Gypsum–anhydrites in 1.9 Ga Vempalle Formation, Cuddapah basin, India: A note on the Palaeoproterozoic environment and diagenetic condition

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The Cuddapah basin consists of generally well-preserved Palaeoproterozoic–Neoproterozoic sedimentary and associated volcanic rocks. The detailed lithological studies of sedimentary rocks of Vempalle Formation from the narrow linear belt of 15 km, in the southern margin, show the occurrence of layered gypsum in the cherty dolostone–shale intercalated facies, red shale and phosphatic dolostone facies of the Vempalle Formation. The petromineralogical studies reveal that gypsum is in close association with anhydrites. Microscopically, three different types of gypsum and anhydrite are identified, viz., lath-shaped, equant-shaped and anhedral-shaped grains. The equant variety corresponds to a granular gypsum, whereas the anhedral grains of gypsum exist as the granular and fibrous variety as seen in the hand specimen. The presence of gypsum/anhydrite has been confirmed by the petromineralogical, X-ray diffraction and chemical analytical data. The phosphatic dolostone is the host rock for stratabound type of uranium deposit at Tummalapalle, Cuddapah district, Andhra Pradesh, which is one of the most unique types of uranium mineralisation in the world. Abundant pseudomorphs of gypsum and anhydrite relicts and discontinuous gypsum layers within these dolostones, nodules of chert and gypsum indicate the interrelationship between the diagenesis and genesis of uranium mineralisation which indicates the carbonate precipitation in the sulphate-rich hypersaline environments.

Keywords. Gypsum; Vempalle Formation; Uranium deposit; Cuddapah basin; Andhra Pradesh.

1. Introduction

The crescent-shaped Cuddapah basin of south eastern peninsular India is 440 km long and about 200 km wide, spread over an area of 45,000 km². This basin consists of about 12 km thick well-preserved Palaeoproterozoic–Neoproterozoic sedimentary and associated volcanic succession,

composed dominantly of argillaceous and arenaceous sediments with subordinate calcareous sediments. The Cuddapah basin was first mapped in the 19th century (King 1872), and the majority of the studies were focused on the classification of the Cuddapah succession and reconstruction of the stratigraphy (King 1872; Sen and Narasimha 1967; Rajurkar and Ramalingaswami

1975; Meijerink *et al.* 1984; Nagaraja Rao *et al.* 1987; Ramakrishnan and Vaidyanadhan 2008; Saha *et al.* 2009). The Cuddapah basin is a composite of five sub-basins: the Papaghni, Nallamalai, Srisailam, Kurnool and Palnad (Nagaraja Rao *et al.* 1987). The Papaghni sub-basin is represented by the sediments and volcanics of the Papaghni and Chitravati Groups, separated by a disconformity (Lakshminarayana *et al.* 2001; Chaudhuri *et al.* 2002; Saha and Tripathy 2012). The Vempalle Formation (1900 m thick) of the Papaghni Group is represented by stromatolitic dolostones with subordinate mudstone, sandstone and chert conformably overlying on the siliciclastics of the Gulcheru Formation. The age of sedimentation for the Papaghni rocks is about 2000 Ma (Rai *et al.* 2015; Absar *et al.* 2017).

The present study area is located in the southwestern part of the Cuddapah basin (figure 1A) along with a narrow rectangular belt (15 km × 2 km) between the Rachakuntapalle and Motnupalapalle villages. A number of lithofacies are recognised in the Vempalle Formation of the study area, viz., massive dolostone, polymictic conglomerate, grey shale, phosphatic dolostone, sedimentary breccia, red shale and cherty dolostone (Jeyagopal *et al.* 2008). Out of these, five lithofacies are persistent throughout the study area, viz., massive dolostone, grey shale, phosphatic dolostone, red shale and cherty dolostone (figure 1B). Based on the geological traverses and detailed study, a generalised litho-column of the Papaghni Group of rocks exposed in the study area is shown in figure 2. The halite casts (Phansalkar *et al.* 1991; Patranabis-Deb *et al.* 2012) and localised gypsum moulds (Patranabis-Deb *et al.* 2012) have been reported from the shale intervals, but the layered gypsum occurring within the cherty dolostone–shale facies, red shale and phosphatic dolostone facies are reported for the first time in this paper. The present work is also an attempt to investigate the diagenetic conditions of host sediments. To this end, integrated studies, including the mapping and petrographic study of core samples along with X-ray diffraction (XRD) and geochemical analyses, have been undertaken to prepare a depositional model.

