Structural architecture and geological relationships in the southern part of Chitradurga Schist Belt, Dharwar craton, South India

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Detailed structural mapping in the southern part of Chitradurga Schist Belt (3.0–2.5 Ga) (CSB) distributed around the Chikkanayakanahalli–Kibbanahalli area was carried out. Sargur Group, Basement Gneiss, Bababudan Group, Chitradurga Group, and Hiriyur Group of rocks are well preserved in the investigated area. Unconformable relation between Basement Gneiss–Sargur Group and Bababudan Group is defined by oligomict conglomerate with quartzite clast and occasionally preserve granite clast. A polymictic conglomerate separates Bababudan and Chitradurga Groups; similarly, Chitradurga and Hiriyur Groups are also separated by a polymictic conglomerate. A new zone, Akkanahalli Zone, in the eastern margin of the study area is proposed which is belonging to Sargur Group. Zircon grains in the metatuff sample from this zone provide an age of 3313 ± 6 Ma. Six stages of deformation events are recognized in the study area. General trend and megascopic structures in the mapped area have resulted from the earlier two stages of deformations (D2 and D3). The D2 stage structure is distinctly characterized by a fold–and–thrust belt consisting of a NNW–SSE trending fold zone sandwiched between a pair of NNW–SSE trending thrust faults dipping east. Deformation during the D3 stage resulted in regional-scale sinistral shear zones, such as N–S striking Gadag–Mandya Shear Zone, and narrow N–S and NW trending sinistral ‘echelon’ shear zones. Based on our structural and field relationship it is proposed that CSB developed in an immature or failed rift setting where shallow marine sequence and shelf deposits are predominant. Sediments and volcanic rocks were unconformably deposited horizontally above Basement Gneiss and later got deformed together in a sinistral transpression setting.

Keywords: Dharwar craton, Chitradurga Schist Belt, Fold-and-thrust belt, Transpression

INTRODUCTION

The Archean-Proterozoic (3.0–2.5 Ga) transition is regarded as a period when substantial modification of the crustal process occurred (Nicoli et al., 2016). Several researchers considered this stage in the Earth’s history as the kickoff period for plate tectonics (e.g. Belousova et al., 2010; Dhuime et al., 2017). Also, detritus supply to the convergent zones increased remarkably, and this sparked reworking of existed landmasses (Valley et al., 2005; Nicoli et al., 2016). Therefore, a detailed investigation of the 3.0–2.5 Ga transition period would provide important clues about crust–mantle evolution, crustal reworking, and tectonic settings in which the crustal growth has occurred (Jayananda et al., 2013).

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Dharwar Craton (DC) is a tilted crustal section exposing the granite–greenstone association in the north and granulites in the south (Radhakrishna, 1983). Archean-Proterozoic (3.0–2.5 Ga) rocks are well preserved in DC as several narrow greenstone belts (Jayananda et al., 2013). Chitradurga Schist Belt (CSB) is one among them and situated along the central part of the craton, which is widely studied using multi-disciplinary approaches (e.g. Chadwick et al., 1981, 2000, 2007; Gokarn et al., 2004; Chardon et al., 2011; Hokada et al., 2013; Mishima et al., 2017). However, detailed structural maps are absent for the southern part of the schist belt, except for some very local regions (e.g. Mukhopadhyay et al., 1981).

The motive for this work is to present a detailed geological and structural data for the southern part of CSB distributed in and around the Chikkanayakanahalli and Kibbanahalli area. Using this we will elucidate the structural and metamorphic evolutionary history of differ-
ent groups of rocks distributed in the study area. Based on the field and structural evidence, we have interpreted the depositional and deformational history of the CSB and discussed the regional tectonic implications.

**GEOLOGICAL BACKGROUND**

DC is conventionally divided into Western Dharwar Craton (WDC) and Eastern Dharwar Craton (EDC) (Fig. 1a) based on the differences in crustal thickness, characteristics and distribution of greenstones, Basement Gneiss and younger granites (Swami Nath and Ramakrishnan, 1981; Jayananda et al., 2006; Jayananda et al., 2013). WDC and EDC are separated by a steep mylonitized sinistral shear zone (Chitradurga Shear Zone) along the margin of CSB (Chadwick et al., 2000). This shear zone was represented as Gadag–Mandya Shear Zone (GMSZ), starting from Gadag in the north to Mandya in the south (Sengupta and Roy, 2012). WDC is composed of comparatively older (3.4–3.0 Ga) Peninsular Gneiss of TTG (Tonalite–Trondhjemite–Granodiorite) composition (Peucat et al., 1993). Greenstones of two different generations—older Sargur Group (>3.0 Ga) and younger Dharwar Supergroup (3.0–2.6 Ga) have been identified from WDC (Nutmam et al., 1992, 1996). Dharwar Supergroup is distributed in WDC as linear schist belts (Fig. 1a) such as Shimoga, Chitradurga, Bababudan, and Kudremukh Groups (Jayananda et al., 2013, 2018; Giri et al., 2019).

