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## Precambrian continental strain and shear zone patterns: South Indian case

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[1] This study addresses the tectonic and mechanical significance of crustal-scale strain and shear zone patterns in the South Indian Precambrian lithosphere. It is based on a tectonic map of the Dharwar craton derived from LANDSAT imagery, existing documentation, and our own field observations. We document the contrasted responses of the two main parts of the craton to late Archean (2.56–2.51 Ga) shortening. The old (>3 Ga) lithosphere of the Western Dharwar craton stabilized at 2.61 Ga underwent moderate shortening and strain localization along spaced shear zones. The Eastern Dharwar craton, rejuvenated by late Archean juvenile magmatic accretion, responded to shortening by flowing laterally against the Western Dharwar craton. Shortening operated without significant thickening because of the high buoyancy of the juvenile crust and the very low strength of its mantle lithosphere. The late Archean crustal-scale shear zone network did not accommodate large displacements and only contributed to smoothing out of strain heterogeneities during the latest stages of flow. The shear zone pattern only reflects the symmetry of the regional finite strain field of a wide hot orogen. It does not result from terrain amalgamation but accompanies crustal flow and does not compare with those of modern active margins, which accommodate unidirectional transpression. Our analysis further suggests that the shear zones bounding the craton did not record large horizontal displacements during final assembly of Gondwana but rather transverse shortening and vertical extrusion.

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### 1. Introduction

[2] Archean cratons are often seen as wide orogenic domains of amalgamated cordilleran-type terranes [*van der Velden et al.*, 2006]. The field structural signatures of collage by collision is however barely documented as it is severely altered if not erased by tectonothermal episodes producing homogeneous strains and HT-LP metamorphism over very large domains comprising previously assembled terranes [*Choukroune et al.*, 1995, 1997; *Hamilton*, 1998; *Chardon et al.*, 2002; *Bédard et al.*, 2003; *Nitescu et al.*, 2006]. Such strain patterns are invariably associated with the development of anastomosing crustal-scale shear zones with transcurrent/transpressive kinematics [*Platt*, 1980; *Chown et al.*, 1992; *Choukroune et al.*, 1995, 1997] and

accompany the last addition of juvenile magmas to the crust, which leads to late growth and recycling of Archean lithospheres on their way to cratonization [*Chardon et al.*, 2002].

[3] Understanding deformation of Archean lithospheres requires structural analysis on a craton scale, of particular interest being the relations between shear zones and regional strain patterns [*Coward et al.*, 1976; *Park*, 1981; *Chown et al.*, 1992; *Choukroune et al.*, 1995; *Treloar and Blenkinsop*, 1995]. Such an approach has been adopted for the present study, which aims to evaluate the tectonic and mechanical significance of the regional strain and shear zone patterns of the Dharwar craton (South India) with an emphasis on the 2.56–2.51 Ga tectonoplutonic episode that ultimately led to its stabilization in the latest Archean. This study is based on a new comprehensive structural map of the craton derived from LANDSAT imagery, existing documentation, and our own field data. Our work on late Archean deformation also led us to reevaluate the kinematic significance of the Proterozoic shear zone system that bounds the craton to the south.

### 2. Geology of the Dharwar Craton

[4] As a result of a post-Archean northward tilt, the Dharwar craton (Figure 1) exposes an oblique panel of

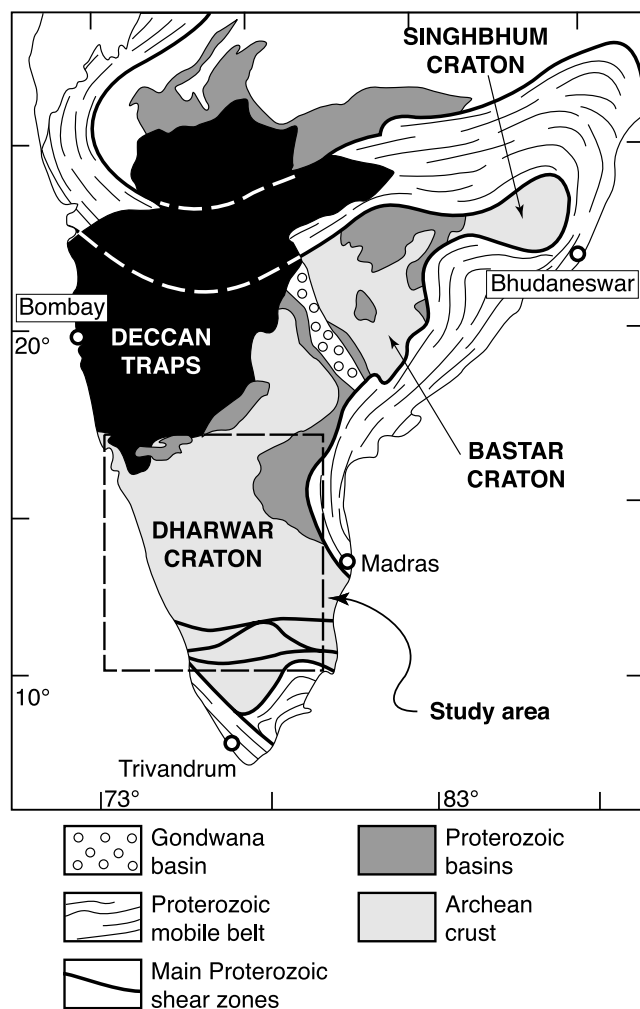
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**Figure 1.** Simplified geology of the South Indian Shield (compiled from *Drury et al.* [1984], *Radhakrishna and Naqvi* [1986], *Ghosh et al.* [2004] and the present study).

crust, documented by a continuous increase in P-T conditions recorded from north to south, from 4 Kb/450°C to 8 Kb/800°C [*Raith et al.*, 1982; *Raase et al.*, 1986] (Figure 2). The craton exposes an unbroken amphibolite-granulite transition zone [*Pichamuthu*, 1965; *Hansen et al.*, 1984, 1995] in which all rock types grade into charnockites (Figure 2). The transformation of migmatites into charnockites results from a static dehydration process producing orthopyroxene by upward streaming of CO<sub>2</sub>-rich fluids [*Janardhan et al.*, 1982].

[5] The craton is divided in two subblocks named hereafter the Western Dharwar craton (WDC) and Eastern Dharwar craton (EDC) (Figure 2). According to *Swami Nath et al.* [1976], the EDC is typified by volcanics-dominated greenstone belts, whereas the WDC comprises mature, sediment-dominated greenstone belts. The boundary between the WDC and the EDC would coincide with the eastern margin of the Chitradurga greenstone belt [*Swami Nath and Ramakrishnan*, 1981] (Figure 2). This boundary marks a drop in crustal thickness from 42–51 km for the WDC to 34–39 km for the EDC [*Sandeep Gupta et al.*, 2003b; *Singh et al.*, 2004; *Jayananda et al.*, 2006].

[6] TTG gneisses form the dominant crustal component of the craton. Geochronological and isotopic data provide an age range of 3.3 to 2.7 Ga for the emplacement of the magmatic precursors to the gneisses, with neodymium model ages as old as 3.8 Ga [e.g., *Peucat et al.*, 1993; *Jayananda et al.*, 2000; *Chadwick et al.*, 2000]. A group of 2.61 Ga potassic granitic plutons mark the youngest plutonic activity in the WDC [*Jayananda et al.*, 2006, Figure 2]. 2.56–2.51 Ga juvenile plutonism and intense anatexis are widespread in the EDC [e.g., *Peucat et al.*, 1993; *Jayananda et al.*, 1995, 2000; *Chadwick et al.*, 2000], the latest of the juvenile bodies being the Closepet batholith (Figure 2). Late Archean juvenile crust also forms migmatitic complexes such as that of the Krishnagiri area [*Condie et al.*, 1982; *Peucat et al.*, 1989, 1993] (Figure 2).

[7] Two generations of greenstones are recognized in the WDC [*Swami Nath et al.*, 1976]. The older (3.35–3.0 Ga) Sargur Group form intensely deformed greenstone belts that are unconformably overlain by the younger (3.02–2.52 Ga), moderately deformed Dharwar Supergroup greenstone belts [*Peucat et al.*, 1995; *Nutman et al.*, 1996; *Trendall et al.*, 1997a, 1997b; *Jayananda et al.*, 2008]. EDC greenstones seem to be coeval with the youngest stratigraphic units of the Dharwar Supergroup [e.g., *Vasudev et al.*, 2000].

[8] Regional granulite metamorphism overlaps with 2.56–2.51 Ga juvenile plutonism [*Peucat et al.*, 1989, 1993]. Charnockitization overprints indistinctively 2.56–2.52 Ga juvenile crust (e.g., Krishnagiri, Nilgiris; Kollimalai) or older crust (e.g., BR Hills) and U-Pb data indicate that high-grade metamorphism ended by 2.50 Ga at the latest [*Peucat et al.*, 1993 and references therein; *Mahabaleswar et al.*, 1995; *Ghosh et al.*, 2004] (Figure 2).