2. Methodology

Total five borehole core samples have been selected for petrominerological studies, chemical analysis

and XRD analysis. The presence of thin gypsum layers in the cherty dolostone–shale facies, red shale and phosphatic dolostone facies has been confirmed.

2.1 Hand specimen study of gypsum

Gypsum observed in the study area is colourless to white, transparent to translucent, showing vitreous to silky lustre. It mainly occurs as layers parallel to bedding. The thickness of gypsum layers varies from 0.5 to 5 cm. Mainly two types of gypsum have been identified in hand specimen, the fibrous and the granular variety (figure 3). At places the lath-shaped gypsum is replaced by a halite/calcite and at places only the lath-shaped cast is present and the halite/calcite has been removed (figure 4).

2.2 Studies under microscope

Petrographically, gypsum and anhydrite are differentiated on the basis of an interference colour. Gypsum is identified from the first-order grey colour unlike anhydrite with the second-order interference colour. It is also known that they are readily soluble in water and easily leached from the host rocks. They are observed to be replaced by dolomite and quartz and also calcite at places, which indicate their formation in the tidal flat and/or lagoon facies (Aleali *et al.* 2013). Microscopically, three different types of gypsum and anhydrite are identified, namely (i) lath-shaped grain, (ii) equant-shaped grain and (iii) anhedral-shaped grain. The lath-shaped anhydrites are greater than 1 cm in length and few mm thick. This shape is very typical of gypsum, which has been converted to anhydrite (figure 5). The equant anhydrite is equidimensional in nature and varies from very fine-grained to medium-grained crystals. They are up to 1 mm in size and form a mosaic texture (figure 6). In hand specimen, they are seen as granular gypsum. It is in association with gypsum that both the minerals transform into one another by the addition and removal of water. These are generally formed in the tidal flat environment, especially in the supratidal zone (Aleali *et al.* 2013). The anhedral grains of gypsum are partially elongated and form a mosaic texture (figure 7). It is also a part of granular and fibrous variety of gypsum in the samples.

2.3 Geochemistry

The chemical analysis of CaO and SO₄ was carried out at the AMD Laboratory in

Figure 1. (A) Geological map of the southern part of the Cuddapah basin showing the study area in the southwestern part. (B) Geological map of the study area showing the different exploratory blocks from Motnutralapalle to Rachakuntapalle area and the transverse section across the TPLII79 borehole showing uranium mineralisation in the Vempalle Formation.

Bengaluru. The samples were powdered to 200# size (1# = 75 μ m), ignited to remove carbonaceous species, followed by acid digestion (HF+HNO₃) and analysed in inductively coupled plasma-atomic emission spectrometer. The instrumental detection limit is 10 ppm, with <1%

error. The results exhibit the presence of CaO and SO₄ in the samples in significant quantity. The CaO values range from 26.60 to 28.25% with an average of 27.36%, whereas SO₄ values range from 53.15 to 61.15% with an average of 56.94%.

Figure 2. Generalised litho-column of the Papagani Group of rocks in the study area, Cuddapah district, Andhra Pradesh.

2.4 XRD analysis

The XRD study was carried out in AMD, Hyderabad using the Siemens D-500 diffractometer. Two samples (TPL-64/1 and KNL-50/1) were studied using the XRD analysis for identification to confirm the presence of gypsum (figure 8).

