td>
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<td>0.22</td>
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<td>Er</td>
<td>5.32</td>
<td>1.47</td>
<td>3.04</td>
<td>3.77</td>
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<td>Yb</td>
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<td>1.77</td>
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<tr>
<td>Lu</td>
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<td>0.29</td>
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<tr>
<td>Total REE</td>
<td>1075.68</td>
<td>836.9</td>
<td>430.67</td>
<td>367.46</td>
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</tr>
</tbody>
</table>

been interpreted in terms of mixing (Jayananda et al., 1995a). The most striking features are the high Sr and Ba contents, reaching up to 1591 ppm and 3007 ppm respectively, in intrusive facies and low Ni and Cr (generally less than 36 ppm to 93 ppm respectively) even in less differentiated samples, suggesting their derivation from highly enriched mantle (Jayananda et al., 1995a).

REE patterns of intrusive facies are LREE-rich (LaN = 798–248), highly fractionated (La/YbN = 20–35) with slightly negative or no Eu anomalies (Jayananda et al., 1995a; this study), whereas anatectic facies display less enriched (LaN = 227–130), but similar REE patterns [Fig. 7(a)].

#### 3.2. Bangalore area

Granites of the Bangalore area occur as large sheets or dykes intruding the TTG Peninsular gneiss basement. Several distinct facies can be observed.

- Coarse- (IND 61a, IND 61b, BH 41a) to medium-grained (IND 61d, BH 41b) grey granites (quartz + K-feldspar + plagioclase \((\text{An}_{10-15})\) + biotite (frequently altered to chlorite) ± hornblende with accessory interstitial zircon, allanite, apatite, sphene and opaques. They exhibit a hypidiomorphic granular texture. Replace and intergranular myrmekites are common.
- Whitish leucocratic granitic veins and dykes (IND 61c, IND 61e). Except for the lack of amphibole, they are similar in mineralogy to the grey granites.

Both facies are highly differentiated (SiO2 = 70–75%) and have similar compositions. In Harker’s binary plots the major elements define linear trends except for Na2O and K2O (Fig. 5). In the Ab-An-Or diagram of O’Connor (1965) all samples plot in the granite field (Fig. 3), and in a K-Na-Ca triangle (Fig. 4) they belong to a calc-alkaline differentiation trend.

Trace elements (except Ba) define clear, but...
distinct linear trends for the grey granites on the one hand, and the leucogranites on the other hand; the strongest differences appear for Rb and Y, as the leucocratic granites bear significantly higher contents for both elements. In both facies, Ba and Sr contents are relatively high compared with their silica contents (1257 ppm and 288 ppm respectively), although their abundances are less compared with the Closepet batholith. Ni and Cr contents are low (<4 ppm and 25 ppm respectively). The REE patterns [Fig 7(b)] display rather high LREE contents (La<sub>n</sub>/Yb<sub>n</sub> = 277–182), generally lower than the Closepet batholith, and are highly fractionated (La/Yb<sub>n</sub> = 18.9–63.9) with Eu
anomalies that are slightly negative in the grey granites but strongly negative in the leucocratic granites.

3.3. Hoskote–Kolar area

The granitoids of Hoskote–Kolar area are granodioritic to granitic in composition (Fig. 3).

- Granodiorites [quartz + plagioclase (An_{10–20}) + K-feldspar + hornblende + biotite] with accessory zircon, sphene and allanite are fine- to medium-grained rocks with a hypidiomorphic granular texture. High temperature deformation textures, such as reduction of grain size and corroded boundaries of quartz grains, are common. Plagioclase frequently shows alter-
Granites [quartz + plagioclase (An10-15) + K-feldspar + biotite with accessory zircon, apatite, allanite, sphene and opaques] are medium- to coarse-grained and occasionally contain 1–2 cm K-feldspar phenocrysts. They display hypidiomorphic granular to porphyritic texture. 

SiO$_2$ ranges from 69 to 75%; in Harker’s binary diagram the major elements define linear trends (Fig. 5), and on the K–Na–Ca triangular diagram all the samples plot a calc-alkaline differentiation trend (Fig. 4).

Trace elements are also correlated with SiO$_2$ (Fig. 6) for the granite; granodiorite samples plot outside for most elements. Only Ba and Y show notable scattering. Ba and Sr contents are relatively high (1491 ppm and 556 ppm respectively), whereas Ni and Cr contents are low (<7 ppm and 35 ppm) as observed in Bangalore granites. The REE contents are highly variable but generally characterized by high LREE contents (La$_N$ = 426–117). The granodiorite displays strongly fractionated REE patterns (La$/$Yb$_N$ = 50.2–78.2) and shows slight positive to negative Eu anomalies [Fig. 7(c)], whereas granite shows moderate to strongly fractionated REE patterns (La$/$Yb$_N$ = 16–60.9) and negative Eu anomalies [Fig. 7(c)].

3.4. Western margin of the KSB

The quartz monzonites [quartz + plagioclase (An20–30) + K-feldspar + hornblende ± clinopyroxene ± biotite with accessory phases are zircon, apatite, allanite, sphene and opaques] are medium- to coarse-grained and show hypidiomorphic granular texture. The clinopyroxene occurs mainly as interstitial grains, which is highly unstable, being replaced by hornblende–biotite association. SiO$_2$ contents of the analysed samples range from 59 to 67%, which makes them less differentiated than Hoskote–Kolar granitoids immediately to the west. In the Ab–An–Or diagram (Fig. 3) these rocks plot in the granodiorite field with the exception of two samples, which extend into the tonalite domain. On Harker’s binary plots the major elements define good linear trends (see Fig. 5).

Similar to other granitoids of the present study, on the K-
Na–Ca triangular plot (Fig. 4) they define a classical calc-alkaline differentiation trend.

Trace elements on Harker’s binary diagrams show linear trends with the exception of Ba, which is more dispersed (see Fig. 6). Although Sr and Ba contents remain high (866 ppm and 1258 ppm respectively), the Ba content is generally lower compared with the other areas of the present study, whereas Sr contents are lower than the intrusive facies of the Closepet batholith. On the other hand, Ni and Cr contents are rather high (maximum 45 ppm and 149 ppm respectively). Such trace elemental characteristics probably reflect chemical heterogeneity of the source or independent magmatic evolution histories. LREE contents (La\textsubscript{N110–145}) are significantly lower compared with the other rocks studied in the west. The REE patterns are moderately fractionated (La/Yb\textsubscript{N}=21.3–30.6) and display slight negative Eu anomalies [Fig. 7(d)].

