



Structures and Their Tectonic Implications of the Southern Part of Cuddapah Basin, Andhra Pradesh, India

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Abstract

Systematic structural observations in field outcrops can give clues to interpret orogenic events. Deformational structures studied in basement complexes as well as Cuddapah basinal sedimentary rocks indicate at least three events. The formation of N–S trending greenstone belts on gneissic basement complex is related to the oldest Kenoran orogeny. The later developed Hudsonian orogeny is related to opening of basin and numerous younger pluton as well as mafic dike emplacements. The Grenville or Eastern Ghats Orogeny is most intensively imprinted in the Cuddapah basin sedimentary rocks. The crescent shape of the Nallamalai fold belt in the east is due to the E–W compression related to thrusting followed by NNE–SSW compression. The E–W maximum compression (σ_1) is related to the Eastern Ghats Orogeny, which is responsible for the development of several sympathetic E–W faults due to N–S extension (σ_3). The formation of the Palaeo–Mesoproterozoic supercontinent Columbia is related to the E–W compression and the Napier Complex of east Antarctica connected with India occupying the indentation of the E part of the Cuddapah basin. Palaeostress study from the southern part of Cuddapah basin reveals that the initial E–W compression and associated fracturing produced E–W extensional regime, and subsequent NNE–SSW shear developed conjugate fracture set. However, the initial E–W compression was associated with the N–S extension component to develop broadly E–W parallel normal faults such as Vempalle fault and later strike-slip faults related to changes in the stress field. The proposed model explains the development and evolution of the Cuddapah basin as a new insight into the regional geodynamics.

Keywords Stress analyses · Palaeostress orientation · Tectonics · Deformation

1 Introduction

The intensity of structural deformation in the crescent-shaped Proterozoic Cuddapah basin (India) increases towards east. The Nallamalai fold belt, at the eastern part of the basin, consists of a deep crustal fault: the Rudravaram line (Meijerink et al. 1984; Nagaraja Rao et al.

1987; Matin and Guha 1996; Mukherjee 2001; Saha and Tripathy 2012; Matin 2014; Chetty 2011). The eastern margin of the Cuddapah basin is in thrust contact with Nellore Schist Belt which in turn is juxtaposed with the Eastern Ghats Mobile Belt (EGMB). The EGMB trends NE for ~ 900 km and thrust towards NW. EGMB is formed due to the Grenville orogeny or locally called as the Eastern Ghats orogeny. Out of two types of structural geometry in EGMB (Chetty and Murthy 1994), complex fold patterns are developed by compression. The later formed ductile shear zones are formed by strike-slip tectonics. The former suggests that the initial deformation phase causes isoclinal recumbent folding by NW-directed imbricate thrusting with NW vergence and a regional NE axial trend (Chetty and Murthy 1993, 1994). The later phase open folds with SE plunging axes to tight upright folds suggest ~ NNE–SSW compression. The tectonothermal events of the Pan-African orogeny related

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to formation of Late Neoproterozoic supercontinent Gondwana and opening of Neoproterozoic ocean between the African cratons and India/Antarctica (Mozambique Ocean) resulted from the breakup of Rodinia during 800–850 Ma (Kröner and Stern 2004). However, India and Antarctica were connected together during the Pan-African events and this is better manifested in the Southern Granulite Terrain (Meert et al. 2010) and also in the Cuddapah basin in the form of various orientations of younger fractures which have affected older trends and modified the basin margin (Goswami et al. 2016a). Because the formation of Gondwana encompassed several continents and extended from the Neoproterozoic to the early Palaeozoic, Pan-African orogeny cannot be considered a single orogeny, but rather an orogenic cycle that included the opening and closing of several large oceans and the collisions of several continental blocks. Later, the Indian Ocean opened in the Mesozoic by ESE–WNW extension related to the NNE–SSW compression. This produced the now crescent-shaped Cuddapah basin. Therefore, the crescent shape with convexity towards the west is possibly due to thrusting and subsequent NNE–SSW compression.

The Cuddapah basin with several sub-basins is a tectonically disturbed basin with different episodes of deformation. A systematic approach to describe the development of different sub-basins with time and tectonics has not so far been attempted in a comprehensive manner. This contribution is intended to fill the gap. The present study area along the southern part of Cuddapah basin (Figs. 1, 2) is mapped during the fieldwork and exhibits tectonic imprints of the EGMB in terms of E–W faults (Fig. 2) such as Idupulapaya fault and ~ northerly dipping Vempalle fault. The Geological Survey of India's overall map of the Cuddapah basin was used as a reference. The Vempalle fault, north to the Idupulapaya fault, runs ~ 40 km from Vempalle village in the west to Kadapa town in the east. It cuts all the three sub-basins of Cuddapah, viz., Papaghni, Nallamalai and Kurnool, and also the Rudravaram line (Goswami et al. 2012). The western tip of the E–W Idupulapaya fault is compensated against parallel strike-slip faults at high angle (Goswami et al. 2016a). These correspond to subsequent NNE–SSW compression after the Eastern Ghats Orogeny (~ 950–1100 Ma), possibly during opening of the Indian Ocean in the Mesozoic.

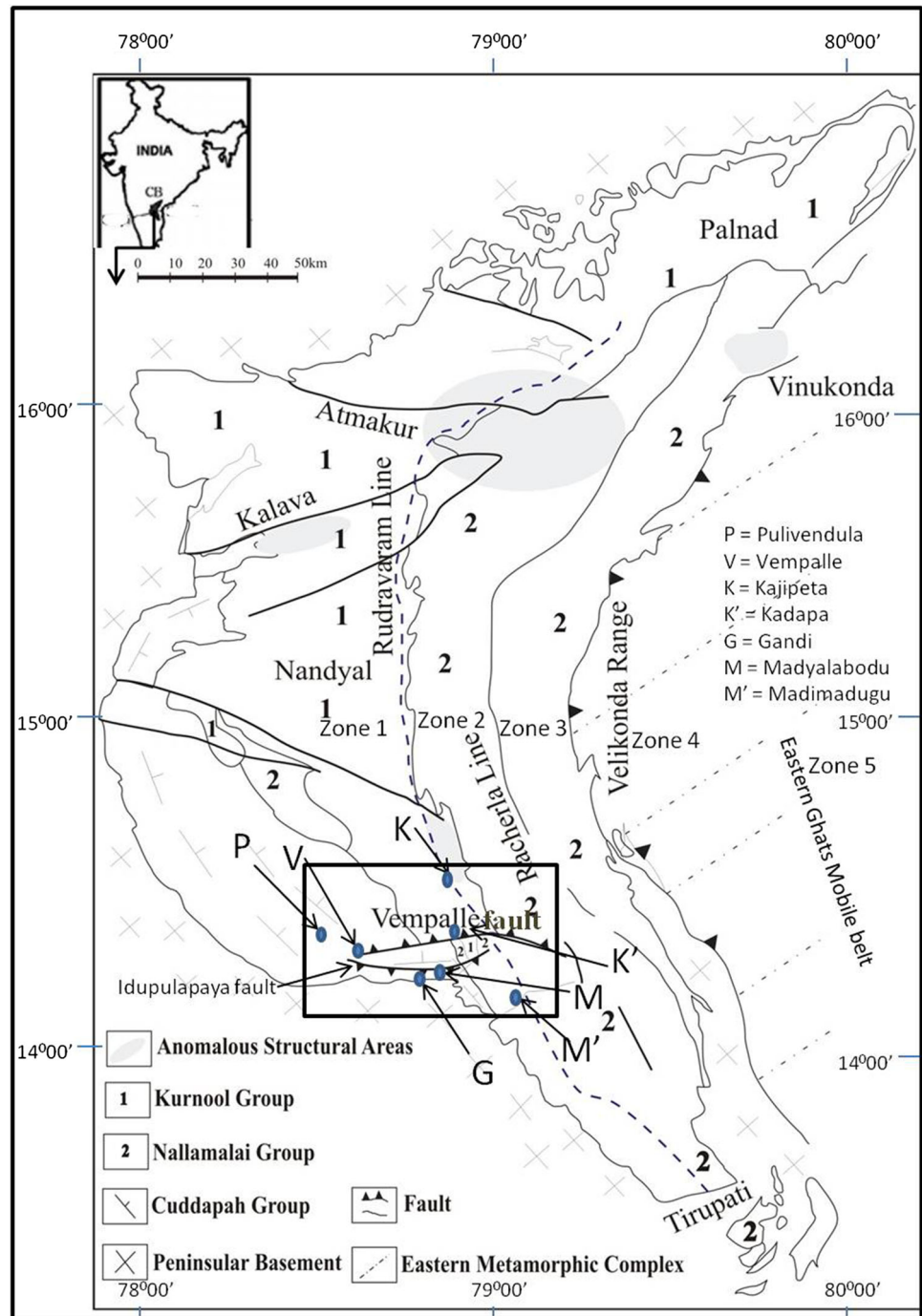
In this study, we document how deformation intensifies towards east and the deformational signatures from the basement rocks to younger sedimentary basinal rocks. This work derived a tectonic model to comprehend the basin evolution and explains the crescent shape of the basin.

