Ion Microprobe U-Pb Age Determinations on Zircon from the Late Archean Granulite Facies Transition Zone of Southern India

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ABSTRACT

The southern Dharwar Craton of Karnataka and Tamil Nadu states in south India exposes a depth profile of Late Archean crust. Amphibolite facies felsic to intermediate Peninsular Gneiss of protolith ages 3.4–2.9 Ga with subordinate infolded supracrustal relics and the large Closepet Granite body give way southward to granulite facies (orthopyroxene-bearing) gneisses over a transition zone about 40 km wide, with mineralogic pressure indicators increasing from about 4 kbar (corresponding to about 15 km paleodepth) to about 7 kbar (corresponding to near 25 km paleodepth). Previous whole rock and zircon geochronology have established that amphibolite facies metamorphism, migmatization, and granite intrusion took place in the latest Archean at 2.53–2.51 Ga. However, some workers have considered the foliated granulites as products of an earlier metamorphism, distinct from the terminal Archean events. This work presents whole rock geochemical studies coupled with ion microprobe $^{207}Pb/^{206}Pb$ ages and Th/U ratios of zircons from banded granulites and orthopyroxene-bearing pegmatoids from three quarries at Chillapura, near Halaguru, Karnataka, at the southern end of the Closepet Granite and well into the granulite transition zone. The majority of the zircons, including all those from the pegmatoidal charnockites, show nearly concordant ages at 2.53 Ga and thus provide a firm temporal link with amphibolite facies metamorphism and granite emplacement at higher crustal levels. Moreover, we propose that the very low Th/U ratios of many zircons ($\leq$0.001) could not reflect precipitation from siliceous magmas of the compositions of their host rocks but more probably record equilibration with a high U/Th metamorphic fluid. Two zircons from one banded granulite showed nearly concordant $^{207}Pb/^{206}Pb$ ages at 2.96 Ga and Th/U ratios at 0.6–1.0, compatible with primary crystallization from a mantle-derived magma with canonical Th/U $\approx$ 4; these older zircons are believed to be relics of a widespread crustal accretion event that built much of the southern Dharwar Craton. A third cluster of slightly discordant ~2.62 Ga zircons with intermediate Th/U (0.2–0.4) from one banded granulite may record a distinct migmatization event, perhaps premonitory to the more profound event at 2.53–2.51 Ga. No evidence is found of an older (Mid-Archean) metamorphic event, which could correspond to what has been termed "synaccretion metamorphism" at ~2.95 Ga. However, the 2.53–2.51 Ga crystallization of zircons in the Chillapura granulites was nearly contemporaneous with the generation of juvenile tonalitic-trondhjemitic crust in the southern part of the Eastern Dharwar Craton. The Chillapura granulite facies metamorphism, together with amphibolite facies metamorphism and emplacement of the Closepet Granite at higher crustal levels, could record remobilization in the interior of the Dharwar Craton in response to an accretionary event at its southeastern margin.

Introduction

Geologic Setting. The Archean terrane of south India is of exceptional interest to the study of early continental evolution. The Dharwar Craton of southern Karnataka and northern Tamil Nadu states (fig. 1) displays the characteristic Archean association of dominant tonalite-trondhjemite-granodiorite (TTG) gneisses, some as old as 3.3 Ga, with infolded metasedimentary and metavolcanic enclaves, Dharwar Greenstone belts, older Sargur schists, and Late Archean K-rich granitic suites, the most impressive member of which is the Closepet Granite. A continuous increase in regional metamorphic grade exists from greenschist and amphibolite facies in the north to granulite facies in the southern part of the craton. The grade increase corresponds to a gradual paleopressure increase from 3–4 kbar in the amphibolite facies part of the terrane to as much as

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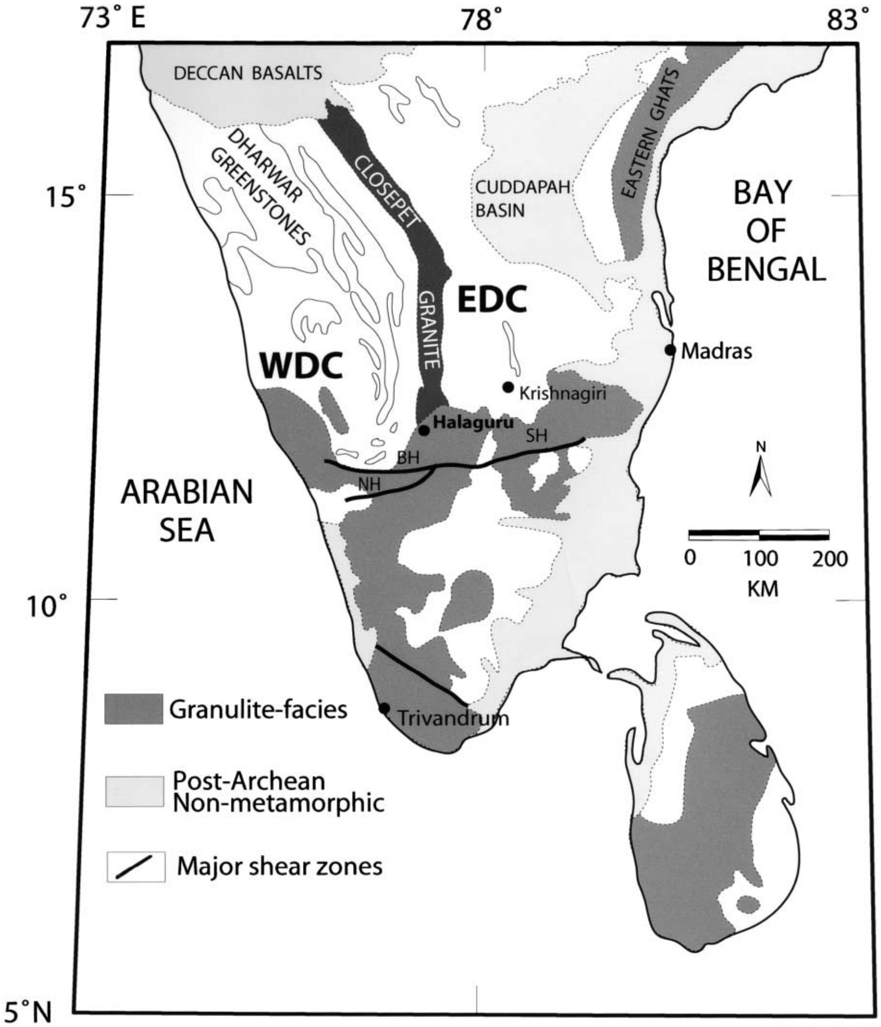


Figure 1. Generalized geology of the Archean Dharwar Craton and the granulite facies terranes of south India and Sri Lanka. *WDC* and *EDC* denote, respectively, the Western Dharwar and Eastern Dharwar Cratons. *NH*, *BH*, and *SH* denote, respectively, the Nilgiri Hills, Biligirirangan Hills, and Shevaroy Hills Archean granulite massifs. The Eastern Ghats granulite terrane and the granulite areas south of the shear zones are of Proterozoic age. The area of the present study lies near the town of Halaguru at the southern end of the Closepet Granite where it impinges on the granulite terrane of southern India (fig. 2).

9–10 kbar, corresponding to 35+ km paleodepth, in the highest-grade charnockitic massifs along the southern margin of the craton, including the Shevaroy, Biligirirangan, and Nilgiri Hills uplifts. Thus, as first recognized by Pichamuthu (1965), a nearly continuous cross section of Late Archean crust, tectonically upturned and beveled by erosion, appears to be exposed in peninsular India.

The terminal Archean Closepet Granite divides the Dharwar Craton into two nearly equal parts (fig. 1). These are sometimes referred to as the western and eastern cratons (Viswanatha and Ramakrishnan 1976; Peucat et al. 1993). The outstanding difference between the eastern and western blocks is the much greater abundance of metasedimentary-metavolcanic (supracrustal) belts and enclaves in the western block (fig. 1). Some workers do not consider the eastern block to be part of the Dharwar Craton proper (Radhakrishna and Naqvi 1986) but assign it to a craton-encircling envelope of "mobile belts" that include the granulite facies terranes on the southern margin. Other workers (Naha et al. 1986) emphasize the structural and lithologic coherence of all parts of the craton, from greenschist to granulite grade.

The pervasive N-S foliation observed throughout

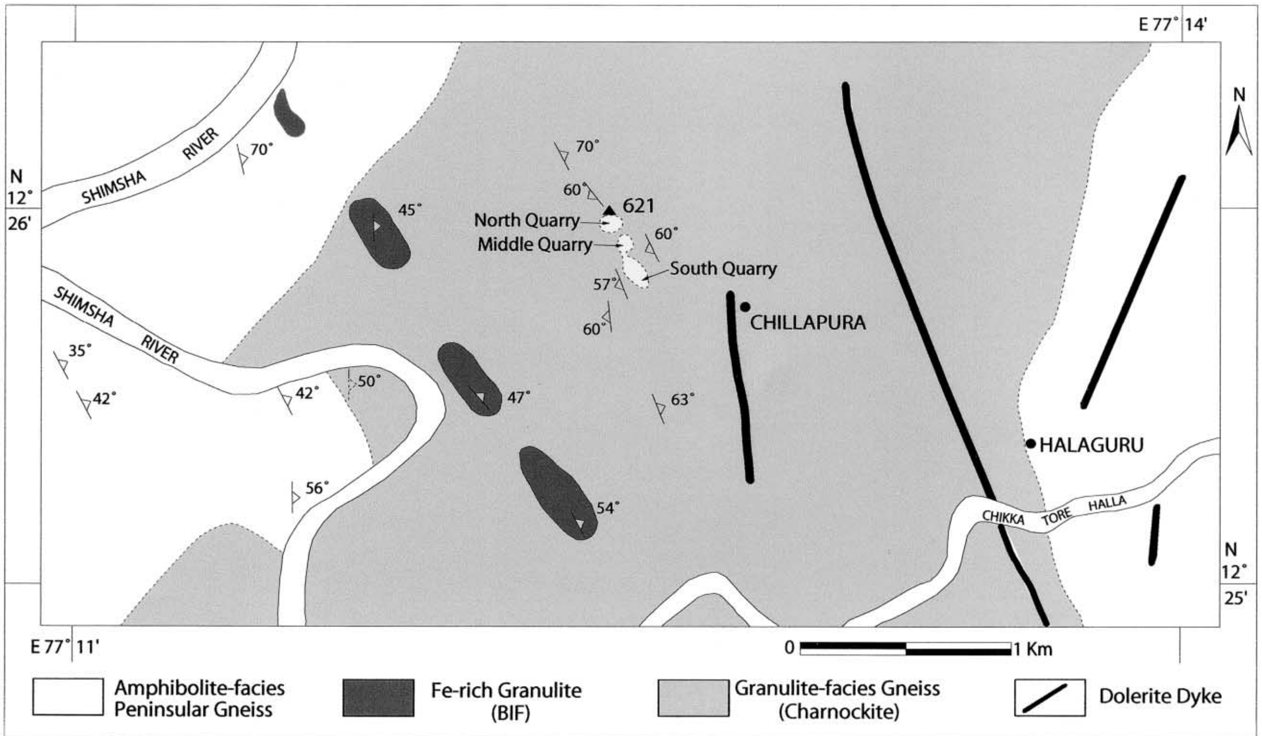


Figure 2. Regional geologic sketch maps of the study area near the southern Closepet Granite in the vicinity of Kabbal and Halaguru, south India.

