

# Petromineralogy and Geochemistry of Uraniferous Banganapalle Quartzite around Chenchu Colony Area, Guntur District, Andhra Pradesh, India

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**Abstract:** The Banganapalle Formation is the lowermost member of the Neoproterozoic Kurnool Group, which is underlain by the Neoarchaeon biotite granite in the western part of the Palnad sub-basin of the Cuddapah Basin. The Banganapalle sediments are represented by 10–173m thick sequence of basal conglomerate/grit and quartzites, with shale intercalations in the Koppunuru–Chenchu colony area, Guntur district, Andhra Pradesh. Significant uranium occurrences (up to 0.035%  $U_3O_8$ ; <0.005%  $ThO_2$ ) hosted by the Banganapalle quartzite have been delineated in the area south of the Chenchu colony, which indicates disequilibrium of uranium in favour of the parent ( $U_3O_8(\beta/\gamma) : U_3O_8(Rae) = 1.05–1.39$ ). The mineralised zones follow the NNW–SSE trending major structural grain of the area signifying their fracture controlled nature. Uranium mainly occurs as fine veinlets of pitchblende within chlorite, as globular patches of urano-organic complex in intergranular spaces, and in adsorbed state in clay, chlorite and iron oxides in the host rock, suggesting epigenetic nature of mineralization. These mineralised siliciclastic rocks show major quartz clast-supported texture, siliceous cement, minor clay/chlorite matrix and negligible lithic fragments, and exhibit high textural and chemical maturity. Based on petromineralogical and geochemical characters, these are classified as quartz arenite. Discriminant function analysis using major oxides indicates distinct quartzose sedimentary provenance, which is further substantiated by the presence of older siliciclastic rocks of the Cuddapah Supergroup to the west and north of the present study area. Furthermore, basement granitoids of adjoining areas have also contributed silica dominant clastic sediments to the system.

**Keywords:** Palnad sub-basin, Banganapalle Formation, Uranium mineralization, Andhra Pradesh.

## INTRODUCTION

The Banganapalle Formation is exposed in two homotaxial intracratonic sub-basins i.e., Kurnool in the west and Palnad in the northeastern part of Palaeo- to Meso-proterozoic Cuddapah Basin (Nagaraja Rao et al., 1987; Lakshminarayana et al., 1999; Saha and Chakraborty, 2003; Ramakrishnan and Vaidyanadhan, 2008; Saha and Tripathy, 2012), and comprises intercalated arenaceous and argillaceous lithofacies with a basal conglomerate unit. In Palnad sub-basin, these sediments are unconformably deposited over older Cuddapah sediments in the eastern part and Neoarchaeon to Paleoproterozoic granitoids (2659±120 Ma to 2268±32 Ma; Pandey et al., 1988; Vimal et al., 2012) in the north and west (Fig. 1). These sediments are well known for their immense economic potential, especially for diamond in conglomerate horizons (King, 1872; Rao, 1969; Sivaji and Rao, 1989; Sivaji et al., 1990). They also mark an

important geological domain, which is temporally and spatially more akin to a highly favourable setup for Proterozoic unconformity-related uranium mineralization (Umamaheswar et al., 2009; Ramesh Babu et al., 2012) as observed in Athabasca Basin, Canada and Pine Creek Geosyncline, Australia (Sibbald, 1988; Needham et al., 1988; Ruzicka, 1996; Gandhi, 2007; Jefferson et al., 2007). Sustained exploration efforts by Atomic Minerals Directorate for Exploration and Research (AMD) in Palnad sub-basin have resulted in delineation of numerous uranium occurrences associated with Banganapalle sediments (conglomerate and arenite horizons) and adjoining basement granites (Jeyagopal et al., 1996; Nageswara Rao et al., 2005; Basu et al., 2008). Furthermore, detailed sub-surface exploration has led to establishing a sizeable uranium deposit in Koppunuru area in the western part of Palnad sub-basin where mineralization occurs in three sub-horizontal lodes, two

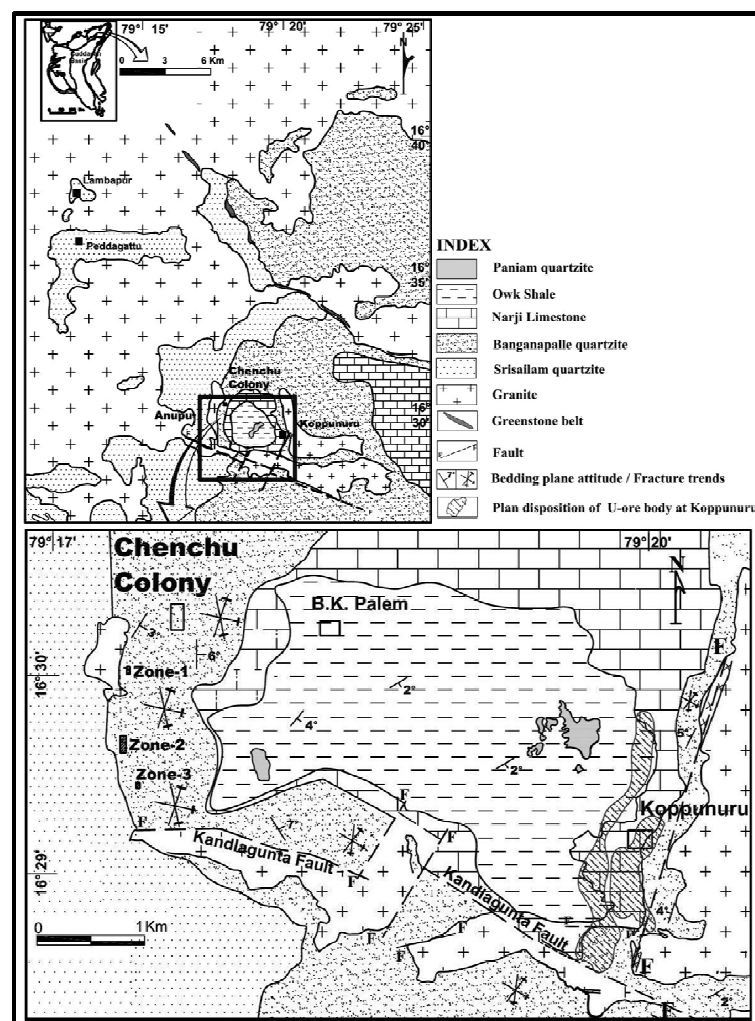


Fig.1. Regional geological map (top) and the geological map of the study area (below) showing the delineated uraniumiferous zones in Banganapalle quartzite to the south of Chenchu colony and the plan disposition of the sub-surface ore body in Koppunuru

of which are confined to the upper quartz arenite unit while the third lode is associated with basal conglomerate/grit horizon and at places transgresses below the unconformity in basement granitoids (Jeyagopal et al., 2011; Verma et al., 2011, Ramesh Babu et al., 2012).

Recent prospecting activities including detailed radiometric surveys and sub-surface exploration in the western extensions of Koppunuru uranium deposit have led to delineation of substantial uranium potential in Chenchu colony and adjoining areas. The favourability of uranium mineralisation is further enhanced by the presence of pre- and post-depositional faults/fractures, several quartz veins/ intrusive mafic dykes in basement granites and profuse quartz veins at places in Banganapalle quartzites, suggestive of reactivation in the area. The present paper deals with the details of the newly delineated uranium occurrence to the south of Chenchu colony area with

special emphasis on the nature and mode of occurrence, and host rock characterization.

## GEOLOGICAL SETUP

### Regional Geology

The Neoproterozoic Palnad sub-basin (~3400 sq. km), located in the northeastern part of the crescent-shaped intracratonic Cuddapah basin, has faulted southern contact marked by the Rudravaram line while the eastern margin has thrust contact with the Nallamalai metasediments. Its western contact with the Srisaillam sub-basin is either marked by a faulted contact or these are separated by a basement high (granite inlier) (Gupta et al., 2010; Banerjee et al., 2012) (Fig.1). The Palnad (Kurnool) sediments were deposited unconformably over the Archaean to Palaeoproterozoic basement granite and gneisses with slivers of older metamorphic rocks and younger granitic intrusives (GSI, 1981, 2001). The basement granitoids are dissected by a number of ENE–WSW, NE–SW, NW–SE and a few N–S trending lineaments represented by dolerite dykes, fractures and faults (Vimal et al., 2012). The Palnad sediments are mainly represented by calcareous/carbonate rocks with minor arenaceous and argillaceous sequences signifying variation in sedimentation pattern and depositional environment. These sediments are classified into Banganapalle, Narji, Auk (Owk), Paniam, Koilkuntla and Nandyal formations and exhibit signatures of post-depositional reactivation in the area in the form of faults and fractures. A generalized lithostratigraphic succession of the study area (after Nagaraja Rao et al., 1987; Ramakrishnan and Vaidyanadhan, 2008) is given in Table 1.

