

Role of hydrothermal activity in uranium mineralisation in Palnad Sub-basin, Cuddapah Basin, India



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ABSTRACT

Unconformity related uranium mineralisation occurs in Banganapalle Formation of Palnad Sub-basin, Cuddapah Basin. Several evidences of hydrothermal activity exist in both basement granite and the cover sediments in Koppunuru and Rallavagu Tanda (R.V. Tanda) uranium prospects of Palnad Sub-basin. Pro-fuse development of fracture filled veins consisting of epidote–quartz, chlorite–quartz and quartz is observed at various depths above and below unconformity. Fluid–rock interaction during the formation of these veins has resulted in the alteration of feldspars and mafic minerals of granite and arkosic quartzite into a mineral assemblage consisting of various proportion of illite, chlorite, muscovite and pyrite, with the intensity of alterations being highest near to the unconformity. Pyrite is often associated with illite dominant alteration zone. We infer that circulation of basinal brine through basement granite and cover sediments was responsible for mobilising uranium from granite and its precipitation at favourable locations in cover sediments. Increase in pH of ore fluid due to illitisation and chloritisation of wall-rock together with availability of carbonaceous matter and pyrite as reductant have controlled the localisation of uranium mineralisation in Banganapalle Formation.

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1. Introduction

Unconformity type uranium deposits are the largest known uranium deposits in the world, in which mineralisation is spatially associated with unconformity between Archean or Paleoproterozoic basement and Meso-Neoproterozoic intracratonic basin. In these deposits, uranium has been mobilised from basement granite, gneisses (Alligator Rivers field, Australia) or graphitic metapelite (Athabasca basin, Canada) by oxidised basinal brine and precipitated in basement rocks or cover sediments proximal to unconformity (Dahlkamp, 1993; Cuney and Kyser, 2009; Jefferson et al., 2007).

Several Proterozoic sedimentary basins rest over the Indian Shield among which Cuddapah Basin is the second largest in outcrop area (~44,000 sq. km), next to Vindhyan basin. It is a crescent shaped easterly concave intracratonic basin lying over eastern Dharwar craton, having a length of 450 km along the arcuate eastern margin and an average width of 150 km. Cuddapah Basin consists of sediment dominated succession characterised by

repetitive sequence of quartzite–shale–carbonate attesting to several cycles of fluvial–shallow marine to shelf–slope–basin sedimentation (Chaudhuri et al., 2002). The aggregate thickness of Cuddapah sediments varies between 6 and 12 km (Ramakrishnan and Vaidyanadhan, 2010). Cuddapah Basin hosts three major types of uranium deposits, which in ascending order of their stratigraphic position are (1) fracture controlled U-deposit in Gulcheru Quartzite (Umamaheswar et al., 2001; Zakaulla et al., 2004; Dwivedy et al., 2006), (2) dolostone hosted uranium deposit in Vempalle Formation (Vasudeva Rao et al., 1989; Roy et al., 1990; Roy and Raju, 2012; Jeyagopal et al., 2012), and (3) unconformity related uranium deposits in Srisaillam and Palnad Sub-basins in the northern part of Cuddapah Basin (Shrivastava et al., 1992; Sinha et al., 1995, 1996; Jeyagopal et al., 1996; Nageswara Rao et al., 2005; Verma et al., 2008, 2009; Umamaheswar et al., 2009; Ramesh Babu et al., 2012).

In the Palnad Sub-basin, uranium mineralisation is mainly confined to Banganapalle sediments at multiple depths between 5 and 40 m above unconformity and to a lesser extent in the basement granite (Gupta et al., 2010, 2012; Jeyagopal et al., 2011; Verma et al., 2011; Banerjee et al., 2012). A medium grade small tonnage uranium deposit has been established in Koppunuru prospect

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(Ramesh Babu et al., 2012). We report the results of our study on hydrothermal activity in basement granite and Banganapalle quartzite occurring in Koppunuru and R.V.Tanda prospects of Palnad Sub-basin.

2. Geological setup

Palnad Sub-basin is located in the northeastern part of Cuddapah Basin (Fig. 1). It consists of a thick sequence of arenaceous, argillaceous and carbonate sediments belonging to Kurnool Group which is divided into six Formations viz., Banganapalle, Narji, Auk, Paniam, Koilkuntla and Nandyal Formation (Table 1). Among these, first two formations are well developed in the studied sections, where Banganapalle Formation is represented by 10–173 m thick quartz arenite and intercalated grey shale sequence with basal conglomerate, which is overlain by 100–260 m thick sequence of massive limestone and intercalated calcareous shale sequence of Narji Formation. The thickness of sedimentary column increases from marginal parts (N and NW) to basin interiors (S and SE) and vary from 10 to ~450 m (Banerjee et al., 2012).

Rocks of Banganapalle and Narji Formations generally exhibit sub-horizontal beds with gentle dips (3–10°) towards SE (Saha and Chakraborty, 2003). Studies on provenance and depositional environment of the Banganapalle sediments in SW part of Palnad Sub-basin have indicated their derivation from the adjoining areas exposing granites and Upper Cuddapah sediments (Gupta et al., 2010, 2012). The maximum age of sedimentation of the Kurnool Group is constrained by the kimberlite pipes (dated –1090 Ma, Anil Kumar et al., 1993) which provided detritus to the diamond-bearing conglomerates at the base of the Kurnool Group.

These cover sediments are deposited unconformably over Neoproterozoic to Paleoproterozoic granites and gneisses (2268 ± 32 to 2494 ± 59 Ma; Pandey et al., 1988, 1995; 2659 ± 120 Ma; Vimal

et al., 2012) and a narrow linear Archaean greenstone belt (Nagaraja Rao et al., 1987; Ramam and Murty, 1997; GSI, 2001). Major part of the Palnad Sub-basin is soil covered and hence outcrops are scanty. Basement granite is exposed as inlier near Anupu, west of Chenchu Colony and east of Koppunuru, and along the up-thrown block of WNW–ESE trending Kandlagunta fault which runs from Anupu to west of Macherla. The granite is grey or pink coloured, medium to coarse grained and often exhibits porphyritic texture. These are profusely traversed by aplite and pegmatite dykes formed during the late stage of granite magmatism and by younger mafic dykes. Limited exposures of unconformity sections are present at Alugurajupalle (Fig. 2) and along Musi river to the east of R.V. Tanda (Fig. 3) where unconformity is marked by basal conglomerate of Banganapalle Formation resting over basement granite.