3.5. Eastern margin of the KSB

Granitoids along the eastern margin of the KSB are termed Kambha gneiss (Balakrishnan and Rajamani, 1987; Krogstad et al., 1991, 1995); further south they are termed Bisanattam granites (Narayanaswamy et al., 1960). These granodiorites (quartz + plagioclase (An15–20) + K-feldspar + biotite ± hornblende with accessory zircon, sphene and opaques) are medium- to coarse-grained and display hypidiomorphic granular texture. SiO\textsubscript{2} content varies from 70 to 74% with high Mg\# (0.30–0.44) and show a calc-alkaline differentiation trend (Balakrishnan and Rajamani, 1987). They are characterized by low LREE (La\textsubscript{N}=45–55; Balakrishnan and Rajamani, 1987) compared with all the rocks studied. The REE patterns are moderately fractionated (La/Yb\textsubscript{N}=14–15) without any significant Eu anomalies (Balakrishnan and Rajamani, 1987).

In summary, although it is difficult to compare the chemical composition or mineralogy of rocks displaying different degrees of differentiation, the following observations can be made from this study:

All the rocks define a calc-alkaline differentiation trend and show no affinity with the trondhjemitic trend typical of Archaean TTG (Martin, 1994). For some constituents (Al\textsubscript{2}O\textsubscript{3}, Fe\textsubscript{2}O\textsubscript{3}, MgO, CaO, K\textsubscript{2}O, Rb, Sr, Cr and V), all the rocks studied follow the same differentiation trend, whereas other constituents (Na\textsubscript{2}O, TiO\textsubscript{2}, P\textsubscript{2}O\textsubscript{5}, Ba, Y, Ni and Cr) show distinct differentiation lines. This, together with their spatial and temporal association, probably implies that these rocks have some genetic relationship, even if their evolution histories may be different at least in detail.

From west to east the LREE contents, as well as LIL elements contents, generally tend to decrease progressively, although contents of these elements remain high, a characteristic feature of the late Archaean magmatism (Stern and Hanson, 1991). The overall contents of transition elements are low (except for the western margin of the KSB), precluding a one-stage mantle-derived origin.

4. Zircon ages

In order to define the basement and timing of calc-alkaline magmatism, we have analysed zircons from Peninsular gneiss basement and intrusive magmatic bodies by the stepwise single zircon evaporation method (Kober, 1986) and the data are presented in Table 3 and Fig. 8(a) and (b).

A sample of Peninsular gneiss (PG2) is a highly coarse-grained biotite-hornblende bearing dark grey tonalitic facies that occurs as large enclaves within typical medium-grained grey gneisses in a large quarry in the southwestern part of Bangalore city (Fig. 2). Zircons are euhedral, elongate, show zoning and generally do not display any overgrowth, but some grains appear to be more complex. A single zircon yielded a \textsuperscript{207}Pb/\textsuperscript{206}Pb age of 3127±8 Ma [Fig. 8(a)]. This age corresponds to a minimum age for the emplacement of the magmatic protoliths of the basement.

The late calc-alkaline magmatic rocks have been dated from several localities.

In the Bangalore area, sample BH 41a is a highly coarse-grained grey granite collected from the southwestern part of Bangalore city in a large quarry at BEML township (Fig. 2). Zircons are clear, euhedral to subhedral in shape [S24 high temperature type of Pupin (1980)] and some are more metamict with brown cores and overgrowths.
<table>
<thead>
<tr>
<th>Sample</th>
<th>Step (A)</th>
<th>208Pb/206Pb measured</th>
<th>207Pb/206Pb measured</th>
<th>207Pb/206Pb Error 1σ × 10^{-4}</th>
<th>206Pb corrected (Ma)</th>
<th>Error 1σ</th>
</tr>
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<tbody>
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<td>3572</td>
<td>0.1865</td>
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<td>0.1700</td>
<td>15</td>
<td>0.1681</td>
</tr>
<tr>
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<td>2.8</td>
<td>19464</td>
<td>0.2038</td>
<td>11</td>
</tr>
<tr>
<td></td>
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<td>0.2050</td>
<td>93</td>
<td>0.2031</td>
</tr>
<tr>
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<td></td>
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<td>59665</td>
<td>0.1696</td>
<td>10</td>
<td>0.1694</td>
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</tbody>
</table>

Two single grains without visible cores indicate a range of $^{206}Pb/^{207}Pb$ ages between 2450 and 2541 Ma (Fig. 8a). The oldest plateau age recorded is 2541 ± 3 Ma.

Five zircon analyses were performed on three distinct samples from the Hoskote-Kolar area. Sample BH 25a is a foliated and sheared coarse-grained grey granite collected in a large quarry at Mettubande village (14 km before Kolar town along Bangalore-Madras National Highway No. 4, Fig. 2). Zircons are euhedral, elongated, clear to brown with fine-zoned structures without any visible overgrowth or cores. Two single grains yielded ages between 2470 and 2540 Ma with a plateau age defined at 2540 ± 4 Ma (Fig. 8a). Sample BH 29 is medium-grained grey granite collected about 3 km east of Malur. Zircons are euhedral and are of S24-25 high temperature types. Two grains analysed did not allow a large acquisition of data, probably because they lost radiogenic lead and thus could be discordant; the ages obtained are ca. 2500 Ma [Fig. 8a]. Sample BH 31 is a coarse-grained grey granite sample collected 0.5 km north of Tekal village (Fig. 2). Zircons are euhedral, elongate and strongly zoned without any inherited cores or overgrowth. A
Fig. 8. (a) Single zircon \(^{207}\)Pb/\(^{206}\)Pb evaporation ages of TTG sample (PG2), Bangalore granite (sample BH41a) and granites of Hoskote-Kolar area (samples BH25a, BH29 and BH31). (b) Single zircon \(^{207}\)Pb/\(^{206}\)Pb evaporation ages of quartz-monzonite from the western margin of KSB (sample 87/S7).
single grain analysed provides a plateau age at 2539 ± 11 Ma [Fig. 8(a)].

In the western margin of KSB, a coarse-grained dark grey quartz–monzonite (sample 87/S7) has been collected about 5 km southeast of Kamasandra village (Fig. 2). The main zircon population is euhedral to subhedral, elongate, brownish and strongly zoned without any visible cores. A few grains of small slightly brown xenocrysts can also be observed. Zircon grains from the main population provide 207Pb/206Pb plateau ages of 2534–2552 Ma [Fig. 8(b)], whereas the xenocryst grains indicate single zircon evaporation ages of 2650–2720 Ma up to 2851 ± 77 Ma. A similar inherited zircon component of 2800 Ma has been described by Krogstad et al. (1991) in the 2631 ± 6 Ma Dod gneiss about 20 km north. The inherited zircon xenocrysts could be derived from 2840 Ma old Champion gneiss, as suggested by Krogstad et al. (1991), or correspond to mixed minimum ages.