CSB is exposed as about 450 km long linear NNW-SSE trending belt from Gadag in the north to Mysore in the south and has a maximum width of around 40 km in the central region (Fig. 1a). The stratigraphic column in CSB can be summarized in decreasing order of age as Sargur Group, Peninsular Gneiss, Dharwar Supergroup, and the younger granites. Rocks of the Dharwar Supergroup are unconformably overlying older Basement Gneiss with enclaves of the Sargur Group (Ramakrishnan and Vaidyanadhan, 2010). Based on the stratigraphic relations the Dharwar Supergroup is divided into three formations: Vanivilas Formation, Ingaldhal Formation, and Hiriyur Formation (Sheshadri et al., 1981). Vanivilas Formation is composed of polymictic conglomerate, chlorite schist, limestone, and Mn–Fe formations. Ingaldhal Formation consists of basic, intermediate to acid volcanic and pyroclastic rocks. A greywacke–argillite sequence with BIF and metabasalts dominate in the Hiriyur Formation (Swaminath and Ramakrishnan, 1981). However, recent studies classified the Chitradurga Group into lower and upper units based on metamorphic grade and geochronological constraints (Hokada et al., 2013). Hiriyur Formation is separated from lower units (Bababudan Group, Vanivilas Formation, and Ingaldhal Formation) by an unconformity overlain by K.M. Kere conglomerate (Mishima et al., 2017).

Our study area is located in the southern part of CSB (Fig. 1a) in and around Chikkamagalur and in the west and Hagalavadi in the east (Fig. 1b). This part of the schist belt is mentioned as Chikkamagalur schist belt in some earlier studies (e.g., Radhakrishna 1983; Devaraju et al., 1986 and references therein). The detailed structural and geological maps were prepared for Doddaguni and Kondi areas, which are south of Chikkamagalur, where multiple deformation stages were identified (Murthi et al., 1981). In this study, we prepared detailed geological and structural maps for an area of ~ 300 km² (Fig. 1b). For the rest of this paper, we will focus on the geological and structural relationships in the evolutionary history of the southern part of the CSB.

**FIELD AND STRUCTURAL RELATIONSHIP**

The stratigraphic division that we followed in this study is mentioned in Figure 2, along with two other previous studies (Sheshadri et al., 1981; Hokada et al., 2013). We propose three divisions for the Dharwar Supergroup of rocks namely Bababudan Group, Chitradurga Group, and Hiriyur Group in descending order of their age. Major lithofacies in each group are also presented in Figure 2. Our field and structural evidence show that Bababudan Group and Chitradurga Group are separated by an unconformity in the Hiriyur Group, which is separated from the Bababudan Group by a polymictic conglomerate (Ramakrishnan and Vaidyanadhan, 2010). Traditionally, the Chitradurga Group is classified into three formations: Vanivilas Formation, Ingaldhal Formation, and Hiriyur Formation (Sheshadri et al., 1981). Vanivilas Formation is composed of polymictic conglomerate, chlorite schist, limestone, and Mn–Fe formations. Ingaldhal Formation consists of basic, intermediate to acid volcanic and pyroclastic rocks. A greywacke–argillite sequence with BIF and metabasalts dominate in the Hiriyur Formation (Swaminath and Ramakrishnan, 1981). However, recent studies classified the Chitradurga Group into lower and upper units based on metamorphic grade and geochronological constraints (Hokada et al., 2013). Hiriyur Formation is separated from lower units (Bababudan Group, Vanivilas Formation, and Ingaldhal Formation) by an unconformity overlain by K.M. Kere conglomerate (Mishima et al., 2017).

**Figure 1.** (a) Generalized map, showing distribution of schist belts in Dharwar Craton. Mapped area of Chitradurga Schist Belt is marked in the rectangle. Position of Dharwar craton in south India also shown in the top right corner of the figure. (b) Detailed map of Chitradurga Schist Belt near Chikkamagalur and Kibbanahalli area with legends and symbols. GMSZ and Akkanahalli Zone are marked separately. Location of felsic tuff sample analyzed for geochronology is marked by a star (c) Cross-section of marked locations (AB, CD, EF, KL, and MN) in the study area. Note the difference in horizontal length scales of two sets of cross-section (AB, MN and CD, EF, KL). Thin dash lines in the cross-section indicating trace of bedding and thick dash lines represent unconformity. Horizontal and vertical scales of cross-section are provided. WDC, Western Dharwar craton; EDC, Eastern Dharwar Craton; BG, Basement Gneiss; F, fault; UF, unconformity; GMSZ, Gadag Mandya Shear Zone.
formity marked by polymictic conglomerate. Similarly, based on our fieldwork for the past 4 years we would like to use the terminology ‘Hiriyur Group’ instead of ‘Hiriyur Formation’. This is supported by the fact that Hiriyur Group sediments have younger depositional ages (Hokada et al., 2013; Nasheeth et al., 2016), which demand a separate origin for the Hiriyur Group of rocks. Moreover, a regional–scale unconformity is marked in between Chitradurga and Hiriyur Groups of rocks in previous studies (e.g. Mishima et al., 2017). These criteria demand these rocks should be considered as part of a separate ‘Group’ than considering as a ‘Formation’ within the Chitradurga Group.

Field relations and major rock types of the study area are shown in Figure 3. Planar and linear structural features presented in stereonet are shown in Figure 4. Microphotographs of the important samples are presented in Figure 5.