Both basement granite and cover sediments show ample evidence of a later hydrothermal activity during which several generations of fracture filling veins have developed in these litho units associated with alteration of wallrocks. These veins consist of quartz $\pm$ chlorite $\pm$ epidote, with a spatial variation in mineral assemblage; quartz is ubiquitous in all the veins, chlorite is common in veins occurring in granite and rarely in cover sediments, while epidote bearing veins are confined to granite away from unconformity. The granite and arkosic quartzite are extensively illitised up to few m on either side of unconformity. The Banganapalle Formation is main pay horizon for uranium in Palnad Sub-basin, especially close to the unconformity contact with the granitic basement in Hill Colony, Koppunuru, Chenchu Colony and Dwarakapuri areas (Jeyagopal et al., 1996; Ramesh Babu et al., 2012). In these prospects, U-mineralisation is confined to basal grit/conglomerate horizon while some mineralised bands are also recorded in upper quartzite unit intercalated with carbonaceous shale. In all these instances organic matter and pyrite

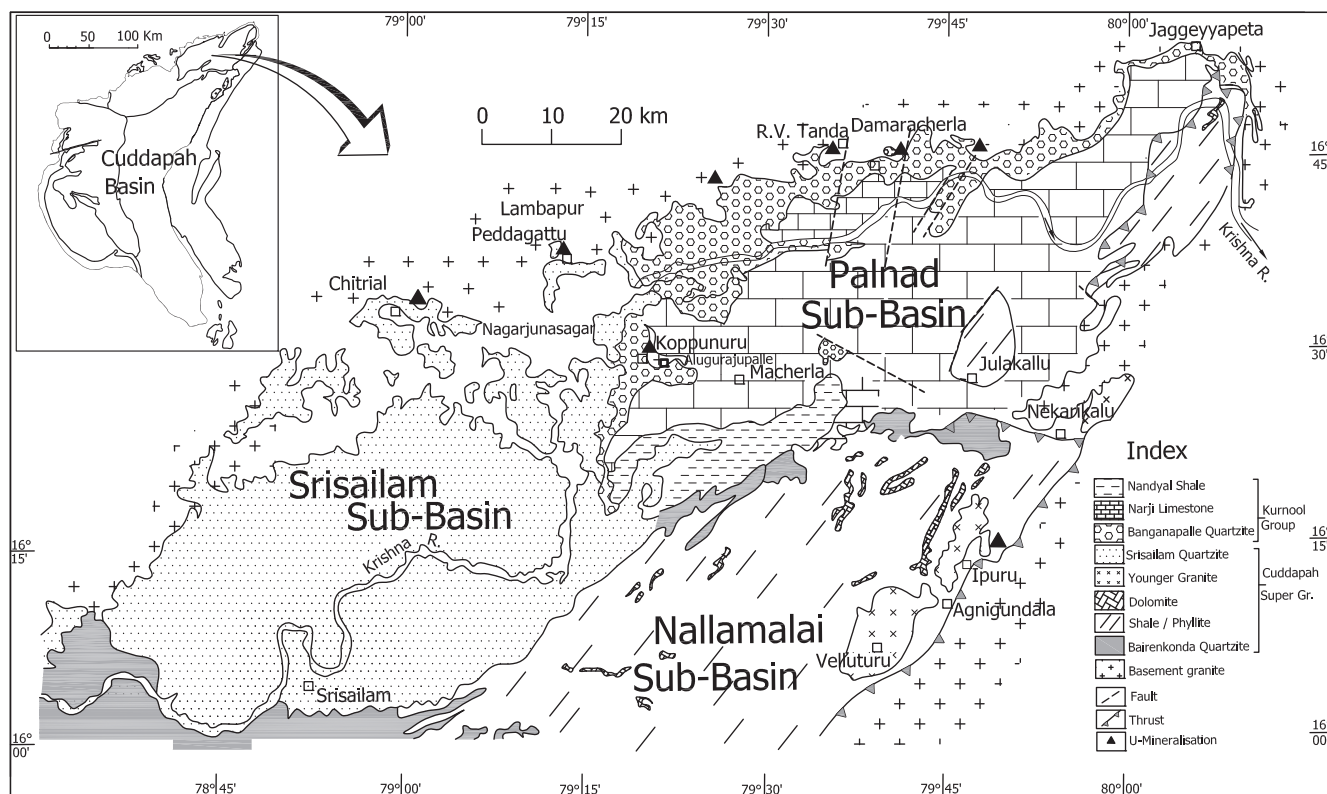
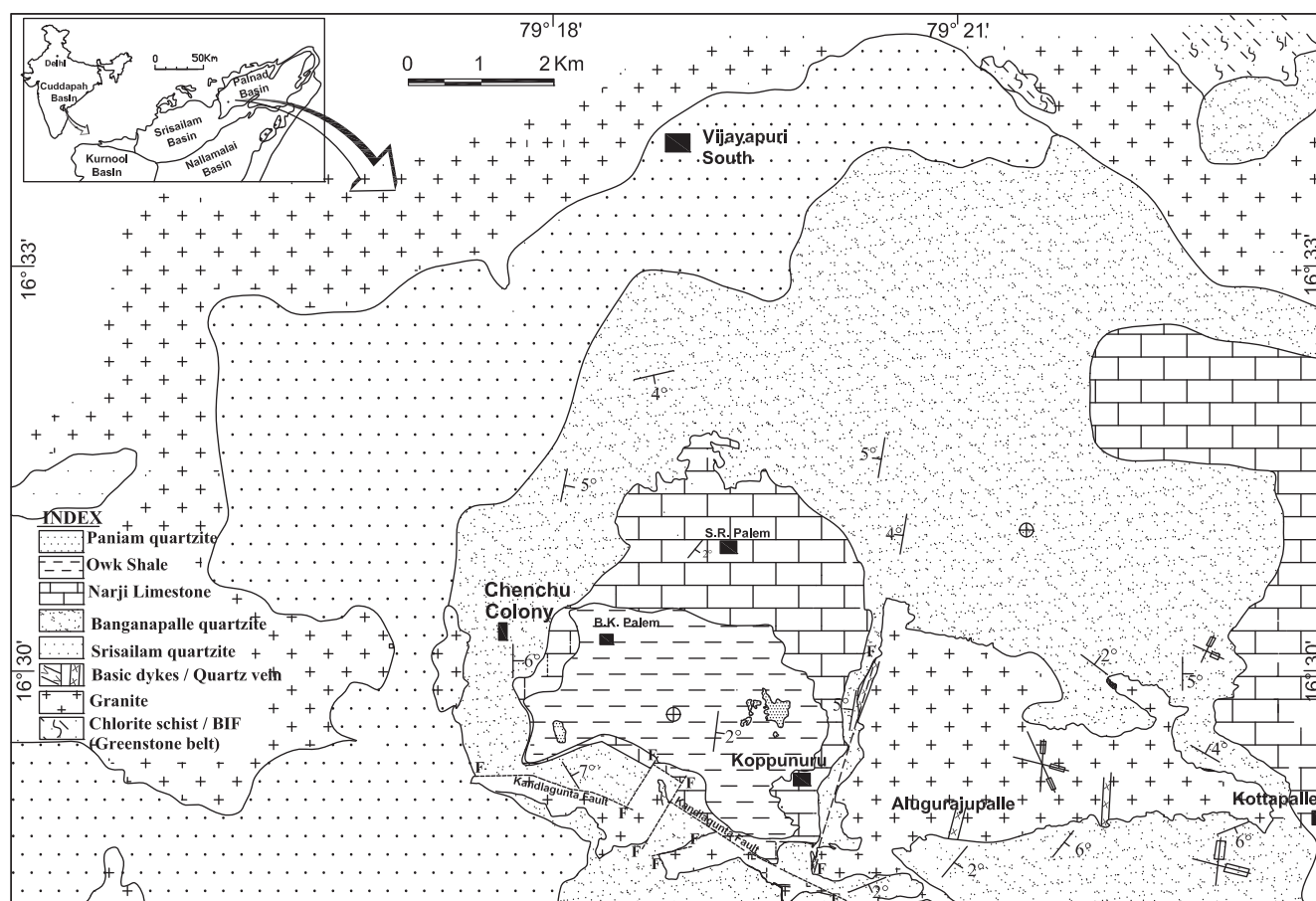


