



SRISAILAM AND PALNAD SUB-BASINS: POTENTIAL GEOLOGICAL DOMAINS FOR UNCONFORMITY-RELATED URANIUM MINERALISATION IN INDIA

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Abstract

The intracratonic Cuddapah Basin is the second largest Purana basins in Peninsular India and its northern part has shown immense potential of uranium mineralisation, especially unconformity-related, with deposits established in the marginal parts of Srisailam and Palnad Sub-basins, Nalgonda and Guntur districts, Andhra Pradesh. These sub-basins expose thick sedimentary columns comprising arenaceous, argillaceous and calcareous sediments of Meso- to Neoproterozoic age and are deposited predominantly over Neoarchaeon to Palaeoproterozoic basement granitoids and greenstone belt of Archaean age. Signatures of substantial basement and post-depositional reactivations are quite apparent in the area represented by multiple faults, fractures and mafic and felsic intrusives. Such geological domains provide spatial and temporal favourability for uranium metallogeny, especially when basement granitoids are fertile. The uranium mineralisation is mainly localised along fracture zones proximal to basement-cover sediment unconformity and occur as elongated pods, fine veins and cavity and grain boundary fillings. Mineralised zones are invariably associated with significant alteration features like illitisation, chloritisation and kaolinization. Primary uranium ore minerals viz. pitchblende, uraninite and coffinite are found generally associated with sulphides and organic matter. However, there is marginal difference in mineralisation pattern in these sub-basins as uranium is mainly hosted by granitoids just below the unconformity in Srisailam Sub-basin while it is dominantly associated with cover sediments in Palnad Sub-basin. Recent integrated surface and sub-surface studies have also indicated uranium potential in deeper parts of these sub-basins.

Keywords: Uranium, Unconformity-related mineralisation, Srisailam and Palnad sub-basins, Nalgonda and Guntur districts, Andhra Pradesh

INTRODUCTION

Unconformity-type uranium deposits continue to be one of the major uranium resources since the early 1970s (Sibbald et al., 1976; Hoeve and Sibbald, 1978; Hoeve et al., 1980; IAEA, 2009) and account for nearly one-third of total world resources (OECD/NEA, 2009; WNA, 2010). These deposits are temporally related to mainly Palaeo- to Mesoproterozoic unconformity and ore zones

spatially occur immediately below, along and above an unconformable contact between intensively altered crystalline basement (mainly metasediments± graphite) and thick pile of overlying clastic sediments (IAEA, 2009). Canada and Australia are the storehouse of unconformity-related uranium deposits and include some of the largest and richest uranium deposits viz., Athabasca Basin in Canada (Cigar Lake, Key Lake and McArthur River) and Pine

Creek Geosyncline in Australia (Jabiluka, Ranger, Nabarlek, Koongarra) (Needham et al., 1988; Sibbald, 1988; Ruzicka, 1996; Thomas et al., 2000; Gandhi, 2007; Jefferson et al., 2007).

In Peninsular India, Mesoproterozoic Cuddapah Basin exposes highly favourable lithostructural setup for unconformity-related uranium mineralisation, especially in the northern part (Fig. 1). This is evident from medium grade and small to medium tonnage uranium deposits established at Lambapur, Peddagattu and Chitrial in Srisailam Sub-basin and Koppunuru in Palnad Sub-basin (Fig. 2) (Shrivastava et al., 1992; Dwivedy, 1995; Sinha et al., 1995, 1996; Jeyagopal et al., 1996, 2011; Banerjee, 2005; Nageswara Rao et al., 2005; Verma et al., 2008, 2009, 2011; Umamaheswar et al., 2009; Gupta et al., 2010, 2012). However, these uranium deposits marginally differ from the classical unconformity-type deposits of Canada and Australia as the basement rock here is mainly represented by Neoarchaeon granite gneisses and Paleoproterozoic granitoids as compared to graphitic metapelites elsewhere. The present paper deals with uranium metallogeny in Srisailam and Palnad sub-basins with special emphasis on the characterisation of unconformity-related uranium deposits contained in them.

GEOLOGICAL SETTING

Regionally, the crescent shaped intracratonic Cuddapah Basin (second largest Purana basins) occupies an area of ~44,500 sq km and exposes 6 to 12 km thick Meso- to Neoproterozoic volcano-sedimentary sequence belonging to Cuddapah Supergroup and Kurnool Group (Nagaraja Rao et al., 1987; Saha and Tripathy, 2012) (Fig. 1). The basement predominantly consists of Archaeon gneisses with slivers of older metamorphic rocks and younger granite intrusives of Neoarchaeon to

Paleoproterozoic age. These 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. The western half of the Cuddapah Basin is undeformed and sediments have normal depositional contact with the crystalline basement, while those in the eastern half are tightly folded (Nallamalai fold belt; NFB) and drape around either basement inliers like Iswarakuppam dome or intrusive granites viz., Vellataru and Ippuru granites. The contact between NFB and undeformed western sub-basins are demarcated by a prominent lineament (nearly N–S trending fault) called the ‘Rudravaram Line’. The eastern margin has thrust contact, where Archaeon gneisses and Dharwar metasediments are thrust over Nallamalai sediments and further in the north Nallamalais are thrust over Narji Formation of Kurnool Group. The Cuddapah sediments are predominantly arenaceous to argillaceous with subordinate calcareous units and are well developed in Papaghni, Nallamalai and Srisailam sub-basins (Fig. 1). These are overlain by Neoproterozoic Kurnool sediments dominated by carbonate facies with subordinate arenaceous and argillaceous facies and are well developed in Kurnool and Palnad sub-basins. Regional lithostratigraphic succession of Cuddapah Basin is given in Table 1.

Srisailam and Palnad sub-basins, important geological domains for unconformity - related uranium mineralisation, are located in the northern part of the Cuddapah Basin covering parts of Nalgonda and Guntur districts, Andhra Pradesh. In the NE part of the Cuddapah Basin, a 25 km long NW–SE trending older schist belt around Peddavoora forms basement high and marks the boundary between Srisailam and Palnad sub-basins (Fig. 2). Brief lithostructural details of these sub-basins are given below.

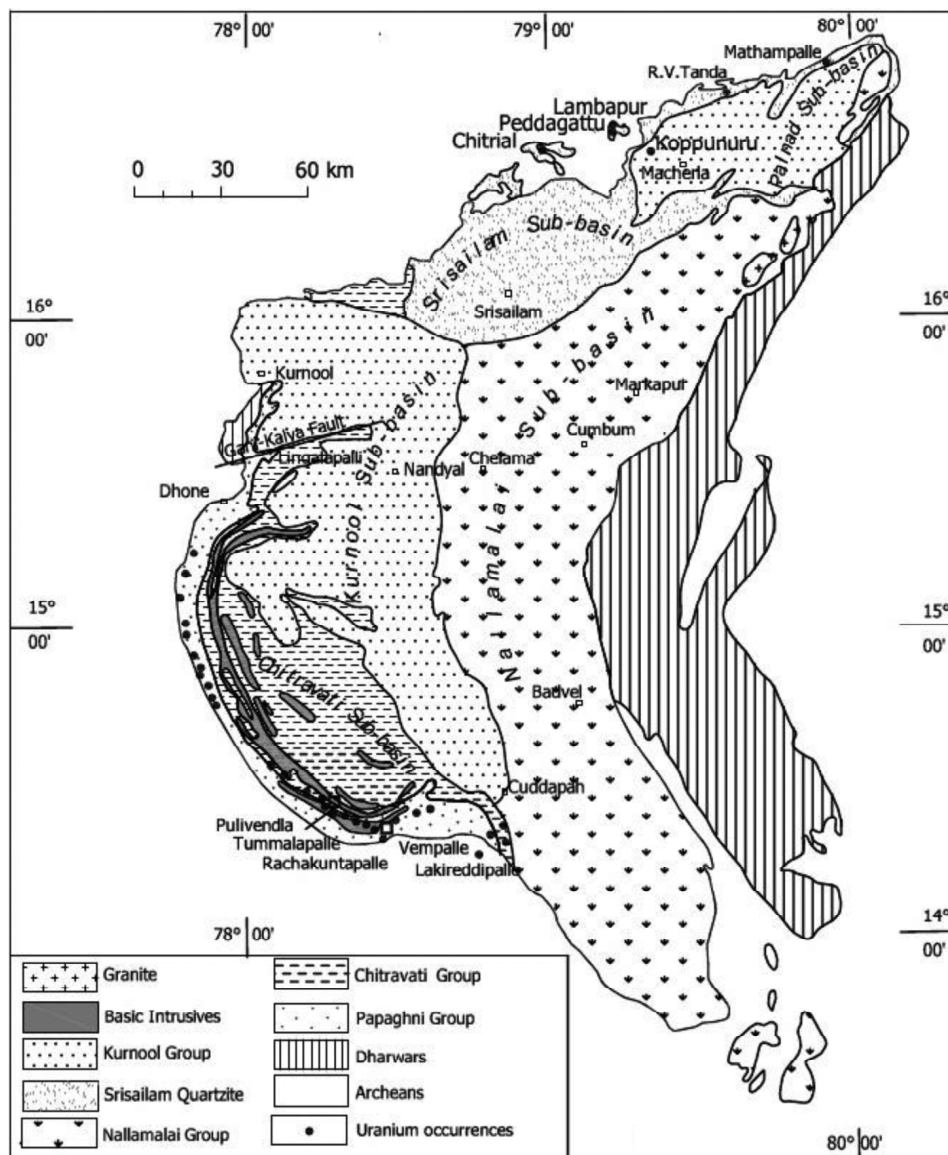


Fig. 1. Geological map of Cuddapah Basin showing uranium occurrences

SRISAILAM SUB-BASIN

This sub-basin occupies nearly 3000 sq km area in the northwestern part of the Cuddapah Basin and exposes Srisailam Formation, the youngest member of Cuddapah Supergroup. The Srisailam Formation is mainly arenaceous with minor argillaceous bands/ intercalations and shows sub-horizontal dips towards southeast. It attains a maximum

