IOSR Journal of Applied Geology and Geophysics (IOSR-JAGG)
e-ISSN: 2321–0990, p-ISSN: 2321–0982.Volume 6, Issue 5 Ver. I (Sep. – Oct. 2018), PP 86-95
www.iosrjournals.org

Uranium Mineralisation around Mulapalle, SW of Lakkireddipalle, Kadapa district, Andhra Pradesh, India and Laboratory-Scale Mineral Processing of its Uranium Ore

R. Dhana Raju[1*], Y. Lakshminarayana[2] and Ch. Sudhakar[3]
[1]1-10-284/1, Begumpet, Brahmanawadi Lane 5, Hyderabad – 500 016, India
[2]16-1-3/10, B.R. Nagar, Amadalavalasa, Srikakulam Dist., Andhra Pradesh – 532 185, India
[3]502, Shanti Imperial, Santosh Nagar Colony, Mehdipatnam, Hyderabad – 500 028, India
**Corresponding author: R. Dhana Raju,*

Abstract: *Uranium mineralisation around Mulapalle (SW of Lakkireddipalle in the Kadapa district of Andhra Pradesh, India), occurs within the Archaean - Palaeoproterozoic structurally complex granitic terrain, present in the southern environs of the Mesoproterozoic Cuddapah Basin. The host rocks for the mineralisation are deformed, metamorphic and K-Fe-Mg-Ti metasomatic variants of the Closepet-equivalent granitoid (~ 2.5 Ga), occupying fracture zones, in the form of cataclasite, mylonite and phyllonite. Two types of U-mineralisation with poly-modal U-phases were recorded in this area: (i) minor, older, high-temperature, syn-magmatic type, manifested as euhedral - subhedral inclusions of uraninite and brannerite, present within the gangue minerals; and (ii) more dominant, younger, low-temperature, hydro (epi)-thermal type, in the form of skeletal crystals of uraninite, veins/vein-lets and fracture-fillings of pitchblende, coffinite and brannerite. Besides, some U is associated with leucoxene, anatase and limonite. Other ore minerals associated with these U-phases are mostly Fe-oxides in the form of hematite and specular hematite, with lesser sulphides of pyrite, galena, chalcopyrite, pyrrhotite and arsenopyrite. Preliminary laboratory-scale mineral processing of the U-ore (Sericite-chlorite-quartz-hematite phyllonite) from this area, which assayed 0.20%* U_3O_8 *with little* ThO_2*, resulted in 75% U-leachability, with 180 kg/tonne* H_2SO_4 *and 10 kg/tonne* MnO_2 *(as oxidant). The leached pulp was further subjected to vacuum filtration to separate leach liquor that was then subjected to purification/solvent extraction, and U was precipitated as Magnesium Di-Uranate (yellow cake).*

Keywords: *Uranium mineralisation, U-ore processing, Mulapalle, Kadapa district, Andhra Pradesh, India.*

Date of Submission: 01-10-2018 Date of acceptance: 16-10-2018

I. Introduction

The Department of Atomic Energy (DAE) under the Government of India is mandated to work for the Country's nuclear industry, mainly for the generation of clean nuclear power, besides other applications of nuclear sciences to industry, health, agriculture and defence, preferably using indigenous nuclear resources. Since 1948, the Atomic Minerals Directorate (AMD) for Exploration and Research, which is the oldest and front-end unit of DAE, has been exploring for Radioactive Minerals [RM of Uranium (U) and Thorium (Th), besides Rare Metals (RM: Nb-Ta, Li, Be and Cs) and Rare Earth Elements (REE: La to Lu and Y)] in different parts of India. In this, during the last few years the State of Andhra Pradesh has emerged as the no. 1 state in India for the resource-base of both Atomic Minerals and Valuable Heavy Minerals (VHM: ilmenite, rutile, zircon, monazite, garnet and sillimanite) in mineral sands (Dhana Raju and Venkat Reddy, 2016). Sustained efforts of numerous geo-scientists of AMD during the last 8 decades led to the establishment of a resource-base of 2,73,956 t U_3O_8 and 1,173 million tonnes (m te) VHM (till end of December, 2017; Nanda, 2018), under different categories of resources. In this India's total U-resource, over 50% is contributed by the large tonnage (> 0.15 m te) but low-grade (~ 0.045% U_3O_8) strata-bound phosphatic, siliceous, carbonate-hosted U-deposit that is presently under exploitation by the Uranium Corporation of India Ltd., a public sector unit under DAE in the Tummalapalle – Giddankipalle area in SW part of the Cuddapah Basin (CB) (Vasudeava Rao *et al.,* 1988; Dhana Raju *et al*., 1993, Jeyagopal and Dhana Raju 1998). In addition to this deposit, others, both within and in the environs of CB, include the unconformity-proximal type U-deposit, mostly in the basement granite and lesser in its overlying quartzite, in the Lambapur – Peddagattu – Chitrial - Koppunuru areas in N and NE parts (Sinha *et al.,* 1995; Jeyagopal *et al.,*1996) and U-prospects of (i) hydrothermal-type mineralisation in the quartzite in the Gandi area in SW part (Umamaheswar *et al.* 2001), (ii) fracture-controlled mineralisation around Lakkireddipalle in the southern environs (Dhana Raju *et al.,* 2002) and (iii) shear zone-hosted mineralization, close to the SE-margin in the Kasturigattu - Gudarukoppu - Kulluru area (Thimmiah *et al.*, 1986; Veerabhaskar *et al.,* 1991; Rai *et al.,* 1995), thereby making the CB and its environs (Fig. 1a) as India's emerging U-hub

(Dhana Raju, 2009a). Exploration for U in the crystalline terrain in the southern environs of CB was started in late 1980s, when U-mineralisation was discovered by Bidwai and Madhusudan Rao (1988) in the 16 km-long T. Sundupalle – Sanipaya basement fracture zone that is SE and E of the present study area of Mulapalle (Fig. 1b). U-mineralisation in the Mulapalle area in the southern environs of CB occurs in a large network of fractures within a crystalline complex (Fig. 1b). Salient aspects of this U-mineralisation as well as results of a preliminary laboratory-scale mineral processing of its U-ore, i.e., sericite-chlorite-quartz-hematite phyllonite (Sudhakar, 1996) are presented in this paper.