the Dharwar Craton was created by profound compression and shearing in the Late Archean. Some of the prominent greenstone belts, such as the Chitradurga Belt, have been interpreted as volcanic-sedimentary graben that were emplaced in an active strike-slip deformational regime analogous to basins athwart the present-day San Andreas Fault system of California (Chadwick et al. 1989). Emplacement of the Closepet Granite was probably guided by the same structure-making process that caused the steep N-S gneissic foliation and linear greenstone belts (Jayananda et al. 1995). Pronounced N-S foliation in some parts of the southern Closepet Granite demonstrates that granite intrusion was in part syntectonic, although it may have outlasted active deformation (Jayananda and Mahabaleswar 1991). Comparison of the maps of Devaraju and Sadashivaiah (1969) and Mahabaleswar and Naganna (1981) in the granulite facies transition zone near the Closepet Granite with LANDSAT image E077-001 (January 10, 1977) shows that the N-S structural grain of the craton continues uninterrupted into the granulite facies zone. This fact, together with the similarity of lithologic components in the low-grade and high-grade terranes (quartzofeldspathic gneisses with enclaves of quartzites, amphibolites, metapelites, and calcareous rocks) makes it evident that the granulite facies metamorphism is an overprint on cratonal rocks, some of which went through earlier upper-crustal cycles.

The region south of Satnur and Halaguru of southern Karnataka is of particular interest in that it lies at the mutual juncture of three domains: amphibolite-facies Peninsular Gneiss, the Closepet Granite, and the granulite facies terrane (fig. 2). Larger bodies of equigranular and porphyritic K-feldspar granite pinch out and disappear into migmatitic gneisses almost precisely where the charnockitic (orthopyroxene-bearing) rocks come in. In the vicinity of Halaguru, light-banded and dark-banded foliated charnockitic rocks dominate (fig. 3*A*). Banding consists of alternating felsic and mafic layers with widths of a few centimeters and complex migmatization. Mobilizates are leucocratic orthopyroxene-bearing pygmatic lenses, pods, pegmatites, and tabular sheets (fig. 3*B*). Still farther south, garnet makes its appearance in quartzofeldspathic rocks, and the banding becomes less pronounced in outcrops, possibly because of decrease of biotite in favor of garnet.

A noteworthy feature of the granulite facies tran-

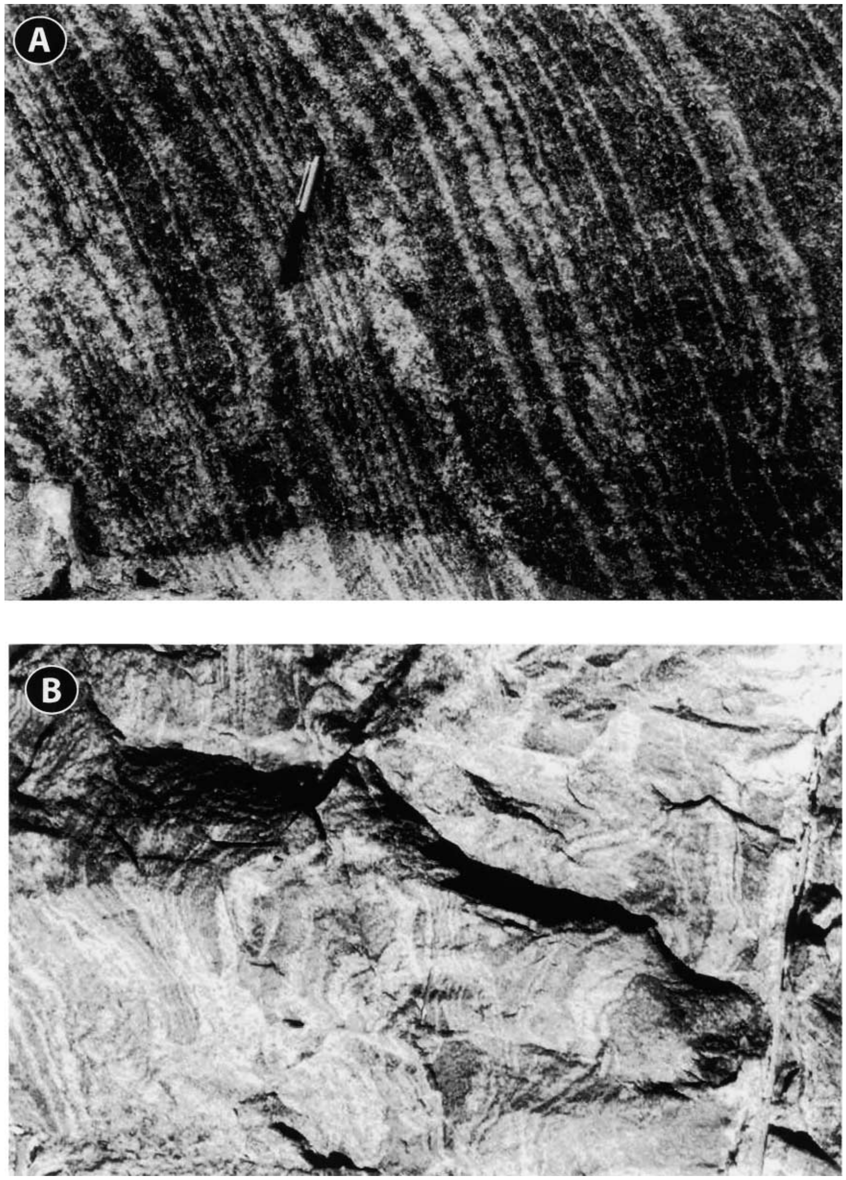


Figure 3. *A*, Strongly banded charnockite. More than 60% of the bands are mafic, being in the compositional range of quartzdiorite-diorite. Location: southern face of North Quarry, Chillapura (*pen for scale*). *B*, Typical inhomogenous-looking and chaotically banded migmatitic charnockite. All the phases in the rock are in granulite facies. Location: north face of North Quarry, Chillapura. (View is approximately 2.2 m across; photos: T. C. Devaraju.)

sition zone is the phenomenon of incipient charnockite, first discovered by Pichamuthu (1961) in a rock quarry at Kabbal, Karnataka (fig. 2). Discrete veins and nebulous patches of orthopyroxene-bearing rocks are recognizable as dark streaks and splotches against lighter-colored migmatitic gneisses in fresh quarry exposures. Subsequently, many similar occurrences have been identified at the southern termination of the Closepet Granite (fig. 2) and elsewhere along the southern high-grade margin of the Dharwar Craton (Ramiengar et al. 1978; Hansen et al. 1987). All workers who have studied incipient charnockite in detail have concluded that it results from the passage along deformation zones and lithologic contrasts of some kind of low-$P(H_2O)$ fluid, either CO_2-rich (Janardhan et al. 1982; Friend and Nutman 1992) or as a concentrated brine (Newton et al. 1998) or both, as coexisting immiscible fluids. The charnockitic alteration consists of the breakdown of hornblende, with some involvement of biotite and the appearance of orthopyroxene, and is essentially a metamorphic dehydration reaction, although field relations show that it is closely associated with granite emplacement in the southern Closepet region (Friend 1983).

Some workers, starting with Pichamuthu (1961), have drawn a distinction between foliated ("massif") charnockite and incipient charnockite, inferring that the former type resulted from an earlier cycle of metamorphism (Pichamuthu and Srinivasan 1984). Others (Viswanathan 1969; Raith and Srikantappa 1993) regard the incipient charnockite as a local phenomenon, perhaps a minor rejuvenation around the margins of a preexisting granulite terrane. In support of an earlier and more fundamental granulite metamorphism, some groups have found evidence for older charnockite enclaves as multiply folded relics in fold hinges in amphibolite facies gneiss in granulite transition areas (Naha et al. 1993). The structural studies are unsupported by radiogenic isotope evidence, however, and unambiguous age determinations confirming more than one episode of Archean granulite facies metamorphism have not yet been presented.

Previous Geochronologic Work. Many whole rock U-Pb, Rb-Sr, and Sm-Nd studies have shown that the bulk of the Peninsular Gneiss in the Western Dharwar Craton was derived from Archean mantle at 2.9–3.4 Ga (see Peucat et al. 1993 for a review of the geochronology). Smaller amounts of juvenile quartzofeldspathic crust were accreted in the eastern block at 2.5 Ga. In the Krishnagiri area of the eastern block (fig. 1), the major period of crustal accretion was at 2.55–2.52 Ga. Whole rock initial isotope ratios correspond to direct mantle derivation with no record of prior crustal residence (Peucat et al. 1989), a finding that has been confirmed by single-crystal zircon U-Pb geochronology (Peucat et al. 1993). Zircons from amphibolite facies gneiss and charnockitic gneiss from the Krishnagiri area yield identical ages. Single monazite crystals from foliated charnockitic rocks at 2.515 ± 0.005 Ga were interpreted by Peucat et al. (1993) as the age of granulite facies metamorphism. The gneiss precursors therefore had such a short crustal residence time that the metamorphism was termed "syn-accretion" by Peucat et al. (1989).

