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Geological field study of the Papaghni Group, Cuddapah Supergroup in Andhra Pradesh, Southern India

Ramesh Chandra Behera[1] & Sahendra Singh[1]

[1] Indian Institute of Technology (Indian School of Mines) Dhanbad, Jharkhand, India.

RCB, 0000-0003-0716-5943; SS, 0000-0002-8125-0073.

Corresponding e-mail address: r.behera1996@gmail.com

Cover page figure: Panoramic view of the Papaghni Group rocks of the Cuddapah Supergroup exposed near Narpala, Andhra Pradesh, southern India.

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ABSTRACT

The Cuddapah Basin, one of the largest Proterozoic basins in India, provides crucial insights into the Proterozoic Earth's sedimentary and tectonic evolution. The Papaghni Group forms the basal unit of the Proterozoic Cuddapah Supergroup and represents a key lithostratigraphic sequence in the Cuddapah Basin. The Group consists of the Gulcheru Quartzite and Vempalle Formation and contains information related to the sedimentation history, depositional environments, and tectonic evolution of the region. The stratigraphy of the Papaghni Group furnishes the history of rifting, sedimentation, and periodic basin subsidence, influenced by the regional and global geodynamic processes i.e., Columbia supercontinent assembly. Well preserved stromatolites within the Vempalle Formation highlight early microbial activity in carbonate precipitation. The study of stromatolites from the Vempalle Formation reveals a depth partitioned microbial growth pattern controlled by energy conditions, salinity, and sediment influx. The variation in stromatolitic morphology, from laminated forms in shallow intertidal settings to columnar and domal structures in deeper marine environments, highlights their adaptive capability in response to paleoenvironmental changes. Furthermore, mafic flows, dykes, and hydrothermal mineralisation within the sequence indicate multiple extensional phases, correlating with global supercontinent cycles. The study highlights extensive field observations, petrographic analyses, and ore mineral assemblages, contributing to a holistic understanding of the region's geodynamic evolution.

Keywords: Cuddapah, stromatolite, hydrothermal.

PROGRAM SUMMARY

Day 1 and 2: Fieldwork in Pulivendla Region (Stops 1 and 2)
Halt: Pulivendla.
Focus: Sedimentological and stratigraphic analysis of the Gulcheru Quartzite and Vempalle dolostone.
Key Locations & Observations:

- Vempalle, Tummalapalle, Rachakuntapalle, Kanampalle, Giddankapalle, and Kottala.
- Study of Gulcheru Quartzite – basal conglomerates, sedimentary structures, and collection of structural data.

Examination of Vempalle dolostone – stromatolitic structures, oolitic limestone, and cherty dolostone.
Evening session: Discussion and data compilation.

Day 3: Fieldwork in Anantapur Region (Stop 3)
Halt: Anantapur.
Focus: Lithostratigraphy and sedimentary features of the Vempalle Formation.
Key Locations & Observations:

- Muchukota, Joolakalva, Madalapalle, and Narpala
- Detailed study of Gulcheru Quartzite – facies variations and depositional environment.
- Vempalle dolostone – characteristics of stromatolitic and oolitic limestone, cherty dolostone.

Evening session: Discussion and documentation.

Day 4: Fieldwork in Dhone Region (Stop 4)
Halt: Dhone.
Focus: Structural geology and magmatic intrusions in the Cuddapah Basin.
Key Locations & Observations:

- Dhone and Jaladurgam.
- Gulcheru Quartzite – field observations on lithofacies and sedimentary structures.
- Vempalle dolostone – stromatolitic dolostone and its paleoenvironmental significance.
- Dolerite dyke – field identification, study of intrusion characteristics, and its role in mineralisation.

Evening session: Integration of observations with previous days' findings.

SAFETY

Most of the outcrops are located along roadsides and small hillocks, requiring rigorous walks through rough terrains, making solid field boots essential. The necessary equipment should also include sunscreen lotion, sunglasses, and a sun hat to protect against the typically warm weather in Andhra Pradesh from late September to early October, though a raincoat is recommended for unexpected rainfall. Field safety primarily depends on self-awareness, and all attendees participate in excursions at their own risk. Some areas consist of flat terrains with tall grasses, so staying alert for the presence of poisonous snakes is crucial. Additionally, having a local person accompany the team is advisable for better communication with local communities.

Emergency contact number:
Police – 100
Fire: 101
Medical Help line: 108

HOSPITALS

- Sree Siri Emergency Hospital, Pulivendula-Parnapalle Rd, Pulivendula, Andhra Pradesh 516390
- Sahari Multi-speciality Hospital, 12-2- 863, 1st Cross Rd, Central Exchange Colony, Sai Nagar, Anantapur, Andhra Pradesh 515001
- New Govt General Hospital Dhone, Dronachalam, Andhra Pradesh 518222

– Matrusri Multispeciality Hospital, Ananthapur road, near Tikka lakshmamma avva temple, Gooty, Andhra Pradesh 515401

HOW TO REACH THE AREA

The study area is accessible by road, and railway. The nearest major railway stations are Pulivendula, Anantapur, and Dhone, all well connected to major cities in Andhra Pradesh. The nearest airports are Kadapa Airport (~70 km) and Bengaluru International Airport (~250 km). From these hubs, the field locations can be reached by state highways and district roads using hired vehicles or private transport.

ACCOMMODATION

Accommodation facilities are available at Pulivendula, Anantapur, and Dhone, including guest houses, budget hotels, and private lodges. These towns serve as convenient base stations for daily field excursions. Advance booking is recommended during peak seasons.

PERMITS AND LOCAL PERMISSIONS

No special permits are required to access the outcrops described in this field guide, as most exposures occur along public roads, village paths, and open hillocks. However, prior permission from local landowners and village authorities is advised for detailed fieldwork and sample collection.

BASE MAPS AND NAVIGATION

Field navigation was carried out using **Survey of India topographic sheets (57 J/11, 57 J/12, 57 J/15, 57 J/16, and 57 F/14)**, Google Earth imagery, and handheld GPS devices. Geological boundaries and field stops were recorded using GPS coordinates and later integrated into the geological map of the study area.

INTRODUCTION

The Cuddapah Basin, an extensive Proterozoic intracratonic sedimentary basin in the Eastern Dharwar Craton, comprises a diverse sequence of siliciclastic, carbonate, and volcanic rocks (Rao et al., 1987; Saha & Tripathy, 2012; Sankar et al., 2014; Sai et al., 2017, 2023; Sheppard et al., 2017; Goswami & Dey, 2018; Goswami et al., 2018). Spanning over 44,000 square kilometers, the Cuddapah Basin is among the oldest and largest preserved basins in the Indian subcontinent (Rao et al., 1987; Mazumder & Eriksson, 2015). The basin records crucial information about the early Earth's tectonic and sedimentary history, offering insights into the Proterozoic paleoenvironments, sedimentation dynamics, and tectonic processes that shaped the Indian shield. The Cuddapah Basin in southern India is a significant sedimentary basin known for its diverse mineral resources, including uranium, asbestos, gypsum, baryte, and gold (Murthy, 1950; Sundaram et al., 1989; Kumar et al., 2012; Bhattacharjee et al., 2018; Goswami et al., 2018, 2019, 2021; Raju, 2024).

The Papaghni Group, predominantly exposed along the western and southwestern margins of the basin, is the oldest sequence and plays a critical role in deciphering the basin's tectonostratigraphic evolution. The sedimentary successions within the Papaghni Group reflect diverse depositional settings, ranging from fluvial to shallow marine, indicating significant paleoenvironmental shifts. The presence of mafic sills and volcanic flows within the Group further suggests episodes of extensional tectonics and magmatic activity influencing basin development (Rao et al., 1987).

A comprehensive field study of the Papaghni Group is essential to unravel its lithostratigraphic framework, depositional environment, and structural deformations. Previous studies have provided fundamental insights into the sedimentological, geochemical, and geochronological aspects of this sequence (Rao et al., 1987; Ramam & Murty, 1997; Lakshminarayana et al., 2001; Basu et al., 2009; Patranabis-Deb et al., 2012, 2018; Saha & Tripathy, 2012; Matin, 2015; Goswami et al., 2017a; Bhattacharjee et al., 2018, 2020, 2024; Sai et al., 2022), yet several gaps remain in understanding its precise depositional history and tectonic implications. Therefore, this work aims to document the lithological variations, sedimentary structures, and mineralisation features of the Papaghni Group, integrating field study with petrographic observation.

GEOLOGICAL BACKGROUND

The Cuddapah Basin, the second largest Proterozoic sedimentary basin in India, is a crescent shaped intracratonic basin within the Peninsular Indian Shield. It is bordered by the Archean Peninsular Gneissic Complex (PGC), comprising mainly tonalite–trondhjemite–granodiorite suites, greenstone belts, and gneissic basement, along its western, northern, and southern margins, while its eastern margin is thrusted by the Nellore Schist Belt. The basin contains a 12 km thick succession of sedimentary rocks, known as the Cuddapah Supergroup, along with intrusive bodies. The Cuddapah Supergroup is divided into four groups: Papaghni Group, Chitravati Group, Nallamalai Group, and Kurnool Group (Fig. 1) (Saha & Tripathy, 2012).

The Papaghni Group nonconformably overlies the Archean gneisses of the Dharwar Craton, with a thickness of approximately 2110 m (Fig. 2). It is subdivided into two formations: the Gulcheru Formation, comprising conglomerate, sandstone, and quartzite lithounits, and the Vempalle Formation, which consists of stromatolitic dolomite, shale, basic intrusives, and associated acid volcanic units (Rao et al., 1987; Goswami et al., 2020; Sai et al., 2023). The Chitravati Group, overlying the Papaghni Group, has a thickness of 4975 m and consists of the Pulivendla Quartzite, Tadpatri Formation, and Gandikota Quartzite formations (Rao et al., 1987; Saha & Tripathy, 2012). The upper boundary of the Chitravati Group is marked by the basal conglomerate horizon of the Kurnool Group.

The Nallamalai Group, located in the eastern part of the Cuddapah Basin, features the intensely deformed Nallamalai Fold Belt and includes the Maidukuru thrust, indicating that the Nallamalai Group is an allochthonous unit positioned between the Chitravati and Kurnool Groups (Saha et al., 2010; Patranabis-Deb et al., 2012; Saha & Tripathy, 2012; Tripathy et al., 2019). The Srisailam Formation, considered as part of the Nallamalai Group, consists of well-sorted, medium grained quartzite layers over 600 m thick (Rao et al., 1987; Patranabis-Deb et al., 2012). The younger Kurnool Group, situated in the central and northern part of the basin, comprises alternating layers of quartzite, shale, and limestone. All Groups within the Cuddapah Supergroup commence with quartzite and are succeeded by finer shale, indicating a shallow marine environment.

TECTONICS

The Cuddapah Basin has been interpreted as a Proterozoic intracratonic rift basin formed due to crustal bulging, erosion, and subsequent subsidence (Drury, 1984; Meijerink et al., 1984). However, alternative models have suggested that the basin may represent a peripheral foreland basin developed in response to the collision between the Indian Craton and the Antarctica block during the assembly of the Columbia supercontinent (Singh & Mishra, 2002; Matin, 2015).

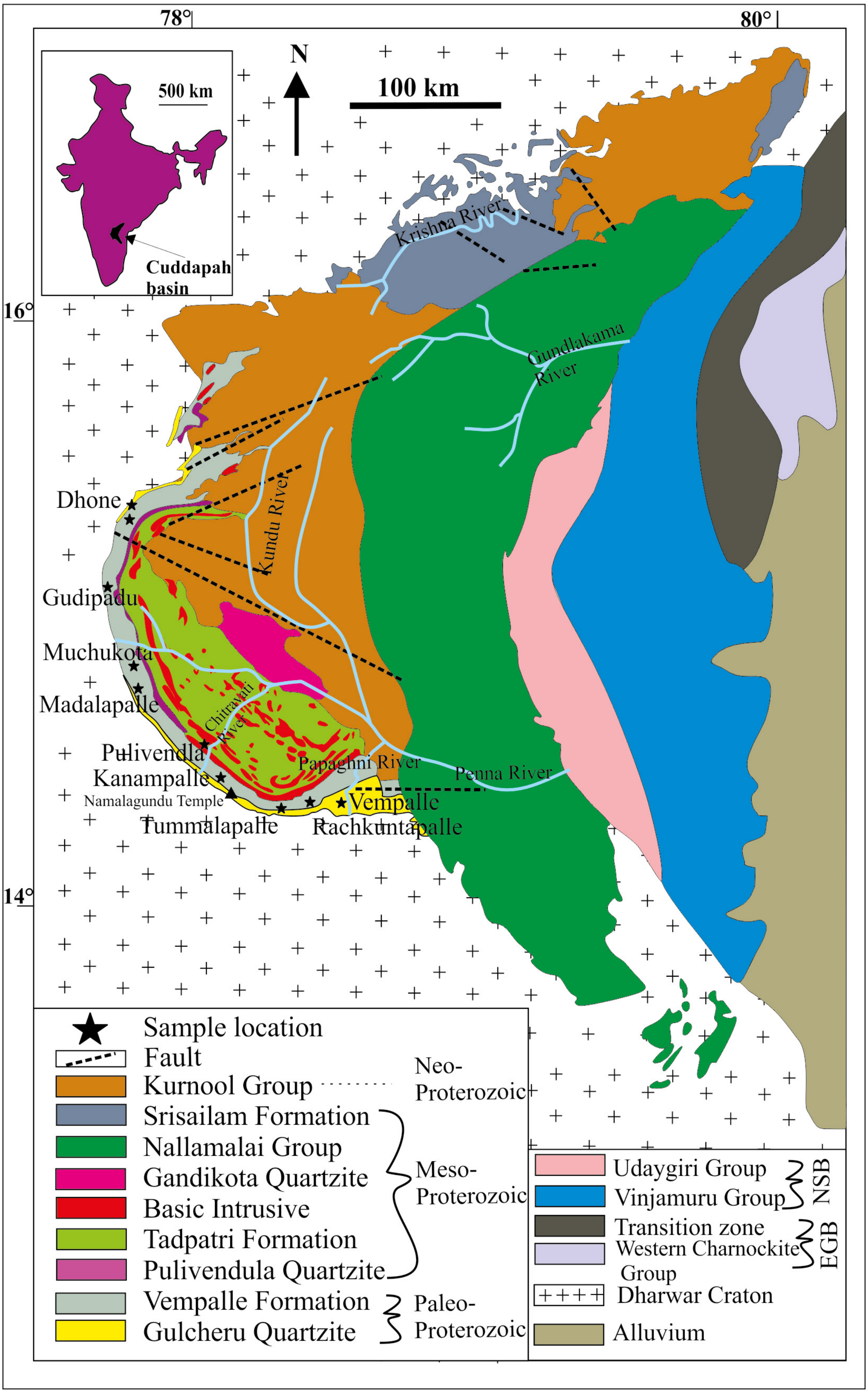

Fig. 1 - Regional Geological map of the Cuddapah Supergroup (modified after Rao et al., 1987) (Abbreviations used: EGB- Eastern Ghat Belt, NSB- Nellore Schist Belt).

