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Proterozoic mountain building in Peninsular India: an analysis based primarily on alkaline rock distribution

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Abstract – Peninsular India was assembled into a continental block *c.* 3 million km^2 in area as a result of collisions throughout the length of a 4000 km long S-shaped mountain belt that was first recognized from the continuity of strike of highly deformed Proterozoic granulites and gneisses. More recently the recognition of a variety of tectonic indicators, including occurrences of ophiolitic slivers, Andean-margin type rocks, a collisional rift and a foreland basin, as well as many structural and isotopic age studies have helped to clarify the history of this Great Indian Proterozoic Fold Belt. We here complement those studies by considering the occurrence of deformed alkaline rocks and carbonatites (DARCs) in the Great Indian Proterozoic Fold Belt. One aim of this study is to test the recently published idea that DARCs result from the deformation of alkaline rocks and carbonatites (ARCs) originally intruded into intra-continental rifts and preserved on rifted continental margins. The suggestion is that ARCs from those margins are transformed into DARCs during continental, or arc–continental, collisions. If that idea is valid, DARCs lie on rifted continental margins and on coincident younger suture zones; they occur in places where ancient oceans have both opened and closed. Locating sutures within mountain belts has often proved difficult and has sometimes been controversial. If the new idea is valid, DARC distributions may help to reduce controversy. This paper concentrates on the Eastern Ghats Mobile Belt of Andhra Pradesh and Orissa, where alkaline rock occurrences are best known. Less complete information from Kerala, Tamil Nadu, Karnataka, West Bengal, Bihar and Rajasthan has enabled us to define a line of 47 unevenly distributed DARCs with individual outcrop lengths of between 30 m and 30 km that extends along the full 4000 km length of the Great Indian Proterozoic Fold Belt. Ocean opening along the rifted margins of the Archaean cratons of Peninsular India may have begun by *c.* 2.0 Ga and convergent plate margin phenomena have left records within the Great Indian Proterozoic Fold Belt and on the neighbouring cratons starting at *c.* 1.8 Ga. Final continental collisions were over by 0.55 Ga, perhaps having been completed at *c.* 0.75 Ga or at *c.* 1 Ga. Opening of an ocean at the Himalayan margin of India by *c.* 0.55 Ga removed an unknown length of the Great Indian Proterozoic Fold Belt. In the southernmost part of the Indian peninsula, a line of DARCs, interpreted here as marking a Great Indian Proterozoic Fold Belt suture, can be traced within the Southern Granulite Terrain almost to the Achankovil-Tenmala shear zone, which is interpreted as a strike-slip fault that also formed at *c.* 0.55 Ga.

Keywords: India, alkaline rocks, carbonatites, continental rifts, continental collisions, suture.

1. Introduction: looking at a great fold belt in a new way

Radhakrishna & Naqvi (1986, fig. 1) identified a 4000 km long S-shaped mountain belt that weaves its way across Peninsular India (Fig. 1). That Great Indian Proterozoic Fold Belt records the Proterozoic continental and arc-system collisions that assembled India during a long history of deformation with discrete episodes that have yielded a wide range of isotopic and tectonically inferred ages between *c.* 2.0 Ga and *c.* 0.55 Ga (e.g. Chetty & Murthy, 1994; Şengör & Natalin, 1996; Roy & Kataria, 1999; Ramakrishnan, Nanda & Augustine, 1998; Srikantia, 1999; Gopalakrishnan, Subramanian & Upendran, 2001; Dobmeier & Raith, 2003), although the idea of a role for continental and arc collisions in the formation of the belt has not been fully or universally accepted (e.g. Mahadevan, 1999; Roy & Kataria, 1999). For those who accept the idea of collision, questions remain about such topics as: When and where did rifted continental margins to the Dharwar, Bhandara (Bastar), Singhbum and Bundelkhand cratons initially form? What was the role of arc-systems during continental margin evolution? Can an Altaid style of evolution (Şengör & Natalin, 1996) be discerned within the belt? Did objects of continental dimensions collide with craton margins more than once during the evolution

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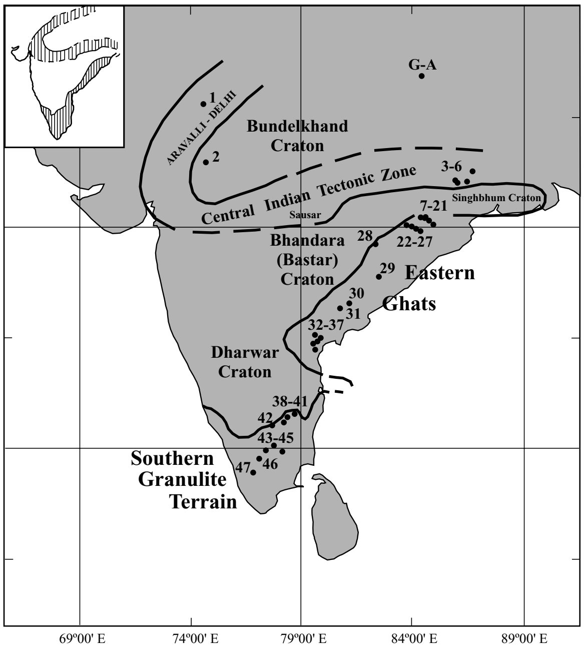

Figure 1. Deformed alkaline rocks and carbonatites (DARCs) in the Great Indian Proterozoic Fold Belt. Forty-seven DARCs are known from within the 4000 km long mountain belt (inset). Great Indian Proterozoic Fold Belt boundaries shown by heavy and dashed lines and numbers of DARCs correspond with those of Table 1. G-A is the Gorkha-Ampipal Proterozoic DARC of Nepal which appears unrelated to the Great Indian Proterozoic Fold Belt. No comparable concentration of DARCs has yet been recognized in any of the world's other mountain belts. DARCs indicate the locations of intra-continental rifts that became rifted continental margins and on which sutures have later formed during continental collision (see Fig. 2). The line of DARCs in this figure defines the approximate location of a suture zone that formed on the site of rifted continental margins of India's Archaean Cratons. The suture zone extends for the length of the Great Indian Proterozoic Fold Belt.

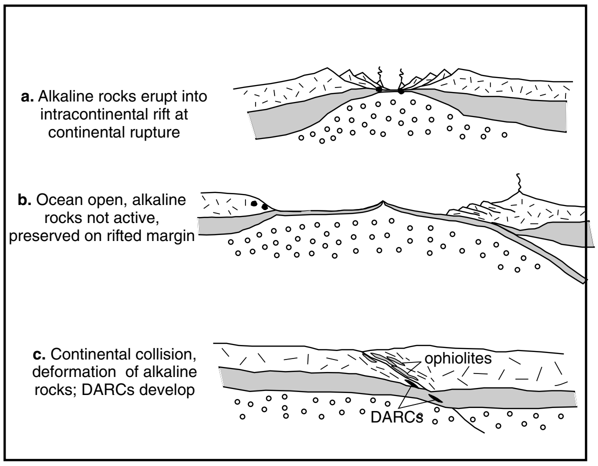

Figure 2. Sketch illustrating the origin of DARCs by the deformation of ARCs at continental collision. Alkaline rocks and carbonatites (ARCs, black dots in a) erupt into an intra-continental rift while that rift is extending. In (b) the ARCs are shown (black dots) as inactive but preserved at a rifted continental margin. When a continental collision occurs (c) the ARCs (shown as black lenses) are deformed and become DARCs. Gneissic DARCs, recording both the rifting and the collisional parts of the Wilson cycle of ocean opening and ocean closing, define suture zones in the Great Indian Proterozoic Fold Belt as they do in other mountain belts. All the complexities that develop during intervals such as that represented by the middle sketch (b) and of which there is clear evidence in the Great Indian Proterozoic Fold Belt have been omitted.

of the belt? What collisional events are recorded, particularly in the well-studied Eastern Ghats, for times before the final assembly of Gondwana? What was the time of that final collision? Did the final collisional phase involve only the East Antarctic continent or did it also involve other continents or arc systems? In an attempt to contribute to the resolution of some of these questions we focus on the distribution and significance of alkaline and carbonatitic rocks (ARCs) in the Great Indian Proterozoic Fold Belt. All of those ARCs have been deformed and have become DARCs (Burke, Ashwal & Webb, 2003). Our analysis concentrates on the Eastern Ghats Mobile Belt in Andhra Pradesh and Orissa where alkaline igneous and metamorphosed rocks are best known (Leelanandam, 1989*a*, 1998; Mazumder, Rao & Nathan, 2000). Treatment of the full length of the Great Indian Proterozoic Fold Belt from Kerala and Tamil Nadu to the Himalaya is necessarily less complete (Fig. 1).

In a recent study (Burke, Ashwal & Webb, 2003) based on the analysis of a comprehensive catalogue of the alkaline rocks of Africa (Woolley, 2001), the familiar association of alkaline rocks and carbonatites (ARCs) with intra-continental rifts and their consequent common occurrence at rifted continental margins has been confirmed. A less-expected result of that analysis was that *c.* 90% (28 out of 32) of the catalogued Deformed Alkaline Rocks and Carbonatites (DARCs) of Africa lie on Proterozoic suture zones (Burke, Ashwal & Webb, 2003). The remaining four occurrences in Africa lie on a line that may also be a suture zone (Tack *et al.* 1994). The suggested explanation for the coincidence of DARCs with suture zones is that alkaline rocks initially emplaced into intra-continental rifts and later preserved at rifted continental margins become deformed when involved in collisions between continents or between arcs and continents (Fig. 2).

Alkaline rocks when originally emplaced are characteristically without internal structure, although some carbonatites intruded at shallow depths display sub-volcanic structures such as cone-sheets. The occurrence of metamorphic structure in nepheline syenites and carbonatites may, therefore, be considered evidence of their involvement in the intense convergence that is associated with the establishment of suture zones. If the Burke, Ashwal & Webb (2003) explanation of the origin of DARCs is correct, and so far it has only been tested in Africa where it works very well (Burke, Ashwal & Webb, 2003; Gerber *et al.* 2004), then an

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additional way of recognizing the sites of collisions, and especially continental collisions, will have become available. Here we: (1) use the Eastern Ghats Mobile Belt as a test area to see whether the idea of DARCs being localized along both ancient rifted continental margins and suture zones that have later formed on those margins appears viable on the basis of evidence from India, and (2) apply the findings in the Eastern Ghats Mobile Belt to DARC distribution in the full length of the Great Indian Proterozoic Fold Belt.