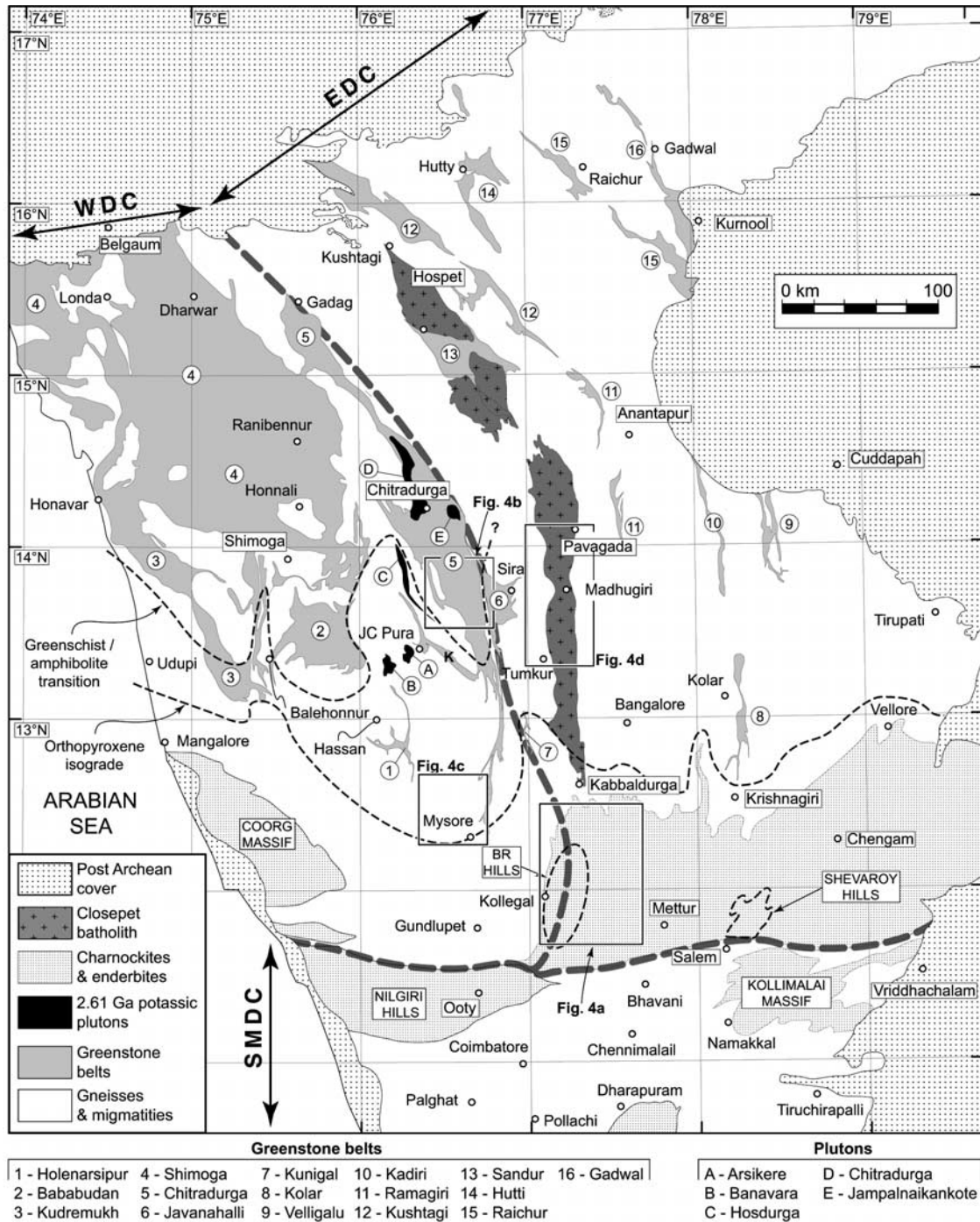
[9] The southern margin of the Dharwar craton (SMDC) is made of late Archean charnockitic crust partly rejuvenated in the Neoproterozoic [e.g., *Bhaskar Rao et al.*, 2003; *Ghosh et al.*, 2004] (Figure 2). The SMDC is affected by the E-W trending Cauvery shear system [*Drury and Holt*, 1980; *Chetty*, 1996; *Jain et al.*, 2003] (Figure 1), which bounds the charnockite massifs and was active until the early Cambrian [*Meissner et al.*, 2002].

### 3. Late Archean Regional Deformation: Previous Works and Interpretations

[10] *Drury and Holt* [1980] established the first tectonic map of the craton on the basis of 80-m-resolution LANDSAT images. This map shows a series of sinistral shear zones curved parallel to the structural grain of the craton (e.g., Figure 2). On the basis of a study of the Dharwar Supergroup, *Chadwick et al.* [1989] later proposed a late Archean sinistral transpressive kinematic model for the regional shear zones of the central WDC. Following *Drury* [1983], work by *Bouhallier et al.* [1993, 1995] and *Bouhallier* [1995] allowed refining the deformation and shear zone patterns of the WDC, by pointing to the occurrence of a conjugate set of NNE-trending dextral shear zones, and to a component of bulk E-W shortening in the WDC.

[11] *Chadwick et al.* [2000] have reported regional, NW-trending sinistral shear zones from the northern EDC, which they consider as a magmatic arc formed in a context of sinistral-oblique convergence at a modern-like active plate



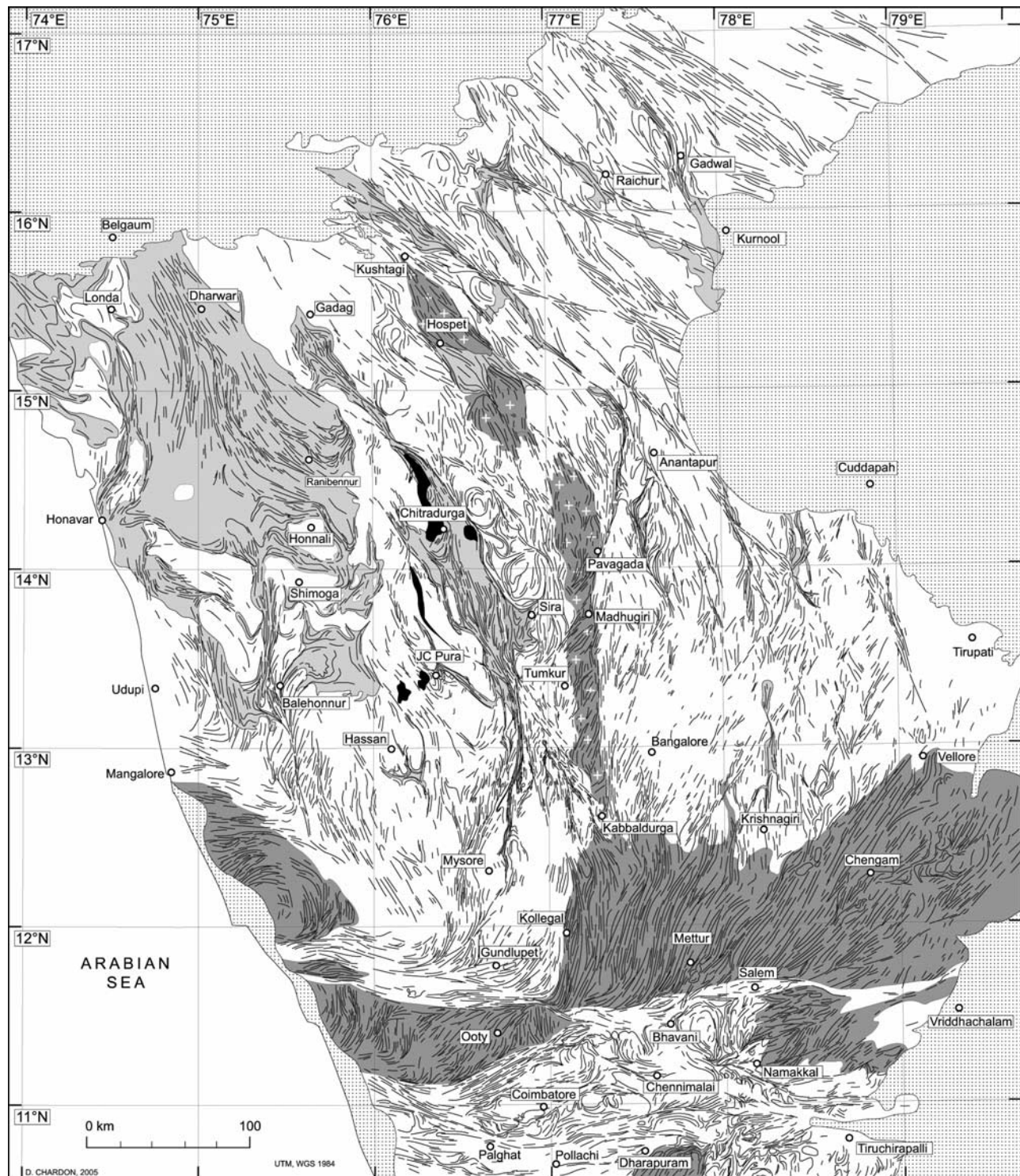


**Figure 2.** Geological map of the Dharwar craton (derived from Figure 3). The only greenstone belts of the Sargur Group that are shown are the Holenarsipur (1) and Kunigal (7) belts. Thick grey dashed lines represent the approximate boundary between the Western Dharwar craton (WDC) and the Eastern Dharwar craton (EDC) as well as the northern boundary of the southern margin of the Dharwar craton (SMDC). Metamorphic isogrades are modified after *Raith et al.* [1982]. K-Kibbanahalli Arm.

margin. For these authors [*Chadwick et al.*, 2007], the entire Dharwar craton would be a Late Archean transpressive, west-vergent fold-and-thrust belt linked to a detachment located at 18–20-km depth.