thickness of 419m towards eastern and central parts of the sub-basin (Banerjee et al., 2012). On the northwestern margin, it rests non-conformably over Archaean gneisses (2638 ± 94 Ma to 2659 ± 120 Ma; Vimal et al., 2012) and younger granites (Mahboobnagar granite: 2268 ± 32 Ma to 2482 ± 70 Ma; Pandey et al., 1988). They unconformably overlie Nallamalai Group of rocks on the southern and

Table 1. Regional lithostratigraphic succession of Cuddapah Basin and Kurnool Sub-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	100-200
		Banganapalle Quartzite	10-50
~~~~~ Unconformity ~~~~~			
Cuddapah Supergroup	Srisailem Quartzite		300
	~~~~~ Unconformity ~~~~~		
	Nallamalai Group	Cumbum Formation	2000
		Bairenkonda Quartzite	1500-4000
	~~~~~ Angular Unconformity ~~~~~		
	Gandikota Quartzite		300
	Chitravati Group	Tadpatri Formation	4600
		Pulivendla Quartzite	1-75
	~~~~~ Disconformity ~~~~~		
Papaghni Group	Vempalle Limestone	1900	
	Gulcheru Quartzite	28-210	
~~~~~ Nonconformity ~~~~~			
Archaean and Dharwars		Intrusive grey, medium grained, chloritised biotite granite Gneisses/greenstones	

eastern margins of the sub-basin. The northwestern fringes of Srisailem Sub-basin exhibit highly dissected topography as apparent from numerous isolated flat topped hills rising between 100m to 150m above the ground level and forming outliers in granitic country viz., Lambapur, Peddagattu, Chitrial, Amrabad and Akkavaram (Fig. 2).

The basement rocks are mainly represented by grey, coarse grained biotite granites, which are at places highly epidotised and pyritized. These are profusely traversed by dolerite dykes exhibiting NNW–SSE, NW–SE, E–W and NNE–SSW trends, and quartz and pegmatitic veins. These granitoids are essentially composed of quartz, orthoclase,

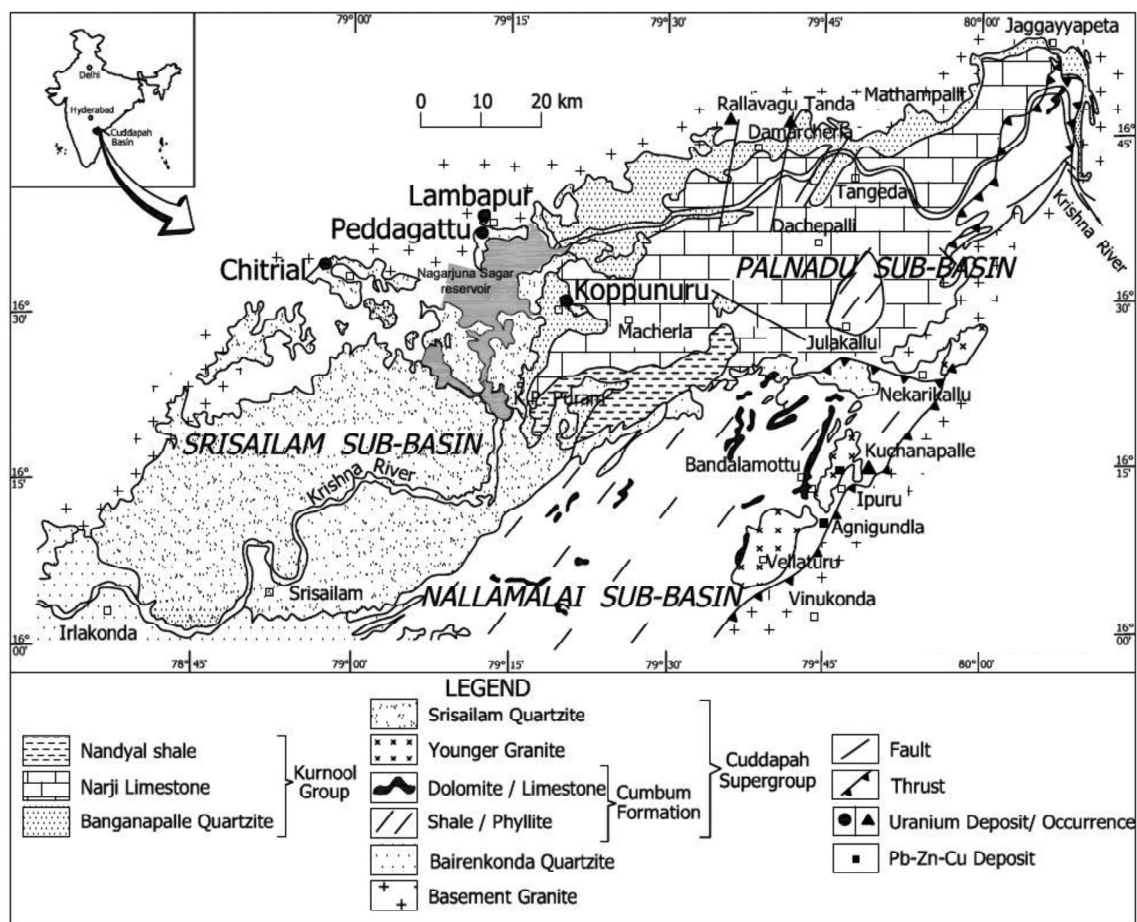


Fig. 2. Geological map of northern part of Cuddapah Basin showing disposition of Srisailam and Palnad sub-basins and location of Lambapur, Peddagattu, Chitrial and Koppunuru deposits

microcline, plagioclase and biotite, with accessory zircon, apatite and allanite (Verma et al., 2009). In addition, presence of some other ore minerals such as pyrite, anatase, limonite and goethite are also recorded.

Srisailam Formation mainly comprises intercalated sequence of quartzite, siltstone and grey shale (Nagaraja Rao et al., 1987) and represented by basal pebbly conglomerate horizon followed sequentially upward by green gritty quartzite, intercalated sequence of dark grey well laminated shale-quartzite and sub-feldspathic to feldspathic quartzite in Lambapur, Peddagattu and Chitrial outliers (Verma et al., 2009). Quartzites are often ferruginous and at places glauconitic in nature.

Various sedimentary structures viz., bedding, cross bedding, laminations and ripple marks are recorded in Srisailam sediments. They are also affected by prominent N-S, NNE-SSW and NW-SE trending fractures/faults.

PALNAD SUB-BASIN

The Palnad Sub-basin (~3400 sq. km) comprises sequence of arenaceous, argillaceous and carbonate sediments belonging to Kurnool Group and indicate variation in sedimentation pattern and depositional environment. These sediments unconformably overlie the older Cuddapah sediments in the eastern part whereas older granitoids form basement in the north and west (Fig. 2). The Kurnool sediments are divided into six formations viz., Banganapalle

Narji, Auk (Owk), Paniam, Koilkuntla and Nandyal formations (Table 1). The Banganapalle Formation is the oldest sedimentary lithounits of the Palnad Sub-basin and represented by 10–173m thick quartz arenite and intercalated grey shale sequence with basal conglomerate (Banerjee et al., 2012). This is overlain by thick sequence of massive limestone with silicic stylolytes and flaggy calcareous shale belonging to Narji Formation (Table 1). The Auk Formation consists of ferruginous ocherous calc-shale while a few outliers of younger Paniam quartzite occur at ridge tops. The overall thickness of the Kurnool sediments around Koppunuru area varies from 10m to 205m and dips are gentle (3-5°), mostly following the basement topography (Gupta et al., 2010).

The granitoids exhibit basement highs in the eastern and western part of Koppunuru area whereas in the southern sector these are exposed along the up-thrown block of WNW–ESE trending Kandlagunta fault. This fault is further offset by younger N–S trending faults. Similarly, basement granitoids exhibit faulted contact in northern parts of Palnad Sub-basin, where several radioactive anomalies are delineated (Fig. 3). The basement granitoids show highly fractured nature, and is traversed by dolerite dykes and quartz veins at several places.

The Banganapalle Formation is main pay horizon for uranium in Palnad Sub-basin (Koppunuru area), where it unconformably rests over the granitic basement. Exposed surface sections predominantly show monotonous sequence of Banganapalle quartzite, probably due to their gentle dips. However, sub-surface exploration has revealed thickness and sedimentary facies variation in Banganapalle sequence, and it is classified into five major lithofacies (Gupta et al., 2010). Presence of soft-sedimentary deformational

structures (penecontemporaneous deformation) like load structure, convolute bedding/laminations, and slump structures such as micro-slips, gravity faults and folds are prominent in quartzite-grey shale and shale-siltstone intercalated sequences indicate perturbation and submergence of the basin contemporaneous to deposition. Glauconite with traces of carbonaceous matter in different lithofacies indicates marginal marine, mildly alkaline and reducing depositional condition.