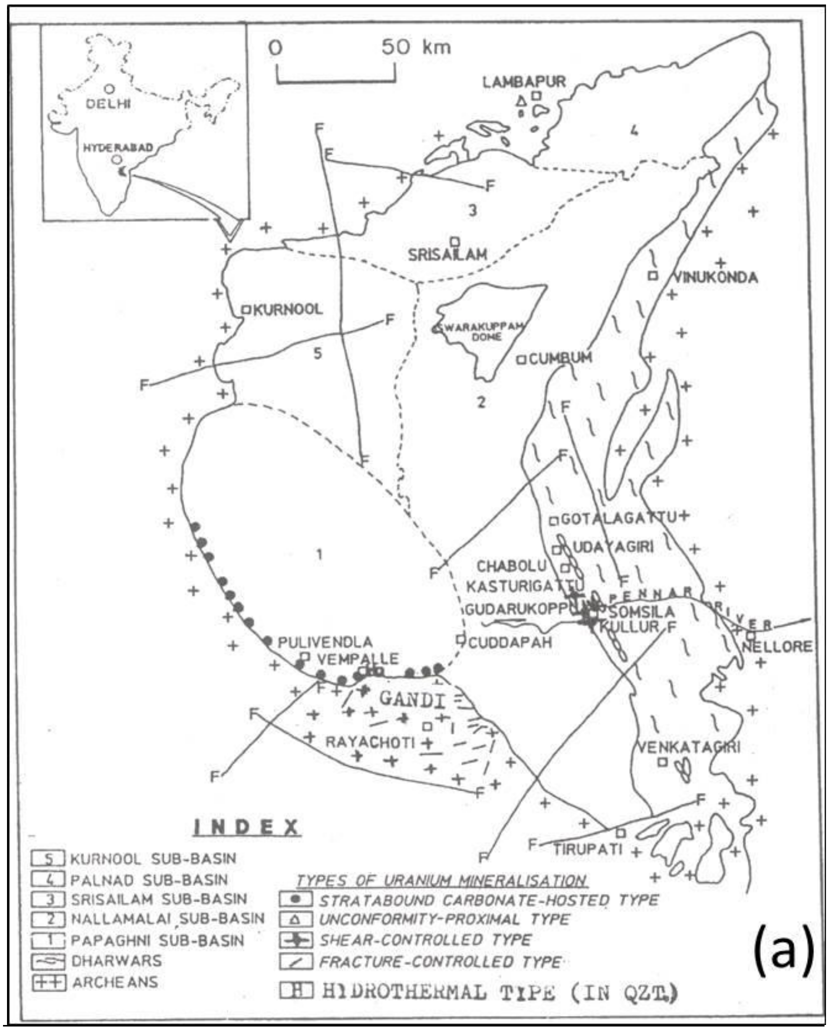

Fig. 1a. Cuddapah basin and its sub-basins, with location of different types of U-deposits and-prospects, both within and in its environs.

II. Geological Setting

The area around Lakkireddipalle and Rayachoti (Fig. 1b) in the southern environs of CB is largely occupied by the basement granitoids, comprising grey coloured Archaean (~ 3 Ga) Peninsular Gneiss in low-lying terrain with a few occasional ridges, intruded by a pink granite that occurs as mounds and resembles the pink phase of the ~ 2.5 Ga Closepet Granite and, hence, is designated here as the Closepet Granite-equivalent. Both the grey and pink granitoids in the area are affected by deformation and fracturing. This granitic terrain is criss-crossed by mafic dykes (dolerite and lesser gabbro), quartz veins/reefs and notable fracture system. The fracture system comprises 2 sets of major fractures, *viz.*, relatively older, trending ENE-WSW, and younger, trending NNE-SSW. In a majority of these fractures, deformed variants of granitoids occur in the form of cataclasite, mylonite and phyllonite. These, mainly along the ENE-WSW fracture system and its zones of intersection with the NNE-SSW trending fractures, within the Closepet Granite-equivalent pink granitoids, constitute the loci for the U-mineralization that was recorded in over 50 fractures (each 750 m to 2.5 km in length) at Mulapalle, Chanchalapalle, Burjupalle and Payalapalle, all located NW of Rayachoti (Dhana Raju *et al.*, 2002; Fig. 1b). Field traverses in these areas revealed that mylonite and opaque-rich phyllonite, present almost exclusively in the fracture zones (200 to 450 m in length with width of 1to7 m), are radioactive, assayed 0.01-0.53% eU_3O_8 with negligible Th, with 15-40% disequilibrium in favour of parent U. These deformed variants of granitoids within the fractures exhibit large-scale metamorphic (greenschist facies) and metasomatic effects as well as a host wall-rock alterations of hematitisation/limonitisation, chloritisation and sericitisation.