**Sargur Group**

Sargur Group identified in the study area is dominated by metamorphosed ultramafic, mafic, and sedimentary rocks. Ultramafic and mafic rocks include komatiite, serpentinite, dunite, pyroxenite, gabbrro, amphibolite, and chlorite–actinolite schist. Meta–sedimentary rocks are dominated by fuchsite–bearing quartzite, magnetite schist, metacarbonate, and metamorphosed sandstone–mudstone successions with well–preserved graded bedding. Sargur Group of rocks is preserved as regional–scale enclaves within the Peninsular Gneiss which indicates it is the oldest group of rocks in the DC. Sargur Group separated from younger volcano–sedimentary rocks of Bababudan and Chitradurga Groups, either by unconformity or by strike–slip faults.

**Basement Gneiss**

TTG and granites identified from the study area are either massive or foliated in appearance with occasional mafic enclaves. Enclaves are generally amphibolite in nature and in some locations ultramafic enclaves are also present. Foliated TTG has biotite and muscovite along the foliation plane, however, near the GMSZ it generally has chlorite and muscovite aligned along the shear plane. Near Kibbanahalli, migmatites and weakly foliated granites with biotite along their foliation plane are also present. No cross–cutting relationship by granite on the CSB is observed.

**Bababudan Group**

Two oligomictic conglomerate units are observed towards 6 km south and 6 km east of Kibbanahalli, which form the bottommost layer of the Bababudan Group, rest directly above the Sargur Group and the Basement Gneiss (Fig. 1b). These oligomictic conglomerate have an amphibole–rich matrix and quartzite clasts (Fig. 3a) and mark the unconformity between Sargur Group–Basement Gneiss and Bababudan Group. Fining upward sequence in the clast distribution is evident in the outcrop scale. Bababudan Group of rocks are dominated by metamorphosed volcanic, volcanoclastic, and sedimentary rocks. Unlike the Sargur Group, ultramafic rocks are very rare in the Bababudan Group. Meta–volcanic rocks in the Bababudan Group are amphibolite, metabasalt, metadolerite, and chlorite–actinolite schist. Meta–dolerite cross–cuts amphibolite and metabasalt, indicating it is younger. Volcaniclastic rocks in the group are bedded–tuff and volcanic sandstone with randomly oriented amphibole grains (Fig. 5a). Cross–bedded fuchsite/muscovite–bearing quartzites (Fig. 3b), sandstone–siltstone/mudstone succession, stromatolite limestone, and BIF are major sedimentary rocks in the Bababudan Group exposed in the investigated area. Quartzite has well–preserved cross–bedding structures indicating a shallow marine depositional environment. Moreover, fuchsite mica in quartzite probably points to the common ultramafic source for them similar to the fuchsite quartzite in the Sargur Group. Limestones in the Bababudan Group have well–preserved stromatolite. These limestones are either calcite–rich or dolomite–rich, and dolomite aggregates are also seen as boudins inside calcite–rich portions. They are also present as alternating bands with quartzite,
Figure 3. (a) Deformed quartz pebble conglomerate to the east of Kibbanahalli with amphibole-rich matrix represents Basement Gneiss-
Bababudan unconformity (b) Cross-bedded quartzite of Bababudan Group (c) Slump deposits in BIF of Bababudan Group. Fe rich layer
injects into quartz layer indicating soft-sediment deformation is also marked in the bottom left corner. (d) Clast-supported, polymictic
conglomerate with granite and amphibolite clast. This outcrop exposed to the 8 km east of Kibbanahalli town and represents Bababudan-
Chitradurga unconformity. (e) 2 generation folding in Fe-formation of Chitradurga Group. D₂ folding with west-dipping axial plane. D₅
folding with E-W trending, shallow dipping axial plane, note the refolding of F₂ fold around F₅ axes (f) Intensely sheared and elongated
conglomerate from Chitradurga-Hiriyur Group boundary, showing east-side-up motion sense. (g) Sheared conglomerate in the eastern
margin of Chitradurga Group, with quartzite clasts in sandstone matrix showing a sinistral sense of movement (h) Conformable contact
relation between metatuff and chlorite-actinolite schist of Akkanahalli Zone.
Figure 4. Stereoplots of lineation, foliation and bedding from different parts of the study area classified based on the groups and deformation history. (a) Foliation planes in Sargur Group, as enclaves in basement gneiss (b) Lineation and poles to S3 foliation in Akkanahalli Zone (Sargur Group) rocks which are part of GMSZ. (c) Lineation and poles to S3 foliation in Basment Gneiss, part of GMSZ. (d) Poles to S0, S1, S2, and S3 with L2 and L3 lineations in Bababudan Group of rocks. (e) Poles to S0, S1, S2, and S3 with L2 and L3 lineations in Chitradurga Group. (f) Poles to S0, S1, S2, and S3 with L2 and L3 lineations in Hiriyur Group. (g) Poles to the S0, S1, S2, and S3 foliation of D2 folding in Bababudan and Chitradurga Group across AB transect in Figure 1c, data related to angular bedding relation is not included. (g) Poles to the foliations of D5 folding in the same AB transect. (h) Bedding relation between Bababudan and Chitradurga Group.
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which are cut across by younger quartz veins. A gradual transition from this banded limestone–quartzite to massive limestone, rich in muscovite is present in some locations to the northwest of Thimmanahalli.
Chitradurga Group