2 Geology

The polyhistoric, intracratonic Cuddapah basin comprises the Cuddapah Supergroup and the Kurnool Group of sediments. The Cuddapah Supergroup is developed in Papaghni, Nallamalai and Srisailam sub-basins and Nallamalai Group is highly deformed and folded. The Nallamalai fold belt, east of these sub-basins, is affected intensely by the Eastern Ghats Orogeny and shows eastward tightened folds. At the contact between this fold belt and the “Krishna province” (Dobmeier and Raith 2003) at the westernmost part of the EGMB is a westerly dipping overthrust (Dasgupta et al. 2013). The Kurnool Group of rocks is deposited in the Kurnool and the Palnad sub-basins. The detailed stratigraphy, structures/tectonics, and evolution of the Cuddapah basin are given in Nagaraja Rao et al. (1987; also Ramakrishnan and Vaidyanadhan 2008; King 1872 for summary).

The sub-elliptical Papaghni sub-basin consists of the Papaghni Group of sedimentary, intrusive and volcanic rocks. The Papaghni Group consists of the Gulcheru Formation (conglomerate, sandstone and shale), and the Vempalle Formation (dolomite and shale) represents the lower part of the Cuddapah Supergroup. The upper part of the Vempalle Formation is marked by the presence of sills and basic flows (Nagaraja Rao et al. 1987). The overlying Chitravati Group is separated disconformably from the underlying Papaghni Group. The Chitravati Group consists of the Pulivendula Formation (quartzite), Tadpatri Formation (shale and dolomite) and the Gandikota Formation (quartzite). Conglomerates containing quartz, chert, jasper and volcanic clasts, grits and quartzitic sandstones of Pulivendula Formation overlie the Vempalle Formation in paraconformable contact. The Tadpatri Formation contains many basaltic and picritic sills and lava flows and acid volcanics. The litho units strike NNW at the NW part and dip 15°–17° due NNE. An E–W swing in strike with the northerly ~ 10° dip in the southern portion of Papaghni sub-basin is noteworthy. Nallamalai consists of the arenaceous dominated Bairenkonda and argillaceous Cumbum Formations (GSI 1981). The Nallamalai Group, in the southern part of the Cuddapah basin, rests over the Papaghni Group with an angular unconformity south to Kadapa town. Further south, it rests directly on the granitic basement (Fig. 1). Nagari quartzite (Bairenkonda—in the northern part) is a formation name and consists of conglomerate, grit and quartzite with shale intercalations. The polymictic conglomerate clast consists of quartzite, chert, jasper and vein quartz pebbles, set in a siliceous and ferruginous matrix. The Pullampet Shale (Cumbum—in the N part) Formation conformably overlies the Nagari quartzite. The Nagari–Pullampet formational contact is marked by

Fig. 1 Map of Cuddapah basin. Black rectangle indicates the study area. Modified after Meijerink et al. (1984). Patches show area of anomalous structures as shown by Meijerink et al. (1984)

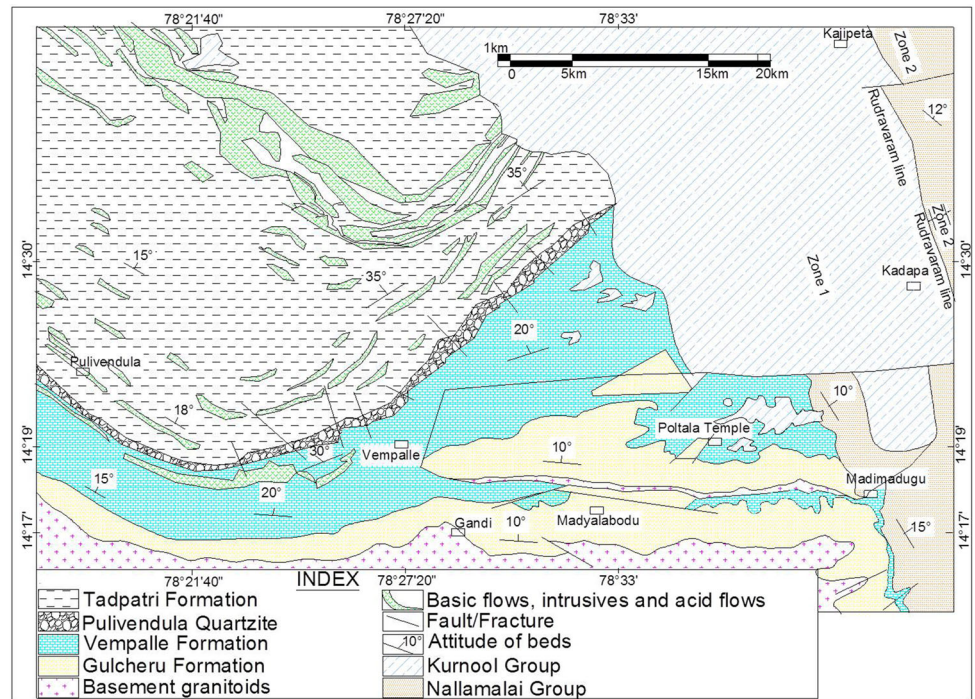


ferruginous chert and jasper with lensoid dolomites. In general, this formation is more calcareous than its equivalent Cumbum unit. The Kurnool Group of sediments is mainly under a soil cover in the study area. The Banganapalle quartzite lies as hilltop cappings surrounded by older Tadpatri and Gandikota Formation as outliers at places near Papaghni and Kurnool sub-basin margin. Koilkuntla limestone is grey, flaggy and at places massive. They are more siliceous and argillaceous than the Narji

limestone. The argillaceous Nandyal Shale has calcareous intercalations.

The basement of the Cuddapah basin is composed of a number of N–S trending greenstone schist belts, gneisses with N–S gneissic foliation, younger N–S oriented batholithic granitoids and mafic dikes and quartz reefs.

Fig. 2 Geologic map of the study area (toposheet no. 57J/7 and 11). An angular unconformity between the Kurnool and the Papaghni unit is shown at the central right part of the map



3 Field Observations

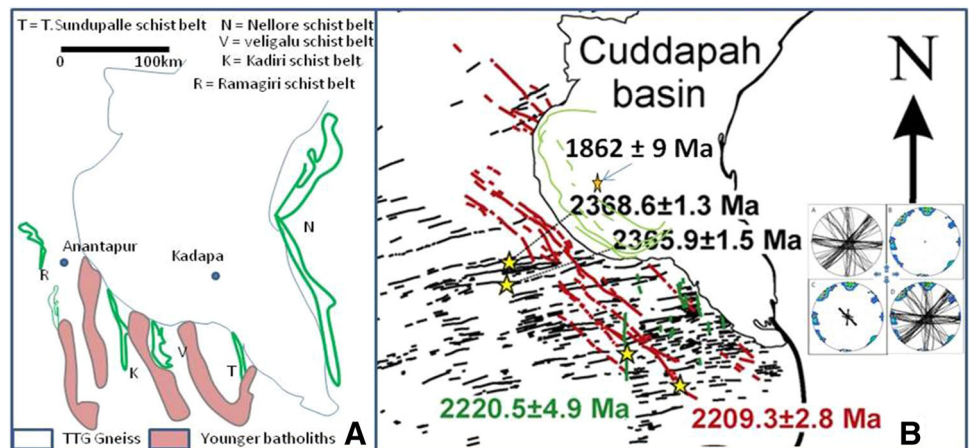
The narrow N–S linear greenstone belts and gneissic basement complex are studied to interpret the history of Cuddapah basin formation (Fig. 3a). The greenstone granite terrain is mostly composed of metamorphosed volcano-sedimentary sequences that were often affected by plutonism related to batholith emplacement. Several sets of dike and fracture trends are marked along the E–W, NE–SW and NW–SE and N–S directions (Fig. 3b). U–Pb baddeleyite dating of dikes after French and Heaman (2010) in the basement suggests E–W dikes were the oldest (about 2.36 Ga), followed by N–S (about 2.22 Ga) and then NW–SE dikes (about 2.20 Ga). In field, the observed

cross-cutting relationships support the same. The bimodal volcanics inside the basin is much younger (about 1.86 Ga; Sheppard et al. 2017).

The non-systematic vein arrays in the older granitoid with weakly developed N–S gneissosity are randomly oriented and infill with secondary quartz and rarely calcite. This is indicative of high strain rate events that blast older rocks apart due to high pressures during younger granite intrusions with high volatile contents, which might have made hydrofracturing to produce such random breakage (Fig. 4).