Fig. 1. Geological map of northern part of Cuddapah Basin showing disposition of Srisailem and Palnad Sub-basins (after Nagaraja Rao et al., 1987) and location of different uranium deposits and occurrences (after Ramesh Babu et al., 2012).

Table 1

Stratigraphic succession of Palnad Sub-basin, Cuddapah Basin (after Nagaraja Rao et al., 1987).

Supergroup/Group/Subgroup	Formation	Thickness (m)
Kurnool Group	Kundair Subgroup	
	Nandyal Shale	50–100
	Koilkuntla Limestone	15–50
	Paniam Quartzite	10–35
Paraconformity		
	Jammalamadgu Subgroup	
	Auk (Owk) Shale	10–15
	Narji Limestone	100–260 ^a
	Banganapalle Quartzite	10–173 ^a
Nonconformity		
Archaean and Dharwar	Intrusive grey, medium grained, chloritised biotite granite Gneisses/greenstones	

^a Revised thickness based on borehole data (after Banerjee et al., 2012).**Fig. 2.** Geological map of Koppunuru prospect, western part of Palnad Sub-basin (after Gupta et al., 2012).

commonly occur in mineralised horizons, which suggest that they might have played significant role as reducing agent in fixation of the uraniferous lodes (Jeyagopal et al., 2011). In addition, sporadic radioactive anomalies are also present in granite and mafic dykes adjacent to faulted contact between basement and cover sediment in northern part of Palnad Sub-basin (Nageswara Rao et al., 2005; Ramesh Babu et al., 2012). A cross section showing distribution of uranium deposits in Palnad Sub-basin is given in Fig. 4.

3. Sampling and analytical techniques

Samples for present study were collected from outcrops and coring boreholes drilled by Atomic Minerals Directorate for Exploration and Research (AMD), Govt. of India. Outcrop samples of

granite and quartzite were collected from Anupu, Koppunuru, Althugurajupalle and along Musi river near R.V. Tanda.

Sub-surface core samples of granite ($n = 64$) and cover sediments ($n = 30$) were collected from 3 vertical boreholes of Koppunuru prospect (KPU-141c, 161c and 162c) and 1 vertical borehole of R.V. Tanda prospect (RVT-114). Unconformity was recorded in KPU-141c, 161c, 162c and RVT-114 at 127.30, 197.10, 78.20 and 68.50 m depths, respectively. Uranium mineralisation ($>0.020\%$ U_3O_8) was recorded proximal to unconformity in gritty quartzite along boreholes KPU-141c (between 106.15 and 106.95 m depth) and KPU-161c (117.6–118.05 m and 195.25–195.45 m depths), and granites in boreholes KPU-141c (127.35–128.05 m and 134.75–137.15 m depths) and RVT-114 (76.30–77.20 m depth). No uranium mineralisation was recorded in borehole KPU-162c. Granite samples in these boreholes were available up to 21.45 m below unconformity.