URANIUM METALLOGENY

Extensive integrated exploration activities by Atomic Minerals Directorate for Exploration and Research (AMD) have resulted in delineation of Srisailam and Palnad sub-basins as potential geological domains for unconformity-related, fracture controlled type of uranium mineralisation. This is evident from uranium deposits established at Lambapur, Peddagattu and Chitrial in Srisailam Sub-basin and Koppunuru in Palnad Sub-basin. Uranium mineralisation is mainly proximal to unconformity contact between Palaeoproterozoic granite and Meso- to Neoproterozoic siliciclastic cover rocks. In Lambapur, Peddagattu and Chitrial deposits, ore bodies are confined to highly altered, sheared and fractured granites just below the unconformity contact, while grit/conglomerate and upper quartzite horizons just above the unconformity host ore bodies in Koppunuru area. Details of uranium metallogeny including host rock characterisation of these sub-basins are discussed below.

MINERALISATION IN SRISAILAM SUB-BASIN

Surface radiometric surveys by AMD during last two decades have delineated significant uranium mineralisation at several outliers in marginal parts of Srisailam Sub-basin viz. Lambapur, Peddagattu, Chitrial, Amrabad

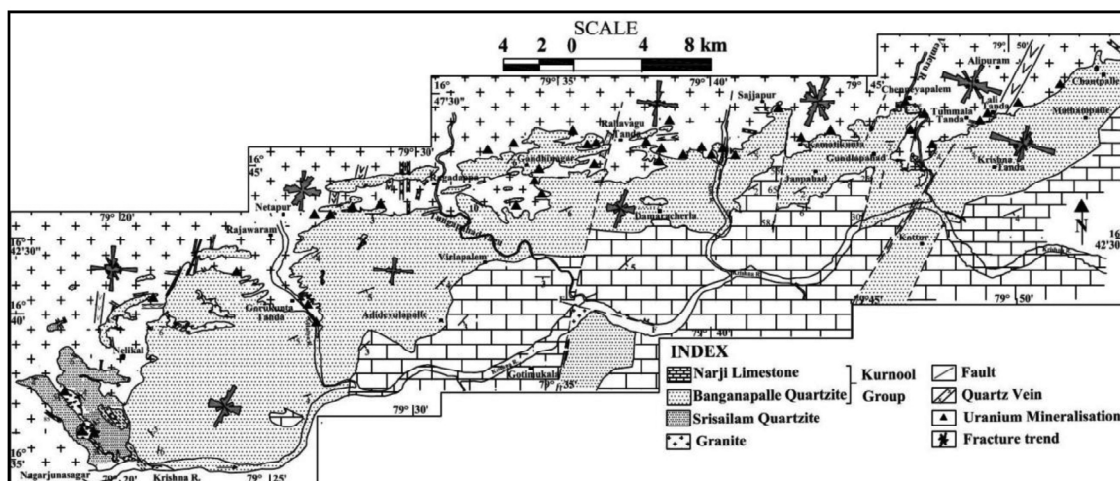


Fig. 3. Geological map of northern part of Palnad Sub-basin showing distribution of radioactive occurrences close to the basement–cover sediment contact zone

and Mannanur (Fig. 2). Uraniferous occurrences are mainly associated with the basement granites in Lambapur (upto 0.49% U_3O_8 with 0.01% ThO_2 ; $n=4$; Shrivastava et al., 1992) and Chitrial (upto 0.317 % U_3O_8 with <0.005% ThO_2 ; $n=65$; Ramesh Babu et al., 2010) areas, where mafic dykes in basement granitoids have also indicated anomalous radioactivity (upto 0.45% U_3O_8 with <0.005% ThO_2 ; $n=3$). Besides, uranium mineralisation (upto 0.065% U_3O_8 with 0.056% ThO_2 ; $n=4$) is also recorded at places in pebbly sandstone close to the unconformity in these outliers. In addition, Srisailam quartzites in Lambapur area have assayed upto 0.50% U_3O_8 with negligible Th ($n=3$).

Based on the geological favourability and surface uranium anomalies, extensive sub-surface exploration was taken up in Lambapur-Peddagattu sector and subsequently in Chitrial area, which has resulted in establishing nearly 20000 tonnes of low to medium grade uranium deposits in Srisailam Sub-basin. These exploration activities have confirmed unconformity proximal nature of uranium mineralization and its association with both the basement granite and the overlying Srisailam

sediments. More than 90% of the main ore body occurs in granite at varying depths from the surface i.e., 1 to 55m at Lambapur (Fig. 4), 42 to 62m at Peddagattu (Fig. 5a, b) and 3 to 82m at Chitrial (Fig. 6a, b). The ore bodies show gentle dips ($3-5^\circ$) towards southeast, which is in conformity with the basement slopes. Though the ore body appears to be a blanket along the unconformity, the richer grade pods are confined to definite trends viz., NNE–SSW and NW–SE (Lambapur), WNW–ESE and N–S (Chitrial). It has been observed that these fractures and their intersections are locales of higher grade mineralisation. The intensity of fractures within the granite and their intersections with the unconformity, thus apparently controls the grade of mineralization.

Host Rock Characterization: Granite-gneisses, granodiorite, granite, minor amount of diorites and linear Peddavoora schist belt form the basement rocks. Peddavoora schist belt comprises mafic rocks, schists and BIF. Basement rocks are deformed and intruded by a swarm of dolerite dykes of two to three generations and quartz reef/veins. Uranium mineralization is hosted essentially by coarse grained grey granite. Other mineralized

lithounits are quartz arenite/sandstone and dolerite.

(a) Basement Granitoids: These are medium to coarse grained and show hypidiomorphic granular texture. These granitoids are generally fractured (Fig. 7a) and exhibit varying degree of deformation ranging from the grain boundary restriction to entire rock ramification. They comprise quartz, microcline-microperthite, orthoclase-microperthite and plagioclase as essential minerals while biotite, chlorite, sphene, zircon, apatite and fluorite occur as minor/accessory minerals. Opaques are rare and represented by mainly pyrite and hydrous iron oxide. At places, microcline-microperthite shows post-crystalline deformation with fractures hosting clusters of chlorite, sphene and epidote and also uraninite with secondary development of uranophane.

Moderate to intense alteration in the form of chloritization of biotite and sericitization and illitisation of plagioclase is common (Fig. 7b-

d). Development of secondary biotite is also observed at places. Fractures are filled with clay material, secondary spherulitic biotite and hydrous iron oxide. Wall rock altered zones in mineralised sectors exhibit association of variable concentrations of uranium with irregular masses of illite, sericitized-clay, sericitized-feldspar, chlorite and anatase. Iron alteration in the form of hematitisation and presence of carbonaceous matter are also observed at places in mineralized granites (Fig. 7e). Occasionally, fractures in radioactive granites are seen filled with carbonaceous matter (Fig. 7f)