The pillow basalt morphology as a stratigraphic “way-up” indicator signifies that the sequence has been inverted due to the deformation. Since a newly formed pillow settles

Fig. 3 a The generalized sketch of the Cuddapah basin outline and its basement provenance with linear greenstone belt and younger plutons. **b** The trends of the dikes of different ages in and around Cuddapah basin (modified after French and Heaman 2010 and Sheppard et al. 2017)



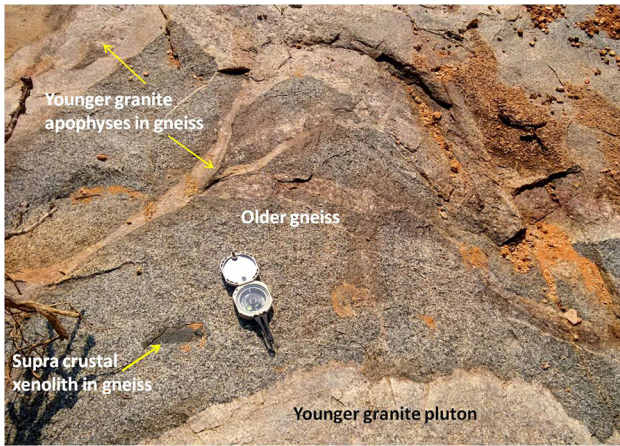
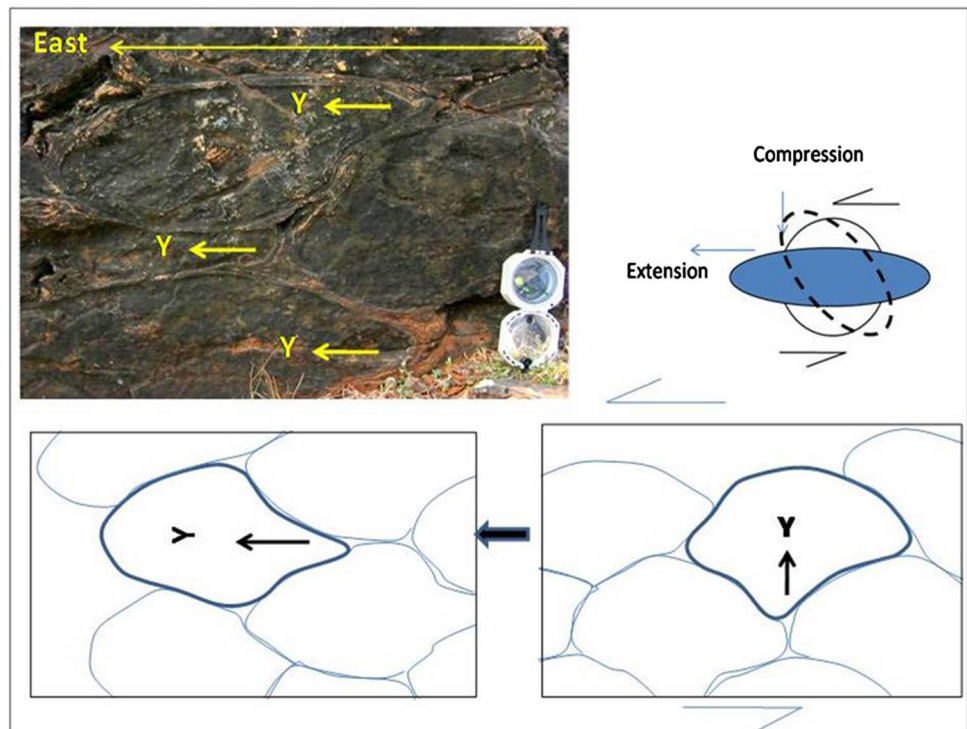


Fig. 4 Field photograph showing three different generations of rock types as ancient supracrustals–older gneiss–younger granitoids

into the junction between two underlying pillows, it forms a downward pointing cusp which has provided a useful way-up indicator in this deformed pillow-basalt terrain (Fig. 5) of greenstone belt.

Regional-scale E–W shearing and associated compression is responsible for the megascopic structures such as schistosity, gneissosity, conjugate joints and younger dike emplacement. However, apart from the major E–W compression, evidence of intermediate-scale N–S shearing is also noted, related to the development of localized secondary folds at certain places (Fig. 6).

Fig. 5 Metabasic pillow lavas within Ramagiri schist belt. Easterly rotation and stretching of pillows by progressive shearing leads to entrance of initial sphere into oblate ellipsoid field. Exposure shows pillows of about 20–35 cm size



The nonconformity contact between the basement granitoids and the Gulcheru quartzite is situated at relatively higher elevation than the Cuddapah basin margin (Fig. 7). These bordering topographic highs are characteristic of rift basins, called “rift shoulders” (Bhattacharya and Chakraborty 2000). Accommodation space develops vis-a-vis sedimentation due to synsedimentary faulting (Fig. 8). Apart from this, the large-scale curved normal faults and associated mafic emplacements are also confirmed from deep seismic sounding (DSS) profile (GSI 1981).

The Idupulapaya fault shows northern up-thrown block and the Vempalle fault shows northern down-thrown block (Fig. 2), with relatively steeper fault planes. In the former case, basement granitoids are exposed in the middle part of the fault with maximum slip. The central part of the fault shows maximum slip, as expected theoretically (Mukherjee 2014). However, near the western tip of the Idupulapaya fault, the Gulcheru quartzite is in contact with the Vempalle Formation in the N block. This discontinuity in the strike of Gulcheru quartzite is due to a possible NNE–SSW fault. On the other hand, the S block exhibits strike continuation. Therefore, the Idupulapaya fault with northern hanging wall block is a high-angle reverse fault. However, high-angle reverse fault with dip $> 60^\circ$ is difficult to develop as per the fault dynamics (Anderson 1951). Thus, the obvious explanation is that the fault reactivated (Misra and Mukherjee 2015 for global context) and occupied former sites of the normal faulting that occurred during the



Fig. 6 **a** NW–SE basic dike cutting across granite. The dextral sense of share can be interpreted from the systematic fractures with NNW–SSE trend confined within the dike only. Thus, progressive shearing leads to shifting of extension field from NE to SW direction to ENE–WSW, which is responsible for the development of NNW–SSE parallel share fractures within the basic dike. **b** Conjugate fractures in

quartz veins show E–W direction of maximum compression along the acute bisector. **c** Part of the N–S trending regional fault zone shows typical brecciation. **d** The E–W shear zone shows dextral sense in the gneissic complex. **e** Refolded foliation planes indicates more than one generation of deformation



Fig. 7 Nonconformity between basement and cover sediments of Cuddapah basin, Gandhi area ($14^{\circ}17'N$; $78^{\circ}29'E$). Photo length ~ 500 m

Eastern Ghat Orogeny (Grenville) during 950–1100 Ma (Ramakrishnan and Vaidyanadhan 2008) and later overprinted by reverse fault along the existing weak zones during the NNE–SSW compressional event, possibly during the opening of the Indian Ocean. The high dip of reverse fault is largely inherited from a previous event of normal faulting (Goswami et al. 2016a). The northerly dipping Vempalle fault plane with normal faulting brought the older Nagari quartzite in contact with the younger Kurnool Formation (Goswami et al. 2012). Therefore, the E–W compression of the Eastern Ghats Orogeny developed

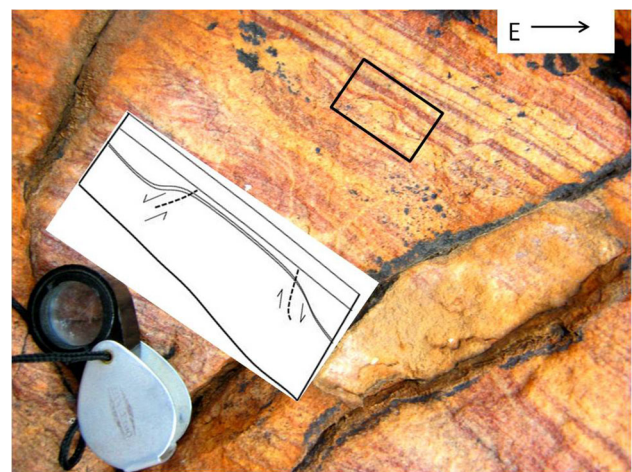


Fig. 8 Synsedimentary semi-ductile fault with normal drag in the planar outcrop of Gulcheru quartzite, Madyalabodu area ($14^{\circ}18'N$; $78^{\circ}33'E$). Varying sediment thickness indicates the differences in elevation of the depositional surface on the footwall and hanging wall sides. 3 cm longest diameter of hand lens

\sim E–W striking normal faults within the Cuddapah sediments.

The sub-parallel E–W normal faults and NNE–SSW sinistral strike-slip faults together swerved the Papaghni

sub-basin rocks at the S. The strike-slip faults exhibit step-overs, where one strike-slip fault segment ends and the other initiates. In this way, all the litho units shifted northerly as right step-over (Goswami et al. 2016a). Since the left lateral fault steps en echelon to the right, the overlap zone must be compressed (Suppe 1985). Thus, the right step-over with left-handed sense produced a pop-up structure (Fig. 9, cartoon), as the restraining step-over in strike-slip tectonics produce pop-ups (McClay and Bonora 2001). Isolated drag folds (Fig. 9) also develop seldom within the uplifted pop-up block.

Aerial surveys recognized five tectonic zones (zone 1–zone 5) within the Nallamalai sub-basin (Meijerink et al. 1984) and mutual boundaries of these zones define deep faults, thrusts or general tectonic lines. All along the western part of the Nallamalai basin, near horizontal to monoclinical structures (strike 150° , dip amount 5° due 60°) of Nagari quartzite connote gently tilted crustal blocks as zone 1. However, mostly close to tight upright folds exist within the Pullampet Formation (Fig. 10a) in zone 2 (Meijerink et al. 1984): E to the Rudravaram line. The Rudravaram line (Narayanaswami 1966), a prominent N–S trending zone of deep tectonic lineament, separates zone 1 and 2 (Kaila and Tiwari 1985). NNW–SSE sub-vertical axial planar cleavages are frequently observed (Fig. 10b) along hinge zones in zone 2. The high angle between bedding and cleavage (Fig. 10c, d) points to a hinge area of regional-scale fold where local upright folds occur as minor component of the regional-scale folding and thrusting with E–W compression. E to Kajipeta village, older Nallamalai Group of rocks thrust over younger Kurnool Group (Fig. 11a), and Koilkuntla limestone beds of Kurnool shows recumbent folding. Typical slickensides are common features in the area that give additional information on interlayer movement in fold and along fault planes (Fig. 11b, c).