3. Results

After detailed lithological studies of the grab and borehole core samples from the study area

(figure 1), it is observed that gypsum is not common in outcrop but present in the core samples. In fact, the high solubility in water leads to the removal of gypsum in the surficial environment. Being softer than the sandstone and shale preservation potential is less and thus rarely well preserved and exposed. The occurrence of gypsum and anhydrite in the clayey-carbonate sediments of the Vempalle Formation in association with halite, calcite and dolomite is an indication of shallow water environment that contains dissolved solids. The systematic core samples in the hand specimen and microscopic scale suggest the occurrence of a layered gypsum, not known hitherto in the cherty dolostone–shale facies, red shale and at places in phosphatic dolostone facies of the Vempalle Formation, and briefs the geological significance of the occurrence of the evaporites. Gypsum, the most common of any sulphate mineral is usually formed in the high evaporative environment. The presence of another pseudomorph, anhydrite, indicates dehydration possibly due to burial during diagenesis. Gypsum can also be regenerated from anhydrite after upliftment and exposure to less saline water and increase in volume (Boggs 2006). Geochemically, gypsum is the first mineral to form from brine. The anhydrites are formed due to the removal of water from gypsum due to dehydration during the burial and diagenesis.

4. Discussion

4.1 Palaeoenvironmental reconstruction

Broadly, the depositional environment for Cuddapah sediments proposed by Nagaraja Rao *et al.* (1987) is peritidal complex with the shallow marine carbonate shelf and beach environment. Further,

Figure 3. Gypsum layer occurs parallel to bedding. Two types of gypsum are identified: fibrous (F) and granular (G).

Figure 4. Gypsum layer (G) and lath-shaped gypsum (L) replaced by halite/calcite.

Chakrabarti *et al.* (2014) explained about the supratidal to the deep sub-tidal environment of deposition. Our study reflects a similarity and if we see in detail, the cherty dolostone–shale facies forming the top most and thickest unit of the Vempalle Formation consists of wave ripples, fenestrae, dissolution cavities, desiccation cracks, small-to-large columnar and domal stromatolites. These are interpreted to have been deposited in intertidal to supratidal environments and the red shale facies that is sandwiched between lower phosphatic dolostone and upper cherty dolostone–shale facies with the presence of evaporite gypsum in the upper as well as lower part of the shale indicates sub-aerial exposure of tidal flat (Bhattacharjee *et al.* 2012). Based on the sedimentological attributes Goswami *et al.* (2015, 2017a, b) described the Papaghani sub-basin as a shallow small basin lying close to the shore in arid condition. The presence of sedimentary features, such as mud cracks and ripple marks, indicates its shallow water condition. Due to the intense evaporation, there was supersaturation of water with enriched magnesium by the continuous inflow of normal sea water and by the precipitation of CaCO_3 and sulphate. The temperature condition during the Proterozoic is reconstructed on the basis of oxygen and silicon isotopes from the rock (mostly the

diagenetic chert) samples (Knauth 2005; Shields and Kasting 2006). The predicted Precambrian sea temperature is much hotter, i.e., $55^\circ\text{--}85^\circ\text{C}$ during the period of 2000–3500 million years ago. Thus, about 50°C temperature during this dolomite precipitation environment was dry and warm enough to permit the net evaporation with progressive removal of water. This was helpful to concentrate dissolved solids to the point where the water became oversaturated with respect to the dissolved solids. Therefore, a period of enclosed or restricted basin set-up is predicted. The restrictions in the water replenishment within the basin is indicating a period of low rainfall. Therefore, inflow of groundwater and river runoff was restricted. As suggested by Hefferan and O'Brien (2010), the sequence of minerals precipitated by progressive evaporation is (i) calcite/dolomite (at $>50\%$ evaporation, >70 ppt salinity), (ii) gypsum (at $>75\%$ evaporation, >135 ppt salinity), (iii) halite (at $>90\%$ evaporation, >350 ppt salinity) and (iv) K and Mg minerals (at $>96\%$ evaporation, >750 ppt salinity). In addition to the burial and diagenesis, higher temperatures and salinities must have favoured the dehydration of gypsum to anhydrite in such supratidal environment and thus the replacement of gypsum by anhydrite or halite. The dehydration and associated volume loss are

Figure 5. Laths (L) of anhydrite replaced after gypsum in dolomite, 5X, TL, XN.