[12] *Jayananda and Mahabaleswar* [1991], along with *Bouhallier* [1995], noted the synkinematic character of the Closepet batholith with respect to the regional shear zone pattern. *Newton* [1990], followed by *Moyen et al.* [2003],





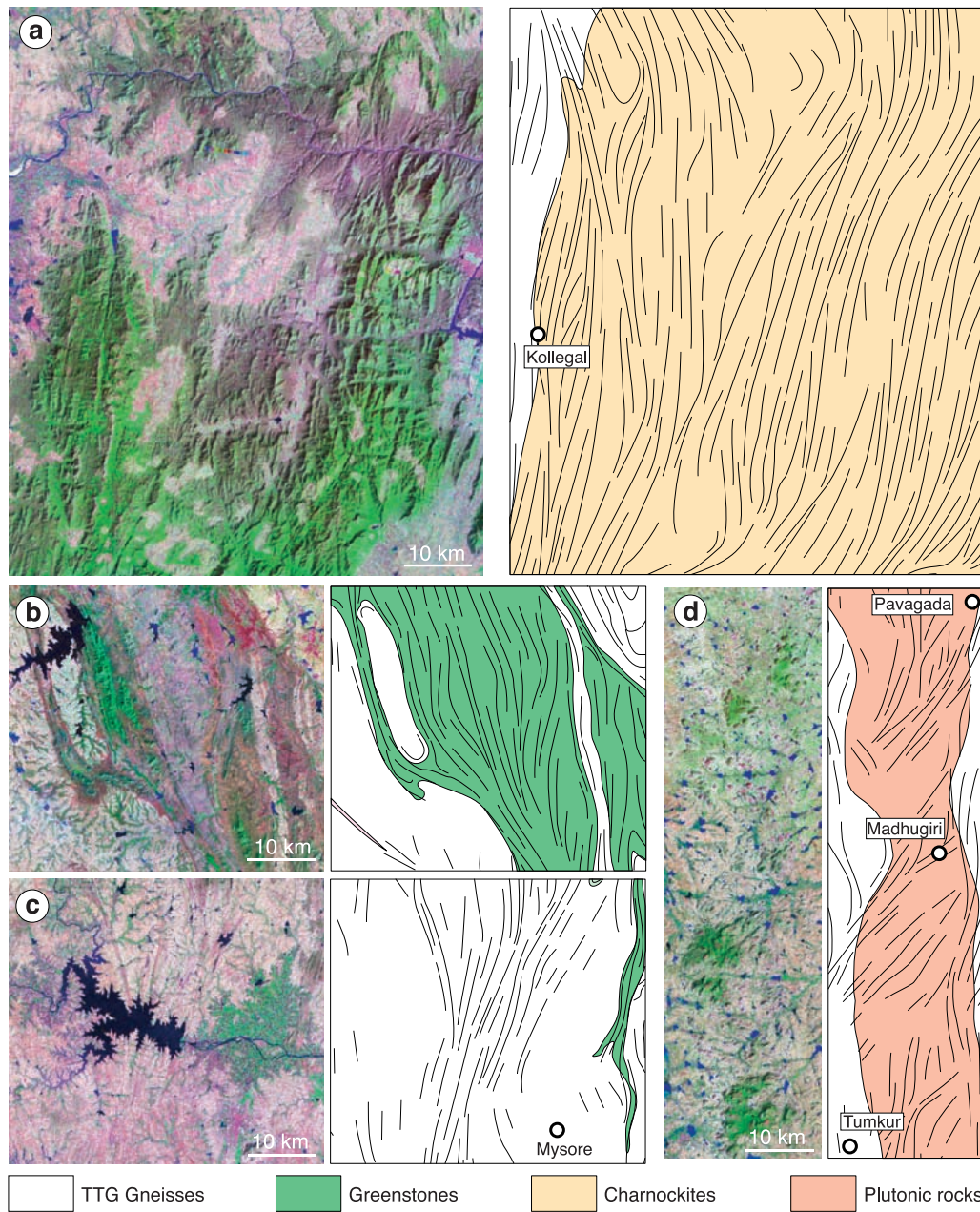
**Figure 3.** Tectonic fabric map of the Dharwar craton derived from LANDSAT data. See Figure 2 for geological caption. Geological contours for the Shimoga and Kudremukh greenstone belts are adapted from *Geological Survey of India* [1981]. Source for complementary data (geological contours and/or field foliation measurements) in the northern part of the Eastern Dharwar craton: *Geological Survey of India* [1978, 1980, 1983, 1995a]. Post-Archean mafic dykes are omitted.

viewed the main mass of the batholith as intruding a N-S trending dextral shear zone.

[13] *Chardon and Jayananda* [2008], extending the work of *Chardon et al.* [2002], have suggested that the EDC

developed bulk, horizontal plane strain on a crustal scale between 2.56 and 2.51 Ga during magmatic juvenile accretion. Plane strain was achieved through lower-crustal horizontal constrictional flow perpendicular to the shortening





**Figure 4.** Examples of the main radiometric facies on LANDSAT images and their interpretation. (a) Charnockites of the BR hills area. (b) Supracrustals from the Central Chitradurga greenstone belts. (c) TTG gneisses from the Mysore area. (d) Plutonic rocks of the Closepet batholith. Frames of the maps are located on Figure 2.

direction. Thinning due to constriction is interpreted to compensate magmatic accretion and limited upper crustal tectonic thickening [Chardon and Jayananda, 2008].

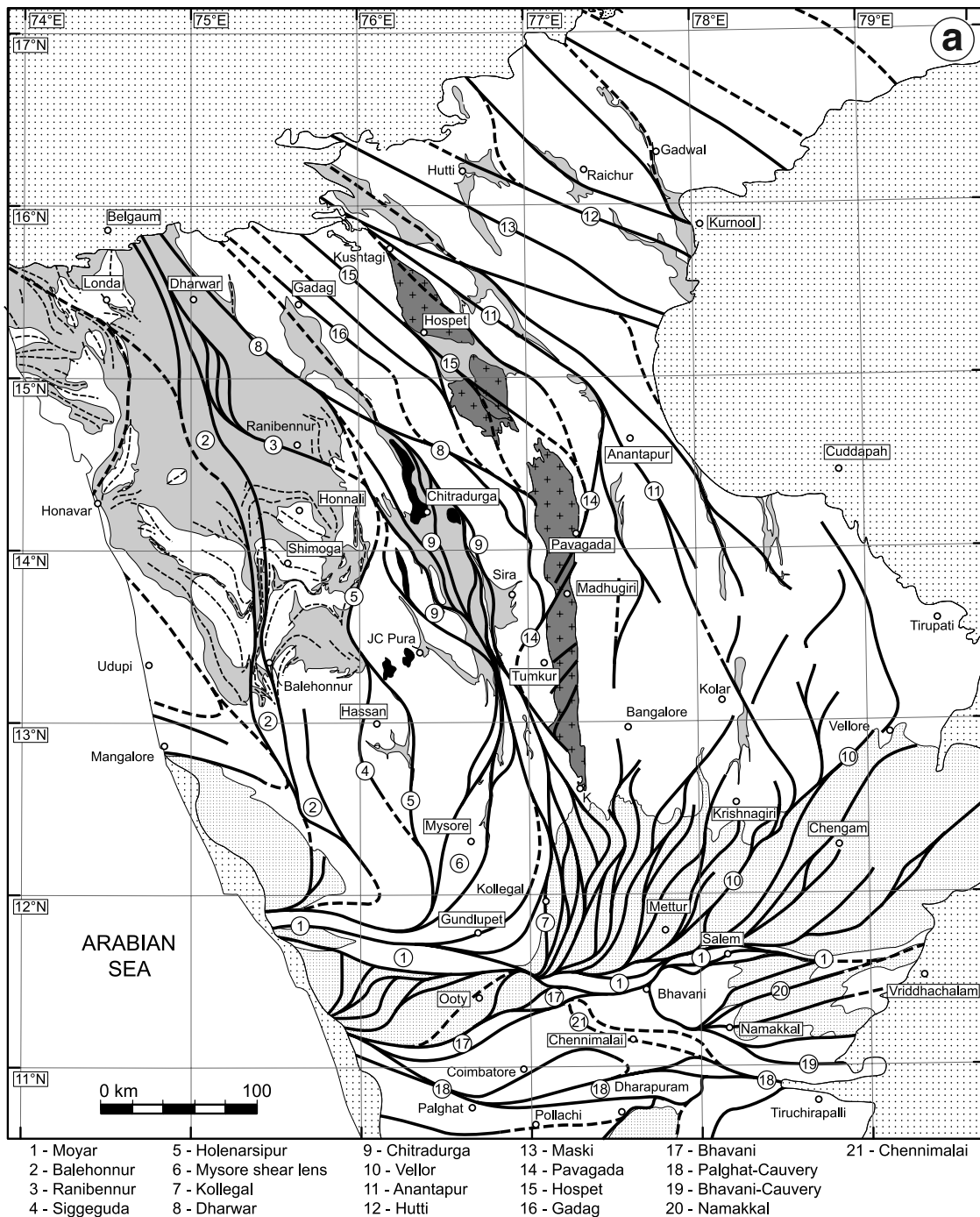
**4. Satellite Data and Structural Interpretation**