### LOCAL GEOLOGY

Chenchu colony and the adjoining areas (16°29'–16°30': 79°17'–79°20'; T.S. No. 56 P/7) fall in the westernmost part of the Palnad sub-basin and is separated from the Srisaillam sub-basin by an inlier of Neoarchaeon biotite granite (2659±120 Ma; Vimal et al., 2012) (Fig. 1). Basement granitoids are also exposed to the south of the study area along the up-thrown block of WNW–ESE trending post-Kurnool fault (Kandlagunta Fault). This fault is further offset by younger N–S trending faults. The basement granitoids are highly fractured while profuse mafic intrusives (dolerite dykes) and quartz veins are common. Deformation features at micro-level are observed in the form of intense micro-fracturing, occasional kinking/curved cleavage traces in biotite, randomly oriented fractures filled with fine grained quartz and sericite. Crushing/granulation of

**Table 1.** Generalized lithostratigraphic succession in the northern part of the Cuddapah Basin (after Nagraja Rao et al., 1997; Ramakrishnan and Vaidyanadhan, 2008)

| Supergroup/Group/<br>Subgroup |                                                                                  | Formation              | Thickness<br>(m) | Thickness (m)<br>(Banerjee et al.,<br>2012)* |
|-------------------------------|----------------------------------------------------------------------------------|------------------------|------------------|----------------------------------------------|
|                               | Kundair<br>Subgroup                                                              | Nandyal Shale          | 50-100           |                                              |
|                               |                                                                                  | Koilkuntla Limestone   | 15-50            |                                              |
|                               |                                                                                  | Paniam Quartzite       | 10-35            |                                              |
|                               | ~~~~~ Paraconformity ~~~~~                                                       |                        |                  |                                              |
|                               | Jammalamadgu<br>Subgroup                                                         | Auk (Owk) Shale        | 10-15            | 100 – 260                                    |
|                               |                                                                                  | Narji Limestone        | 100-200          |                                              |
|                               |                                                                                  | Banganapalle Quartzite | 10-50            |                                              |
| ~~~~~ Unconformity ~~~~~      |                                                                                  |                        |                  |                                              |
| Cuddapah<br>Supergroup        | Srisailem Quartzite                                                              | 300                    | 254 – 419        |                                              |
| ~~~~~ Nonconformity ~~~~~     |                                                                                  |                        |                  |                                              |
| Archaean and<br>Dharwars      | Intrusive grey, medium grained, chloritised biotite granite Gneisses/greenstones |                        |                  |                                              |

\* Thickness data based on core drilling in the northern part of the Cuddapah Basin

quartz and feldspar along grain margins, and segregation of crushed matter around grain boundaries are also observed in the granites of Anupu area. These granites are unconformably overlain by sub-horizontal beds of Palnad sediments. The overall thickness of the Palnad sediments in this part varies from 10m to 205m and the dips are gentle ( $3^{\circ}$ – $5^{\circ}$ ), mostly following the basement topography (Gupta et al., 2010).

The Banganapalle Formation is the oldest sedimentary lithounit in the study area and is represented by 10–173m thick quartz arenite and intercalated grey shale sequence with basal conglomerate/grit at the bottom (Fig. 2a) (Banerjee et al., 2012). Based on subsurface data (borehole core) Banganapalle sediments of Koppunuru-Chenchu colony area have been classified into five lithofacies, i.e., basal conglomerate (LF-1), quartzite–shale intercalations (LF-2), lower quartz arenite (LF-3), shale–siltstone intercalation (LF-4) and upper quartz arenite (LF-5), and their deposition is inferred to be in inter- to supratidal flat tectono-sedimentary environment under stable shelf condition (Gupta et al., 2010). These sediments are overlain by thick sequence of massive limestone with silicic stylolites and flaggy calcareous shale belonging to the Narji Formation, which has upward gradational contact with ferruginous/limonitised, yellowish ocherous calc-shale (Auk Formation). Finally, this is overlain by the Paniam Formation, which occurs as outliers/discontinuous ridges of quartzite in the area between Koppunuru and Chenchu colony (Fig. 1).

Banganapalle quartzites are predominantly light grey to dull white, medium to fine grained, well sorted and predominantly

consist of uniform rounded to sub rounded quartz clasts. They also exhibit reddish-brown colour at places, especially in the basal parts (Fig. 2b). At places, these quartzites show intense fracturing and profuse quartz veining (Fig. 2a-c). The fractures are sub-vertical to vertical and predominantly trend in NNE–SSW, NNW–SSE and ESE–WNW directions. Significant ferruginous coatings are seen along the fracture planes. Another distinct feature is the presence of cubic and circular to semi-circular pits/vugs (Fig. 2d) on surface giving rise to pitted appearance at places, which is due to the leaching out of pyrite crystals and small mud-balls from these quartzites. The Banganapalle Formation exhibits a gentle eastern slope in the study area around Chenchu colony whereas its thickness is controlled by the basement topography (Gupta et al., 2010).

## URANIUM MINERALISATION

Uranium mineralisation established in Palnad sub-basin is mostly fracture-controlled, proximal to the unconformity contact and hosted by both the Banganapalle sediments and the basement granite (Jeyagopal et al., 2011; Latha et al. 2011; Verma et al., 2011; Shobhita et al., 2014). Recent radiometric survey in the western extension areas of Koppunuru uranium deposit has resulted in delineation of Banganapalle quartzite hosted three radioactive anomalous zones of 45m (N-S) x 15m (E-W), 130m (N-S) x 45m (E-W) and 40m (N-S) x 25m (E-W) dimensions in the area south of Chenchu colony (Fig.1). Isorad mapping was carried out in Zone-2 with relatively larger

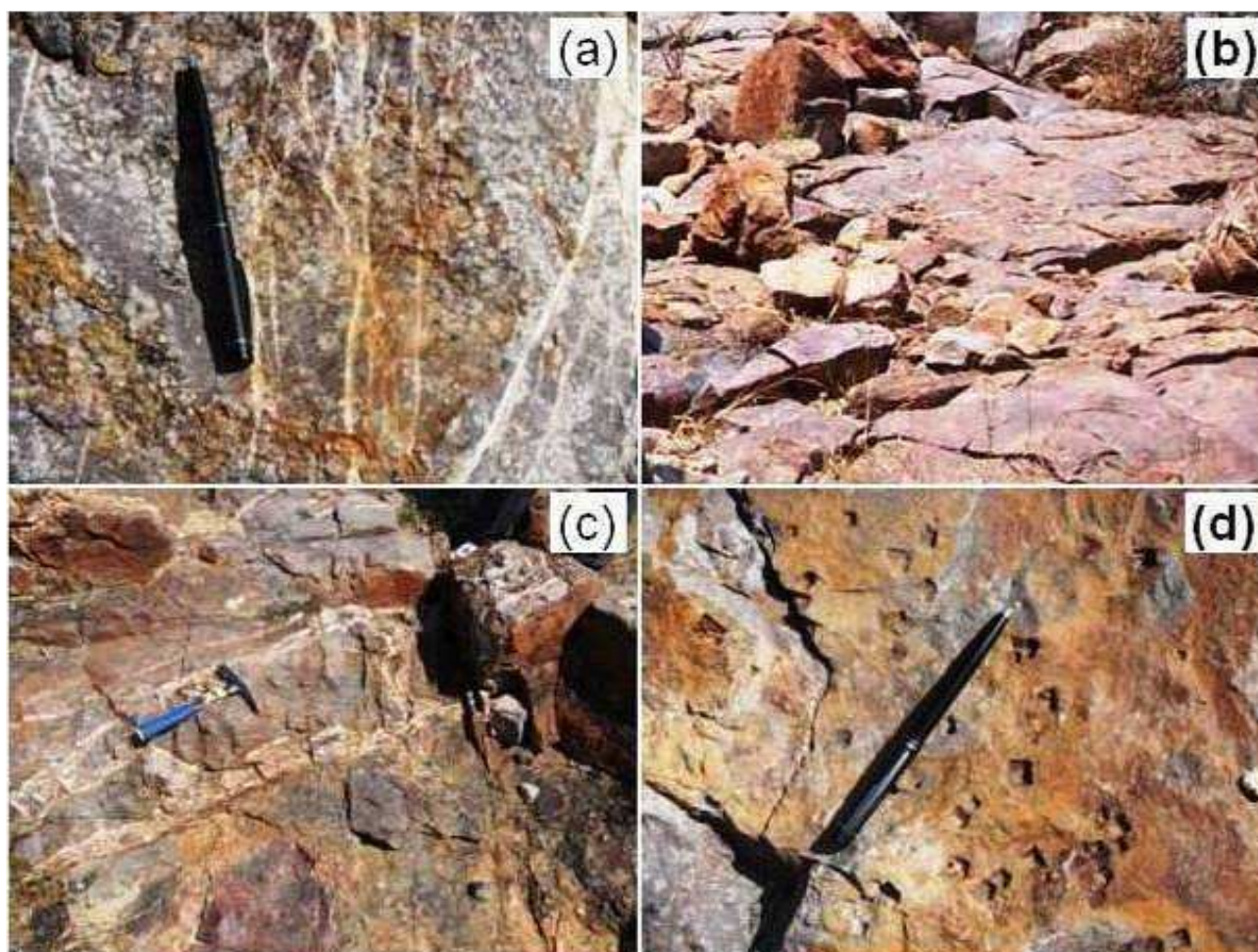


**Fig.2.** Field photographs showing different features associated with Banganapalle Quartzites of Chenchu colony and adjoining areas. **(a)** Gritty quartzite showing close spaced thin quartz veins. **(b)** Profuse fracturing/jointing in quartzites with reddish brown colour at top surface. **(c)** Quartz veins and fractures in quartzite signifying post-depositional reactivation. **(d)** Cubic vugs created by leaching of pyrite.

strike extension, to trace the trend of surface expression of uranium mineralisation. The samples from radioactive zones were subjected to radiometric assay, petromineralogical studies and whole rock geochemistry to understand the nature of uranium mineralisation and its relation to the host rock.