Figure 6. Equant anhydrite (E) replaced after gypsum in dolomite, 5X, TL, XN.

responsible for nodular or chicken-wire anhydrite formation.

4.2 Diagenetic history

The diagenetic history of the entire dolomitic host rock unit is possible to understand from the combined petrography and geochemical study of the chert nodules, dolostone and gypsum–anhydrites. The understanding of the diagenetic condition is relevant in the present context to derive a depositional model of gypsum. It is a point to note that gypsum and anhydrite cannot form together and dehydration of gypsum during the diagenesis is a significant phenomenon. Therefore, to understand the diagenetic history, the following additional discussion is noteworthy. The phosphatic dolostone in the Vempalle Formation hosts uranium mineralisation and consists of mixed siliciclastics, carbonate

Figure 7. Anhedral gypsum (G) in dolomite, 5X, TL, XN.

and phosphatic associations. This dolostone hosted stratabound uranium deposit at Rachakuntapalle–Motnupalapalle areas is one of the most unique types reported only in the Cuddapah basin, India (Vasudeva Rao *et al.* 1989; Rai *et al.* 2002, 2010). In this deposit, the uranium mineralisation occurs as two bands, hangwall and footwall with a vertical separation of 1–3 m. Both the bands show the isotropic character along and across the strike in terms of grade and thickness. The uniformity in thickness of ore body, large lateral extent of the mineralisation, the absence of a hydrothermal vent and associated alterations, and lack of kink in mineralised band suggests a diagenetic origin of mineralisation (Phansalkar *et al.* 1991; Jeyagopal *et al.* 2008; Rai *et al.* 2011, 2015; Bhattacharjee *et al.* 2012; Patranabis-Deb *et al.* 2012; Aleali *et al.* 2013). The diagenetic origin is further substantiated by Goswami *et al.* (2015) on the basis of petrography of dolostone and nodular chert and the other organic as well as inorganic geochemical data (Rai 2012). The microbial mat and stromatolites in the Gulcheru and Vempalle Formation are already reported with categorisation (Goswami *et al.* 2016a, 2017b). The close association of phosphatic dolostone with evaporites, particularly gypsum and anhydrite points towards the interrelationship between the diagenesis and meteoric water reflux and genesis of uranium mineralisation. The impervious evaporites and shale units have acted as a cap and possibly helped in the preservation of uranium mineralisation. The chert is widespread as nodules of different shape in the Vempalle dolostone. According to Goswami *et al.* (2015), the chert nodules are formed during the diagenesis

Figure 8. X-ray diffractogram showing peaks associated with gypsum (Gy): (A) bore hole sample no. TPL-64/1 and (B) bore hole sample no. KNL-50/1.

when carbonic acid formed due to organic activity. Acidity lowered the pH along pore spaces to dissolve carbonates and is replaced by the silica precipitation. The role of organic matter as a reductant for uranium precipitation is well documented (Goswami *et al.* 2017a). The stable isotopic data interpretation of Rai (2012) suggests that the uranium-bearing meteoric water influx during the diagenesis is related to the uranium mineralisation. Mostly, the primary dolomite is evidenced and the dolomitisation of calcite is so far not very common.

The absence of features such as incomplete dolomitisation of calcite and scattered rhombs of dolomite growing in a mass of calcite points to the primary dolomite as dominant.

Therefore, based on the above discussion on diagenetic mechanism, it can be described that the varying thickness and number of the gypsum layers suggest that they were not deposited as continuous sheets over the region, but rather formed as lenses in the isolated bodies of water along the margin of a sea that was subjected to intermittent fluctuations

Figure 9. (A) Schematic diagram shows the initial rifting due to stretching and development of normal fault bound graben basin. The upwelling of CaCl_2 along the faulted pathway and the mixing with primitive ocean water. (B) The part of the rift basin shows an enlarged view of the oceanic basin marginal section. The shore profile shows the transgressive events with a progressive rise in sea level. The sandstone, shale and carbonate sequences are shown to change their respective position with transgression. (C) The peak of transgression is followed by a short-term stable sea level when the microbial activities lead to the formation of the mat and stromatolitic structures. The regression starts with the falling sea level and development of extended supratidal beach and barrier bar and creation of a lagoon with limited connectivity with main sea water.