[14] We have used GeoCover™ orthorectified LANDSAT Thematic Mapper mosaics with a pixel size of 28.5 m. The three spectral bands used are band 7 (midinfrared wavelengths, displayed as red), band 4 (near-infrared wavelengths, displayed as green), and band 2 (visible green

wavelengths, displayed as blue). Contrast enhancement was obtained using the LOCAL algorithm (www.earthsat.com).

[15] Figure 3 summarizes the distribution and trends of linear/curvilinear features extracted manually using geographic information system software. These features are the expression of the textural and compositional fabrics of the various rock types making the regional tectonic fabrics of the craton.

[16] Charnockites show distinguishably higher fabric intensity than that of any other rock type (Figure 3). Their



**Figure 5.** (a) Shear zones of the Dharwar craton derived from Figure 3. Shear zones or shear zone boundaries are shown by thick black lines (dashed where inferred). See Figure 2 for geological caption. Axial traces of folds/domes in the northern part of the WDC are shown by thin dashed lines. (b) Index map for the structural domains in the Dharwar craton. These domains are defined for the convenience of the structural analysis and may comprise rock masses with contrasted pre-2.50 Ga magmatic/isotopic records, especially in the Eastern Dharwar craton.

fabric is made of sharp ridges that can be traced for tens of kilometers (Figure 4a). This banding parallels a regional foliation resulting from the transposition of mafic slivers within intermediate/felsic migmatites. Fabrics within greenstone belts are defined by elongate inselbergs (Figure 4b) marking erosional and radiometric contrasts between felsic

and mafic volcanic layers, gabbroic sills and quartzite/greywacke beds. Fabrics in TTG Gneisses are due to transposed slivers of darker gneisses or amphibolites (Figure 4c). Plutons display inselberg topography controlled by a foliation, a compositional banding or syn- to late plutonic dykes (Figure 4d). Noncharnockitic migma-



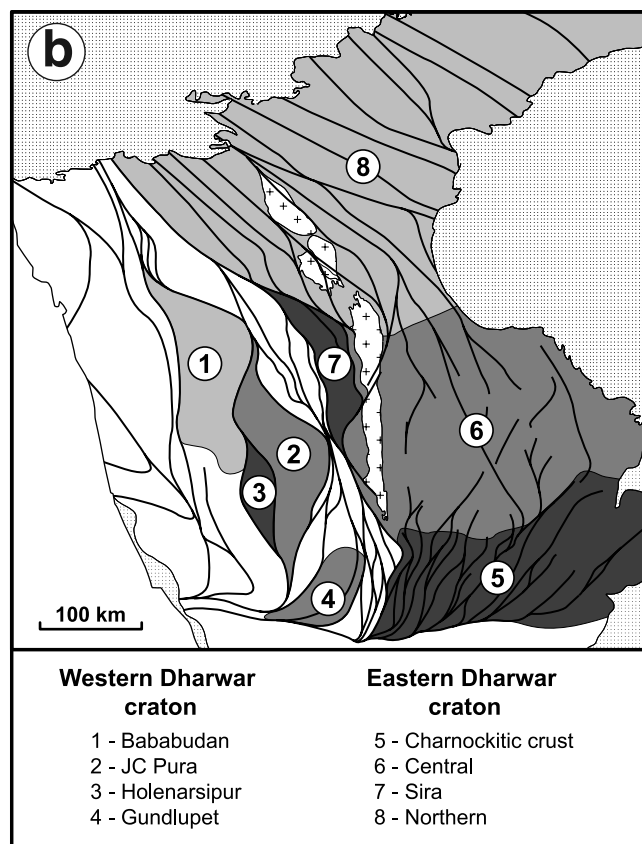


Figure 5. (continued)

tites have intermediate radiometric signatures, in between those of TTG gneisses and plutons.

[17] Interpretation of the structural patterns and identification of strain gradients in shear zones are based on the geometrical analysis of the fabric patterns of Figure 3 (i.e., shape of the trajectories, deflection, clustering, rectilinearity), structural observations reported in the literature and our own field data collected during four field seasons between 1998 and 2003. Field observations reported below are our own, except where authors are quoted. In the following, see Figure 2 for greenstone belt numbers, Figure 5a for shear zone numbers, and Figure 5b for the names of the structural domains discussed in the text.

## 5. Structural Pattern of the Western Dharwar Craton

### 5.1. Shear Zones

[18] The Balehonnur shear zone (2) is the westernmost first-order structure mapped with confidence (Figure 5a). Despite the occurrence of shallowly plunging lineations and left-lateral kinematic indicators, fabric trajectories suggest a significant component of shortening across the shear zone (Figures 3 and 5a). The southern strand of the Balehonnur shear zone is not well defined but has to be deflected into the Moyar shear zone (1). The shear zone merges with the Ranibennur shear zone NW of Honnali (Figure 5). The Holenarsipur greenstone belt (1) belongs to a lens-shape

domain bounded by two linked sinistral shear zones that are the Sigegudda shear zone (4) and the Holenarsipur shear zone (5) (Figure 5a).

[19] The Chitradurga shear system (9) is a curved array of anastomosed shear zones. In the south, it consists in a northward-converging pattern of dextral and sinistral shear zones (i.e., the dextral Mysore shear lens (6), the Kollegal shear zone (7) and the anastomosed shear system between Kollegal and Kabbaldurga) that merge around 13°30'N and diverge northward to form a duplex that ends NE of Ranibennur (Figure 5a). North of that point, the Chitradurga shear system is confined to a single trace (i.e., the Dharwar shear zone (8)) making the eastern boundary of the Shimoga greenstone belt (Figure 5a). Foliation trajectories as well as field kinematic analysis indicate that the various branches of the duplex have an apparent sinistral component of shearing (Figure 6).

## 5.2. Deformation Patterns Outside the Shear Zones

### 5.2.1. Bababudan Domain

[20] In the Bababudan domain (Figure 5b), the basal unconformity of the Dharwar Supergroup in the Bababudan greenstone belt (2) has been activated as a décollement accommodating centripetal collapse of the belt, indicative of an early stage of sagduction [Chardon *et al.*, 1998]. Sagduction-related strain patterns became partly overprinted by shortening and sinistral shearing along the Balehonnur (2) and Holenarsipur (5) shear zones [Chardon *et al.*, 1998]. Shortening is well documented around the Honnali and Shimoga domes [Chadwick *et al.*, 1989, 1991]. Early amplification of these domes is not older than 2.61 Ga i.e., the age of the felsic volcanics lying stratigraphically under the strata affected by the uplifts (U-Pb date by Trendall *et al.* [1997b]).