2. DARCs in the Eastern Ghats Mobile Belt

About 60 alkaline rock complexes, including lamprophyric and carbonatitic complexes, have been recognized in southern and eastern India (Mazumder, Rao & Nathan, 2000, figs 1, 2). We confine our consideration to nepheline syenites and carbonatites because only those rock-types are recognized to be strongly associated, when initially erupted, with intra-continental rifts (Woolley, 2001).

2.a. DARCs of the Eastern Ghats Mobile Belt: 15 to 20° N

Nine nepheline syenite and carbonatite bodies within this part of the Eastern Ghats Mobile Belt define a discontinuous NE-trending array nearly 500 km long (Figs 1, 3; Table 1; Leelanandam, 1989*a*, 1993, 1998; Mazumder, Rao & Nathan, 2000). The bodies, all of which are DARCs, lie on or close to the Sileru shear zone (Figs 3, 4; Mazumder, Rao & Nathan, 2000, fig 5). Ramakrishnan, Nanda & Augustine (1998) identified that shear zone as separating a Western Charnockite Zone from the rest of the Eastern Ghats Mobile Belt (Fig 4). We interpret the Western Charnockite Zone to be composed of up-thrust deep-seated Archaean rocks of the Bhandara (Bastar) craton that were caught up and reactivated during one or more of the several convergent plate boundary events that affected the Eastern Ghats Mobile Belt between *c.* 1.8 Ga and *c.* 0.55 Ga (cf. Bhadra, Gupta & Banerjee, 2004). We similarly interpret the Jeypore Province and those parts of the Krishna Province of Dobmeier & Raith (2003, table 1) to the west of the Sileru shear zone as corresponding to the Western Charnockite Zone and, similarly, to be composed of up-thrust and reactivated Bhandara craton rocks. In a continental-collision interpretation, the Western Charnockite Zone represents a part of the rifted margin of the Bhandara (Bastar) craton that became involved in convergent plate-margin tectonics at one or more times between initial ocean formation and final continental collision in the Eastern Ghats Mobile Belt. A granulite facies transition zone marking the Eastern Ghats Front (Ramakrishnan, Nanda & Augustine, 1998, p. 1) bounds the Western Charnockite Zone to the west and the Sileru shear zone marks its boundary in the east. The Sileru shear zone with its coincident line of nepheline syenites and carbonatites (Figs 1, 3, 4) is interpreted, because of its concentration of DARCs, to mark the position of the rifted margin of an ancient continent of which the Bhandara craton forms a part. The Sileru shear zone marks not only that rifted margin but also a suture zone that later formed on the rifted margin as a result of arc or continental collision.

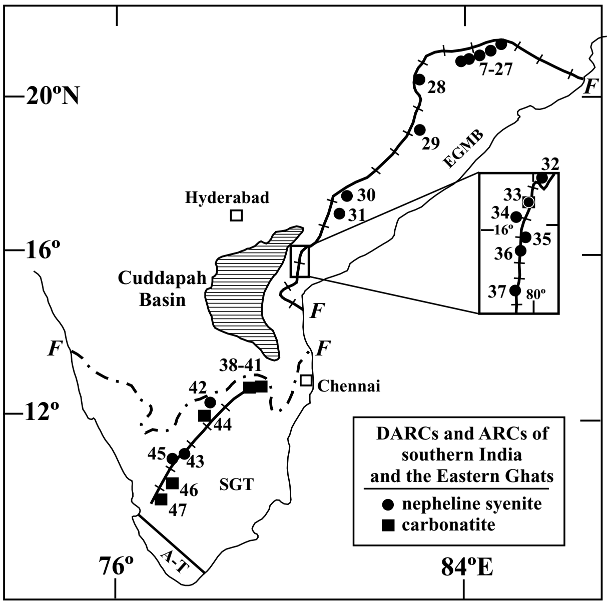

Figure 3. DARC (deformed alkaline rock and carbonatite) occurrences in southern India and the Eastern Ghats. All DARC occurrences in the Eastern Ghats Mobile Belt crop out within 30 km of a suture zone (hatched line). Fermor's line (F–F) coincides with that suture zone in the Eastern Ghats, but in southern India Fermor's line (dashes and dots), which forms the boundary of the Southern Granulite Terrain, is not a suture zone. The ten DARCs of southern India, which crop out within the Southern Granulite Terrain lie along a newly postulated suture zone. The position of the Achankovil-Tenmala shear zone (A-T) is indicated. Numbers of DARCs are those of Table 1. Map modified from Figure 1 of Leelananadam (1989*a*). The inset shows the DARCs of the Prakasam Alkaline Province (Leelanandam, 1989*b*).

Gneissic structures have been well described from nepheline syenites of the Prakasam Alkaline Rock Province (Leelanandam, 1989*b*; nos 32–37 in Fig. 1 and Table 1, inset to Fig. 3) that lie on or close to the Sileru shear zone at Elchuru (Leelanandam, 1989*b*; Cyzgan & Goldenberg, 1989), Purimetla (Ratnakar & Leelanandam, 1989), Settupalle and Uppalapadu (Leelanandam & Krishna Reddy, 1981; Cyzgan & Goldenberg, 1989). At Elchuru (Fig. 5), Leelanandam (1989*b*) has shown: (1) that the gneissic structure and the boundaries of the nepheline syenite are concordant with the foliation of the surrounding granodiorite gneiss and (2) that the foliation is more intense in the outer subsolvus part of the body. The inner part of the Elchuru body, consisting of hypersolvus nepheline syenite gneiss, is less intensely deformed. Leelanandam's work at Elchuru shows that individual outcrops and relatively small areas within DARC

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Table 1. Occurrences of deformed alkaline rocks and carbonatites (DARCs) in India

	Locality	Rock type(s)	Province	Latitude °N	Longitude °E	Key reference
1	Kishangar	Neph. gneiss	Rajasthan	26° 35′	74° 53′	Srivastava (1989); Roy & Dutt (1995)
2	Newania	Carbonatite	Rajasthan	24° 40′	74° 00′	Srivastava (1989)
3	Beldih	Neph. gneiss	W. Bengal	23° 01′	86° 15′	Mazumder (1978)
4	Sushina	Neph. gneiss	W. Bengal	22° 57′	86° 37′	Battacharyya & Chaudari (1986)
5	Kushunda	Neph. gneiss	W. Bengal	23° 33′	86° 53′	Mazumder (1978)
6	Santuri	Neph. gneiss	W. Bengal	23° 33′	86° 45′	Bhaumik, Mukherjee & Basu (1990)
7	Baradangua	Neph. gneiss	Orissa	21° 04′	85° 05′	Leelanandam (1989*a*)
8	Kankarakhol	Neph. gneiss	Orissa	21° 20′	84° 42′	Rath, Sahoo & Satpathy (1998)
9	Durhukajharan					
10	Chhalak	*Twelve*				
11	Hinduja nala	*named*				
12	Dalak	*DARC*				
13	Kapagola	*occurrences*				
14	Sadhubahali	*between*				
15	Khandadhuan	*Kankarakhol*				
16	Rairatanpur	*and*				Rath, Sahoo & Satpathy (1998)
17	Polpani	*Lodhajari*				
18	Chingrijharan					Mazumder, Rao & Nathan (2000)
19	Burbura					
20	Lulang					
21	Lodhajari	Neph. gneiss	Orissa	21° 12′	84° 57′	Rath, Sahoo & Satpathy (1998)
22	Rairakhol	Neph. gneiss	Orissa	21° 04′	84° 20′	Panda *et al.* (1993)
23	Kharsali	Neph. gneiss	Orissa	21° 03′	84° 24′	Mazumder, Rao & Nathan (2000)
24	Kusarimunda	Neph. gneiss	Orissa	21° 04′	84° 16′	Mazumder, Rao & Nathan (2000)
25	Gungijhara	Neph. gneiss	Orissa	21° 05′	84° 17′	Mazumder, Rao & Nathan (2000)
26	Rasibida	Neph. gneiss	Orissa	21° 07′	84° 12′	Mazumder, Rao & Nathan (2000)
27	Machibahal	Neph. gneiss	Orissa	21° 10′	84° 09′	Mazumder, Rao & Nathan (2000)
28	Khariar	Neph. gneiss	Orissa	20° 20′	82° 38′	Mahadevan (1999)
29	Koraput	Neph. gneiss	Orissa	18° 49′	82° 43′	Bose (1970); Sarkar *et al.* (1989)
30	Kunduluru	Neph. gneiss	Andhra Pradesh	17° 40′	81° 24′	Leelanandam (1989*b*)
31	Kunavaram	Neph. gneiss	Andhra Pradesh	17° 20′	81° 10′	Ratnakar & Leenanandam (1989); Clark & Subbarao (1971)
32	Kotappa Konda	Neph. gneiss	Andhra Pradesh	16° 08′	80° 02′	Ratnakar & Leenanandam (1989)
33	Elchuru	Nep. gn./Carb.	Andhra Pradesh	16° 06′	79° 56′	Ratnakar & Leenanandam (1989); Subba Rao *et al.* (1989)
34	Settupale	Neph. gneiss	Andhra Pradesh	16° 01′	79° 52′	Ratnakar & Leenanandam (1989)
35	Pasupugallu	Neph. gneiss	Andhra Pradesh	15° 44′	79° 46′	Ratnakar & Leenanandam (1989)
36	Purimetla	Neph. gneiss	Andhra Pradesh	15° 35′	79° 51′	Ratnakar & Leenanandam (1989)
37	Uppalpadu	Neph. gneiss	Andhra Pradesh	15° 35′	79° 46′	Leelanandam & Krishna Reddy (1981)
38	Elagiri	Nep. gn.?/Carb.	Tamil Nadu	12° 31′	78° 35′	Mazumder, Rao & Nathan (2000)
39	Koratti/Sevattur	Nep. gn.?/Carb.	Tamil Nadu	12° 25′	78° 31′	Mazumder, Rao & Nathan (2000); Anil Kumar & Gopalan (1991)
40	Samalpatti	Nep. gn.?/Carb.	Tamil Nadu	12° 20′	78° 22′	Mazumder, Rao & Nathan (2000)
41	Pikkili	Neph. gneiss	Tamil Nadu	12° 09′	78° 00′	Mazumder, Rao & Nathan (2000)
42	Hogenakal	Carbonatite	Tamil Nadu	12° 07′	77° 45′	Srinivasan (1977)
43	Ariyalur	Carbonatite	Tamil Nadu	11° 05′	78° 50′	Grady (1971)
44	Pakkanadu	Carbonatite	Tamil Nadu	11° 40′	77° 50′	Mazumder, Rao & Nathan (2000)
45	Sivamalai	Neph. Gneiss	Tamil Nadu	11° 03′	77° 36′	Mazumder, Rao & Nathan (2000)
46	Kambammettu	Carbonatite	Tamil Nadu	09° 44′	77° 44′	Mazumder, Rao & Nathan (2000)
47	Munnar	Carbonatite	Tamil Nadu	10° 02′	77° 03′	Santosh *et al.* (2003)

bodies may show little sign of deformation. Detailed mapping is in many cases needed before a body can be identified with confidence as a DARC. Mazumder, Rao & Nathan (2000) reported observations similar to those made at Elchuru by Leelanandam (1989*b*) from other complexes within the Eastern Ghats Mobile Belt and commented, in their discussion of the nepheline syenite bodies of that belt, that '. . . . . every one of these bodies is foliated and concordant . . . .' (Mazumder, Rao & Nathan, 2000, p. 104).