The only detailed zircon work reported in the southern Closepet Granite is from the study of Friend and Nutman (1991, 1992), who used the ANU SHRIMP-I ion microprobe. These workers obtained precise Pb-Pb ages for migmatitic gneiss from the Kabbal quarry and for homogeneous granite from near Ramnagaram (formerly Closepet), 25 km north of Kabbal. The granite contains a single concordant suite of zircons at 2513 ± 5 Ma. Their migmatitic gneiss sample from Kabbal is a duplex sample containing both amphibolite facies (hornblende-biotite) gneiss and incipient charnockite (granitic orthopyroxene granulite) obliterating the foliation of the gneiss. Zircons in the incipient charnockite portion appeared to be somewhat embayed and corroded at the margins but are otherwise identical in aspect to the zircons of the amphibole-biotite gneiss portion. Both the charnockitic and noncharnockitic portions contained zircons with darker cores yielding $^{207}Pb/^{206}Pb$ ages at 2700–3050 Ma, with a well-defined pooled mean of 2963 ± 4 Ma (Friend and Nutman 1992). Clear overgrowths on the cores and one well-formed limpid zircon were at 2528 ± 5 Ma. Field relations indicate that the charnockite was emplaced late in the Closepet intrusive sequence, since the charnockitic alteration characteristically overprints migmatization, although rare granite seams are found that crosscut the charnockite (Friend 1983). The sequence of events associated with Closepet Granite emplacement in the southern Closepet region thus seems to be (1) migmatization of Peninsular Gneiss with some new growth of zircon at 2528 Ma and (2) intrusion of the larger discrete granite bodies about 15 m.yr. later, nearly synchronous with charnockitic alteration. The charnockitic alteration did not recognizably reset the isotopic makeup of the older zircons.

Geochronologic studies in the high-grade terrane south of the Closepet region are few. Hansen et al. (1997) obtained a whole rock Rb-Sr isochron on foliated charnockite from a single quarry at Chillapura, near Halaguru. Their age at 2501 ± 54 Ma is coincident with those of Closepet Granite at Ramnagaram and incipient charnockite at Kabbal. These workers also obtained a whole rock isochron at 2541 ± 165 Ma on incipient charnockite in migmatized gneiss at Honganuru on the western flanks of the Biligirirangan Hills, about 100 km south of Halaguru. Initial $^{87}Sr/^{86}Sr$ ratios for the Halaguru and Honganuru isochrons are quite high (0.705 and 0.709, respectively), which indicates a long crustal residence time prior to granulite facies metamorphism. When the isotopic data from the two widely separated localities are plotted on the same isochron diagram, an errorchron results with an apparent age of 2990 Ma and a low initial Sr isotope ratio of 0.703. This is a result very similar to that of Mahabaleswar and Peucat (1988), whose whole rock Rb-Sr errorchron from several different quarries in the Satnur-Halaguru-Sivasamudram (SHS) area were at 2950 Ma and an initial ratio of 0.702.

Table 1. Modal Mineral Analyses of Charnockites/Granulites from Chillapura Quarries

Sample	Ch Zr 1 1	Ch Zr 5 2	Ch Zr 7 3	Ch Zr 3 4	Ch Zr 4 5
Quartz	15.9	12.7	14.7	28.6	15.1
Plagioclase	60	60.8	69.8	68.9	79.0
K-Feldspar	6.7	.4	2.0	–	3.0
Orthopyroxene	12.3	13.8	9.5	1.1	+
Clinopyroxene	–	4.2	–	–	–
Hornblende	–	2.3	–	–	–
Biotite	1.1	0.6	.9	–	2.2
Fe oxide	2.7	3.8	.7	.7	.5
Apatite	.9	1.0	1.7	.5	.2
Zircon	.5	.3	.7	.2	+
Garnet	–	–	–	–	–

Note. 1–3 = felsic (acid intermediate granulite) charnockite; 4, 5 = pegmatitic (granulite) charnockite; + = trace.

Hansen et al. (1995) interpreted their data and Mahabaleswar and Peucat's (1988) multiquarry errorchrons as a "regional isochron" that dates a major crustal accretion event in southern Karnataka, when a large volume of juvenile continent was extracted from a nearly homogeneous reservoir, that is, the upper mantle. This point of view was also taken by Mahabaleswar et al. (1995), reinterpreting the conclusion of Mahabaleswar and Peucat (1988) of a major metamorphic episode at about 3.0 Ga.

The only reported U-Pb zircon work on the SHS area is from Mahabaleswar et al. (1995). Single zircon crystals from foliated charnockites collected from unspecified localities in this area gave two clusters of points by the evaporation method: a slightly discordant age at 2995 ± 5 (1σ) Ma on elongate crystals with textures attributed to magmatic growth and a diffuse cluster of ages from rounded crystals with a mean age at 2549 ± 50 Ma. A single monazite crystal yielded a $^{207}Pb/^{206}Pb$ age at 2507 ± 5 Ma, regarded as a metamorphic age set in cooling past ~750°C. Detailed geochemical work by Mahabaleswar et al. (1995) on amphibolite facies and charnockitic gneisses indicated that most major and trace rock components remained inert during the granulite facies metamorphism except for the depletion of heavy rare earth elements and enrichment of the light rare earth elements.

Scope of the Present Work. This study was undertaken with a number of objectives in mind:

1. To provide further detailed geochronology that could link the foliated charnockites of the South Indian Shield more firmly with the Peninsular Gneiss, Closepet Granite, and incipient charnockite of the granulite facies transition zone.

2. To attempt to discriminate age components of zircons in part on the basis of morphology (darker crystal cores, featureless overgrowths, and well-formed limpid crystals) and primarily by zircon and whole rock trace element chemistry. Various workers have correlated zircon morphologic features with processes of juvenile crustal accretion, anatexis and migmatization, and metamorphic growth or dissolution, perhaps by the action of metamorphic fluids. We have applied trace element, Th/U whole rock/zircon partitioning, and zircon saturation systematics to constrain the role of fluids in neoform (metamorphic) zircon growth. We also use these data to evaluate the potential for zircon inheritance in some of these rocks.

3. To attempt to identify an older generation of indubitably metamorphic zircons in foliated charnockite, which could bear on the problem of a pre-2.6 Ga regional high-grade metamorphism in the South Indian Shield. Information on this subject could bear on the general problem of synaccretion metamorphism as a general feature of continental evolution.

Local Geology and Sample Description

The study area at Halaguru lies in the regional amphibolite facies to the granulite facies transition zone of southern Karnataka and near the southern terminus of the Closepet Granite (fig. 2). The dominant country rock is a close association of amphibolite facies and granulite facies portions occurring within the amphibolite facies gneisses as patches of variable size that increase and coalesce southward (Devaraju and Sadashivaiah 1969). Apart from the difference of metamorphic grade, the orthopyroxene-bearing granulite facies gneisses are very similar in field and petrologic features to their lower-grade equivalents. Both types of banded gneisses enclose conformable suites of high-grade Fe-Mn-Al-rich and Ca-Mg-rich metasediments and are intruded by basaltic dike swarms of Early Pro-

Table 2. Whole Rock Geochemistry of Charnockites/Granulites from Chillapura Quarries

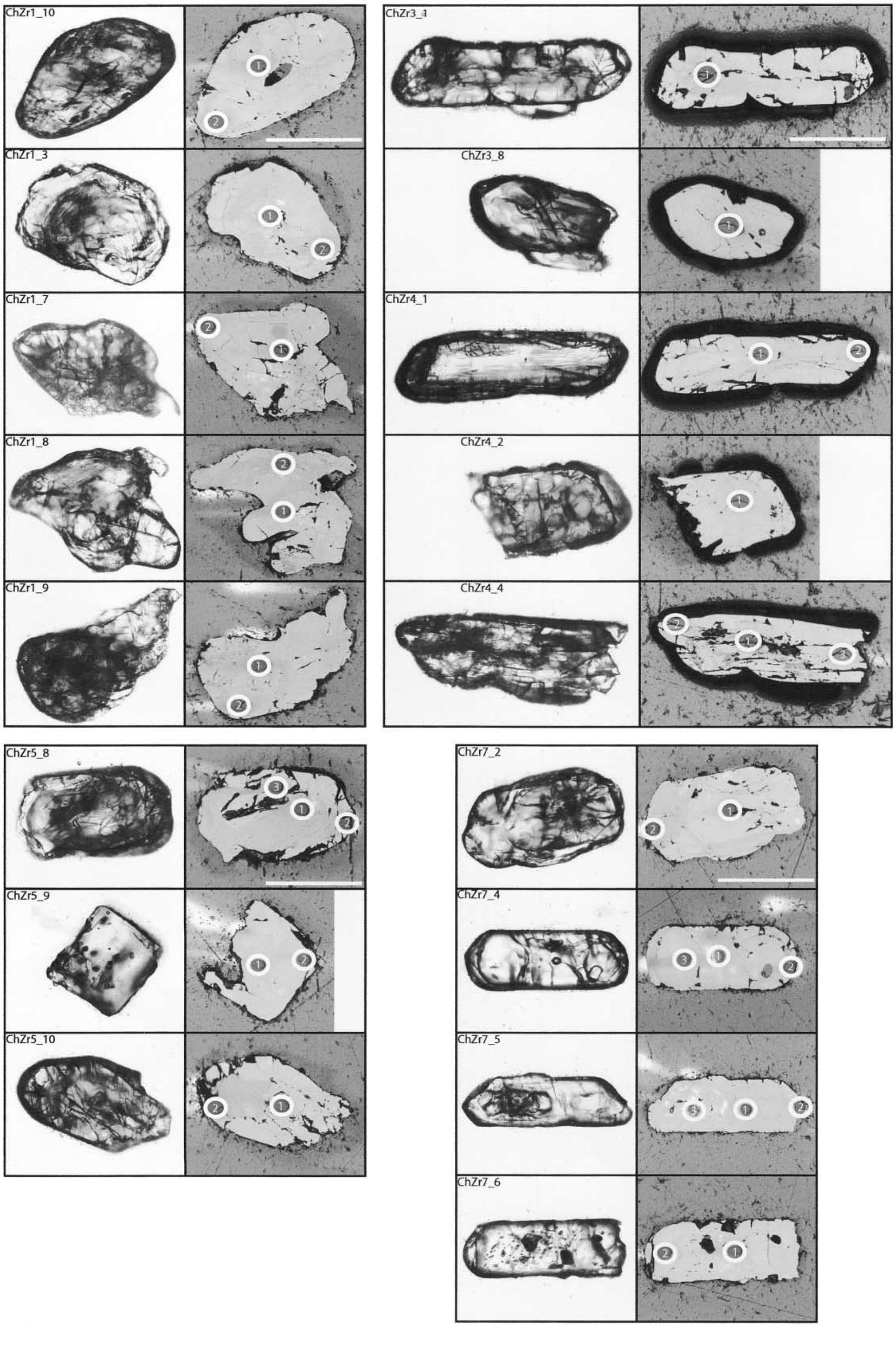
Sample	Ch Zr 1	Ch Zr 3	Ch Zr 4	Ch Zr 5	Ch Zr 7
SiO_2	73.02	72.35	73.92	61.43	70.75
Al_2O_3	11.96	014.76	14.66	14.58	13.43
Fe_2O_3	6.48	2.67	2.20	11.07	5.56
MnO	0.078	.112	.040	.159	.092
MgO	0.92	.46	.30	1.75	1.91
CaO	2.58	3.01	3.70	5.25	3.05
Na_2O	2.95	3.84	4.03	3.92	3.60
K_2O	2.20	2.54	1.15	.69	1.83
TiO_2	.447	.152	.093	1.375	.438
P_2O_5	.08	.03	.02	.41	.11
L.O.I.[a]	...	.14	.1	...	...
Total	100.32	100.07	100.21	100.12	100.43
Rb	37	57	13	3	40
Sr	182	272	366	249	171
Y	18	5	2	36	25
Zr	479	113	174	385	272
Nb	5	3	1	14	9
La	50.6	17.0	12.5	37.6	44.0
Ce	91.8	26.8	17.9	79.6	82.6
Pr	10.6	2.53	1.60	9.53	9.44
Nd	44.7	8.8	5.5	41.5	40.2
Sm	7.6	1.3	.7	8.5	7.2
Eu	1.95	1.60	1.21	2.12	1.48
Gd	7.1	1.3	.6	8.3	7.0
Tb	.9	.2	0	1.3	1
Dy	4.2	1.0	.3	7.4	4.7
Ho	.8	.2	0	1.4	.9
Er	2.1	.6	.2	3.9	2.5
Tm	.28	.09	0	.59	.38
Yb	1.6	.6	.3	3.6	2.3
Lu	.26	.10	.05	.46	.34
Hf	11.8	3.2	5.0	8.7	7.3
Pb	17	16	13	11	13
Th	5.8	.8	.5	.9	12.4
U	.5	.3	.4	.2	.7
Th/U	1.16	2.67	1.25	4.5	17.7
$[Th/U]_{zircon}$[b]	.23	.53	.25	.90	3.54
M[c]	1.44	1.45	1.44	1.97	1.51