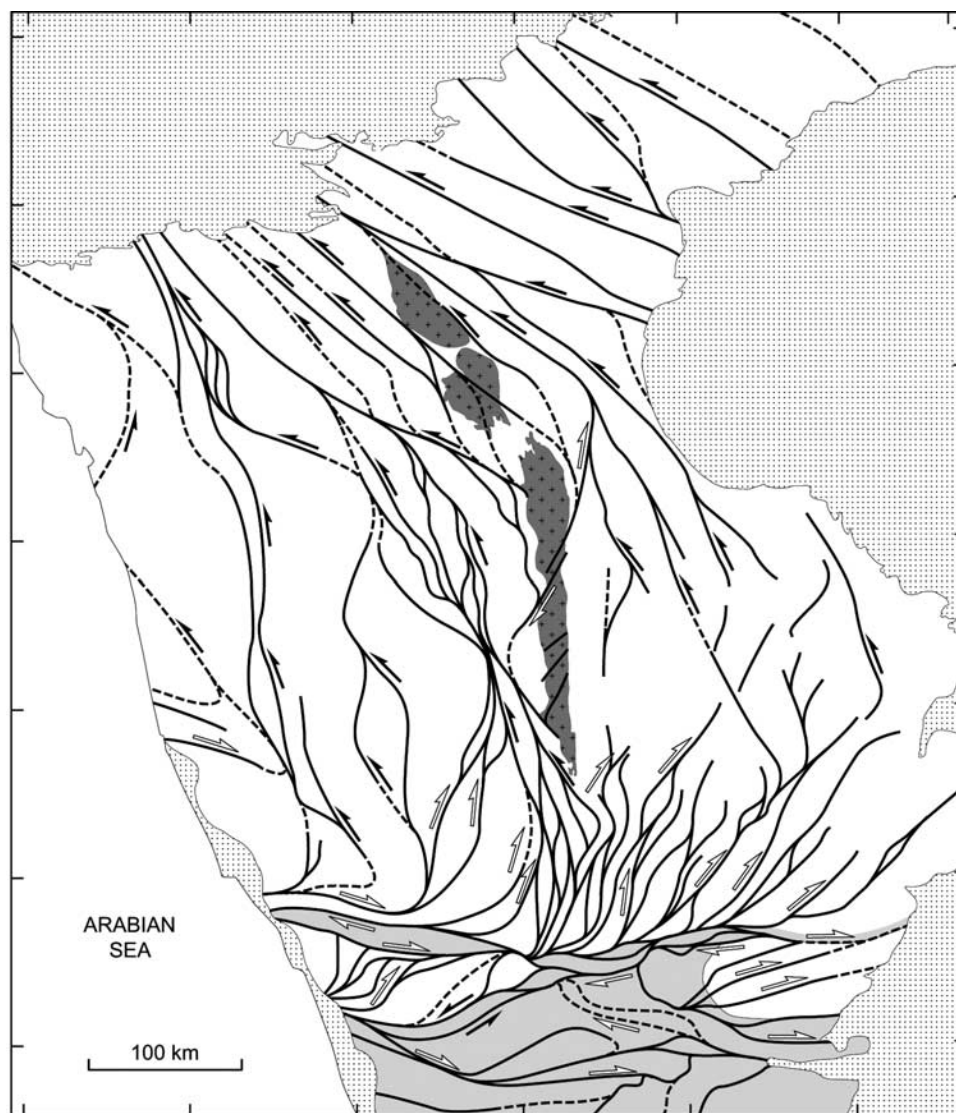
### 5.2.2. JC Pura Domain (Figure 5b)

[21] Near J.C. Pura town, the 2.61 Ga Arsikere pluton (Figures 2 and 5a) intrudes a diapiric dome-and-basin foliation pattern affecting 3.1–3.0 Ga gneisses and Sargur-type greenstones [Chardon *et al.*, 1996; Chardon, 1997; Jayananda *et al.*, 2006]. The pluton is syn-kinematic with respect to the development of the domes and basins delineated by the S1 foliation, which is therefore 2.61 Ga old [Jayananda *et al.*, 2006]. The S1 diapiric foliation pattern is unconformably overlain by the Kibbannahalli Arm of the Chitradurga greenstone belt (Figure 2). The arm is affected by an S2 cleavage associated with a décollement that reworks its basal unconformity [Chardon *et al.*, 1996]. Downward relative displacement of the greenstones with respect to their basement on both limbs of the Arm points to the sagduction of a greenstone trough after 2.61 Ga and before or during regional strike-slip shearing [Chardon *et al.*, 1996; Jayananda *et al.*, 2006].

### 5.2.3. Holenarsipur and Gundlupet Domains

[22] Structural analysis in the Holenarsipur and Gundlupet domains (Figure 5b) shows that these localities represent two levels of exposure of the same diapiric dome-and-basin pattern [Bouhallier *et al.*, 1993, 1995]. Domes and basins are flattened parallel to the regional structural grain and affected by the regional shear zones, attesting to bulk shortening and strike-slip shearing during or after diapirism [Bouhallier *et al.*, 1993, 1995]. Garnet-whole rock Sm-Nd





**Figure 6.** Shear zone pattern of the Dharwar craton and their kinematics, simplified from Figure 5a. The crust rejuvenated by Neoproterozoic deformation is shaded.

isochrone ages of the greenstones from both localities range from 2.56 to 2.45 Ga [Bouhallier, 1995]. The Holenarsipur and Gundlupet diapiric patterns and those of the JC Pura domain may be contemporaneous at 2.61 Ga, Sm-Nd isotopic systems and fabrics in Holenarsipur and Gundlupet having undergone static resetting around 2.5 Ga. Another possibility is that the Holenarsipur-Gundlupet diapiric patterns are older than 2.61 Ga (possibly at 3.2–3.1 Ga [Peucat *et al.*, 1995]).

### 5.3. Coorg Charnockite Massif

[23] The Coorg massif (Figure 2) shows a subrounded fabric pattern (Figure 3). In its northern part, fabrics trend E-W across the charnockites' boundary and interfere with the Balehonnur shear zone (2) (Figure 5a). E-W fabrics extend to the noncharnockitic crust SE of Udipi and may correlate with the E-W trending fabrics and fold pattern mapped SW of Londa (Figures 3 and 5a). Fabrics are N-S trending in the

southeastern part of the massif and are deflected into the Moyar shear zone (1) (Figures 3 and 5a).

## 6. Structural Pattern of the Eastern Dharwar Craton

### 6.1. Charnockitic Crust

[24] The shear zone pattern in the EDC charnockites (Figure 5b) consists of an anastomosing shear-lenses system trending N- to NNE (Figure 5a). East of the BR Hills, shear lenses have a fish-like asymmetrical shape indicative of a dextral component of shearing (Figures 2 and 6). The southeastern branches of the Chitradurga shear zone system (9) merges with the shear-lenses system along the eastern edge of the B.R. Hills where they give way to a duplex-like stack of shear lenses against the NNE-trending dextral shear system (Figure 5a). Field structural observations between Krishnagiri and Kabbaldurga (Figure 5a) are consistent with the NNE trending shear zones being dextral and bearing a

shallowly plunging stretching-mineral lineation [see also *Chetty et al.*, 2003].

[25] East of Krishnagiri and Mettur, the dextral shear system gives way to a rather homogeneous pattern of NE-trending fabrics associated with some dextral shear zones at low angle to those fabrics (Figures 3 and 5a). Fabric trajectories are perturbed in the vicinity of late Proterozoic alkaline intrusions southeast of Krishnagiri and around folded mafic layers east of Chengam [*Geological Survey of India*, 1995b; *Anil Kumar et al.*, 1998] (Figure 3). The Vellore shear zone (10) bears shallowly plunging lineations and is dextral [*Chetty et al.*, 2003]. The fabrics and shear zones in the EDC charnockites are all right-laterally deflected into the Moyar shear zone (Figure 6).

### 6.2. Central Domain

[26] The central domain (Figure 5b) displays a homogeneous deformation pattern characterized by a pervasive, shallowly dipping foliation, which is variously overprinted by a steeply east-dipping foliation [*Chardon and Jayananda*, 2008]. Flat and steep planar fabrics are at least in part coeval as they are both migmatitic and bear a common, shallowly plunging, strike-parallel lineation. This strain pattern reflects horizontal longitudinal constriction throughout the central domain [*Chardon and Jayananda*, 2008]. The composite fabric of the central domain is still documented south of the orthopyroxene isograd where it becomes affected by the EDC charnockite shear system. The Closepet batholith is syn-kinematic with respect to the development of the regional penetrative fabric pattern. It has a funnel shape and emplaced into the constrictional fabric interference pattern [*Chardon and Jayananda*, 2008].

[27] A systematic network of macroscopic, conjugate strike-slip shears is documented throughout the central domain, with dextral shears trending NE to NNE and sinistral shears trending NW to NNW [*Mukhopadhyay and Haimanot*, 1989; *Chardon et al.*, 2002, *Harish Kumar et al.*, 2003; *Chardon and Jayananda*, 2008, and our own observations]. This shear zone pattern contributes to horizontal lengthening parallel to the strike of the steep fabrics [*Chardon et al.*, 2002; *Chardon and Jayananda*, 2008].

[28] The main mass of the Closepet batholith contains N- to NW trending fabrics (Figure 3). Oblique fabric belts underline the trace of several NE to NNE trending dextral shear zones within the batholith, corresponding to belts of pervasive CS fabrics in the field [*Chardon and Jayananda*, 2008] (Figures 3 and 5).

### 6.3. Sira Domain

[29] The Sira domain (Figure 5b) is characterized by a very shallowly dipping foliation rotated into large, open elliptical folds (Figure 3) affecting sills of banded tonalitic gneisses with stretching-mineral lineations trending parallel to the major map axes of the folds. Preliminary U-Pb and Neodymium data indicate that the Sira tonalite sills crystallized at 2.56 Ga and are juvenile (*Chardon et al.*, in preparation).