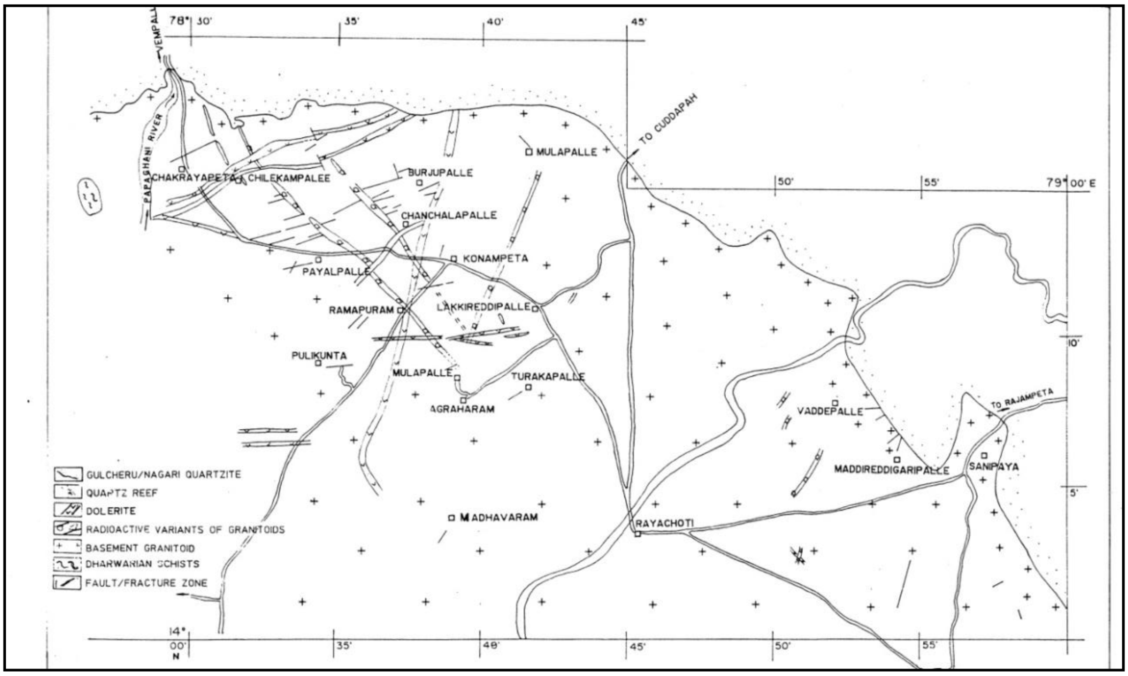

Fig.1b. Geological map of the Mulapalle – Lakkireddipalle – Rayachoti area in the Kadapa district, Andhra Pradesh, India, with locations of the U-mineralised Fracture Zones.

III. Materials And Methods

Different methods of investigation adopted and materials involved in each of these are given below, starting from the sample collection in the field till laboratory-scale mineral processing of the U-ore from the Mulapalle area, through preparation of thin and polished thin sections for petro-mineragraphic study, CN (Cellulose Nitrate) film autoradiography on even surfaced hand specimens and polished thin sections of the radioactive samples, chromogram study on both radioactive hand specimens and polished thin sections, X-Ray Diffraction (XRD) study on selected radioactive samples and geochemical analysis on petrographically-characterised representative samples for major, minor and trace elements. Details of these methods of study can be had from Dhana Raju (2009b and c).

1. ***Sample Collection and Specimen Preparation:*** Over 50 samples, each of 3-4 kg, of different rock types in the study Mulapalle area were collected at more or less regular intervals, with sample locations selected after the field traverses. They were examined for their characteristic megascopic features of structures like phyllitic, schistosity, gneissosity, micro-folding, etc., and surface features. Representative specimens from each sample were selected in the laboratory for preparation of (a) thin and polished thin sections for microscopic study, (b) CN film autoradiography, (c) XRD study and (d) geochemical analysis.

2. ***Preparation of Thin and Polished Thin Sections:*** For this, each selected specimen was first sawed into a small wafer in the required orientation and then mounted in thermoplast of lakeside cement of M/s. Buehler, USA and was subjected to grinding sequentially with 60, 100, 400, 600 and 800 mesh carborandum powder. About 15 minutes time was given for grinding at each step. After grinding, the specimen slide was subjected to polishing with 6, 1 and 0.5 micron-sized diamond paste. Twenty minutes time was given for polishing at each step and “hifin” fluid was used as lubricating agent. Thin and polished sections were used for petro-mineragraphic study under both transmitted and reflected light microscopy with a Leica microscope.

3. ***CN film autoradiography:*** CN film, in the form of flexible sheets, was used as a Solid State Nuclear Track Detector (SSNTD) for detecting alpha particles. For this study on both even surfaced hand specimens and

polished thin sections of radioactive samples, the colourless, transparent, 100-micron thick and sensitive to alpha particles of < 4 MeV CN 85 film, procured from M/s. Kodak-Pathe, Paris, was used for location of 'Radioactive Minerals' (RM) by recording alpha tracks, emitted by RM, and their distribution in the film, seen after exposure and etching with 10% K (OH) solution.

4. ***Chromogram study:*** This method was used on even surfaced hand specimens and polished thin sections so as to locate easily leachable U-minerals like uraninite, pitchblende, coffinite and uranyl minerals. The materials required for this study are: (a) photographic paper, soaked in fixer solution and dried; (b) 10% nitric acid and (c) potassium ferrocyanide (solution) in water. First, the photographic paper treated with nitric acid was evenly pressed for about 60 seconds on the surface of the levelled/polished slab or uncovered polished thin section. Next, this paper was treated with the potassium ferrocyanide solution by sprinkling, when brown, rose red and blue coloured spots appeared corresponding, respectively, to leachable minerals of U, Cu and Fe.

5. ***Preparation of specimen powders for radiometric and chemical analysis:*** From large samples collected in the field, representative specimen-pieces of about 1 kg were crushed into small pieces in a crusher. Next, these small pieces were ground in a shatter box (of M/s. Spex Industries, USA) for about 6 minutes to obtain -200 mesh (-74 micron) size material. This material was subjected to coning and quartering to get a representative portion. From this powder, 300-400 g was used for radiometric analysis, while ~ 25 g powder was further ground in an agate mortar to obtain powder of -300 mesh size, and this ultrafine powder was used for chemical analysis.

6. ***Radiometric analysis:*** Contents of radio-elements (U, Th and K) of radioactive samples [drawn in the field from radioactive areas that record > 5 X bg (background) in a hand-held scintillometer] were determined by a single channel gamma-ray spectrometer (ECIL make, Hyderabad, India) having a thallium-activated sodium iodide crystal of 4" x 5", with measurements at 2.62 MeV for Th, 1.76 MeV for U and 1.46 MeV for K (using direct determination of K^{40} as it is a gamma ray emitter).