in water level. The post-depositional gypsum veins are observed to cut fine siliciclastics and mud rocks. This indicates the remobilisation of gypsum upon shallow burial. The gypsum occurs initially as an admixture with siliciclastic sediment. The presence of nodular or chicken-wire anhydrite is regarded as a diagenetic structure (Blatt 1992). The diagenetic cycle of gypsum–anhydrite is shown in the proposed comprehensive model (figure 9).

4.3 Comprehensive depositional model

The intra-cratonic rifting and sedimentation in the Cuddapah basin is studied on the basis of geological, geochemical, geomorphological and petromineralogical guides (Nagaraja Rao *et al.* 1987; Ramakrishnan and Vaidyanadhan 2008; Chakraborty *et al.* 2012; Goswami *et al.* 2016b). However, according to Absar *et al.* (2017) the back-arc extensional mechanism is related to the opening of the Papaghni sub-basin. We support the rifting model on the basis of a few additional observations as follows:

1. The Gulcheru quartzite indicates the alluvial fan to fluvial followed by shallow marine depositional settings (Goswami *et al.* 2017b), which is very commonly encountered in rift basins (Bhattacharya and Chakraborty 2000).
2. The contact between the basement granitoids and Gulcheru quartzite at relatively higher elevation again support the ‘Rift shoulder’ (Bhattacharya and Chakraborty 2000).
3. The presence of syn-sedimentary faults (Goswami *et al.* 2016b) is also a characteristic feature in this setting. In fact, the accommodation space for more sediments is created by syn-sedimentary faults during rifting.
4. The deep seismic sounding (DSS) profile across the basic intrusive in the Papaghni sub-basin (GSI 1981) suggests the lopolithic emplacements and such champagne glass structures occur due to the normal faulting and crustal melting associated with rifting as in the Koilismaa complex (Hefferan and O’Brien 2010). Based on the above-mentioned points, it can be described that initially the rifted Papaghni sub-basin was infilled by continental clastics of the Gulcheru Formation and the progressive extension caused thinning of crust and sinking of rift floor below the sea level. The fluctuations on the sea level were rapid with small-scale progressive and regressive phases (figure 9). The sequence with chert–dolomite/calcite–shale–arenite in the study area represents the regression in which the minor fluctuation events are also noticed. The grab sample and drill core sample study also revealed the upward succession from the earlier subtidal carbonate sediments through intertidal arenite/shale to supratidal sediments consisting of shale, evaporite and carbonate mixtures. The photographs in figure 1 (B) show the above-mentioned sequence in which the uraniferous dolostone is impure in nature with arenitic bands. The cycles of transgression and regression are not dealt in detail in this context. The presence of stromatolites in this sequence possibly is related to sulphate reducing bacteria of that time, which have supported the dolomite precipitation by removing sulphate from water (Goswami *et al.* 2015, 2017a). The alteration during the burial and diagenesis by groundwater is already mentioned to be a phenomenon related to the uranium mineralisation (Rai 2012; Bhagat *et al.* 2014). Therefore, it is natural to expect the alteration of evaporites associated with other rocks. The burial alteration by ground water (Borchert 1977), seawater mixing with bicarbonate-rich river water (Valyashko 1972), bacterial sulphate reduction (Sonnenfeld 1984) and contemporaneous dolomitisation of coexisting marine carbonates by seawater brines in a marine evaporite environment (Holland 1978) may lead to the origin of these MgSO_4 poor salts. According to Hardie (1978), these MgSO_4 poor salts cannot be derived by normal evaporation of modern seawater and sulphate-enriched brine but upwelling CaCl_2 -rich brines in rift setting like the African rift in the present day. The average $>50^\circ\text{C}$ temperature of atmosphere during the period of rifting suggests a freely available epithermal condition. Therefore, in this rift setting, the arid climate and hindrances in the hydrologic input were achieved in mountains encircled sedimentary basin for short time when the basin floor became rain-shadow deserts locally. Meanwhile, with the minor subsidence of the basin floor, the inflow of brine was at a higher rate than the sand and mud influx into the basin as per the general concept (Hardie 1990). However, the coastal depressions and supratidal areas became sites where the isolated water bodies were created with a shallow inlet or a slightly permeable seal with the main water body. The CaCl_2 -rich brine circulation along the deep faulted pathway of rift is