In summary, our geochronologic data indicate a major episode of widespread magmatic activity to the east of Closepet batholith during 2530–2550 Ma. Further, it appears that late Archaean magmatic events in the Dharwar craton are restricted not only to the Closepet batholith but rather widespread throughout the eastern Dharwar craton. The 2550–2538 Ma ages obtained (except the inherited grains) on the granites studied are interpreted as corresponding to the crystallization of zircon during their magmatic emplacement. They are similar to the ages obtained by Peucat et al. (1989, 1993a) for the juvenile gneisses and granites of the Krishnagiri area and also to the ages obtained by Krogstad et al. (1991) for the Putta granite in the western margin and the Kambha gneiss in the eastern margin of the KSB. However, this magmatism appears to slightly pre-date (20–30 Ma) the emplacement of the Closepet batholith (Friend and Nutman, 1991; Jayananda et al., 1995a).

From zircon ages it is clear that the 2550–2530 Ma period in the eastern Dharwar craton is characterized by an abundant calc-alkaline magmatism sharing common features (shear deformation, high LILE and LREE), although minor differences in both timing and chemical characteristics suggest different magmatic histories in detail.

5. Nd–Sr isotopes

Nd and Sr isotope data, together with Nd model ages, $e_{Nd}(T=2540 \text{ Ma})$ values and initial Sr ratios at 2540 Ma, are presented in Table 4 and $e_{Nd}$ versus $I_{Sr}$ diagram (Fig. 9).

In the present study the TTG Peninsular gneisses of the Bangalore area show high negative $e_{Nd}$ values ($−5$ to $−8$) at 2540 Ma with $T_{DM}$ Nd model ages ranging from 3100 to 3400 Ma using a depleted mantle model, which corresponds to $e_{Nd}(T=2540 \text{ Ma})$ values in agreement with those suggested by Nägler and Kramers (1998) for the Archaean (see Appendix A). These model ages are similar to that defined for the 3300 Ma old Peninsular gneisses in the western Dharwar Craton (Peucat et al., 1993a). The TTG studied is characterized by initial Sr ratios at 2540 Ma ranging from 0.7029 to 0.7135, except one sample that shows an impossible value (<0.700 at 2540 Ma) indicative of post-Archaean alteration. On the other hand, the TTG gneisses of the western margin of the KSB show $e_{Nd}$ values ($−5$ to $−6$ at 2540 Ma) with $T_{DM}$ ages close to 3000 Ma and initial Sr ratios mainly radiogenic (0.7047 to 0.7135 at 2540 Ma). These values are comparable with gneisses of the western margin of the Closepet batholith (0.704–0.737; Jayananda et al., 1995a).

Isotopic data of various facies of the Closepet batholith have already been presented by Jayananda et al. (1995a). The intrusive facies show $e_{Nd}$ values ranging from $−1$ to $−4$ at 2520 Ma with $T_{DM}$ ages of 2700–2900 Ma, indicating a juvenile input in their genesis; anatectic facies show $e_{Nd}$ values ($−4$ to $−8$ at 2520 Ma) more similar to TTG basement with $T_{DM}$ ages in the range 2900–3300 Ma. Initial Sr ratios range from 0.7020 to 0.7170 at 2520 Ma and are in agreement with Nd isotope data, suggesting contributions from mantle as well as ancient crust. In the $e_{Nd}(T=2540 \text{ Ma})$ versus $I_{Sr}$ diagram (Fig. 9), the Closepet samples plot along a mixing hyperbola extending between the depleted mantle array and the field of Peninsular gneisses.
Table 4

<table>
<thead>
<tr>
<th>Sample</th>
<th>Sm (ppm)</th>
<th>Nd (ppm)</th>
<th>εNd</th>
<th>TDM, 2540 Ma</th>
<th>Rb (ppm)</th>
<th>Sr (ppm)</th>
<th>εSr</th>
<th>Error 2m(x10^6)</th>
<th>I(Sr) at 2540 Ma</th>
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<td>17.1</td>
<td>0.082</td>
<td>0.510527</td>
<td>4.10</td>
<td>1</td>
<td>0.15</td>
<td>58.2 ± 467</td>
<td>0.71439</td>
</tr>
<tr>
<td>BH27c</td>
<td>2.19</td>
<td>6.29</td>
<td>0.082</td>
<td>0.512864</td>
<td>4.10</td>
<td>1</td>
<td>0.15</td>
<td>291 ± 55.2</td>
<td>0.85229</td>
</tr>
<tr>
<td>BH29</td>
<td>8.83</td>
<td>58.5</td>
<td>0.081</td>
<td>0.510882</td>
<td>3.34</td>
<td>7</td>
<td>0.20</td>
<td>223 ± 277</td>
<td>0.789929</td>
</tr>
<tr>
<td>BH31</td>
<td>5.42</td>
<td>44.9</td>
<td>0.073</td>
<td>0.510616</td>
<td>3.39</td>
<td>7</td>
<td>0.20</td>
<td>39.9 ± 199</td>
<td>0.724671</td>
</tr>
<tr>
<td>W margin of KSB granites</td>
<td></td>
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<td></td>
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<tr>
<td>BH33</td>
<td>0.48</td>
<td>3.14</td>
<td>0.092</td>
<td>0.510543</td>
<td>3.34</td>
<td>7</td>
<td>0.20</td>
<td>127 ± 611</td>
<td>0.722432</td>
</tr>
<tr>
<td>BH37</td>
<td>7.18</td>
<td>42.2</td>
<td>0.083</td>
<td>0.511048</td>
<td>3.31</td>
<td>7</td>
<td>0.20</td>
<td>54.7 ± 870</td>
<td>0.704430</td>
</tr>
<tr>
<td>BH29</td>
<td>6.19</td>
<td>34.9</td>
<td>0.070</td>
<td>0.511718</td>
<td>3.29</td>
<td>7</td>
<td>0.20</td>
<td>79.7 ± 555</td>
<td>0.717590</td>
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<td>Duplicate</td>
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</table>

Bangalore grey granites exhibit a large range of εNd values (0 to −3) with TDM Nd model ages close to 2800–2900 Ma, whereas the two leucocratic granite samples display Nd model ages up to 3200–3400 Ma and high negative εNd values (−7) at 2540 Ma. Their I(Sr) values range from 0.701 to 0.704 at 2540 Ma. Three samples have an abnormal I(Sr) < 0.700 at 2540 Ma corresponding to samples with high Rb/Sr ratios, which suggests alteration during post-Archaean processes. In the εNd versus I(Sr) diagram (Fig. 9) all the samples that are not significantly changed during post-Archaean alteration plot along a mixing line between the mantle and crustal component (TTG Peninsular gneisses).