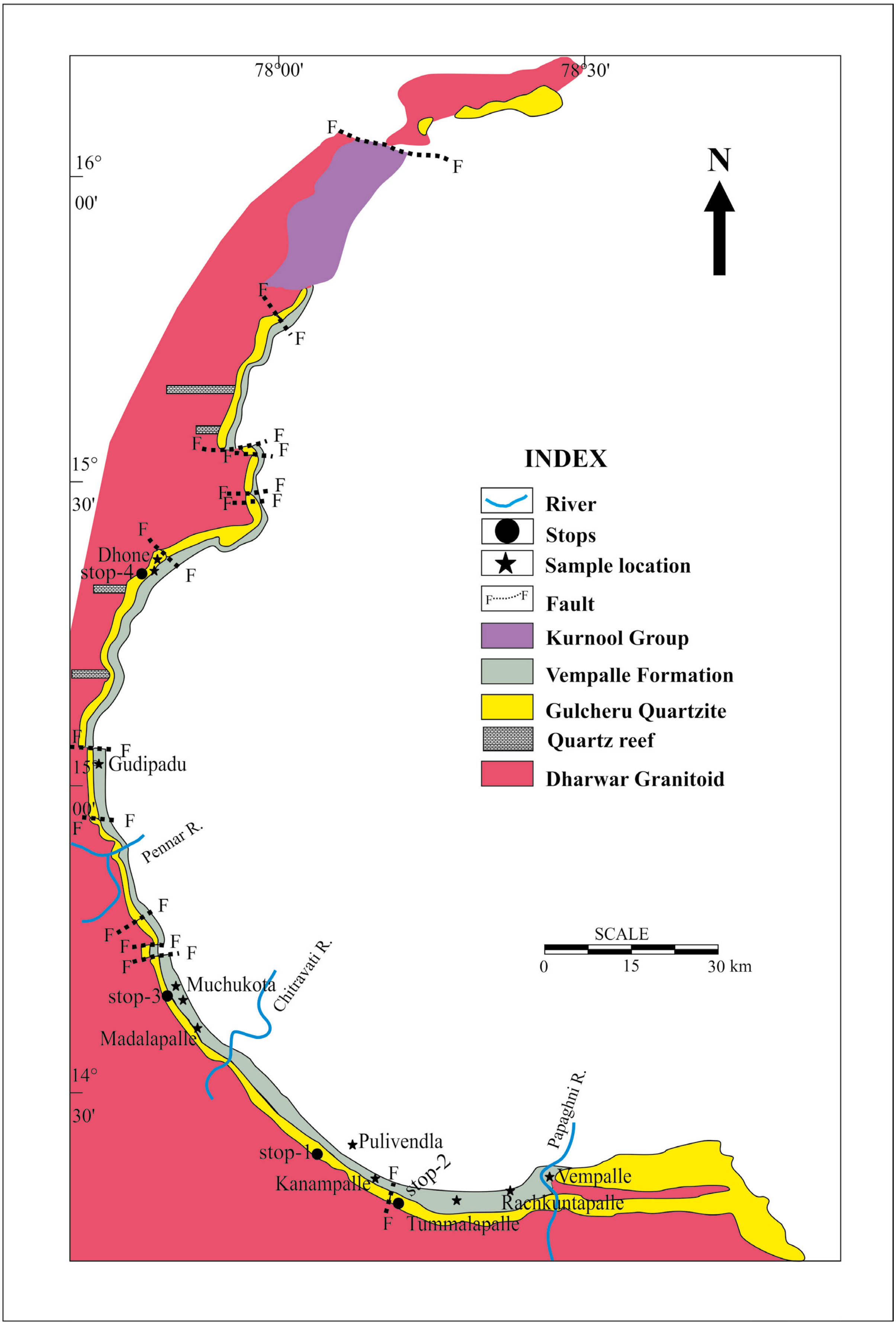

Fig. 2 - Geological map of the lower Cuddapah Basin showing the distribution of the Papaghni Group, including the Gulcheru Quartzite and Vempalle Formation, along with the Dharwar granitoid basement, major faults, rivers, quartz reefs, and stop locations (redrawn after Lakshminarayana et al., 2001 and Saha & Tripathy, 2012).

FIELD OBSERVATIONS AND INTERPRETATIONS

Gulcheru Quartzite: It is the lowermost formation of the Cuddapah Supergroup (Fig. 1, Table 1). It is characterised by conglomerates, pebbly quartzites, and intercalated shales. Nonconformity between the Gulcheru Quartzite and basement Peninsular Gneiss (Fig. 3) is exposed near Namalagundu Temple along the Kadiri- Pulivendula highway (Fig. 4). This outcrop distinctly exhibits the erosional contact between the basement gneiss and the overlying Gulcheru Quartzite. The sharp nonconformity suggests a significant depositional hiatus, marking the transition from an Archean crystalline basement to Proterozoic sedimentation.
The basal conglomerates at this contact indicate a fluvial dominated depositional environment. The presence of

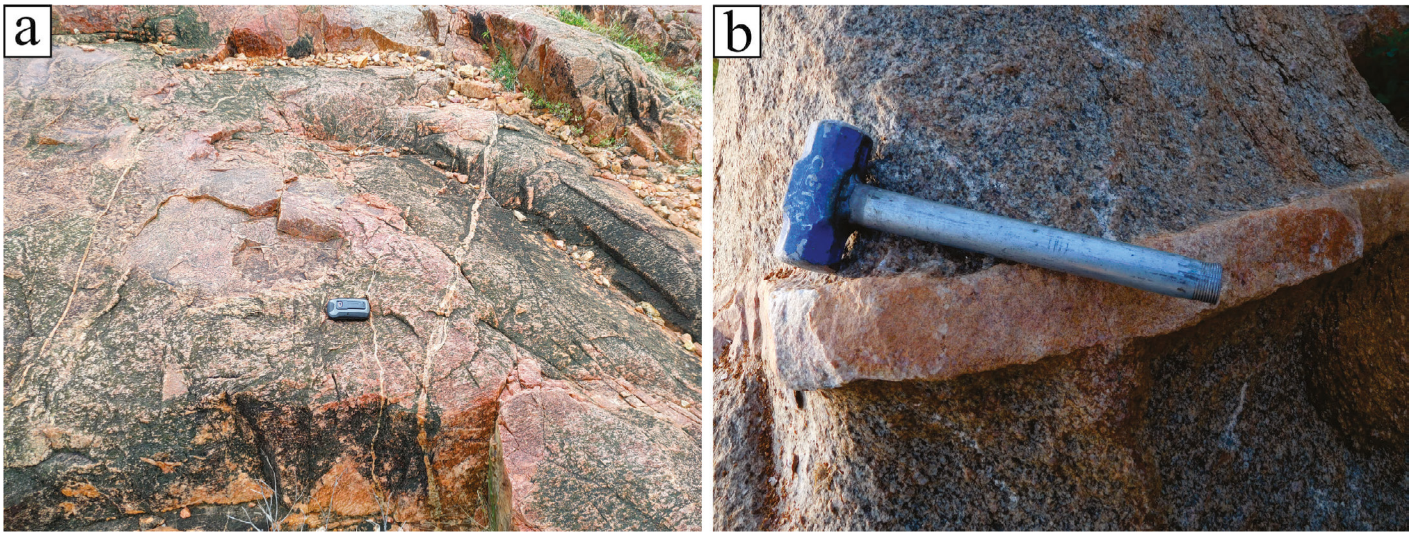

Fig. 3 - (a, b) Basement granitoid exposed in Kanampalle.

Table 1- Stratigraphy of Cuddapah Supergroup (after Rao et al., 1987 and Saha & Tripathy, 2012)

	KURNOOL GROUP	Nandyl Shale	Shale, siltstone
		Koilkuntala Limestone	Limestone, marly limestone
		Paniam Quartzite	Quartz arenite
		Owk Shale	Shale, siltstone, and minor quartz arenite
		Narji Limestone	Micritic limestone
		Banganapalli Quartzite	Conglomerate, arkosic and feldspathic sandstone
^^^^Unconformity^^^^			
		Srisailam Formation	Pebbly grit, quartzite, heterolithic shale andsandstone
--*Tectonic contact*-*-*			
	NALLAMALAI GROUP	Cumbum Formation	Shale, dolomite, limestone, quartzite
		Bairenkonda Quartzite	Pebbly grit quartzite, heterolithic shale- sandstone
--*Tectonic contact*-*-*			
CUDDAPAH SUPERGROUP	CHITRAVATI GROUP	Gandikota Quartzite	Quartzite
		Tadipatri Formation	Shale, tuffs, quartzite, stromatolitic dolomite dolerite/ basalt
		Pulivendla Quartzite	Conglomerate and quartzite
	^^^^Unconformity^^^^		
	PAPAGHNI GROUP	Vempalle Formation	Stromatolitic dolomite, sandstone, dolerite/ basalt (intrusive)
		Gulcheru Quartzite	Conglomerate, pebbly sandstone, feldspathic sandstone, quartz arenite
^^^^Unconformity^^^^			
Archean granite, gneiss, and greenstone			

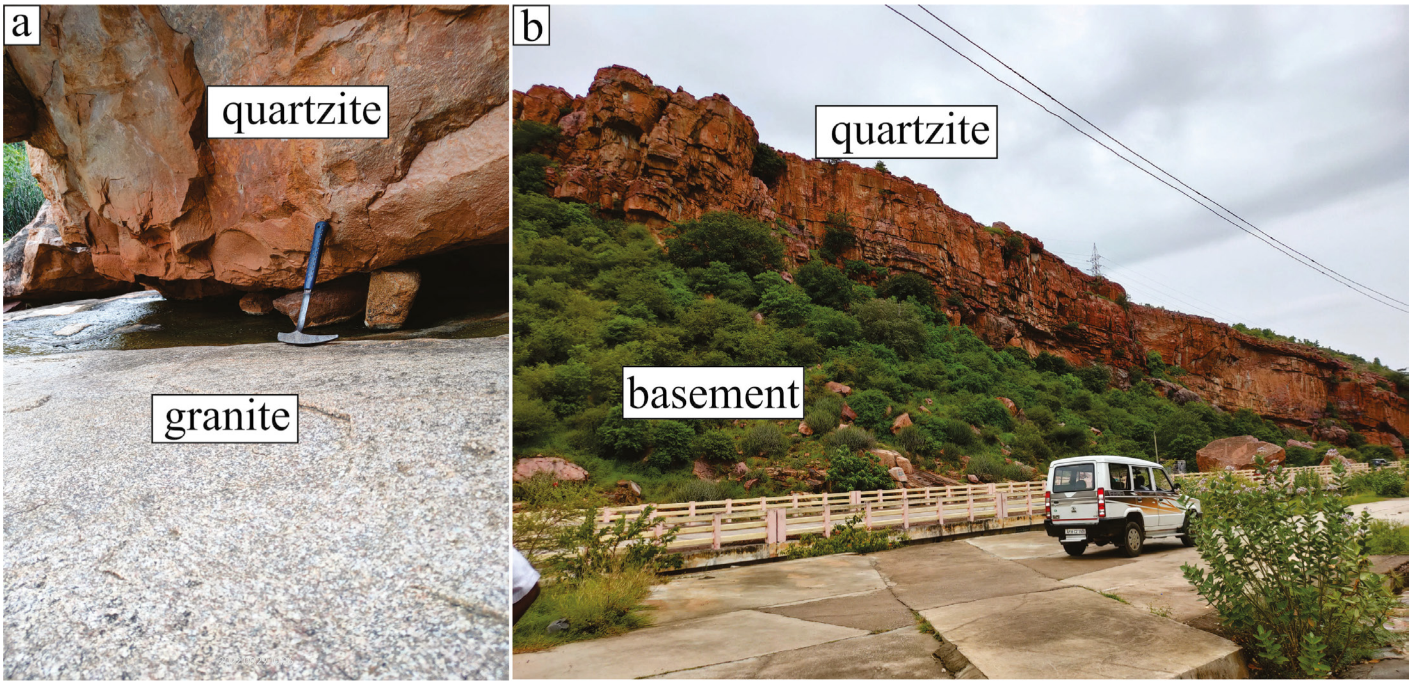

Fig. 4 - (a, b) Eparchean unconformity exposed in Kanampalle village showing the contact between Archean basement and Paleoproterozoic Gulcheru Quartzite.

polymictic conglomerates with diverse clast compositions, including quartz, feldspar, and jasper fragments (Fig. 5a–c), suggests deposition under high energy fluvial conditions. The clast supported fabric, angular to sub-rounded clasts, and poor sorting indicate proximal sedimentation associated with braided river systems. Locally developed breccia layers within the quartzite (Fig. 5d) reflect episodes of rapid sediment accumulation. Petrographic observations reveal that the conglomerates are dominated by detrital quartz and feldspar grains, while calcite occurs as intergranular cement, filling pore spaces between framework grains (Fig. 6). The calcite cement is diagenetic in origin and represents post-depositional carbonate precipitation rather than a primary detrital component.