We conclude on the basis of published studies and of unpublished field observations (by C.L.) that: (1) gneissic structures concordant with those in the surrounding country rocks are universal among the nepheline syenites of the Eastern Ghats Mobile Belt and (2) all are therefore DARCs and (3) these DARCs lie within a suture zone that is close to the Sileru shear zone and to the shear zone's along-strike extensions to the north and the south.

2.b. DARCs of the Eastern Ghats Mobile Belt north and east of 20° N, 83° E

Craton border structure in the Eastern Ghats Mobile Belt north and east of 20° N, 83° E differs from that further south (Figs 1, 3). In that region Ramakrishnan, Nanda & Augustine (1998, fig. 2) identified the Western Charnockite Zone and the adjoining zone transitional to the craton only in a relatively small area at *c.* 21° N, 83° E. Along the rest of the 250 km long border of

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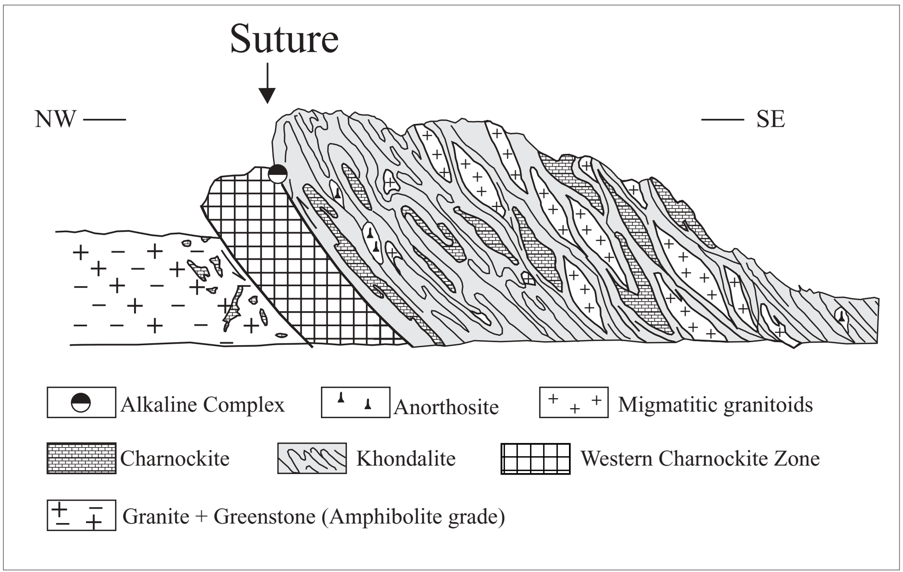

Figure 4. Cross-section of the Eastern Ghats Mobile Belt at about 17° N, modified slightly from Ramakrishnan, Nanda & Augustine (1998, fig. 6). The alkaline complex shown beneath the word 'Suture' marks the position of the Prakasam Province DARCs (nos 32–37), which lie close to the Sileru shear zone (Mazumder, Rao & Nathan, 2000) and the edge of the Western Charnockite Zone of the Eastern Ghats Mobile Belt. The rocks of the Western Charnockite Zone are formed from the deep crust of the Bhandara craton reactivated and thrust to the northwest during convergent events. The alkaline rocks of the Eastern Ghats were erupted into an intracontinental rift, came to occupy a rifted continental margin, and were finally caught up in a collision at which time they developed their gneissic structure. Anorthosites that are concentrated close to the suture zone on which the DARCs are localized may represent parts of the roots of Andean-type volcanoes. The section is generalized. For example, it does not show such features as the occurrence of amphibolite facies rocks within the region of charnockite, khondalite and anorthosite southeast of the suture zone.

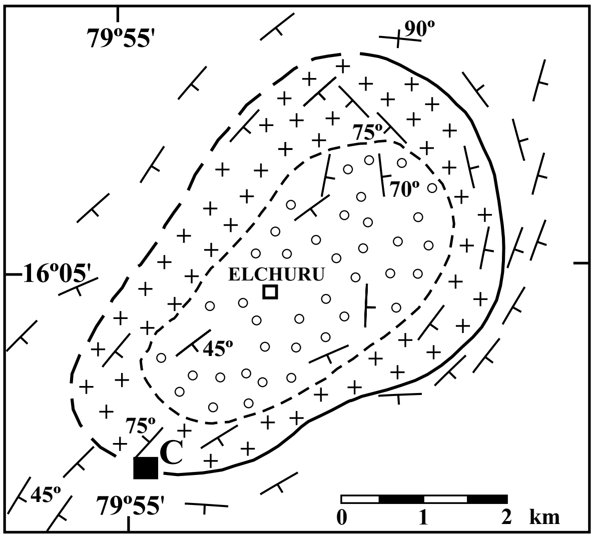

Figure 5. Structure of the Elchuru DARC, simplified from Leelanandam (1989*b*, fig. 3). A relatively unstructured hypersolvus nepheline syenite gneiss (open circles) lies within a subsolvus nepheline syenite gneiss (crosses) that is itself surrounded by concordant granodioritic gneiss (unornamented). Planar structure symbols without numbers indicate the inclination of gneissic layering with dips of between 50° and 70°. Less abundant gentler and steeper dips are labelled. The black square (C) marks the location of a carbonatite dyke. Elchuru is considered to have been erupted as an ARC into an intracontinental rift and to have been later involved in a continental collision that generated gneissic structure turning Elchuru from an ARC into a DARC.

the Eastern Ghats Mobile Belt on either side of that area, the garnet–sillimanite–gneiss-bearing Western Khondalite Zone of this belt is directly juxtaposed against the Bhandara and Singhbhum cratons. This juxtaposition we attribute to removal of both the Western Charnockite Zone and the granulite facies transition zone by intense tectonism at, before, or after the time of continental collision. Intense tectonism in the area was emphasized by Bhattacharyya (1997), who postulated oblique collision from structural evidence for the existence of a transpressional regime. The area of the Eastern Ghats Mobile Belt border east of 84° E was interpreted as showing great tectonic complexity by Crowe, Cosca & Harris (2001), who considered that a *c.* 100 km by *c.* 200 km area occupying the northern boundary of this belt east of 84° E was dominated, at least during its later history, by strike-slip faulting (see the mapped fault patterns in Crowe, Cosca & Harris, 2001, fig. 1 and Dobmeier & Raith, 2003, fig. 3). $^{40}Ar/^{39}Ar$ isotopic ages from that area record a range of ages with peaks at *c.* 750 Ma and 550–500 Ma subsequent to a dominant 1100–950 Ma metamorphism. Both the later events have been associated with movement on major ESE-trending shear zones and with fluid flow within these shear zones (Crowe, Cosca & Harris, 2001). The occurrence within this region of discrete blocks that have yielded Archaean ages (Crowe, Cosca & Harris, 2001) indicates that, as is the case in the Western Charnockite Zone, rocks from

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the neighbouring craton, in this case the Singhbhum craton, have been caught up during the evolution of the Eastern Ghats Mobile Belt.

The nepheline gneisses of Khariar (Fig. 3; Table 1; Fig. 1, no. 28) crop out within the part of the Eastern Ghats Mobile Belt that suffered intense NW–SE collisional tectonism but was not involved in the later ESE-trending strike-slip dominated movements. Discontinuous outcrops of the Khariar nepheline gneisses strike N–S over a distance of *c.* 30 km (Fig. 3; Table 1; Mazumder, Rao & Nathan, 2000, figs 3, 4; Dobmeier & Raith, 2003, fig. 3), and occupy the contact between Archaean rocks of the Bhandara (Bastar) craton and the Western Khondalite Zone of the Eastern Ghats Mobile Belt. We interpret the Khariar DARCs as occupying a suture zone that we extend along strike to join the Sileru shear zone suture (Fig. 3). In terms of the model of Burke, Ashwal & Webb (2003) and Figure 2, the Khariar rocks record (a) initial eruption into an intra-continental rift established within the Bhandara (Bastar) craton, (b) subsequent formation of a rifted continental margin to that craton and (c) suturing during a collisional event in the course of Eastern Ghats Mobile Belt evolution.

Twenty DARCs (nos 8–27 in Fig. 1 and Table 1) have been mapped in the ESE-trending strike-slip dominated area of the northeastern Eastern Ghats Mobile Belt (east of 84° E). These nepheline gneiss occurrences are distributed *c.* 100 km to the west of the Barandagua body (Fig. 3; no. 7 in Fig. 1 and Table 1). Occurrences forming the Kankarakhol-Lodhajari complex of Rath, Sahoo & Satpathy (1998; nos 8–21 of Fig. 1 and Table 1) occupy a *c.* 30 km long line close to one of the main strike-slip faults of the region (Mazumder, Rao & Nathan, 2000, fig. 2; Dobmeier & Raith, 2003, fig. 3). Six more bodies (nos 22–27 of Fig. 1 and Table 1) lie about 40 km to the southwest and near to an ENE-trending left-lateral strike-slip fault. Before movement on that fault, DARCs 8 to 27 are suggested to have cropped out in a single line. The area marginal to the Eastern Ghats Mobile Belt east of 84° E has a long and complex geological history (Dobmeier & Raith, 2003, p. 152), including evidence, in what we suggest to be a fragment of the Singhbhum Craton, of extensive magmatic activity as far back as 2.8 Ga (Crowe, Cosca & Harris, 2001). Recognition of a rifted margin and sutured boundary marked by nepheline gneiss DARCs in the northeastern parts of the Eastern Ghats Mobile Belt may help in local testing of the model of Figure 2 and in clarification of the regional structure.