[30] Flat fabrics are overprinted by the easternmost trace of the Chitradurga shear system and by the strain aureole of the Closepet batholith. Gneisses with subhorizontal foliations occupy large tracts of the crust exposed between the Chitradurga greenstone belt and the Closepet batholith [see also *Chadwick et al.*, 2000, Figure 3]. We correlate the flat

foliation affecting the Sira tonalitic gneisses with the penetrative flat foliation documented throughout the central domain, where it interferes with the regional steep foliation [section 6.2, *Chardon and Jayananda*, 2008].

### 6.4. Northern Domain

[31] The northern domain (Figure 5b) contains syn-kinematic plutons and batholiths [*Chadwick et al.*, 2000, 2001], large diatexitic bodies, and greenstone belts elongated parallel to the regional NW-trending structural grain (Figure 3).

[32] North of the latitude of Madhugiri, the regional fabric and sinistral shear zones are deflected into a series of WNW trending shear zones of apparent sinistral kinematics (Figures 3 and 5a). The fabric pattern from Gadwal toward the NE (Figure 3) becomes rectilinear and denser, suggesting high homogeneous deformation and a regional strain gradient into a WNW-trending sinistral shear system. South of Anantapur, the shear zones of the northern domain split into branches of the conjugate pattern of the central domain (Figure 5a).

[33] The Hospet shear zone (15) coincides with a fault within the Sandur greenstone belt (Figures 2 and 5a) interpreted by *Chadwick et al.* [1996] as a SW-verging reverse fault. Along this fault, various shear criteria attest to a consistent component of left-lateral shearing (*Mukhopadhyay and Matin* [1993]; our own observations). The shear zone may even dip steeply to the SW and some NE side-down kinematic indicators are documented. The Hospet shear zone (15) is therefore a transpressive sinistral shear zone [see also *Mukhopadhyay and Matin*, 1993]. Similar kinematics may be inferred for the WNW-trending shear zone trending SW of Gadag (Figure 5a) through the Chitradurga greenstone belt by comparing our data with that of *Chadwick et al.* [2003]. Interpretation of the fabric map combined with the work of *Matin* [2006] within the Kushtagi greenstone belt (Figures 2, 3, and 5a) also reveals the left-lateral transpressive kinematics of deformation.

### 6.5. Transpressive Kinematics and Crustal Flow

[34] Strain patterns in the EDC developed under conditions of intense anatexis [*Chadwick et al.*, 2000; *Chardon and Jayananda*, 2008]. Fabrics in the juvenile tonalitic gneisses of the Sira domain are indicative of vertical shortening and horizontal spreading of the mid crust following emplacement of early juvenile crust in the Late Archean at 2.56 Ga. Steep fabrics were progressively superimposed onto the flat fabrics throughout the EDC, leading to forced horizontal flow perpendicular to the direction of shortening. This process continued during emplacement of successive batches of juvenile magmas until 2.51 Ga [*Chardon and Jayananda*, 2008]. The regional arcuate fabric pattern of the EDC follows the overall shear zone pattern, suggesting arcuate crustal flow against the WDC and interdependence of flow and regional shear zones.

[35] Stretching-mineral lineations have preferential steep plunges within greenstone belts and are consistently shallowly plunging in the country rocks within or outside the shear zones throughout the EDC [*Mukhopadhyay and Matin*, 1993; *Chadwick et al.*, 1996, 2000; *Chardon et al.*, 2002; *Matin*, 2006; *Chardon and Jayananda*, 2008]. Within shear zones, lineations vary from horizontal to downdip along



strike going from the migmatites to the interior of the greenstone belts. Outside regional shear zones, there are also very common sharp gradients in the reorientation of lineations from strike-parallel to down-dip in gneissic rocks toward the granite-greenstone contact. Such granite-greenstone contacts may show both reverse and normal kinematics.

[36] The above considerations indicate strong strain partitioning between the two dominant lithologies as suggested by *Chadwick et al.* [2000]. Partitioning is due to transpression and sagduction of greenstones [*Chardon et al.*, 2002], or most likely to the combination of both. This is consistent with horizontal displacements on the regional shear zones being small, as attested by limited offsets of the greenstone belts by the shear zones (e.g., Kolar (8), Velligalu (9), Kadiri (10) greenstone belts; Shimoga belt (4) along the Dharwar shear zone (8); Figures 2 and 5a).

### 6.6. Case for a “Mettur Shear Zone”?

[37] A reflection seismic profile shot between the Krishnagiri area and Bhavani has been interpreted by *Vijaya Rao et al.* [2006] as the signature of late Archean collision along the “Mettur shear zone” [*Drury et al.*, 1984], which would correspond to the belt of NE trending foliations mapped between Mettur and Chengam (Figure 3). This interpretation is based on the deepening of the Moho and the convergent reflection pattern toward the central part of the profile. A thicker crust to the SE of Mettur would be in agreement with the contrasted fabric/shear pattern documented between the EDC charnockites shear system and the NE trending fabrics mapped to the East of Mettur (Figure 3). However, the Krishnagiri-Salem corridor (Figure 3) exposes an unbroken crustal section characterized by a continuous increase in the P-T conditions recorded by the late Archean charnockites [*Hansen et al.*, 1995]. We therefore interpret this contrast in crustal thickness to mark the boundary of two distinct crustal segments juxtaposed before latest Archean deformation and granulite metamorphism.

## 7. Structural Pattern of the Southern Margin of the Craton

### 7.1. Shear Zones

[38] The Moyar shear zone (1) (Figures 3 and 5) is characterized by very steep foliations bearing steeply (mainly) to moderately plunging lineations. The shear zone is interpreted to be dextral and transpressive [*Chetty and Bhaskar Rao*, 1998, 2006a; *Bhadra*, 2000; *Meissner et al.*, 2002; *Jain et al.*, 2003; *Chetty et al.*, 2003] and recorded HT-HP metamorphism [*Raith et al.*, 1990; *Srikantappa et al.*, 2003]. Regional deflection of fabrics and shear zones attests to a major component of right-lateral slip along the shear zone (Figures 3, 5, and 6).

[39] The Bhavani shear zone (17) bounds the Nilgiri massif to the south and merges with the Moyar shear zone at the eastern tip of the massif (Figures 3 and 5). The shear zone bears lineations with moderate to steep pitches toward the SW. Pervasive left-lateral shearing is observed in the field [*Jain et al.*, 2003] and attested by fabric deflection toward the shear zone (Figures 3 and 5a). The shear zone cuts across the granulite isogrades of the Nilgiri massif and contains lenses of high-pressure mafic granulites [*Raith et al.*, 1990, 1999].

[40] The Palghat-Cauvery shear zone (18) is a network of E-W shear zones that stretches from the west coast to the east coast (Figures 3 and 5a). Foliations in the shear zone are steep; lineations are moderately to gently plunging eastward and westward [*Jain et al.*, 2003]. Though fabric trajectories suggest apparent right-lateral sense of shear (Figure 3) [see also *D’Cruz et al.*, 2000], the shear zone may not have accommodated major dextral shearing. Indeed, field analysis reveals a pervasive conjugate strike-slip shear band pattern with the shear zone [*Jain et al.*, 2003].

[41] The Bhavani-Cauvery Shear zone (20) flanks the Bhavani dome to the West and merges with the Palghat-Cauvery shear zone south of the Kollimalai massif (Figures 3 and 5). The shear zone is cored by retrogressed charnockites with consistently shallowly east-plunging lineations [*Chetty and Bhaskar Rao*, 2006b]. Apparent dextral sense of shear is suggested by regional fabrics deflection (Figures 3, 5, and 6). The shear zone records UHT and HP metamorphism [*Shimpo et al.*, 2006].

[42] The WNW trending Chennimalai shear zone (21) stretches from the Bhavani shear zone to the Palghat-Cauvery shear zone. Regional patterns of deflection fabrics indicate an apparent right-lateral sense of movement for this shear zone (Figure 6).

[43] U-Pb systematics of the shear zones described above provide ages between 800 and 525 Ma [*Ghosh et al.*, 2004; *Collins et al.*, 2007]. Cooling below biotite Rb-Sr closing temperature took place until 450 Ma [*Meissner et al.*, 2002].

### 7.2. Late Archean Charnockite Massifs and Shear Zones

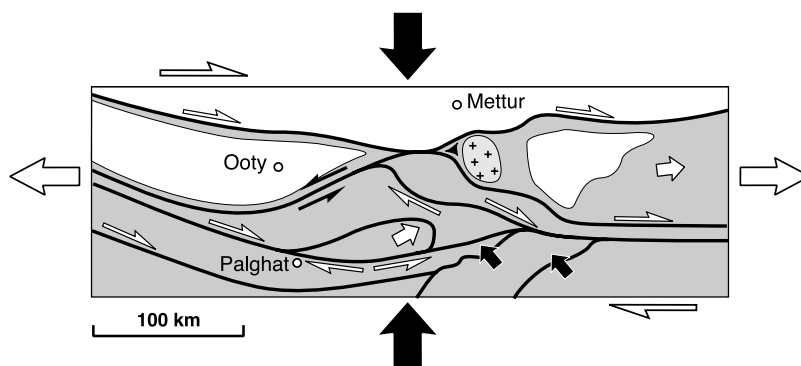
[44] The Nilgiri Hills show a shear zone pattern similar to and kinematically compatible with that of the EDC charnockites (Figures 3 and 5). These shear zones are apparently dextral and are N- to NE trending; they are dragged into the Moyar and Bhavani shear zones (Figure 6).