#### Isorad Mapping

4-channel Portable Gamma Ray Spectrometer (PGRS) was used for in-situ measurement of gross counts corresponding to total radioactivity as well as radio elemental concentrations of uranium (U), thorium (Th) and potassium (K) in ppm. This instrument comprises 8085 microprocessor, standard peripherals and 1.75" x 2" size thallium activated sodium iodide scintillation detector.  $\text{Cs}^{137}$  is used as reference isotopic point source. The total count energy window for measuring total radioactivity is set from 0.4 to 3.0 MeV. The uranium and thorium measurements are based on their decay daughter product  $\text{Bi}^{214}$  and  $\text{Tl}^{208}$  at gamma energies 1.76 MeV and 2.62

MeV, respectively. Potassium (%) is measured from  $\text{K}^{40}$  at 1.46 MeV. A summary of radio elemental concentrations recorded during isorad mapping is given in Table 2.

Based on the variability of gamma counts, isorad mapping was carried out in a 5m x 5m square grid layout and measurements of radioelemental abundances were taken at 256 grid nodes covering a total area of 5850 sq m in Zone-2. Contour plots of total radioactivity and U/Th ratio indicate a NNW–SSE trend of uranium mineralisation in this zone (Fig 3). This

**Table 2.** Summary of radio elemental concentrations recorded during isorad mapping of Zone-2, south of Chenchu colony, Guntur District

| N = 256        | Total Radio-activity (eU) ppm | Uranium (U) ppm | Thorium (Th) ppm | Potassium (K)% | U/Th      |
|----------------|-------------------------------|-----------------|------------------|----------------|-----------|
| Zone- 2,       | <2 – 189                      | <2 – 191        | <5 – 19          | <1 – 5.9       | 0.12 – 66 |
| Chenchu colony | Av. 30.84                     | Av.11.34        | Av. 2.94         | Av. 1.28       | Av. 4.08  |

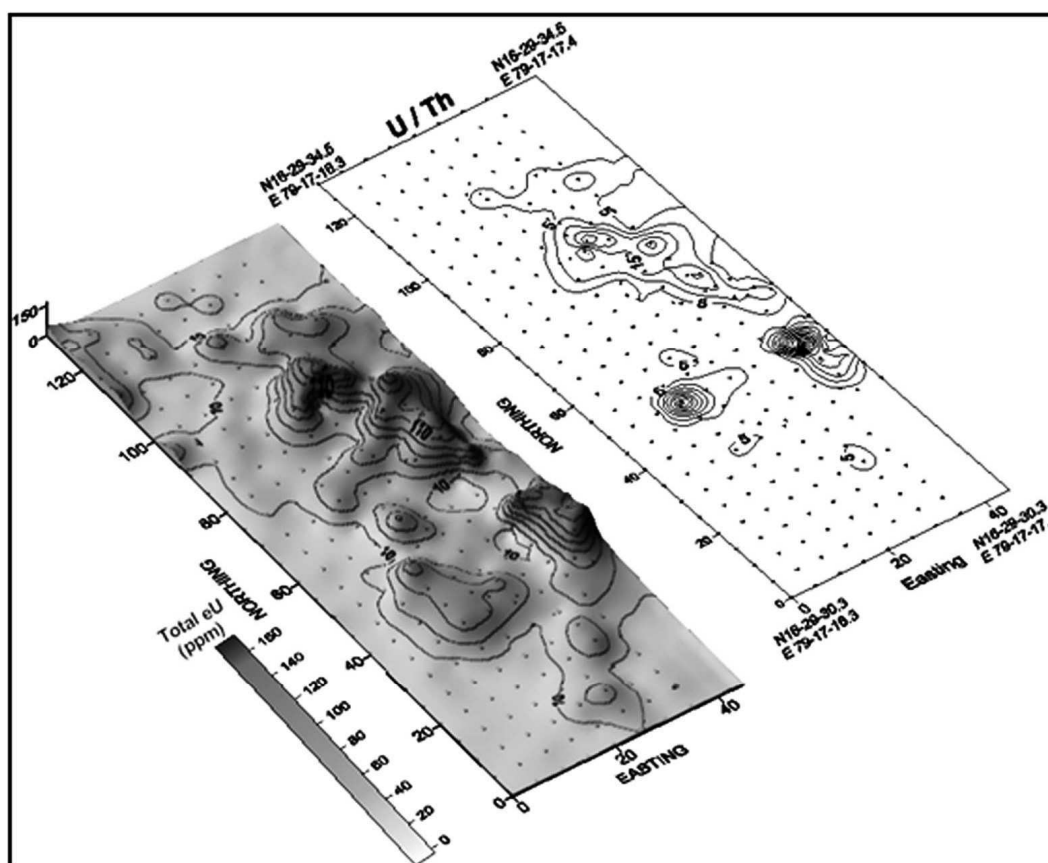


Fig.3. Total radioactivity (eU ppm) and U/Th ratio contour maps of Uraniferous Zone-2, south of Chenchu colony

trend is synchronous with the prominent fracture pattern of the host Banganapalle quartzite.

#### Radiometric Assay and Disequilibrium Studies

The state of disequilibrium of uranium series, which can be categorized in four general types, is very significant from uranium exploration point of view (Rosholt, 1958). Equilibrium is attained in a Uranium series when all the daughter products decay at the same rate in which they are produced from the parent isotope in an ideally closed system. At equilibrium each of the daughter products would be present in a constant proportion to its parent isotope. However, due to various geologic and/or physico-chemical processes the equilibrium condition in radioactive disintegration series is often disturbed in a radioactive mineral and causes disequilibrium by means of change in the proportion of the parent isotope to its daughter products (Rosholt, 1959).

In the present study, equilibrium/disequilibrium state were determined using laboratory based High Energy Gamma Ray Spectrometry (HEGS) along with physical assay of  $U_3O_8$  (%) by  $\beta/\gamma$ -method (Acharyulu et al., 2004; Bhaumik et al., 2004). Radioactive samples from the anomalous zones were analyzed

for equivalent  $U_3O_8$  (%e $U_3O_8$ ), radium equivalent  $U_3O_8$  (%Rae $U_3O_8$ ), % $ThO_2$  and %K. The e $U_3O_8$  is the ratio of radioactivity of the sample and a uranium-ore standard which is in equilibrium with all of its decay products while Rae $U_3O_8$  is the estimation of  $U_3O_8$  based on the counting of 1.76 MeV gammas from  $Bi^{214}$  of the Ra-group of the uranium series, with an assumption that it is in equilibrium. Similarly,  $ThO_2$  estimation is based on counting of 2.62 MeV gammas emitted by  $Tl^{208}$  of the thorium series, which invariably remains in equilibrium (Levinson et al., 1978). The actual parent concentration ( $U_3O_8$ ) is estimated by  $\beta/\gamma$ -method wherein simultaneous counting of total beta and total gamma is done (Eichholz et al., 1953). Disequilibrium factor (DF) is given by the ratio of  $U_3O_8$  ( $\beta/\gamma$ ) and Rae $U_3O_8$ , where  $DF = 1$  indicates radioactive equilibrium condition while  $DF > 1$  and  $DF < 1$  suggest disequilibrium in favour of parents and daughters, respectively.

Radiometric assay results of the samples ( $n = 14$ ) collected from Zones 1, 2 and 3 indicate 0.009–0.027%e $U_3O_8$  and <0.010–0.035% $U_3O_8$ ( $\beta/\gamma$ ) (Table 3) with negligible  $ThO_2$  (<0.005%) signifying the uraniferous nature of the mineralisation. In addition, these results also suggest

**Table 3.** Radiometric assay of samples from the radioactive anomaly zones south of Chenchu colony, Guntur district, A.P.