3. An Eastern Ghats Mobile Belt suture: ophiolitic slivers, a gravity anomaly, Fermor's line and calcic anorthosites

The linear distribution of DARCs in the Eastern Ghats (Figs 1, 3) is consistent with the model (Fig. 2) of

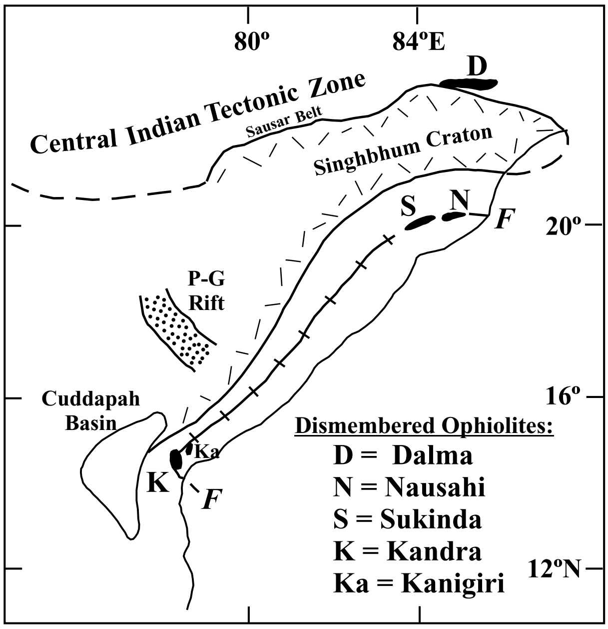

Figure 6. Sketch map of eastern India showing rocks considered to represent fragments of dismembered ophiolites (black lenses). Suture zones along craton margins have been independently identified in this paper from their association with DARCs. Dismembered ophiolites have been recognized at Dalma (Yellur, 1977; Gupta; Basu & Ghosh, 1980; Sarkar, 1982; Chakraboti & Bose, 1985), Nausahi and Sukinda (Page *et al.* 1985; Leelanandam, 1990) and Kandra and Kanigiri (Leelanandam, 1990; Nagaraj Rao, Katti & Roop Kumar, 1991). P-G Rift – Pranhita-Godavari rift; F–F – Fermor's line.

gneissification of alkaline rocks during continental collision, but there is other evidence from the vicinity of that line indicating that it marks a suture zone. Previous investigators have identified the suture zone on the basis of: (1) outcrops of ophiolitic slivers, (2) a paired gravity anomaly and (3) the location of 'Fermor's line'. We add to those suture recognition criteria (4) the proximity of highly calcic anorthosite bodies to the postulated suture.

3.a. Dismembered ophiolites in the Eastern Ghats Mobile Belt

Leelanandam (1990) and Nagaraj Rao, Katti & Roop Kumar (1991) identified a possible suture and collision site when they showed that the Kandra metamorphosed mafic and ultramafic rocks of Andhra Pradesh (Fig. 6) and nearby rocks at Kanigiri (15° 25′ N, 79° 30′ E, Fig. 6) represent dismembered ophiolitic fragments. The 40 km long outcrop of the Kandra rocks exposes amphibolitic metabasalts that locally show relict pillow structures and are partly spilitic. Metacherts are associated with the metavolcanic rocks, metagabbroic units show cumulate textures, spinifex textures have been recognized and ultramafic slivers, now consisting of talc-chlorite schists, complete the picture of a dismembered ophiolite. Rocks similar to the Kandra rocks crop out sporadically for at least 50 km along strike to the north–northeast of the Kandra occurrences. The Inukurti anorthosite (Narsimha Reddy *et al.* 2003), which crops out within *c.* 20 km of the Kandra rocks, is an occurrence of high-calcic anorthosite of the type recognized elsewhere to characterize fragments of older Precambrian ocean floor (Ashwal, 1993, pp. 5–81). The occurrence of the Inukurti anorthosites within 'voluminous amphibolites' (meta-basalts) (Dobmeier & Raith, 2003, p. 153) is consistent with that idea. Mukhopadyay, Ray & Guha (1994) used geochemical data to suggest that amphibolites in this area represent rocks formed in a back-arc environment, and Hari Prasad *et al.* (2000) interpreted other geochemical data as indicating the juxtaposition of rocks from an oceanic island arc with those of a continental margin arc. These interpretations are both compatible with occurrence of the rocks in proximity to a suture zone.

Near the northeastern margin of the Eastern Ghats Mobile Belt, ultramafic rocks that have been suggested to be fragments of dismembered ophiolite have been described from Sukinda and Nausahi (Fig. 6) (Page *et al.* 1985). These rocks lie on the Sukinda thrust that Ramakrishnan, Nanda & Augustine (1998, p. 15) mapped as the northern contact of the Eastern Ghats Mobile Belt with the Singhbhum Craton, and Dobmeier & Raith (2003) considered to be the southern margin of one of their Eastern Ghats Mobile Belt provinces. The outcrops are near to a major ESE-trending strike-slip fault (Dobmeier & Raith, 2003, fig. 3). The general location of the suture zone in this region can be defined, on the basis of DARC and dismembered ophiolite distribution, as occupying a roughly E–W-trending zone around 21° N that extends eastward from 83° E to the unconformity beneath Phanerozic rocks (Fig. 1).

3.b. Calcic anorthosite bodies in the Eastern Ghats Mobile Belt: possible Andean arc roots

Ashwal (1993, pp. 288–92) suggested that anorthosites with highly calcic plagioclase (> 90 % An) and associated rocks might have formed deep beneath Andean Arcs. Occurrences of such calcic anorthosites in the Eastern Ghats Mobile Belt lie to the east of the Western Charnockite Zone and close to the suture zone postulated on the basis of DARC distribution (Fig. 4). Other rocks in the region include charnockites, enderbites and a variety of granodiorites and granites that may also have formed at various depths beneath Andean arc volcanoes. Dobmeier & Raith (2003, p. 156) suggested that one body, the Chanduluru composite pluton of Nagasai Sharma & Ratnakar (2000), has 'chemical characteristics [that] point to emplacement in an Andean-type arc'.

3.c. Bouguer gravity anomalies of the Eastern Ghats Mobile Belt

Paired Bouguer gravity anomalies, negative over the craton and positive over the adjacent mobile belt with a transition close to the intervening suture zone, were recognized as characteristic features of Precambrian collisional mountain belts (Gibb & Thomas, 1976). A paired Bouguer anomaly signature has long been recognized in the Eastern Ghats Mobile Belt (e.g. Subrahmanyam & Verma, 1986; Singh & Mishra, 2002). On the basis of the location of the transition between positive and negative Bouguer anomalies, which globally has been recognized to have a typical horizontal spatial resolution of a few tens of kilometres, the location of the suture zone from the gravity signature matches that defined on the basis of the distribution of DARCs, calcic anorthosites and dismembered ophiolitic slivers.

3.d. Fermor's line in the Eastern Ghats Mobile Belt

Fermor (1936) drew a line on a regional map that bounded charnockite occurrences; this soon came to be known as 'Fermor's line' (Figs 1, 3; Ramakrishnan, Nanda & Augustine, 1998, pp. 2–5). The line consists of two very different parts: a NE-trending part within the Eastern Ghats Mobile Belt that lies roughly parallel to the coast, and a more irregular, roughly E–W-trending part further south that crosses the entire southern Indian peninsula. In drawing his line within the Eastern Ghats Mobile Belt, Fermor did not consider the charnockites of the Western Charnockite Zone. In Figure 3 we have drawn Fermor's line in the position depicted in Leelanandam (1998). Putting the line in that position places it close to the line of DARCs, the Sileru shear zone, a concentration of calcic anorthosites, the line of ophiolitic slivers and the change in sign of the Bouguer gravity anomaly, all of which we have interpreted to indicate the approximate position of a suture zone. Leelanandam (1990) pointed out that all the occurrences of DARCs within the Eastern Ghats Mobile Belt lie within 30 km of Fermor's line and suggested that the coincidence was likely to be tectonically significant.

At both its northern end in Orissa and its southern end in Andhra Pradesh, the NE-trending part of Fermor's line turns eastward toward the Bay of Bengal (Fig. 3), indicating that the continuation of the suture zone may be sought elsewhere. In Orissa the line lies close to the margin of the strike-slip-dominated region of the Eastern Ghats Mobile Belt (Crowe, Cosca & Harris, 2001; Dobmeier & Raith, 2003, fig. 3).

3.e. Isotopic ages of DARCs of the Eastern Ghats Mobile Belt

With one exception (Aftalion *et al.* 2000), published ages of DARCs of the Eastern Ghats Mobile Belt are Rb/Sr ages. Unfortunately, in the absence of age determinations that make use of other isotopic systems from the same rocks, such as high resolution ages on zircons, Rb/Sr ages have proved notoriously hard

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to interpret. We therefore concur with Dobmeier & Raith (2003, p. 156) who wrote, 'Overall, however, the chronology of magmatism and the effects of regional deformation and metamorphism on the plutons are poorly constrained'. If the evolution of the Eastern Ghats Mobile Belt has been as depicted in the model cross-sections of Figure 2, then the parent ARCs of the DARCs were emplaced at initial continental rupture, which could have been as long ago as *c.* 2 Ga. Final collision of the Eastern Ghats Mobile Belt cannot be younger than the final assembly of Gondwana at *c.* 0.55 Ga but could also have been at *c.* 1 Ga or *c.* 0.75 Ga. The Rb/Sr ages of DARCs of the Eastern Ghats Mobile Belt, most of which form a group at 1.3 ± 0.1 Ga, seem to us more likely to record a mixture of eruptive and metamorphic ages than either an initial rifting or a collisional age. They could, however, represent a discrete rifting event and a later collisional event at a time within the long-duration Wilson cycle represented in the Eastern Ghats Mobile Belt.

3.f. Tectonic evolution of the Eastern Ghats Mobile Belt related to DARCs

Our reluctance to accept the published Rb/Sr isotopic ages of the alkaline rocks of the Eastern Ghats Mobile Belt at their face values has made us unprepared, as yet, to follow Dobmeier & Raith (2003) fully in their comprehensive synthesis of the crustal structure and evolution of this belt. Although a wealth of isotopic, structural and petrological information has been brought together in that study, we consider that it may be premature to distinguish a Krishna Province including Vinjamuru and Ongole domains from the rest of the Eastern Ghats Province.

