ISSN: 2230-9926

Available online at http://www.journalijdr.com

IJDR

International Journal of Development Research
Vol. 08, Issue, 08, pp. 22507-22514, August, 2018

ORIGINAL RESEARCH ARTICLE

URANIUM MINERALIZATION FROM GUDARUKOPPU, SE-MARGIN OF THE CUDDAPAH BASIN, A.P., INDIA AND LABORATORY-SCALE MINERAL PROCESSING OF ITS U-ORE

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ARTICLE INFO

Article History:
Received 17th May, 2018
Received in revised form
21st June, 2018
Accepted 14th July, 2018
Published online 31st August, 2018

Key Words:
U-mineralisation,
U-Mineral Processing,
Gudarukoppu U-ores,
Cuddapah basin, India.

ABSTRACT

U-mineralization in the Gudarukoppu area, close to the SE-margin of India's Mesoproterozoic Cuddapah basin is of a low-temperature, remobilized, hydro (epi)-thermal vein-type that appears to be a consequence of regional deformation - metamorphism-K-Mg-Fe-P-B-metasomatism, all of which affected the area to different degrees within the structurally weak major shear zone. Its U-ore (quartz apatite cataclasite, assaying 0.29% U3O8 and < 0.01% ThO2) was subjected to a preliminary laboratory-scale mineral processing study. This resulted in 78% U-leachability with 180 kg/ton H2SO4 and 50 kg/ton each of MnO2 and FeSO4 at 45°C temperature. The leached pulp was further subjected to vacuum filtration to separate leach liquor that was then subjected to purification and solvent extraction, when U was precipitated as Magnesium Di-Uranate (yellow cake), analysing 70% U3O8. To reduce both high acid-consumption and operation-cost during processing of the ore for preparation of yellow cake, (a) removal of phosphate by flotation before acid-leaching, (b) introduction of FeSO4 to the leaching circuit to maintain the required oxidation-reduction potential (- 430mv) in the system and (c) extraction of light REEs (~0.25%) from apatite (gangue) are suggested for further study.

Citation: Dhana Raju, R., Lakshminarayana, Y. and Sudhakar, Ch. 2018. "Uranium mineralization from gudarukoppu, se-margin of the Cuddapah Basin, A.P., India and laboratory-scale mineral processing of its u-ore", *International Journal of Development Research*, 8, (08), 22507-22514.

INTRODUCTION

India's Mesoproterozoic Cuddapah Basin (CB), with an extent of ~ 44,500 sq km area and high mineral potentiality for both metallic and non-metallic resources, which are under exploitation since many decades include lead, zinc, copper, iron, manganese, limestone, dolostone, barite, asbestos, phosphorite, dimensional stones and diamonds, is emerging as a U-hub (Dhana Raju, 2009a). During the last 7 decades, exploration for radioactive minerals by the scientists of the Atomic Minerals Directorate (AMD) for Exploration and Research of the Department of Atomic Energy (DAE), Govt. of India resulted in establishment of 2,73,956 t U_3O_8 (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 but low-grade strata-bound phosphatic, siliceous carbonate-hosted U-deposit (presently under exploitation by the UCIL of DAE) in the Tummalapalle – Giddankipalle area in SW part of 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 mineralization in the quartzite in the Gandi area in SW part (Umamaheswar *et al.* 2001), (ii) fracture-controlled mineralization 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) (Dhana Raju, 2009a) (Fig. 1a). U from the above deposits and prospects is mainly meant for use as the fuel for 20 operating, 4 under construction and 10 proposed PHWR-type nuclear power plants in India that is going for clean nuclear power and

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renewable energy (wind, solar, hydro and bio) so as to reduce much the ill-effects of greenhouse gases, which are causing global warming with disastrous consequences like rise of sea level, submergence of coastal areas, melting of glaciers, etc.

In the study area of Gudarukoppu, the shear zone extends for a length of 750 m, within which the U-mineralized zone occurs for a length of 70 m and width of 1-2 m (Fig. 1b). In this mineralized zone, U-mineralization is hosted by quartz-apatite cataclasite and apatite-bearing biotite quartz of eldspathic schist.