The present study area covers up to zone 2, which is separated from zone 3 by the Racherla line after Meijerink et al. (1984). In zone 3, more tight nature of folds in slate and phyllite of Pullampet Formation were reported. Further E, zone 4 starts after crossing a deep-seated high-angle reverse fault identified by Kaila et al. (1979) based on DSS. Zone 4 is dominated by high-amplitude overturned and isoclinal folds. Zone 5 is not very clearly defined but is dominated by imbricated thrusts, metamorphism and folding.

The Vempalle fault is well defined up to zone 2, where the general strike of bedding N to the Vempalle fault is NW, whereas in the southern part it varies from NW to E. The dip generally ranges from 10° to 50° with relatively low dip at W. The Nallamalai Group of rocks are multiply folded and faulted. It is geometrically much easier to deform an already folded surface by oblique shearing along the folded limb. The earlier phase folding is characterized by NNW–SSE fold axes with sub-vertical axial planes. Subsequently, type-2 interference has produced the non-plane non-cylindrical folding in which earlier and later generation folds have mutually perpendicular axes and axial planes (Fig. 12a, b). Numerous well-developed close cylindrical folds have 75° – 85° (sub-vertical) NNW–SSE axial planes. The poles of fractures surrounding the Rudravaram line and the Vempalle fault are plotted in a stereogram along with the NNW–SSE sub-horizontal axial trend of the upright fold in zone 2 (Fig. 13a). Here, out of two major extension fractures, one sub-vertical set is normal to the fold axis, thus providing profile planes at places (Fig. 10a). Another set is parallel to the fold axis and sub-vertical near the hinge area; the dip of the fracture gradually decreases from $\sim 70^\circ$ to 40° in both the sides of the hinge along the fold limbs. Two other sets of ESE–WNW and ENE–WSW fractures at low angle ($< 60^\circ$) represent conjugate shear fractures. Progressive E–W shear lowered

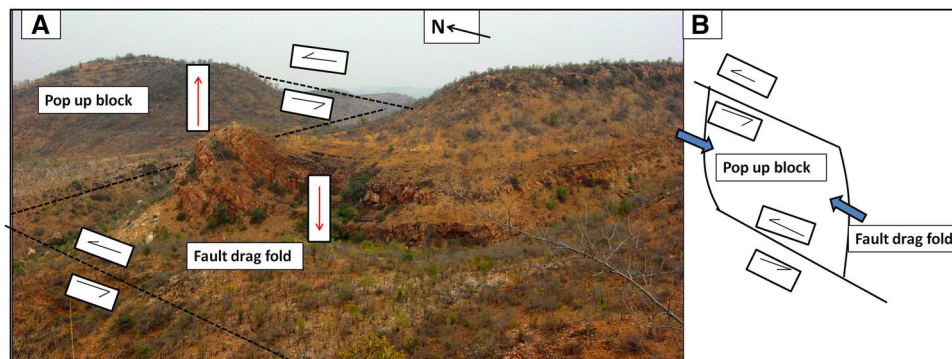


Fig. 9 a Drag fold in Gulcheru quartzite ($14^\circ 17'N$; $78^\circ 27' 20''E$), S to Vempalle, formed due to E–W pop-up block faulting and the red vertical arrows shows block slip. b The right step-over pattern of

sinistral-parallel N–S strike-slip faults form pop-up structures in between, and the fault-bound uplifted pop-up block fault produces drag fold. Photo length ~ 600 m

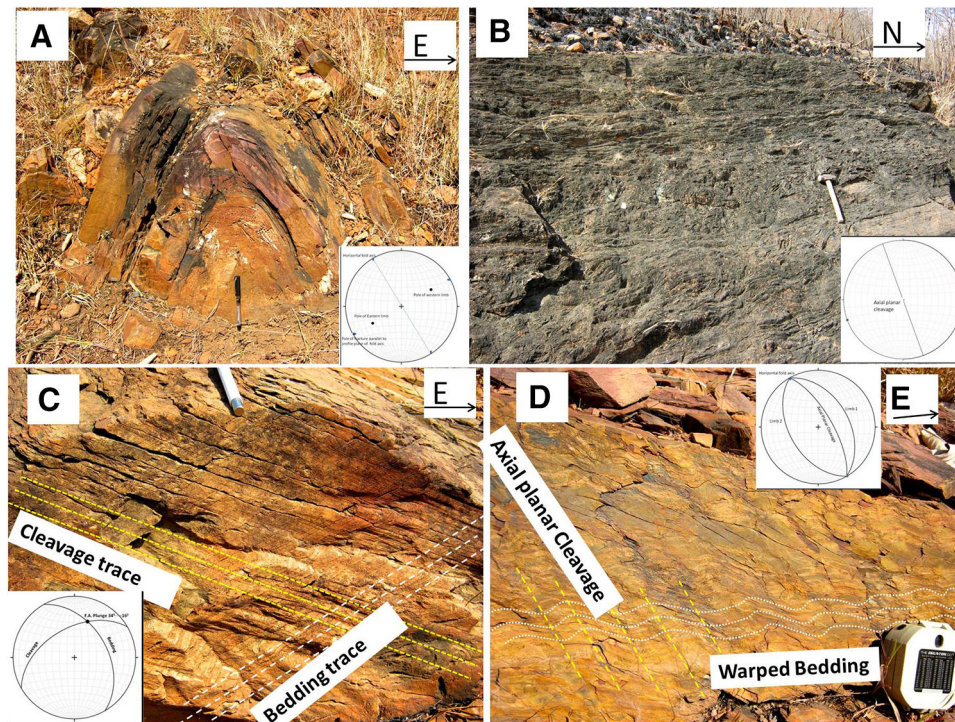


Fig. 10 **a** Tight upright folds (in vertical section view) developed within the Pullampet Formation (silt stone), SE to Kadapa ($14^{\circ}22'N$; $78^{\circ}41'20''E$) in zone 2. Pen length 14 cm. **b** Axial planar cleavage. Plan view. In Pullampet siltstone of Nallamalai Group ($14^{\circ}22'30''N$; $78^{\circ}41'20''E$), SE to Kadapa; hammer length 31 cm. **c** The relatively lower angle between bedding and cleavage (on vertical section view

in Pullampet siltstone) points to limb portion of fold away from hinge, SSE to Kadapa ($14^{\circ}21'50''N$; $78^{\circ}41'10''E$); 7 cm part of pen is seen. **d** High angle between bedding and cleavage (viewing sub-vertical section) along hinge of small-scale fold in Pullampet siltstone), SSE of Kadapa ($14^{\circ}21'50''N$; $78^{\circ}41'10''E$), 8 cm diameter of closed Brunton compass

the wavelength to amplitude ratio producing type-3 refolding (Fig. 13b). At places, the E–W dextral shear zone bounded en echelon fractures (Fig. 14a), which are often quartz filled (Fig. 14b) and affected by several events of deformation. En echelon in fringes intersect the main joint faces at $\sim 20^{\circ}$ – 25° , and the sigmoid profiles of fractures are cross-sectional views that aid in determining the rotation sense by non-coaxial shear. The en echelon gash fractures originate as tension fractures that parallel the major stress axis orientation σ_1 : $\sim N15^{\circ}E$ (Fig. 14b, cartoon 3). However, the change in stress field is also observed due to local perturbation and reactivation as well (Fig. 14c). Plumose structures connote the local direction of fracture propagation towards WSW. The direction of propagation (Pollard and Aydin 1988) is along the plumose axis and opposite to the direction in which the barbs converge (Fig. 15). Both fault-cast veins and fibrous veins developed along the fracture planes (Fig. 16). The former were produced during slip at moderate temperature in voids, since fault plane is non-planar with steps and undulations (Suppe 1985). Fibrous quartz observed along veins due to long continued slip. These veins appear to be slickensided because they are casts of actual slickensides along faulted wall.

4 Palaeostress Study

We analyse palaeostress along west Gandi–east Madimadugu tract in Gulcheru, Pulivendula and Nagari quartzite, respectively. The analysis is representative of brittle regime deformation such as fault and fracture. A Mohr diagram for palaeostress is constructed to show the extension and shear fracture orientation to interpret the stress events. Field study suggested dominantly E–W tension fracture and the acute bisector of conjugate fractures (Fig. 17a, b) that trend $\sim N15^{\circ}E$ – $S15^{\circ}W$, which are the directions of principal compressive stress (σ_1) for different times. Since the E–W extension fractures are affected by the later shear fractures (Fig. 17a), the stress field changed presumably temporally. This implies the Eastern Ghats Orogeny comprises more than one deformation phase, which matches with the EGMB evolution. The distinct periods (probably 1.50–0.5 Ga) of active deformation with specific style and orientation phases are separated by periods of milder or no deformation. During this interval, the orientation of the stress field might have changed. Even the later phase of the Indian plate movement in Mesozoic must have been feebly imprinted in the form of N–S extension joint. After plotting all the poles of fracture data