Radioactive granite core samples have indicated presence of pitchblende/uraninite and coffinite as primary uranium ore minerals (Fig. 7g-j) while secondary ore minerals are represented by autunite and U-Ti complexes (Fig. 7k-h). This is further confirmed by EPMA studies, which also signifies their epigenetic nature based on association and paragenetic

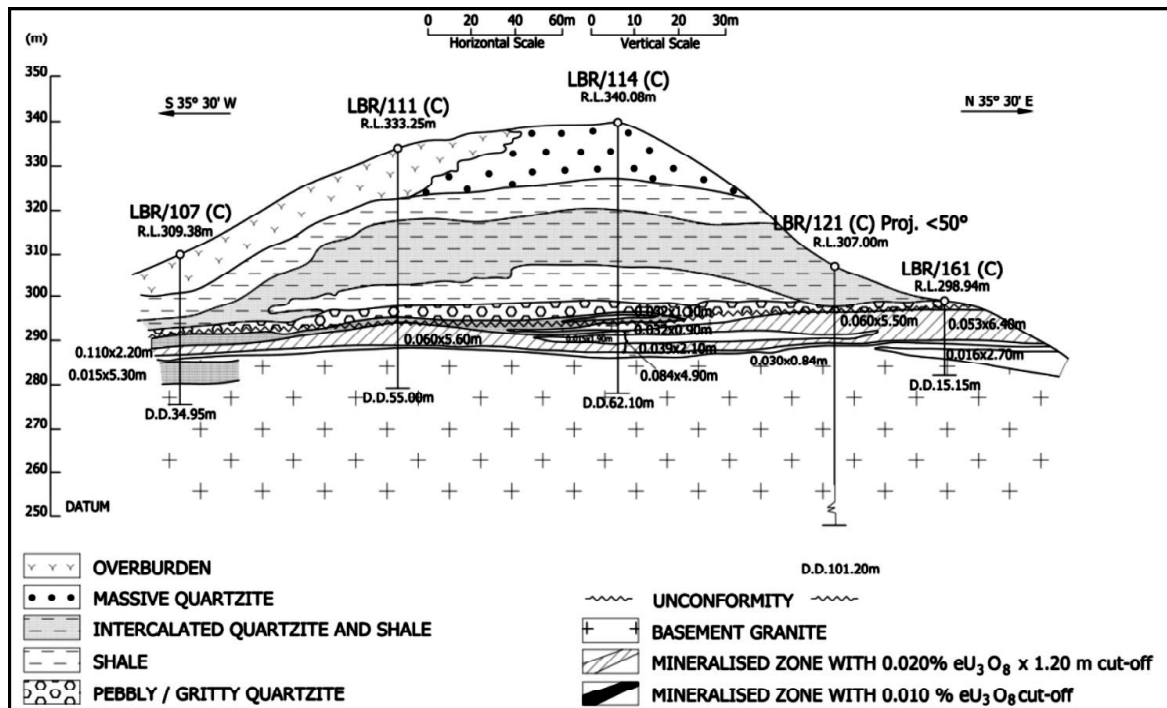


Fig. 4. A borehole correlation section showing disposition of ore body in Lambapur deposit

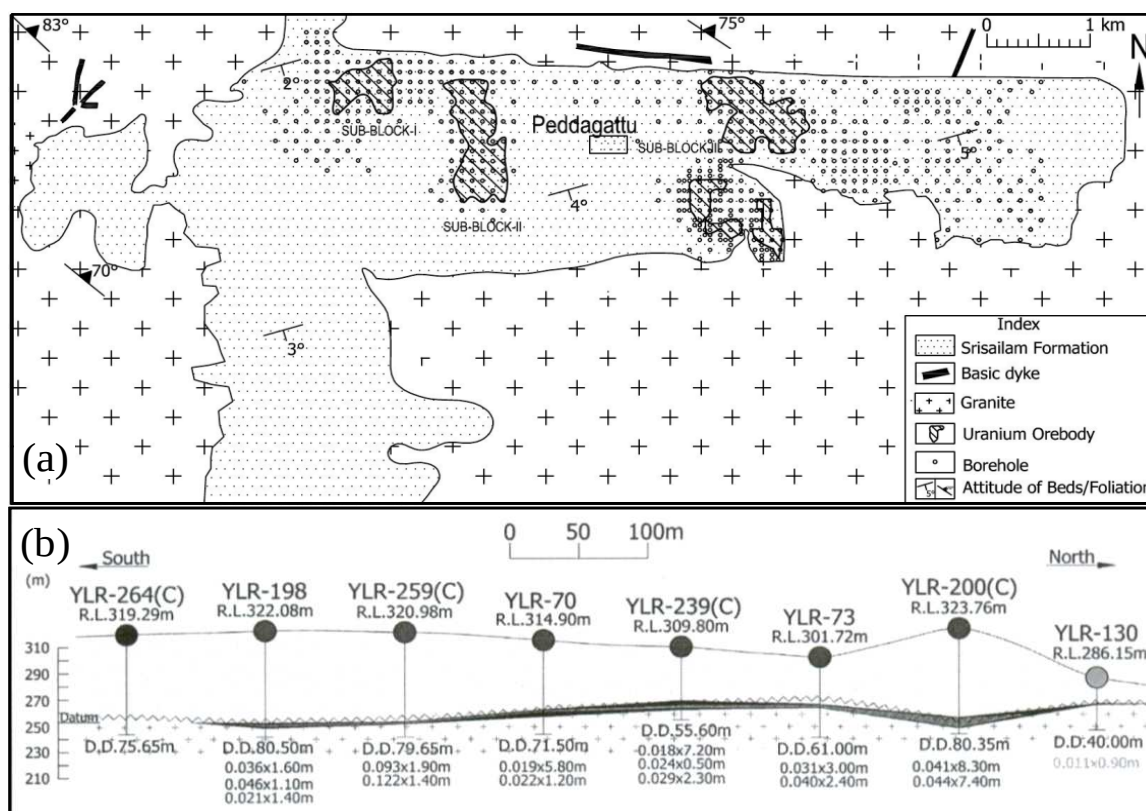


Fig. 5a. Geological map and ore body configuration of Yellapur–Peddagattu area

b. A borehole correlation section showing disposition of uranium ore body

sequence. Various phases of uranium ore minerals i.e., botryoidal and massive pitchblende in fractures (Fig. 7g); coalesced minute pitchblende/uraninite with a rim of chlorite in sericitized feldspar (Fig. 7i); and coffinite (Fig. 7h) in intimate association with pitchblende as alteration rim or aggregate of minute pellets, are quite apparent. Shrinkage cracks are common in pitchblende veins, which are healed with disseminated galena and occasional pyrite grains. In addition, U-Ti-complexes occurring as granular masses in cavities and fracture planes closely associated with hydrous iron oxides (Fig. 7k). Secondary uranium ore minerals generally occur along fractures ramifying the rock and in the cavities of feldspar and quartz (Fig. 7l). Besides, adsorbed uranium on hydrous iron oxide and clay is also observed. Apart from these, minor

amount of uranium is contained in resistate minerals such as allanite and zircon. Various sulphide ore minerals viz., galena, pyrite and chalcopyrite are seen associated with pitchblende as minute disseminations and as thin stingers healing the syneresis cracks. Occasionally, they occur as minute inclusions in chlorite and fine disseminations in sericitised feldspar.

Geochemically, granitoids (n=35) around Srisailam Sub-basin are characterised by 63.10–78.00% SiO₂, 0.02–0.52% TiO₂, 12.47–19.66% Al₂O₃, 0.58–4.99% Fe₂O₃(total), 0.01–1.59% MgO, 0.05–3.67% CaO, 0.24–3.19% Na₂O and 4.71–9.60wt% K₂O (Verma et al., 2008; Ramesh Babu et al., 2010). They exhibit Al₂O₃ and K₂O enriched nature, while Na₂O and CaO show depletion as compared to Average Proterozoic Granite (APG; Condie,

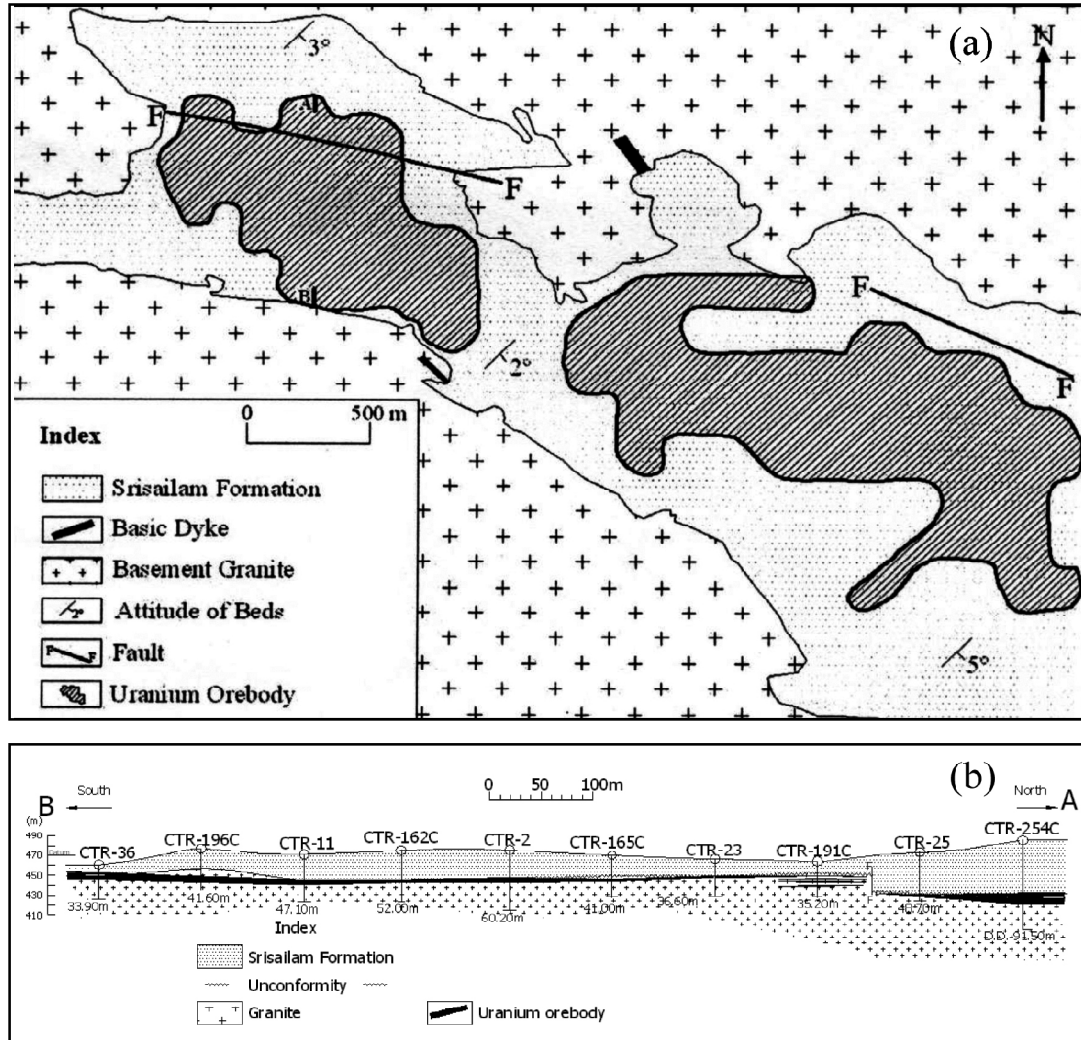


Fig. 6a. Geological map and ore body configuration of Chitrial area
b. A borehole correlation section showing disposition of uranium ore body

1993). This is probably due to the widespread sericitization of feldspars. MgO also shows marginal enrichment, which is corroborated by the chloritization of biotite. These granitoids are peraluminous with mean A/CNK value of 1.36 (0.91–1.83) and exhibit large variation in K_2O/Na_2O ratio (1.82–31.37; Av. 4.92). Rb, Th and Cr show marked enrichment as compared to APG whereas Ba, Sr and Y show depletion. This signifies highly differentiated nature of studied granitoids. Besides, anomalous

enrichment of Pb (Av. 234 ppm) in these granitoids can be directly attributed to higher radioelemental contents.

EPMA studies of radioactive core samples of granitoids of Chitrial area have identified uranium mineral phases as pitchblende, coffinite, autunite, and complexes as U-Si, U-Si-Ti and U-Si-Al. UO_2 content in pitchblende and coffinite range from 71.37 to 88.14% and 59.97 to 73.91% (Rajaraman et al., 2011).

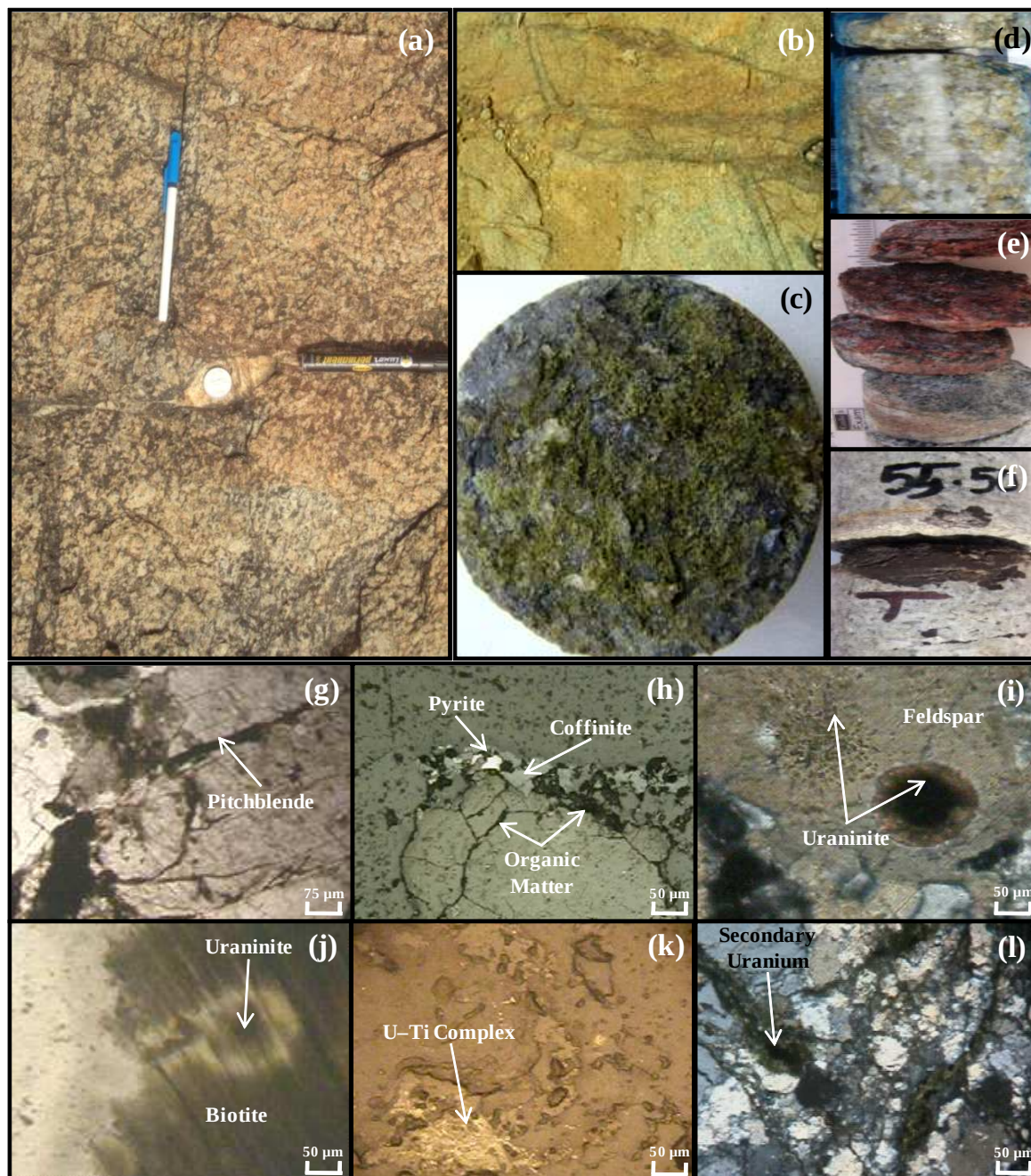


Fig. 7. (a) Radioactive granite showing fractured nature (b) Granite with chlorite veins (c) Clinochlore disseminations in granite core sample (d) Illitisation in granite core sample (e) Hematitisation of granite core sample (f) Carbonaceous matter along fractures in granite (g-l) Photomicrograph showing various association of pitchblende, coffinite, U –Ti complex and secondary uranium with pyrite, carbonaceous matter, feldspar and biotite as fracture fillings/inclusions

(b) Srisailam sediments: Srisailam cover sediments are mainly represented by quartz arenites (quartzite), feldspathic sandstone and arkose. These siliciclastic sediments are often intercalated with dark grey/black/green shale and siltstone. Sandstones show loose packing and consist of detrital clasts of quartz, alkali feldspar and plagioclase alongwith lithic fragments, glauconite, biotite and chlorite. The alkali feldspars are as high as 40% in some of the samples. Tourmaline, zircon, monazite, anatase, allanite, sphene, rutile, pyrite and goethite have been identified as heavy minerals in it. Matrix constitutes very fine silt sized quartz, feldspars, biotite and rare chlorite (both detrital and authigenic). Hydrous iron oxide occasionally smears the matrix components imparting light brown coloration to the sandstone. Uranium mineralisation in cover sediments mainly occurs as fracture fillings and indicated by the presence of discrete ore minerals pitchblende and uranophane. Besides, U-Ti complex, adsorbed uranium on hydrous iron oxide and zircon also contribute towards radioactivity.

Geochemically, cover sediments (n=7) exhibit wide variation in SiO_2 and Al_2O_3 contents i.e., 64.98–94.15% and 0.91–18.62%, respectively, which is directly proportional to the variation in major framework components viz., quartz and feldspar suggesting unstable depositional domain (Ramesh Babu et al., 2010). Very low CaO (0.04–1.16%; Av. 0.28%) and Na_2O (<0.01 to 3.40%; Av. 0.56%) contents indicate derivation of these sediments from chemically weathered terrain. Similarly, wide variation in K_2O content (0.09–7.40%; Av. 1.93%) signifies the role of basinal tectonics in intermittent contribution of fresh feldspar rich sediments responsible for such fluctuations. SiO_2 – K_2O + Na_2O plot (not shown) indicates derivation of these sediments in passive continental margin set up. Some of the