7. ***Chemical analysis:*** This was carried out by various instrumental methods, titrimetry and gravimetry for different major, minor and trace elements, as per the methods detailed by Satyanarayana (1986), Sudhakar and Dhana Raju (2004) and Dhana Raju (2009c), with the starting material of -300 mesh powder (prepared as given at 5 above). Under this, stock solution-A was used for determination of Al, Fe (total), Mg, Ca and Mn by AAS (instrument: AA 1475 of Varian Techtron, Australia); Si (using solution-B), Ti and P by spectrophotometry (instrument: UV-240 Shimadju, Japan); Na and K by flame photometry (instrument of AMIL, India); Pb, Cr. Ga, V, Cu, Ni and Co by DC-Arc Emission Spectrography (instrument: Hilger Watts E 742, England); U by laser fluorimetry (instrument: Syntrex UA-3, Canada); Ba, V and Y by ICP-AES (instrument: 8410 Plasma Scan of Labtam, Australia); Fe^{2+} by titrimetry; and Loss-on-Ignition (LoI) by gravimetry.

8. ***Mineral Processing:*** Bulk sample (1-2 kg) of the U-ore (sericite-chlorite-quartz-hematite phyllonite) that was fully characterized earlier by the methods given above, was subjected to comminution by crushing it first in a jaw-crusher and next in roll-crusher to obtain material of -100 mesh (149 micron) size, since sieve analysis data and experiments conducted earlier in the laboratory on it pointed its optimum pre-determined size as -100 mesh (- 149 microns). The -100 mesh size material was then subjected to physical beneficiation involving, sequentially, de-sliming, bromoform-separation, magnetic separation on bromo-heavies using first a low-powered hand magnet and then by Frantz isodynamic separator at 0.2 to 0.3 amp to remove magnetite and other magnetic minerals like hematite. The non-magnetic heavy fraction was subjected to chemical-analysis by weight and mineral-analysis by volume. After these operations, hydrometallurgy by acid-route (since the ore has major silicate gangue in the form of quartz, feldspars and biotite) was adopted for extraction of U. This involved leaching by acid solvent (H_2SO_4), with maintenance of oxidation – reduction by MnO_2 and $FeSO_4$ for dissolution of U. Series of hot agitation experiments at 45°C were conducted with different parameters. The materials used and methodology adopted for mineral processing this U-ore are the same as that used for the nearby Gudarukoppu U-ore (Dhana Raju *et al.,* 2018) and the reader is referred to this paper for details. Lastly, U was precipitated as Magnesium Di-Uranate (MDU, yellow cake), using magnesium oxide, followed by vacuum filtration.

IV. Results

Different investigative methods and materials (detailed in the preceding section) used in the present study led to the results, detailed below.

1. ***Geological set-up:*** The Mulapalle area is a part of the Archaean - Palaeoproterozoic crystalline basement complex along the southern environs of the Mesoproterozoic Cuddapah Basin (CB). The basement complex comprises granite, gneiss, older metamorphic rocks and Veligallu greenstone belt, and is a part of the Peninsular Gneissic Complex. The basement granitoid is mainly of two colours – grey and pink, with the former being dominant. Based on the amount of mafic minerals, there appears to be two phases of granitoids, with the older grey coloured hornblende granitoid recorded at Rayachoti, Reddipalle, Lakkireddipalle and Sibyala similar to the Archaean (~ 3 Ga) Peninsular Gneissic Complex (PGC) and younger pink coloured biotite granitoid, occurring as mounds and seen at Mulapalle, Virapalle and Pulikunta being the equivalent of Closepet Granite (~ 2.5 Ga).

2. ***Petromineragraphy, CN film autoradiography and chromogram:*** Petrographic study on less deformed-metamorphosed granitoids and their highly deformed variants namely sericite-chlorite-quartz-hematite (± apatite) phyllonite, mylonite and cataclasite led to the following notable features: (a) Textural change from massive of the granitoid to different deformation textures like cataclastic, mylonitic and mostly phyllitic; (b) Intense alteration, mainly hematitisation, limonitisation and sericitisation; (c) Notable effects of K-Mg-Fe-Ti metasomatism, mineralogically manifested, in the form of biotite, sericite, anatase and specular hematite; (d) The observed mineral assemblage of cataclasites, mylonies and phyllites indicates that the degree of metamorphism in the area is low-grade of the greenschist facies at high P_{H2O}; (d) Mineragraphic study indicated two types of U-mineralisation: (i) syn-magmatic type, manifested as euhedral *uraninite* and *brannerite*, present as inclusions in major gangue minerals of quartz and feldspar; and (ii) hydro (epi)-thermal type in the form of skeletal uraninite, veins/vein-lets and fracture-fills of *pitchblende*, *coffinite* and *brannerite* (Figs. 2 to 7). These U-minerals were located by CN film autoradiography and were identified by reflected light microscopy. Other ore minerals include mostly Fe-Ti oxides and hydroxides in the form of hematite, specular hematite, limonite, rutile, anatase, leucoxene and lesser sulphides that include pyrite, galena, chalcopyrite, pyrrhotite and arsenopyrite. Some U is associated with limonite, anatase and leucoxene, as indicated by sparse tracks on CN films due to alpha particles, emitted by these minerals.

3. ***XRD study:*** XRD study on methylene iodide-heavy fraction of uraniferous rocks confirmed the presence of uraninite, pitchblende, brannerite and coffinite, earlier identified by mineragraphic study under reflected light microscopy, as given above.

4. ***Radiometric analysis:*** Amongst the analysed rocks, sericite-chlorite-quartz-hematite phyllonite recorded high radioactivity up to 0.20% U_3O_8 and < 0.01% ThO_2.