Hoskote-Kolar granitoids are characterized by εNd (T = 2540 Ma) values very close to zero (0 to +1) with younger TDM Nd model ages of 2600–2700 Ma. They display initial Sr isotopic compositions ranging from 0.701 to 0.702, for samples having high Sr contents (>460 ppm). Samples with lower Sr content and high Rb/Sr ratios show abnormal values (<0.700) at 2540 Ma. This could be related to an opening of the Rb-Sr system during the Paleoproterozoic E-W shearing observed further south (Peucat et al., 1993a).
transition elements contents, it is likely that these granites may not be primary mantle melts, but rather products of complex magmatic evolution. The granites that occur between the Closepet batholith and the KSB area show a general geographical evolution from west to the east, with negative $e^{\text{Nd}}(T)$ values ($-7$ to $0$) in the western part, to slightly negative to positive $e^{\text{Nd}}(T)$ values ($-1$ to $+3$) to the east. These characteristics are in good agreement with the geochemical data, wherein the intrusive facies of the Closepet batholith are characterized by strong enrichment in incompatible elements, whereas a progressively lesser degree of enrichment is observed in Bangalore, Hoskote–Kolar, the western margin of the KSB and there is a slight depletion along the eastern margin of the KSB.

Along the eastern margin of the KSB, granodioritic Kambha gneiss shows positive $e^{\text{Nd}}$ ($T = 2532$ Ma) values ($0$ to $+3$) with $T_{\text{DM}}$ Nd model ages of 2500–2700 Ma, and plot close to depleted mantle array. Directly south of the KSB, 2550–2535 Ma old granites and gneisses of the Krishnagiri area also exhibit a similar range of initial $e^{\text{Nd}}$ ($0$ to $+3$ at 2540 Ma) values (Peucat et al., 1989, 1993a).

In summary, with the exception of the leucocratic facies of Bangalore area, all the granitoids in this zone display isotopic characteristics that demonstrate a major juvenile input to their genesis. However, it should be noted that crustal influence can be evidenced in some of these rocks (Bangalore, Closepet). Finally, given the low transition elements contents, it is likely that these granites may not be primary mantle melts, but rather products of complex magmatic evolution. The granites that occur between the Closepet batholith and the KSB area show a general geographical evolution from west to the east, with negative $e^{\text{Nd}}(T)$ values ($-7$ to $0$) in the western part, to slightly negative to positive $e^{\text{Nd}}(T)$ values ($-1$ to $+3$) to the east. These characteristics are in good agreement with the geochemical data, wherein the intrusive facies of the Closepet batholith are characterized by strong enrichment in incompatible elements, whereas a progressively lesser degree of enrichment is observed in Bangalore, Hoskote–Kolar, the western margin of the KSB and there is a slight depletion along the eastern margin of the KSB.

This feature could be interpreted, either in terms of variation in the source of the magmas (enriched source in the west, to nearly chondritic if not depleted in the east), or in terms of decreasing crustal influence (from highly contaminated magmas in the west to purely mantle-derived melts in the east) or both. Assuming all the observed variations are caused by varying degrees of interaction with the ancient crust, the expected ‘pure’ mantle source would be close to $e^{\text{Nd}}(T = 2540$ Ma) = $+3$, and the resulting magmas similar to the granites east of the KSB (i.e. Nd = 8–16 ppm, etc.). In this assumption, all other magmatic suites are expected to plot in between this end-member and the field of TTG gneisses, which is clearly not the case (Fig. 10). This demonstrates that at least a part of the variation is caused by evolution of the primary source. Nevertheless, it is clear that these magmatic bodies are, in general, not totally devoid of crustal component, as demonstrated by the occasional TTG enclaves, except in the eastern margin of the KSB. On the other hand, Closepet batholith and Bangalore granites (to a lesser extent) display isotopic signatures typical of crust-mantle interactions with dispersion along mixing lines, whereas Hoskote–Kolar and the western margin of the KSB have isotopic characteristics close to chondritic mantle with minor or no interactions with the crust, as all the samples are isotopically very similar. Further, the granodiorites of the eastern margin of the KSB show Nd isotopic characteristics of slightly depleted mantle
The isotopic data of Jayananda et al. (1995a) show that all the facies of the Closepet batholith are related to mixing between two distinct end-members: a mantle-derived magma and a crustal component. Geochemical modelling using major and trace elements (Moyen, 1996; Moyen et al., 1997a,c) leads to the following model: mantle-derived melts [similar to the ‘sanukitoids’ of Stern and Hanson (1991)] intrude the hot gneissic basement and induce its anatexis. The resulting anatectic melts, mixed together with mantle-derived magmas, could account for the mineralogical, chemical and isotopic characteristics of the whole Closepet batholith.

The nature of the source of the primary magma has also been investigated. The most mafic components, which are expected to have least crustal influence, still show $\varepsilon_{\text{Nd}} = -3$ (Moyen, 1996), leading to the conclusion that this isotopic signature reflects the source of primary magmas and is not related to emplacement history.

6. Petrogenesis and sources

Some of the late Archaean granitoids in the eastern Dharwar craton have already been studied by several workers, who proposed petrogenetic models (Friend, 1983; Condie et al., 1985; Allen et al., 1986; Balakrishnan and Rajamani, 1987; Newton, 1990; Jayananda et al., 1992, 1995a; Krogstad et al., 1995). On the other hand, the data presented in this paper are qualitatively used to constrain both petrogenetic mechanisms and sources of granitoids from Closepet batholith to the east up to the KSB.

6.1. The Closepet batholith

It has long been considered that the Closepet batholith has an anatectic origin (Friend, 1983; Allen et al., 1986; Newton, 1990). This hypothesis has been negated by Jayananda et al. (1992), since the batholith contains early fractionated mafic facies ($\text{SiO}_2 < 50\%$) that cannot be produced through partial melting of surrounding TTG basement ($\text{SiO}_2 68–75\%$). This implies that at least the more mafic components of the Closepet batholith are mantle derived.

The isotopic data of Jayananda et al. (1995a) show that all the facies of the Closepet batholith are related to mixing between two distinct end-members: a mantle-derived magma and a crustal component. Geochemical modelling using major and trace elements (Moyen, 1996; Moyen et al., 1997a,c) leads to the following model: mantle-derived melts [similar to the ‘sanukitoids’ of Stern and Hanson (1991)] intrude the hot gneissic basement and induce its anatexis. The resulting anatectic melts, mixed together with mantle-derived magmas, could account for the mineralogical, chemical and isotopic characteristics of the whole Closepet batholith.