| R.A. Zone/<br>Dimension | Sample<br>No. | % eU <sub>3</sub> O <sub>8</sub> | % U <sub>3</sub> O <sub>8</sub> | % Ra(U <sub>3</sub> O <sub>8</sub> ) | %ThO <sub>2</sub> | Disequilibrium<br>factor |
|-------------------------|---------------|----------------------------------|---------------------------------|--------------------------------------|-------------------|--------------------------|
| Zone-1<br>(45m x 15m)   | Z-1/ 1        | 0.023                            | 0.032                           | 0.023                                | <0.005            | (+) 1.39                 |
|                         | Z-1/ 3        | 0.013                            | 0.015                           | 0.012                                | <0.005            | (+) 1.25                 |
| Zone-2<br>(130m x 45m)  | Z-2/ 1        | 0.024                            | 0.033                           | 0.024                                | <0.005            | (+) 1.38                 |
|                         | Z-2/ 2        | 0.018                            | 0.020                           | 0.017                                | <0.005            | (+) 1.18                 |
|                         | Z-2/ 3        | 0.027                            | 0.035                           | 0.027                                | <0.005            | (+) 1.30                 |
|                         | Z-2/ 4        | 0.019                            | 0.020                           | 0.019                                | <0.005            | (+) 1.05                 |
|                         | Z-2/ 5        | 0.023                            | 0.029                           | 0.023                                | <0.005            | (+) 1.26                 |
|                         | Z-2/ 9        | 0.014                            | 0.017                           | 0.014                                | <0.005            | (+) 1.21                 |
|                         | Z-2/ 10       | 0.009                            | <0.010                          | 0.009                                | <0.005            | -                        |
| Zone-3<br>(40m x 25m)   | Z-3/ 1        | 0.016                            | 0.016                           | 0.016                                | <0.005            | Equilibrium              |
|                         | Z-3/ 3        | 0.016                            | 0.016                           | 0.016                                | <0.005            | Equilibrium              |
|                         | Z-3/ 4        | 0.012                            | <0.010                          | 0.012                                | <0.005            | -                        |
|                         | Z-3/ 5        | 0.012                            | 0.016                           | 0.012                                | <0.005            | (+) 1.33                 |
|                         | Z-3/ 7        | 0.013                            | <0.010                          | 0.012                                | <0.005            | -                        |

disequilibrium in the uranium series in favour of parents as U<sub>3</sub>O<sub>8</sub>( $\beta/\gamma$ ) values are more than RaeU<sub>3</sub>O<sub>8</sub> values (DF= 1.05–1.39), except for two samples Z-3/1 and 3 of zone-3 showing equilibrium condition (DF=1). A positive slope in the scatter plot between %RaeU<sub>3</sub>O<sub>8</sub> and %U<sub>3</sub>O<sub>8</sub> ( $\beta/\gamma$ ) also suggests a chemically open system and disequilibrium in favour of parents (Fig. 4).

### PETROMINERALOGY

The radioactive siliciclastic rocks of the study area are mostly light grey in colour but the upper part shows pinkish to reddish brown straining due to the presence of iron oxides and seasonal water action. They are fine to medium grained, hard and compact in nature and occasionally have saccharoidal

appearance. Brief details of different petromineralogical attributes pertaining to these rocks are described below.

### Mineralogical and Textural Attributes

The host arenaceous rock is composed of >80% quartz clasts and minor to accessory amounts of feldspar, chlorite, sericite, clay, iron oxides, organic matter, pyrite, collophane, tourmaline, zircon and glauconite and is identified as quartz arenite. The framework clasts (0.5–1.0mm) are predominantly represented by monocrystalline quartz with some polycrystalline quartz grains and rare grains of metamorphic quartz (Fig. 5a) and vein quartz. Modification of originally rounded quartz clast by secondary overgrowth is common. Overgrown quartz is often welded by authigenic quartz into a mosaic of interlocking sutured aggregates. The quartz clasts generally exhibit smooth extinction while some clasts are slightly elongated and display undulose extinction signifying mild deformed nature. It is apparent that the deformation is mostly post-compaction/diagenesis as indicated by the presence of undulose extinction in the secondary overgrowth and its optical continuity with the quartz clast. Framework grains also show minor presence of 0.1mm to 0.3mm size, tabular to sub angular feldspar clasts (microcline, orthoclase and plagioclase). Feldspars exhibit alteration to chlorite, which occurs as tiny spherulitic flakes in the intergranular spaces and along the weak planes (Fig. 5b). Cementing material is essentially siliceous and mostly precipitated in the intergranular spaces while matrix accounts for <2% of the rock and comprises clay, sericite and chlorite. Cryptocrystalline, colloidal collophane was also observed as very fine aggregates along grain boundaries (Fig. 5c).

Pyrite is recorded as one of the important accessory ore minerals and occurs as randomly distributed euhedral to

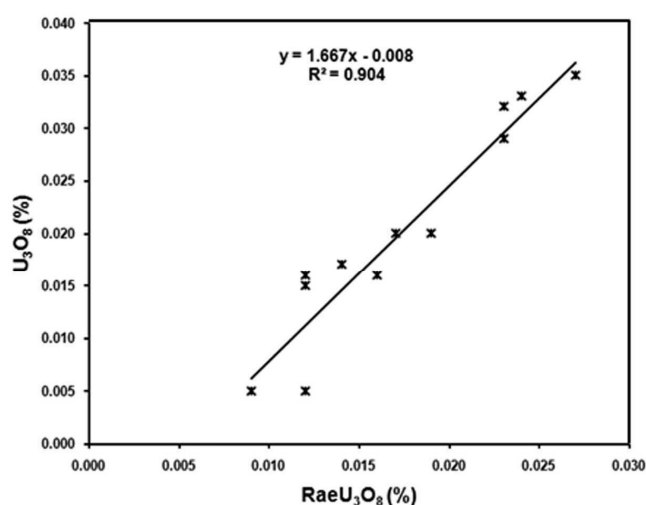


**Fig.4.** Binary RaeU<sub>3</sub>O<sub>8</sub> (%) vs U<sub>3</sub>O<sub>8</sub> (%) plot for samples from uraniferous zones indicating disequilibrium in favour of parents

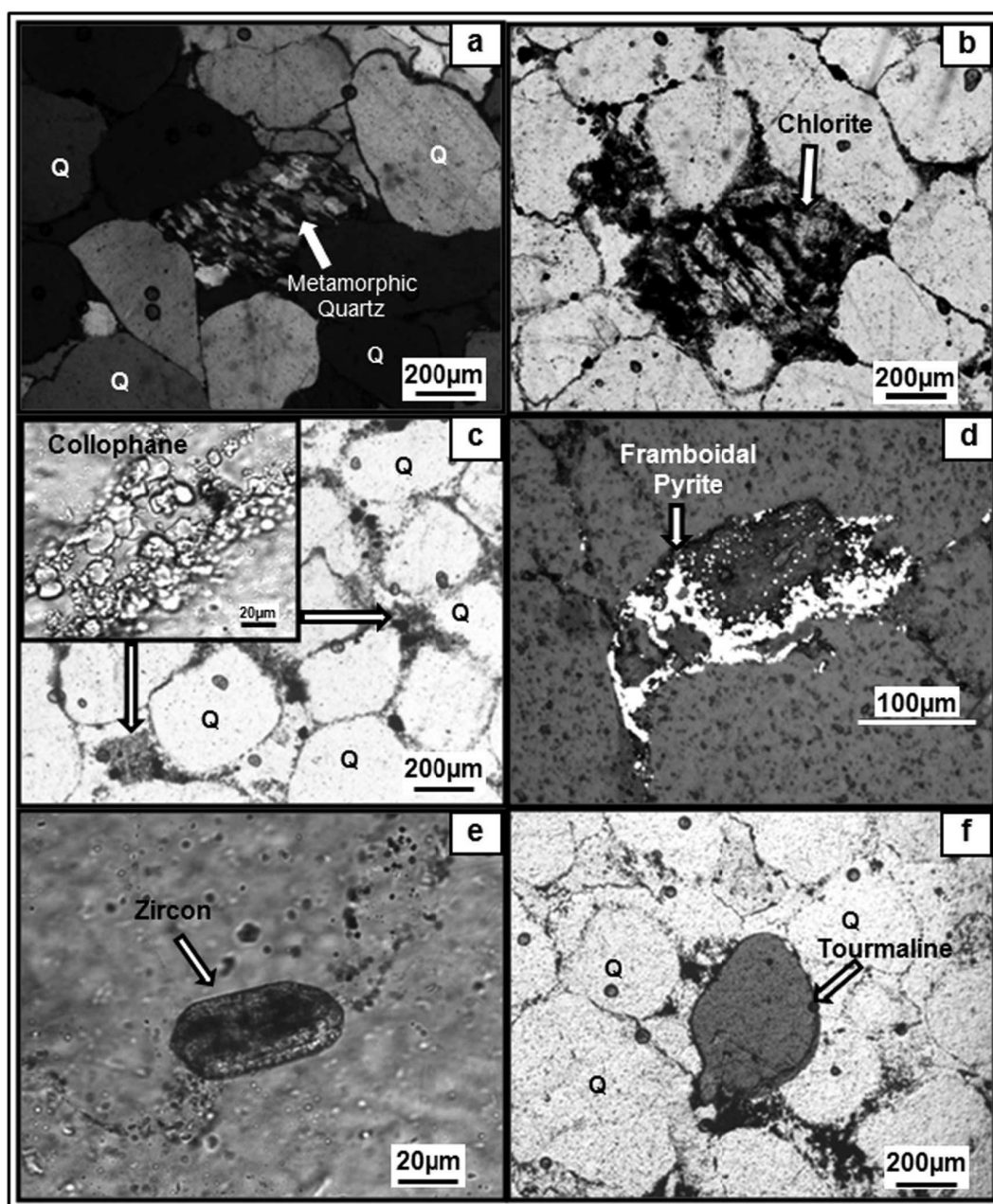


**Fig.5.** Photomicrograph showing various features of uraniferous quartz arenite of Chenchu colony area. (a) Overall texture of quartz arenite with rare metamorphic quartz clast (TL, Transmitted Light). (b) Spherulitic flakes of chlorite along the intergranular spaces and cleavages of feldspar (TL). (c) Fine aggregates of colloidal Collophane along grain boundaries (TL). (d) Framboidal pyrite in intergranular space (RL, Reflected Light). (e) Euhedral zoned zircon within quartz clast (TL). (f) Rounded tourmaline grain within quartz (Q) clasts (TL)

subhedral framboidal pyrite grains (Fig. 5d). Rare zircon grains are observed as inclusions in quartz. These are mostly euhedral in shape and zoned in nature (Fig. 5e). A few rounded grains of tourmaline (Fig. 5f) are also observed. Small opaque masses of organic matter are seen in the intergranular spaces at places. These occur as globular masses and thin veins. They display bireflectance and low anisotropism under cross polars.