5. ***Geochemical analysis:*** Six whole-rock samples, *viz.*, two samples (MFZ-70 and MFZ-74) of altered granite and granite mylonite, and 4 samples (MFZ-75, 69, 71 and 67) of phyllonites, were analysed chemically for their major, minor and trace elements (Table 1). Chemical analysis of the U-ore (Sericite-chlorite-quartz-hematite phyllonite) analysed 0.20% U_3O_8 with negligible Th. Examination of the data in Table 1 reveals the following geochemical patterns: (a) major elemental composition of the altered granitoids is much similar to a low-Ca normal granite, except for high depletion in Na_2O and low order concentration of Fe_2O_3 and to some extent MgO; these features are due to alterations that affected the precursor granitoids in the form of high-degree hematitisation and low degree chloritisation; (b) trace element contents also are more or less comparable to that of normal low-Ca precursor granite, excepting for higher contents of Rb (by about 2 orders), U (3-6 orders) and Th (3-4 orders), and depletion of Ba (by 2-3 orders); however the Th/U value remains at 3-4 like that of normal granite; (c) compared to the altered granitoids, the phyllonites are marked by depletion, to various degrees, of SiO_2, and marked enrichment of Fe_2O_3, Al_2O_3, CaO, K_2O, TiO_2 and P_2O_5; these patterns are mineralogically expressed by varying degrees of alterations, namely hematitisation, leucoxinisation/formation of anatase, illitisation, chloritisation and little apatitisation; and (d) amongst the trace elements, the phyllonites, compared to the altered granitoids, are characterised by enrichment of Rb, U, Pb, Sc and Hf, with depletion of Zr, Th and Cs, resulting in very low values of < 1 for Th/U and of 2 for Zr/Hf, respectively, compared to the usual values of 3.5-4 and 40 in a normal granite. Furthermore, trace elemental data on highly radioactive drill-core samples with U_3O_8 up to 0.20% (Sudhakar and Dhana Raju, 2004) showed that they are characterised by higher contents of Pb, Cr, Ga, Ti, Zr and Y, and depletion in Cu, Co and Ni, with no Th.

6. ***Mineral Processing*i** The U-ore from Mulapalle that was subjected to laboratory-based mineral processing (Sudhakar, 1996) is the ‘Sericite-chlorite-quartz-hematite phyllonite’. Preliminary laboratory-scale mineral processing study on this U-ore that assayed 0.20% U_3O_8 with little ThO_2 resulted in 75% U-leachability with 180 kg/tonne H_2SO_4 and 10 kg/tonne MnO_2 (as oxidant). The leached pulp was further subjected to vacuum filtration to separate leach liquor that was then subjected to purification and solvent extraction, and U was precipitated as Magnesium Di-Uranate (MDU, yellow cake).

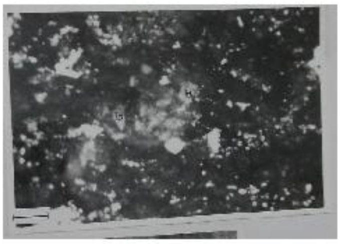

FIG.2

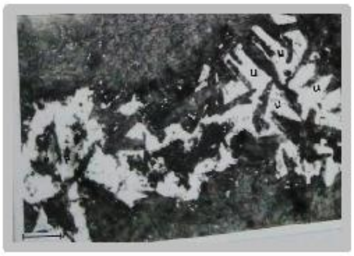

FIG.3

FIG.4

FIG.5

FIG.6

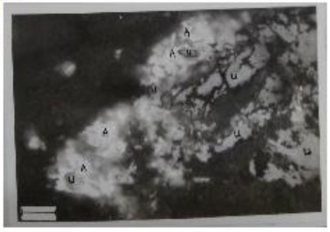

FIG.7

Fig. 2. Brannerite (B) in association with hematite and specular hematite (white) in phyllonite from Mulapalle. Note ultrafine grains of galena (white) within brannerite. Refl. Light. In oil. Bar: 0.04 mm.

Fig. 3. Uraninite (U) and pitchblende (P), as fracture-fillings in the matrix, in sericite-quartz-chlorite mylonite from Mulapalle. Refl. Light. In oil. Bar: 0.6 mm.

Fig. 4. Skeletal uraninite (U) as fracture-filling in the sericite-rich matrix of granite cataclasite from Mulapalle. Ref. light. In oil. Bar: 0.057 mm.

Fig. 5. Uraninite (U), associated with specular hematite (H), as fracture-filling in the sericite-rich matrix of hematite-sericite phyllonite from Mulapalle. Refl. light. In oil. Bar: 0.08 mm.

Fig. 6. Replacement of Uraninite (U) by specular hematite (H) in the hematite-sericite phyllonite from Mulapalle. Ref. light. In oil. Bar: 0.08 mm.

Fig. 7. Replacement of Uraninite (U) by anatase (A) along fractures in the sericite-rich matrix of granite cataclasite from Mulapalle. Ref. Light. In oil. Bar: 0.068 mm.

Table 1. Chemical analysis (major and minor oxides, in wt. %, and trace elements, in ppm) of the Granitoids (sl.nos. 1 and 2) and Phyllonites (sl. nos. 3 to 6) from the Mulapalle area, Andhra Pradesh, India*