[a] L.O.I. = loss on ignition.
[b] The predicted Th/U ratio of zircon grown in a melt of given whole rock composition.
[c] Harrison and Watson 1983.

terozoic to Late Proterozoic ages (Ikramuddin and Steuber 1976; Devaraju et al. 1995). Some quarries at the northern limit of the granulite facies patches expose incipient charnockitic alteration of migmatitic gneiss, the best-known example of which is at Kabbal, 12 km northeast of Halaguru (fig. 2).

The samples for this study were collected from three active quarries, here called the North, Middle, and South Quarries, located about 1 km northwest of the village of Chillapura (fig. 2). The freshly quarried rock in the North and Middle Quarries is lighter in color and more regularly banded (fig. 3*A*) than that exposed in the South Quarry, which is closer in appearance to typical greasy-gray charnockite. In all exposures, the dominant rock is well-foliated gneiss with leucocratic quartz-feldspar bands alternating with thinner melanocratic layers enriched in biotite, orthopyroxene, hornblende, and Fe-Ti oxides. Boudinaged enclaves of mafic granulites are common in all the quarries, whereas ultramafic and Fe-rich layers are found only in the North Quarry. Coarse-grained orthopyroxene-bearing leucosomes (charnockitic pegmatites) occupy pods and lenses parallel to banding, necks of boudins, and narrow tabular bodies that crosscut the banding (fig. 3*B*). The strike of the banding is predominately within 10° of north, and dips are mostly westward, from shallow to steep. The variable intensity of deformation of the leucosomes suggests that migmatization started during active deformation and may have outlasted it.

Plagioclase (oligoclase, commonly antiperthitic)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ChZr5_8
ChZr5_9
ChZr5_10
ChZr7_2
ChZr7_4
ChZr7_5
ChZr7_6

and quartz make up at least 80% of the felsic granulite. K-feldspar is seen only occasionally as discrete grains. The plagioclase shows marked strain effects: wavy extinction and bent twin lamellae. Elongate-oriented inclusions of a dark mineral are common. Antiperthitic intergrowths are ubiquitous but are quite unevenly distributed. The rest of a felsic charnockite is made up of orthopyroxene, highly pleochroic biotite, oxide minerals, and common apatite and zircon. Hornblende and clinopyroxene are absent. Mafic granulites consist of about 60% oligoclase-andesine, with the remainder of the rock made up of orthopyroxene, biotite, green-brown hornblende, and very abundant Fe-Ti oxides. Quartz is present in small amounts in most samples. Apatite is common but zircon is scarce. The pegmatoidal charnockites are composed of 90%–95% quartz and remarkably antiperthitic oligoclase, with K-feldspar making up as much as 30% of a feldspar grain. The remainder of a pegmatoidal rock is orthopyroxene, sometimes in centimeter-sized crystals with good morphology, biotite, and Fe-Ti oxides. Apatite and zircon are common and larger than in the banded granulites.

Five specimens from the Chillapura quarries were selected for zircon analysis and geochemical analysis. Mineral modes of the rocks as determined by optical microscope point counting are presented in table 1. Brief descriptions of the rocks are as follows:

Ch Zr 1. Banded felsic granulite, North Quarry. Well-banded ash-gray rock with dark bands 2–6 mm thick. Thicker light bands contain common plagioclase megacrysts up to 1 cm across.

Ch Zr 3. Charnockitic pegmatite, North Quarry. Greasy-gray felsic rock with plagioclase megacrysts up to 3 cm across.

Ch Zr 4. Charnockitic pegmatite, South Quarry. Greasy-gray felsic rock with small clove-brown orthopyroxenes.

Ch Zr 5. Banded granulite, South Quarry. Intermediate rock with relatively high proportion of mafic minerals, sporadic plagioclase megacrysts.

Ch Zr 7. Banded felsic-intermediate charnockite, Middle Quarry. Slight greasy-gray color, dark bands 1–4 cm thick.

Analytical Techniques

Sample Preparation. Freshly broken, unweathered 2–3-kg samples of the five selected rocks were crushed in large steel mortars. Homogenized 200–300-g extracts of the powders were prepared for chemical analysis by ACTLABS of Don Mills, Ontario. The analyses are given in table 2. Portions of the powders were sieved to yield 500-μm separates, which were then passed through heavy liquids to yield a heavy mineral concentrate that was about half zircon. Individual zircons distinguishable by dark to light brown color were handpicked under a binocular microscope, mounted in epoxy resin, and polished in stages, the last stage being a brilliant finish with 0.25 μm alumina paste. Mounted zircons were examined by optical and scanning electron microscopy. Most of the zircons showed elongate rounded forms with darker-textured interiors and somewhat lighter and more featureless margins (fig. 4). Occasionally, a rim was found with well-developed crystal morphology. Apart from variation in grain size, there was little difference in the appearance of the zircons from felsic granulite, mafic-intermediate granulite, or pegmatoidal charnockite.

Ion Microprobe Techniques. All U-Pb ion microprobe analyses of zircons, extracted by conventional heavy mineral separation of whole rock powders, were determined using the UCLA CAMECA *ims*1270 ion microprobe. All samples were coated with ~100 Å of Au using a sputter-coater. The standard operating conditions for analyses presented here are a 5.5 nA O_2^- primary beam focused to an ~ 20 × 25-μm spot; the ion microprobe was operated at a mass resolving power of 6000 with an energy window of 50 eV. An offset voltage of 5–15 eV was used for $^{238}U^+$ relative to Pb^+ and UO^+ to compensate for their contrasting energy distributions. To overcome interferences from $^{176}Hf^{28}Si^+$ (at 204 amu) and to resolve ^{204}Pb requires high mass resolution (MRP ≥ 5500). Oxygen flooding to a pressure of 3.0×10^{-5} torr was employed to increase Pb^+ yields. U-Pb ages were determined by comparison with a working curve defined by multiple measurements of standard zircon AS-3 that

Figure 4. Optical micrographs of zircons from the Chillapura region used in this study (table 3). Sample and zircon grain numbers are indicated on each image. Images in the left-hand columns are in plane-polarized transmitted light; corresponding images in right columns are reflected light. Location identities of ion microprobe spots are shown in the reflected light micrographs and are correlative to reported spot values in table 3. Scale bars on the first picture of each group apply to all views of that group and are 100 μm.