The nature of the source of the primary magma has also been investigated. The most mafic components, which are expected to have least crustal influence, still show $\varepsilon_{\text{Nd}} = -3$. Clinopyroxene, which is the earliest phase crystallizing in the magma, also shows $\varepsilon_{\text{Nd}} = -3$ (Moyen, 1996), leading to the conclusion that this isotopic signature reflects the source of primary magmas and is not related to emplacement history.

Consequently, two hypotheses can be proposed with regards to the source of the Closepet batholith:

1. the source itself is composite, made up both depleted or chondritic mantle component and a crustal component;
2. the source is an enriched mantle.

Since the late co-magmatic, lamprophyre dykes (which are pure mantle products) display the same isotopic composition, the latter hypothesis is favoured. Further, the high LREE level ($\text{La}_{\text{N}} = 708–248$) and the high contents in LILE, such as Ba and Sr in the intrusive facies, are in good agreement with an enriched mantle hypothesis.

6.2. Bangalore granites

All these rocks are granitic in composition, and are very similar in respect to their major elements contents. However, based on trace element and isotopic compositions, it is possible to propose the following petrogenetic hypothesis.

The leucocratic granites (IND 61c, IND 61e) display a high negative $\varepsilon_{\text{Nd}}$ Nd ($-7$) at 2540 Ma.
This can only be interpreted in terms of a major input of old crustal components in their genesis. This hypothesis is supported by the high incompatible element contents (Rb, but to a lesser extent Th, Y and Nb), the very low transition element contents (Ni, Cr, Co and V), and strong negative Eu anomaly (Eu/Eu²⁺ = 0.21). All these features can be interpreted in terms of reworking of TTG Peninsular gneisses.

On the other hand, the grey granites (both coarse- and fine-grained varieties) have an isotopic signature (εNd = 0 to −3 at 2540 Ma) that precludes both a purely anatectic origin, and an entirely mantle-derived origin. This shows that they are probably generated by mixed contributions from mantle and ancient TTG crust. On the other hand, their low contents of compatible elements (Ni, Cr, V) probably imply that fractional crystallization occurred at some stage of their magmatic evolution. Given the relatively little available data, we are not able to be precise on the nature of the crust-mantle interactions leading to their emplacement; an assimilation-fractional crystallization (AFC) process between TTG basement and mantle-derived melts (whether directly or indirectly) seems to be an adequate mechanism to account for both the intermediate isotopic signature and the significant enrichment in incompatible elements and the depletion in compatible elements. If isotopic compositions imply involvement of a mantle component, it is difficult to constrain its nature precisely. High contents in LREE and LILE militate in favour of an enriched mantle hypothesis; Bangalore granites appear to be less enriched than the Chospet batholith for rocks of a similar degree of differentiation. Thus we consider that the source of the Bangalore granites could be an enriched mantle but that the level of enrichment would be lower than in the Chospet batholith.

6.3. Hoskote-Kolar granitoids

Until now, no detailed petrogenetic studies have been conducted on these granitoids. However, based on our data, it is possible to make several observations.

The isotopic characteristics shown in Fig. 9 are consistent with mantle values (εNd = −0.4 to +0.6 and initial Sr of 0.701-0.702 at 2540 Ma). This precludes large-scale crustal contamination by the ancient TTG basement and implies magma derivation mainly from mantle source (whether directly or not). On the other hand, both granodiorite and granite show contrasted trace-element contents for similar major element composition (e.g. the granodiorites the Sr and Ba are double that of the granites). Both show the same age and similar isotopic compositions, which is interpreted as reflecting their derivation from a single source. In this case, the source should be either heterogeneous or affected by different degrees of partial melting to account for the observed chemical variations. However, the silica contents (SiO₂ = 68–75%) and MgO = 0.04–0.21, together with low Ni and Cr contents, are inconsistent with primary mantle melts and indicate, rather, that primary melts have undergone differentiation at some stage of their magmatic evolution, probably through fractional crystallization. Finally, LILE and LREE contents, together with isotopic data (εNd = 0 to +1 at 2540 Ma), suggest e.g. chondritic mantle source.

6.4. Quartz-monzonites of the western margin of the KSB

Nd-Sr isotopic ratios of the samples studied are similar to the Hoskote-Kolar granites (Fig. 9). Immediately north of the present study, Balakrishnan and Rajamani (1987), based on major and trace element data, explained magmatic variation in terms of liquid immiscibility. However, our observed chemical variation is not compatible with liquid immiscibility as quartz-monzonites show linear trends on Harker’s binary plots. This, coupled with absence of any field evidence for coexistence of magmatic rocks of contrasting compositions without intermediates in the study area, also does not favour liquid immiscibility. On the other hand, based on both major element and REE modelling, Reddy (1990) proposed a fractional crystallization model to explain the petrogenesis of quartz monzonites in this area; fractionation of 35 wt% of a cumulate including 48% hornblende, 51% plagioclase (An 38) and 1% magnetite is necessary to account for variations observed between the least- and most-differentiated samples. This model is in agreement with our observed mineralogical and chemical variation.
Isotopic data also confirm this hypothesis; in particular, $^{143}$Nd values ($T = 2540$ Ma) are close to zero in the rocks studied. Further, the low SiO$_2$ levels with high Mg, Ni, Cr and Sr but similar isotopic compositions ($^{143}$Nd close to zero at 2540 Ma) to Hoskote-Kolar granitoids probably reflects their poorly differentiated nature. The isotopic ratios ($^{143}$Nd values $-1$ to 0 at 2540 Ma), as well as relatively low levels of LREE and LILE compared with the Closepet and Bangalore samples, point to c.a. chondritic mantle as the most likely source.

7. Discussion

7.1. Late Archaean events in the Dharwar craton

The late Archaean is a period of intense geological activity in the Dharwar craton. In order to be precise and to constrain the geodynamic setting able to give rise to the magmatic rocks described above, as well as their space-time relationships with general structural patterns and metamorphic gradient, some aspects of the late Archaean evolution are summarized here as follows.

6.5. Granodiorites of the eastern margin of the KSB

Nd-Sr isotope ratios (Krogstad et al., 1995) plot in an area between chondritic to depleted mantle values (Fig. 9) ($^{143}$Nd = 0 to +3 at 2532 Ma); this, coupled with field data (absence of ancient TTG crust), shows their derivation from chondritic to depleted mantle source without any significant crustal influence. Further, these granodiorites are also characterized by very low LREE and LIL contents (Balakrishnan and Rajamani, 1987) compared with all other granitoids studied in the west, showing their derivation as being from slightly depleted mantle.