Fig. 11 a Thrust contact between Nallamalai and Kurnool Group E of Kajipeta (14°41'N; 78°41'20"E) where Nagari/Bairenkonda quartzite is thrust over the Koilkuntla limestone, section view of photograph covering 50 m along E–W. **b** Typical crescentic markings (CM) type slickensides (as per Doblas, 1998) along the Rudravaram line indicating fault movement (14°41'N; 78°41'20"E) in Koilkuntla limestone; coin diameter 2.6 cm. Inset: great circle shows the fault plane and the point on it the slickenside. **c** Flexural slip folding related steps (ST) like slickenside lineation (14°22'N; 78°41'20"E) in Pullampet Shale, as per Doblas (1998). Inset: great circle shows the fault plane and the point on it the slickenside. Visible part of pen length ~ 11 cm

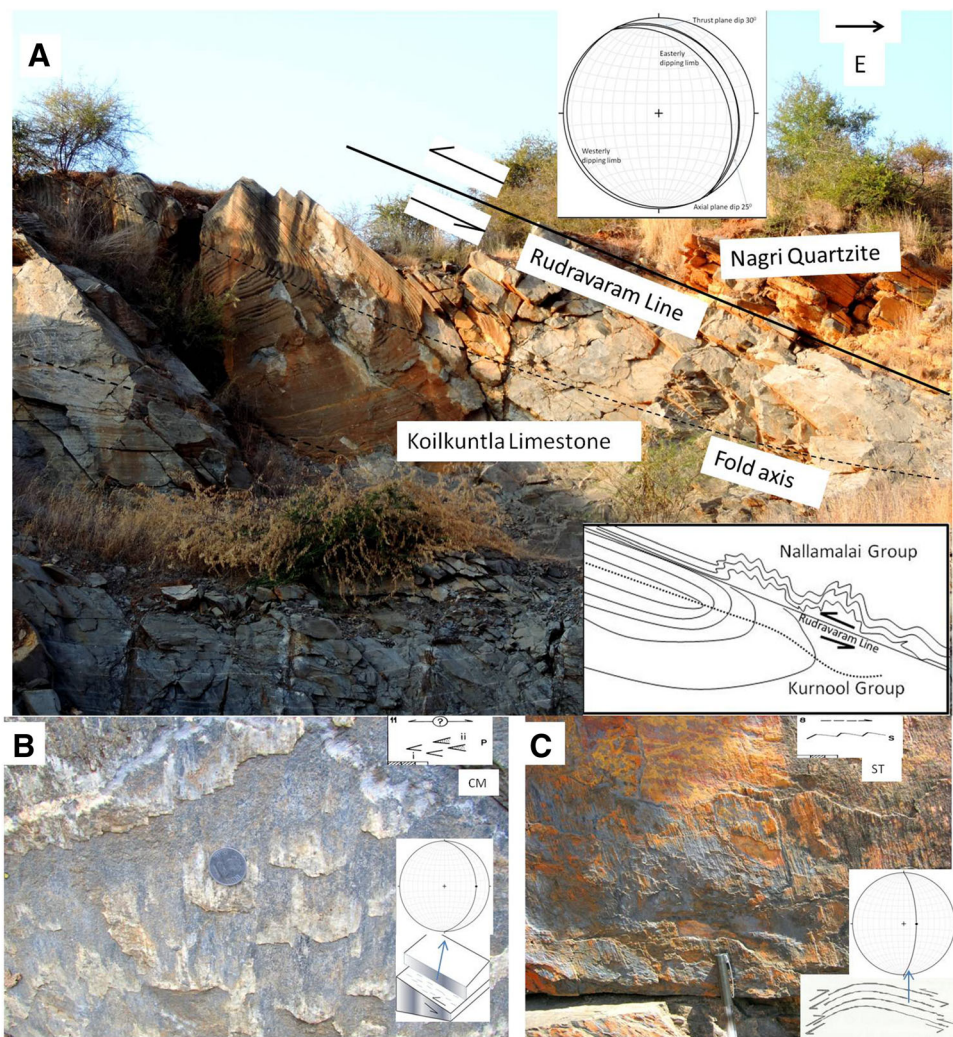
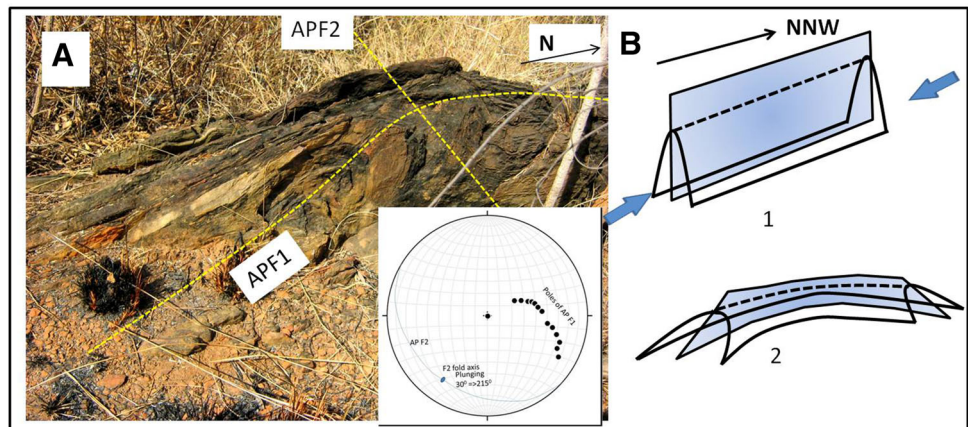


Fig. 12 Mesoscale type-2 superposed refolded upright fold in Pullampet siltstone–dolomite interbands, SE of Kadapa (14°22'N; 78°41'20"E; see Figs. 1, 2 for location), the NNW striking initial axial plane (APF1) is folded with SW plunging axis and SW dipping axial plane (APF2); outcrop length ~ 1.2 m



collected systematically in the field along with major fault planes on the stereonet (Fig. 17c), it is found that most of the earlier generation E–W fractures are sympathetic to the major normal faults such as the Idupulapaya and Vempalle fault of the area. The shear fracture sets are later formed

features along the NE–SW and NNW–SSE, respectively, with acute bisector along N15°E representing σ_1 . The Rose diagram (Fig. 17d) too supports this dominant N95°E, N45°E and N15°W major fracture trends found in this study.

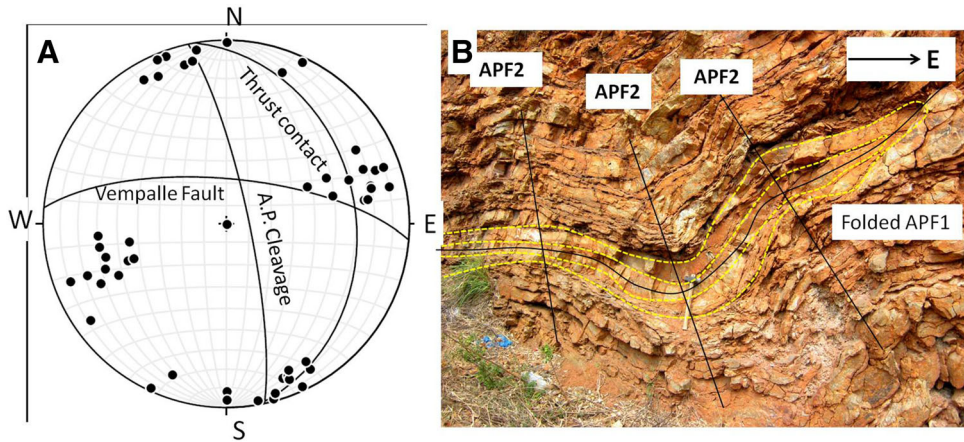


Fig. 13 **a** Stereonet plot of different sets of fracture poles ($n = 86$) around the Rudravaram line, the Vempalle fault and the axial planar cleavage. **b** Road-cutting section view of the type-3 superposed fold in Pullampet siltstone: F1 and F2 fold axes parallel, with their axial

planes at high angle. The photograph is an E–W sectional view taken after facing towards NNW, which is broadly the axial trend of folds. SSE of Kadapa ($14^{\circ}22'N$; $78^{\circ}41'E$; see Figs. 1, 2 for location). Photograph length ~ 5 m