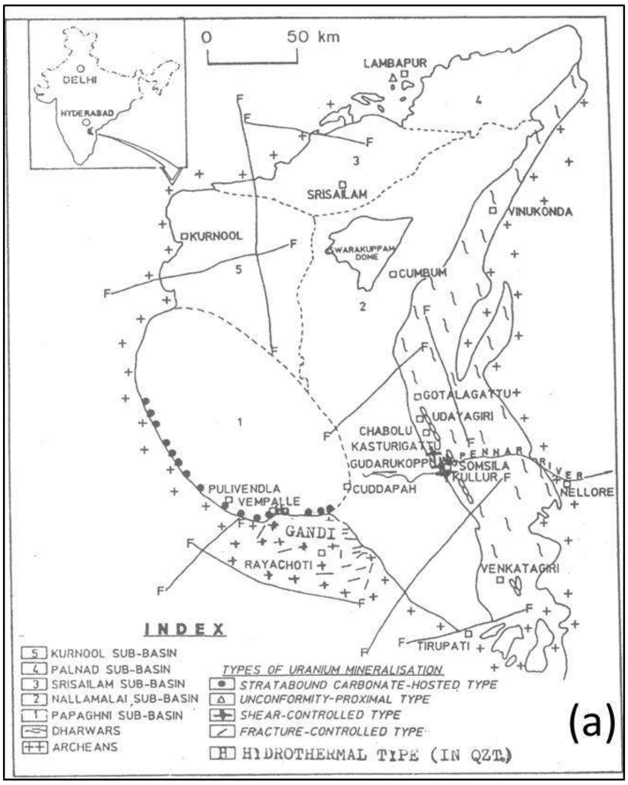

Fig. 1a. Cuddapah basin and its sub-basins, with location of different types of U-deposits and –prospects, both within and in its environs

The U-ore (quartz-apatite cataclasite), with a feed assay of 0.29% U_3O_8 and < 0.01% ThO_2, was subjected to a preliminary laboratory-based mineral processing (Sudhakar, 1996). Salient features of the U-mineralization in the area, methods and materials used in the study, and results, including of mineral processing, are presented and discussed in this paper. Besides, a few suggestions are given for future work toward cost-reduction.

MATERIALS AND METHODS

Different methods of investigation undertaken and materials involved in each of these are given below, starting from the field traverses in the Gudarukoppu area under study till mineral processing of the fully characterized representative U-ore, through the stages of sample collection, 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, fluorescence study under Ultra-Violet (UV) light, X-Ray Diffraction (XRD) study on selected radioactive samples, radiometric analysis, geochemical analysis on petrographically-characterised representative samples for major, minor and trace elements, including Rare Earth Elements (REE). Details of these methods of study can be had from Dhana Raju (2009b and c). Results of these studies on samples of the present investigation are given in the next section.

***Field Study*:** Utilising the geological map of the Gudarukoppu – Kasturigattu area, prepared earlier by Veerabhaskar *et al.,* 1991) (Fig. 1b), a number of field traverses around Gudarukoppu and its environs were carried out to understand different geological aspects like the rock types in the area, their stratigraphic sequence, tectonic and structural relationship, and examination of previously located radioactive anomalies by the officers of AMD, Southern Region (SR), Bangalore.

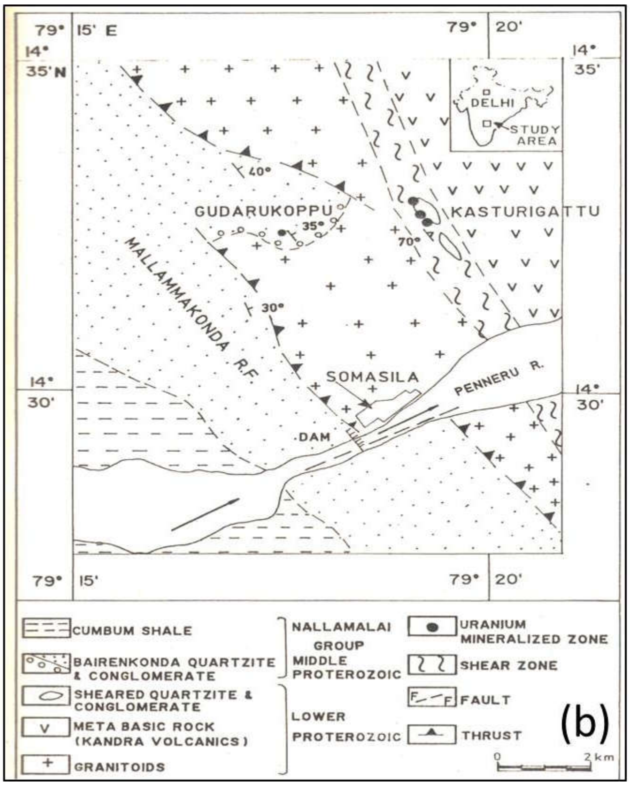

Fig. 1b. Geological map of the Gudarukoppu – Kasturigattu area, Nellore district, Andhra Pradesh, with location of the U-mineralized areas (from Veerabhaskar *et al*., 1991)

***Sample Collection and Specimen Preparation*:** Over 50 samples, each of 3-4 kg, of different rock types in the study 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 like structures like schistosity, gneissosity, micro-folding, etc., and surface features, including encrustations and cavities. 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.