Figure 10. The extensive evaporation in lagoon and supersaturation of water with sulphate and associated salts. Increase in salinity leads to gypsum precipitation in the lagoon and towards the continent gradual temperature and salinity rise favours the direct anhydrite formation as well. The burial and dehydration also favours the anhydrite and volume loss. The meteoric uraniferous water influx during the diagenesis of whole rock sequence leads to uranium precipitation in suitable phosphate-rich dolostones. Later the upliftment caused rehydration and reappearance of gypsum.

possible in such a condition. Rest of the basic criteria for such an evaporite formation was same as that found for any present-day analogous, and fulfilled similarly.

5. Conclusion

Based on the discussions on different factors and variables with possible influence, the following steps are significant to discuss further as a conclusion on the evolutionary model.

The rifting of the Papaghni sub-basin (figure 9A), erosion and sedimentation of the clastic Gulcheru Formation, marine transgression and precipitation of carbonates (figure 9B), microbial activities in static environment, small-scale fluctuation and regression (figure 9C), barrier development in supratidal areas and isolation of depressed water bodies from main sea, evaporation and supersaturation followed by precipitation of evaporites in isolated ponds, progressive burial and initiation of diagenesis and anhydrite formation from gypsum by dehydration, meteoric uraniferous

water influx and mineralisation along suitable loci, upliftment and hydration and reappearance of gypsum (figure 10).

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References

- Absar N, Nizamudheen B M, Augustine S, Managave S and Balakrishnan S 2017 C, O, Sr and Nd isotope systematics of carbonates of Papaghni sub-basin, Andhra Pradesh, India: Implications for genesis of carbonate-hosted stratiform uranium mineralisation and geodynamic evolution of the Cuddapah basin; *Lithos* **263** 88–100.
- Aleali M, Rahimpour-Bonab H, Moussavi-Harami R and Jahani D 2013 Environmental and sequence stratigraphic implications of anhydrite textures: A case from the Lower