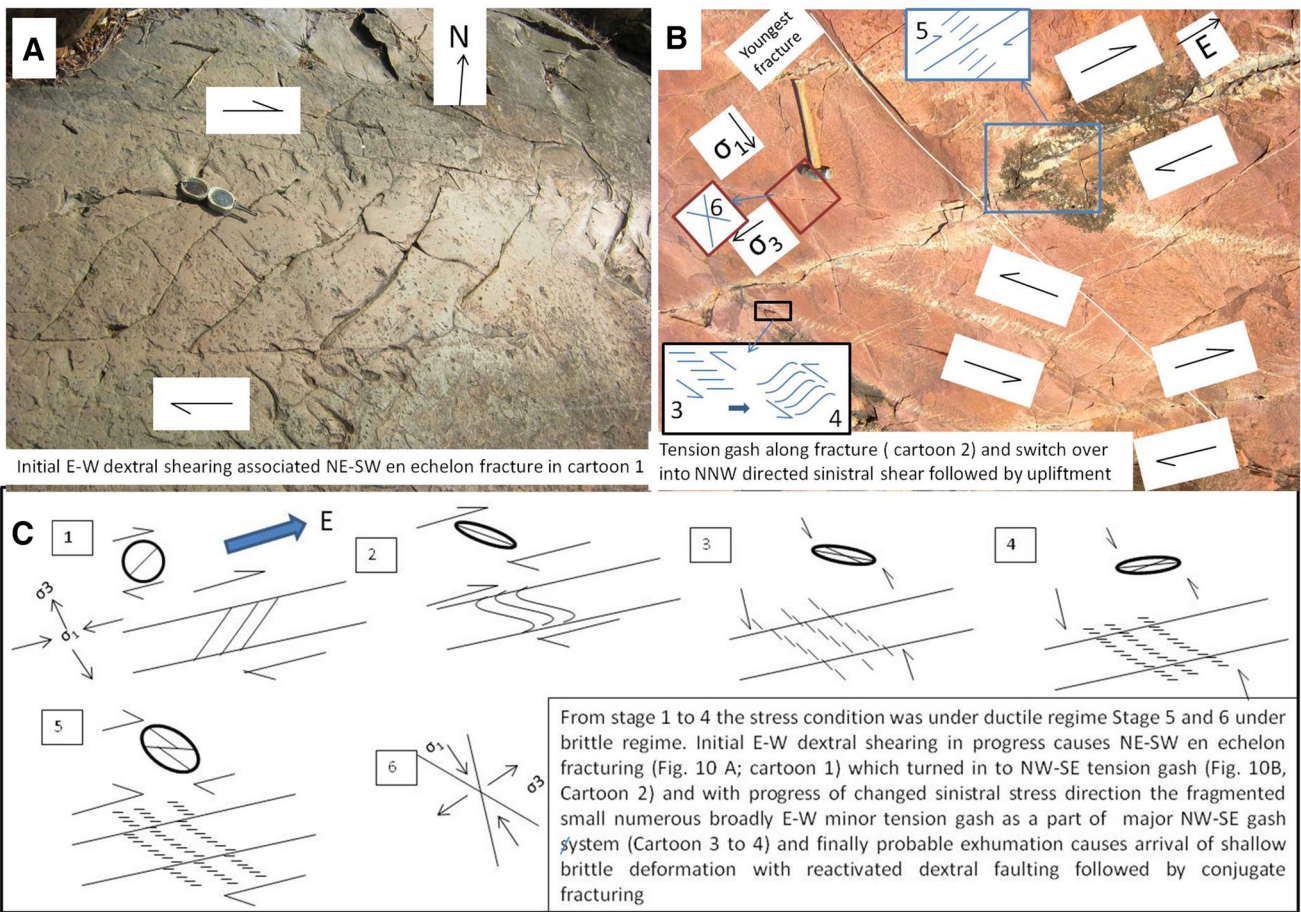


Fig. 14 Outcrop plan view of en echelon vein and tension fracture. **a** Broadly, E–W dextral shear zone in Pullampet siltstone, defined by nearly straight and non-parallel Y-planes that bound sigmoid-shaped P-planes. At $14^{\circ}19'N$; $78^{\circ}41'E$; Length of Brunton ~ 29 cm. **b** Outcrop plan view of sigmoid and planar en echelon quartz veins in Nagari quartzite shows complex shear; at $14^{\circ}22'N$; $78^{\circ}41'20''E$

with regional E–W and NNE–SSW and reactivated E–W fault perturbed local stress, NNE of Madimadugu (see Figs. 1, 2 for location). Hammer length 31 cm. **c** Evolution of stress–strain history with successive stages from ductile to brittle regime, indicating uplift and exhumation

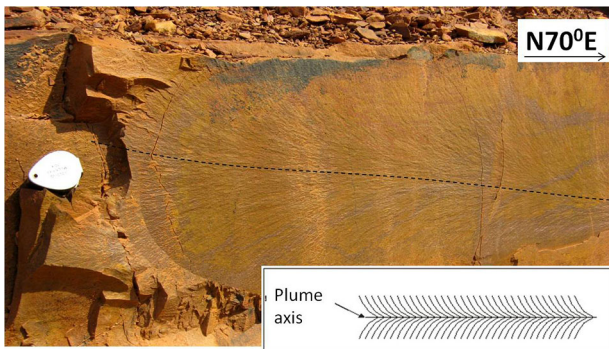


Fig. 15 Outcrop section view of plume structure (S-type) on joint (N70°E) surface (14°19'N; 78°40'30"E), in Nagari quartzite WNW of Madimadugu (see Figs. 1, 2 for location). 4 cm longest diameter of hand lens

As in Ghosh (1993), during fracturing:

$$\tau^2 = 4T^2 + 4T\sigma = 4T(T + \sigma), \quad (1)$$

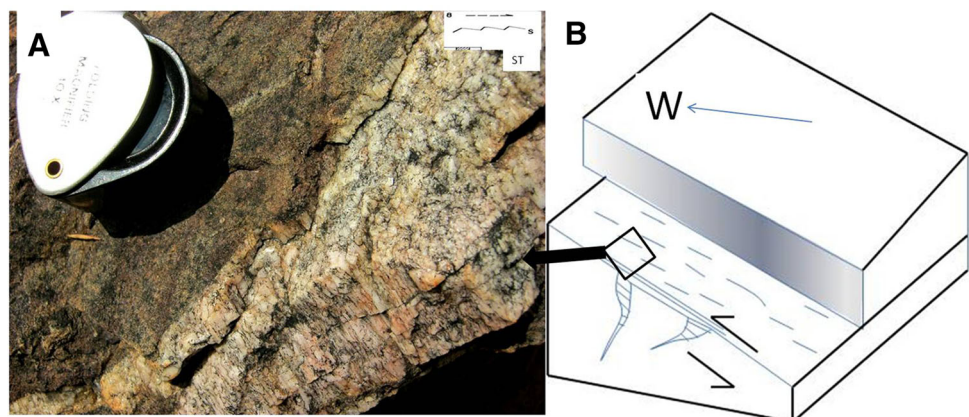
where τ : shear stress, σ : normal stress, T : tensile strength of the rock. The tensile strength of quartzite ranges 21–28 MPa (Suppe 1985 and references therein). We take $T = 25$ MPa for the Gulcheru and the Pulivendula quartzites. As per the Mohr diagram, the earlier generation E–W tension fractures (Fig. 18a) have $\sigma_1 = 3T$, $\sigma_3 = -T$, where a negative sign represents extension (here along N–S) related to fracturing and the angle $2\theta = 0$. Here, θ is the angle between maximum compression (σ_1 i.e. E–W) and normal to the fracture plane, unlike shear-related conjugate fracture set. In this case, $\tau = 0$. σ_2 is the intermediate stress direction, which is vertical in the present context. Therefore, the magnitudes of σ_1 and σ_3 are 75 and 25 MPa, respectively, for extension fractures. However, since the dihedral angle of the conjugate joints in the study area is always $\sim 60^\circ$, the acute bisector is σ_1 and the desired Mohr diagram for conjugate joints is drawn with 2θ value of 60° (Fig. 18b). This yields $\sigma_1 = 5.25T$ and $\sigma_3 = -0.65T$. Therefore, the later formed shear fractures underwent $\sigma_1 = 131.25$ MPa and $\sigma_3 = 16.25$ MPa. The σ_3

is the minimum compression direction. Negative sign means extension. Thus, the N–S extension causing earlier formed E–W tension fracture is related to the Eastern Ghats orogeny with E–W compression (i.e. E–W σ_1 , N–S σ_3 and vertical σ_2). Later formed NNE–SSW compression must have provided conjugate shear fracture and reactivated earlier fractures. The less frequently observed N–S extension joints are developed due to the E–W extension component.

5 Discussions

As per Dasgupta et al. (2013), the Dharwar Craton that surrounds the Cuddapah basin used to be a part of the Archaean supercontinent “Ur” that stabilized ~ 3.0 Ga. The supercontinent consisted of E Antarctica, W Australia, N China and India (Rogers and Santosh 2003). The Kenoran orogeny (~ 2.7 – 2.5 Ga) is related to the initial two-stage growth of the Dharwar craton. According to Jayananda et al. (2013), the two stages are: (1) initial growth of a 2.7–2.6 Ga juvenile crustal province of mafic volcanics and felsic plutons; (2) a 2.58–2.52 Ga felsic volcanics, TTG and calc-alkaline pluton emplacements. The gneiss and greenstone belts are related to the initial ocean–continent convergence (Goswami et al. 2016b, 2017b) with characteristic calc-alkaline volcanism. The Hudsonian orogeny (~ 2.5 – 1.9 Ga), part of the “Columbia” assembly processes (Rogers and Santosh 2003; Mandal et al. 2016), is related to extension mode features like dike intrusions, younger granitic plutonism and initiation of rifting of Cuddapah basin. In fact, the ~ 1.9 Ga dikes were emplaced at the basal part of the then opening Cuddapah basin (Chatterjee and Bhattacharji 2001; Anand et al. 2003; Halls et al. 2007; French et al. 2008; Ravikant 2010). This continental rifting opened an ocean basin and deposited Cuddapah sediments and associated bimodal volcanic emplacements (Goswami et al.