Table 3. Ion Microprobe Analyses of Zircons Separated from Charnockites/Granulites from Chillapura Quarries

Grain spot	$^{206}Pb^{\star}/^{238}U$	$^{207}Pb^{\star}/^{235}U$	$^{207}Pb^{\star}/^{206}Pb^{\star}$	$^{207}Pb/^{206}Pb$ (age)	$\%^{206}Pb^{\star}$	Th/U	$^{208}Pb/^{206}Pb$	$^{204}Pb/^{206}Pb$
Sample Ch Zr 1, banded felsic granulite:								
3_1	.376 ± .053	8.60 ± 1.21	.166 ± .002	2518 ± 18	99.24	.0030	.0155	.00009
3_2	.333 ± .060	7.71 ± 1.39	.168 ± .001	2540 ± 6	99.84	.0018	.0068	.00002
7_1	.464 ± .011	10.88 ± .33	.170 ± .003	2557 ± 28	97.99	.2232	.1305	.00124
7_2	.506 ± .007	12.09 ± .20	.173 ± .001	2590 ± 11	99.60	.1823	.0605	.00024
8_1	.321 ± .063	7.26 ± 1.42	.164 ± .002	2501 ± 21	99.19	.0030	.0111	.00013
8_2	.331 ± .060	7.64 ± 1.38	.167 ± .001	2532 ± 12	99.45	.0007	.0103	.00007
9_1	.354 ± .066	8.59 ± 1.60	.176 ± .001	2614 ± 9	99.65	.2704	.0840	.00004
9_2	.299 ± .066	7.31 ± 1.60	.178 ± .001	2631 ± 11	99.77	.2565	.0752	.00002
10_1	.352 ± .065	8.58 ± 1.60	.177 ± .001	2625 ± 7	99.73	.3657	.1098	.00003
10_2	.320 ± .066	7.81 ± 1.62	.177 ± .002	2625 ± 18	99.26	.2023	.0720	.00011
Sample Ch Zr 3, charnockitic pegmatite:								
1_1	.749 ± .055	17.38 ± 1.27	.168 ± .001	2540 ± 10	99.59	.0188	.0285	.00025
8_1	.659 ± .076	15.11 ± 1.73	.166 ± .001	2522 ± 9	99.92	.0258	.0096	.00004
Sample Ch Zr 4, charnockitic pegmatite:								
1_1	.555 ± .090	12.88 ± 2.09	.168 ± .001	2542 ± 9	100.00	.0161	.0056	.00001
1_2	.613 ± .103	14.13 ± 2.37	.167 ± .001	2530 ± 8	99.99	.0082	.0031	.00001
2_1	.614 ± .085	14.19 ± 1.96	.168 ± .001	2534 ± 9	99.98	.0126	.0035	.00001
4_1	.484 ± .062	11.05 ± 1.42	.166 ± .001	2514 ± 13	99.50	.0799	.0401	.00031
4_2	.648 ± .059	15.31 ± 1.39	.171 ± .001	2571 ± 8	99.45	.0549	.0360	.00034
4_3	.620 ± .112	14.17 ± 2.54	.166 ± .003	2516 ± 28	99.83	.6024	.2083	.00010
Sample Ch Zr 5, banded granulite:								
8_1	.511 ± .005	11.99 ± .12	.170 ± .000	2560 ± 3	99.93	.1484	.0465	.00005
8_2	.503 ± .008	11.34 ± .55	.164 ± .007	2493 ± 71	96.45	.0951	.1085	.00219
8_3	.453 ± .012	10.56 ± .28	.169 ± .002	2547 ± 16	99.41	.1001	.0387	.00036
9_1	.487 ± .016	11.44 ± .89	.171 ± .010	2563 ± 98	96.46	.4701	.2087	.00219
9_2	.494 ± .014	11.88 ± .47	.174 ± .005	2600 ± 50	97.61	.3859	.1739	.00147
10_2	.458 ± .020	10.56 ± .52	.167 ± .003	2530 ± 31	98.60	.0818	.0500	.00086
Sample Ch Zr 7, banded felsic charnockite:								
2_1	.479 ± .009	11.02 ± .31	.167 ± .003	2527 ± 28	98.83	.4432	.1459	.00072
2_2	.490 ± .015	11.32 ± .35	.168 ± .001	2534 ± 7	99.79	.0057	.0041	.00019
4_1	.582 ± .013	17.57 ± .42	.219 ± .002	2972 ± 14	99.55	1.0400	.3073	.00028
4_2	.495 ± .015	12.54 ± .46	.184 ± .003	2687 ± 31	98.52	.1650	.0870	.00092
4_3	.583 ± .028	17.42 ± 1.08	.217 ± .008	2956 ± 57	97.24	.4769	.1970	.00170
5_1	.485 ± .004	11.13 ± .09	.166 ± .001	2522 ± 5	99.82	.0586	.0202	.00011
5_2	.482 ± .010	10.96 ± .23	.165 ± .001	2507 ± 11	99.61	.0741	.0274	.00024
5_3	.487 ± .011	11.45 ± .41	.171 ± .004	2564 ± 40	96.02	.1545	.1385	.00246
6_1	.603 ± .010	17.78 ± .31	.214 ± .001	2936 ± 9	99.64	.5815	.1745	.00022
6_2	.552 ± .015	15.51 ± .50	.204 ± .003	2857 ± 25	98.71	.3157	.1130	.00079

Note. Nomenclature is grain + spot number. Isotopic ratios have been corrected for common Pb. $\%\,^{206}Pb^{\star}$ is the percentage of radiogenic ^{206}Pb. $^{207}Pb/^{206}Pb$ ages are expressed in millions of years (Ma). U-Pb ages were determined by comparison with a working curve defined by measurements of standard zircon AS-3 that yields concordant $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ ages of 1099 ± 0.5 Ma by conventional methods. Error demagnification was applied to the data; all uncertainties are reported at the 1σ level.

yield concordant $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ ages of 1099.1 ± 0.5 Ma (Paces and Miller 1993).

Results of Ion Microprobe Measurements

Ion probe measurements on Chillapura zircons are presented in table 3. Discrete populations can be recognized in the data on the basis of clustering of $^{207}Pb/^{206}Pb$ ages with small uncertainties and by Th/U ratios. A smaller number of measurements show apparent ages intermediate between discrete populations, usually with large uncertainties. These may be considered as mixed or overlap data, following Friend and Nutman (1992).

Pegmatoidal Charnockites. The coarse-grained orthopyroxene-bearing leucosome Ch Zr 3 from the North Quarry gave a $^{207}Pb/^{206}Pb$ age at 2530 ± 10 Ma, taken on the cores of two zircons. The isotopic ratios are slightly reversely concordant (fig. 5). All data regressions were done using the ISOPLOT method of Ludwig (2001). The similar pegmatoid, Ch Zr 4, from the South Quarry gave nearly identical results: 2542 ± 21 Ga (fig. 6). An outstanding feature of both determinations is the low Th/U ratios, 0.01–0.03 for Ch Zr 3 and 0.01–0.08 for Ch Zr 4, with one exception (Ch Zr 4_3, Th/U = 0.6), in contrast to the usual value near 0.8 for zircons from acid to basic igneous rocks (Mahood and Hildreth

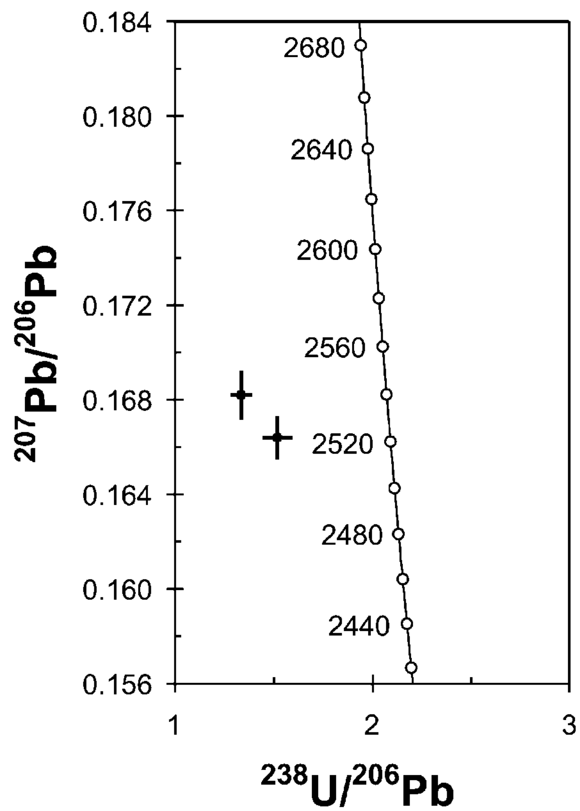

Figure 5. Tera-Wasserburg ($^{207}Pb/^{206}Pb$ vs. $^{238}U/^{206}Pb$) diagram (Ludwig 2001) for zircons extracted from sample Ch Zr 3. Data points are plotted as 1σ error crosses.

1983). No significant differences in age or Th/U ratio are apparent between rims and cores in sample Ch Zr 4.

Banded Granulites. Five grains of Ch Zr 1 from the North Quarry were analyzed. Two grains (3 and 8) were homogeneous and slightly discordant at 2535 ± 19 Ma (fig. 7) with extremely low Th/U ($7 \times 10^{-4} - 0.003$). Two grains (9 and 10) were nearly concordant with a distinctly different $^{207}Pb/^{206}Pb$ age at 2622 ± 9 Ma (fig. 7; table 3) and Th/U of 0.29 ± 0.08. No obvious morphological differences were noted between grains of the two ages. In grain 7, an intermediate apparent age at 2560–2590 Ma with larger uncertainties and Th/U of near 0.2 could represent an overlapping portion of the grain showing both discrete ages.

The intermediate banded granulite Ch Zr 5 from the South Quarry yielded data (fig. 8) similar to the mixed age grain of Ch Zr 1: $^{207}Pb/^{206}Pb$ ages scattered in the range of 2490–2600 Ma with large uncertainties and Th/U scattered in the range 0.1–0.5. No simple zonal variations within a grain could be identified.

Felsic-intermediate banded granulite Ch Zr 7 from the Middle Quarry yielded a distinctly different result (figs. 9, 10). Three analyses (grains 4 and 6; table 3) gave a weighted mean $^{207}Pb/^{206}Pb$ age at 2945 ± 50 Ma (2σ; fig. 10). Grain 4 had a very high Th/U ratio of 1.04 from an interior spot (4_1). An analysis of grain 4 near the rim (4_2) yielded 2687 ± 31 Ma and a much smaller Th/U of 0.17. Grain 6 yielded a high Th/U from an interior spot, with an exterior analysis giving a distinctly younger age, though with large uncertainty and lower Th/U. Two other zircons (2 and 5) yielded the familiar 2524 ± 12 Ma age (fig. 9) with low Th/U (0.006–0.44) in both core and rim.