We consider that the initiation of the Wilson cycle (Burke & Dewey, 1974) recorded in the Eastern Ghats is, at present, best dated by the observation that Atlantic-type ocean margin formation at the edge of the Bhandara (Bastar) craton must have preceded the initiation of sedimentary deposition within the Cuddapah basin. This is because sedimentary rock deposition in the Cuddapah basin appears to have taken place in a foreland basin environment and to be related to convergent plate margin activity. The Cuddapah basin had begun to develop as a foreland basin by 1.8 Ga (see reviews in Dobmeier & Raith, 2003, p. 147–8; Chaudhuri *et al.* 2002; Drury *et al.* 1984; Şengör & Natalin, 1996, p. 499). The rifted margin to the Bhandara craton must, therefore, have formed earlier, perhaps by *c.* 2.0 Ga. Initial eruption of ARCs would have been at that time, or earlier, although later continental rifting episodes may also have occurred. Published Rb/Sr ages for nepheline syenites listed in the Eastern Ghats Mobile Belt are considered to represent something other than, or something in addition to, the times of initial ARC eruption and rifted continental margin formation.

As the Eastern Ghats Mobile Belt Wilson cycle progressed, island arc and Andean margin-type processes began to play a role in the evolution of the rocks now exposed in the belt. Crowe, Cosca & Harris (2001, p. 239) reviewed a substantial set of published U/Pb age determinations from the northern part of the Eastern Ghats Mobile Belt and identified a *c.* 1100 Ma to 950 Ma (*c.* 1 Ga) episode of metamorphism as a highlight. They considered the same *c.* 1 Ga event to be discernable within comparable datasets from further south. Convergence is recognized in the gneissification of the alkaline rocks, that is, in DARC generation, within the Eastern Ghats Mobile Belt, but at present the timing of that gneissification is not clear. Convergence in this belt was certainly complete by the time that eastern Gondwana was finally assembled (*c.* 550 Ma: Santosh *et al.* 2003). By that time the Napier block of eastern Antarctica had become lodged against the fully sutured Eastern Ghats Mobile Belt, perhaps initiating, as Şengör & Natalin (1996, p. 499) have suggested, the collision-induced development of the Pranhita-Godavari rift (P-G in Fig. 9). Published ages for the Eastern Ghats Mobile Belt are likely to include some that have been influenced by some of the later events that contributed to the evolution of the belt. Our preference at present is to limit ourselves to considering the rocks of the Eastern Ghats Mobile Belt as recording a history extending from at least as long ago as 1.8 Ga to *c.* 0.5 Ga. That long interval was dominated by complex convergent and related strike-slip movements but may also have included rifting events. The whole tectonic evolution was perhaps comparable to that recorded in the Altaid mountain belts further north in Asia between *c.* 700 and *c.* 250 Ma (Şengör & Natalin, 1996). The distinction on the basis of Nd model ages of areas of the Eastern Ghats Mobile Belt that contain Archaean material from areas that contain only material that left the mantle to become parts of the continental crust during Proterozoic times and yet other areas that yield both Archaean and Proterozoic ages is reminiscent of the kind of tectonic complexity that was involved in the evolution of the Altaids (Rickers, Mezger & Raith, 2001; Dobmeier & Raith, 2003, p. 157).

4. The Great Indian Proterozoic Fold Belt within the Southern Granulite Terrain of southern India

From the time of its first description (Radhakrishna & Naqvi, 1986; see inset to Fig. 3), the Great Indian Proterozoic Fold Belt has been recognized to extend into the Southern Granulite Terrain that crops out over most of the southernmost part of India. Modern workers generally concur with that idea, but the exact structure of the continuation has proved difficult to establish, at least in part because the Southern Granulite Terrain is not an easy area in which to work out structure. The combination of granulite facies rocks, uneven outcrop distribution and prominent late shear zones has proved particularly challenging for the field geologist.

4.a. Boundary of the Southern Granulite Terrain: the southern part of Fermor's line

Rocks of the Archaean Dharwar craton marking the southwestern boundary of the Eastern Ghats Mobile Belt reach almost to the shore of the Bay of Bengal north of Chennai (formerly Madras, Fig. 3). There the Archaean/Proterozoic Eastern Ghats Mobile Belt boundary is buried under Late Phanerozoic cover. Beneath that cover the boundary executes a 180° turn. As a consequence, a boundary between rocks yielding Proterozoic isotopic ages to the south and Archaean ages to the north emerges from under Phanerozoic cover south of Chennai (Fig. 3). From that point a somewhat irregular, but generally W-trending, boundary extends across the full width of the Indian Peninsula. This boundary, which separates granulite-free Archaean outcrops to the north from the Southern Granulite Terrain, forms the southern part of Fermor's line (Fermor, 1936; Fig. 3). Tectonic interpretation of the southern part of Fermor's line has proved challenging. It is clearly a very different feature from the structurally concordant northern part of the line (Srikantia, 1999, p. 154). Many publications (e.g. Gopalakrishna *et al.* 1986) and our own field observations have shown that it is possible to follow structures across the Fermor's line boundary from rocks with charnockitic assemblages into rocks with amphibolitic assemblages. For that reason, Fermor's line in southern India is unlikely to mark the site of a structural boundary or a suture zone. The observation that no line of dismembered ophiolitic slivers and no paired Bouguer gravity anomaly is associated with the southern part of Fermor's line is consistent with that idea.

It is more appropriate to consider Fermor's line at the Southern Granulite Terrain boundary as a product of static metamorphism (and possibly metasomatism) because it cuts across geological structure (Fig. 7). The event that finally established the thermal structure of the Southern Granulite Terrain has been shown to date from *c.* 550 Ma (e.g. Santosh *et al.* 2003), and to reflect one of the later episodes in the final assembly of Gondwana. The distribution of the older Archaean-aged granulite facies metamorphic rocks in the Southern Granulite Terrain is more complicated. Explaining the outcrop pattern represented by those rocks must await more of the kind of integrated structural and isotopic studies that are beginning to be made in the Southern Granulite Terrain, for example, those of J. G. Ghosh (unpub. Ph.D. thesis, Univ. Cape Town, 1999). The irregularity of the outcrop pattern of the E–W-trending sector of Fermor's line suggests to us that it represents a metamorphic surface ('The SGT (Southern Granulite Terrain) boundary surface') dipping gently to the north, perhaps at $< 5°$ (Fig. 7).

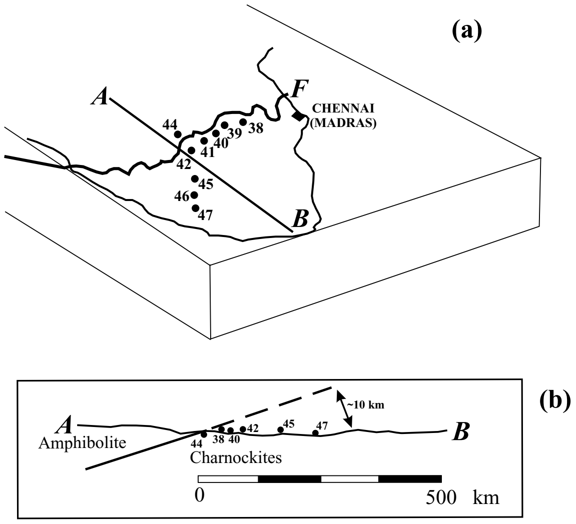

Figure 7. (a) Sketch of an oblique view of southern India from the southwest and (b) a sketch cross-section across Fermor's line (F) in (a). The DARCs of the Southern Granulite Terrain which lie on a suture zone may also lie within *c.* 10 km (vertically or horizontally) of the projected Fermor's line surface, which is suggested to indicate a Late Proterozoic thermal structure. The distribution of the Archaean charnockites and granulites of the Southern Granulite Terrain was established earlier and is unrelated to the Late Proterozoic thermal structure. Numbers of DARCs correspond to those in Table 1.

4.b. Shear zones within the Southern Granulite Terrain

E–W- and NW-trending shear zones form major structural features within the Southern Granulite Terrain (inset to Fig. 8). Those structures are commonly grouped as the Moyar-Bhavani, Palghat-Cauvery and Achankovil-Tenmala shear zones, although other names and map-patterns for shear zones exist (e.g. Santosh *et al.* 2003, fig. 1). Chetty & Bhaskar Rao (2003, especially fig. 2) interpreted the Palghat-Cauvery shear zone as a site of Neoproterozoic transpressional tectonics in a crustal-scale flower structure and Chetty, Bhaskar Rao & Narayana (2003) considered that the Moyar-Bhavani shear zone could mark the location of a Palaeoproterozoic thrust boundary between the Nilgiri block and the Dharwar Craton. They also suggested that Neoproterozoic transpression was localized on flower structures in both the Moyar-Bhavani and Palghat-Cauvery shear zones. Srikantia (1999) suggested, among other possibilities, that the three shear zones might be suture zones separating four gneissic-granulite dominated blocks (Srikantia, 1999, fig. 1). Mukhopadhyay *et al.* (2001) did not see evidence of major transcurrent motion along the Palghat-Cauvery shear zone but did consider that Neoproterozoic amphibolite facies rocks and Late Archaean granulites were juxtaposed in that region

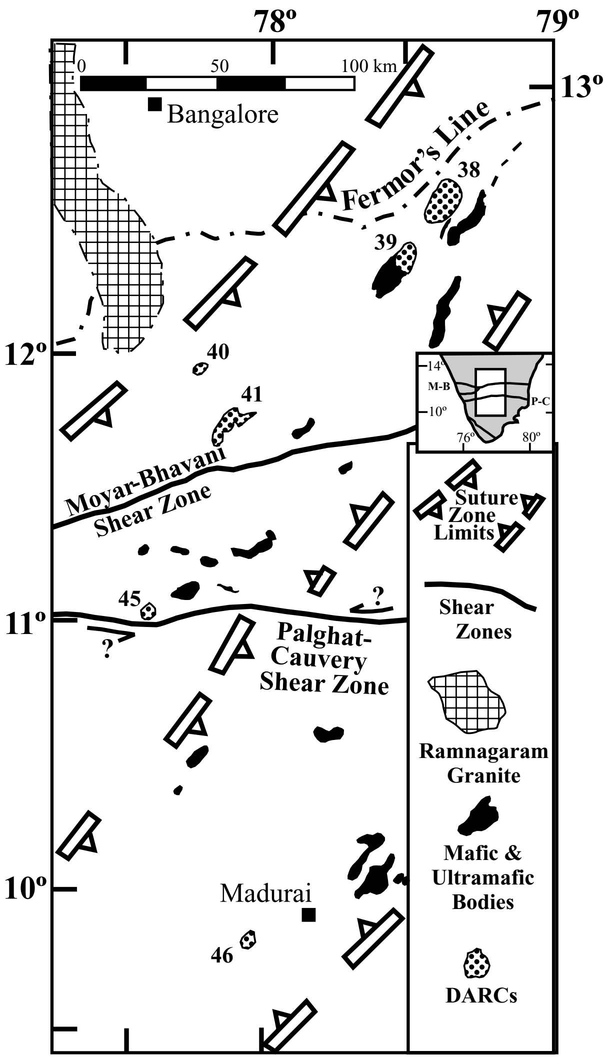

Figure 8. Sketch map of an area between Bangalore and Madurai in which six of the ten DARCs of the Southern Granulite Terrain crop out, showing their locations along a newly postulated suture zone. The DARCs are considered to mark a suture zone by analogy with the line of DARCs in the Eastern Ghats Mobile Belt because: (1) they form a line; (2) they are associated with ultramafic/mafic igneous bodies and (3) they lie close to the abrupt southern termination (it is here suggested at an ancient rifted margin) of the *c.* 500 km long Ramnagaram (formerly Closepet) granite. The postulated suture zone, which can presently only be defined as lying within a *c.* 100 km wide belt, may be offset left-laterally *c.* 100 km by the Palghat-Cauvery shear zone but is not apparently greatly offset by the Moyar-Bhavani shear zone.