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.

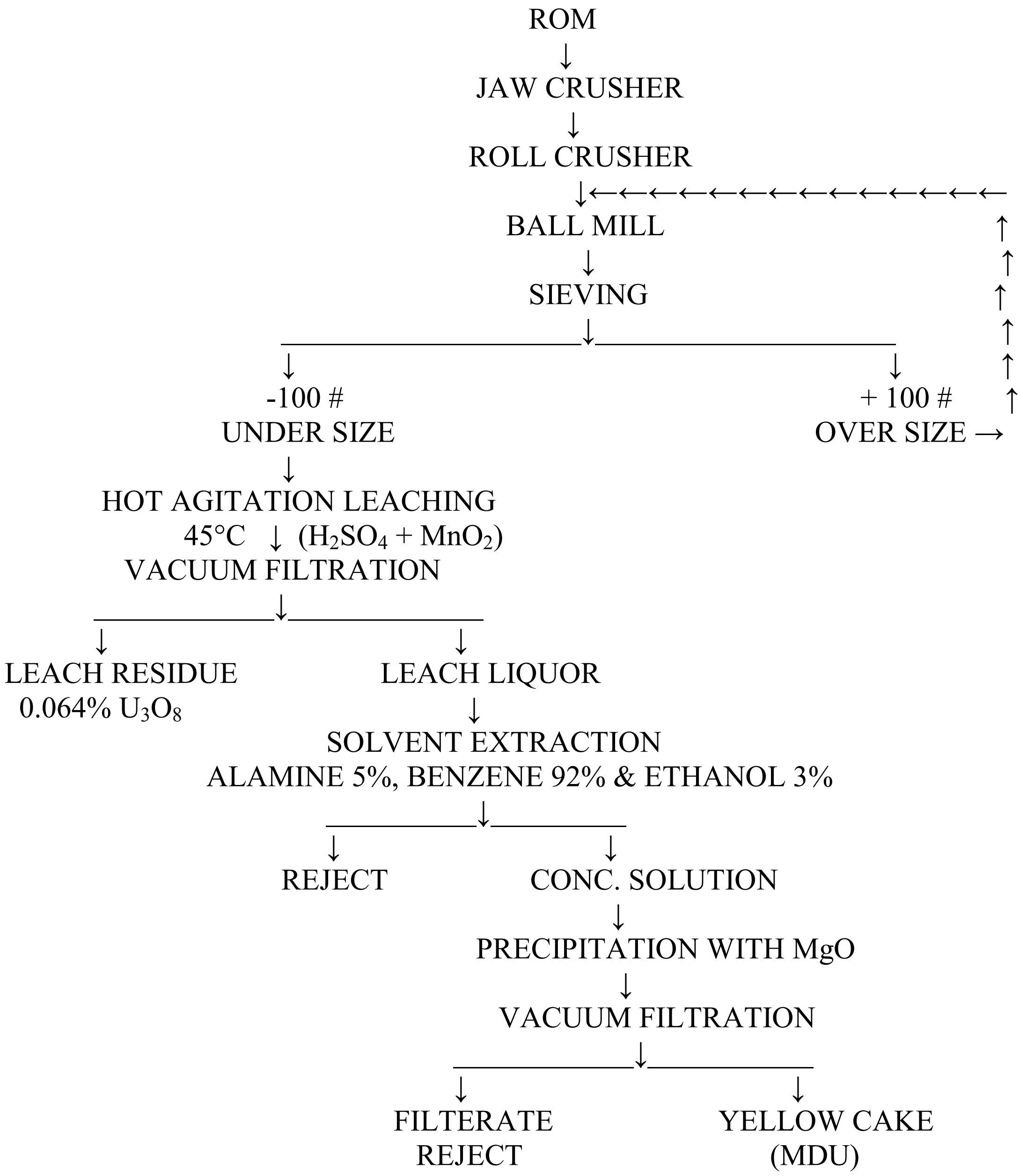

Fig. 2. Flow-Sheet for mineral processing of the Uranium ore (quartz-apatite cataclasite) from Gudarukoppu, Andhra Pradesh, India

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, and CN film autoradiography.