Various alteration features are indicated by the quartz

arenites viz., ferrugination, silicification, chloritisation and kaolinisation. Ferrugination is noted as incipient iron oxide grains in the intergranular spaces of quartz clasts and along the cleavage/fractures in feldspars. Similarly, kaolinisation has led to formation of clay minerals such as illite and kaolinite. Chloritisation is mainly caused by alteration of feldspars while silicification is mainly manifested as secondary overgrowth as discussed earlier.

Dominance of quartz clasts with unimodal size distribution and rounded to sub-rounded/oval shape points towards high degree of mineralogical and textural maturity and suggest their deposition under high energy condition in shallow marine environment.

#### Mode of Occurrence of Radioactive Phases

The mode of occurrence of the radioactive phases may be broadly classified into the following: (a) fine veinlets of pitchblende within chlorite in intergranular spaces, (b) as globular patches of urano-organic complexes with uranium in adsorbed state, (c) as adsorbed uranium in clay, chlorite and iron oxides patches, and (d) as labile uranium along grain boundaries.

Pitchblende is the only primary uranium ( $U^{4+}$  oxidation state) mineral observed in the studied samples. It occurs as fine veinlets in the intergranular spaces and show close affinity to chlorite while at places it is associated with pyrite and organic matter. Under transmitted light, the entire patch of clay, chlorite

and pitchblende is opaque and gives moderate density alpha tracks on CN-85 film on 72 hours of exposure (Fig. 6a, b). Globular masses and veins of urano-organic complexes register medium to low density alpha tracks on CN-85 film (Fig. 6c, d). Adsorbed uranium is also identified as low density and few stray alpha tracks on CN-85 film which corresponds to chlorite, clay, sericite, collophane and iron oxides.

Pitchblende, urano-organic complex are the phases formed under reducing environment, whereas uranium in adsorbed form on hydrous iron oxides, collophane, chlorite and clay indicate oxidizing environment. The mode of occurrence of the uraniferous phases and their intimate association with organic matter and pyrite along thin veins and intergranular spaces suggest epigenetic and epithermal type of mineralization.

#### Modal Analysis

Modal analysis of the siliciclastic rocks ( $n=10$ ) suggests that these are typical quartz arenite with dominance of quartz (clasts and cement) over feldspar, clay, ferruginous matter/

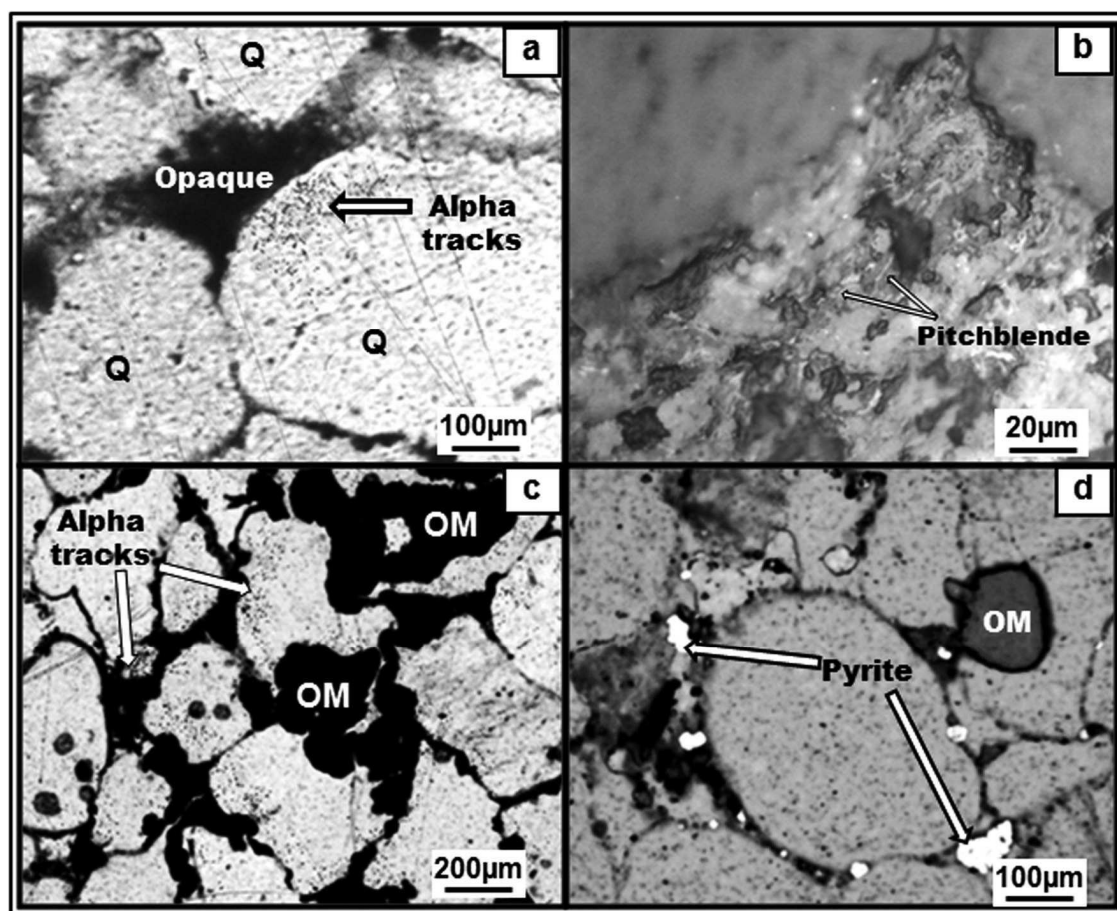


**Fig.6.** Radioactive phases and associated reductants in quartz arenites of Chenchu colony area. (a) Intergranular opaque uraniferous phase showing moderate density tracks (TL). (b) Veinlets of pitchblende in clayey mass within the opaque (RL). (c) Globular mass of urano-organic complex replacing quartz and in the intergranular spaces showing moderate density tracks (TL). (d) Pyrite and organic matter in the intergranular spaces indicative of a reducing environment (RL)

**Table 4.** Modal analysis of quartzite samples from the radioactive anomaly zones south of Chenchu colony, Guntur district, A.P.

| Sample No. | Mono-crystalline Quartz | Poly-crystalline Quartz | Feldspar | Ferruginous matter/Chlorite | Clay  | Quartz Cement |
|------------|-------------------------|-------------------------|----------|-----------------------------|-------|---------------|
| Z-1/1      | 70.20                   | 4.00                    | 6.30     | 4.70                        | 1.80  | 13.00         |
| Z-1/3      | 60.70                   | 9.90                    | 1.10     | 1.10                        | 3.40  | 8.90          |
| Z-2/3      | 71.90                   | 5.90                    | 13.20    | 4.30                        | 0.90  | 3.80          |
| Z-2/4      | 72.90                   | 2.30                    | 9.80     | 0.10                        | 4.00  | 8.60          |
| Z-2/5      | 71.10                   | 11.60                   | 6.70     | 3.70                        | 1.70  | 5.20          |
| Z-2/9      | 67.40                   | 3.80                    | 6.70     | 0.60                        | 1.00  | 2.00          |
| Z-2/10     | 81.20                   | 5.80                    | 2.60     | 7.10                        | 0.00  | 3.30          |
| Z-3/3      | 59.00                   | 2.00                    | 3.10     | 5.50                        | 2.00  | 19.80         |
| Z-3/4      | 65.90                   | 7.40                    | 4.80     | 8.00                        | 10.00 | 11.90         |
| Z-3/5      | 67.00                   | 13.20                   | 2.80     | 8.00                        | 4.30  | 2.50          |

chlorite and insignificant lithic rock fragments (Table 4). Overall quartz content varies from 73.2% to 90.3% with an average of 83.2% and shows dominance of monocrystalline quartz (59–81.2%; av. 68.7%). Other significant siliceous representations are, polycrystalline quartz (2.0–13.2%; av. 6.6%) and quartz cement (2.0–19.8%; av. 7.9%). Feldspar (1.1–13.2%; av. 5.7%), ferruginous matter/chlorite (0.1–8.0%; av. 4.3%) and clay (0.0–10.0%; av. 2.9%) are minor components. One of the samples (Z-2/5) shows significant presence of

organic matter (2.5%). In the classical Dickinson's sandstone compositional triangular diagram ( $Q_t$ -F-L) (Dickinson and Suczek, 1979; Dickinson et al., 1983), all samples plot along the  $Q_t$ -F axis due to the negligible presence of volcanic/sedimentary/metamorphic lithic fragments. The samples straddle in the 'Craton Interior' field suggesting that they are derived from recycled quartzose sources (Fig. 7).

## GEOCHEMISTRY

A total of 16 grab samples of uraniferous quartz arenites were collected from three radioactive zones (Zone1– 4 nos.; Zone2– 7 nos.; Zone3– 5 nos.) of Chenchu colony area and studied for whole rock geochemistry. During sampling proper care has been taken to collect unaltered fractions of quartz arenite.