Fig. 16 Outcrop view of exposed inclined fault plane and quartz vein in Pullampet siltstone on which fibrous quartz vein shows slickenlines (14°22'N; 78°41'20"E), SE of Kadapa (see Figs. 1, 2 for location), similar to step-like lineations as per Doblas (1998). 4 cm longest diameter of hand lens



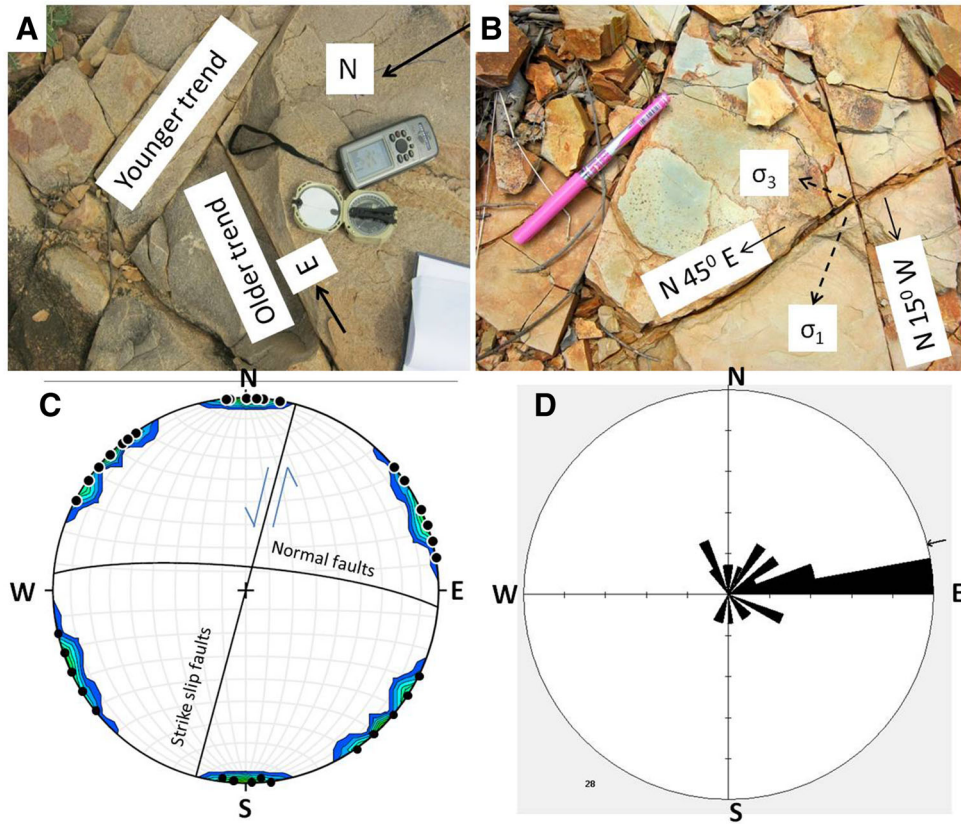
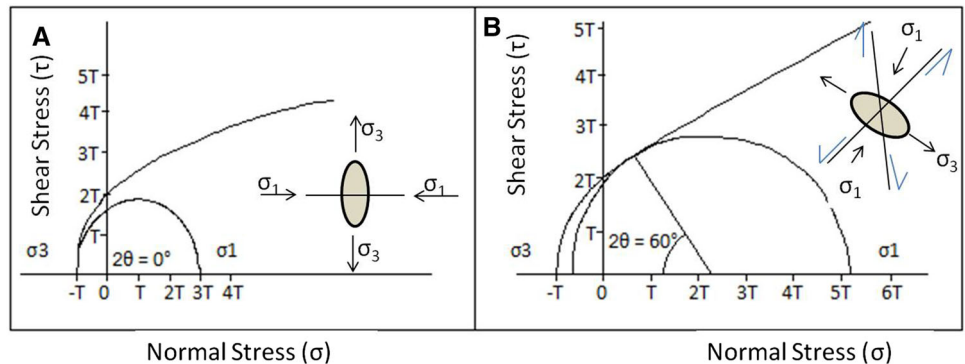


Fig. 17 **a** Outcrop plan view of E–W extension joint cut by later generation joint set in Gulcheru quartzite Madyalabodu area (14°18'N; 78°33' E; see Figs. 1, 2 for location); 8 cm diameter of compass. **b** Outcrop plan view of conjugate shear fracture shows acute bisector or, maximum compressive stress (σ_1) along N15°E. The obtuse bisector as minimum stress (σ_3) and vertical intermediate stress (σ_2) direction is along the intersection line of fracture planes in Gulcheru quartzite at Madyalabodu area (14°18'N; 78°33'E; see

Figs. 1, 2 for location). Pen length 14 cm. **c** Stereo plot of major normal fault and strike-slip faults and poles of fracture sets ($n = 36$) from the study area shows major E–W sub-vertical extension fracture set sympathetic to E–W normal faults and conjugate set of NNW–SSE and NE–SW vertical fracture with some irregular non-systematic fracture related to later stage of NNE–SSW shear and exhumation. **d** Rose diagram of the fracture trends ($n = 28$) shows broadly N95°E, N15°W and N45°E trends of major fracture sets

Fig. 18 Stress condition represented by parabola [$\tau^2 = 4T^2 + 4T(\sigma - T)$] for extensional and conjugate joints. τ : shear stress; T : tensile strength of the rock; and σ : normal stress



2017a). After this, extensional setting modified into subduction while fold thrust belts at the eastern margin of the Cuddapah basin formed simultaneously ~ 1.87 Ga (Saha et al. 2010). Further, the onset of the Grenville/Eastern Ghats Orogeny is responsible for the sub-parallel E–W faulting. The two cratonic blocks came closer with a remnant ocean basin and emplaced the Kandra Ophiolite

Complex (Kumar et al. 2010). Interestingly, the Napier Complex was positioned just S of the EGB occupying the indentation of the eastern part of Cuddapah basin and remained as a part of India until the opening of the Indian Ocean in the Jurassic period (Dasgupta et al. 2013). The concave east of the coastline in the east of Cuddapah basin indicates earlier developed weaker zone.

The Cuddapah Supergroup represents a Palaeoproterozoic intracratonic basinal sequence. These Palaeoproterozoic rocks occur within various cratons of India and Himalaya and bear significant information about the early Earth's tectonothermal events and surface processes (Saha and Mazumder 2012; Mandal et al. 2015, 2016, and references therein). At the S and W margins of the Cuddapah basin, alluvial fans have developed extensively. Deep-seated (blind) faults near the margin indicate early passive rifting of the upper granitic crust producing accommodation space in the Papaghni sub-basin. Two competing hypotheses for the initiation of basinal subsidence and deposition exist: (1) thermal trigger by mantle plume produced the basin (Chatterjee and Bhattacharji 2001); (2) deep basin margin faults mainly controlled basin evolution (Chaudhuri et al. 2002). Deep basin margin faults in the basement area are found, and the linear basic intrusions along the fracture parallel to the Papaghni sub-basin outline also point towards the later hypothesis. Deep seismic sounding (DSS) indicated the presence of a 10–11 km-thick sedimentary pile over a 40 km-thick crust in the eastern part of the basin and step faults in the basement (Kaila et al. 1987). The DSS profile has also described a mafic lopolith at a shallow depth in the SW part of the basin and an easterly dipping thrust fault at the eastern margin where high-density lower crust of the EGMB upthrust. In fact, the eastern continental margin of India east to the Cuddapah basin resembles a concave shape, and the basic intrusives in the Papaghni sub-basin also have an eastern concave outline. The Cuddapah basin evolved through the formation of sub-basins separately. The sub-basins were depocentre at different time ranges. If we unfold the crescent shape into linear sub-elliptical shape, it is found that the Papaghni and the Nallamalai are parallel sub-basins with separate depocentres having different depositional timings. The Cuddapah Supergroup is separated from the overlying Kurnool Group by angular unconformity. Goutham et al. (2006) assigned Neoproterozoic age for the Kurnool Group by correlating it with the Upper Vindhyan. However radiometric dating is lacking in correlation. Collins et al. (2015) dated Papaghni and Chitravati Groups up to the Tadpatri Formation as Palaeoproterozoic based on U–Pb ages of detrital zircons and latest Palaeoproterozoic to earliest Mesoproterozoic (1659 ± 22 to ~ 1590 Ma) age for the Nallamalai Group and Srisailam Formation; but the Kurnool Group was dated to be Neoproterozoic (1181 ± 29 – 913 ± 11 Ma). Mishra et al. (1985) found a ~ 4 – 5 km-thick asymmetric lopolith in the Papaghni sub-basin. As per the tectonic map of the Cuddapah basin and its adjacent regions (Chetty 2011), the widespread extension in the upper crust is manifest as listric normal fault in the Papaghni basin and a domino-type faulting in the Nallamalai basin. While extensional

tectonics played a major role in shaping the geometry and kinematics of the basin, the intermittent phases of compression seem to have been derived from major brittle-ductile shears related to Proterozoic collision in the region. The presence of low-dipping detachments and shear zones in the lower crust and their possible link with the extensional faults in the upper crust explain the basin evolution. The fault patterns and kinematic history in conjunction with the crustal architecture have suggested that the evolution is genetically related to the Proterozoic collisional processes and associated crustal-scale transpressional tectonics in the basement at the eastern margin (Chetty 2011). However, such model made by LANDSAT TM data and the available literature must be verified by systematic field studies.

6 Tectonic Model

We note E–W and N–S extension joints from Pulivendula, Vempalle, Madyalabodu and the Poltala temple areas. The older E–W joints are formed by maximum compression (σ_1) along E–W and minimum principal stress (σ_3) along N–S direction. The conjugate joint sets with NE–SW and N15°W–S15°E trends indicate \sim N15°E–S15°W acute bisector (σ_1) direction. Therefore, the maximum compression (σ_1) direction switched from E–W to NNE–SSW with time and later stress is mostly responsible for shear fracture and N–S extension fracture development depending upon rheology and orientation of the litho unit. Figure 19 summarizes a tectonic model of the Cuddapah basin. After rifting and basin filling and subsequent uplift and tilt of the Papaghni sub-basin, the newly developed Nallamalai sub-basin formed along the N–S linear rift. After the Nallamalai, Kurnool sub-basin also developed as a half graben (basin) W to Nallamalai with eastern tectonic margin and western transgressive basin margin. The Vempalle fault is younger and therefore affected both Nallamalai and Kurnool sub-basinal rocks.