Oxides and Elements	1 (MFZ-70)	2 (MFZ-74)	3 (MFZ-75)	4 (MFZ- 69)	5 (MFZ-71)	6 (MFZ-67)
SiO_2	68.58	73.91	40.38	55.01	59.48	65.01
Al_2O_3	15.93	15.93	21.32	17.93	16.94	13.20
Fe_2O_3	1.45	1.47	22.16	12.03	9.31	10.00
FeO	1.63	0.36	0.48	0.48	0.60	0.36
MgO	3.11	0.93	1.16	1.63	1.77	1.01
CaO	0.05	< 0.02	0.84	0.90	0.14	0.89
Na_2O	0.50	0.33	0.56	0.44	0.33	0.25
K_2O	3.95	4.26	6.63	4.95	5.47	3.95
TiO_2	0.20	0.30	2.06	1.84	1.37	1.10
P_2O_5	0.07	0.05	0.37	0.45	0.14	0.36
MnO	0.02	< 0.01	0.01	0.01	< 0.01	< 0.01
LoI	2.50	0.50	2.21	1.97	2.48	1.48
Total	**97.99**	**98.04**	**98.18**	**97.66**	**98.03**	**97.61**
V	72	95	52	140	80	197
Cr	40	< 10	< 10	10	< 10	14
Co	10.8	< 4	< 4	5	8	< 4
Ni	31	< 4	< 4	18	19	6
Cu	4	< 3	3	< 3	< 3	3
Ga	17	16	20	17	19	15
Rb	325	325	596	554	603	321
Sr	< 25	< 25	< 25	< 25	< 25	< 25
Y	11	10	< 10	12	< 10	17
Zr	119	140	64	100	52	66
Ba	144	222	282	216	< 25	188
Pb	< 10	< 10	85	36	20	39
U	23	14	35	20	41	125
Th	57	50	< 2	16	< 2	21
Au (ppb)	< 10	n.d.	n.d.	< 10	n.d.	< 10
Sc	5.9	n.d.	n.d.	39	n.d.	28.5
Cs	7.5	n.d.	n.d.	2.1	n.d.	2.8
Ta	0.7	n.d.	n.d.	0.8	n.d.	0.5
Hf	5.3	n.d.	n.d.	3.8	n.d.	2.3

*From Sudhakar (1996). n.d.: not determined.

The flow-sheet adopted for processing the U-ore (Sericite-chlorite-quartz-hematite phylloite) under study is given in Fig. 8.

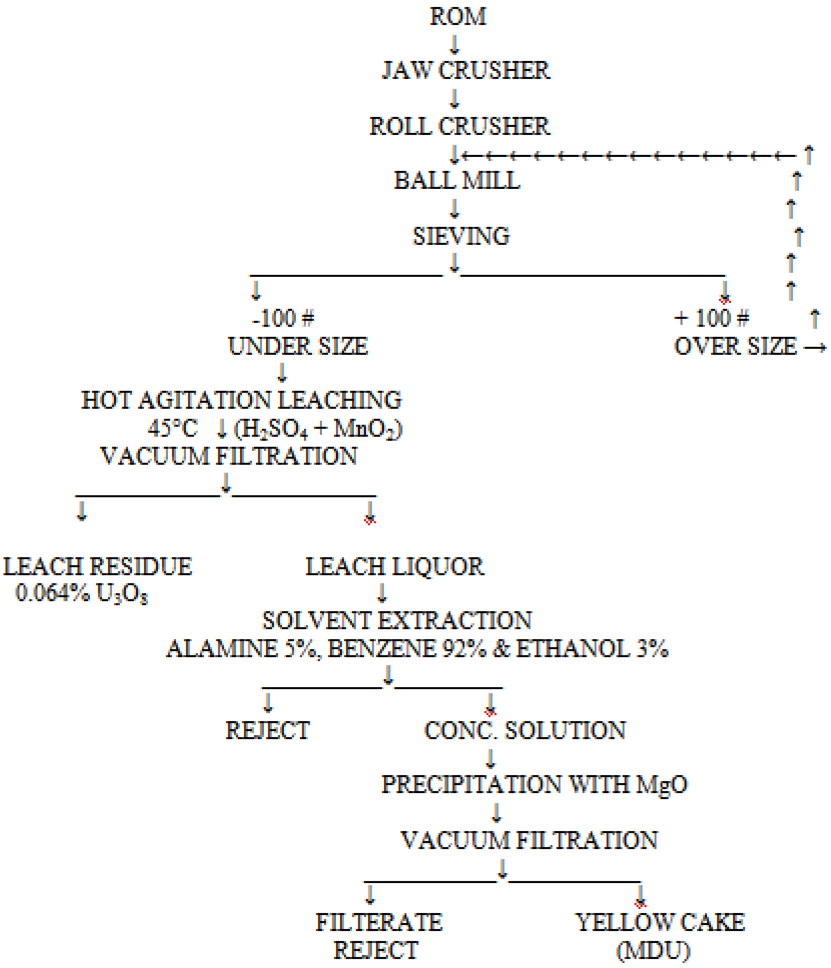

Fig. 8. Flow-Sheet for mineral processing of the Uranium ore (Sericite-chlorite-quartz-hematite phyllonite) from the Mulapalle area, Andhra Pradesh, India.

V. Discussion

In this section, various aspects of the U-mineralisation in the Mulapalle area like parental rock for U, host rocks for U-mineralisation, mineragraphy, type, mineralogical alterations, controls of and guides for U-mineralisation as well as mineral processing of the U-ore from the study area are discussed in the following.

1. ***Parental rock for U-mineralisation and its nature*:** In the Mulapalle area, data on the major elements of the 2 analysed samples of granitoids (Table 1) indicate that they belong to low-Ca, peraluminous (A/CNK > 1.1) and potassic with $K_2O/Na_2O > 3.5$ granite, with loss of Na and concomitant increase of K and Rb, implying some K-metasomatic activity in the area and, hence, openness of the system. Furthermore, these basement granitoids are fertile for U and Th, as indicated, respectively, by their high contents of 14-23 ppm U and 50-58 ppm Th, against 3.5-4 ppm U and ~ 16 ppm Th in normal granites. These geochemical features of the granitoids in the area point out that they are parental to the U-mineralisation, present in their altered and metamorphic-metasomatic variants in the form of phyllonites, mylonites and cataclasites.

2. ***Host Rocks for U-mineralisation*:** Radioactivity, mostly due to U, in the Mulapalle area is almost restricted to the phyllonites (high contents of U up to 125 ppm, Table 1, besides U_3O_8 up to 0.20% in drill-core samples of mineralised zones), which are the deformed, metamorphosed and K-Mg-Fe-Ti metasomatised variants of parental granitoid.