The Gulcheru Quartzite (Fig. 7) exhibits a range of sedimentary structures indicative of deposition in high energy fluvial to shallow marine environments. The presence of ripple marks, including wave and asymmetric ripples (Fig. 8a, b), indicates oscillatory and unidirectional currents, characteristic of intertidal to shallow marine settings. Primary sedimentary structure like tabular cross bedding is present (Fig. 8c), suggest deposition under high energy fluvial conditions. Trough cross bedding (Fig. 8d) in quartzite suggests a fluvial depositional environment (Goswami et al., 2017b). The quartzite exhibits notable variations in clast composition, with dominant quartz fragments (Fig. 9). Geochemical data indicate varying provenance contributions from granitic and greenstone terrains, with mineralogical assemblages reflecting high energy sediment transport processes (Basu et al., 2007).

Vempalle Formation: The Vempalle Formation conformably overlies the Gulcheru Quartzite (Fig. 1) and the gradual transition from quartzite to dolostone suggests a marine transgression, with increasing carbonate deposition under shallow marine to lagoonal conditions. The Vempalle Formation is characterised by cyclic carbonate sedimentation, exhibits two major depositional cycles (Sivasubramaniam et al., 2012). The first cycle includes the supratidal to upper intertidal zone, featuring dolomite interbedded with shale and quartzite, along with flat to wavy stromatolites and desiccation cracks. These sedimentary structures indicate supratidal conditions with periodic emergent phases (Awramik et al., 1976). Cyanobacteria thrived by producing protective substances. The lower intertidal to upper subtidal zone contains tabular bioherms and columnar stromatolites formed under wave agitation, indicative of a dynamic environment (Hoffman, 1976). Second cycle comprises oolitic grainstones and stromatolite intercalations, highlighting salinity variations. The deep subtidal zone features large domal stromatolites, suggesting low energy deposition and periodic storm influence (Grotzinger, 1986; Gururaja et al., 1987).

The massive dolostone, distinguished by its dull white colour, is overlain by a conglomerate layer. This geological formation is prominently visible near the villages of Tummalapalle and Kanampalle. The dolostone exhibits the typical elephant skin weathering (Fig. 10a) formed due to the carbonate dissolution by the acidic rain water. In the Kanampalle area, the Vempalle dolostone exhibits a strike oriented from NNE to SSW, with a dip ranging between 15

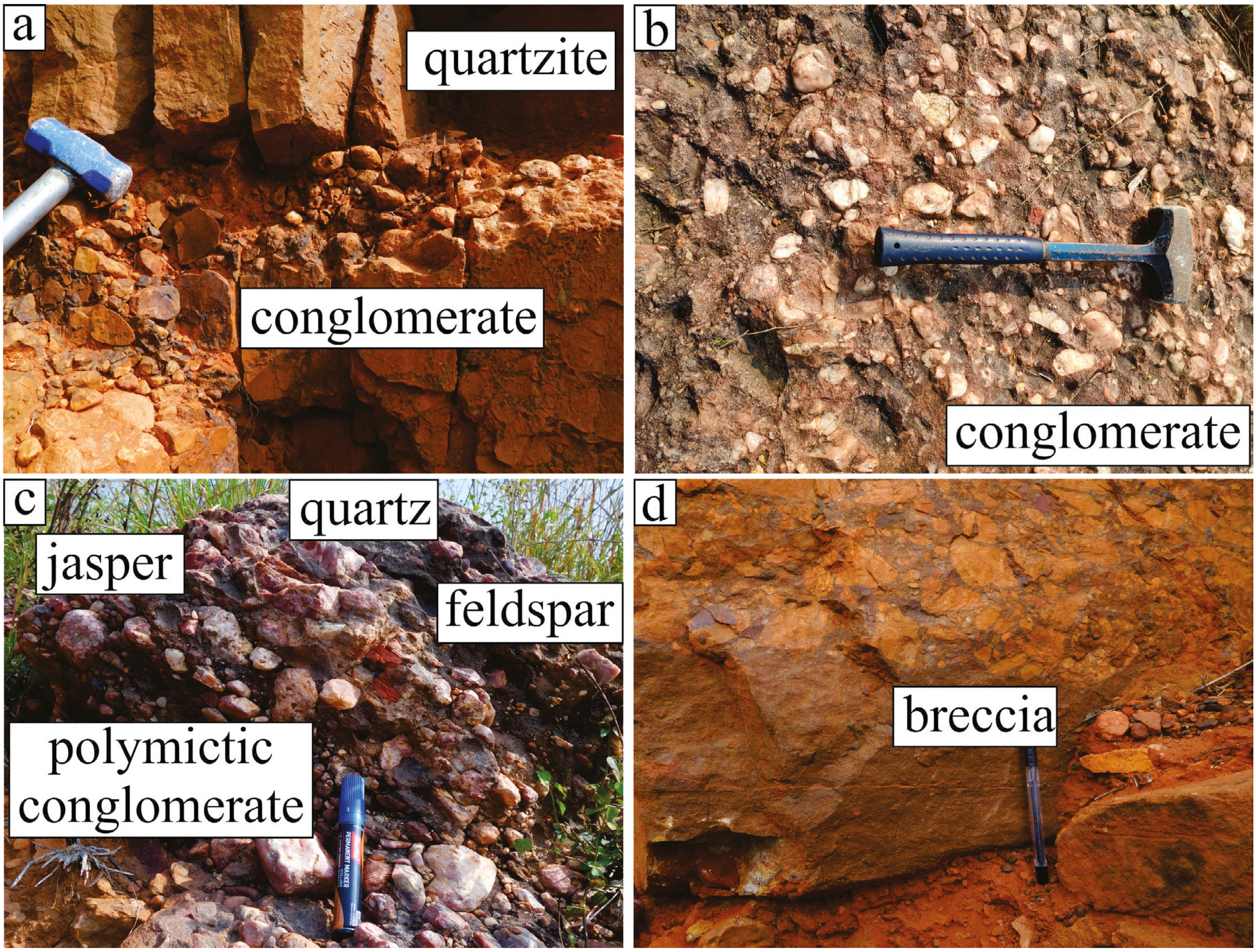

Fig. 5 - (a) conglomerate lies below the Gulcheru Quartzite, (b, c) polymictic conglomerate rich in clasts of quartz, jasper, and minor feldspars, (d) Poorly sorted brecciated Gulcheru Quartzite.

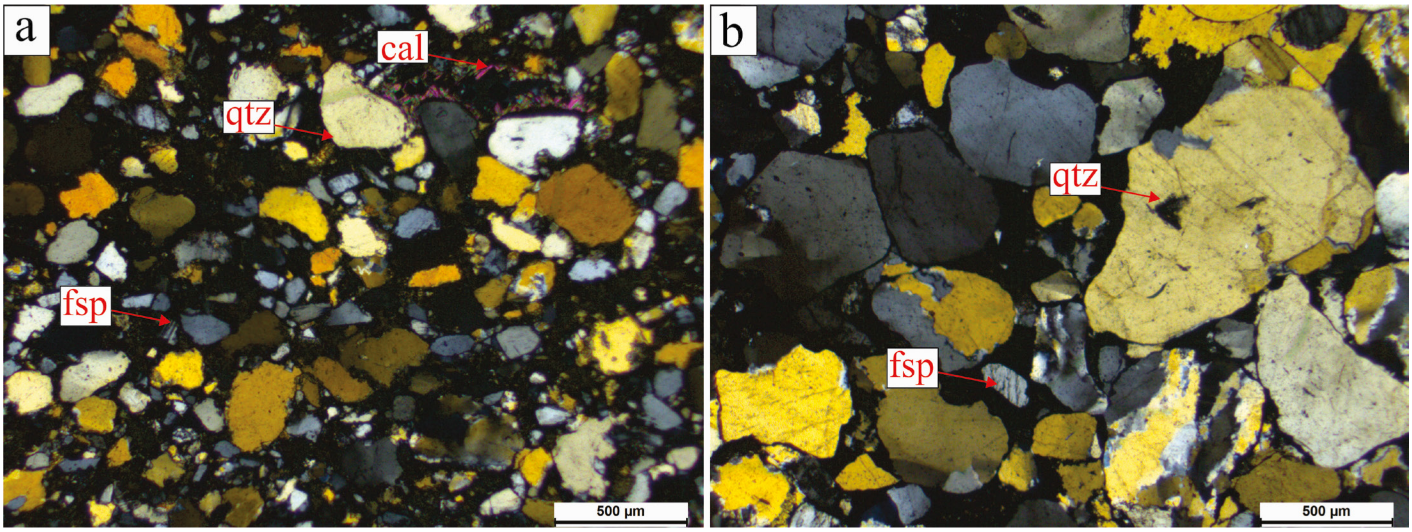

Fig. 6 - (a, b) Photomicrographs of the basal conglomerates showing rounded detrital quartz grains and minor feldspar, with recrystallised calcite occurring as intergranular cement, indicating a diagenetic origin of the carbonate phase.

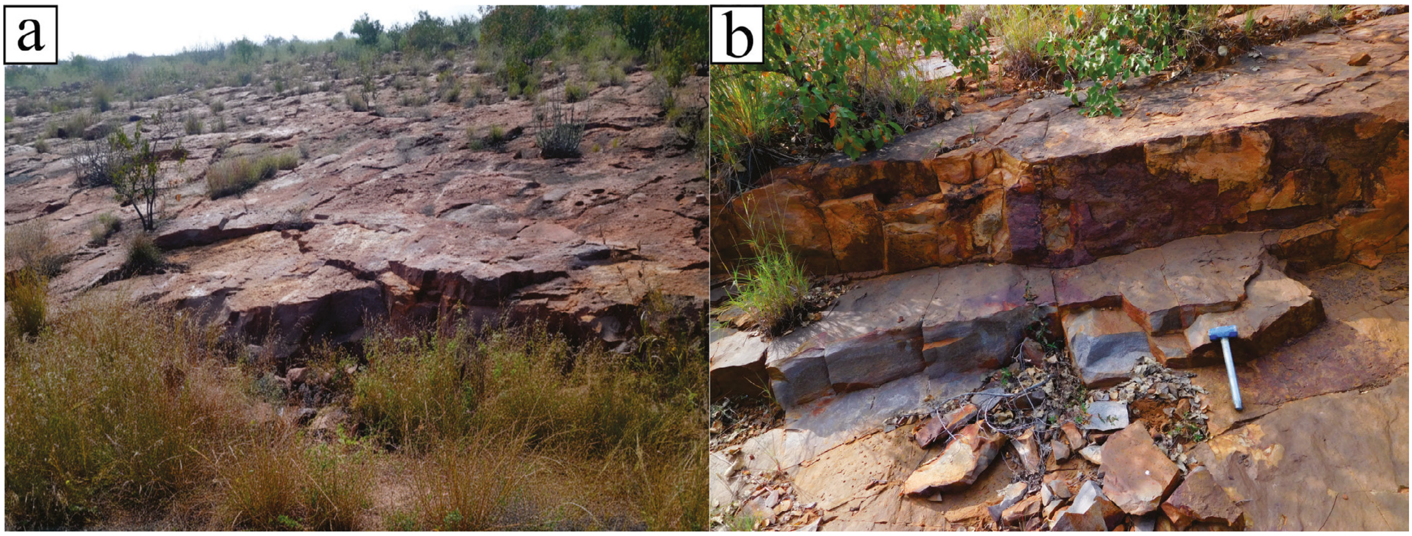

Fig. 7 - (a. b) Roadside exposure of the Gulcheru Quartzite showing gently dipping bedding planes and jointed quartzite surfaces exposed along the road cut near Kanampalle area.

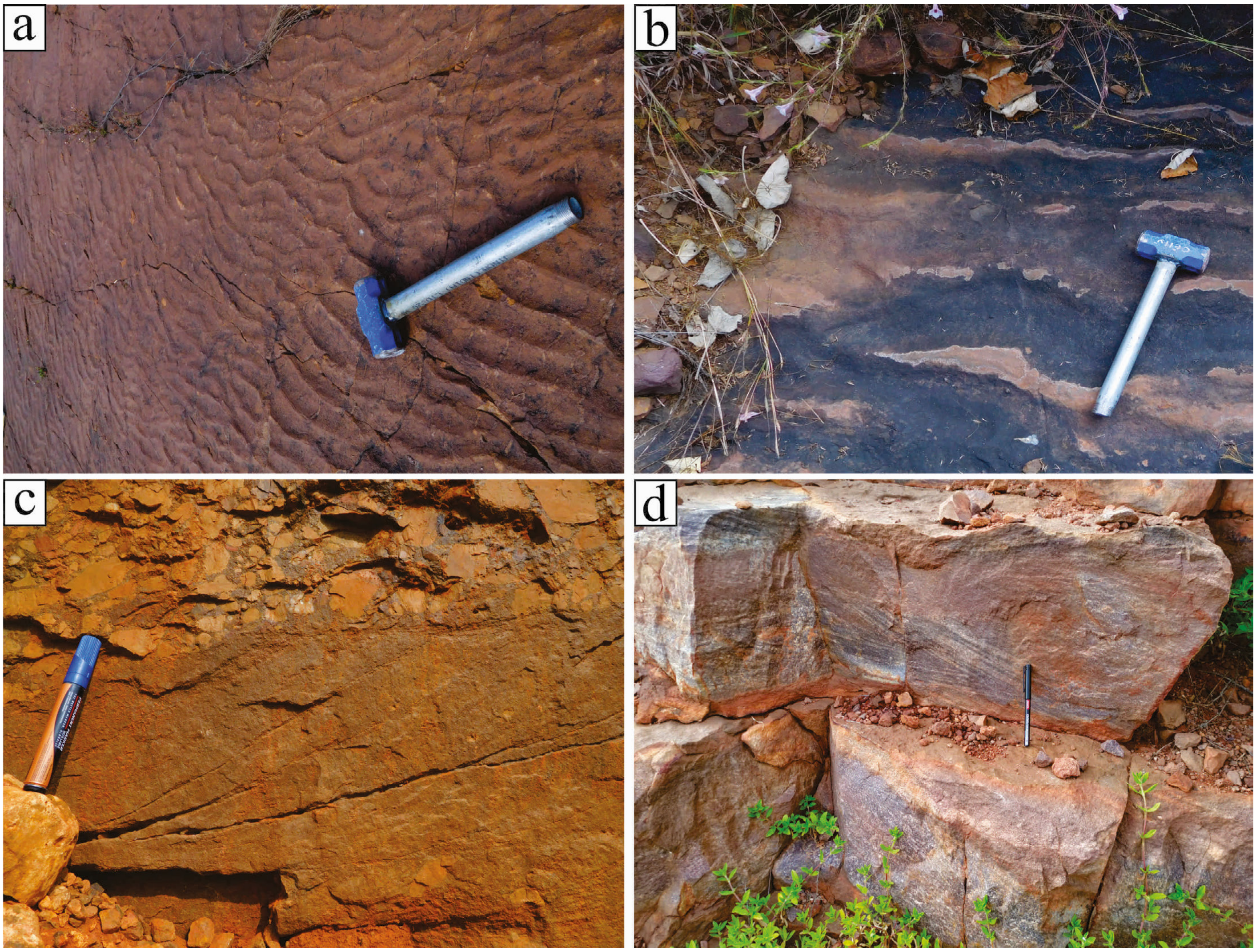

Fig. 8 - (a) Ripple marks within the Gulcheru Quartzite, (b) wavy ripples within the Gulcheru Quartzite, and the dark colour is due to the presence of organic matter, (c) at the bottom, there is tabular cross bedding within the quartzite, while a layer of breccia is present on top, (d) trough cross bedding within the quartzite.