### Methodology

Fresh samples were reduced to small chips using laboratory type jaw crusher and were powdered to –200 mesh using disc mills for maintaining the homogeneity and true representativeness of the sample. Smaller representative volumes of the powder are obtained by coning and quartering from which 1g of sample is transferred to cylindrical sample disc and is pelletized with boric acid as a backing material, at a pressure of 25000 kg/cm<sup>2</sup> in a hydraulic press, to obtain pellets of 41 mm diameter. These samples were analysed for major, minor and some selective trace elements at XRF laboratory, AMD, Hyderabad using PAnalytical Magi XPro PW 2440 WDXRFS unit equipped with a 4 Kw, 60 Kv, 125 mA super sharp end window type X-ray tube. International standard reference materials (SRM's) like ACE, FKN, G-2, GA, GH, GSN, GSP-1, JG1A, JG-2, JG-3, NBS-81A and SiO<sub>2</sub> were used as calibration standards. The major and minor elements were analyzed at 30 KV and 100mA using 300 µm collimator, PX 1 and LIF 200 dispersing crystals and gas flow proportional counter detectors with detection limit of 0.01% whereas the trace elements were analyzed at 50 KV and 60mA using 150 µm collimator, LIF 220 crystals and scintillation and/duplex detectors with detection limit of 10 ppm. The analytical precision (%RSD) and accuracy (%error) was within ±5% for major and minor elements and some trace elements (> 30 ppm) and ± 10 % for some other trace elements (<30 ppm).

### Analytical Results

Analytical results of mineralised quartz arenites are given in Table 5. Synthesis of analytical data indicates high SiO<sub>2</sub> content (92.28–99.42%; av. 95.91%), which is commensurate with comparatively low FeO<sub>(t)</sub> (0.15–0.88%; av. 0.54%), TiO<sub>2</sub> (<0.010–0.90%; av. 0.08%), MgO (0.010–0.26%; av. 0.11%).

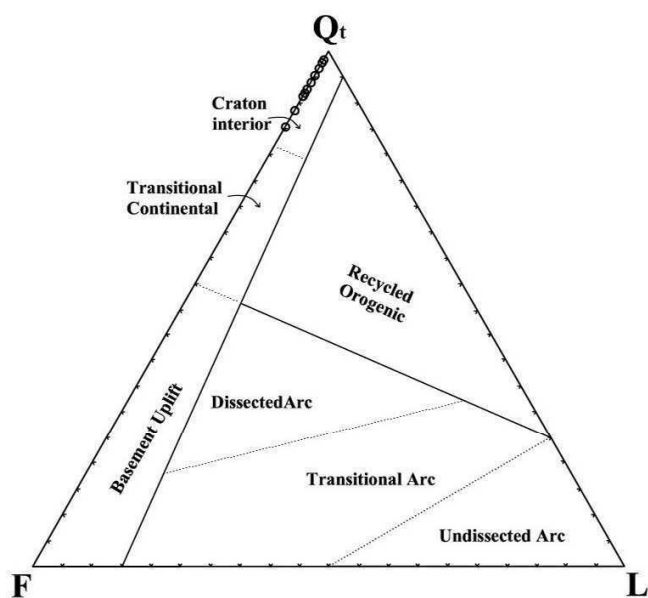


**Fig.7.** Modal analysis based discrimination diagram showing the provenance of the uraniferous Banganapalle quartzite of Chenchu colony area. Detrital grain parameters are:  $Q_t$  (Total quartz grains including mono- and polycrystalline quartz grains), F (total Feldspars) and L (Total lithic fragments including volcanic, sedimentary and metamorphic grains). After Dickinson and Suczek (1979) and Dickinson et al. (1983).

**Table 5.** Whole rock geochemical analysis (XRF) of uraniferous Banganapalle quartzite, south of Chenchu colony

| Sample No.                     | Z-1/1        | Z-1/2         | Z-1/3         | Z-1/5        | Z-2/1         | Z-2/3        | Z-2/4         | Z-2/5        | Z-2/6        | Z-2/10       | Z-2/11       | Z-3/1        | Z-3/3        | Z-3/4        | Z-3/5        | Z-3/6         |
|--------------------------------|--------------|---------------|---------------|--------------|---------------|--------------|---------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|---------------|
| Major Oxides (in %)            |              |               |               |              |               |              |               |              |              |              |              |              |              |              |              |               |
| SiO <sub>2</sub>               | 94.18        | 97.30         | 95.17         | 99.25        | 95.34         | 95.36        | 95.90         | 95.27        | 97.11        | 97.16        | 95.87        | 92.28        | 94.88        | 95.45        | 94.66        | 99.42         |
| TiO <sub>2</sub>               | <0.01        | 0.90          | <0.01         | <0.01        | 0.13          | 0.03         | 0.04          | <0.01        | 0.01         | 0.01         | <0.01        | 0.04         | <0.01        | <0.01        | 0.01         | <0.01         |
| Al <sub>2</sub> O <sub>3</sub> | <0.01        | <0.01         | <0.01         | <0.01        | <0.01         | <0.01        | <0.01         | <0.01        | <0.01        | <0.01        | <0.01        | <0.01        | <0.01        | <0.01        | <0.01        | <0.01         |
| FeO(t)                         | 0.15         | 0.67          | 0.64          | 0.59         | 0.43          | 0.25         | 0.31          | 0.34         | 0.88         | 0.44         | 0.43         | 0.87         | 0.43         | 0.46         | 0.86         | 0.86          |
| MgO                            | 0.13         | 0.11          | 0.17          | 0.05         | 0.12          | 0.03         | 0.01          | 0.09         | 0.05         | 0.03         | 0.06         | 0.12         | 0.14         | 0.24         | 0.26         | 0.22          |
| MnO                            | <0.01        | 0.01          | <0.01         | <0.01        | <0.01         | <0.01        | <0.01         | <0.01        | <0.01        | <0.01        | <0.01        | <0.01        | <0.01        | <0.01        | <0.01        | <0.01         |
| CaO                            | 2.50         | 1.21          | 2.46          | <0.01        | 2.29          | 2.13         | 2.18          | 2.27         | 0.42         | 0.76         | 1.43         | 3.38         | 2.21         | 2.00         | 2.28         | <0.01         |
| Na <sub>2</sub> O              | <0.01        | <0.01         | 0.09          | <0.01        | <0.01         | <0.01        | <0.01         | <0.01        | <0.01        | <0.01        | <0.01        | <0.01        | <0.01        | <0.01        | <0.01        | <0.01         |
| K <sub>2</sub> O               | <0.01        | <0.01         | <0.01         | <0.01        | <0.01         | <0.01        | <0.01         | <0.01        | <0.01        | <0.01        | <0.01        | <0.01        | <0.01        | <0.01        | <0.01        | <0.01         |
| P <sub>2</sub> O <sub>5</sub>  | 1.90         | 0.92          | 1.87          | <0.01        | 1.74          | 1.62         | 1.66          | 1.73         | 0.32         | 0.58         | 1.09         | 2.57         | 1.68         | 1.52         | 1.73         | 0.14          |
| <b>Total</b>                   | <b>98.86</b> | <b>101.12</b> | <b>100.40</b> | <b>99.89</b> | <b>100.05</b> | <b>99.42</b> | <b>100.10</b> | <b>99.70</b> | <b>98.79</b> | <b>98.98</b> | <b>98.88</b> | <b>99.26</b> | <b>99.34</b> | <b>99.67</b> | <b>99.80</b> | <b>100.64</b> |
| Trace Elements (in ppm)        |              |               |               |              |               |              |               |              |              |              |              |              |              |              |              |               |
| Cr                             | 28           | 31            | 30            | 31           | 36            | 32           | 31            | 38           | 43           | 37           | 40           | 40           | 38           | 37           | 35           | 38            |
| Co                             | 66           | 65            | 124           | 79           | 108           | 169          | 79            | 95           | 141          | 75           | 84           | 139          | 81           | 78           | 145          | 80            |
| Rb                             | 42           | 28            | <10           | 33           | 33            | 34           | 29            | 27           | <10          | 18           | <10          | <10          | <10          | <10          | <10          | <10           |
| Sr                             | 62           | 55            | 49            | 44           | 46            | 32           | 44            | 34           | 112          | 54           | 43           | 66           | 40           | 61           | 49           | 15            |
| Y                              | 22           | 21            | 40            | <10          | 19            | 14           | 13            | 17           | 16           | 19           | <10          | 40           | 33           | 31           | 20           | <10           |
| Zr                             | 49           | 35            | <10           | <10          | 40            | 40           | 37            | <10          | 52           | 32           | 90           | <10          | <10          | 92           | <10          | <10           |
| Nb                             | <10          | 11            | 10            | <10          | 13            | 41           | 27            | <10          | 16           | <10          | <10          | 14           | <10          | <10          | 14           | 13            |
| Ba                             | 85           | 107           | 75            | 28           | 98            | 96           | 58            | 95           | 225          | 190          | 75           | 90           | 70           | 91           | 36           | <10           |
| Ce                             | 37           | 40            | 38            | 35           | 25            | 15           | 19            | 20           | 53           | 26           | 26           | 52           | 26           | 28           | 52           | 22            |
| Pb                             | 86           | 30            | 55            | 51           | 101           | 95           | 51            | 89           | 56           | 139          | 29           | 89           | 68           | 77           | 32           | 46            |
| Th                             | <10          | <10           | <10           | <10          | <10           | <10          | <10           | <10          | 11           | <10          | <10          | <10          | <10          | <10          | <10          | <10           |
| U                              | 403          | 73            | 185           | <10          | 309           | 278          | 247           | 220          | 68           | 130          | 71           | 184          | 93           | 87           | 140          | <10           |

Note: Al<sub>2</sub>O<sub>3</sub>, K<sub>2</sub>O (both <0.010%), Ni, Cu, Zn and Ga (all <10 ppm) were treated as below detectable limit.