Discussion

Distinct correlations between the measured Th/U and $^{207}Pb/^{206}Pb$ ages for zircons sampled from the Chillapura quarries emerge from the present data, as shown in figure 11. The coarse-grained pegmatoidal samples (Ch Zr 3 and Ch Zr 4) give zircon Pb/Pb ages near 2530 Ma and, with one exception, have low Th/U ratios, whereas the zircons from banded granulites show two distinct trends:

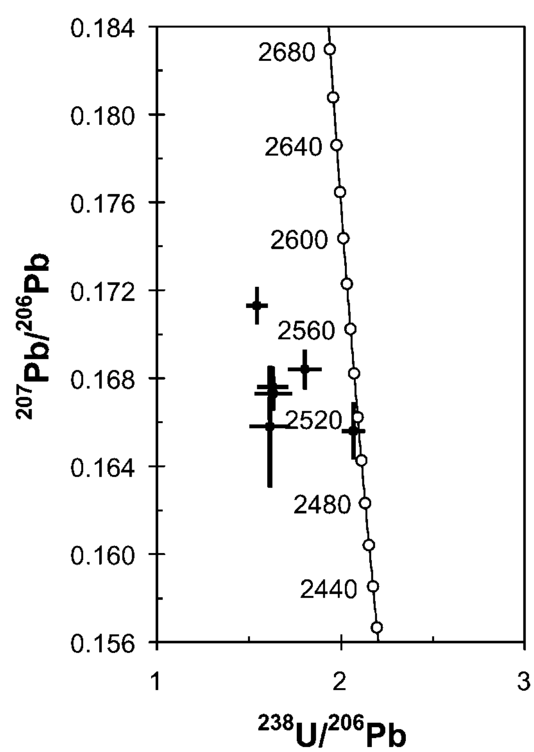

Figure 6. Tera-Wasserburg ($^{207}Pb/^{206}Pb$ vs. $^{238}U/^{206}Pb$) diagram for zircons extracted from sample Ch Zr 4. Data points are plotted as 1σ error crosses.

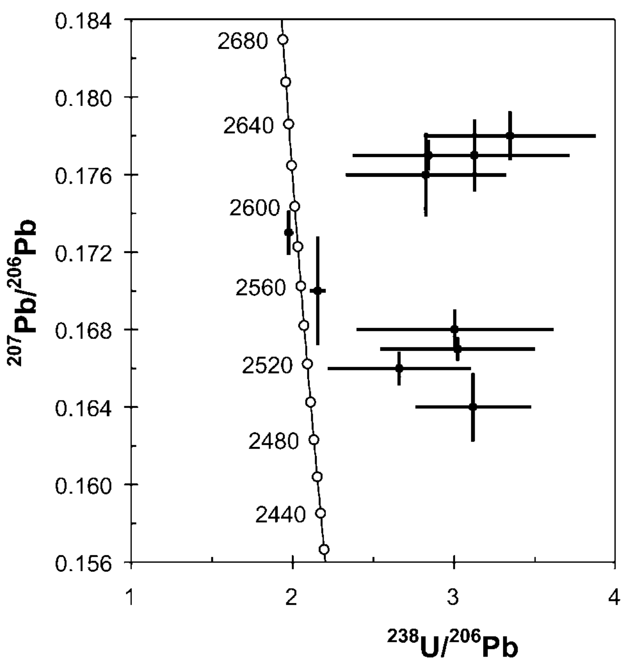

Figure 7. Tera-Wasserburg ($^{207}Pb/^{206}Pb$ vs. $^{238}U/^{206}Pb$) diagram for zircons extracted from sample Ch Zr 1. Data points are plotted as 1σ error crosses.

(1) a dominant age population near 2530 Ma with Th/U ratios varying from very low (down to 7×10^{-4}) to 0.6 and (2) a scattering of ages from 2970 Ma down to 2550 Ma with high Th/U ratios (1.0–0.1). The remarkable right-angle distribution in zircon $^{207}Pb/^{206}Pb$ age versus Th/U of figure 11 evidently bears on Th/U fractionation involved in different magmatic and/or metamorphic processes of crystallization of the zircons and their host granulites.

Zircon is recognized as the only magmatic phase in ordinary igneous rocks that could significantly fractionate Th from U (table 1); therefore, the crystallizing melt of the protolith to the Chillapura rocks would have probably maintained a Th/U ratio similar to the typical Th/U ratio of ~4 for TTG (Taylor and McLennan 1985) until zircon saturation. The predicted Th/U ratio for zircons crystallizing from a melt of $Th/U \approx 4$ and assuming $K^{liq/zir}_{Th/U} = 5$ ($\pm$ factor of 2; such that $2.5 \leq K^{liq/zir}_{Th/U} \leq 10$; Mahood and Hildreth 1983) can be used to discriminate between magmatic-derived zircons and those that crystallize from metamorphic fluids (Mojzsis and Harrison 2002). Figure 12 shows zircon saturation curves from Harrison and Watson (1983) of felsic to intermediate granitoid magmas, as functions of temperature and alkalinity index ($M = [Na + K + 2Ca]/[Al \times Si]$). At probable temperatures of magmatic crustal accretion (~950°C), the precursors to our granulite samples would have been substantially undersaturated in zircon and therefore would be very unlikely to have inherited zircons (e.g., from primordial amphibolite crust) but would have precipitated zircon only at near-solidus temperatures (800°–750°C), with zircon Th/U ratios near magmatic values of 0.8. From these considerations we infer that the present high Th/U zircons, which include all those of ages greater than 2620 Ma, probably date a primary crustal accretion event. The younger zircons with much lower Th/U reflect equilibrium with some medium other than primary granitoid magmas of the bulk compositions of the Chillapura granulites. A minority of younger zircons have Th/U in ranges that are interpretable if they were equilibrated with magmas of the bulk compositions of the rocks containing them. These relationships are diagrammed in figure 13, where $^{207}Pb/^{206}Pb$ age is correlated with Th/U and the range of predicted magmatic $[Th/U]_{zircon}$ based on the whole rock values reported in table 2.

During prograde metamorphism, Th/U ratio gen-

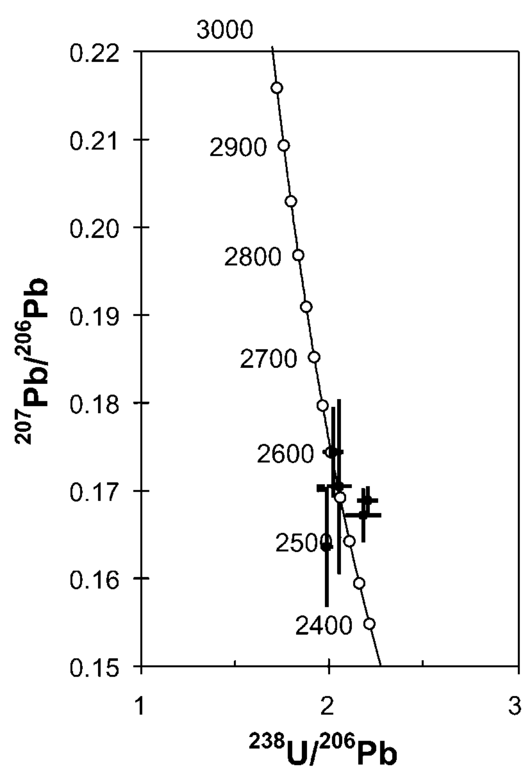

Figure 8. Tera-Wasserburg ($^{207}Pb/^{206}Pb$ vs. $^{238}U/^{206}Pb$) diagram for zircons extracted from sample Ch Zr 5. Data points are plotted as 1σ error crosses.

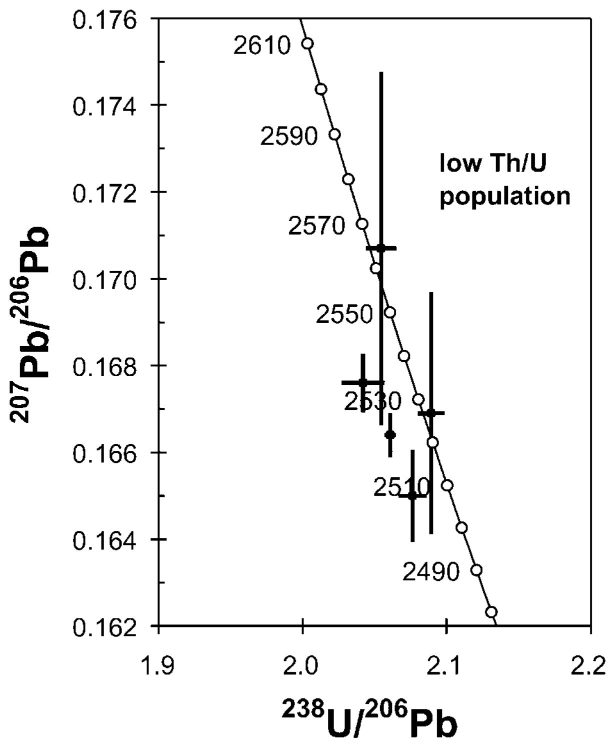

Figure 9. Tera-Wasserburg ($^{207}Pb/^{206}Pb$ vs. $^{238}U/^{206}Pb$) diagram for zircons extracted from the low Th/U population of zircons from sample Ch Zr 7 (table 3). Data points are plotted as 1σ error crosses.

erally increases in orthogneisses from an average of ~4 to as high as 50 (e.g., Janardhan et al. 1982). For the Chillapura rocks of this study, we notice that sample Ch Zr 7 has a Th/U ratio of ~18 (table 2). These differences in whole rock Th/U imply that U is preferentially leached relative to Th during the generation of metamorphic fluids and that those fluids are characterized by low Th/U (Mahood and Hildreth 1983; Nozhkin and Turkina 1995). Hence, the Th/U ratio of zircon formed by metamorphic fluids during granulite recrystallization could be lower (in some cases, substantially lower) than the magmatic value, explaining the decrease in two to three orders of magnitude in the younger zircons and zircon overgrowth populations of Ch Zr 1, Ch Zr 4, and Ch Zr 7 relative to core values.

Figure 13*A* shows that the population of zircons in the banded granulite Ch Zr 1, which record ages at 2622 ± 9 (2σ) Ma, have Th/U, which is compatible with crystallization from a melt of the host rock composition. The Th/U values are lower than those of the 2970 Ma zircons in sample Ch Zr 7 and probably record a distinct high-grade event involving migmatization. It is probable that this partial melting event was provoked by an influx of metamorphic fluids of high U/Th. The 2622 Ma event was overprinted at 2535 ± 8 Ma by a high-grade event that left a dominantly metamorphic Th/U signature, consonant with zircons in Ch Zr 3, and zircons of this age and Th/U signature are ubiquitous in all of our samples. The younger metamorphic age corresponds closely to the migmatization age at 2528 ± 5 (2σ) reported by Friend and Nutman (1992) from the southern Closepet Granite terrane.