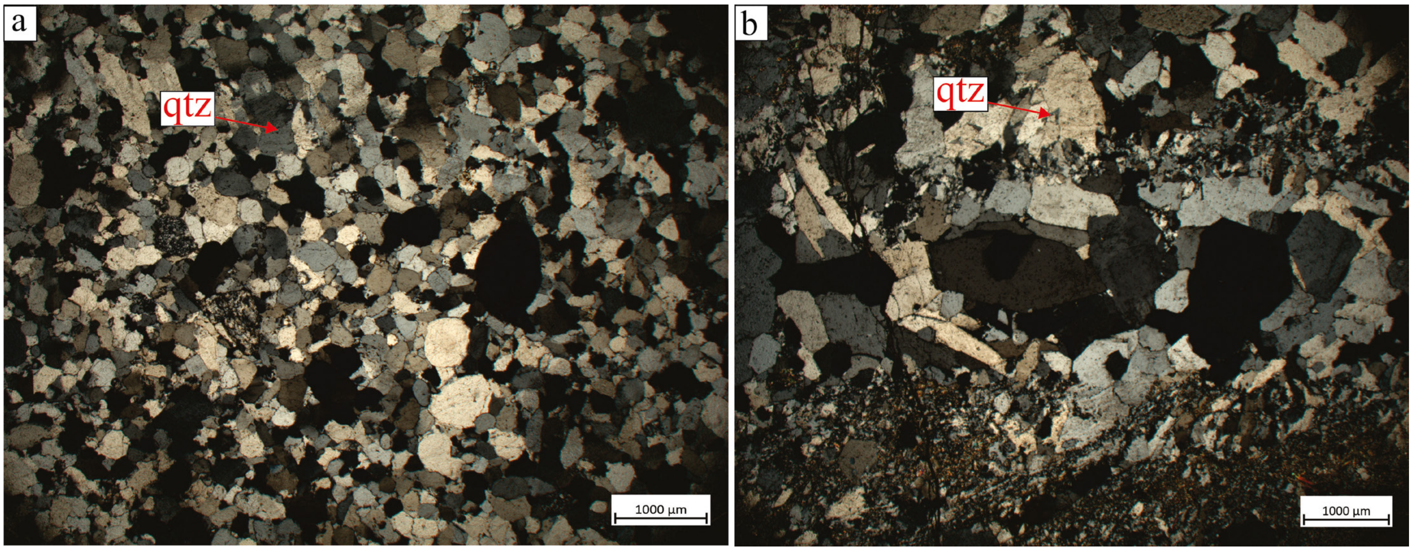

Fig. 9 - (a, b) Photomicrographs of quartzite.

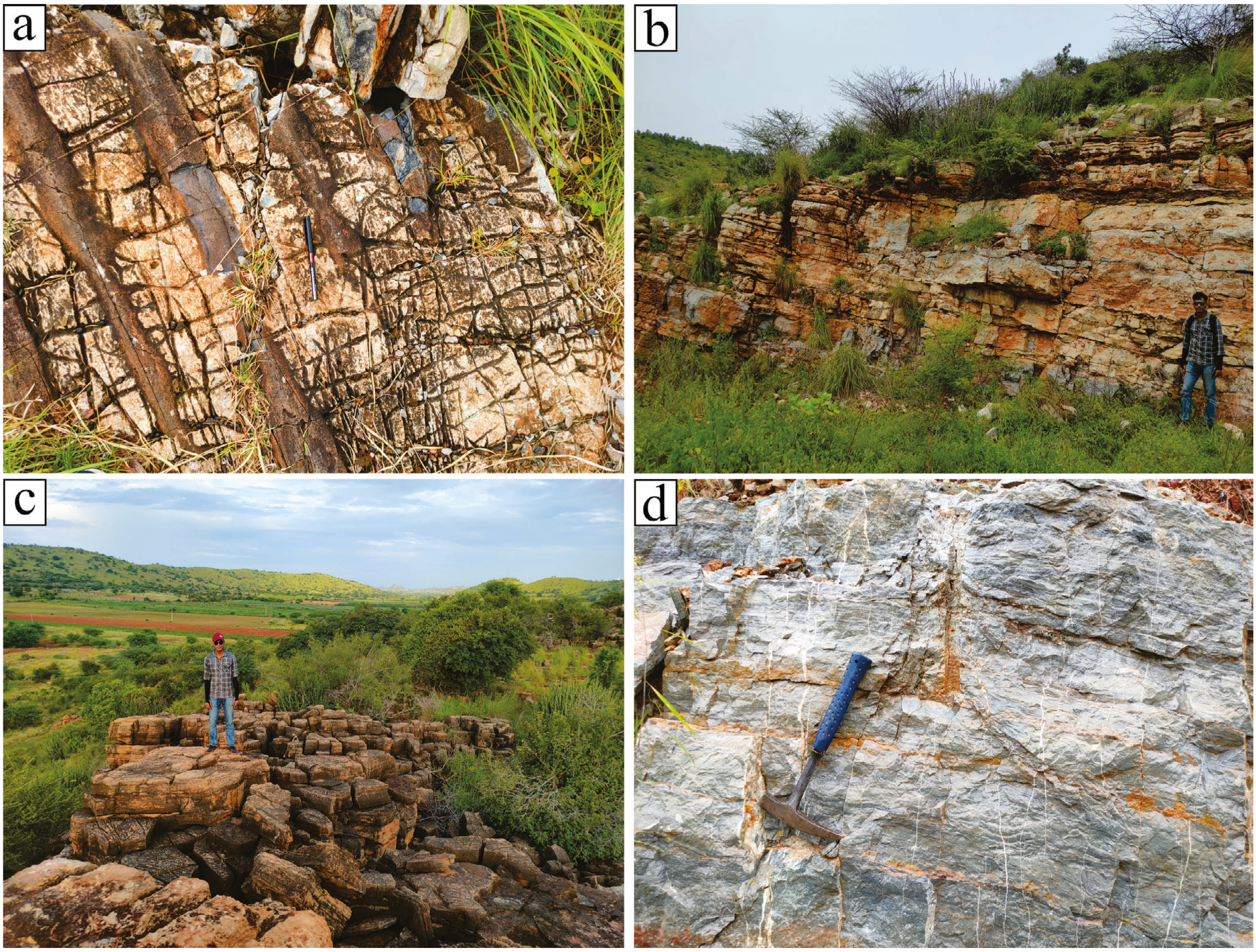

Fig. 10 - (a) Elephant skin weathering observed within the dolostone, (b) exposed dipping strata of Vempalle dolostone near Muchukota area, (c) Vempalle dolostone, (d) multiple quartz-calcite veins intruding within the Vempalle dolostone.

and 20 degrees towards the east (Fig. 10b, c). The later hydrothermal activity within the Vempalle dolostone is clearly indicated by the presence of vertical quartz and calcite veins cutting through the dolostone (Fig. 10d).

The petrography of the Vempalle dolostone indicates the presence of both fine and coarse dolomite crystals (Fig. 11a). The size variation among grains implies differences in nucleation rates and fluid chemistry during formation. These grains are distinguished by their rhombic cleavage (Fig. 11b), high order birefringence, and contact twinning (Fig. 11c). Well defined rhombic crystal faces with sharp boundaries (Fig. 11d, e), indicating early stage dolomite formation under controlled geochemical conditions. Zoning across the dolomite grain indicate about multiple phases of dolomitisation (Fig. 11d). The rhombic morphology suggests low-Mg calcite replacement by dolomite or direct precipitation from dolomitising fluids. Recrystallised dolomite grains along with quartz grains (Fig. 10f) are also observed in the dolostone indicate to diagenetic overprinting, possibly driven by fluid migration, pressure solution, and hydrothermal alterations, which influenced the mineralogical evolution of the Vempalle Formation.

The presence of folded thin quartz veins in dolostone (Fig. 12) indicates a secondary structural feature, indicating brittle ductile deformation of early formed veins due to tectonic compression. These veins originally formed from silica rich fluid infiltration along primary bedding planes, which acted as mechanical anisotropies. The occurrence of recrystallised carbonate veins along with distressed grain boundaries (Fig. 13) suggests fluid rock interactions. This supports the idea of multiple diagenetic phases, involving initial vein formation from fluid infiltration, followed by recrystallisation due to tectonic stress or metamorphism within the Vempalle Formation.

Ore minerals such as pyrite, chalcopyrite, magnetite, hematite, and goethite are identified within the Vempalle dolostone (Fig. 14). Pyrite, the most abundant sulfide, occurs as anhedral to euhedral grains ranging from 5 to 150 microns in size (Fig. 14a). The close association with chalcopyrite (Fig. 14b) suggests their simultaneous precipitation from metal bearing hydrothermal fluids under reducing conditions (Behera et al., 2026). Magnetite (Fig. 14c), often observed replacing pyrite, likely formed during the same hydrothermal event under slightly more oxidizing conditions. Subsequent exposure to near surface oxidizing environments led to the alteration of pyrite and magnetite into hematite, and eventually into goethite. Goethite typically displays colloform banding (Fig. 14d), a textural feature characteristic of supergene enrichment processes. This progression of mineral phases reflects a multistage mineralisation history involving initial hydrothermal deposition followed by later supergene oxidation.

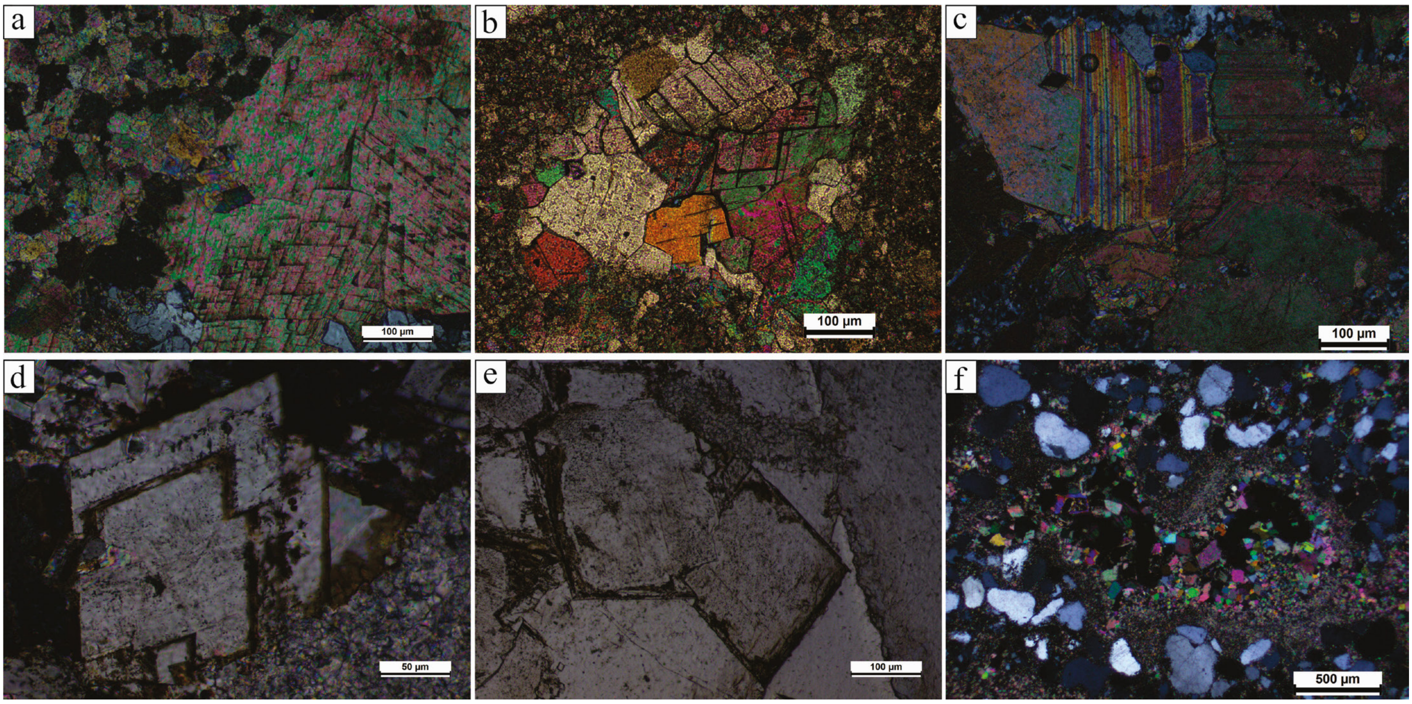

Fig. 11 - Photomicrographs of (a) finer and coarser dolomite crystals (b) dolomite crystals with prominent rhombic cleavage and higher birefringes, (c) dolomite grains showing contact twinning under XPL, (d, e) rhombic crystals of dolomite, (f) recrystallised dolomite and quartz grains.