[45] The Namakkal shear zones (20) are parallel, ENE-trending, dextral shear zones passing through the Kollimalai massif (Figures 5a and 6). One of these shear zones bear charnockitized tonalitic gneisses that yielded a  $2537 \pm 1$  Ma U-Pb zircon age and a  $2507 \pm 5$  Ma monazite age, interpreted as the age of charnockitization [*Ghosh et al.*, 2004]. This attests to the Late Archean age of the Namakkal shear zones.

### 7.3. Noncharnockitic Crust

[46] Noncharnockitic crust is characterized by N- to NNW trending folds deflected into the regional shear zones (Figures 3 and 5). SW of Bhavani, the strain pattern is constrictional and characterized by folded migmatitic foliations bearing gently to moderately plunging lineations [*Chetty and Bhaskar Rao*, 2006c]. Constrictional strain is interpreted to take place within a complex fabric triple point flanking the Bhavani dome.

[47] The fabric pattern east of the Bhavani dome (Figure 3) appears to extend into the northwestern part of the Kollimalai massif, suggesting this structural pattern is at least partly Late Archean in age (section 7.2). This domain can be seen as the pressure shadow of the Bhavani dome preserving late Archean strain patterns during Neoproterozoic shearing (Figure 7).



**Figure 7.** Kinematic interpretation of the late Neoproterozoic Cauvery shear system, southern margin of the Dharwar craton. The crust rejuvenated by Neoproterozoic deformation is shaded. The Bhavani dome is shown by crosses.

## 7.4. Tectonic Implications

### 7.4.1. Late Neoproterozoic Kinematics

[48] Steep lineations argue for a dip-slip/transpressive component in the Moyar shear zone. The shear zone is also pinched-off into lens-shaped domains (Figure 6). This, together with the fabric pattern of the noncharnockitic crust and shear zone pattern of the SMDC reflects N-S shortening and E-W stretching against the Dharwar craton while down-dip stretching and/or flattening were taking place within the Moyar shear zone and other strands of the Cauvery shear system. This is consistent with sinistral shearing along the Bhavani shear zone, conjugate dextral movement along the Bhavani-Cauvery and Chennimalai shear zones and coaxial shortening within the Palghat-Cauvery shear zone (Figure 7). The noncharnockitic crust of the SMDC was therefore submitted to strain partitioning and constriction in between the Nilgiri Hills and the Bhavani dome/Kollimalai massif as a result of N-S shortening (Figure 7).

### 7.4.2. Displacement on the Moyar Shear Zone

[49] The pressure gradient in late Archean granulite metamorphism across the Moyar shear zone is the signature of the juxtaposition of the Nilgiri charnockite massif with the noncharnockitized WDC along the shear zone in the latest Archean, during and after peak granulite metamorphism [Raith *et al.*, 1990, 1999]. A restoration of finite horizontal dextral slip on the shear zone may be proposed. The working hypothesis considering 120 km of horizontal offset (Figure 8) complies with (1) the continuity of the regional N- to NE trending late Archean dextral shear zones in the charnockites and (2) the matching of late Archean crust across the Moyar shear zone. This reconstruction indeed juxtaposes the eastern part of the Nilgiri massif, essentially made of 2.7–2.5 Ga juvenile, metavolcano-sedimentary enderbites [Raith *et al.*, 1999], and the late Archean Shevaroy Hills crust [Peucat *et al.*, 1989, 1993, in preparation] where metasediments have been reported [Hansen *et al.*, 1995].

## 8. Discussion

### 8.1. Tectonic and Mechanical Significance of Late Archean Fabrics and Shear Zones

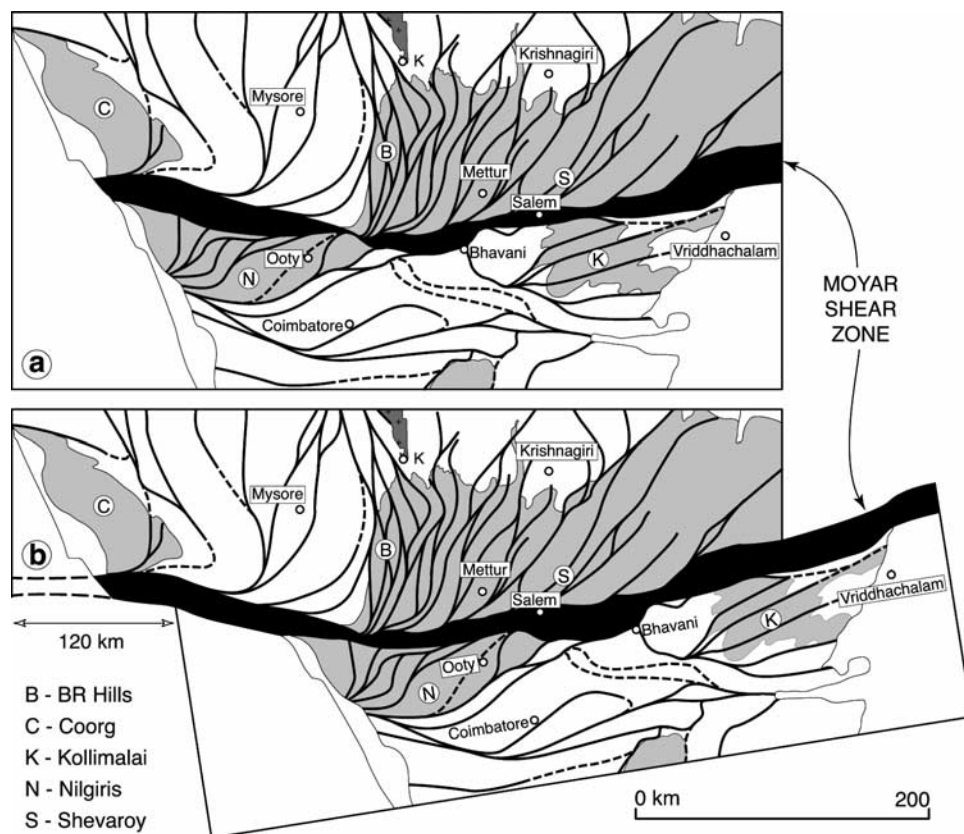
[50] Thrusting invoked by Chadwick *et al.* [2000, 2003, 2007] to support their Late Archean, SW-vergent fold-and-

thrust belt model for the entire Dharwar craton is not substantiated on the simple basis of stratigraphic or metamorphic breaks across the thrusts inferred by these authors. Furthermore, significant Late Archean crustal thickening of the Dharwar craton is precluded by the nearly isobaric cooling paths [Raith *et al.*, 1983] of the granulites [Chardon *et al.*, 2002]. Thrusting is in fact poorly documented on a structural basis too. Structures are almost systematically upright at the level of exposure in the middle and upper crust (i.e., above 13°N) but are interpreted to become shallower and to branch on a subhorizontal detachment in the deeper crust [e.g., Chadwick *et al.*, 2007]. This configuration is not observed at deeper crustal levels (Chardon *et al.* [2002], Chardon and Jayananda [2008] present study). Furthermore, the shear zones affecting the Chitradurga greenstone belt and interpreted as thrusts by Chadwick *et al.* [2007] are continuous from the amphibolite isograd to the deepest crustal levels of the craton (up to 28 km paleodepth [Hansen *et al.*, 1995] (Figure 5a). This precludes the occurrence of a midcrustal detachment on which such thrusts would branch.

[51] The only unambiguous shear criteria reported by Chadwick and coworkers [Chadwick *et al.*, 2000, p. 95; Chadwick *et al.*, 2003, p. 656] are extensional shear bands affecting shallowly dipping foliations that bear N- to NW-trending lineations in gneisses in the vicinity of the northern Chitradurga greenstone belt (Figure 2). This kinematic configuration does not support SW-vergent thrusting. It is indicative of orogen-parallel shearing on flat fabrics. This shearing would be consistent with orogen-parallel flow fabrics and extensional shear zones documented in the Central and Sira domains by Chardon and Jayananda [2008] (Figure 5b).

[52] Steep dip-slip reverse and normal faulting must have taken place in the upper crust of the Dharwar craton as a result of transpression and/or sagduction of greenstone belts [Chardon and Jayananda, 2008]. However, the available metamorphic and structural data preclude the occurrence of Late Archean thrusts in the Dharwar craton. The penetrative strain pattern of the EDC is indicative of orogen-parallel flow responding to transverse shortening [Chardon and Jayananda, 2008]. As stated above, crustal thickness of the Dharwar craton remained nearly stable during late Archean tectonism. Therefore the combination of shorten-





**Figure 8.** Restoration of right-lateral displacement along the Moyar shear zone. (a) Present configuration. (b) Configuration after removal of 120 km of E-W slip and  $9^\circ$  rigid body, anticlockwise rotation of the southern block. Charnockites are shown in grey. Salem has been kept attached to the northern block. Letters in the explanation refer to charnockite massifs. K-Kabbaldurga.