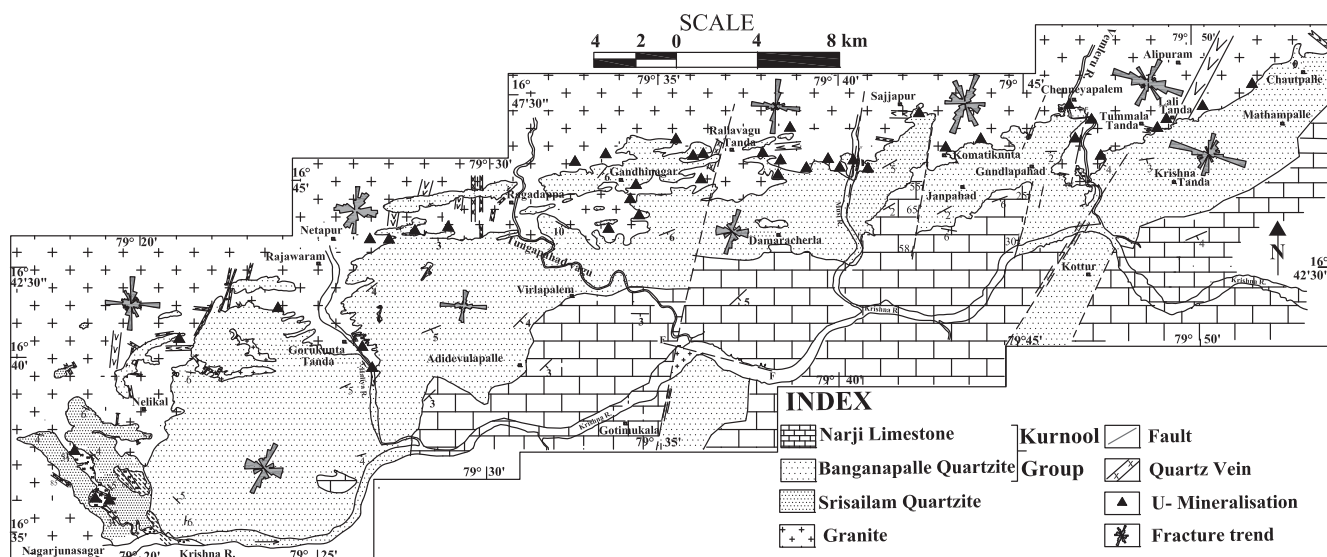


Fig. 3. Geological map of R.V. Tanda prospect, northern part of Palnad Sub-basin (after Ramesh Babu et al., 2012).

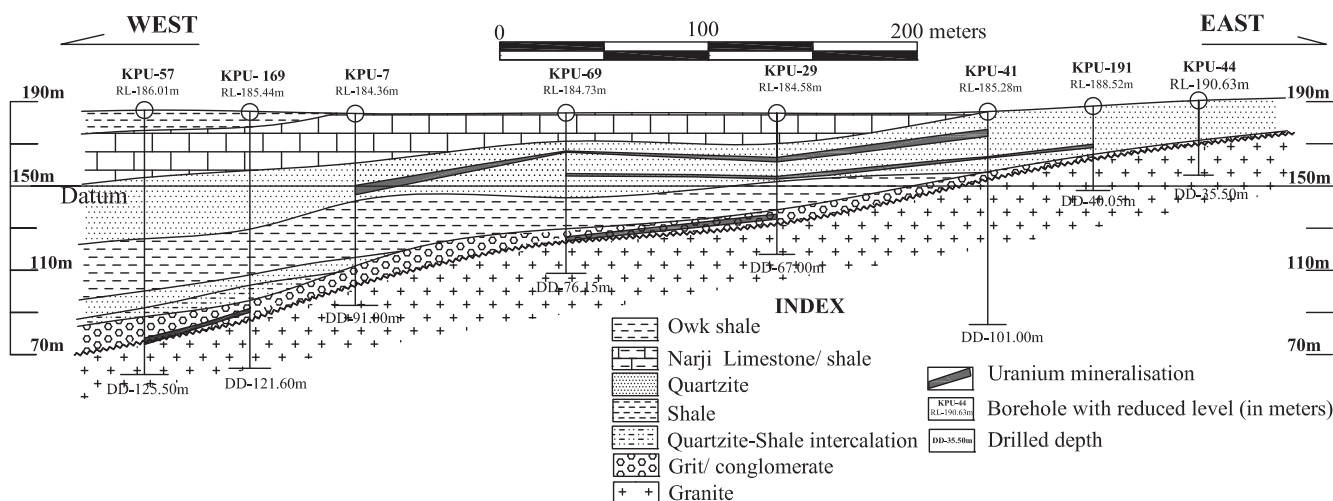


Fig. 4. Borehole correlation section of uranium deposit in Koppunuru prospect (Ramesh Babu et al., 2012).

Selected samples were studied in detail by optical microscopy, supplemented by X-ray diffraction, and fluid inclusion analysis. Optical microscopy and fluid inclusion analysis were carried out using Olympus BX51P microscope, Linkam THMSG600 heating-freezing stage equipped with QICAM firewire camera and supported by Linksys32 software. X-ray diffraction analysis was done on a PANalytical XPert Pro system supported by XPert Highscore and ICDD PDF4. These analyses were carried out at Department of Earth Sciences, Pondicherry University.

4. Petrography

The granite is grey or pink coloured, medium to coarse grained and often exhibits porphyritic texture. It consists of quartz, microcline, sodic plagioclase along with minor amount of biotite, hornblende, zircon and monazite. Evidence of cataclastic deformation is common in granite close to unconformity.

Banganapalle Formation consists of quartz arenite which is pebbly in basal part, intercalated with carbonaceous shale. The quartz arenite consists of well indurated, moderate to well sorted,

subrounded to rounded clasts of quartz and minor amount of feldspars bound by silica cement and matrix. Pyrite, glauconite and anatase are the main accessory minerals. Hydrothermal activity in various lithounits is manifested by development of fracture filling veins and associated wallrock alteration. The veins in deeper part of granite (>70 m below unconformity) are either monomineralic, composed of quartz, epidote, chlorite, or contain various proportions of these minerals (Fig. 5). In the upper levels of granite, veins are dominantly composed of quartz often associated with chlorite, while illite and pyrite are present in these veins near to unconformity. Veins hosted by cover sediments are also quartz rich and occasionally contain chlorite (Fig. 6). The veins have lateral and depth continuity up to few m. Thickness of these veins ranges from few micron to 4.2 m, thicker veins localised in granite near to unconformity (Fig. 7).