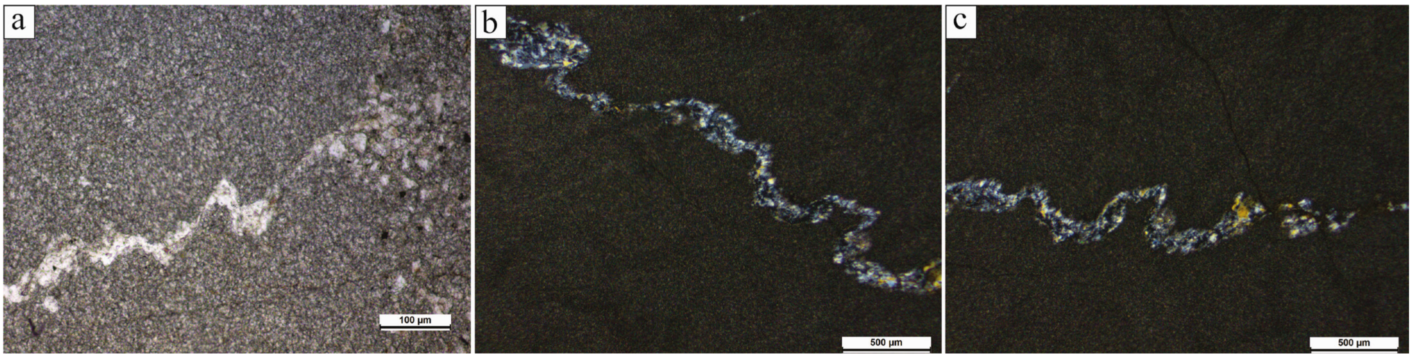

Fig. 12 - (a, b, c) Photomicrographs of folded quartz vein within the Vempalle dolostone

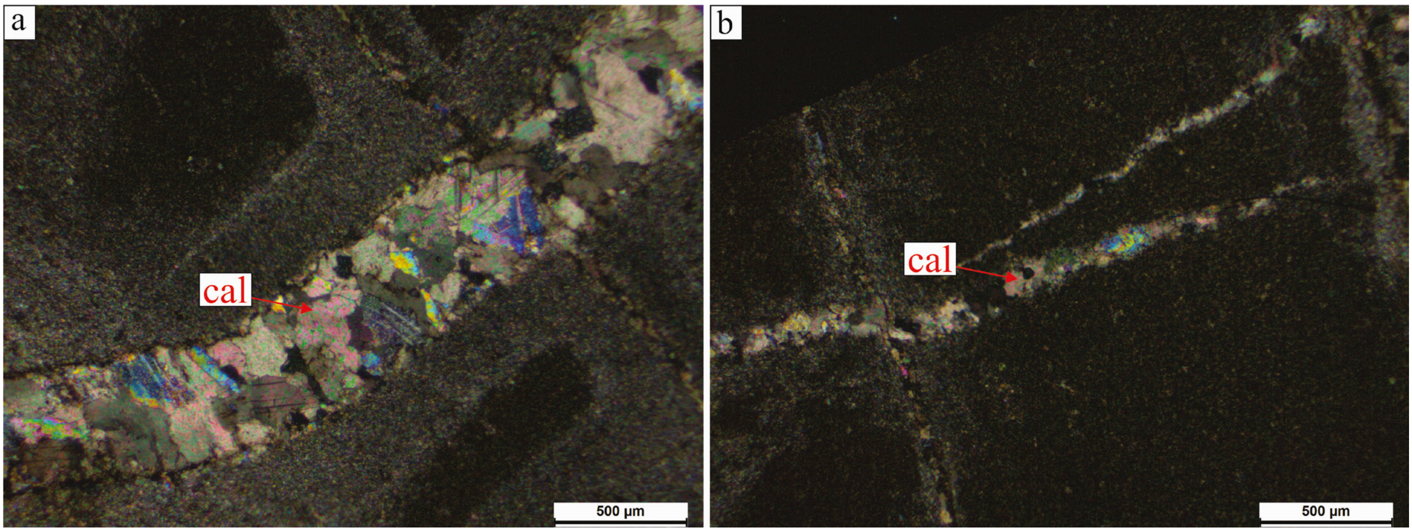

Fig. 13 - (a, b) Recrystallised calcite veins within the dolostone.

This Vempalle Formation predominantly comprises stromatolitic dolomites, shale, chert, and siliceous oolites. The dolomitic sequences with well preserved stromatolitic structures suggest a shallow marine to tidal depositional environment.

Stromatolites are among the oldest known life forms, with a record extending from the Archean to the present (Landing & Johnson, 2024). They are organo-sedimentary structures formed by microbial communities, primarily cyanobacteria, which trap and bind sediments while precipitating carbonates (Awramik et al., 1976). The Paleoproterozoic Vempalle Formation of the Cuddapah Supergroup showcases well preserved complex stromatolitic structures formed by microbial mats (Riding & Sharma, 1998; Goswami et al., 2016a).

The best preserved stromatolite buildups are found in the upper middle lithounits of the Vempalle Formation, with minor siliciclastic influx (Patranabis-Deb et al., 2012). Continuous exposures along Kanampalle village allow detailed analysis of stromatolite structures, spatial distribution, and role in carbonate platform development. The different facies suggest that the microbial mats responsible for stromatolite formation adapted to a range of energy conditions and substrate types, influencing the observed variation in morphology (Callefo et al., 2021).

The morphology of stromatolites was influenced by different types of algae and environmental factors such as sunlight, water depth, carbonate production, and siliciclastic input, resulting in larger wave resistant structures (Sandberg, 1985). Laminar stromatolites within the Vempalle dolostone (Fig. 15a) provide strong evidence of microbial activity, indicating shallow marine conditions with periodic subaerial exposure. Conical stromatolites (Fig. 15b) ranging in diameter from a few millimeters to several centimeters were formed in the high energy environment (Kuang et al., 2019). Additionally, columnar stromatolites (Fig. 15c) suggest stable depositional environments with consistent carbonate precipitation, likely occurring in intertidal to shallow subtidal settings. Domal shaped stromatolitic colony (Fig. 15d) within the dolostone indicates about the activity of cyanobacteria in shallow and sunlit prone areas (Kuang et al., 2019). The presence of spherical stromatolites (Fig. 15e,

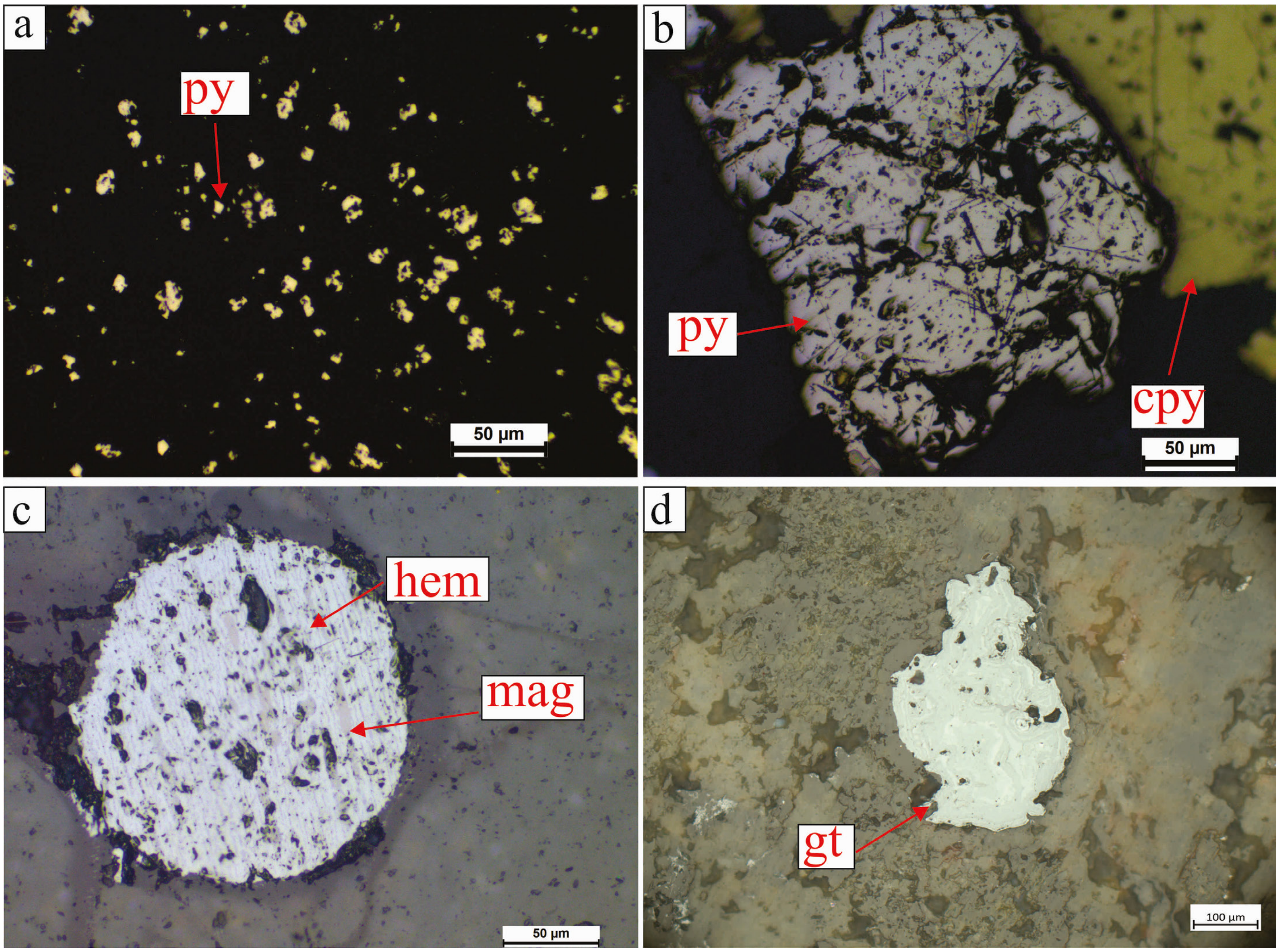

Fig. 14 - Photomicrographs of (a) fine grained pyrite phases within the dolostone, (b) coarse euhedral pyrite grain sharing grain boundary with chalcopyrite, (c) rounded magnetite grains that's oxidised to hematite, (d) typical colloform banding texture of goethite.

f) further supports microbial carbonate production, likely influenced by periodic environmental fluctuations. These various stromatolitic associations highlight the dynamic and evolving depositional environments of the Vempalle dolostone.

Siliceous ooids in the Vempalle Formation suggest high energy wave agitation within shallow marine conditions, promoting the formation of coated carbonate grains (Mathur et al., 2014). The oolitic carbonates comprise ooids of different dimensions, showing grain supported textures. These ooids are typically spherical to oval, with some being semicircular or elongated (Fig. 16). These ooids are studied under microscope to observe the texture and mineralogical association. Ooids exhibit both concentric and radial patterns (Fig. 17a), with the former being more common. Quartz veins are observed intruding within the ooids (Fig. 17b).

Siliceous, calcareous cored ooids are identified (Fig. 17c, d). Siliceous ooids consist entirely of chert and quartz, while calcareous ooids are enrich in carbonate minerals (Fig. 17c). Cementing material is either carbonate or chert mineral. The intergranular spaces are filled by quartz grains creating a mosaic appearance with the presence of different sizes of quartz (Fig. 16d). Oolites showing radial pattern consist of fibrous calcite (Fig. 16e), giving them a sector like appearance. Ooids with a carbonate rich core and chert rich rim show zonation (Fig. 16f), featuring an outer cryptocrystalline quartz rim and an inner carbonate mineral forming a mosaic (Fig. 17e, f). Recrystallisation, varying in coarseness, occurs during diagenesis causes precipitation of large quartz crystals in between the ooids (Fig. 17 d, f).

Exposure of laminar cherty dolostone reveals primary sedimentary layering (Fig. 18a). The folded cherty dolostone layers exhibit soft sedimentary deformation, a primary deformation feature (Fig. 18b). Subsequently, quartz and calcite veins intruded along fractures (Figs. 17c, 17d), representing tertiary structural elements related to late stage hydrothermal activity. The intense folding seen

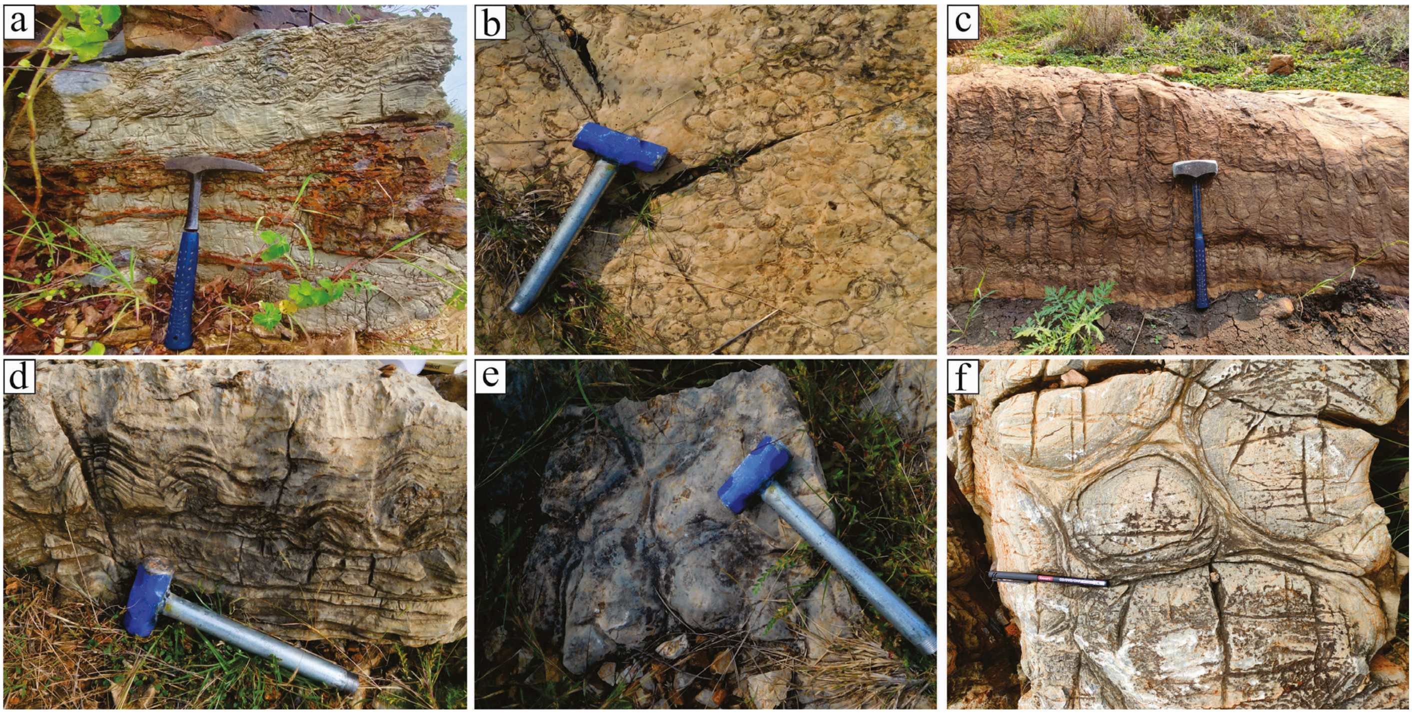

Fig. 15 - (a) laminar stromatolites exposed near Kanampalle village, (b) conical stromatolitic association with diameters varies from millimeter to centimeters, (c) columnar stromatolitic association, (d) domal stromatolitic colony, (e, f) spherical association of stromatolites within the Vempalle dolostone.