- Triassic of the Central Persian Gulf; *J. Asian Earth Sci.* **75** 110–125.
- Bhagat S, Goswami S and Pandey S 2014 Systematic stable isotopic and petrographical studies of the mineralized and non-mineralised dolostone borehole core samples from Tummalapalle and extension areas to understand dolomitisation processes vis-a-vis uranium mineralisation; Unpublished R & D Report of F.S. 2013–14, AMD, DAE.
- Bhattacharjee P, Vijaya Kumar T, Murugan M G and Vidyasagar D 2012 Depositional environment of Vempalle Formation of Cuddapah basin in Eguvapalle–Nallagondavaripalle area, Kadapa district, Andhra Pradesh, India; *Explor. Res. At. Miner. (EARFAM)* **22** 81–91.
- Bhattacharya A and Chakraborty C 2000 *Analysis of sedimentary successions: A field manual*; Oxford & IBH Publishing Co. Pvt. Ltd., New Delhi.
- Blatt H 1992 *Sedimentary petrology*; 2nd edn, W.H. Freeman, 514p.
- Boggs S Jr 2006 *Principles of sedimentology and stratigraphy*; 4th edn, Pearson Education, Inc., Upper Saddle River, NJ.
- Borchert T H 1977 On the formation of lower Cretaceous potassium salts and tachyhydrite in the Sergipe Basin (Brazil) with some remarks on similar occurrences in West Africa (Gabon, Angola, etc.); In: *Time and strata bound ore deposits* (eds) Kelmm D D and Schneider H J, Springer, Berlin, pp. 94–111.
- Chakrabarti G, Shome D, Kumar S, Stephens G M and Kah L 2014 Carbonate platform development in a Paleoproterozoic extensional basin, Vempalle Formation, Cuddapah Basin, India; *J. Asian Earth Sci.* **91** 263–279.
- Chakraborty P P, Sarkar S, Patranabis-Deb S 2012 Tectonics and sedimentation of Proterozoic Basins of Peninsular India; *Proc. Indian Nat. Sci. Acad.* **78**(3) 393–400.
- Chaudhuri A K, Saha D, Deb G K, Patranabis-Deb S, Mukherjee M K and Ghosh G 2002 The Purana basins of southern cratonic province of India – A case study for Mesoproterozoic fossil rifts; *Gondwana Res.* **5** 23–33.
- Goswami S, Bhattacharjee P, Bhagat S, Suresh Kumar and Zakaulla S 2015 Petrography of chert nodules in stromatolitic dolostone of Vempalle Formation, along Tummalapalle–Motnupalapalle, Cuddapah basin, India; *Indian J. Geosci.* **69** 13–24.
- Goswami S, Mukherjee A, Zakaulla S and Rai A K 2016a Microbial mat related features in Palaeoproterozoic Gulcheru Formation and their role in low grade uranium mineralisation; *Int. J. Petrochem. Sci. Eng.* **1**(4) 19p, <https://doi.org/10.15406/ipcse.2016.01.00019>.
- Goswami S, Mukherjee A, Zakaulla S and Rai A K 2016b Stress states, faulting and their effects on the Papaghni Group, Cuddapah basin, India: A study along Giddankivaripalle–Madyalabodu tract; *Indian J. Geosci.* **70**(1) 17–33.
- Goswami S, Bhagat S, Zakaulla S, Suresh K and Rai A K 2017a Role of organic matter in Uranium mineralisation in Vempalle Dolostone; Cuddapah Basin, India; *J. Geol. Soc. India* **89**(2) 145–154.
- Goswami S, Mukherjee A, Bhattacharjee P and Zakaulla S 2017b Primary sedimentary structures and MISS in Gulcheru quartzite along SW part of Cuddapah Basin; *J. Geol. Soc. India* **89**(5) 511–520.
- GSI 1981 *Geological and mineral map of the Cuddapah basin*; 2nd edn, (1:250,000), Geological Survey of India, Calcutta, India.
- Hardie L A 1978 Evaporites, rifting and the role of CaCl_2 hydrothermal brines; *Geol. Soc. Am., Abs. Programs* **10**(7) 416.
- Hefferan K and O'Brien J 2010 *Earth materials*; John Wiley & Sons Ltd, Wiley–Black Well, UK.
- Holland H D 1978 *The chemistry of the atmosphere and oceans*; Wiley-Interscience, New York.
- Jeyagopal A V, Dhana Raju R, Maithani P B and Chaki A 2008 Cyclic sedimentation and classification of the Papaghni Group of sediments, Cuddapah basin, Andhra Pradesh; *J. Geol. Soc. India* **71** 363–370.
- King W 1872 Cuddapah and Kurnool formations in the Madras Presidency; *Mem. Geol. Surv. India* **8** 1–346.
- Knauth L P 2005 Temperature and salinity history of the Precambrian ocean: Implications for the course of microbial evolution; *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **219** 53–69, <https://doi.org/10.1016/j.palaeo.2004.10.014>.
- Lakshminarayana G, Bhattacharjee S and Ramanaidu K V 2001 Sedimentation and stratigraphic framework in the Cuddapah basin; *Geol. Surv. India, Spec. Publ.* **55** 31–58.
- Meijerink A M J, Rao D P and Rupke J 1984 Stratigraphic and structural development of the Precambrian Cuddapah Basin, SE India; *Precamb. Res.* **26** 57–104.
- Nagaraja Rao B K, Rajurkar S T, Ramalingaswami G and Ravindra Babu B 1987 Stratigraphy, structure and evolution of Cuddapah Basin; In: *Purana Basins of Peninsular India* (ed.) Radhakrishna B P, *Geol. Soc. India* **6** 33–86.
- Patranabis-Deb S, Saha D and Tripathy V 2012 Basin stratigraphy, sea-level fluctuations and their global tectonic connections – Evidence from the Proterozoic Cuddapah Basin; *Geol. J.* **47** 263–283.
- Phansalkar V G, Kale A S, Karmalkar N R and Kale V S 1991 An unusual evaporite association from the Papaghni Group, Cuddapah Basin; *J. Geol. Soc. India* **37** 75–79.
- Rai A K 2012 Mineralogy, geochemistry and fluid inclusion studies in stratabound uranium deposits of Vempalle dolostone around Kanampalle, SW part of Cuddapah basin, AP, India; Ph.D. Thesis (unpublished), University of Mysore.
- Rai A K, Zakaulla S, Jeygopal A V, Vasudeva Rao M, Nagbhushna J C and Vardaraju H N 2002 Uranium mineralisation in southwestern part of Cuddapah basin, Andhra Pradesh; *Expl. Res. Atomic Min.* **14** 79–94.
- Rai A K, Zakaulla S and Chaki A 2010 Proterozoic stratabound carbonate rock (dolostone) hosted uranium deposits in Vempalle formation in Cuddapah basin, India, IAEA; In: *International symposium on uranium raw material for nuclear fuel cycle*, June 22–26, Vienna, Austria.
- Rai A K, Zakaulla S, Vidyasagar D, Murgan M G, Birua M K and Sivasubramanian R 2011 Geochemistry of the uraniferous dolostones from areas around Kanampalle in south western margin of Cuddapah basin; *Indian Mineral.* **45**(1) 24–35.
- Rai A K, Pandey U K, Zakaulla S and Parihar P S 2015 New 1.9–2.0 Ga, Pb–Pb (PbSL), age of dolomites from Vempalle Formation, Lower Cuddapah Supergroup,