3. ***Mineragraphy of the U-mineralisation*:** The ore minerals in the U-mineralised phyllonites (cited at item no. 2 under ‘results’ above) are uraninite, pitchblende, brannerite and coffinite associated with oxides of hematite, skeletal hematite, leucoxene and anatase, and lesser sulphides of pyrite, chalcopyrite, pyrrhotite and galena, besides a little arsenopyrite. In this ore, uraninite occurs as inclusions in gangue minerals of quartz and feldspar as well as fracture-filling skeletal grains in gangue, pitchblende occurs as ultrafine

disseminations and granules that constitute either clusters or vein-lets, present along the weak planes and along the grain boundaries of the gangue minerals like quartz. The presence of the U-minerals listed above suggests that the area is potential for U-mineralisation, with a possibility of depth-wise continuity of the U-mineralisation.

4. ***Type of U-mineralisation*:** Two types of U-mineralisation in the study area are recorded. The first one is of high-temperature, syn-magmatic type and is relatively older, as indicated by a number of fine galena (with its Pb being radiogenic) inclusions in the euhedral - subhedral uraninite and brannerite. The other is of low-temperature, hydro (epi)-thermal type in the form of skeletal uraninite, pitchblende, coffinite and brannerite, implying its younger age. The hydrothermal type is more dominant than the syn-magmatic type, and appears to be a consequence of the remobilization of the syn-magmatic U during regional deformation-metamorphism-metasomatism, which affected the area to different degrees, and is mainly related to intense activity of fluids, rich in volatiles such as H_2O and F.

5. ***Mineralogical Alterations*:** Much of the primary feldspar and mafic silicates of the precursor granitoid is substantially altered hydrothermally, due to large scale influx of volatiles resulting in sericitisation and lesser chloritisation. These hydrothermal alterations are accompanied by large scale oxidation of precursor magnetite to hematite and specular hematite, and alteration of ilmenite to leucoxene. The source of Fe and Ti for these alterations appears to be dolerites that are either adjoining or close by to the locales of U-mineralisation. The U-mineralisation in the area is confined to the deformed variants of granitoids, *viz*., phyllonite, mylonite and cataclasites, and is invariably associated with wall-rock alterations of dominant hematitisation, minor sericitisation and lesser chloritisation. This is further corroborated by the patterns of trace element data on some drill-core samples, given earlier (see section 5 under ‘results’), which suggest that amongst the alterations that helped in the concentration of U: (i) hematitisation is the most important one, as suggested by increasing contents of trivalent elements like Cr and Ga, which can substitute Fe^{3+} in hematite; (ii) leucoxenisation of ilmenite and formation of anatase, suggested by high content of Ti; and (iii) chloritisation is not much significant, as evidenced by depletion in both Ni and Co. The intimate association between U-mineralisation and the above cited alterations points out that the labile U, released from the un-deformed fertile granitoids, might have travelled together with hydrotherms along structurally weak planes like fractures, where U is concentrated to the ore-grade. Furthermore, the intimate association of hematite and limonite with the U-mineralisation indicates that soluble U^{6+} form was reduced to U^{4+} form to precipitate in the form of discrete U^{4+}-dominant phases like skeletal uraninite, pitchblende, brannerite and coffinite, due to simultaneous oxidation of Fe^{2+} of magnetite to Fe^{3+} of hematite and limonite.

6. ***Controls of and Guides for U-mineralisation*:** The following are the major controls of U-mineralization in the area: (a) structurally weak zones, mainly in the form of fracture system; (b) lithology, with the host rocks for U-mineralization, namely mostly phyllonites and lesser mylonites and cataclasites, which are the deformed variants of granitoids that are fertile for U; (c) intrusive dolerite and quartz-reef/-veins, located close to the zones of U-mineralization, with the former providing necessary geothermal gradient to remobilize U that led to the younger, dominant hydro (epi)-thermal type U-mineralization; (d) greenschist facies metamorphism and Fe-Mg-K-Ti metasomatism; and (e) oxidation of precursor magnetite to hematite and specular hematite. The guides for U-mineralization in the area are: (a) presence of fracture system in the granitic terrain, with zones of intersection of two or more sets of fracture system being more potential; (b) presence of deformed rocks like phyllites, mylonites and cataclasites, having source in parental fertile (for U) granitoid; (c) occurrence of younger granitoids with intrusive dolerite and quartz-reef/-veins; (d) zones of alteration, especially hematitisation (red coloured), besides sericitisation (colourless) and chloritisation (green coloured).

7. ***Mineral Processing*:** 75% leachability of U was achieved in the laboratory on the U-ore of ‘Sericite-chlorite-quartz-hematite phyllonite’ from the study area, using 150 kg/ton of H_2SO_4 and 10 kg/ton MnO_2 as oxidant. The medium grade U-leachability obtained, in spite of high acid consumption, is ascribed to the presence of some U in brannerite in the ore, which is a refractory mineral from which full extraction of U under the experimental conditions followed is not possible.

Acknowledgements:

The authors sincerely thank their former colleagues in the Southern Region (SR), Bengaluru of the Atomic Minerals Directorate (AMD) for Exploration and Research, Department of Atomic Energy, Govt. of India for their support and help during both field and laboratory investigations, especially Mr. Rajan Chopra during the field work and Mr. K. Muniyappa for studies in the Mineral Technology Lab., SR.

References

[1]. Bidwai, R. and Madhusudan Rao, R. (1988) Radiometric survey in the basement granitoids along the SW margin of the basin. Annual Rep. for the field season, 1987-88, Southern Region, AMD, Bangalore (Unpublished).

[2]. Dhana Raju, R (2009a) Cuddapah basin: India's emerging Uranium-Hub. Jour. Ind. Assoc. Sedimentologists 28 (2), pp. 15-24.

[3]. Dhana Raju, R (2009b) Handbook of Mineral Exploration and Ore Petrology: Techniques and Applications. Geol. Soc. India, Bangalore, India, 494 p.