intercalated dark grey shale samples have analysed upto 0.82% C, which is higher than the average carbon content (0.20%) of Precambrian shales.

EPMA studies of sandstone core samples have identified monazite, xenotime and zircon as radioactive minerals. Monazites are mostly fine grained and occur in the matrix portion. They analysed low thorium (up to 2.29% ThO_2) and high rare earth oxides (>60%). Xenotime contains more Y, P and REEs and less of U and Th. Zircon are fine to medium grained, altered and exhibit metamict nature due to high U (upto 2.95%), Th (upto 3.8%) and REE (upto 3.61) contents. Hafnium concentration also shows wide variation (0.42% to 2.17 % HfO_2).

Geometry of Ore bodies: Various uranium deposits of Srisailam Sub-basin have indicated near tabular and gently dipping (3° – 5° due SE) ore bodies mainly hosted by granites and occur upto a depth of 5m below the unconformity (Fig. 4–6). The ore bodies generally form linear pods with very sharp contacts to that of non-mineralised zones. In Lambapur area, richer ore shoots/pods are mainly confined to NNE–SSW trend which is sympathetic to the trend of mafic dykes and basement ridge. Besides, some high grade ore pods are delineated along NW–SE trends. Similarly, rich grade linear ore pods in Peddagattu deposit are spread over an area of 7 km x 1 km and are confined along N–S and NW–SE trending fractures. As far as Chitrial deposit is concerned, mineralised ore body is delineated over strike length of 1.10 km x 0.775 km and 1.80 km x 0.80 km in western and eastern sector of main block, respectively. Besides, two more tabular ore bodies are established with a separation of nearly 500m in Chitrial block 2. In addition, some non-correlatable isolated ore bodies (granite hosted) are recorded much below the unconformity in deeper sections. Major mineralisation trends of linear ore pods

are indicated by N–S, NNW–SSE and WNW–ESE in Chitrial area.

Ore mineralogy: Various ore minerals identified in different uranium deposits in Srisailam sub-basin is described below.

Lambapur uranium deposit: The major ore minerals identified are uraninite, pitchblende, uranophane, adsorbed uranium on goethite, iron oxide and feldspar. In addition, several fractures in mineralised granites are filled with drusy quartz associated with kasolite and galena. Other ore minerals include pyrite, chalcopyrite and marcasite.

Peddagattu uranium deposit: Uraninite, pitchblende, uranophane and kasolite are the main uranium bearing ore minerals recorded in this deposit. In addition, some sulphide ore minerals such as chalcopyrite, pyrite and galena are also identified.

Chitrial uranium deposit: Pitchblende and coffinite are identified as primary uranium ore minerals in this deposit, while autunite, U-Ti complex, uranophane, phosphuranylite and masuyite occur as secondary uranium minerals.

Age of mineralisation: Radiogenic Pb of uraninite of Lambapur deposit have been dated as 480–500 Ma while the Sm–Nd data of uraninite yield an isochron age of 1327 ± 170 Ma with an initial δ_{Nd} value of -12 indicating a LREE enriched source for the Sm and Nd in the uraninite. These data also suggest the possibility of granitic rocks of basement being the ultimate source of the Sm and Nd in the uraninite. The Sm–Nd age of 1327 Ma represents the time of primary crystallization of the minerals and the c.500 Ma of radiogenic Pb indicate the age of the recrystallisation of the uraninite, which resulted in the complete loss of radiogenic Pb isotopes from it. Thus, two main events of uranium mineralisation and remobilisation in Lambapur can be deciphered

viz., (i) 1300–1400 Ma primary mineralisation event and (ii) 450–550 Ma later rejuvenation event. This age relationships can be extended to other deposits of Srisailam Sub-basin, which are located in the vicinity of Lambapur with similar geological setup.

MINERALISATION IN PALNAD SUB-BASIN

Surface uranium occurrences in Koppunuru and adjoining areas are mostly associated with Banganapalle Formation (130–5500 ppm U_3O_8 ; Jeyagopal et al., 1996, 2011) proximal to the unconformity with the basement whereas sporadic radioactive occurrences in granites and basic dykes are observed at several places along the northern margin of Palnad Sub-basin (Fig. 3). Pitchblende is the main uranium mineral, which occurs as colloform aggregates and puckered veins in quartzites and gritty sandstones. At places, higher concentrations of radioelements are found to be associated with carbonaceous matter occurring along intergranular spaces. Besides, low order radioactivity in the quartzites is also attributed by the resistate minerals such as monazite and zircon. Yellow-brown surface coatings of secondary uranium minerals on weathered surfaces of quartzites are common.

Sub-surface exploration in Koppunuru area has confirmed that uranium mineralization is mainly confined to cover sediments, and established a medium grade deposit of about 2500 tonnes. Ore body occurs in the form of sub-horizontal lodes predominantly hosted by the basal grit/conglomerate unit of Banganapalle Formation (Fig. 8a). In some of the horizons, this grit hosted mineralisation continues in basement granitoids below the unconformity (Fig. 8b). In addition, part of the uranium mineralisation is also hosted by Banganapalle quartzites located 5–40 m above the unconformity contact (Fig. 8a, b). At places,