Unconformable boundary relation between the Bababudan Group and the Chitradurga Group is defined by a polymictic conglomerate located towards 8 km east of Kibbanahalli (Figs. 1b and 3d). This conglomerate is clast-supported in the major part of the exposure. Basaltic fragment-rich matrix is observed in some parts of the outcrop with granite, amphibolite and quartzite clasts. Toward SW of Hagalavadi, there is another conglomerate layer of 100 m-thickness, in the eastern margin of the Chitradurga Group (Fig. 1b). This conglomerate layer is completely different from the Chitradurga–Hiriyur boundary conglomerate; granite and quartzite clasts are present in them with a siliceous or shaly matrix. This conglomerate is severely sheared, and its clasts are strongly elongated (Fig. 3g). Bedding in Bababudan and Chitradurga Groups shows an oblique contact relation in the western part (Fig. 4i) and a parallel contact in the eastern part, probably because of their angular to parallel unconformable relation and similar relationship is also present in the geological map (Fig. 1b). Corresponding to this, cross-sections (AB and MN in Fig. 1c) also depict the angular and parallel unconformable relation in the west and the east, respectively within the folded zone. Major rock types within the Chitradurga Group of the study area are metabasalt, metapelites, iron formation (both banded magnetite quartzites and Mn-bearing iron formations, Fig. 3e), felsic volcanics, and limestone. Basalt in this group is metamorphosed under the greenschist facies condition. In the study area, these basalts are present above sandstone-mudstone succession and metapelites (see cross-sections EF and KL in Fig. 1c). Limestone in the Chitradurga Group is seen as lenses in metapelites and Fe-formation.

Hiriyur Group

Stratigraphically the Hiriyur Group overlies the Chitradurga Group. Our detailed field observation near the contact zone shows that both groups are separated by an unconformity to the east of Thimmanahalli (Fig. 1b). This unconformity is represented by a 600 m-thick conglomerate layer (Fig. 3f) and has a ferruginous sandstone matrix with clasts of schist, granite, BIF, basalt, and quartzite. Also, it is associated with sandstone-mudstone succession. Hiriyur Group is dominated by the presence of metatuff waacke with quartz, feldspar, calcite, chlorite, and muscovite as the main assemblage (Fig. 5c). Primary depositional features such as graded bedding are also well-preserved. Near Buddigudda kaval ~ 6 km northeast of Thimmanahalli, a ~ 5 km wide mafic volcanic rock unit is observed which is the youngest unit in the Hiriyur Group (See cross-sections CD and EF in Fig. 1c). This mafic unit generally has fine-grained NW-SE trending, weakly deformed metabasalt. We assume contact between these mafic units and sedimentary rocks is a conformable one, even though clear contact relation is not preserved. Other than metatuff waacke, layers of BIF, and ferruginous chert are also identified in the Hiriyur Group.

Metamafic to metaultramafic rocks (Akkanahalli Zone)

To the east of the Hiriyur Group and the western edge of GMSZ, a zone of metamafic/metaultramafic rocks along with layers of metamafic BIF are present. This zone is in fault contact with the Hiriyur Group. While, in the southeastern part of the study area, this zone is in fault contact with the Chitradurga Group. Faults which mark the boundary in this region show a strike-slip sinistral sense of movement. Metamafic and metaultramafic rocks are generally rich in dolomite, chlorite, actinolite, and quartz (Fig. 5g). Moreover, opaque phases such as magnetite, chromite, rutile, and ilmenite are present as inclusions within chlorite and dolomite. Metatuff is in conformable contact with metamafic rock (Fig. 3h). All the rock types in this area are strongly foliated and asymmetrical fold and asymmetrical shear structures are also present.

U–Pb analysis in 90 spots on 90 grains of zircon from the metatuff sample in Akkanahalli Zone was carried out using the Agilent 7500a quadrupole ICPMS with laser ablation system of New Wave Research UP-213 in Nihon University. We followed analytical procedures described in Ueda et al. (2018). Calibrations and data quality control were undertaken using the standard silicate glass SRM610 and 91500 standard zircon. The accuracy of our analyses was verified using the Plešovice zircon.

The metatuff sample is rich in quartz and plagioclase, minor quantities of K-feldspar is also present and, muscovite is developed along shear planes (Fig. 6a). Zircon grains are generally present along grain boundaries and as inclusions in muscovite. Zircon grains in this sample are 50–100 µm long, euhedral, elongated and show oscillatory zoning indicating magmatic crystallization (Fig. 6b). Nine concordant grains provided a weighted mean of $^{207}\text{Pb} / ^{206}\text{Pb}$ ages as 3313 ± 6 Ma with an MSWD of 1.3 (Fig. 6d), which is also consistent with an upper intercept age of 3318 ± 13 Ma (Fig. 6c) for the discordant grains. The weighted mean of $^{207}\text{Pb} / ^{206}\text{Pb}$ of all the analysis including discordant grains (3311 ± 7) is almost identical to that from discordant grains. This result supports that $^{207}\text{Pb} / ^{206}\text{Pb}$ was fairly robust during the lead loss event.
and based on these facts 3.31 Ga is considered as crystallization age of the felsic tuff sample.