along a narrow transition. The occurrence of great shear zones that developed during Late Proterozoic times (*c.* 750–500 Ma: Chetty, Bhaskar Rao & Narayana, 2003), and their preservation in granulite facies rocks, has made it difficult to map older suture zones in the way that has proved feasible in the Eastern Ghats Mobile Belt and the Aravalli parts of the Great Indian Proterozoic Fold Belt, where rocks are preserved in amphibolite facies and late shearing across the trend of the mobile belt is less prominent.

4.c. A suture zone within the Southern Granulite Terrain

Gopalakrishnan, Subramanian & Upendran (2001) identified several parts of what were suggested to have been a long-lived Andean margin in the area south of the Palghat-Cauvery shear zone. The idea that the presence of a long-lived Andean margin is recorded in the rocks of that area for times between 1.5 Ga and 1.0 Ga and possibly longer is discernable in various forms in earlier publications, for example, that of Şengör & Natalin (1996, p. 499). We concur that the rocks of an Andean margin are preserved within the Southern Granulite Terrain and favour the idea that the margin in question occupied the edge of a continental object which collided with a rifted margin of the Dharwar Craton.

Gopalakrishnan, Subramanian & Upendran (2001) distinguished four 'micro-terranes' separated by 'palaeosutures' within the Southern Granulite Terrain. They considered, as we do, that alkaline-syenites and related rocks within the Southern Granulite Terrain are tectonically significant, but their interpretation contrasts with ours in so far as they associated the alkaline plutons of the Southern Granulite Terrain with abortive rifting, while we associate those bodies (because they are DARCs) with intra-continental rifting, ocean opening and later ocean closure. Recognizing that the identification of suture zones within the Southern Granulite Terrain is difficult, we here use the distribution of the DARCs of that terrain to show where we suggest that a suture zone can be discerned and draw attention to other evidence which we consider consistent with that suggestion.

Ten DARCs (Table 1 and Fig. 1, nos 38–47; see also Figures 3, 8) have been described from within the Southern Granulite Terrain (Mazumder, Rao & Nathan, 2000; Ratnakar & Leelanandam, 1989). Those DARCs are mainly carbonatites. They characteristically show less conspicuous signs of deformation than nepheline syenites. Rocks at Pakkanadu (no. 44) are strongly deformed, but some occurrences, such as Hogenakal (Table 1, no. 42), show only deformed calcite twin lamellae. An approximately N–S trend in the alignment of alkaline bodies and carbonatites within the Southern Granulite Terrain was pointed out by Nair & Santosh (1984). In interpreting that alignment, Mazumder, Rao & Nathan (2000, p. 108–9, fig. 14) related four or more syenite and carbonatite bodies in Tamil Nadu to a NNE-trending Dharampuri rift or shear zone embodying the Palakoddu and Javadi Hill (Harur) lineaments of earlier studies.

We develop the line of thought originated by these authors by interpreting the ten DARCs within the Southern Granulite Terrain as occupying a *c.* 500 km long by *c.* 100 km wide NNE-trending belt between *c.* 79° E, 13° N and *c.* 77° E, 10° N. The belt is perhaps offset *c.* 100 km at the Palghat-Cauvery shear zone (Fig. 8). Because the DARCs form a roughly linear array (Figs 3, 8) we infer them, by analogy with our interpretation of the line of DARCs in the Eastern Ghats Mobile Belt, to indicate the locations of both an ancient rifted margin to the Dharwar craton and a Proterozoic suture zone within the Great Indian Proterozoic Fold Belt. Others (e.g. Nair & Santosh, 1984; Gopalakrishnan, Subramanian & Upendran, 2001) have suggested an association between rift structures and at least some of the alkaline rocks of the Southern Granulite Terrain. Our suggestion is that the deformation of the alkaline rocks, which we agree are likely to have been originally erupted into rifts, developed during later collisions (Santosh, 1989).

The suture zone that we discern within the Southern Granulite Terrain is much less well defined than the suture within the Eastern Ghats Mobile Belt. That difference we attribute to the tectonic complexity and to the metamorphic state of the Southern Granulite Terrain. Nevertheless, as in the Eastern Ghats Mobile Belt, there are features of our postulated Southern Granulite Terrain suture zone, besides the occurrence of a line of DARCs, which can be interpreted to indicate the location of a rifted margin and a suture. For example, the 500 km long N–S-trending Ramnagaram (formerly Closepet) granite outcrop of the Dharwar craton ends abruptly (Fig. 8). Formation of a rifted margin at *c.* 12° N, 77° E could have truncated the Ramnagaram granite in just that way. The truncation is in the right place and, within poor resolution, took place at *c.* 2 Ga. Dismembered ophiolites have not yet been discerned within the Southern Granulite Terrain. This is not surprising because many of the features by which remnants of ophiolites can be recognized, including pillow lavas, sheeted dykes and cherts, are unlikely to survive in the granulite facies conditions represented in the rocks of the Southern Granulite Terrain. The dozen or so mafic and ultramafic rock complexes mapped within the region of the postulated suture zone (Fig. 8) could represent ophiolitic material, although mafic and ultramafic rock complexes within granulite terrains can certainly represent other environments, such as the roots of arc volcanoes. Geochemical and isotopic evidence may in the future help in telling whether ophiolitic material is represented within the Southern Granulite Terrain. There is no paired Bouguer gravity anomaly in the vicinity of the postulated Southern Granulite Terrain suture zone such as has been considered indicative of the presence of a suture in the Eastern Ghats Mobile Belt and elsewhere. That absence may be a consequence of the Late Proterozoic (*c.* 550 Ma) tectonic events in the area.

The zone within the Southern Granulite Terrain in which ten DARCs and about a dozen mafic and ultramafic complexes occur crosses both the Moyar-Bhavani and the Palghat-Cauvery shear zones (Fig. 8, inset). In the region shown in Figure 8, no offset of the DARC belt across the Moyar-Bhavani shear zone (at *c.* 11° 30′ N) can be recognized, but on the south side of the Palghat-Cauvery shear zone (at *c.* 11° N), the belt containing the DARCs and the mafic and ultramafic complexes looks to have been offset *c.* 100 km to the east by left-lateral movement. Further south, the Achankovil-Tenmala shear zone (de Wit, 2004; Braun & Kriegsman, 2003) cannot be seen to affect the line of DARCs because the most southwestern DARC within the Great Indian Proterozoic Fold Belt is no. 47 (Munnar or Mannar) at 77° E, 10° N, about 100 km northeast of that shear zone. Our conclusion is that the suture zone within the Southern Granulite Terrain extends from *c.* 79° E, 13° N as a roughly 500 km long NNE-trending line to within a few tens of kilometres of the Achankovil-Tenmala shear zone. Because no DARCs have yet been identified on the southwestern side of the Achankovil-Tenmala shear zone, the further extension of the line of DARCs, the ancient rifted margin, the Proterozoic suture zone and, indeed, of any internal structures within the Great Indian Proterozoic Fold Belt that might serve to indicate offset along the shear zone are at present unknown.

4.d. Isotopic ages of DARCs and the timing of events within the Southern Granulite Terrain

Mazumder, Rao & Nathan (2000, table 4) listed a variety of Rb/Sr and K/Ar isotopic ages obtained by several different authors from the DARCs of the Southern Granulite Terrain. Those ages mainly fall in a range between 750 Ma and 800 Ma, although older ages in the range from 1920 Ma (Crawford, 1969) to 2000 Ma have also been reported (Natarajan *et al.* 1994; see also Anil Kumar *et al.* 1990). Late Proterozoic ages were reported by authors at the *Symposium on Carbonatites and Associated Alkaline Rocks of Tamil Nadu* (2001). Of particular interest from that meeting were electron microprobe ages on monazite of 750 ± 2 and 759 ± 3 Ma (Möller *et al.* 2001). Two data points from those monazites yielded > 1100 Ma ages and a ‘microcracked’ monazite yielded an age of 550 Ma (Möller *et al.* 2001). A whole rock Pb/Pb isochron of 801 ± 11 Ma for Sevattur was reported at the same meeting (Schleicher, 2001). The picture of the tectonic history of the area now occupied by the Southern Granulite Terrain that emerges from these isotopic measurements is of several episodes of Late Proterozoic activity between *c.* 0.9 Ga and *c.* 0.55 Ga, perhaps all associated with various late collisional events during the evolution of the Great Indian Proterozoic Fold Belt. The few ages around 2.0 Ga may relate to an earlier time when rifting of the Dharwar craton and initiation of an Atlantic-type ocean margin to that craton were in progress. Those ages could also relate to the time of the initial emplacement into the continental crust, as ARCs, of the DARCs now exposed within the Southern Granulite Terrain.