Hydrothermal alteration of granite and quartz arenite has resulted in replacement of feldspars by chlorite, illite and muscovite with highest intensity of alteration near to unconformity. Chloritisation is common in deeper part of granite with chlorite forming rim around feldspars. XRD analysis shows that the chlorite from vein as well as altered wall rock is clinocllore, mostly ferroan



Fig. 5. Granite cut by multiple generations of hydrothermal veins at Anupu.



Fig. 6. Quartz veins in quartzite few m above unconformity, near Alugurajupalle.



Fig. 7. Quartz reef hosted by granite near Alugurajupalle.

clinochlore variety. Illitisation is the predominant alteration near to unconformity often accompanied by the precipitation of pyrite in intergranular spaces or along thin fractures (Fig. 8). Pyrite occurs as discrete euhedral crystals and as colloform aggregates which sometimes contain inclusions of carbonaceous matter (Figs. 9 and 10). In some instances illite and pyrite have formed simultaneously in veins and elsewhere illite occupies the corroded boundary of pyrite (Fig. 11). Muscovite occurs in minor amount along

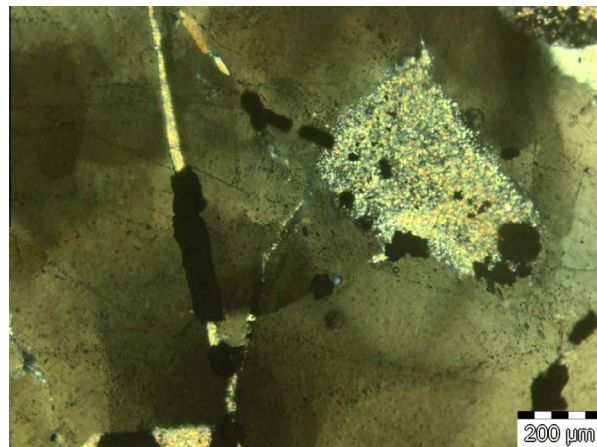


Fig. 8. Thin veins containing illite and pyrite in quartz arenite. Transmitted light, crossed polars.

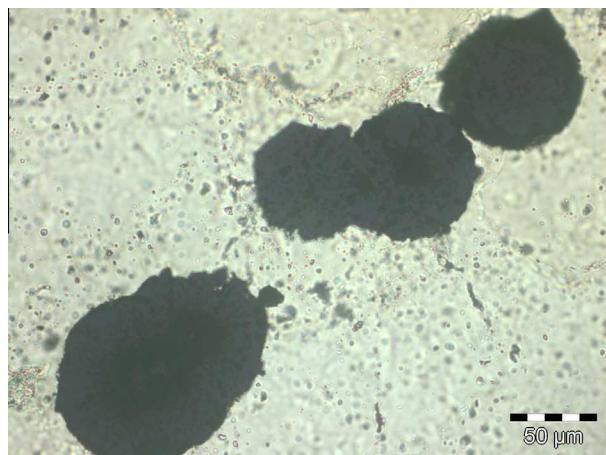


Fig. 9. Quartz arenite containing colloform pyrite with inclusions of carbonaceous matter. Transmitted plane light.

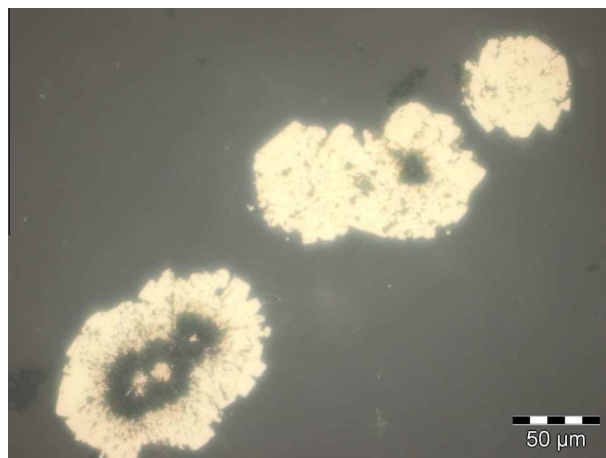


Fig. 10. Same as Fig. 9, in reflected plane light.

with chlorite or illite (Fig. 12). In the non-mineralised borehole KPU-162c and poorly mineralised RVT-114 the intensity of hydrothermal alteration is significantly less compared to other boreholes.

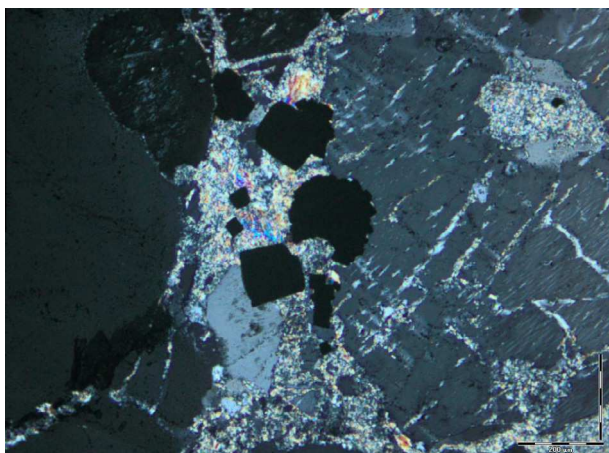


Fig. 11. Introduction of pyrite and illite along intergranular spaces and fractures in granite. Transmitted light, crossed polars.

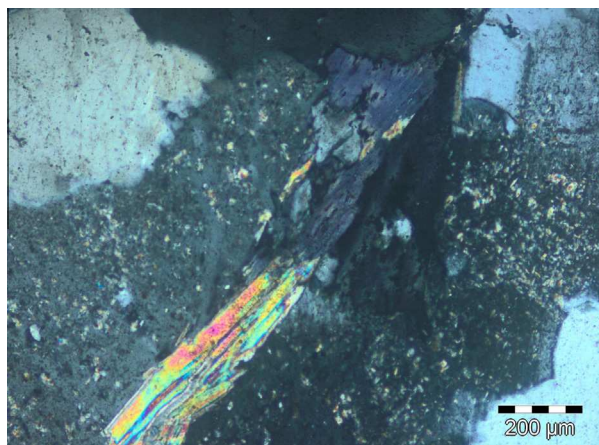


Fig. 12. Chlorite (violet) and muscovite replace feldspars in granite. Transmitted light, crossed polars.