Metatu­ff is in conformable contact with metama­fi­c rocks (Fig. 3j) and points to the fact that this entire metamorphosed metavolcanic–metaultramafic association belongs to the older Sargur Group. The presence of a conglomerate layer (Fig. 3g) to the SW of Hagalavadi implies unconformity between Sargur and Chitradurga Groups. Similar metatu­ff–meta­ma­fi­c rock conformable relation is reported from the Holenarsipur Schist Belt of Sargur Group by Peucat et al. (1995), felsic volcanic (rhyolite flow) in their study also shows crystallization age of 3.298 ± 7 Ma.

Since this metamafic/metultramafic rock zone is lithologically different from other parts of the CSB, we will address it as Akkanahalli Zone (AZ) hereafter.

**Structural relations in CSB**

Six events of deformation processes are identified, based on the nature and sequence of deformations in the study area (Fig. 7). Four early–stage deformations (D0 to D3) are of penetrative type, but the later–stages (D4 and D5) are of non–penetrative type, forming localized shear zones and minor folds.

D0 event is characterized by the formation of lithological boundaries, bedding, sedimentary structures, and slump folds (Fig. 3c). Slump folds, which have no axial plane cleavage, are well–preserved in BIF and limestone formations. In BIF, soft–sediment deformation signatures such as injection of the iron–rich layer into the quartz–rich layer are examined (Fig. 3c). We interpret this type of structure as developed before the solidification of sediments, i.e. syn–sedimentary deformation. Angular, poorly sorted and fractured BIF distributed in the iron matrix are also associated with this type of folding in BIF. Slump folding and sedimentation followed by the formation of bedding–parallel schistosity (S1) which has occurred during peak metamorphism (D1). The observed S0 and S1 structures are commonly deformed by the post–D1 deformations and associating recrystallization of metamorphic minerals, so deformation and tectonics during the D0 and D1 are difficult to understand.

The D2 stage is characterized by an NNW–SSE trending fold zone sandwiched between NNW–SSE trending reverse faults dipping east with dip–parallel lineation (L2), showing an east–side–up motion sense (Figs. 3f and 5f). Two major reverse faults identified from the study area are in the Basement Gneiss–Bababudan Group and Chitradurga–Hiriyur Group boundary zone (Figs. 1b...
A fold zone is made up of five F2 folds on a geological map—scale (Fig. 9). These F2 folds in the fold zone are tight to isoclinal. They have NNW–SSE trending, vertical to west–dipping axial planes and 10–20° plunging hinge lines (Fig. 4g). Their plunging directions vary from the south to the north on a regional scale. These folds exhibit a well-developed NNW–SSE trending axial plane cleavages (S2). Wavelengths of these folds range from 1–4 km (cross-sections AB and MN in Fig. 1c). Field and microscopic observations show some typical examples for cleavage refraction and buckling due to the competency contrast between lithologically different layers (Fig. 5d). Field and microscopic observations show some typical examples for cleavage refraction and buckling due to the competency contrast between lithologically different layers (Fig. 5d). Due to the folding and rotation of bedding (S0) and schistosity (S1) by D2 deformation, S0, S1, and S2 generally trend NNW–SSE in the Bababudan Group (Fig. 4d), Chitradurga Group (Fig. 4e) and Hiriyur Group (Fig. 4f). Sargur Group as enclaves in the Basement Gneiss have generally E–W trending foliation (Fig. 4a). Sargur Group of the Akkanahalli Zone has N–S trending vertical foliation (Fig. 4a). Sargur Group of the Akkanahalli Zone has N–S trending vertical foliation (Fig. 4a). D3 event is recognized as a regional scale strike-slip dextral shear. D3 shear zones ranging from few centimeters to kilometer-scale thickness are identified from the study area. The whole Akkanahalli Zone and Basement Gneiss to the east of Akkanahalli Zone were strongly sheared during D3 and formed the major sinistral shear zone. This shear zone is 1–2 km wide, N–S striking and nearly vertical dipping GMSZ (Figs. 1b and 9). In GMSZ, the N-S trending shear planes (S1) and horizontal lineations (L1) are strongly developed (Figs. 4b and 4c). This points to the fact that GMSZ extends into the schist belt rather than restricting in the granitic rocks. N–S or NNW–SSE trending minor D3 shear zones are sometimes observed across all Groups in the map (Fig. 1c) and S1 shear planes are locally developed (Figs. 4b–4f). From the geological map in Figure 1c, it is evident that D2-related reverse faults are cut across by D3 sinistral shear zones. Since attitudes and shear sense of D3 shear zones do not vary between limbs of F2 fold, D3 shearing is considered to be unmodified and predated by D2 folding.

Dextral shear zones are identified from two localities (to the east of Chikkana yakanahalli and to the west of Hagalavadi) with NW–SE strike, dipping to the east and N–S strike with vertical dip, respectively (Figs. 1b and 9). N–S trending dextral shear zone associated with quartzite to the west of Hagalavadi can be traced at least 20 km along the strike (Fig. 1b) and is approximately 100 m wide. These strike-slip dextral shear zones, in which strong S4 foliation developed were resulted from the D4 event. F2 folds are refolded by Type 3 interference folding in local scale within some parts of the study area and formed E–W trending folds with almost horizontal axial planes (Figs. 3e and 4h). In this study, these minor folds (F5) are regarded as the resultants of the final, D5 stage of deformation event even though the spatial relation between D4 and D5 events is not clear.