5. Continuation of the Great Indian Proterozoic Fold Belt into the Central Indian Tectonic Zone

The northeasternmost part of the Eastern Ghats Mobile Belt suture zone is defined by the 30 km long set of nepheline syenite gneiss outcrops that forms the WNW–ESE-trending Kankarakhol-Lodjahari complex (nos 8–21 in Table 1) at *c.* 21° 15′ N, 84° 50′ E and by the Barandangua body (no. 7 at 21° 04′ N, 85° 05′ E). These DARCs decorate the boundary between the Eastern Ghats Mobile Belt and the Singhbhum craton close to the place where that boundary disappears under Phanerozoic sedimentary rocks (Fig. 6). As in Tamil Nadu, where the Archaean/Proterozoic boundary south of Chennai executes a 180° turn beneath younger cover, the boundary between Proterozoic rocks of the Great Indian Proterozoic Fold Belt and the Singhbhum craton executes a 180° turn under Phanerozoic sedimentary rocks to emerge in West Bengal close to 23° N (Fig. 6). The Great Indian Proterozoic Fold Belt is represented for the next 1000 km by a partly buried, W-trending mountain belt that crosses the entire Indian peninsula (Fig. 1). That belt is commonly called the Central Indian Tectonic Zone or CITZ (see, e.g. Acharyya, 2003).

In West Bengal and Bihar there are sufficient occurrences of DARCs, anorthosites and dismembered ophiolites (Fig. 6) for a suture zone at or close to the Great Indian Proterozoic Fold Belt margin to be traced at the surface for *c.* 300 km. Four nepheline syenite gneiss bodies cropping out at the Proterozoic/Archaean contact (no. 6 at 23° 33′ N, 86° 45′ E, and no. 3 at 23° 01′ N, 86° 15′ W) ornament the northern margin of the Singhbhum craton in West Bengal (Mazumder, 1978; Mazumder, Rao & Nathan, 2000, pp. 106–7, figs 1, 8). DARC 3 lies on a 120 km long shear zone that extends into Bihar. Carbonatites have been penetrated in mineral exploration drill-holes along that shear zone (Mazumder, Rao & Nathan, 2000, p. 107). These four DARCs serve to define the continuation of the Great Indian Proterozoic Fold Belt suture zone into the Central Indian Tectonic Zone. Supporting evidence for the existence of a suture zone comes from: (1) the association of the 32 km long Bankura anorthosite with the line of the DARCs on the northern margin of the Singhbhum craton and (2) the outcrop on the Singhbhum craton boundary further to the west in Bihar of the Dalma greenstones (Fig. 6), which have been considered, on various compositional and structural grounds, to represent a dismembered ophiolite (Yellur, 1977; Gupta, Basu & Ghosh, 1980; Sarkar, 1982; Chakraboti & Bose, 1985).

6. Continuation of the Great Indian Proterozoic Fold Belt from the Central Indian Tectonic Zone into Gujarat, Rajasthan

Şengör & Natalin (1996, fig. 21.10) elaborated on the original interpretation of the Great Indian Proterozoic Fold Belt by Radhakrishna & Naqvi (1986) and we have followed their model. We show the Great Indian Proterozoic Fold Belt in Figure 9 as continuing from the Eastern Ghats Mobile Belt first by occupying the buried curve around the eastern end of the Singhbhum craton and then by becoming the Central Indian Tectonic Zone. The Sausar Mobile belt that crops out between *c.* 79° E and 84° E is generally recognized to be part of the Central Indian Tectonic Zone (e.g. Acharyya, Bandyopadhyay & Roy, 2001), although not all agree with Mishra *et al.* (2000), Yedekar *et al.* (1990), Jain, Yedekar & Nair (1991), Rao & Reddy (2002) and Roy & Prasad (2001) that a suture, the ‘Central Indian Suture’, occupies the Central Indian Tectonic Zone throughout its length. Recognition that the last amphibolite facies metamorphism in the Sausar belt occurred between 800 Ma and 900 Ma and that the records of the Sausar main granulite belt and the more northern Sausar granulite belts differ before *c.* 1100 Ma (Roy *et al.* in press) indicates a complex history. Suturing of the Bundelkhand and Bastar cratons has taken place within the Central Indian Tectonic Zone. The rocks of the Sausar belt record convergent plate margin phenomena over a long interval, perhaps extending from *c.* 1400 Ma to *c.* 800 Ma (Roy *et al.* in press).

At the western end of the Central Indian Tectonic Zone, the Great Indian Proterozoic Fold Belt turns to the northeast to become well exposed in the Aravalli and Delhi fold belts of northeastern Gujarat and Rajasthan (Fig. 9). In central Rajasthan, the Kishangar nepheline syenite gneiss (Table 1, no. 1) at 26° 35′ N, 74° 53′ E (Gupta *et al.* 1997; Roy & Dutt, 1995) is a DARC exposed in a region where rocks of the Delhi Group abut directly against rocks of the ancient banded gneiss complex of the Bundelkhand craton and the Bhilwara metasedimentary rocks that Şengör & Natalin (1996, p. 499) interpreted to be its rifted-continental-margin cover. The Bhilwara rocks may be correlatable with the Kisengarh Group of Roy & Dutt (1995, table 1). Rocks of the Aravalli Group and the Rakhabdev suture zone that separate the ancient banded gneiss from the Delhi Group further south (Fig. 9; Sinha-Roy, 1999, fig. 1) appear to have been cut out from this area (Gupta *et al.* 1997) or to be completely covered by rocks of the South Delhi fold belt (Sinha-Roy, 1999, p. 95, fig. 6). The Newania carbonatite (Table 1, no. 2) that crops out about 200 km south of Kisengarh has been intruded into Bundelkand gneisses and is possibly the least deformed of all Indian Proterozoic DARCs. We consider it to be related to the Kisengarh nepheline syenite gneiss emplacement event because the two bodies have yielded similar ages of *c.* 1.5 Ga (Srivastava, 1989, p. 5). It is clear from Figure 9 that the occurrence of nepheline syenite gneiss in the Gorkha-Ampipal area of the Lesser Himalaya of Nepal (Dhital, 1995) does not lie along strike of the Kisengarh gneiss. For that reason Gorkha-Ampipal is not here considered to be part of the Great Indian Proterozoic Fold Belt array of DARCs.

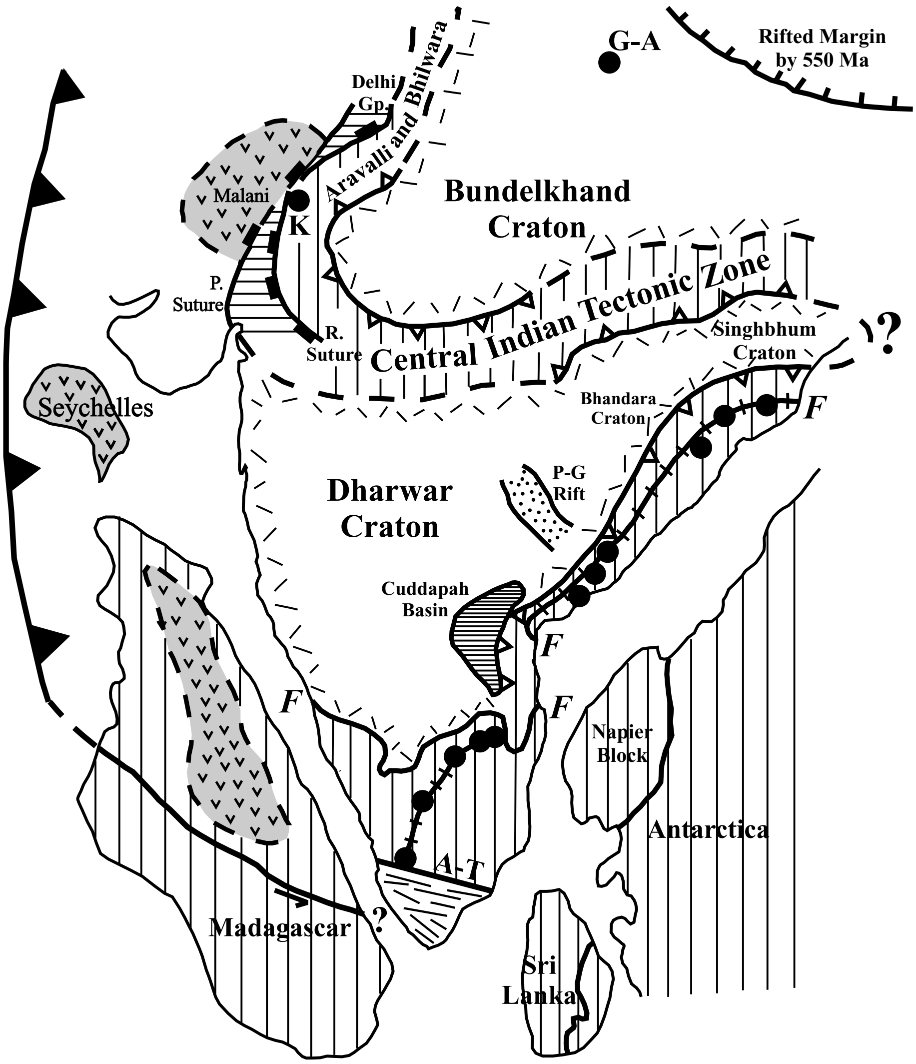

Figure 9. Sketch map (based mainly on Şengör & Natalin, 1996, fig. 21.10 and Torsvik *et al.* 2001) showing a possible reconstruction of the Indian Peninsula and then neighbouring continents at *c.* 750 Ma. DARCs, including those of the Southern Granulite Terrain and the Eastern Ghats Mobile Belt as well as the Kishangar nepheline gneiss, are shown as black circles. The Malani–Seychelles–Madagascar Andean arc that was active at *c.* 750 Ma occupies one continental margin of a *c.* 3 million km^2 area continental block. Suture zones involved in the assembly of India include (1) the Rakhabdev suture (R.), (2) the Phulad suture (P.), (3) the Sileru shear zone suture and the coincident Fermor's line (F–F) of the Eastern Ghats and (4) the SW-trending suture zone within the Southern Granulite Terrain of southern India. That suture zone is last discerned entering an area close to the Achankovil-Tenmala shear zone (A–T) near the southern tip of India. The relationship of India to Eastern Antarctica at this time (shown here as in Şengör & Natalin, 1996, fig. 21.10) remains uncertain. The Pranhita-Godavari rift (P-G) was suggested by Şengör & Natalin (1996) to be a rift formed as a result of collision in the Eastern Ghats. The Gorkha-Ampipal nepheline gneiss (G-A) is a DARC in the Lesser Himalaya that appears to be unrelated to the DARCs of the Great Indian Proterozoic Fold Belt.