In summary, in the eastern Dharwar craton during 2540–2520 Ma all the granitoids show a major juvenile mantle input in their genesis. This petrogenetic study confirms the conclusion drawn from isotopic data.

Several evolutions can take place from west to east. Interactions between the mantle-derived magmas and ancient TTG crust progressively decrease from west to east, from strong crust-mantle interactions defined by intense migmatization of surrounding basement and mixing-hybridization of crustal and mantle-derived magmatic materials in the Closepet batholith, to limited assimilation in the Bangalore area, and no or restricted crust-mantle interactions in the Hoskote-Kolar area and western/eastern margin of the KSB. It also appears that the mantle components evolve from west to east, from an enriched mantle beneath the Closepet batholith, to a nearly chondritic mantle in the Kolar area, and finally to a depleted mantle to the east of the KSB.

7.1.1. Crustal accretion

Large amounts of juvenile crustal materials were accreted in the Dharwar craton around 2500 Ma; besides the Closepet batholith and all the granitoids described in this paper, we suspect that there are numerous calc-alkaline intrusions in the northern part of the eastern Dharwar craton that could be related to this accretion (Chadwick et al., 1996, 1997) (see map Fig. 1). Additionally, abundant juvenile crust accretion in the amphibolite-granulite facies transition zone of Krishnagiri is also related to this event (Peucat et al., 1989, 1993a). In this area, it is worth noting that, from north to south, i.e. from shallow to deeper structural levels, mafic magmatic materials progressively become more abundant.

The Closepet batholith is a 400 $\times$ 20 km$^2$ magmatic body; the pressure conditions in the surrounding basement range from 8 kbar in the southernmost end (30 km crustal depth) to 3 kbar (10 km) in the north (Chadwick et al., 1981 and references cited therein). This implies that the volume of the juvenile component of the Closepet batholith during the late Archaean was at least $1 \times 10^5$ km$^3$. The other granites to the east of the Closepet batholith have, all together, a surface area at least two or three times larger. Consequently, the volume of juvenile magmatic material added during the late Archaean could be as large as $(3-4) \times 10^5$ km$^3$ without taking into account the juvenile crust in the Krishnagiri area.

7.1.2. Reworking of old crust

As already described earlier in this paper, the old TTG basement is intensely migmatized in the
southern part of the Dharwar craton. Such an intense migmatization needs a large amount of heat input, which may have been carried by the mantle-derived melts. In some places, like in the Closepet batholith area, this event is clearly related to the intrusion of mantle-derived magmas; however, the migmatization is far more widespread and needs a regional-scale heating. Indeed, zircon U-Pb SHRIMP data (2528-2510 Ma) and Sm-Nd garnet-whole-rock isochrons (2528-2523 Ma) of migmatitic gneisses show that the reworking event is spatially associated with juvenile magmatic accretion (Friend and Nutman, 1992; Jayananda et al., 1996). Locally, the mantle-derived magmas were vectors of heat advection and induced more pronounced migmatization in their vicinity.

7.1.3. Hot-metamorphism

The regional metamorphism has been studied by several workers (e.g. Janardhan et al., 1982; Raith et al., 1982; Hansen et al., 1984; Gopalakrishna et al., 1986; Raase et al., 1986; Bouhallier, 1995). It grades from greenschist in the north, to granulite-facies to the south. The peak conditions of metamorphism are 800-850 °C and 8-9 kbar [garnet-plagioclase-pyroxene-quartz thermobarometer (Perkins and Newton, 1981)]. This metamorphism, occurring close to 2500 Ma, displays high temperatures but no substantial increase in pressures, particularly in the amphibolite-granulite transition zone, pointing to an anticlockwise isobaric cooling path (Jayananda et al., 1996, 1998 and references cited therein). Such patterns are classically related (Percival, 1994) to underplating of hot magmas beneath a pre-existing crust, which provide the heat and fluids required for the regional metamorphism.

7.1.4. Deformation

Recent structural work, mainly focused on the western Dharwar craton (Bouhallier et al., 1993, 1995; Choukroune et al., 1995; Chardon et al., 1996, 1998; Chardon, 1997) and some places of the eastern Dharwar craton [Kunigal area (Bouhallier, 1995)], shows that the late Archaean structures can be described as follows.

1. Dome and basin structures, where the greenstone belts form large sinking basins (‘sagduction’), and the gneissic basement display domal structures. Chardon (1997) demonstrated, using analogue modelling and rheological calculations that imply a soft-basement: an inverse density stratification (dense volcanic greenstones overlying lighter TTG gneisses) will survive until the gneissic basement is heated enough to become more ductile; this can happen at any time after the emplacement of juvenile magmas. At that time the sagduction of high-density supracrustal materials starts. In the eastern Dharwar craton the sagduction (and thus the softening of the crust) is synchronous (Bouhallier, 1995; Jayananda et al., 1998) with all the previously described 2500 Ma juvenile magmatic events and is associated with the reheating of the crust.

2. Late transpressive deformation created large shear zones; these shear zones guided the emplacement of granitic intrusions like the Closepet batholith, as described by Jayananda and Mahabaleswar (1991).

In summary, the late Archaean events are due to intense reheating of the crust (on a regional scale) in transpressive context and this reheating is spatially associated with a major episode of juvenile magmatic accretion.

7.2. Geodynamic models

Since several models (collision, subduction or mantle plume) have already been proposed to account for the features of the late Archaean events in the Dharwar craton, it is adequate to test each model in regards to our petrological and geochemical data.

7.2.1. Collision models

Continental collision involves juxtaposition of two terrains with distinct geological histories that frequently cause reworking leading to formation of anatectic granites, whose geochemical characteristics (low compatible element contents, high incompatible element contents, high Al) are compatible partly with our observations. However, isotopic data clearly demonstrate a major juvenile input in the late Archaean magmatism, which is not commonly observed in collisional belts. Additionally, reworking of old crust in the collision zone leads to discrepancies between zircon ages
and Nd model ages, e.g. as observed in the Pan-African collision zone of Madurai block, southern India (Jayananda et al., 1995b); this peculiar feature is also not observed in the eastern Dharwar craton. Further, collision involves enormous thickening and thrusting with clockwise isothermal decompression P–T–t paths and rapid cooling rates. On the contrary, in the Dharwar craton metamorphic P–T conditions display both anticlockwise P–T–t paths and slow cooling rates that are not in agreement with collisional regimes. Consequently, a collision model cannot account for the geochemical and isotopic characteristics of the late Archaean magmatism we have described and the structural and metamorphic patterns observed in the Dharwar craton.