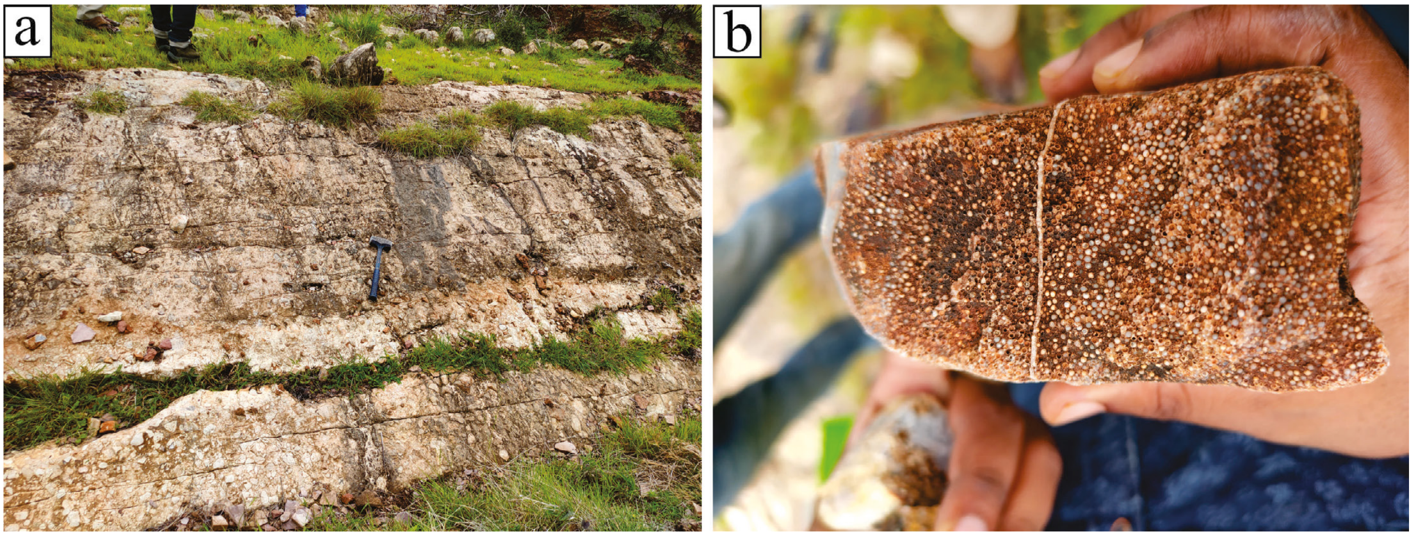

Fig. 16 - (a) Exposed Vempalle dolostone enriched with oolitic association, (b) hand specimen of ooids in the Vempalle dolostone.

in cherty dolostone (Fig. 19) likely results from compaction and syn-sedimentary loading, modified by subsequent tectonism (Goswami et al., 2012, 2016b; Mukherjee et al., 2019).

The stromatolitic dolostone in and around Tummalapalle characterised by intercalated laminar chert layers (Fig. 20a). The extensive development of chert bands within the dolostone indicates early diagenetic silicification (Goswami et al., 2015, 2023). Some horizons of the Vempalle dolostone are silicified causes hosting chert nodules and red color is due to the presence of iron minerals (Fig. 20b). Dark colored chert nodules present within the dolostone indicates about the enriched organic matter (Fig. 20c). Several chert nodules are found at the hinge area of the domal stromatolitic association indicating about preferred silicification area (Fig. 20d).

Purple shale is the uppermost lithounits of the Vempalle Formation. This unit is thinly laminated and horizontally

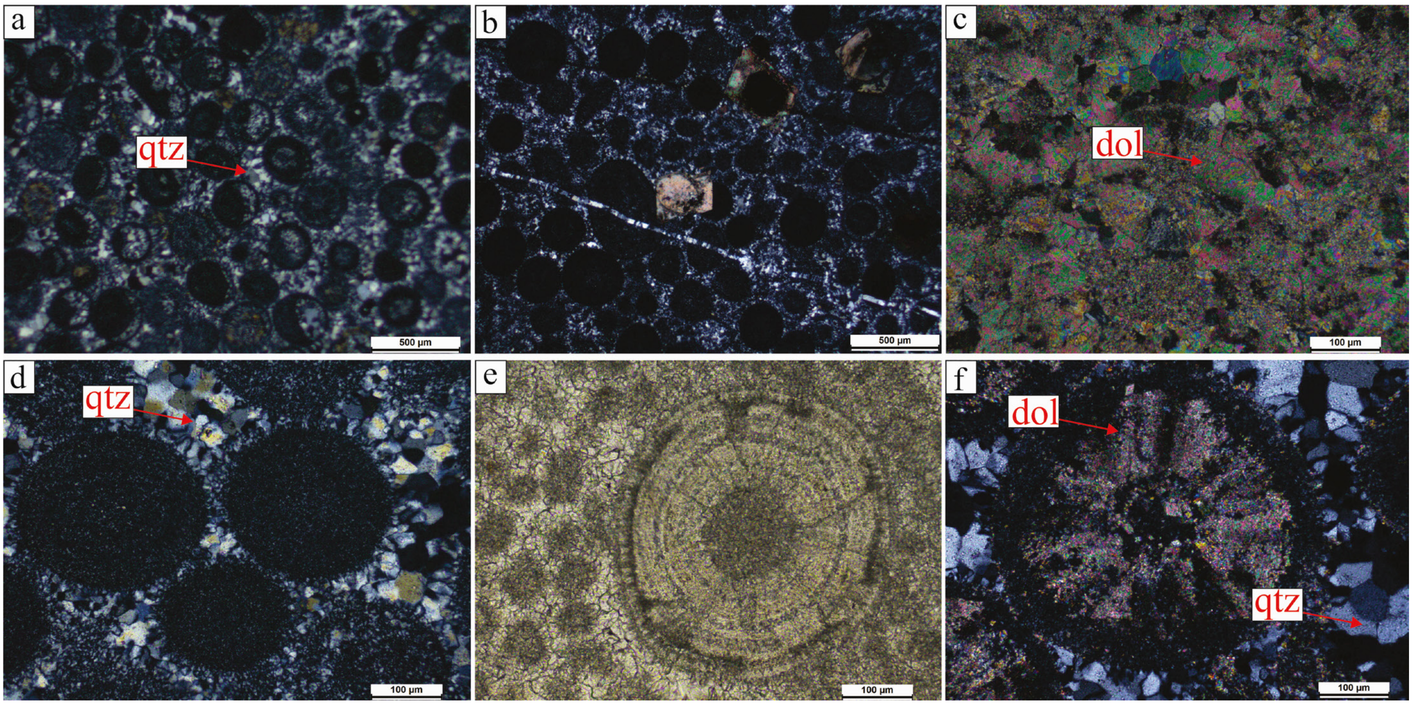

Fig. 17 - Photomicrographs of ooids within the Vempalle dolostone showing (a) spherical to oval shape and the diameter varies from 50 micron to 300-micron, (b) quartz vein crosscutting the ooids, (c) recrystallised dolomite within the ooids, (d) radial pattern of ooids with secondary quartz and chert mineralisation (e) radial pattern of ooids, (f) an ooid showing a fibrous pattern with an outer rim enriched with chert, and an inner core enriched with dolomite. Additionally, secondary quartz mineralisation is observed around the ooid.

continuous (Fig. 21a). Calcite veins are also observed within the purple shale unit (Fig. 21b).The distinctive coloration of the purple shale indicates oxidation conditions, suggesting periodic subaerial exposure and fluctuating redox environments within the depositional basin (Bhattacharjee et al., 2012).

The presence of dolerite dykes (Fig. 22a) cutting through the Vempalle Formation indicates post depositional magmatic activity, possibly related to regional extensional tectonics. The dolerite dyke is well exposed near Dhone area. The fractures within the dolerite dykes (Fig. 22b) served as potential conduits for fluid migration, influencing hydrothermal mineralisation within the surrounding sedimentary units. The dolerite is enriched with ore minerals like pyrite, chalcopyrite, and magnetite (Fig. 22c). The contact between dolerite dyke and Vempalle dolostone causing hydrothermal alteration, leading to the formation of chrysotile minerals (Fig. 22d).

Petrographic observations of the dolerite reveal an abundance of minerals such as pyroxene, hornblende, plagioclase feldspar, and other opaque minerals (Fig. 23a, b). The dolerite is distinguished by the ophitic texture (Fig. 23c, d). At the interface between the dolerite and dolostone, fibrous chlorite and quartz minerals develop, sharing irregular grain boundaries with the dolomite grains (Fig. 24a). The presence of fibrous mineral phases clearly indicates hydrothermal activity (Fig. 24b, c, d).

The presence of ore minerals such as pyrite, chalcopyrite, magnetite, covellite, hematite, and goethite within the dolerite provides insights into the fluid composition (Behera et al., 2025). The euhedral shape of pyrite grains (Fig. 25a) suggests hydrothermal or volcanic activity. The co-precipitation of pyrite and chalcopyrite is indicated by their shared grain boundaries (Fig. 25b). Magnetite found around pyrite grains (Fig. 25b, c, e, f) points to an oxidizing environment. Covellite, found at the grain boundaries (Fig. 25c, d), is an altered product formed from the oxidation of chalcopyrite. Goethite, displaying colloform banding texture (Fig. 25e), forms from the oxidation of magnetite. The conversion of magnetite to hematite within the magnetite grains indicates a martitisation texture (Fig. 25f).

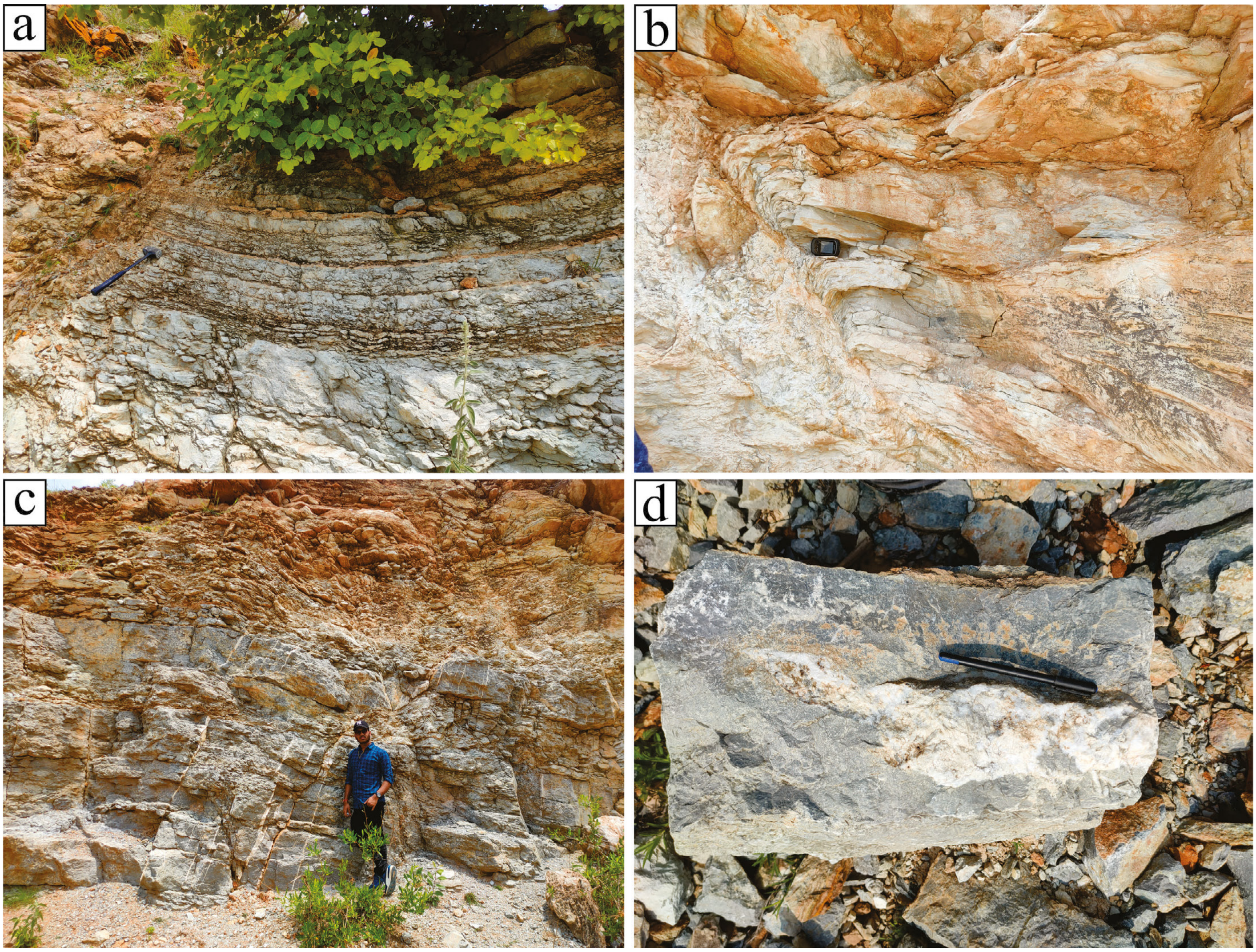

Fig. 18 - Exposure of (a) laminar cherty dolostone, (b) folded cherty dolostone layer, (c) quartz veins crosscutting the cherty dolostone, (d) hand specimen showing calcite vein within the dolostone.