[4]. Dhana Raju, R. (2009c) Handbook of Geochemistry: Techniques and Applications in Mineral Exploration. Geol. Soc. India, Bangalore, India, 520 p.

[5]. Dhana Raju, R., Lakshminarayana, Y. and Sudhakar, Ch. (2018) Uranium mineralisation from Gudarukoppu, SE-margin of the Cuddapah basin, A.P., India and Laboratory-scale mineral processing of its Uranium Ore. Intl. Jour. Dev. Res. (IJDR, online journal), 8 (8), pp. 22507-22514.

[6]. Dhana Raju, R., Roy, Minati, Roy, Madhuparna and Vasudeva, S.G. (1993) Uranium mineralisation in the south-western part of the Cuddapah basin: A petromineralogical and geochemical study. Jour. Geol. Soc. India 42 (2), pp. 135-149.

[7]. Dhana Raju, R., Umameshwar, K., Tripathi, B.K., Rai, A.K., Zakaulla, S., Thirupathi, P.V. and Nanda, L.K. (2002) Structurally-controlled and crystalline rock-hosted uranium mineralization in the southern environs of the Cuddapah basin, Andhra Pradesh, India. Exploration And Research For Atomic Minerals (EARFAM) 14, pp. 95-108.

[8]. Dhana Raju, R and Venkat Reddy, D. (2016) Atomic-/RMRE-Minerals and Heavy Minerals in Coastal Mineral Sands in Andhra Pradesh, India: Resources, Attributes and Need for Their Holistic Development. Intl. Jour. Earth-sciences and Engineering (IJEE) 9 (4), Invited Paper, 7 p.

[9]. Jeyagopal, A.V. and Dhana Raju, R. (1998) Recognition criteria and sedimentology of the dolostone-hosted stratabound uranium mineralization in Vempalle formation, Cuddapah basin, Andhra Pradesh, India. *In*: (Ed. R.N. Tiwari) Recent Researches in Sedimentary Basins, Proceedings of the National Symposium, Indian Petroleum Publishers, Dehra Dun, pp. 172-179.

[10]. Jeyagopal, A.V., Kumar, P. and Sinha, R.M. (1996) Uranium mineralisation in the Palnadu sub-basin, Cuddapah basin, Andhra Pradesh, India. Curr. Sci. 71, pp. 957-959.

[11]. Nanda, L.K. (2018) Message from Director. AMD Newsletter 24, January issue, p. 1.

[12]. Rai, A.K., Sharma, S.K., Umamaheswar, K., Nagabhushana, J.C. and Vasudeva Rao, M. (1995) Uranium mineralization in the eastern margin of Cuddapah basin. Abstract vol., Geol. Soc. India Ann. Conv. and Seminar on 'Cuddapah basin', Thirupati, Sept. 9-12.

[13]. Satyanarayana, K. (1986) Geochemistry of amphibolites and associated rocks in parts of the Nellore-Gudur pegmatite belt, Andhra Pradesh, India. Ph.D. thesis in Geology, Faculty of Science, Osmania University, Hyderabad, India, 286 p.

[14]. Sinha, R.M., Shrivastava, S.K., Sarma, G.V.G. and Parthasarathy, T.N. (1995) Geological favourability for unconformity related uranium deposits in the northern parts of the Cuddapah Basin: Evidence from Lambapur uranium occurrences, Andhra Pradesh, India. Exploration And Research For Atomic Minerals (EARFAM) 8, pp. 111-126.

[15]. Sudhakar, Ch. (1996) Geochemistry of the crystalline rocks around Rayachoti, Cuddapah district and Kasturigattu, Nellore district, Andhra Pradesh, India. Ph.D. thesis in Geology, Faculty of Science, Bangalore University, Bangalore, India, 181 p.

[16]. Sudhakar, Ch. and Dhana Raju, R. (2004) Geochemistry of the Granitoids and their deformed, altered variants around Rayachoti, Cuddapah district, Andhra Pradesh and its bearing on uranium mineralization. Jour. Applied Geochemistry 6 (2), pp. 147-163.

[17]. Thimmaiah, M., Ramachar, T.M., Veerabhaskar, D. and Jayaram, K.M.V. (1986) The uraniferous biotite-sericite schist of Kasturigattu hillock, north-east of Somasila, Nellore district, Andhra Pradesh. Curr. Sci. 55, p. 350.

[18]. Umamaheswar, K., Sharma, U.P., Zakaulla, S., Basu, H., Thomas, A.M. and Ali, M.A. (2001) Occurrence of gold in association with uranium in Gulcheru quartzite of Cuddapah basin, Gandi – Rachakuntapalle area, Cuddapah district, Andhra Pradesh. Curr. Sci. 81 (7), pp. 754-756.

[19]. Vasudeva Rao, M., Nagabhushana, J.C. and Jeyagopal, A.V. (1989) Uranium mineralization in the Middle Proterozoic carbonate rock of the Cuddapah Suprgroup, Southern Peninsular India. Expl. Res. At. Miner. 2 (EARFAM), pp. 29-38.

[20]. Veerabhaskar, D., Sarkar, M., Thimmaiah, M., Sharma, M. and Dhana Raju, R. (1991) Uranium mineralization at Kasturigattu, Nellore district, Andhra Pradesh, India: An example of shear-controlled, syngenetic - remobilized type in Proterozoic Granitic and low-grade metamorphic rocks. Exploration And Research For Atomic Minerals (EARFAM) 4, pp. 27-37.

-----O-----

IOSR Journal of Applied Geology and Geophysics (IOSR-JAGG) is UGC approved Journal with Sl. No. 5021, Journal no. 49115.

R. Dhana Raju, "Uranium Mineralisation around Mulapalle, SW of Lakkireddipalle, Kadapa district, Andhra Pradesh, India and Laboratory-Scale Mineral Processing of its Uranium Ore." IOSR Journal of Applied Geology and Geophysics (IOSR-JAGG) 6.5 (2018): 86-95.