these mineralized lodes show splitting into two branches and spread over a wide plan area. Some isolated non-correlatable mineralized zones at depth within the basement granitoids are also observed.

Host Rock Characterization: Uranium mineralization is hosted essentially by Banganapalle sediments with minor contribution from basement granitoids as already discussed above. Basement granitoids show signatures of substantial reactivation and are profusely traversed by mafic and felsic intrusives of multiple generations. Some of the mafic dykes are found to be mineralised. Similarly, Banganapalle sediments are also impacted by post-depositional deformations, which might have facilitated mobilisation and enrichment of uranium at suitable locales.

a) Basement granitoids: Basement granitoids are essentially composed of orthoclase, microcline, perthite, quartz and plagioclase, while anatase, pyrite, chalcopyrite, galena, marcasite, goethite and leucosene are identified as ore minerals. Variable degree of mineralogical alterations in granites resulting in an assemblage composed of sericite, muscovite and chlorite signifying illitisation and chloritization in the area.

Geochemically, granitoids of Koppunuru area (n=24) are characterised by moderate SiO_2 (62.09–74.01%), high Al_2O_3 (13.31–24.23%), moderate to high K_2O (3.09–7.05%) and low CaO (av. 0.54%) contents (Jeyagopal et al., 2011). These granites are peraluminous, sub-alkaline and low calcic and show moderately differentiated nature. They also contain high intrinsic uranium content (<5–39ppm; Av. 19ppm; n=30) and moderate thorium content (<5–43ppm; Av. 8.3ppm; n=30). Average U/Th ratio (3.80) in Koppunuru area is much higher as compared to the general abundance (0.25) in granites suggesting their fertile nature.

As compared to this, the granitoids (n=8) exposed around Palnad Sub-basin show restricted abundance for SiO_2 (61.81–69.31%) and Al_2O_3 (14.31–17.24%) whereas wide variation were observed in MgO (0.54–3.14%), FeO^t (1.73–12.94%), CaO (0.34–8.20%), TiO_2 (0.17–1.07%) and P_2O_5 (0.08–0.36%) (Vimal et al., 2012). Total alkali content varies from 5.32 to 9.22% with an overall predominance of sodium over potassium. These granitoids are medium- to high-K, calc-alkaline rocks belonging to granite–granodiorite–tonalite suit with predominant metaluminous nature and indicated their formation during the collisional and extensional tectonic stages of the evolution and cratonization (Vimal et al., 2012).

b) Banganapalle cover sediments: The cover rocks comprise intercalated sequence of quartzite ($\pm$ shale) which is conformably overlain by limestones and shale (Narji Formation). The basal conglomerate/grit unit of Banganapalle Formation is represented by polymictic, poorly sorted, immature, grit to pebble size clasts (~60% of the rock volume), with minor grey to greenish grey shale intercalations (Fig. 9 a–c). This unit has non-conformable contact with granites (Fig. 9e). They comprise pebbles of granite, shale, quartzite, vein quartz, quartz arenite and basic rock. The interstitial material consists of subrounded quartz and feldspar clasts bound by predominantly sericitic matrix with minor chlorite, while framboidal and anhedral pyrite occurs as disseminations, intergranular fracture fillings and segregations. Geochemically, these (n=24) are characterized by wide spread in SiO_2 (64.92–97.97%), Al_2O_3 (0.39–17.7%) and FeO^t (0.09–5.98%) and are moderately rich in K_2O (av. 2.8%), Na_2O (av. 1.03%) and poor in MgO, MnO, CaO and TiO_2 contents (Gupta et al. 2012). The wide variations in major oxide compositions further support the presence of polymictic clasts. Besides, these conglomerates/

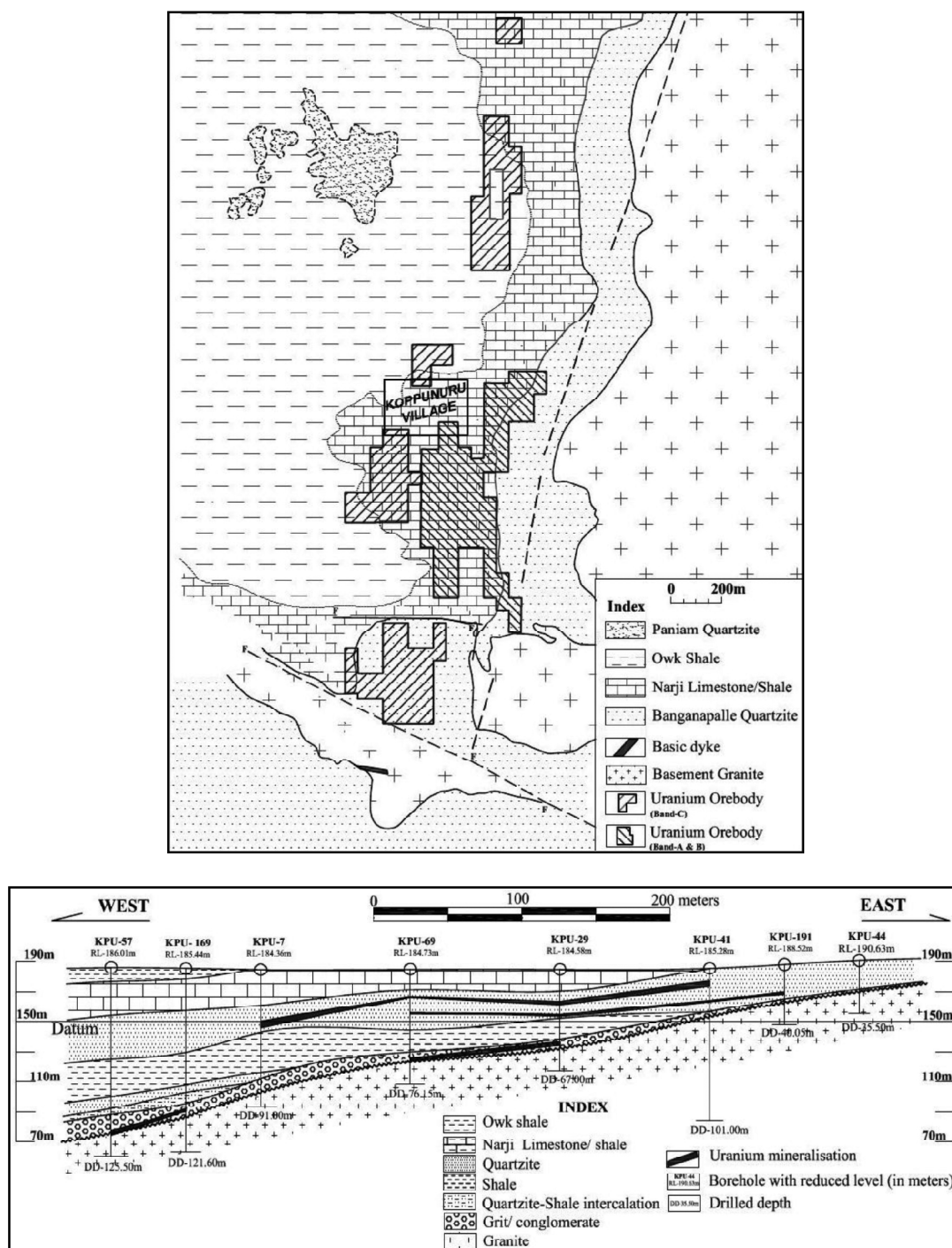


Fig. 8a. Geological map and ore body configuration of Koppunuru area
b. A borehole correlation section showing disposition of uranium ore body

grits are enriched in U, Th, Rb, Pb and Y and depleted in Cr, Ba, Sr and Zr as compared to Proterozoic equivalents (Gupta et al., 2012). Illitisation is common alteration feature in conglomerate/grit as substantiated by the presence of higher K_2O in ~79% of samples as compared to cratonic shales and quartzite (Condie, 1993).

Quartz arenites are light grey in colour, medium to fine grained, well sorted and saccharoidal in nature and exhibit high chemical maturity. They comprise ~90% (by volume) framework clasts dominated by quartz (~97%; Fig. 9d). The quartz is mainly monocrystalline in nature and commonly exhibit secondary overgrowths. Other minor minerals include feldspars, biotite, chlorite, sericite and chert. Besides, glauconite is conspicuous in quartz arenite indicating reducing depositional environments (Fig. 9f). Occasional thin laminations of shale and rounded aggregates of carbonaceous matter are also observed. Various alteration features such as ferrugination, silicification, chloritisation and kaolinisation are quite common. Geochemically, quartz arenite/quartzite (n=33) indicates higher SiO_2 content (92.18%), which is commensurate with comparatively low average Al_2O_3 (2.25%) and FeO^t (2.81%) contents (Gupta et al., 2012). They also exhibit low to very low content of other major oxides while trace element distribution pattern has indicated enrichment of U and Th and depletion of Sr, Ti, Ba and Zr as compared to average upper crust composition (Karuppan et al., 2010; Gupta et al., 2012).