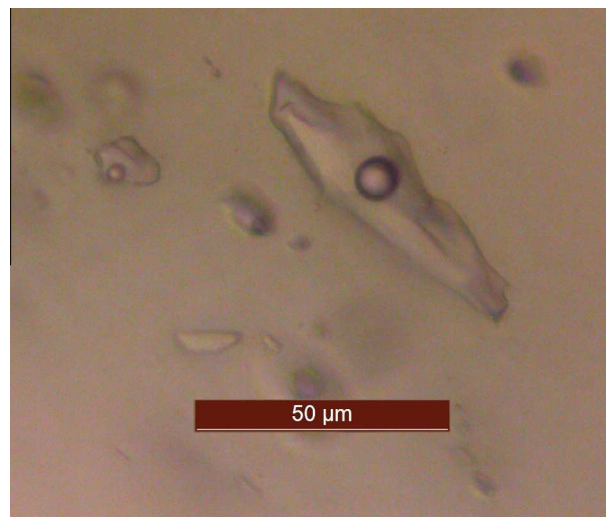


Fig. 13. Fluid inclusions in quartz: aqueous biphasic (Type Ia).

5. Fluid inclusion studies

Doubly polished wafers (0.25–0.35 mm thick) were prepared for ten samples of quartz from quartz veins occurring at various depths above and below unconformity, including 9 from boreholes and 1 from outcrop (Table 2). Three types of aqueous fluid inclusions (aqueous monophase, biphasic and polyphase) (Figs. 13–15) were observed in these samples. A brief description of petrography of these three types of fluid inclusions is given below.

5.1. Type Ia & b: aqueous biphasic

These inclusions are oval, rectangular or irregular shaped, up to 50 μm in size, have a liquid and a vapour phase with degree of fill in the range of 0.80–0.95. Type Ia inclusions are larger, distributed randomly or parallel to crystal growth zones and these are

Table 2

Microthermometric data of primary aqueous biphasic inclusions in vein quartz from outcrop and boreholes of uranium prospects in Palnad Sub-basin.

Outcrop sample/Bore Hole No.	Depth w.r.t. UC in m ^a	n	Size (μm)	Shape	T_{eut} (°C)	T_{m-ice} (°C)	T_h (°C)	Salinity (wt%) NaCl Eqvt.
P3b1	–2	17	4–12	Oval, rectangular, irregular	–21.2 to –24.5	–1.9 to –6.9	123–137.3	3.2–10.4
KPU 141c	–11	11	6–12	Oval, rectangular, irregular	–32.1 to –37.7	–0.1 to –3.2	140–172	0.2–5.3
KPU 162c	+0.2	6	8–12	Oval, irregular	–23.1 to –23.9	–1.1 to –10.2	109.5–137.3	1.9–14.1
	–0.2	13	2–10	Oval, irregular	–22.7 to –32.2	–3.7 to –9.7	102.1–143	6.0–13.6
KPU 161c	+76	18	10–50	Oval, rectangular, irregular	–21.4 to –24.1	–0.3 to –4.9	114.5–163.9	0.5–7.7
	–0.5	12	5–10	Oval, rectangular, irregular	–22.1 to –24.9	–4.9 to –8.3	115–171.1	7.7–12.0
	–1.3	12	4–10	Oval, irregular	–22.5 to –34.3	–2.3 to –6.4	132–218	3.9–9.7
	–5.3	9	4–8	Oval, rectangular, irregular	–32.3 to –33.9	–2.9 to –5.5	126.9–163	4.8–8.6
	–21	12	6–30	Oval, rectangular, irregular	–32.3 to –42.3	–2.3 to –8	112.3–226.4	3.9–11.7
RVT 114	–10	11	8–10	Oval, rectangular, irregular	–49.8 to –53	–11.3 to –26.1	102.2–133.1	15.3–>23.2

^a + and – refer to depth of sample above and below unconformity respectively.

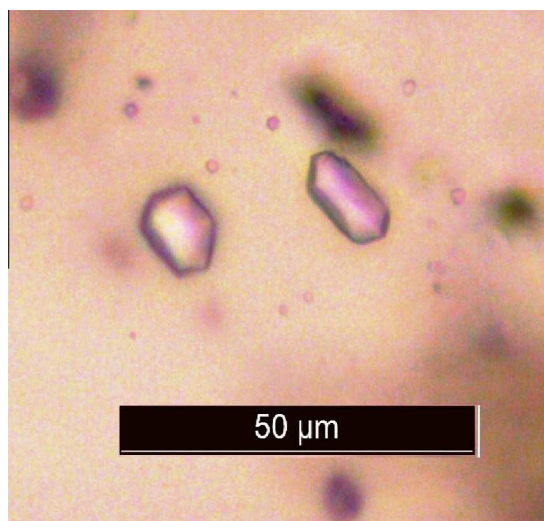


Fig. 14. Fluid inclusions in quartz: aqueous monophasic (Type II).

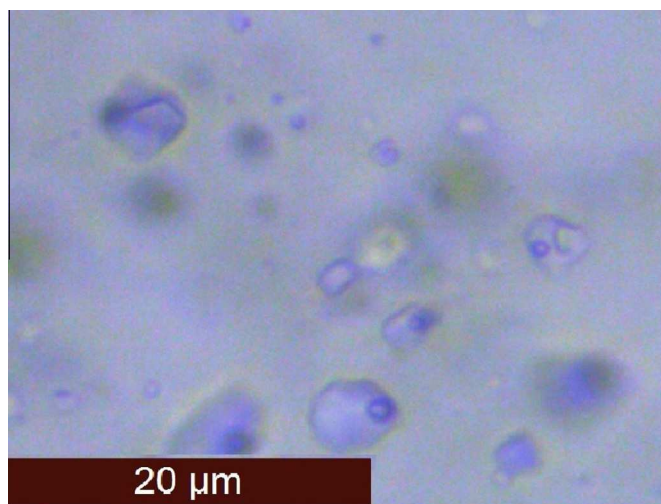


Fig. 16. Coexisting Type Ia, II and III inclusions in quartz.