**MICROSTRUCTURAL DETAILS AND METAMORPHIC RELATIONS**

Metavolcanic rocks of Bababudan Group in the CSB are mainly metamorphosed in the amphibolite grade (Fig. 5a). Preliminary analysis shows that these amphiboles are Ca-rich, indicating low-grade amphibolite facies condition. Amphiboles are grown in S1/S2 foliation planes indicating that the deformation has occurred during amphibolite facies conditions at least in metavolcanic rocks. Volcanoclastic sandstone has more quartz and plagioclase in the matrix with two types of amphiboles. One generation of amphibole grains are aligned parallel to the foliation (type A), and other generation of amphiboles (type B) are randomly aligned (Fig. 5a). This implies two-generation amphibole growth in the Bababudan Group, and the exact reason behind this is not clear yet. In chlorite–actinolite schist, chlorite is seen as the crenulated porphyroclast within a quartz-rich matrix, and actinolite is developed along S4 shear planes (Fig. 5b). S–C–C' relation shows...
a dextral sense of movement. Pyrite is also present as an accessory phase in this sample. Quartzites in the Bababudan Group are having muscovite in their \(S_2/S_3\) foliation plane; in some localities presence of fuchsite is also noted.

For samples from Chikkaramapura (13 km NE of Kibbanahalli) within a narrow shear zone in the Bababudan–Chitradurga Group boundary, biotite is seen along ‘\(S\)’ foliation, and muscovite is developed along ‘\(C\)’ planes, and S–C fabric shows a sinistral sense of motion (Fig. 5e). Similarly, within folded samples also muscovite is developed along the grain boundaries of biotite, indicating the same retrograde metamorphic condition for both \(D_2\) folding and \(D_1\) shearing (Fig. 5d). In some samples two generations of biotite are present, the first generation in the matrix is probably detrital in origin. The second generation of biotite is developed along the shear planes along with muscovite.

Hiriyur Group rocks have chlorite and muscovite developed along the shear planes. Typical sandstone from Hiriyur Group has quartz, plagioclase, calcite and muscovite as the main assemblage, with chlorite and muscovite aligned along the \(S_1\) foliation plane (Fig. 5e). Shear related, \(S_1\) foliation shows a sinistral sense of motion (Figs. 5c and 5e). S–C–C’ fabric defined by muscovite and asymmetrical tails around quartzite clast in the conglomerate sample of the Chitradurga–Hiriyur boundary shows east–side–up motion sense (Figs. 3f and 5f), indicating a reverse sense of movement.

Sheared rocks from the Akkanahalli Zone of GMSZ also have chlorite in the shear plane, and some samples have muscovite developed along the \(S_1\) shear plane (Fig. 5g). S–C–C’ shear planes are prominent, suggesting a sinistral sense of movement.

It is evident from the above-mentioned fact that, from the lower to upper layer of the stratigraphic column, the metamorphic grade has a transition between Bababudan, Chitradurga, and Hiriyur Groups along with the Akkanahalli Zone. Metavolcanic rocks in the Bababudan Group are metamorphosed in amphibolite facies condition. Metasedimentary rocks in both, Bababudan and Chitradurga Groups are metamorphosed in biotite–muscovite grade, but the Hiriyur Group, Akkanahalli Zone, and GMSZ region are metamorphosed in muscovite–chlorite grade, consistent with the observations in Hokada et al. (2013).

**DISCUSSION**

**Depositional environment of CSB**

The stratigraphic and structural discontinuities across different groups are evident in our field observations, geological map (Fig. 1b), and structural cross-sections (Fig. 1c). Previous geochronological data of sedimentary rocks from the CSB also support this notable difference in the age of source rock for different groups. The oldest age of sedimentation of rocks from the Bababudan Group and the Chitradurga Group are well-bracketed within the age limit 3.14 Ga and 3.22–2.92 Ga, respectively (Hokada et al., 2013). This indicates that basement rocks including granite and the Sargur Group probably served as a source for sediments of Bababudan and Chitradurga Groups. Chadwick et al. (1981, 2007) highlighted that the variable uplift of the basement rocks probably initiated the deposition of conglomerate as sedimentary slumps in the basin. The basal conglomerate of the Bababudan Group of our study is composed of coarse fragments of quartzite and a finer-grained elastic matrix. The matrix in sandstone is made up of sand-sized grains of quartz, feldspars, metavolcanic clasts, and mafic and ultramafic mineral particles. Based on this fact, we consider that the basal conglomerate was deposited in a basin close to the mafic volcanic source and quartzite-rich source.