***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 and 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.

***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 ferrocydanide solution by sprinkling, when brown, rose red and blue coloured spots appeared corresponding, respectively, to leachable minerals of U, Cu and Fe.

***Fluorescence study under UV light*:** This was carried out on the surface of hand specimens, uncovered polished slabs and polished thin sections of radioactive samples by exciting them with short wavelength (185-300 nm) UV light from the MINERALIGHT model MPR2 of M/s. Ultraviolet Products Inc., San Gabriel, California 91778, USA, when weak yellowish-green fluorescence was recorded from a secondary uranyl mineral that was scratched from hand specimen and its powder was later identified by XRD study.

***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 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, 200-300 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.

***Radiometric analysis*:** Contents of radio-elements (U, Th and K) of radioactive samples [drawn in the field from radioactive areas that record > 5X 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).

***Chemical analysis*:** This was carried out by various instrumental methods, titrimetry and gravimetry for different major, minor and trace (including RE) elements, as per the methods detailed by Satyanarayana (1986) and Dhana Raju (2009c), with the starting material of -300 mesh powder. 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; Loss-on-Ignition (LoI) by gravimetry; and REE by INAA.

***Mineral Processing*:** Bulk sample (1-2 kg) of the U-ore (quartz-apatite cataclasite) 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 (Table 1) 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. The non-magnetic heavy fraction was subjected to chemical analysis for CaO and P_2O_5, and mineral-analysis by volume. After these operations, hydrometallurgy by acid-route (since the ore has silicate gangue in the form of quartz and other silicate minerals like biotite and zircon) 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 (Table 2). The leached pulp was subjected to vacuum filtration to separate the leach liquor from the residue. As the leach liquor contains U and contaminants like Fe^{3+}, Fe^{2+}, V, Mn, Ca, Mg, Ti, silicic acid and others, a purification process was adopted. In this, the initial step was to bring the transfer of the desired U from the feed solution (aqueous phase one) into organic or solvent phase, which is termed as ‘extraction’. The second step, called ‘stripping’ recovers the purified and concentrated U-product into the second aqueous phase, after which the barren organic liquid is recycled to the extraction step. Extraction of either the cationic or anionic form causes a shift in the equilibrium to form more of the removed ions until extraction is completed. Solvents like alamine 336 (tertiary amine), other secondary amines and alkyl phosphoric acid extract U from sulphate solutions in the extraction stage, as per the following equation:

$$2R_2NH_2^{+} + UO_2(SO_4)^{2-} \rightarrow R_2\,NH_22UO_2(SO_4)_2 \quad .....(1)$$

In the stripping stage, as per the following equation, U was removed in the aqueous phase consisting of 1 to 3 molar chloride or carbonate solutions:

$$R_2NH_2\,2UO_2(SO_4)_2 + 2Cl \rightarrow 2R_2NH_2Cl + UO_2(SO_4)_2^{2-} \quad .....(2)$$

Usually 5% solution of the extracts used in alcohol is normally added to prevent formation of emulsion during shaking.

Next, U was precipitated as ‘yellow cake’ by addition of magnesium oxide. This operation of precipitation was carried out in a beaker, followed by vacuum filtration. U_3O_8 content of the yellow cake was determined.

Material balance: Based on 1 kg ore, it is assumed that the ore contains 0.3% U_3O_8. Pyrolusite (MnO_2) and strong acid (H_2SO_4) were used. Evaporation during leaching was ignored. Knowing the maximum % leachability in 666 ml solution, leached residue was assayed for U_3O_8. After stripping, the solution was precipitated with MgO, which yielded MDU (Magnesium Di-Uranate, yellow cake) that was assayed for U_3O_8.

RESULTS

Different investigative methods and materials (detailed in the preceding section) used in the present study, starting from field work involving traverses, radiometric survey, study of stratigraphic - structural – tectonic – mineralization - alteration aspects and sample collection at regular interval in the Gudarkoppu area till mineral processing of its U-ore, through various intermediate studies (*viz.,* preparation of thin and polished thin sections, and powders of bulk sample for radiometric- and chemical-analysis, petro-mineragraphy, fluorescence under UV light, CN film autoradiography, chromogram, XRD, major-minor-trace element, including REE, analysis and comprehensive characterization of the U-ore before mineral processing) led to the results, detailed below.