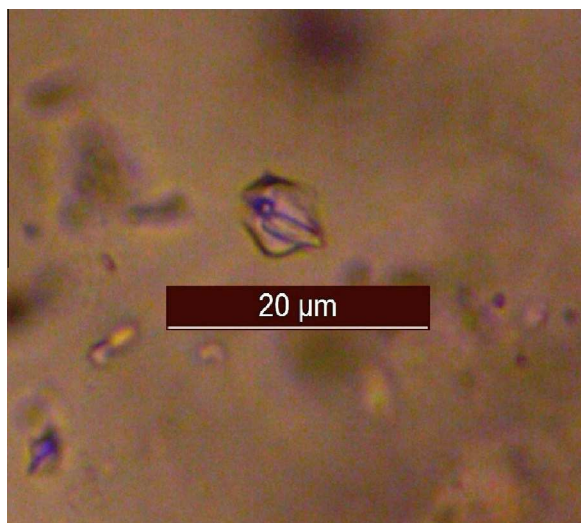


Fig. 15. Fluid inclusions in quartz: aqueous polyphasic (Type III).

recognised as primary inclusions by the criteria of Roedder (1984) and Shepherd et al. (1985). Type Ib inclusions occur as arrays along healed fractures, and these are secondary.

5.2. Type II: aqueous monophasic

These inclusions are mostly rounded whereas some are negative crystal shaped, contain only a liquid phase, and up to 12 μm in size. These inclusions occur either as arrays along healed fractures or in proximity to Type Ia inclusions; the former are clearly secondary inclusions, while the latter may have formed by leakage of Type Ia inclusions.

5.3. Type III: aqueous polyphasic

These inclusions are elliptical to rounded in shape, 3–10 μm in size and dominantly contain a liquid along with a solid and relatively small vapour phase. These inclusions are observed only in 4 of the studied samples which are within 2 m from unconformity.

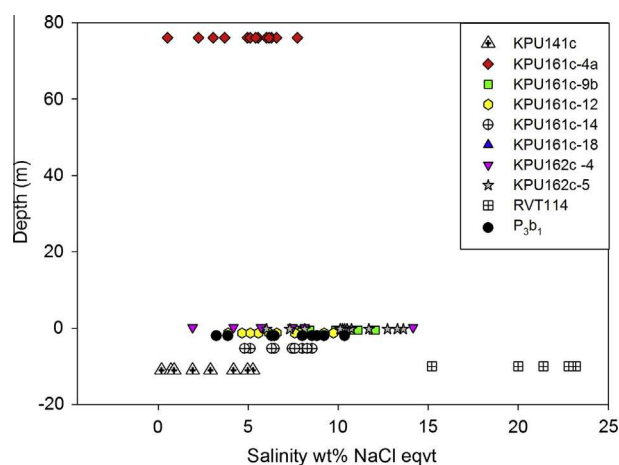


Fig. 17. Salinity versus depth (+ = above unconformity, – = below unconformity) plot of primary aqueous biphasic inclusions in quartz.

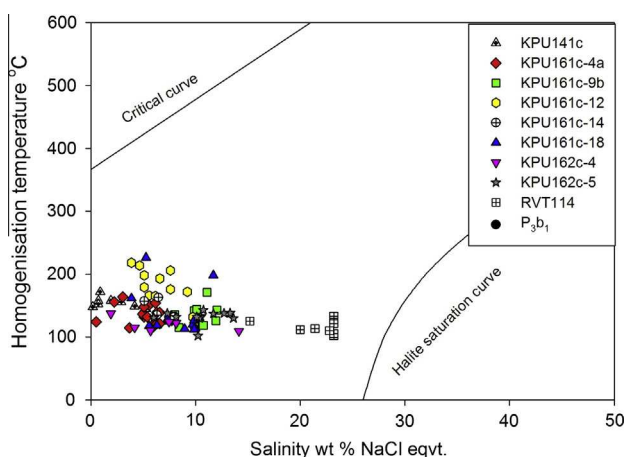


Fig. 18. Salinity versus T_h plot (Shepherd et al., 1985) of primary aqueous biphasic inclusions in quartz.

In some instances these inclusions are found near to Type Ia and II inclusions (Fig. 16). These inclusions may also have formed by leakage of Type Ia inclusions.

5.4. Type Ia inclusions are abundant in all the samples while Type II, Ib and III inclusions are less common in this order

Microthermometric experiments were carried out by standard techniques (Roedder, 1984; Goldstein and Reynolds, 1994) on the primary aqueous biphasic inclusions (Type Ia) which are larger than 4 μm . Eutectic temperature (T_{eut}) and final ice melting temperature ($T_{\text{m-ice}}$) were observed after complete freezing of fluid inclusions to -110°C followed by warming at $3-5^\circ\text{C}/\text{min}$, and T_{h} was observed by heating the inclusions at the rate of $5^\circ\text{C}/\text{min}$. T_{eut} of fluid inclusions were used to infer the major chemical components present in aqueous solution based on the values reported for pure systems (Crawford, 1981; Shepherd et al., 1985; Spencer et al., 1990; Davis et al., 1990), and salinity was calculated from $T_{\text{m-ice}}$ (Bodnar, 1993; Bodnar and Vityk, 1994).