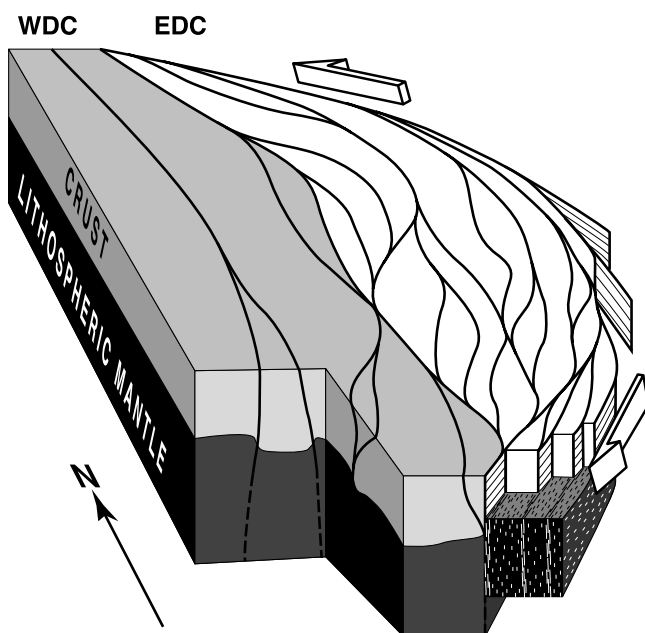
ing and lateral flow resulted in net plane strain deformation of the EDC with the volumetric part of strain being due to juvenile magmatic accretion [Chardon and Jayananda, 2008]. In the framework of a sustained crustal thickness, lower crustal longitudinal flow absorbed and mitigated thickening of the upper crust.

[53] Distributed strain in the crust of the EDC suggests that its lithospheric mantle was mechanically weak, precluding the development of major lithospheric thrusts or faults typical of colder modern lithospheres [Choukroune *et al.*, 1995; Cagnard *et al.*, 2006; see also Brun, 2002]. The basaltic liquids that differentiated to produce the late Archean felsic juvenile bodies found throughout the EDC [Jayananda *et al.*, 2000] must have percolated massively and pervasively through the underlying lithospheric mantle [Arndt and Goldstein, 1989]. This suggests that the EDC lithospheric mantle was strongly attenuated. In other words, it was weak or even absent.

[54] The basaltic parental melts to the late Archean juvenile crust of the EDC are the most likely source for the fluids that allowed charnockitization of the crust [Newton *et al.*, 1998]. The cause for extensive charnockitization of the EDC is therefore also due to the attenuation of its mantle lithosphere during late Archean tectonomagmatism. This further suggests that the crust of the EDC may have been directly in contact with the asthenosphere at that time.

[55] To summarize, the EDC is a wide hot orogen developed in a lithosphere that was too weak to sustain thickening and that flowed laterally in response to shortening [Chardon *et al.*, 2002; Chardon and Jayananda, 2008; Cagnard *et al.*, 2006; Cruden *et al.*, 2006; Rey and Houseman, 2006; Duclaux *et al.*, 2007]. By contrast, the WDC preserves 2.61 Ga and/or older tectonoplutonic patterns outside late Archean shear zones. Because it was partly cratonized by 2.61 Ga [Jayananda *et al.*, 2006], the WDC did not weaken as much as the EDC and did not therefore develop pervasive strains at 2.56–2.51 Ga. Rather it saw its pre-2.56 Ga granite-greenstone patterns moderately shortened and distorted along the strike-slip shear zones. The WDC has been protected from rejuvenation at 2.56–2.51 Ga because it was shielded by a lithospheric root already built, at least partly, by 2.61 Ga [Jayananda *et al.*, 2006]. By contrast, the EDC had virtually no mantle lithosphere during Latest Archean tectonomagmatism. This contrast may still be seen in today's drastically different crustal and lithospheric thicknesses of the WDC and EDC [Sandeep Gupta *et al.*, 2003a, 2003b], indicative of diachronous and distinct cratonization process of the two lithospheric segments (Figure 9).

[56] The craton-scale arcuate conjugate shear zone pattern may be seen as an interference between two shear systems: a NE trending dextral shear system in the south and a sinistral, WNW trending shear system in the north (Figure 6). The



**Figure 9.** Sketch summarizing Late Archean (<2.56 Ga) shear zone pattern and kinematics of the Dharwar craton. WDC-Western Dharwar craton; EDC-Eastern Dharwar craton. Crust devoid of post-2.61 Ga granitoids (WDC) is shown in grey. Relative crustal thicknesses are adapted from Sandeep Gupta *et al.* [2003a]. Main shear zones of the Western Dharwar craton offset the Moho [Sandeep Gupta *et al.*, 2003a; Jayananda *et al.*, 2006], attesting to its high strength in the late Archean compared to the Eastern Dharwar craton.

central domain of the EDC is a buffer zone between the two shear systems (Figures 3 and 6) where the macroscopic conjugate shear zone pattern and the composite fabric accommodating crustal flow are best preserved.

[57] Kinematics of the interfering shear systems described above are compatible with radial shortening and concentric stretching of a continental arc (the EDC) being indented by the less deformable WDC (Figure 9). Within that framework, shear zones, which have limited finite horizontal slip, are transfer shears adjusting strain incompatibilities between differentially flowing lens-shaped domains during lateral extrusion and spreading of the arc. Indentation of the EDC could have accompanied early diffuse slip of the Moyar shear zone. This hypothesis is supported by the fan-shape pattern of shear zones in the charnockitic crust after restoration of slip along the Moyar shear zone (Figure 8).

## 8.2. Proterozoic Tectonics at the Southern Margin of the Craton

[58] The last stages of Late Neoproterozoic orogeny at the southern margin of the Dharwar craton did not involve major transcurrent displacements. Strain patterns of the SMDC resulted from pure shear-dominated transpression accompanied by downdip stretching/shearing within the shear zones. HT-HP metamorphism along the Cauvery shear system is consistent with vertical extrusion having taken place within the shear zones as a result of high-angle or

even head-on convergence [e.g., Thompson *et al.*, 1997; Jain *et al.*, 2003].

[59] One may speculate that final assembly of this part of Gondwana did not involve large transcurrent displacements because of the peculiar geometric configuration of the Neoproterozoic mobile belts fringing the Dharwar craton. Indeed, the Cauvery shear system lies in the hinterland of a syntaxis connecting the East-African NW trending mobile belts and the East Indian - Enderby Land mobile belts trending N-S (relative to today's orientation of Peninsular India; e.g., Chetty [1995] and Martelat *et al.* [2000]).

## 9. Conclusions

[60] The present work provides general insights into the mechanical behavior of continental lithospheres in the Precambrian. These may be summarized as follows.

[61] 1. Newly formed/rejuvenated continental lithosphere lacks a stiff mantle and responds to shortening by flowing laterally against a previously stabilized continental nucleus that develop moderate strain. Flow of weak lithosphere operates without significant thickening because the juvenile/rejuvenated crust flows under its own weight and cannot sustain thickening.

[62] 2. Crustal-scale shear zones do not accommodate significant displacement and do not play a major role in the deformation of weak lithospheres. They contribute to smoothing out of late strain heterogeneities between differentially flowing rock masses, flow being also noticeably partitioned between greenstones and gneisses due to their contrasted density and strength. Shear zone patterns and kinematics in weak lithospheres therefore primarily reflect the symmetry of the regional finite strain field of wide hot orogens.

[63] 3. Finite strain and shear zone patterns developed in weak Precambrian lithospheres do not result from terrain amalgamation but from later crustal flow. Contrary to the common view, these strain fields are not readily comparable to those of Phanerozoic active margins, which are characterized by unidirectional partitioned transpression.

[64] 4. Shear zones bounding Archean cratons may not have recorded large horizontal displacements during final assembly of Gondwana in the late Neoproterozoic but rather transverse shortening and vertical extrusion.

[65] **Acknowledgments.** This study is dedicated to the memory of Hugues Bouhallier. We are indebted to P. Choukroune for starting Indo-French structural investigations in the South Indian Archean and for guidance and encouragement since then. We thank B. Mahabaleswar for support and discussions over the years. T. R. K. Chetty thanks the director, NGRI, for encouragement and permission to publish these results. Fieldwork was funded by the Indo-French Centre for the Promotion of Advanced Research (projects 1111-1 and 2307-1). LANDSAT TM images were used courtesy of NASA (<https://zulu.ssc.nasa.gov/mrsid/>). The paper benefited from constructive reviews by A. Cruden and an anonymous referee.

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