The Bababudan Group of rocks which rest above the basal conglomerate is marked by an abundance of cross-bedded quartzites, volcanoclastic sediments, and amphibolites and lack of deep marine formations. Cross-bedded quartzites of the Bababudan Group from the study area are considered as shallow marine tidal deposits, similar to the interpretation made on cross-bedded quartzites and sandstone–mudstone facies association from the western margin of the CSB by Bhattacharya et al. (2015) and Kataoka et al. (2015). Stromatolite limestones also imply a shallow marine depositional environment for the Bababudan Group. Association of BIFs and cross-bedded sandstones within the Bababudan Group points to their shallow marine origin. Slump folding and syn-sedimentary deformation structures in BIFs of the Bababudan Group indicate their deposition in an active tectonic environment. The abundance of amphibolites and volcanoclastic sediments suggests active mafic volcanism during the formation of Bababudan Group. Moreover, our field observations did not show any evidence of accretionary mélanges, deep-marine sediments, and ophiolite sequence of oceanic crust within the Bababudan Group. From field and stratigraphic relations, it is clear that sedimentation and basin filling of the Bababudan Group started from basal conglomerate deposited directly above the Basement Gneiss and were followed by shallow-marine sediments.

The basal polymictic conglomerate of the Chitradurga Group unconformably covering Bababudan Group have clasts of both amphibolites and granites, showing that the basement and Bababudan Group were the possi-
ble source rocks (Fig. 8a). Chitradurga Group in the study area is rich in iron formations. Mn-bearing iron formations in the Chitradurga Group underlain by orthoquartzite and sandstones have similar stratigraphic relation with Armod–Bisgod region’s Mn formation of the WDC (Sethumadhav et al., 2010). Based on this, Mn formations in our study area are also interpreted to be deposited in localized shelf margins or shallow shelf niches similar to the Armod–Bisgod region. As described earlier, slump folds and deposits dominated in BIF formations of the Chitradurga Group also points to their deposition in an active tectonic, shallow marine environment. The geochemical study of the BIF around the Chitradurga region of CSB also shows deposition in an evolving rift environment (Rao and Naqvi, 1995). An early rift stage to arc-back arc spreading tectonic setting is attributed to the BIF in the Dharwar craton (Mukhopadhyay, 2019). The aforementioned points also support the fact that the BIF was evolved in an immature oceanic environment. As discussed above, similar to the Bababudan Group, shallow–marine sediments dominate the Chitradurga Group. Moreover, our field observations did not produce any evidence of accretionary mélanges, deep–marine sediments and ophiolite sequence of oceanic crust within the Chitradurga Group.

The Hiriyur Group unconformably overlies the Chitradurga Group (cross-sections CD and EF in Figs. 1c and 8b). A major population of detrital zircon grains in the Hiriyur Group is having an age of ~ 2.63 Ga (Hokada et al., 2013). Youngest detrital zircon reported from the Hiriyur group is 2.54 Ga whereas older ones >3.0 Ga are also reported (Nasheeth et al., 2016). The provenance of these zircon grains is interpreted as rocks derived during the second stage of the crustal formation event (2.58–2.54 Ga) as proposed by Jayananda et al. (2013). The above fact implies that sediments of the Hiriyur Group were supplied from the eastern part of the study area, consistent with Nasheeth et al. (2016). Metabasalts including pillow lava is present within the Hiriyur Group in the northern part of the CSB and our study area also. These pillow lavas are chemically similar to be emplaced in shallow marine marginal inter/back–arc basin settings (Duraswami et al., 2013). We interpret that the Hiriyur Group was formed as a comparatively younger failed rift and thrust upon to existing crustal mass during the final shortening process (Figs. 8b and 8c).

Figure 8. Simplified sedimentation and deformation related structures interpreted on a regional scale for the study area, a view from south (not to scale). (a) Depositional relation between Chitradurga and Bababudan Group, note angular to parallel unconformity between two groups. (b) Depositional relation between Chitradurga and Hiriyur Group. (c) Schematic section of the study area, fold zone is sandwiched between two listric thrust faults and GMSZ post-dates thrust zones. This schematic section resembles a fold–and–thrust belt developed in an inversion tectonic related rift margins. Combination of reverse faults and GMSZ represent sinistral transpression. G, Basement Gneiss; S, Sargur Group; B, Bababudan Group; C, Chitradurga Group; H, Hiriyur Group.
Hokada et al. (2013) described the metamorphic grade in Bababudan Group, Chitradurga upper unit and Chitradurga lower unit as low-grade amphibolite, biotite-muscovite, and muscovite-chlorite respectively. Our study area, 60 km south of their study area, also has identical metamorphic mineral assemblages. From this fact, we consider that metamorphic grade variation is regionally preserved throughout the CSB.

**Structural evolution of CSB**

In the central to the western part of the study area, there is an NNW–SSE trending F₂ fold zone consisting of two anticlines and three synclines with the NNW–SSE trend. The fold zone is sandwiched between two NNW–SSE trending D₂ reverse faults (Figs. 8c and 9). A combination of folds and reverse faults with the same trend characterizes fold-and-thrust belt, inverted back-arc basin and failed rift, in which reverse faults have a listric shape (e.g., Sato and Kato, 2010; Poblet and Lisle, 2011). Considering the competency of granite, it is unlikely that thick granite basement and thin schist layers (thickness of less than several kilometers) form together anticlines and synclines with a wavelength of 1–4 km. To avoid folding of a thick granite and thin schist layers together, the NNW–SSE trending reverse faults bordering the fold zone should have a listric shape passing under the fold zone and separate the folded schist layers from the basement granite. Moreover, geophysical studies around the southern part of CSB shows the thickness of sediments overlying Basement Gneiss is 0.5–2 km (Bhagya and Ramadass, 2016). From these, it is considered that the NNW–SSE trending reverse faults are thrusts with a listric shape and together with F₂ fold zone form a fold-and-thrust belt in the study area (Fig. 8c). NNW–SSE regional trend of CSB results from folding, faulting, and rotation of rocks by the D₂ deformation.