Shales are dark grey in colour, sub-horizontally laminated and show fine intercalations of light grey siltstone. Microscopically, they exhibit foliation defined by continuous, sub parallel sericite-rich bands alternating with granular arenaceous bands consisting of mainly quartz with minor microcline and plagioclase. At places, chlorite

is associated with sericite. This facies is marked by the significant presence of sulphides and amorphous carbon. Pyrite is the major sulphide ore mineral and exhibits either colloform/framboidal nature (Fig. 9g) or occurs as fine disseminations, thin stringers and veinlets. Geochemically, shales (n=14) have indicated moderate to high SiO_2 (57.37–81.50%), Al_2O_3 (6.82–23.02%), FeO^t (3.96–10.98%), K_2O (0.78–7.27%) and TiO_2 (0.24–0.99%), moderate MgO (0.72–1.52) and low Na_2O (0.01–1.13%) and CaO (0.04–0.27%) (Gupta et al., 2012). These shale samples are enriched in Cr, Rb, Zr, Pb and U and exhibit depletion in Sr, Ba, Ni and Th. Potassic alteration in the form of illitisation, as observed in petrography, is further corroborated by presence of higher K_2O content as compared to cratonic shales in 93% samples.

Geometry of Ore body: Uranium mineralization in Koppunuru area is hosted in three ore lodes i.e., lode 'A', 'B' and 'C' in unconformity proximal setup (Fig. 8a, b). The uranium ore zones are predominantly confined to sediments (85%) just above the unconformity while granite played subordinate role. Lode 'A' is developed over a plan width of 600m in N–S and 300m in E–W direction (Fig. 8a) and occurs about ~20 m below the surface. This lode is hosted by quartzite and is intercepted at depths ranging from 7.55 to 47.45 m. Lode 'B' occurs 7-10m below lode 'A' and is hosted by quartzite over a plan width of 700m in N–S and 200m in E–W direction (Fig. 8a). This lode is intercepted at depths ranging from 14.05 - 37.05 m. Lode 'C' is the main ore grade mineralization along the unconformity contact, in grit/conglomerate or granite. This lode constitutes four ore lenses at different depths (29.75–165.25m) along the unconformity contact and spread over a plan width of 2.3 km in N–S and strike length of 400m in E–W direction. Major part of the ore lode is hosted

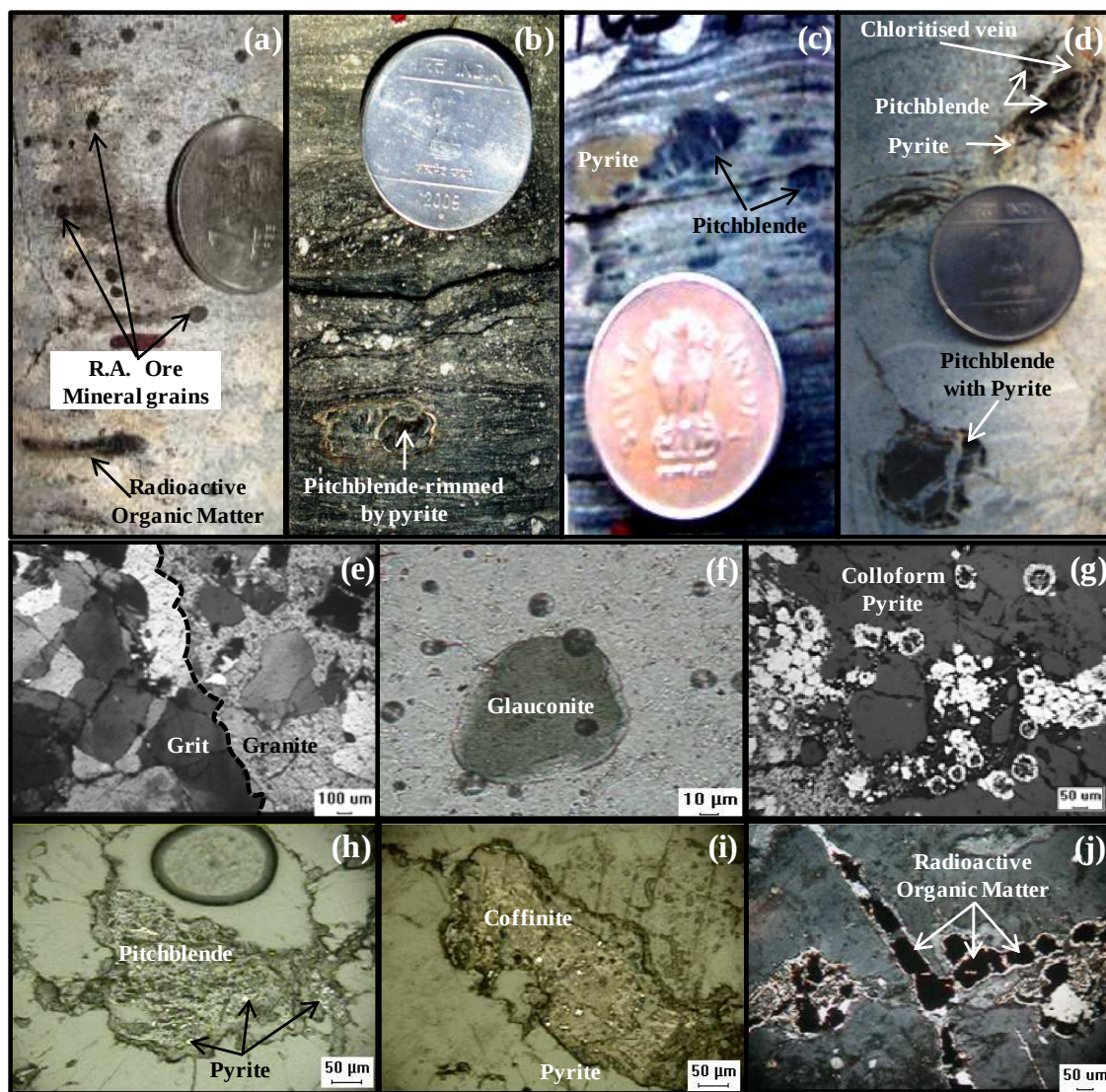


Fig. 9. (a–d) Radioactive core samples indicating various association of uranium mineralisation
(e) Photomicrograph showing non-conformity contact between granite and pebbly grit horizon **(f)**
 Photomicrograph of glauconite grain in quartz arenite **(g)** Photomicrograph of colloform/framboidal
 pyrite and amorphous carbon in shale **(h–j)** Photomicrograph showing various uranium ore minerals and
 their association with pyrite and organic matter

in grit/conglomerate which at places transgresses below the unconformity to granites.

Ore mineralogy: Uranium mineralisation in Koppunuru area is mainly associated with conglomerate and quartz arenite as discussed earlier. Pitchblende and coffinite are identified as primary uranium ore minerals in Koppunuru

deposit (Fig. 9h, i). In addition, uranophane, phosphuranylite, metazeunerite and U-Ti complex occur as secondary uranium minerals. The radioactive minerals are epigenetic in nature and occur as fine veins, fracture/cavity and grain boundary fillings. Other ore minerals include galena, pyrite, chalcopyrite, pyrrhotite, maeracite and traces of pentlandite. It is

observed in Koppunuru area that organic matter and pyrite are normally occurring in mineralized horizons (Fig. 9j), which suggest that they might have played significant role as reducing agent in fixation of the uraniferous lodes (Jeyagopal et al., 2011).

As far as uranium ore minerals in basement granitoids are concerned, it is represented by pitchblende and coffinite occurring as stringers and veins. In addition, variable concentrations of uranium also occur in adsorbed form and found to be associated with sericitic clay, chlorite, glauconite, biotite and hydrated iron oxides.

EPMA studies of mineralised phases have indicated that pitchblende and coffinite contain 73.47 to 78.58% UO_2 and 63.45–71.53% UO_2 , respectively, while mixed phases analysed lesser content of uranium oxide (42.14 – 47.90% UO_2) (Verma et al., 2011).

Age of mineralisation: Basement granitoids in Palnad Sub-basin have indicated comparable Rb–Sr (2659 ± 120 Ma) and Pb–Pb (2638 ± 94 Ma) isochron ages, while One radioactive granite sample dated by Pb–Pb method has shown an age of 1545 ± 140 Ma with model $\mu_1 = 8.3 \pm 1.4$ and MSWD = 55 (Vimal et al., 2012). This younger Pb–Pb age with high MSWD value is presumably due to the local redistribution of U and Pb in the sample and found to be coeval to that of initial age of uranium mineralization found in Lambapur deposit. In addition, preliminary dating of uraniferous quartzite samples of Koppunuru area by Pb–Pb step leaching (PbSL) method has indicated 576 ± 180 Ma, 891 ± 160 Ma and 936 ± 60 Ma as mineralisation ages. This suggests multi-episodic nature of mineralisation where uranium concentration/enrichment took place in different phases.

DISCUSSION AND CONCLUSIONS

Palaeo- to Mesoproterozoic Cuddapah