These samples have moderately high CaO (<0.010–3.38%; av. 1.72%) and P<sub>2</sub>O<sub>5</sub> (<0.010–0.90%; av. 0.08%) while Al<sub>2</sub>O<sub>3</sub>, MnO, Na<sub>2</sub>O and K<sub>2</sub>O contents are mostly below detectable limit. In the major element based chemical classification diagram (Herron, 1988) samples straddle the fields of quartz

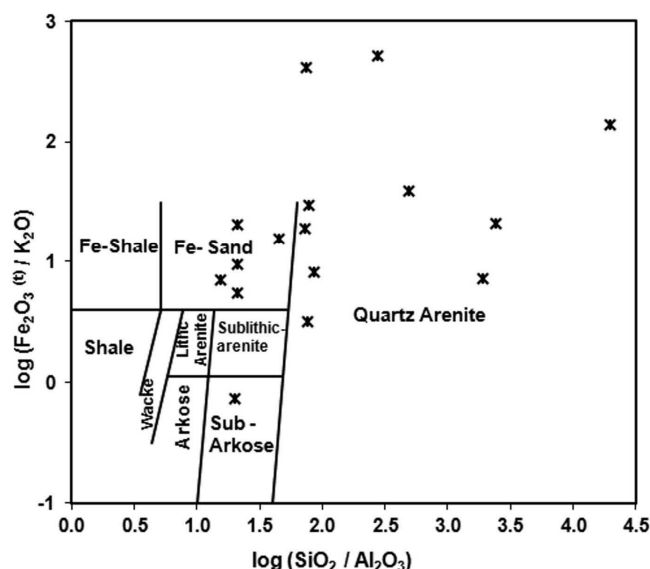


**Fig.8.** Chemical composition of Banganapalle Quartzite and their classification as per sand class scheme (after Herron, 1988)

arenite and Fe-sand (Fig. 8) whereas limited variation in major oxide contents may be related to its mineralogical composition and maturity. Low TiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub> content reflects the negligible phyllosilicate content of the arenites (Dabard, 1990), while very low (below detectable limit) content of Na<sub>2</sub>O and K<sub>2</sub>O supports the rare presence of feldspars as observed in petromineralogical studies. Presence of some resistant minerals in the system is indicated by Y (upto 40 ppm), Nb (upto 41 ppm) and Zr (upto 92 ppm) contents while higher uranium concentration (upto 403 ppm) confirms the uraniferous nature of the quartzite. High SiO<sub>2</sub> content together with the petromineralogical attributes suggest felsic and quartzose sedimentary provenance while restricted concentration of Co (65–169 ppm), Cr (28–43 ppm) and insignificant Ni (<10 ppm) content suggest limited contribution from mafic rocks. This is further supported by the classification plot based on Discriminant function coefficients as F1 and F2 scores (Roser and Korsch, 1988), using TiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, FeO<sub>(t)</sub>, MgO, Na<sub>2</sub>O and K<sub>2</sub>O, suggesting quartzose sedimentary provenance (Fig. 9). High SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> ratios also support the above inference (Potter, 1978). It is observed that the radioactive Banganapalle quartzites are enriched in SiO<sub>2</sub>, CaO, P<sub>2</sub>O<sub>5</sub>, Sr, Y, Nb, Pb and U and depleted in TiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, FeO<sub>(t)</sub>, MgO, MnO, K<sub>2</sub>O, Na<sub>2</sub>O, Zr, Ni and Rb as compared to Proterozoic equivalents (Condie, 1993).

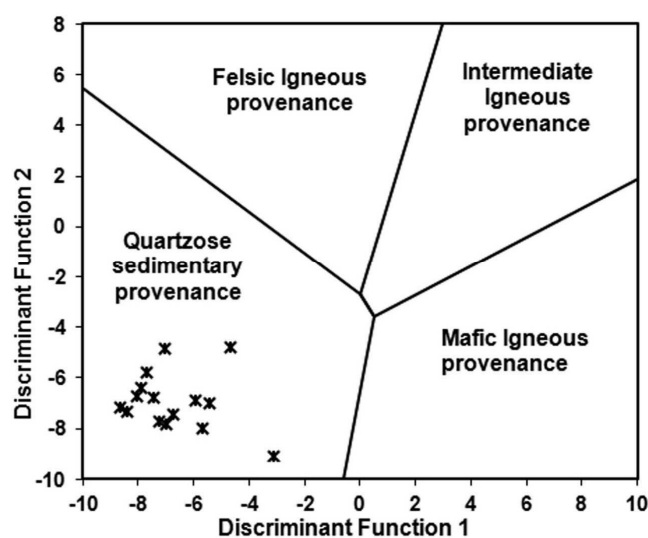


Fig.9. Discriminant Function Diagram for sedimentary provenance of Banganapalle Formation using major elements (after Roser and Korsch, 1988).

$$\text{Discriminant Function 1} = (-1.7773 \cdot \text{TiO}_2) + (0.607 \cdot \text{Al}_2\text{O}_3) + (0.76 \cdot \text{Fe}_2\text{O}_3) + (-1.5 \cdot \text{MgO}) + (0.616 \cdot \text{CaO}) + (0.509 \cdot \text{Na}_2\text{O}) + (-1.224 \cdot \text{K}_2\text{O}) + (-9.09)$$

$$\text{Discriminant Function 2} = (0.445 \cdot \text{TiO}_2) + (0.07 \cdot \text{Al}_2\text{O}_3) + (-0.25 \cdot \text{Fe}_2\text{O}_3) + (-1.142 \cdot \text{MgO}) + (0.438 \cdot \text{CaO}) + (1.475 \cdot \text{Na}_2\text{O}) + (1.426 \cdot \text{K}_2\text{O}) + (-6.8)$$

#### Correlation of Major Oxides and Trace Elements

Very high content of silica and negative correlation of  $\text{SiO}_2$  with  $\text{CaO}$  ( $r = -0.955$ ),  $\text{Na}_2\text{O}$  ( $r = -0.110$ ),  $\text{MgO}$  ( $r = -0.156$ ),  $\text{P}_2\text{O}_5$  ( $r = -0.951$ ) and other trace elements indicate high chemical maturity of the arenites. Weak, but positive correlation of  $\text{FeO}^t$  ( $r = 0.197$ ) and  $\text{MnO}$  ( $r = 0.205$ ) with  $\text{SiO}_2$  suggest minor ferrugination of quartzite which may be attributed to surficial oxidation processes. This is substantiated by the petrographic observations indicating presence iron oxides in the intergranular spaces. High positive correlation co-efficient between  $\text{CaO}$  and  $\text{P}_2\text{O}_5$  ( $r = 0.999$ ) corroborates the presence of collophane while moderate positive correlation between  $\text{U}$  and  $\text{P}_2\text{O}_5$  ( $r = 0.687$ ) suggests either marginal association of radioactivity with phosphatic phases or their role in uranium fixation in the system. In addition, negative correlation between  $\text{U}$  and  $\text{Th}$  ( $r = -0.209$ ) signifies decoupling of  $\text{U}$  from  $\text{Th}$  and its mobilisation in the system due to highly oxyphile nature. Positive correlation between  $\text{U}$  and  $\text{Pb}$  ( $r = 0.475$ ) indicates radiogenic nature of  $\text{Pb}$  in quartzite.

#### Qualitative Test for Phosphate

Although the quartz arenites have moderately high  $\text{P}_2\text{O}_5$  content and positive correlation with  $\text{U}$ , the absence of any discrete phosphatic minerals such as apatite is conspicuous. Petromineralogical studies have revealed that collophane is the

only phosphate bearing phase occurring along grain boundaries. However, to confirm the presence of phosphate in Banganapalle quartzite of study area, samples ( $n = 5$ ) from the uraniferous zones were subjected to chemical qualitative test for phosphates (AMD, 2003). 200 mesh powdered rock sample was brought to solution by dissolving in 100ml of dil.  $\text{HNO}_3$  (3%) and heating upto  $40^\circ\text{C}$ . About 25 ml of the solution (aliquot) was filtered and treated with 10 ml of vanadomolybdate solution (reagent), which is prepared by dissolving 1.25 g of ammonium metavanadate in 400ml of 1:1  $\text{HNO}_3$  and mixing the solution with another solution of 50 g of ammonium molybdate in 400 ml of distilled water. A typical canary yellow colour exhibited by all five samples in the resulting solution confirms the presence of phosphate. However, it is pertinent to mention that any significant relationship between uranium bearing phases and collophane could not be established under microscope. This is also evident from CN film study where only stray traces of alpha tracks are seen associated along the collophane bearing grain boundary sites.