DeCelles *et al.* (2000, fig. 2) have shown that the ages of detrital zircons in the Nawakot Group of the Lesser Himalaya of Nepal are concentrated in the 2.0 to 1.8 Ga range, which is compatible with the idea that rocks of the Great Indian Proterozoic Fold Belt may have provided sediment sources for that unit. The same authors reported a concentration in Proterozoic rocks of the Greater Himalaya of detrital zircon ages between 0.8 Ga and 1.0 Ga. That distinct population could also indicate that rocks of the Great Indian Proterozoic Fold Belt were involved as sediment sources. The line separating the two Himalayan detrital zircon populations is that of the outcrop of the Main Central Thrust. DeCelles *et al.* (2000) suggested that the separation might indicate the location of a previously unidentified Proterozoic suture zone in the place at which the Main Central Thrust presently crops out. The proximity of the Gorkha-Ampipal nepheline syenite gneiss to the Main Central Thrust (Dhital, 1995, fig. 2) suggests to us that if DeCelles *et al.* (2000) have located a new suture zone close to the Main Central Thrust then the Gorkha-Ampipal body may be a DARC lying on that suture.

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7. The Great Indian Proterozoic Fold Belt in a regional context

Our discussions of DARC distribution and of suturing are here accommodated to studies that place the Great Indian Proterozoic Fold Belt in a more regional context. Figure 9, which is based on the work of Radhakrishna & Naqvi (1986), Şengör & Natalin (1996, especially figure 21.10), Torsvik *et al.* (2001) and Ashwal, Demaiffe & Torsvik (2002), shows part of Eastern Gondwana as it may have been in Late Proterozoic times.

The Kishangar nepheline gneisses (Table 1, no. 1) and the Newania carbonatite (Table 1, no. 2) appear to have developed from ARCs erupted into rifts that later formed an Atlantic-type margin to the Bundelkhand craton, but all the other DARCs of Table 1 appear to have developed from ARCs that had been erupted into rifts that later formed Atlantic-type margins to the Dharwar, Bhandara (Bastar) and Singhbhum cratons. The winding S-shaped outcrop of the Proterozoic fold belts of India (Fig. 9) is reminiscent of the structure within the Altaid Mountains of Asia (Şengör & Natalin, 1996). The Malani rhyolite and the Erinpura granitic rocks of the northwestern part of the Indian peninsula and comparable rocks in the Seychelles and Madagascar fit with the Altaid structural pattern. The Malani–Seychelles–Madagascar rocks have been interpreted (Ashwal, Demaiffe & Torsvik, 2002; Torsvik *et al.* 2001) as indicating the location of a 750 Ma Andean arc. A postulated Malani–Seychelles–Madagascar Andean arc can be envisaged as having occupied one margin of a continental object *c.* 3 million km^2 or more in area that included the Indian cratons after they had become wrapped up in the matrix of Proterozoic mountain belts that makes the Great Indian Proterozoic Fold Belt. Şengör & Natalin (1996, p. 500) suggested that the assembled object may also have included the Lhasa block, but as yet no Proterozoic rock outcrops are known on that block.

The time of assembly of the 3 million km^2 continental object that makes up Peninsular India and of its incorporation into Gondwana and possibly also into an earlier continental assembly is of great interest to those considering the times of assembly and rupture of the postulated ancient super-continents. Our study is unable to contribute to that subject. We have been able to map within the Great Indian Proterozoic Fold Belt, on a reconnaissance scale and over a distance of *c.* 4000 km, both a rifted continental margin and a suture that developed on that margin, but times of initial continental margin formation and of suturing cannot be established with available isotopic data. Isotopic ages from within the Great Indian Proterozoic Fold Belt show that folding, faulting, igneous activity and metamorphism extended over an interval from at least as early as *c.* 1.8 Ga to *c.* 0.55 Ga. Episodes of intense tectonic activity have been discerned in the Eastern Ghats Mobile Belt, particularly between *c.* 1.1 Ga and *c.* 0.9 Ga, but tectonic activity in the Great Indian Proterozoic Fold Belt may have been almost continuous at some level over more than 1 Ga. Distinguishing episodes of continental assembly and continental disruption must depend more on information about the arrangement of ancient objects of continental dimensions on the Earth's surface (that is, on palaeolatitudinal studies) than on identifying the timing of particular tectonic events within a mountain belt. Published isotopic ages and other geological information indicate to us that one possibility is that the assembly of India was complete by *c.* 1 Ga and that an alternative is that assembly became complete by *c.* 750 Ma (Crowe, Cosca & Harris, 2001; Santosh *et al.* 2003).

Whether it was assembled at *c.* 1 Ga or *c.* 750 Ma, the continental object that now makes up most of the Indian peninsula became a part of Gondwana at the time it was assembled. Eastern Gondwana is likely to have been larger in area at that time than during Early Palaeozoic times because the Great Indian Proterozoic Fold Belt strikes northeastward toward the Himalaya (Fig. 9) and its projection makes a high angle with what had, by the beginning of Phanerozoic time (550 Ma), become a rifted margin to Gondwana. The rifted margin could have been that of a marginal basin.

At the other end of its 4000 km long strike-length, the suture marking Proterozoic closure in the Great Indian Proterozoic Fold Belt is last seen entering a region that contains the Achankovil-Tenmala Proterozoic shear zone near the southern tip of India (Fig. 9). If final closure was at *c.* 750 Ma in the south, as it was in Rajasthan (Torsvik *et al.* 2001), then the suture could have been offset on that *c.* 550 Ma shear zone (Fig. 6). There is a single DARC of unknown age at Makairingobe in Madagascar (Burke, Ashwal & Webb, 2003, fig. 1, inset and table 1; Welter, 1964). It is an intriguing, although an admittedly remote, possibility that the nepheline gneiss at Makairingobe marks the extension of the suture zone that we have discerned within the Great Indian Proterozoic Fold Belt from its last discernable location within the Southern Granulite Terrain.

The assembly of the Indian peninsula had ended before the time at which Gondwana, with an area of *c.* 80 million km^2, became complete at *c.* 550 Ma. How and whether the Indian peninsula was related to other parts of Gondwana before 550 Ma remains unresolved. Torsvik *et al.* (2001, fig. 7) show one interpretation. The idea that eastern Gondwana was assembled into its final configuration by *c.* 750 Ma is compatible with the conditions sketched in Figure 9. The possibility has also been suggested that eastern Gondwana was assembled by as long ago as *c.* 1 Ga (e.g. Santosh *et al.* 2003, fig. 18b). Resolving the timing of assembly of continental objects in the general region of the Indian peninsula during the Proterozoic awaits new U/Pb age determinations that can be linked to new information about palaeolatitudinal, including palaeomagnetic, indicators. Until that time, there cannot help but be a strong element of speculation in all histories of reconstruction. With that limitation in mind we here present tentative tectonic suggestions about the history of the Great Indian Proterozoic Fold Belt that embody our observations about DARCs. We emphasize that these conclusions are presented so that they can be tested, improved upon or simply proven wrong when the results of new U/Pb and new palaeolatitudinal indicator studies become available:

(1) Intracontinental rifts and a rifted continental margin formed close to the site of the Sileru shear zone in the Eastern Ghats Mobile Belt and on the Dharwar craton side of a suture zone within the Southern Granulite Terrain of southern India. That rifted margin, which may have extended through much of the length of the Great Indian Proterozoic Fold Belt, could have formed as long ago as *c.* 2 Ga.
(2) Convergent plate boundary processes began to be involved at that continental margin, as well as in Gujarat and Rajasthan and possibly throughout the entire length of the Great Indian Proterozoic Fold Belt by 1.8 Ga.
(3) A major episode of convergent plate margin activity at *c.* 1 Ga has left a record in the Eastern Ghats Mobile Belt. It is not possible to conclude from the evidence available whether that event reflects arc-system or continental collisional activity.
(4) Ages are scattered widely in the Eastern Ghats Mobile Belt from 850 Ma into the earliest Phanerozoic (after 550 Ma). Several peaks in numbers of analyses have been recognized. At or before that time the Indian peninsula had been assembled. These events in the Eastern Ghats Mobile Belt were roughly contemporary with both an arc-collisional event and the establishment of the Malani–Seychelles–Madagascar Andean arc on the opposite side of the newly assembled continental object.
(5) Rifting at the Himalayan margin by 550 Ma and offsetting of the Southern Granulite Terrain suture zone at *c.* 550 Ma, possibly into Madagascar along the Achankovil-Tenmala shear zone, complete the picture. By 550 Ma the assembly of Gondwana was largely complete.

8. Summary and conclusions

(1) Forty-seven DARCs ranging from 30 m to 30 km in length, mainly in the Eastern Ghats Mobile Belt and the Southern Granulite Terrain, have been recognized in the Great Indian Proterozoic Fold Belt (Fig. 1).
(2) Those DARCs are concentrated within a few tens of kilometres of what may be a single suture zone (Figs 3, 4, 8).
(3) Proterozoic nepheline syenites and carbonatites of India are all gneissic and are therefore DARCs (Fig. 5).
(4) On the hypothesis that DARCs mark suture zones and that their parent ARCs mark the sites of intra-continental rifting (Fig. 2; Burke, Ashwal & Webb, 2003), the Sileru shear zone and its correlative extensions to the north and to the south in the Eastern Ghats Mobile Belt mark a suture zone at which both continental breakup and continental collision are recorded.
(5) That conclusion is consistent with documented occurrences within the Eastern Ghats Mobile Belt of dismembered ophiolitic fragments, a Bouguer gravity anomaly sign change, the distribution of calcic anorthosites and Fermor's line.
(6) The hypothesis that a line of DARCs marks a suture zone has been successfully tested in the Eastern Ghats. This is the first test of the hypothesis outside Africa.
(7) The location of a suture zone within the Southern Granulite Terrain has been postulated on the basis of DARC distribution. That suture zone is not coincident with Fermor's line (Figs 7, 8).
(8) DARCs lie on suture zones throughout the full length of the Great Indian Proterozoic Fold Belt, but evidence is less complete than in the Eastern Ghats Mobile Belt.
(9) The timing of events during the operation of the Wilson cycle that is recorded in the Eastern Ghats Mobile Belt and the Southern Granulite Terrain is at present poorly constrained. Initial rifting of a continental margin could be as old as *c.* 2 Ga. The onset of convergent plate margin processes appears to have begun by *c.* 1.8 Ga. Convergent plate boundary phenomena have left peaks in isotopic records at *c.* 1 Ga and *c.* 750 Ma. Final assembly of Gondwana has left a further record at *c.* 550 Ma.
(10) Extending consideration to the entire area of the Indian peninsula and making use of observations in Gujarat, Rajasthan, Nepal, the Seychelles and Madagascar helps in the construction of a tentative tectonic history for the Great Indian Proterozoic Fold Belt.

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