Basin in the eastern Dharwar craton of the peninsular India provides an ideal spatial and temporal setup for uranium mineralisation, where Srisailam and Palnad sub-basins in the northern parts hold significant potential to host unconformity-related fracture controlled type of deposit. However, uranium mineralisation in these sub-basins shows some dissimilarity to that of classical unconformity-type uranium deposits, especially in respect of basement rocks which lack metapelites/graphitic metapelites. The uranium deposits at Lambapur, Peddagattu and Chitrial in Srisailam Sub-basin and Koppunuru in Palnad Sub-basin are mainly confined proximal to the unconformity plane between fertile, fractured granitoids and siliciclastic cover sediments. In addition to this, ground radiometric surveys and limited sub-surface exploration based on integrated approach have resulted in delineation of significant uranium anomalies/occurrences in other outliers viz., Akkavaram and Amrabad and along basin margins in Srisailam Sub-basin and Musi river, Damaracherla–Chenneyapalem and Malkacherla–Ragadappa sectors in Palnad Sub-basin. Uranium mineralisation in these sub-basins is characterised by the following features.

- Basement is represented by Neoarchaean to Paleoproterozoic granitoids (2268 ± 32 Ma to 2659 ± 120 Ma; Pandey et al., 1988, Vimal et al., 2012) and occasional linear belts of older metasediments (Peddavoora Schist belt). Basement is profusely traversed by multiple generations of mafic dykes, which might have been provided thermal gradient facilitating uranium mineralisation process in Srisailam and Palnad sub-basins.
- Cover sediments are represented predominantly by marginal marine arenaceous Srisailam and Banganapalle formations. These are separated from

basement rocks by Meso- and Neoproterozoic unconformity in Srisailam and Palnad Sub-basins, respectively. The cover sediments are also subjected to post-depositional tectonic activity as evidenced by the presence of faults and fractures.

- Uranium mineralisation is concentrated mainly in the marginal (peripheral) part of these sub-basins, where thickness of cover sediment is comparatively less (10 to ~200m). However, recent exploration activity in deeper parts of Srisailam and Palnad Sub-basins has yielded positive results (Banerjee et al., 2012).
- The basinal topography, fractures and dykes mainly control the mineralisation, while repeated tectonic activity and extensive alterations have played significant role in remobilisation and concentration of uranium. Ore body generally occurs as elongated pods and gentle dipping tabular body following the unconformity/basement slope. In the Chitrial area, it is observed that though uranium concentration is intercepted along the unconformity, the higher values (~0.1%U₃O₈) are mainly confined to the trends sympathetic to the fractures affecting basement and/or sediments viz., N20°W–S20°E and N70°W–S70°E trends in Main Block, Block-1 and Block-2, and N–S in Block-4. Incidentally, the ground magnetic surveys carried out in Chitrial Main Block have indicated magnetic low (probably due to alterations in basement rocks) along N70°W–S70°E trend coinciding with mineralization trend (Rajaraman et al., 2011). Similarly, N–S to NNE–SSW and WNW–ESE are identified as predominant trends of mineralisation in Koppunuru area. These features bring out the importance of the role of structure as major conduit for migration of ore bearing

hydrothermal fluids and its fixation at suitable locales, especially along the intersection of fractures in these sub-basins.

- Ore bodies are hosted by either or both basement granite and cover sediments. However, majority of uranium bearing ore bodies in Srisailam Sub-basin (>90%) is confined to granites whereas cover sediments (>85%) predominates in Palnad Sub-basin. Besides, association of uranium mineralisation with various alteration features viz., illitisation, chloritization, kaolinization and ferrugination in these sub-basins is quite apparent.
- Major primary ore minerals identified are pitchblende/uraninite and coffinite. Secondary uraniferous ore minerals include uranophane, kasolite, phosphuranylite, metazeunerite and U-Ti complexes. These are invariably associated with sulphide ore minerals viz., galena, pyrite, chalcopyrite, pyrrhotite, pentlandite and marcasite. The mineralisation is found to be low temperature hydrothermal in nature. Besides, presence of organic matter in mineralised zones is quite apparent, especially in sediment hosted ore bodies. Thus, it can be inferred that sulphides and organic matter might have acted as reductants and helped in fixation of uranium in the system.
- Preliminary studies on mineralisation age has indicated 1300-1400 Ma as primary mineralisation event and 450-550 Ma as complete rejuvenation event in Srisailam Sub-basin. Similarly, basement granitoids in Palnad Sub-basin has indicated 1500 Ma as primary mineralisation event (Vimal et al., 2012) while preliminary studies of quartzite samples has indicated multi-episodic mineralisation ages spanning from

576±180 Ma, to 936±60 Ma.

Various favourability factors as discussed above, suggest that southern continuity of known uranium deposits in Srisaillam Sub-basin holds immense potential to host large tonnage and medium grade ore deposits in unconformity-proximal setup, especially in deeper parts where thickness of cover sediments is >300m. Similarly, entire northern margin and deeper parts of Palnad Sub-basin provides excellent possibilities of locating sizeable uranium deposits.

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