## DISCUSSION AND CONCLUSION

Report of new uraniferous occurrences in Proterozoic unconformity-proximal setup in the western extensions of Koppunuru uranium deposit strengthens the continuity of mineralisation in the marginal parts of the Palnad sub-basin. The brief details of the provenance, nature of uranium mineralisation and future potential of the area is discussed below.

#### Provenance

The Banganapalle Formation gained importance for its sediment hosted mineral wealth and hence studied in detail about various depositional attributes in different sectors by several workers (Vijayam and Reddy, 1976; Sivaji and Rao, 1989; Lakshminarayana et al., 1999), who envisaged shallow marine depositional environment with provenance comprising granites in the north and west, while older Cuddapah sediments dominated the southern parts. In the study area, massive and thickly bedded quartz arenite units of Banganapalle Formation show at places primary sedimentary structures like asymmetric ripple marks, cross and trough beddings which have substantiated the north-western and westerly direction of sediment supply (Gupta, 2010). Recent geochemical studies on Banganapalle sediments of Koppunuru area have also indicated derivation of these sediments from Upper Cuddapah quartzose sedimentary provenance in the west and south vis-à-vis some contribution from first cycled granitic material (Gupta, 2012).

In the present study area around Chenchu colony, high

proportion of quartz clasts, unimodal nature, textural features such as medium to fine sub angular to sub rounded grains, moderate to high sorting and low proportion of feldspar and lithic fragments suggest transportation of these sediments from uplifted cratonic areas and subsequent deposition in stable sites (Taylor and McLennan, 1985; Potter, 1978, 1986). Discrimination function based plots using major oxide data suggest a definite quartzose sedimentary provenance (Fig. 9). However, the dominance of monocrystalline quartz grains over polycrystalline quartz may be the result of the disaggregation of original polycrystalline quartz during high energy or long distance transport from the quartzose source (Dabbagh and Rogers, 1983), while it is also possible that some part of the sediments were derived from a granitic source (Basu et al., 1975). The later view is further substantiated by the presence of zircon as inclusions in quartz grain suggesting their derivation from granitic source. In view of these features, we infer a dual provenance (quartzose and granitic) for studied quartzites in the extreme western part of Palnad sub-basin, where contribution from the granitic source is nominal.

#### Nature of Uranium Mineralisation

The western part of the Palnad sub-basin has notable favourable factors for uranium metallogeny. These include fertile basement-cum-provenance with high intrinsic U (19ppm U, 8.3ppm Th, U/Th ratio of 3.80,  $n=30$ ; Jeyagopal et al., 2011) in granitoids, pre- and post-depositional reactivation and tectonic deformations which are important for the mobilization and fixation of radioelements at suitable locales viz., fracture zones and unconformity planes. Felsic and mafic intrusives in basement granitoids might have provided necessary geothermal gradients for scavenging and mobilisation of uranium in the system.

A low temperature, fracture controlled, epigenetic metallogenic event is inferred for the uranium mineralisation associated with Banganapalle sediments in the study area. This is similar to that of Koppunuru deposit (Jeyagopal, 1996, 2011; Gupta, 2010, 2012; Verma, 2011) located ~5 km south-east of present uranium occurrence as evident from the concurrence of uranium mineralisation and fracture trends of the host Banganapalle quartzite and the occurrence of pitchblende as fine veinlets along mineralised fracture zones. Negative correlation of uranium with thorium and high U/Th ratio suggest enrichment of uranium in the sediments due to tectonic and hydrothermal activities. Porosity and permeability of the mature quartz arenite favoured smooth transmission of mineralised solutions. Significant role of prolonged and multiple generations of hydrothermal activity is further supported by the intensive alterations extending across the unconformity, with quartz dominant mineralogy of hydrothermal veins and

illitisation in cover sediments, while chlorite dominant mineralogy is common in basement granitoids with prominent chloritisation and epidotisation. Fluid inclusions in hydrothermal quartz in mineralised cover sediments reveal NaCl-dominant fluid composition and homogenisation temperature ranging from 81.7°C to 163.9°C (Thomas et al., 2014), which further corroborates low-temperature, epigenetic mineralisation in the area.

A dominant disequilibrium in favour of parents exhibited by the radioactive samples may possibly be attributed either to daughter product deficiency due to chemical leaching of the daughter products ( $Ra^{226}$  being easily leachable) of uranium decay series or additional influx of fresh uranium to the system. Presence of traces of urano-organic complexes and biogenic pyrite in the host quartzite confirms the role of organic matter and pyrite as favourable reductants, which might have helped in precipitation of uranium from solutions probably derived from adjoining fertile granitic provenance and channelized along post Kurnool fault/fracture systems. Organic matter in the cover sediments might have also migrated through the action of basinal/hydrothermal fluid movement along fractures due to syn-sedimentary tectonics and/or through thermal alteration of organic matter resulting in generation of liquid hydrocarbon amenable to migration (Gauthier-Lafaye and Weber, 1993; Parnell, 1993; Landais, 1996; Spirakis, 1996). The migrated organic matter was precipitated as epigenetic pore-fillings/fracture fillings and normally shows strong reducing characters. Interaction between uraniferous fluids and redistributed organic matters has further enhanced uranium precipitation under reducing conditions with high silica activity, which is evident from the presence of globular masses of urano-organic complexes along fractures and intergranular spaces in a quartz clast dominated system. Furthermore, presence of framboidal pyrite indicates that sulphur reducing bacteria might have also played a significant role in the uranium precipitation process as apparent from intimate association of pyrite and uraniferous phases.

The uranium mineralisation in the Palnad sub-basin of the Cuddapah Basin, in general, exhibits several characteristic features of unconformity-related deposits and can be categorised as “stratiform fracture-controlled” sub-type of “Proterozoic unconformity” type uranium mineralisation as per the IAEA new classification scheme (Bruneton et al., 2014). Important characteristics are Neoarchean to Palaeoproterozoic basement and Meso- to Neo-proterozoic cover sediments, pre- and post-depositional tectonic activity leading to development of dilatational structures and providing geothermal gradient, development of ore zones immediately below, along and above an unconformable contact, signatures of intense alteration of both basement and cover sediments, and presence of suitable

reductants in the form of pyrite and organic matter (Jeyagopal et al., 1996; Verma et al., 2009; Gupta et al., 2010, 2012; Ramesh Babu et al., 2012; Thomas et al., 2014). It is pertinent to note that >85% of the uranium-bearing ore bodies are confined to cover sediments in the Palnad sub-basin (Ramesh Babu et al., 2012) and are associated with extensive illitisation of feldspars near the unconformity (Thomas et al., 2014), while at places mineralisation is granite hosted and occur just below the unconformity. However, they exhibit some dissimilarity to the previously known classical unconformity-type uranium deposits of Australia and Canada, now re-classified as “basement-hosted” and “unconformity-contact” sub-types of “Proterozoic unconformity” type uranium mineralisation (Bruneton et al., 2014). The basement rocks in the Canadian and Australian uranium deposits essentially comprise metapelites/graphitic metapelites in addition to granite and gneisses, while the unconformity lies mainly between Palaeoproterozoic metasediments and Mesoproterozoic siliciclastic rocks. In contrast, mineralised zones in the Palnad sub-basin have predominantly Neoarchean basement granitoids unconformably overlain by Neoproterozoic siliciclastic cover sediments. Moreover, the thickness of the cover sediments has also played an important role in the Canadian uranium deposits in Athabasca basin where the average grade of ore increases with increase in thickness of cover sediments (Gandhi, 2007; Jefferson et al., 2007) as exemplified by Rabbit Lake (0.27%  $U_3O_8$  at surface level), Midwest Lake (5.47%  $U_3O_8$  at 210m depth), Cigar Lake (18.3%  $U_3O_8$  at 450m depth) and McArthur River (24.28%  $U_3O_8$  at

>570m depth) deposits. As compared to this, in the Palnad sub-basin the uranium mineralisation is mainly confined to the marginal (peripheral) parts of the basin where the average thickness of cover sediments is <100m. Furthermore, classical unconformity-related uranium deposits are generally associated with development of several metres thick paleosol beneath the unconformity and exhibit strong alteration of basement granitoids to illite, hematite, kaolinite and chlorite (Hoeve and Quirt, 1984), which is practically lacking in Palnad sub-basin except for the strong illitisation of granitoids (Thomas et al. 2014). Probably non-availability of graphitic metapelites in basement, absence of paleosol and felsic volcanics, limited post-depositional reactivation and less thickness of cover sediments might have resulted in development of a comparatively low grade uranium mineralisation in the study area. Nevertheless the delineated uraniferous zones in Banganapalle quartzite with disequilibrium in favour of parents at south of Chenchu colony bears utmost significance as it opens up a potential target horizon with identical geological setup between Chenchu colony and Koppunuru for follow up sub-surface exploration to establish additional uranium resources in the area.

*Acknowledgements:* The authors are thankful to Director, AMD, Hyderabad for granting permission for presentation and publication of the paper in International Conference on “Future Challenges in Earth Sciences for Energy & Mineral Resources (ESEMR-2013)” held at ISM, Dhanbad. We are also thankful to the anonymous reviewer whose constructive suggestions have helped in improving the manuscript.

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