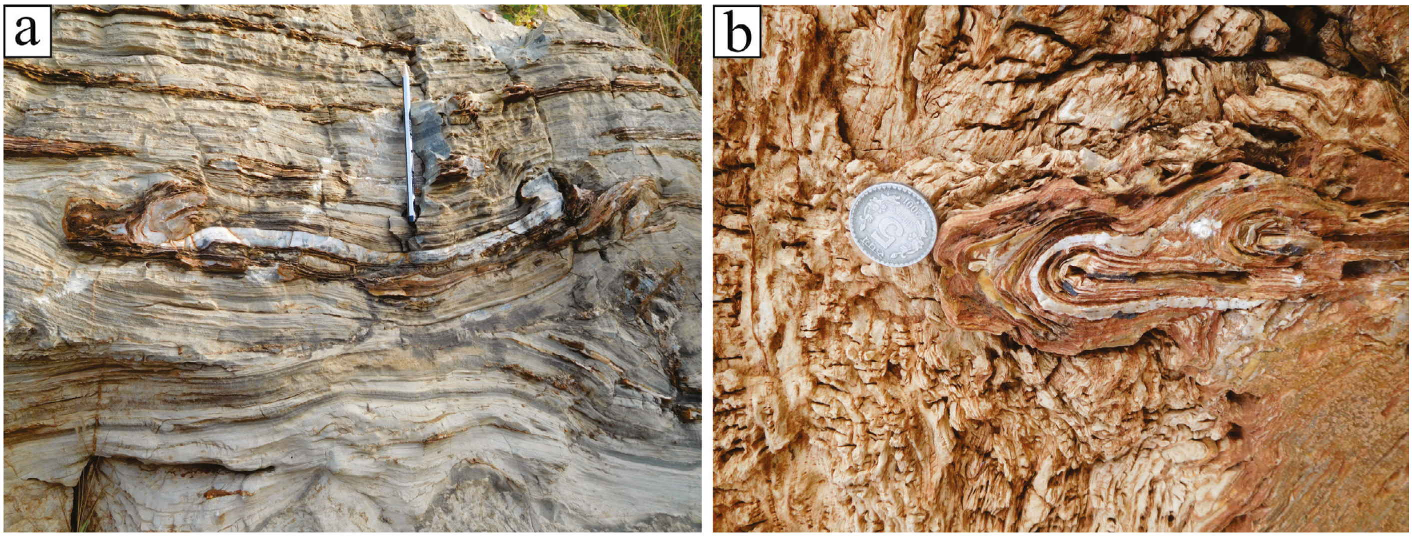

Fig. 19 - (a, b) folded chert layers within the Vempalle dolostone.

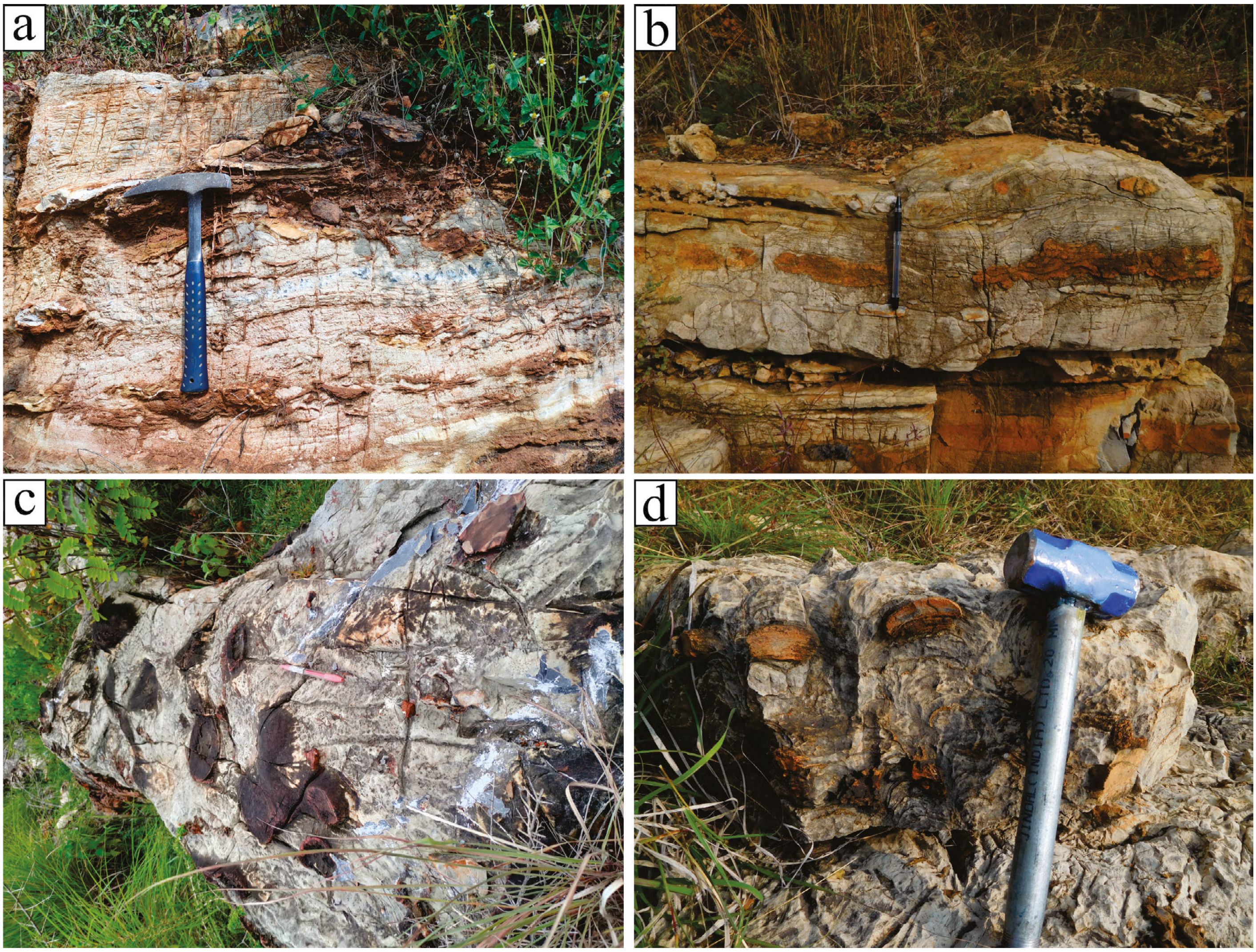

Fig. 20 - Exposure of: (a) laminar chert layer within stromatolitic dolostone, (b) chert nodules within the dolostone exhibiting a red color due to iron content, (c) chert nodules along the lateral extent of the dolostone showing a dark color attributed to organic matter, (d) chert nodules located at the hinge area of domal stromatolites.

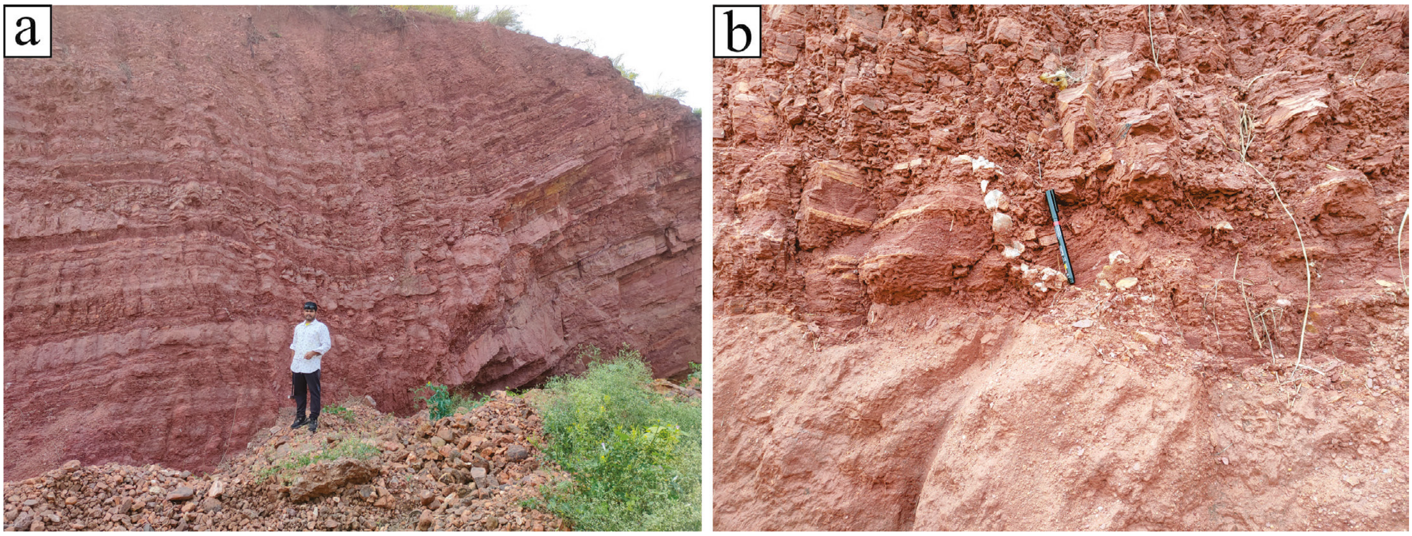

Fig. 21 - Exposure of (a) thick succession of lamellar purple shale, (b) calcite vein within the purple shale.

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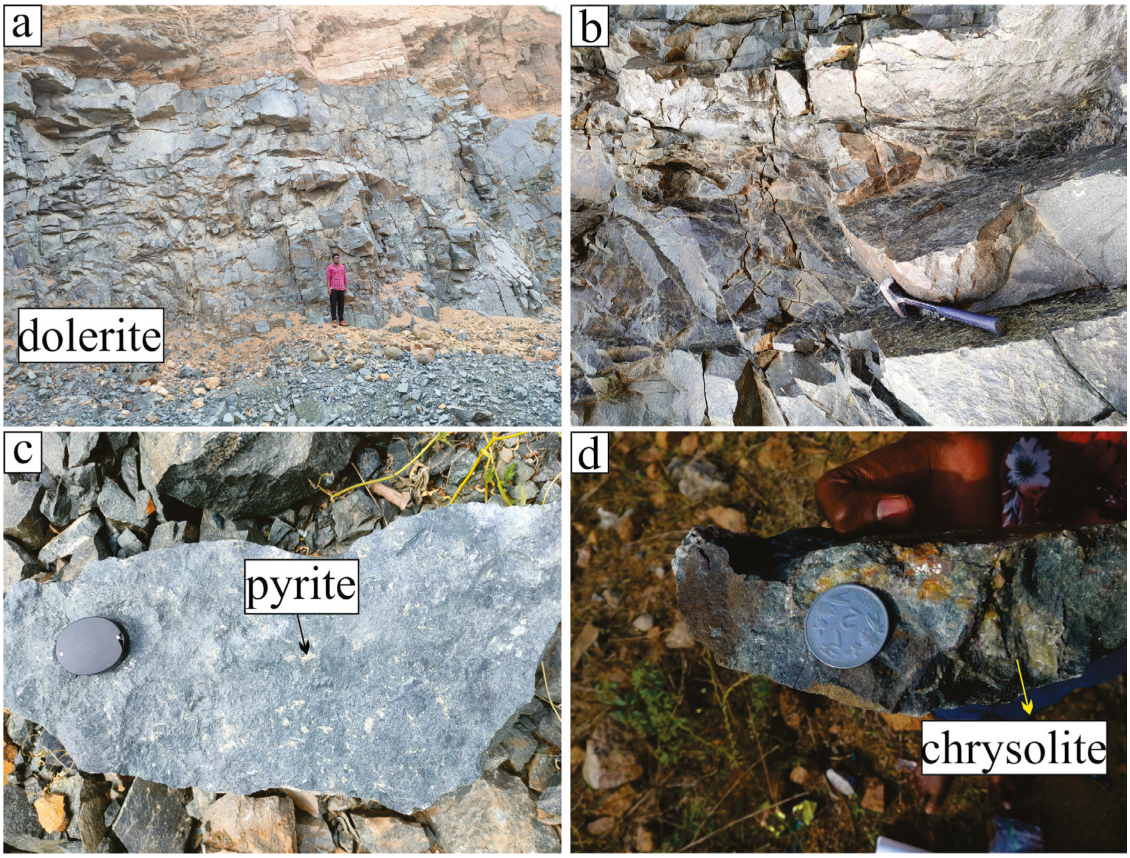

Fig. 22 - Exposure of (a) dolerite dyke in Dhone area, (b) fractures within the dolerite body, (c) pyrite grains within the dolerite, (d) chrysotile asbestos at the boundary between dolerite and dolostone.