Deep seismic studies by Kaila et al. (1979) revealed NNW–SSE to N–S lineaments extending up to the Moho, and that the basin first developed in the western part by down-faulting. Note that Moho is elevated beneath the rift zones (Allen and Allen 2005). The sub-basin marked by \sim NE tilt consists of abundant fine clastics and carbonates. The thick pile of Tadpatri indicates that the rate of subsidence of the basin was coeval to sedimentation in the central part of the basin (Nagaraja Rao et al. 1987), which is also supported by the synsedimentary faults with mostly N–S direction in hand specimen scale. The typical rift flank topography bordering the basin as rift shoulder is a characteristic feature for both the Papaghni and the Nallamalai sub-basins. However, as far as the time scale and

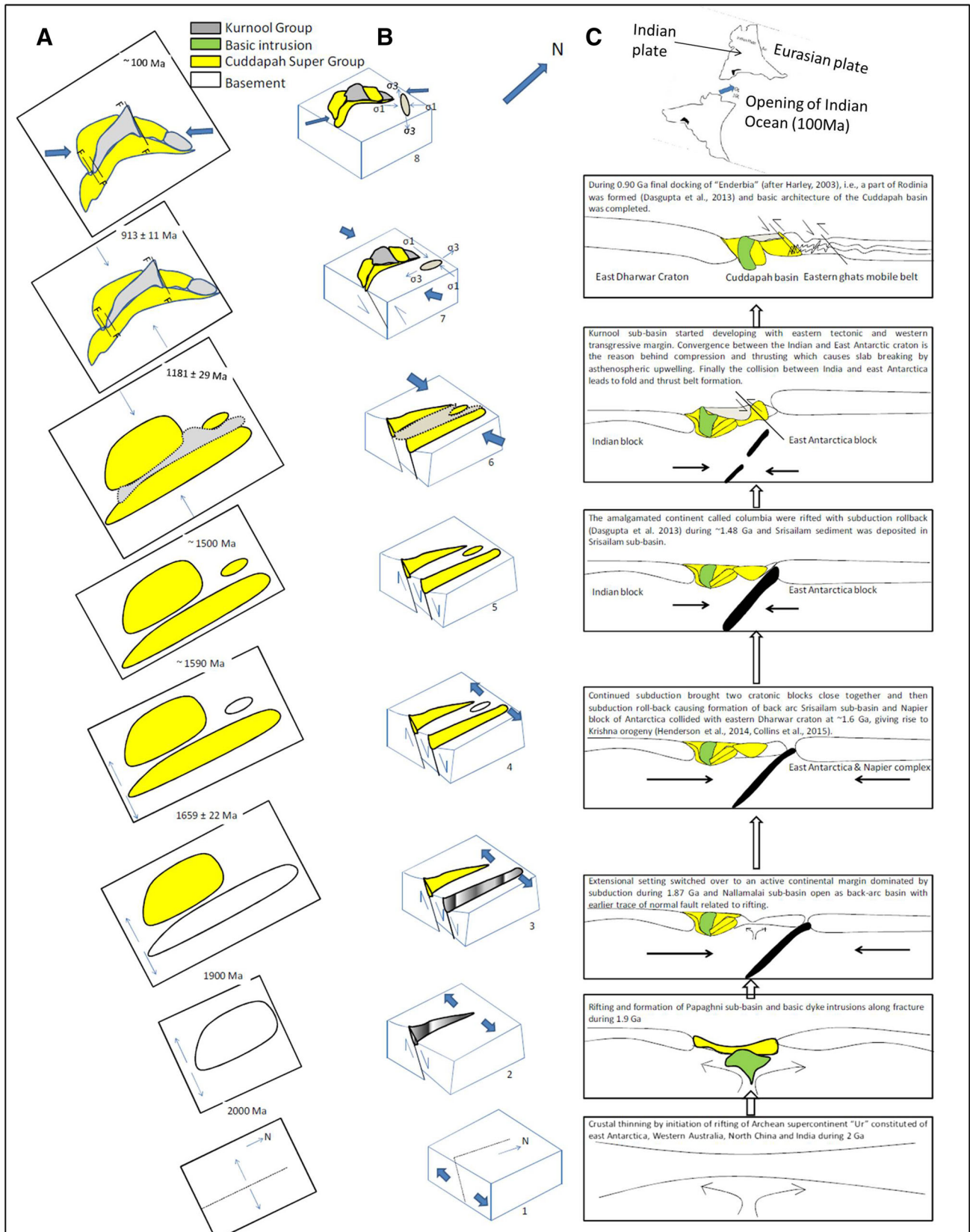


Fig. 19 Cuddapah basin evolution: a in plan. b As block diagrams. c As tectonics

magnitude of extension is concerned, the rifting of Nallamalai sub-basin is a relatively later event. Sub-parallel dip slip normal faulting E of the earlier formed Papaghni rift developed the Nallamalai basin. As per Friedmann and Burbank (1995), the rifting of the Cuddapah basin can be classified as ‘supra detachment’ category in which the basin exhibits wide extended domain with thickened crust and the master faults/detachments are gently (up to 30°) dipping. Unlike the ‘discrete continental rifts’ that extend slowly over long time with steep (45°–70°) master fault angles, supra-detachment Cuddapah rift altogether took a lesser period of extension.

The Nallamalai rock (Bairenkonda/Nagari quartzites) lying on the basement granitoids in the southernmost part of Cuddapah basin also exhibits typical rift shoulder. The polymictic conglomerate with boulder to pebble size clasts at the base of the Nallamalai (Fig. 20) has constituents derived from the Papaghni and Chitravati Groups. Thus, after sediment filling, the eroded Papaghni sediments were transported to Nallamalai sub-basin and these two sub-basins (i.e. Papaghni and Nallamalai) were joined by later tectonics. Initial elliptical shape is the relatively preferred shape of intracratonic rift basins in general and henceforth the initially elliptical Nallamalai sub-basin deformed by compression in the eastern side during the Eastern Ghat Orogeny. The relatively longer Nallamalai basin axis could become slightly concave towards E and folding and thrusting developed ~ N–S lineaments, which must have imparted additional anisotropy and competence contrast to intensify the curvature. Srisailam and Palnad sub-basins do not come within the study area. However, according to Nagaraja Rao et al. (1987), after the Nallamalai event, foundering of the basement parallel to the NE–SW



Fig. 20 Polymodal polymict conglomerate with boulder to cobble sized clast range at the base of Nallamalai rocks, W to Madimadugu (14°18'N; 78°39'E). See Figs. 1 and 2 for location. ~ 168 cm tall human marker

lineaments ‘Pari Passu’ with the uplift of the Nallamalai sub-basin formed the Srisailam sub-basin. Kurnool and Palnad sub-basins started developing at the end as half graben basin W to Nallamalai, with eastern tectonic margin and western transgressive basin margin by tectonic reactivation. The entire system enjoyed a NNE–SSW compression as indicated by the superposed folds, right step-over pattern of parallel strike-slip faults, high-angle reverse movement of initially normal Idupulapaya fault and other drag folds (Goswami et al. 2016a). Minor structures such as joints, veins, shear fractures, small-scale folds and faults, slickenlines, crustal fibre lineations and cleavages are observed at different parts of fold belt in Nallamalai rocks (Figs. 8, 9, 10, 11, 12, 13, 14, 15, 16, 17) and the surrounding study area because of different local strain environments. Therefore, remote E–W compression provided fold and thrust belt in Nallamalai and the local N–S extension component of stress produced E–W sub-parallel normal faults further W to the Nallamalai belt. Note the state of stress causes shear fracture following the Mohr–Coulomb criterion for materials of any rheology and therefore faulting took place where shear to normal stress ratio reached the failure envelope. Hence, the local stress field determines the attitude of a newly created fault.

The presented basin evolution model is easier to justify from field observations. Stepwise evolution points to initiation of rifting in the basement followed by Papaghni sub-basin formation and infilling and creation of another sub-parallel rift. The later rift was the depocentre for the Nallamalai Group. During Nallamalai basin infilling, small Srisailam depression too started developing with sediments slightly younger than that of Nallamalai. After a time gap, the newly developed depocentre for Kurnool Group was created. The Kurnool Group of rocks are found in Kurnool and Palnad sub-basins and thus suggests time equivalence and geographic continuity of the two sub-basins during the initial stage. The later tectonic activities geographically separated litho units in the two separated sub-basins, i.e. Kurnool and Palnad. The Eastern Ghats Orogeny affected the basin, and the thrusting along with E–W faulting in the eastern part of the basin is responsible for its crescent shape, which further intensified during the opening of the Indian Ocean and Indian plate movement during the Mesozoic.

7 Conclusions

The crescent shape of the Cuddapah basin is mainly due to the thrusting related to the Eastern Ghat Orogeny. Progressive stages of rifting and development of sub-basins are imprinted in the rocks that occur as basin fill. The later

phases of deformations have also slightly modified and produced the final shape of the basin.

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