The old zircons of Ch Zr 7, interpreted as dating the protolith accretion event, are contained in the granulite with the highest Th/U value, which almost certainly is a metamorphic depletion signature. No reason is apparent for this coincidence and nothing else seems extraordinary about the bulk composition or mineralogy. The preservation of some old zircons through the profound high-grade event at 2630 Ma probably results from quite variable exposure of the rocks to metamorphic fluids, with strong layer-parallel channelization and relatively small fluid/rock ratios. It is probable that a thorough search in the Chillapura quarries would turn up many more examples of older Archean zircons.

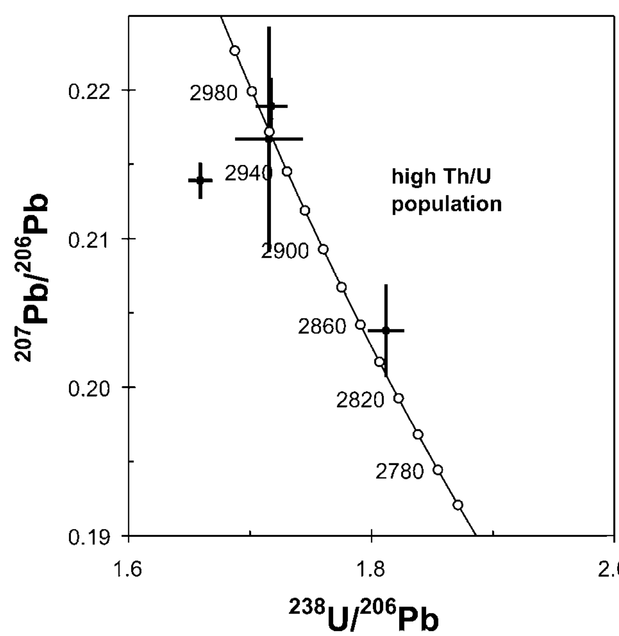

Figure 10. Tera-Wasserburg ($^{207}Pb/^{206}Pb$ vs. $^{238}U/^{206}Pb$) diagram for zircons extracted from the high Th/U population of zircons from sample Ch Zr 7 (table 3). Data points are plotted as 1σ error crosses.

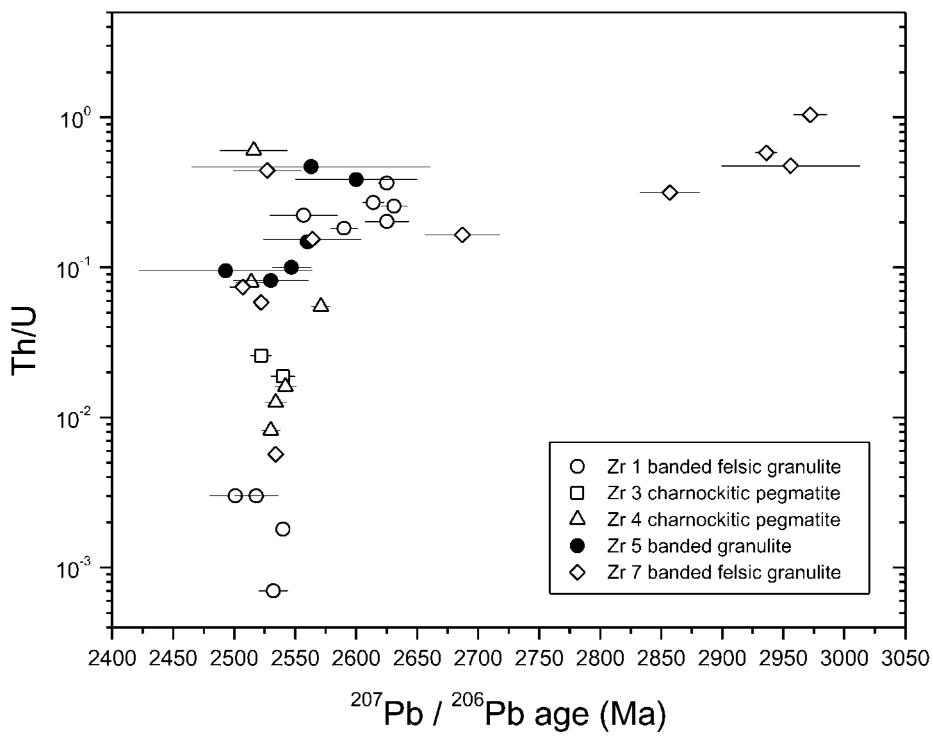

Figure 11. Compilation of $^{207}Pb/^{206}Pb$ ion microprobe ages from Chillapura zircons in this study. The zircon population at ~2.95 Ga, interpreted to be the magmatic age of sample Ch Zr 7, has uniformly high $[Th/U]_{zircon}$. Younger zircons generally exhibit a large range of Th/U values more characteristic of a metamorphic origin and correlated with previously recognized events at ~2.53 Ga as well as a whole rock Rb-Sr isochron of ~2.5 Ga (see table 3 for whole rock data for each of these samples).

Interpretations and Conclusions

The $^{207}Pb/^{206}Pb$ age and Th/U relations revealed by the present measurements are shown in figures 11 and 13. Two clear-cut conclusions can be drawn:

1. The orthopyroxene-bearing pegmatoidal segregations Ch Zr 3 and Ch Zr 4 show consistent $^{207}Pb/^{206}Pb$ ages of ~2530 Ma with low Th/U ratios. This age is identical to that revealed by zircons dating the migmatite formation at Kabbal in the amphibolite facies region at the southern end of the Closepet Granite (Friend and Nutman 1992). There is thus a firm temporal link between anatexis in the amphibolite facies and granulite facies portions of what appears to be a continuous section of Archean crust. The majority of the analyses from the banded granulites gave ages at 2510–2560 Ma with small errors and low Th/U. There is thus coherence with the whole rock Rb-Sr isochron from Chillapura of Hansen et al. (1997) of 2501 ± 54 Ma.

2. Cores of a few zircons from one sample, the felsic-intermediate granulite Ch Zr 7 from the Middle Quarry, gave a weighted mean $^{207}Pb/^{206}Pb$ age at 2945 ± 10 (2σ) Ma. These have high Th/U ratios in the range expected for magmatic zircons.

A few measurements fall between the age clusters of 2530 and 2950 Ma, but most of these have large uncertainties and are probably data overlap. A possible exception is the seemingly discrete cluster from one felsic granulite, Ch Zr 1, which showed ages near 2620 Ma, with small error. These have Th/U ratios in the range 0.29 ± 0.08. We interpret this age to represent migmatite zircon growth at ~2620 Ma in a discrete period of metamorphism.

Friend and Nutman (1992) classified zircons from rocks at Kabbal into three Th/U categories:

1. Old zircons, nearly concordant at 2.96 Ga, have Th/U close to 1.0. These were interpreted to represent crystallization from mantle-derived calc-alkaline magmas that congealed to form the primitive crust of southern Karnataka, that is, the precursor to the dominant gneiss country rock. Textures of the older zircons (cores with fine oscillatory zoning) indicated that they were preserved through younger metamorphism and anatexis.

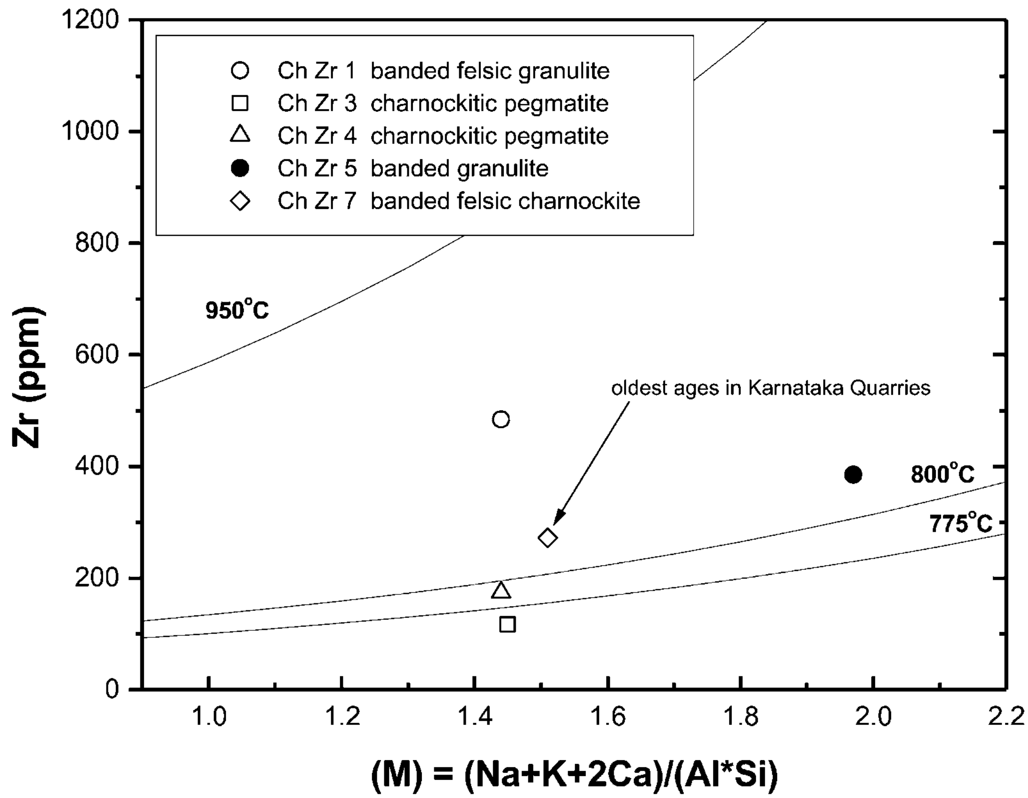

Figure 12. Zircon saturation curves (Harrison and Watson 1983) plotted for a source temperature of 950°C and lower temperatures (800°C, 775°C) at or near the freezing point of granitoid melts (Wyllie et al. 1997). At the source temperature of 950°C for granitoids, only Ch Zr 1 is not severely undersaturated in Zr ($M = 1.44$, $[Zr]_{wr} = 479$ ppm; table 2). It should be noted that these rocks are highly altered from their original granitoid compositions with respect to many trace elements (fig. 13), and the oldest zircon populations (from Ch Zr 7) are from rocks well below the melting temperature of tonalite-trondhjemite-granodiorite (TTG) compositions.