Following variations are observed in major components, salinity and T_{h} of Type Ia inclusions present in samples from various depths above and below unconformity. Quartz veins hosted by quartzite at 76.0 and 0.2 m above unconformity show T_{eut} in the range of -21.0 to -24.1°C which corresponds to NaCl solutions. Salinity of these inclusions ranges from 0.5 to 14.1 wt% NaCl equivalent and T_{h} (L + V $\rightarrow$ L) from 81.7 to 163.9°C . Quartz veins from granite occurring at 0.2–5.3, and 11.0–21.0 m below unconformity show T_{eut} in the range of -21.2 to -34.3°C and -32.1 to -42.3°C respectively indicating that the composition of aqueous solution is NaCl–KCl dominant near to unconformity and MgCl_2 dominant at deeper level. Salinity of inclusions in these granite hosted veins varies widely at every depth in the range of 0.2–13.6 wt% NaCl equivalent. T_{h} (L + V $\rightarrow$ L) of these inclusions varies from 102.1 to 226.4°C with $T_{\text{h-max}}$ observed at deeper level. Quartz vein from R.V. Tanda shows T_{eut} of -49.8 to -53°C indicating the presence of CaCl_2 in aqueous solution with salinity 15.3 to >23.2 wt% NaCl equivalent and T_{h} (L + V $\rightarrow$ L) 102.2 to 133.1°C .

6. Discussion and conclusion

In Palnad Sub-basin, hydrothermal activity has resulted in uranium mineralisation at three different horizons of Banganapalle quartzite above the unconformity and relatively less mineralisation in basement granite. However, hydrothermal veins and associated alteration are observed both in cover sediments and basement granite over a wide range of depth on either side of the unconformity.

There are multiple generations of hydrothermal veins consisting of identical mineral assemblage at every depth in basement granite and cover sediments while there is a spatial variation in vein mineral assemblage characterised by the presence of epidote in deeper level of granite, chlorite commonly in granite and less in cover sediments, and quartz at various depths in granite and cover sediments. Based on available evidence we interpret that these veins developed during a prolonged episode of hydrothermal activity straddling across the unconformity with a spatial variation in mineral assemblage of these veins, particularly in the relative proportion of quartz, chlorite and epidote.

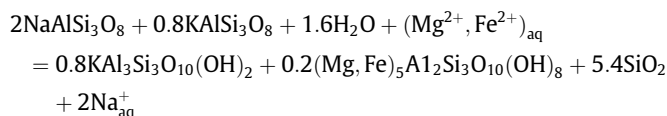
Basement granite and feldspathic quartzite of cover sediment are extensively altered close to unconformity while the degree of alteration diminishes away from the unconformity. Illitisation of feldspars is the predominant alteration in both these lithounits near to the unconformity, accompanied by development of muscovite and chlorite to lesser extent. In illitised zones pyrite occurs as colloform aggregates and discrete euhedral crystals often containing inclusions of carbonaceous matter.

Fluid inclusion study of hydrothermal quartz reveals the presence of primary aqueous biphasic inclusions having a wide range of salinity near to the unconformity (1.9 to >23.2 wt% NaCl

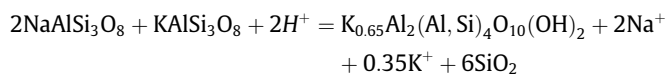
equivalent) and relatively narrow range (0.2–11.7) away from the unconformity (Fig. 17). The composition of these aqueous fluids varies with depth: NaCl–KCl dominant in veins from cover sediments and granite near to unconformity and MgCl_2 dominant with increasing depth below unconformity. Fluid inclusions in quartz vein from R.V. Tanda show the presence of CaCl_2 . T_{h} (L + V $\rightarrow$ L) of Type Ia fluid inclusions in all the studied samples ranges from 81.7 to 226.4°C with higher values observed at deeper levels. The maximum cumulative thickness of cover sediments reported from Palnad Sub-basin is 633 m and the present thickness of cover sediments in Koppunuru and R.V. Tanda prospects ranges from 60 to 200 m. It is therefore expected that the studied vein samples would have formed at less than 650 m depth at pressure less than 200 bar. Hence pressure correction on T_{h} of Type Ia inclusions is negligible (Potter, 1977) and therefore T_{h} values may be considered to represent temperature of quartz precipitation in various hydrothermal veins.

Salinity versus homogenisation temperature plots of Type Ia inclusions in vein quartz from various depths (Fig. 18) shows a relatively wide range of salinity and a narrow range of T_{h} which could have resulted from mixing of fluids of various salinities during hydrothermal activity. Low to moderate salinity aqueous fluid inclusions are interpreted to be the basinal brine which circulated through the cover sediments and granite, while the hypersaline inclusions are the compositionally evolved brines formed due to hydrothermal alteration.

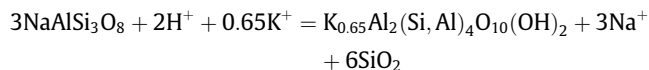
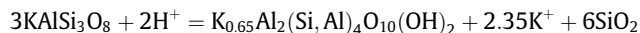
Development of muscovite and chlorite along the grain boundary of feldspars can be explained by reaction of feldspars with aqueous fluid containing Mg^{2+} (Giggenbach, 1988).



Illitisation is the result of fluid–rock interaction which involves exchange of H^+ from fluid and Na^+ , K^+ from feldspars of wallrock, which leads to increase in pH and salinity of the fluid as shown by following reaction (Giggenbach, 1997).



Alternately, either of the feldspars could have altered to illite by the following reactions.



The above alteration reactions demonstrate that acidic hydrothermal fluid has circulated through basement granite and cover sediments. Such fluid could have leached uranium from the granite. Granite in Koppunuru area is reported to contain high intrinsic U ($<5-39$ ppm with mean value of 19 ppm), moderate Th content ($<5-43$ ppm, mean 8 ppm) and average U/Th ratio of 3.8 suggesting its fertile nature (Ramesh Babu et al. 2012). The increase in pH following the above reactions would have influenced precipitation of uranium. However, non-availability of reductant in illitised granite near to unconformity might be responsible for insignificant uranium mineralisation in granite. We therefore infer that uranium mineralisation in cover sediments of Palnad Sub-basin resulted from increase in pH of hydrothermal fluid following illitisation of arkosic sandstone and availability of carbonaceous matter as reductant.

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