- Eastern Dharwar craton, India; *J. Geol. Soc. India* **86**(2) 131–136.
- Rajurkar S T, Ramalingaswami G 1975 Facies variation within the Upper Cuddapah Strata in the northern part of Cuddapah Basin; In: *Precambrian Geology of the Peninsular Shield, Part 1. Geological Survey of India, Miscellaneous Publication*, Geological Survey of India, Kolkata, **23**, pp. 157–164.
- Ramakrishnan M and Vaidyanadhan R 2008 Geology of India, Vols. **1** and **2**; *Geol. Soc. India, Text Book Ser.* **556** 994p.
- Saha D and Tripathy V 2012 Tuff beds in Kurnool Sub basin, southern India and implications for felsic volcanism in Proterozoic intracratonic basins; *Geosci. Front.* **3**(4) 429–444.
- Saha D, Ghosh G, Chakraborty A K and Chakraborti S 2009 Comparable Neoproterozoic sedimentary sequences in Palnad and Kurnool subbasins and their palaeogeographic and tectonic implications; *Indian J. Geol.* **78** 175–192.
- Sen S N and Narasimha R 1967 Igneous activity in Cuddapah basin and adjacent areas and suggestions on the paleogeography of the basin; In: *Proceeding of symposium; Upper Mantle Project 8*; GRB & NGRI Publication, Hyderabad, pp. 261–285.
- Shields G A and Kasting J F 2006 A palaeotemperature curve for the Precambrian oceans based on silicon isotopes in cherts; *Nature* **443** 969–972, <https://doi.org/10.1038/nature05239>.
- Sonnenfeld P 1984 *Brines and evaporites*; Academic Press, New York.
- Valyashko M G 1972 Playa lakes – A necessary stage in the development of salt-bearing basin; In: *Geology of saline deposit* (ed.) Richter-Bernburg G, UNESCO, Paris, *Earth Sciences Series* **7** 41–51.
- Vasudeva Rao M, Nagabhushana J C and Jeyagopal A V 1989 Uranium mineralisation in the middle Proterozoic carbonate rocks of the Cuddapah Supergroup, southern peninsular India; *Expl. Res. Atomic Min.* **2** 29–38.

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