2. Younger zircons, 2.53 Ga, with intermediate Th/U values (0.2–0.4). These were interpreted as having equilibrated with an anatectic melt. The frozen melt is now represented by migmatite leucosomes.

3. Still slightly younger zircons (2.52 Ga) with low Th/U (0.04–0.08) showing clear overgrowth morphology or as small equant clear grains. These were believed to result from subsolidus metamorphic growth in the presence of an intergranular fluid.

Other authors (Williams and Claesson 1987) had previously ascribed low Th/U ratios in zircons to subsolidus growth from a metamorphic fluid. Additionally, zircons from the Kabbal incipient charnockites showed some corrosion features but no new growth or isotopic resetting.

Our zircons from Chillapura, 20 km south of Kabbal and entirely in the granulite facies, show definite parallel with the Kabbal zircon categories with slight variations. Our zircons from felsic granulites and coarse-grained mobilizates show Th/U ratios that indicate both subsolidus growth and anatectic characteristics according to the criteria of Friend and Nutman (1992). Our old zircon cores from one banded granulite are the age equivalent of their oldest zircons and also show the high Th/U values. We can conclude that virtually the same sequence of zircon-forming events transpired in the foliated charnockites of the Halaguru area as in the amphibolite facies terrane of the Kabbal area. The differences in petrologic characteristics of the two areas (granulite facies vs. amphibolite facies) are presumably the result of a somewhat deeper level of metamorphism in the former terrane; that metamorphism is terminal Archean in age. We can also infer that metamorphic fluids, with either a high affinity for U or relatively depleted in Th, were necessarily an important agency in both terranes. It seems reasonable to suppose

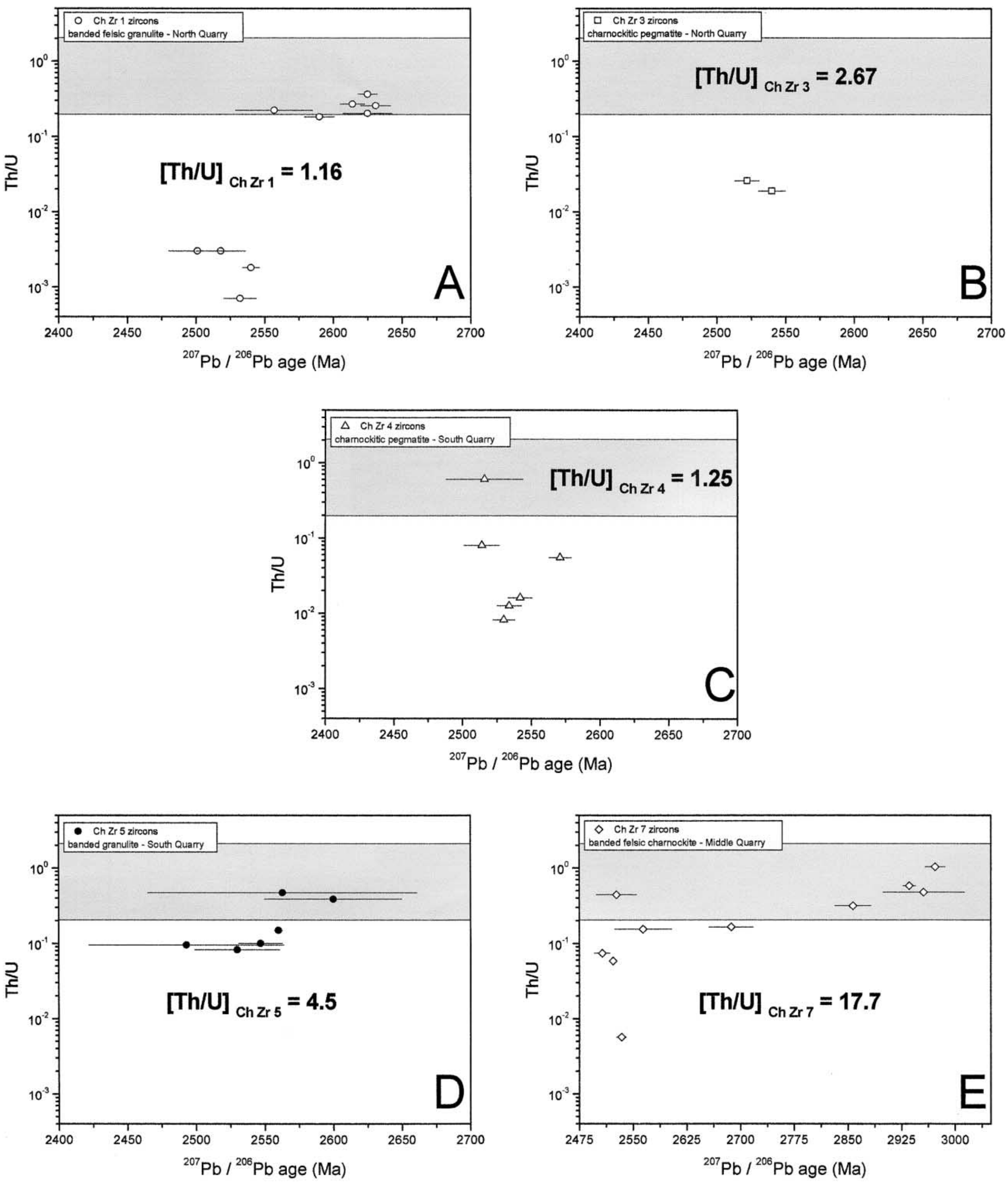

Figure 13. Individual $[Th/U]_{zircon}$ versus $^{207}Pb/^{206}Pb$ plots for zircons from Chillapura Quarries (Ch Zr 1, Ch Zr 3, Ch Zr 4, Ch Zr 5, Ch Zr 7). Note the general correlation between $[Th/U]_{zircon}$ increasing from $<10^{-2}$ to ~1 and increasing age in each case (see also fig. 11; table 3). Gray region in each diagram shows the predicted range of magmatic $[Th/U]_{zircon}$ values crystallizing from melt of typical granitoid $[Th/U]_{wr}$. Compare this magmatic [Th/U] field with the predicted $[Th/U]_{zircon}$ from table 2 assuming $K^{liq/zir}_{Th/U} \approx 5$ (Mojzsis and Harrison 2002). Banded felsic charnockite Ch Zr7 is a striking example of a rock that experienced enrichment in Th (table 2) during charnockitization; zircons therein appear to record magmatic [Th/U] (*gray region*) at greatest ages (~2925 Ma). Whole rock [Th/U] for each sample is indicated.

that influx of fluids from still deeper levels in the crust, either from metamorphic devolatilization reactions or from magmatic exhalations, may have provoked anatexis in both terranes, with development of orthopyroxene-bearing segregates at slightly deeper levels than at Kabbal because of slightly higher temperatures and pressures and lower H_2O activities. Infiltration of fluids with limited anatexis is the scenario advocated by Perchuk et al. (2000) to explain mineral and chemical zonation of incipient charnockites in Sri Lanka.

We find possible evidence in our zircon age versus Th/U systematics for a period of regional metamorphism somewhat older than the dominant 2.53 Ga event. This 2.62 Ga event could possibly correspond to the older charnockite relics revealed by the structural studies of Naha et al. (1993). The presence of 2.95 Ga zircon cores in the Chillapura rocks whose high Th/U ratios betoken a magmatic precursor is consonant with the interpretation of Hansen et al. (1997) that the 2.95 errorchron, which may be constructed from the Rb-Sr data from widely separated quarries in southern Karnataka, represents a major period of juvenile crust accretion at that time. The possibility remains that a much more extensive survey of zircons from the Halaguru and nearby granulite facies areas may turn up some zircons of older Archean ages with the low Th/U ratios indicative of metamorphic processes.

The role of fluids in the metamorphism of the amphibolite facies gneiss–Closepet Granite–charnockitic terrane of southern Karnataka, as well as in other comparable Precambrian high-grade terranes, deserves more study. The highly consistent 8-point Rb-Sr whole rock isochron from the Chillapura North Quarry found by Hansen et al. (1997) indicates that Sr isotopes were homogenized on a quarry scale (tens to hundreds of meters) by the metamorphic event at 2.5 Ga. This would be seemingly impossible in the absence of a very pervasive and interconnected fluid medium, as noted by Hansen et al. (1997). A rising fluid of the necessary low H_20 activity to form pyroxenes at the expense of the hydrates biotite and amphibole would have become increasingly richer in H_2O as it ascended. The transitional granulite facies horizon just north of Halaguru may represent the Late Archean crustal level where metamorphic fluids were becoming incapable of further breakdown of biotite and amphibole. Our results for the Chillapura zircons provide evidence for the continuity of fluid action, as well as temporal continuity, across the Late Archean amphibolite facies to granulite facies transition in southern India.

Our dominant 2530 Ma age of zircons from the granulite facies transition zone of the Western Dharwar Craton is synchronous with magmatic zircon ages of apparently juvenile crust in the Krishnagiri area 100 km to the east. The Late Archean TTG gneisses there show a metamorphic gradient culminating in the granulite facies, quite analogous to those of the present study, except for the absence of a large coeval granite body comparable to the Closepet Granite. The nearly synchronous crustal accretion and high-grade metamorphism in the Krishnagiri–Shevaroy Hills area led Peucat et al. (1989) to the concept of "synaccretion" granulite facies metamorphism.

It seems unlikely that the temporal coincidence of the crustal accretion event in the Eastern Dharwar Craton and the granulite facies metamorphism in the Western Dharwar Craton is merely accidental, but more likely that the latter event is an interior-craton response to marginal accretionary magmatism. The tectono-thermal mechanisms for the accretion-related deep-crustal metamorphism remain obscure. Our work does not reveal a comparable synaccretion metamorphic signature for crust formation at 2.95 Ga in the Western Dharwar, but this may merely signify that the 2.95 Ga gneiss precursors in the Satnur–Halagur area were initially emplaced at high crustal levels above a depth zone where crustal accretion may have been synchronous with, or followed very closely by, granulite facies metamorphism. The limited scope of the sampling in the present study is insufficient to either define or discredit synaccretion metamorphism.

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