7.2.2 Subduction models

Subduction models have been advocated by several workers (Condie et al., 1985; Hansen et al., 1995; Krogstad et al., 1995; Chadwick et al., 1997); three of them are summarized briefly.

In the Krishnagiri–Salem area, Hansen et al. (1995) suggest that stress relaxation during oblique terrain accretion caused remelting of incompatible element-enriched mantle. The resultant alkali-rich basaltic magmas were a potential source of heat and fluids that induced melting of deep crust and genesis of granitic plutons in the middle crust. On the other hand, in the KSB area Krogstad et al. (1995), based on Nd, Sr and Pb isotopic data of the granitoids, concluded that the KSB is a suture separating an older crustal block to the west and a younger crustal block to the east. The western block is characteristic of an active continental magmatic arc of the Andean type, whereas the eastern block is similar to an evolved Phanerozoic island arc.

More recently, Chadwick et al. (1996, 1997) proposed a two-fold division of the Dharwar craton into a western part comprising the Dharwar Supergroup and its sialic basement and an eastern part, the ‘Dharwar batholith’, comprising large tracts of late Archaean juvenile granitoids and minor thin schist belts. They attributed convergent plate setting with subduction from west to east to account for the accretion of late Archaean granitoids in the eastern Dharwar craton (Dharwar batholith).

A subduction zone is frequently considered as a major process for the genesis and accretion of Archaean cratons, thus accounting for the main geological and chemical features of the Archaean greenstone belts, TTG, terrane accretion, etc. In the eastern Dharwar craton the origin of late Archaean magmatism could be related to a subduction zone. In this context, progressive mantle enrichment could be related to an increasing role played by slab melts or fluids. Increasing crustal contamination of old crust could be linked to changes in crustal thickness. However, this model is not supported by structural data such as closure of a subduction zone marked by large-scale thrusting as such horizontal structures are not observed in the Archaean of southern India (Bouhallier, 1995; Choukroune et al., 1995; Chardon, 1997). Metamorphic P–T conditions display high temperatures, but not the high pressures that one would expect in a subduction zone. Additionally, the slow cooling rates (1.5 °C/Ma) observed in the Dharwar craton (Peucat et al., 1993b; Bouhallier, 1995; Jayananda et al., 1996) are not compatible with subduction zone tectonics. Further, the horizontal tectonic models cannot explain either the late Archaean vertical (sagduction) tectonics or the observed north–south metamorphic gradient in the craton and east–west magmatic zonation we described. The low Mg, Ni, Cr and V observed in our rocks (for comparable SiO2 levels), coupled with the absence of poorly differentiated rocks (gabbros and diorites), do not favour a subduction zone context. Also, the pervasive magmatic activity in the eastern Dharwar craton (200 × 500 km2) is too large for a typical subduction zone. Finally, accretion of island arcs would be marked by a distinct age zonation, with increasingly older ages being expected for the magmatic bodies in the western part of the study area, which is contrary to our observed age zonation.

7.2.3 Plume model

Such a model has been advocated by Peucat et al. (1993b) and Choukroune et al. (1995). They considered that the characteristics of the late Archaean magmatic and tectonic events in the Dharwar craton are best explained by a rising mantle plume under a mature Archaean crust in a
compressive context. The plume provides heat that can soften the crust, causes inverse diapirism and induces metamorphism. Melting of the plume is also assumed to produce the huge amounts of juvenile magmas that emplaced in the craton around 2500 Ma.

It appears that this model agrees best with our observations (Fig. 11): the centre of the plume head consists of an enriched 'mantle hot spot' lying below the presently exposed level of the Closepet batholith. Melting of such a plume produces high temperature mafic and alkali-rich magmas; these penetrate the overlying ancient crust, where they strongly interact with the surrounding crust and induce its partial melting. These magmas cool very slowly, as the hot spot maintains high temperatures for a long time; thus they appear to be slightly younger (2518 Ma). The magmas produced have geochemical characteristics reflecting their enriched-mantle origin: slightly negative $\varepsilon_{Nd}$ values, high LREE and LILE contents.

On the contrary, to the east the external part of the plume induces melting of a colder and chondritic to slightly depleted mantle that gives rise to relatively cold and less-enriched magmas that develop less or no interactions with the surrounding ancient crust; they cool more rapidly and consequently give older ages (2552–2532 Ma). Both their isotopic ($\varepsilon_{Nd} = 0$ to $+3$ at 2532 Ma) and chemical (lower LREE and LILE compared with the west) reflect their derivation from chondritic to slightly depleted mantle whose melting is induced by the plume. This hypothesis is in good agreement with their geographical position and isotopic characteristics.

As in modern plumes, large amounts of mafic magmatism should be expected. On the contrary, the late Archaean magmatism is mainly intermediate to felsic with calc-alkaline character. As proposed by Choukroune et al. (1995), when a plume arrives below a matured lithosphere it stalls at greater depth, as the matured crust acts as a thermal barrier, inducing low-degree melting of mantle that results in mainly intermediate magma-tism with subordinate mafic liquids. Subsequently, the magma can evolve by fractional crystallization, giving rise to felsic residual magmas and mafic cumulates.

Indeed, immediately south of the study area, in the amphibolite-granulite transition zone, deeper levels of the magmatic bodies are exposed where tonalitic-granodioritic rocks contain large amounts of mafic/ultramafic co-magmatic enclaves that can occasionally constitute 30–40% of total exposures. Syn-plutonic mafic dykes can also be observed. Such an accumulation of mafic magmas in the deeper levels and of felsic materials at higher levels constitutes strong evidence for a vertical
differentiation of the juvenile crust in response to plume activity. Another related problem is the presence of amphibole in hot spot magmas derived from a plume source, which are generally rather dry. Indeed, the water content in the mantle is very low, about 0.17% (Ringwood, 1975), but it behaves as an incompatible element. Given 0.17% of water content in the mantle: $F = 10\%$ melting incorporates 1.7% of water into melts and $F = 5\%$ melting incorporates 3.4% of water, assuming $D = 0$. Differentiation of such water-bearing parental magmas could give rise to amphiboles in cumulate and residual liquids. The above argument is in good agreement with the reported low pressure cumulate from alkali-basalts of modern ocean islands derived from a plume source (hot spot), which frequently contain cumulus amphibole (Wilson, 1989 and references cited therein).