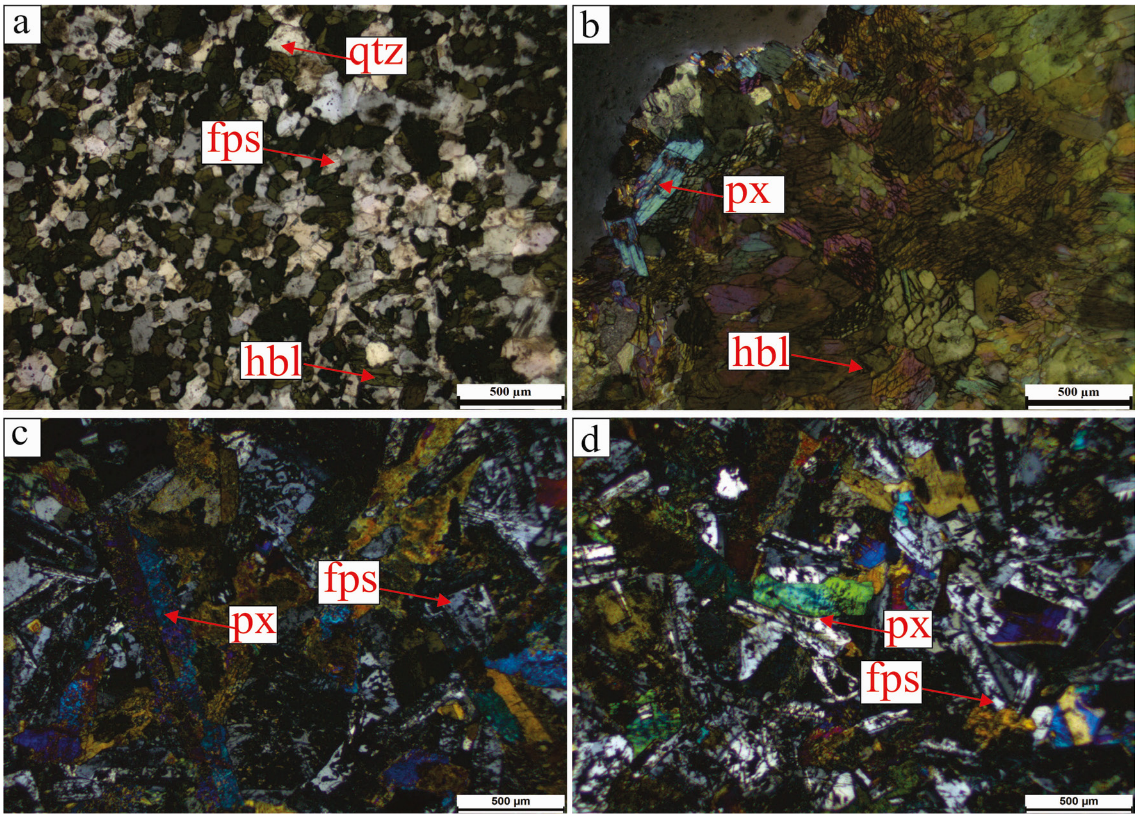

Fig. 23 - Photomicrographs of (a) dolerite showing grains of quartz, feldspar, and hornblende, (b) association of pyroxene and hornblende, (c, d) ophitic texture within the dolerite.

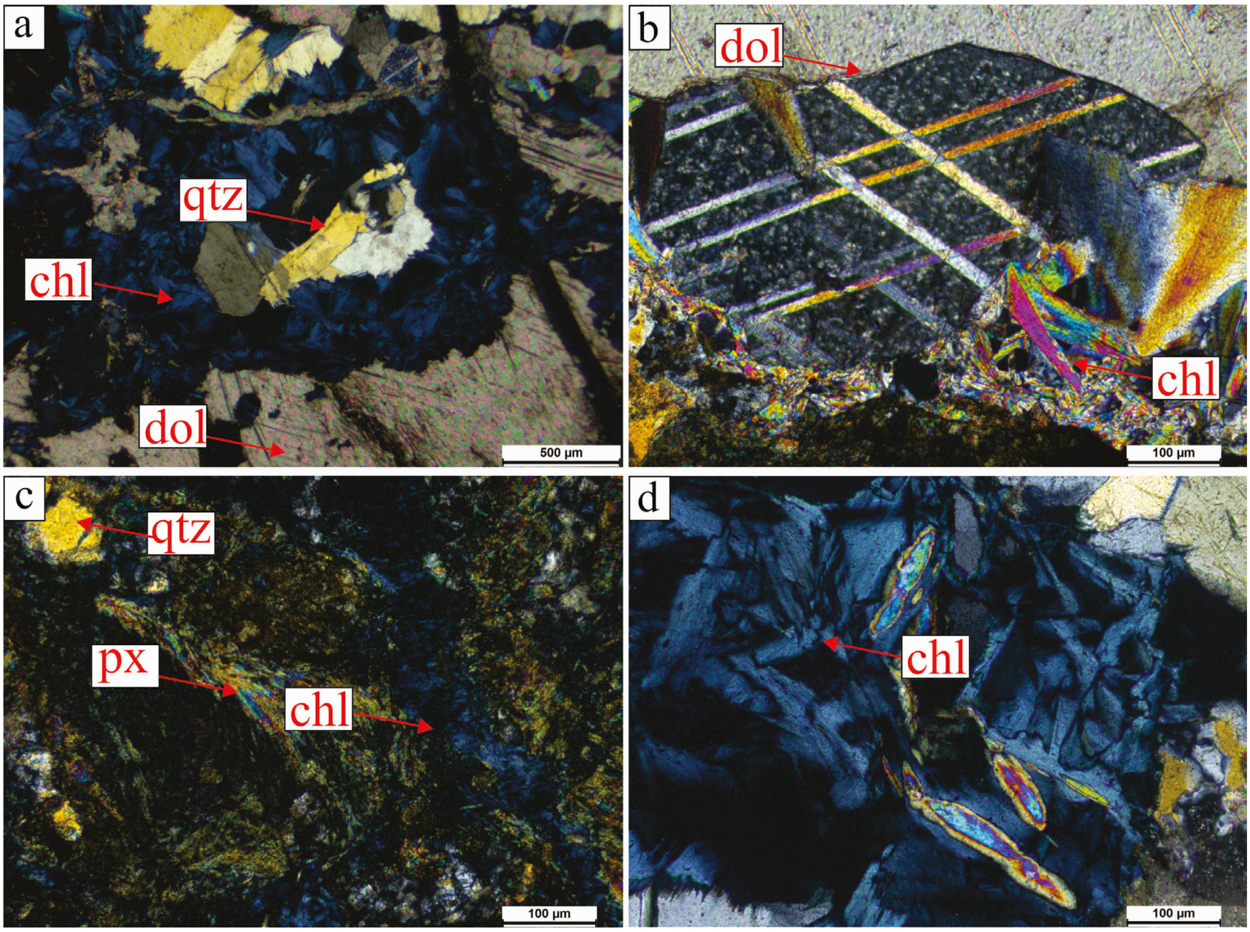

Fig. 24 - Photomicrographs of (a) contact between dolerite and dolostone with well-developed dolomite grains and fibrous chlorite, (b) rhombic cleavage of dolomite with chlorite, (c) association of pyroxene, chlorite, and minor quartz, (d) fibrous chlorite phase.

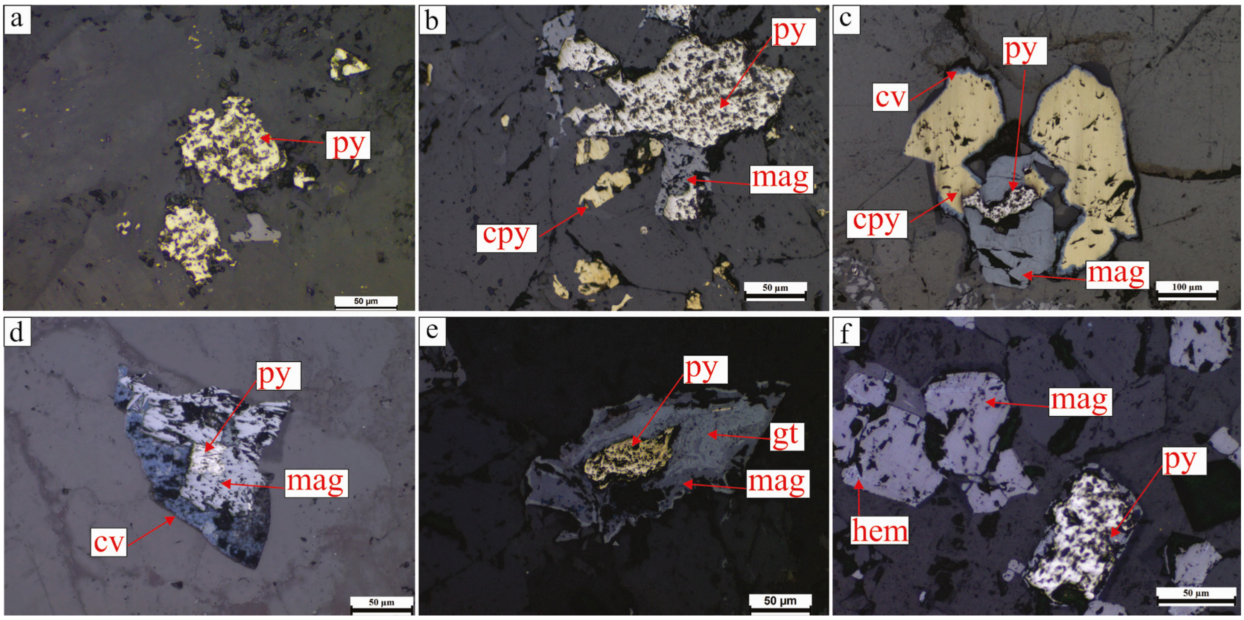

Fig. 25 - Photomicrographs of ore minerals within the dolerite shows (a) euhedral pyrite phases, (b) simultaneous association of pyrite, chalcopyrite, and magnetite, (c) oxidation of pyrite and chalcopyrite grains into magnetite and covellite respectively, (d) association of pyrite, magnetite, and covellite, (e) alteration of pyrite to magnetite and goethite, (f) oxidation of pyrite into magnetite, with subsequent alteration of magnetite to hematite, showing a martitisation texture.

ITINERARY

FIELD ITINERARY AND STOPS

Stop 1 - Eparchean unconformity near Pulivenula

Coordinates: 14°20'16''N, 78°12'04''E
Location: Near Namalagundu temple, along the Kadiri–Pulivendula highway

Lithology: Archean peninsular gneiss overlain by Gulcheru Quartzite.
Key field observations: Sharp nonconformable contact between basement gneiss and quartzite. Basal polymictic conglomerate indicating high energy fluvial deposition.
Geological significance: This stop marks the onset of Proterozoic sedimentation in the Cuddapah Basin (Figs. 2, 3, 4).

Stop 2 - Gulcheru Quartzite and stromatolitic dolostone (Kanampalle–Tummalapalle Area)

Coordinates: 14°18'52"N 78°16'49"E
Location: Kanampalle and Tummalapalle areas, Pulivendula region

Lithology: Conglomerate, pebbly quartzite, quartzite, stromatolitic dolostone, shale, and chert.
Key field observations: Polymictic conglomerates and pebbly quartzite at the base of the Gulcheru Quartzite, well developed sedimentary structures including ripple marks, tabular and trough cross bedding, gradational transition from Gulcheru Quartzite to overlying Vempalle dolostone, laminar, columnar, domal, and spherical stromatolites within the dolostone, elephant skin weathering on dolostone surfaces and quartz–calcite veins.
Geological significance: This stop records the transition from high energy fluvial to shallow marine siliciclastic deposition of the Gulcheru Quartzite to shallow marine carbonate sedimentation of the Vempalle Formation, reflecting progressive marine transgression and microbial carbonate growth in the Papaghni basin (Figs. 6, 7, 9, 14).

Stop 3 - Oolitic limestone and cherty dolostone (Anantapur Region)

Coordinates: 14°50'15''N, 77°51'13''E
Location: Vempalle Formation exposures near Muchukota–Narpala area, Anantapur District, Andhra Pradesh

Lithology: Siliceous oolitic limestone and cherty dolostone.
Key field observations: Well developed ooids displaying concentric and radial internal structures, interbedded chert layers and discrete chert nodules, locally folded cherty laminae within dolostone.
Geological significance: This stop represents deposition under high energy shallow marine conditions, favoring oolite formation, followed by early diagenetic silicification leading to chert development within the carbonate sequence (Fig. 15, Figs. 17-19).

Stop 4 - Dolerite dyke and hydrothermal alteration

Coordinates: 15°19'02''N, 77°54'58''E
Location: Dhone-Jaladurgam area

Lithology: Dolerite dyke intruding Vempalle dolostone
Key field observations: Sulfide mineralisation in dolerite
Geological significance: Represents post-depositional magmatic activity and fluid rock interaction (Fig. 22).

CONCLUSION

The study of the Papaghni Group within the Cuddapah Basin provides significant insights into its stratigraphy, depositional environments, diagenetic history, and tectonic evolution. The Gulcheru Quartzite, representing the basal unit, is characterised by high energy fluvial to shallow marine deposition, evidenced by conglomerates, cross bedded quartzites, ripple marks, and intercalated shale layers. Petrographic and geochemical analyses indicate sediment input from granitic and greenstone terrains, suggesting a dynamic sedimentary regime influenced by fluctuating flow conditions and provenance variations.
The overlying Vempalle Formation, dominated by stromatolitic dolostones, chert, and oolites, marks a marine transgression and a shift to carbonate dominated deposition. The presence of cyclic carbonate sedimentation and well preserved stromatolitic structures highlights the role of microbial activity in carbonate precipitation. Variations in stromatolite morphology reflect changing paleoenvironmental conditions, ranging from shallow intertidal zones to deeper subtidal settings. The occurrence of oolitic cherts in the Vempalle dolostone suggests high energy wave agitation, while petrographic evidence of dolomitisation, silicification, and hydrothermal alterations indicates multi stage diagenetic overprinting. The study also reveals the presence of folded quartz veins, recrystallised carbonate veins, and ore minerals such as pyrite, chalcopyrite, magnetite, hematite, and goethite, indicating a history of fluid rock interactions and hydrothermal activity. The dolerite intrusions observed within the Vempalle Formation further signify post-depositional magmatic activity, with fluid pathways facilitating mineralisation and the formation of hydrothermal alteration zones. These findings also provide valuable insights into Proterozoic basin evolution and the ore forming processes within the Cuddapah Supergroup.

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DECLARATION OF COMPETING INTEREST

The authors confirm that they do not have any known competing financial interests or personal relationships that could have influenced the work presented in this paper.

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