Jayananda et al. (2013) pointed out the presence of 3.27 Ga felsic volcanic rocks to the south of Chitradurga town. A 3.32 Ga old felsic volcanic rock occurs in the northwestern part of the Akkanahalli Zone (Fig. 1b), suggesting that both volcanic rocks and the zone belong to the Sargur Group. The Akkanahalli Zone is strongly sheared and folded during D₂, D₃, and D₄. Therefore, we consider that the Akkanahalli Zone was juxtaposed to the younger sequences during the shortening/collision events (D₂ to D₄) and modified by strike-slip shear during the D₄ event. A similar model is proposed for the shortening process along the boundary zone in the central part of CSB by Sengupta and Roy (2012). The presence of older rocks of the Sargur Group both in the east and the west of the study area supports the notion of the development of failed rift by the fracturing of relatively older basement nucleus.

Our study indicates sinistral shearing (D₃) after ENE–WSW shortening (D₂) in CSB. Chadwick et al. (2000) proposed sinistral transpression by oblique con-
vergence in DC. Sinistral transpression causes simultaneous zone-normal shortening and zone-parallel (strike-slip) sinistral shearing. Temporal and spatial partitioning between the shortening (folding) and shearing can also take place. It is possible that shortening (D3) and sinistral shearing (D3) in the CSB was caused either by strain partitioning during the transpression or by two separate tectonic events.

Previous works explained sinistral transpression was derived from the subduction-related accretionary processes in the Dharwar craton (Chadwick et al., 2000; Jayananda et al., 2013; Manikyamba et al., 2017; Giri et al., 2019). However, our study shows that sedimentary rocks in the study area are not typical of an accretionary prism of subduction origin, but maybe sedimentary rocks that fill a narrow basin, that is, a failed rift zone, created by breaking off a wider granitic continent. The presence of older (>3.0 Ga) Sargur Group rocks on the west and the east (Akkanahalli Zone) of the belt favors this view. Maibam et al. (2011) proposed that WDC and EDC formed as part of a single terrane, using Pb-Pb zircon ages of para- and ortho-gneisses from DC. Their interpretation also supports our idea, a narrow basin (CSB) created by breaking off a stable granitic continent. Therefore, it is considered that the sinistral transpression was created by post-rifting, inversion tectonic related collision events.

The dextral rotation (D4) after the sinistral event (D3) is also identified in the study area. This dextral event possibility associated with the evolution of Clospet granite (Moyen et al., 2001).

Implications for the evolution of DC and Archean crustal growth

Jayananda et al. (2013) explained the Archean crustal growth of DC by the two-stage accretionary scenario considering a west-dipping subducting oceanic slab beneath the WDC and then the EDC. They also showed in their “figure 20” that during the accretion, huge bodies (juvenile arcs) of mafic and felsic rocks had collided with WDC, and DC had grown toward the east. In the previous works, it is mentioned that the Chitradurga Group was formed in the arc or back-arc environments (Chadwick et al., 2000; Jayananda et al., 2013), whilst the Bababudan Group developed in the continental intraplate setting (Chardon et al., 1998). Our study shows that CSB is neither arc nor subduction origins, but maybe sedimentary rocks that filled a narrow failed rift zone, created by breaking off a wider granitic continent. Kusky et al. (2018) proposed that the formation of aulacogens played a vital role in 3.0–2.5 Ga crustal growth. Therefore, we consider the formation of failed rifts is one of the important processes of the continental growth of the DC, at least in the WDC. Moreover, a comparatively thicker oceanic crust in the Archean (Sleep and Windley, 1982) probably get accreted by transpression associated with the strike-slip movement as observed in this study.

CONCLUSIONS

Detailed field and structural studies in the southern part of CSB were carried out. Unconformable relations between basement rocks, Bababudan Group, Chitradurga Group, and Hiriyur Group are identified. Geological and structural relationships between different rock types show these unconformities developed in a sedimentary setting within a shallow marine environment. A progressive change in the metamorphic grade from the Bababudan Group to the Hiriyur Group is observed. Six stage deformation processes are identified from the study area. Four early stages (D0 to D3) deformations were of penetrative type, but those of the later stages (D4 and D5) were of a non-penetrative type. D2 event is characterized by NNW–SSE trending isoclinal folds sandwiched between axial plane trace parallel, NNW–SSE trending east-dipping thrust faults. D3 event was dominated by sinistral strike-slip faults, represented as 1–2 km wide, N-S trending GMSZ and N-S to NNW–SSE trending minor shear zones/faults. D2 thrusting and associated folding along with D3 strike-slip faulting can be explained by the sinistral transpression mechanism. Volcanic and sedimentary rocks of the study area show characteristics evolved in a narrow basin of failed rift zone developed by the fracturing of basement rocks, rather than an accretionary prism evolving during the subduction process. Inversion tectonics related collision events should have resulted in sinistral transpression that post-date rifting events.

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