Furthermore, in situ crystallization of igneous amphiboles while the melt fraction is still as high as 40–50% have been recorded from high temperature ultramafic flows and sills from the Archean Abitibi greenstone belt (Stone et al., 1997). Consequently, we believe that a low degree (about 5%) melting of a plume source incorporates most of the water into the melts, thus accounting for the observed mineralogical and chemical variation.

However, more detailed integrated structural, geochemical and isotopic studies are necessary to define the plume and its interactions with the depleted mantle, as well as with the overlying ancient crust.

7.3. Comparison with other areas

In other late Archaean terrains, some or all features observed in the Dharwar craton have already been described, including those described below.

7.3.1. Sanukitoids

In most Archaean cratons, late K-rich granites have been reported (e.g. Condie, 1981, 1994; Sylvester, 1994; Windley, 1995 and references cited therein). In some areas they have been studied in more detail. The late Archaean granites of the Superior province of Canada were investigated by Stern (1989) and Stern and Hanson (1991). They were first to describe the special characteristics (calc-alkaline differentiation trends, TTG-like REE patterns, strong enrichment in LREE and LIL and generally high Mg#, Ni, Cr) of these rocks and proposed the term ‘sanukitoids’ to describe them. They interpreted formation of sanukitoids by partial melting of an enriched mantle in a subduction zone context. In eastern Finland, Quéré (1985) described late Archaean ‘phenocryst granodiorites’ and interpreted them as reworking of the older basement with the influence of komatiitic flows. In fact, the petrographical and chemical characteristics of these granodiorites are typical of Canadian and Indian sanukitoids. In several other cratons, late Archaean K-rich phenocryst-bearing granodiorites have been reported. As pointed out by Jayananda et al. (1995a) and Moyen et al. (1997c), where data are available, they invariably display ‘sanukitoid-like’ features (e.g. Matok pluton, South Africa (Bohlender et al., 1992); Taishan complex, China (Jahn et al., 1988); Port Martin granodiorites, Terre Adélie, East Antarctica (R.P. Menot, personal communication)).

7.3.2. Dome and basin patterns

Ubiquitous vertical foliations with dome and basin structures are well known characteristic features of many Archaean terrains [see Choukroune et al. (1995) for a review]. The most spectacular have been described in Zimbabwe (Jelsma et al., 1993) or in the Australian Pilbara craton (Collins, 1989; Delor et al., 1991), and they have also been described in India (Bouhallier et al., 1993; Chardon et al., 1996); some structures in the Superior province (Canada) or Reguibat craton (Mauritania) were also interpreted in terms of dome and basin patterns that were subsequently modified by compressive tectonics (Chardon, 1997). Although they are interpreted in terms of classical shearing, fold interferences (e.g. Chadwick et al., 1981, 1985, 1989, 1996; Naha and Chatterjee, 1982), extensional collapse (Kusky, 1993), or nappe tectonics (de Wit, 1982), an alternative possibility that is being increasingly adopted (Bouhallier, 1995; Chardon, 1997) is gravitational collapse of an unstable crust during thermal and accretional events (‘sagduction’). This special tectonic regime is caused by the re-heating of ancient
crust with an inverse density stratification leading to sinking greenstone basins and rising gneiss domes. Such a large-scale heating has been attributed to hot spot activity by Choukroune et al. (1995) and this study.

7.3.3. Hot metamorphism
Granulite metamorphism is a common feature in most Archaean terrains (Percival, 1994 and references cited therein), even if not all granulites are late Archaean: Superior province, Canada [2590–2700 Ma (Mezger et al., 1989)], Napier complex, Antarctica [2500–2460 Ma (Black et al., 1983)], Hebei province, China [ca. 2500 Ma (Sills et al., 1987)], and Wyoming province [2630–2500 Ma (Stuckless et al., 1985)], etc.

All these geological characteristics have been reported at the end of the Archaean in most cratons. Following our interpretation, this would imply that the Archaean-Proterozoic boundary was characterized by an intense plume activity, not only in southern India, but on a global scale. These plumes would be responsible for a special tectonics (sagduction), hot metamorphism and important sanukitoid-like magmatic activity: all the features typical of the late Archaean across the world.

It is worth noting that such a conclusion is in sharp contrast with what is generally proposed for Archaean tectonics: several convincing lines of evidences suggest that most features during the Archaean (except its latest part) are subduction-related [e.g. TTG formation (Martin, 1994), terrain accretion (Choukroune et al., 1997 and references cited therein), back-arc basin emplacement (Lowe, 1994)]. On the other hand, our work suggests that the late Archaean (ca. 2500 Ma) tectonic regimes were dominated by plume activity. Briefly, two contrasted tectonic regimes appear as a succession during the late Archaean, as suggested for the Zimbabwe craton by Dirks and Jelina (1998).

Further, Proterozoic geological activity is mainly plate tectonics driven. This implies that the Archaean-Proterozoic boundary is a very special period, whose geological characteristics match neither Archaean, nor Proterozoic ones. In our hypothesis, this specificity (intense plume activity at the end of the Archaean) could be related to global-scale reorganization of the mantle convection regimes, leading to a transitory high level of plume activity (Richter, 1988; Condie, 1998). Following this reorganization, convection in the mantle would shift to a new, stable regime leading to Proterozoic geological conditions and putting an end to the Archaean.

8. Conclusions
The conclusions of the present study can be summarized as follows:
(1) The late Archaean juvenile calc-alkaline magmatism in southern India is not restricted only to the Closepet batholith, but is rather widespread.
(2) From the Closepet batholith to the east there appears to be at least four distinct magmatic suites. These were generated in the same accretion event (2552–2534 Ma) but with independent magmatic evolution histories.
(3) The late Archaean mantle is heterogeneous; it is highly enriched under the Closepet batholith and chondritic to slightly depleted to the east.
(4) This heterogeneity, as well as other features of the late Archaean domain of southern India, can be interpreted in terms of a rising megaplume.

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Appendix A: Analytical methods
Major and trace elements were analysed using XRF (Phillips PW 1404) at Rennes. The analytical
precisions are as follows: SiO$_2$, 1%; Al$_2$O$_3$, 1.5–3%; FeO$_{tot}$, 2–3%; MnO, 10%; MgO, 1–3%; CaO, 2–5%; Na$_2$O, 1.5–3%; K$_2$O, 2.5%; TiO$_2$, 2–5%; P$_2$O$_5$, 5%. For trace elements the precision is better than 5%; for contents less than 30 ppm the uncertainties are within 10%...


O’Connor, J.T., 1965. A classification for quartz-rich igneous


Richter, F.M., 1989. Re–Os, Rb–Sr and O isotope systematics of mafic rocks around Sakaranahalli (Kolar) South India. J. Geol. 97, 321.