***Geological set-up*:** The Gudarukoppu – Kasturigattu area is a part of the crystalline complex along the SE environs of the Mesoproterozoic Cuddapah Basin (CB). This area lies in between the sedimentary rocks of the Nallamalai Group in the basin to its west and schistose rocks of the Archaean Nellore Schist Belt (NSB) to its east (Fig. 1b). It comprises the basement granitoid and its variants. Due to intense shearing, the original basement granitoid was subjected to different degrees of dislocation and related metamorphism and metasomatism, resulting in schistose/gneissose granitoid, mylonite, quartzofeldspathic schist, quartz-apatite cataclasite,

Table 1. Sieve analysis data of the U-ore (quartz-apatite cataclasite) from Gudarukoppu, A.P., India

Sl. No.	Mesh Size	Av. size in microns	% Weight	Cumulative Weight % Retained	Cumulative Weight % Passing	%U_3O_8 Assay	% Distribution
1.	-10 + 20#	1454	43.15	43.15	56.85	0.237	42.64
2.	-20 + 40#	635	17.86	61.01	38.99	0.227	16.88
3.	-40 + 60#	335	7.44	68.45	31.55	0.213	6.59
4.	-60 + 80#	215	4.46	72.91	27.09	0.246	4.59
5.	-80 + 100#	165	2.68	73.59	24.41	0.251	2.79
6.	-100+ 150#	128	3.87	79.46	20.54	0.289	4.67
7.	-150+200#	90	3.27	82.73	17.27	0.279	3.79
8.	- 200#	75	17.26	100.00	0.00	0.251	18.05

Table 2. Experimental parameters of mineral processing on the U-ore (-100#) from Gudarukoppu, A.P., India

Sl. No.	Time (h)	H_2SO_4 kg/ton	MnO_2 kg/ton	$FeSO_4$ kg/ton	Residue Assay U_3O_8%	BCF*on	Feed	% Leacha- bility
1.	6	9	5	-	0.134	0.390	88	66
2.	6	36	5	-	0.151	0.360	72	58
3.	6	81	9	-	0.127	0.295	58	57
4.	6	108	10	-	0.092	0.303	73	70
5.	6	250	-	-	0.090	0.290	70	69
6.	6	90	-	-	0.116	0.270	53	57
7.	12	225	50	50	0.059	0.275	74	78
8.	12	180	50	50	0.064	0.285	76	78
9.	12	180	100	100	0.070	0.226	54	69
10.	12	180	70	70	0.095	0.246	52	61
11.	12	180	60	60	0.069	0.261	66	76
12.	12	180	100	100	0.070	0.226	54	69

*BCF: Before Calculated Feed.

etc., whereas the 'Kandra volcanic rocks' of NSB, considered as a possible Precambrian Ophiolite Complex (Leelanandam, 1991), led to the development of biotite-chlorite schist and chlorite schist. These crystalline rocks thrusted over the entire margin of CB, resulting in structural complexity. The contact zone between these two major schist bands is highly crushed and sheared, resulting in the formation of fine-grained variants, the zones of which constitute the loci for the U-mineralization in the area.

***Petromineragraphy, CN film autoradiography and chromogram studies*:** Petrographic study on less deformed-metamorphosed granitoids and their highly deformed variants led to the following notable features: (a) Textural change from massive of the granitoid to different deformation textures like cataclastic, mylonitic, schistose and occasional gneissose; (b) Intense alteration, mainly biotitisation and sericitisation; (c) Notable effects of K-Mg-Fe-P-B metasomatism, mineralogically manifested, in the form of biotite, sericite, apatite and tourmaline; (d) The observed mineral assemblage of schists, phyllites and basic intrusive rocks indicates that the degree of metamorphism in the area is low-medium grade type of the upper greenschist to epidote-amphibolite facies at high P_{H2O}; (d) Most of the apatite in the quartz-apatite cataclasite and almost all the variants of the granitoids is secondary as attested by its vein-filling nature; (e) Mineragraphic study indicated that the U-mineralisation is low-temperature, remobilized, epigenetic hydrothermal type related to intense activity of fluids rich in volatiles such as H_2O, Cl, F and B. It is in the form of (a) easily leachable ultrafine *pitchblende* [$(U^{4+}U^{6+}O)_{2+X}$; located by CN film autoradiography], which is present either as disseminations or granules constituting clusters or vein-lets along the weak planes; and (b) easily leachable yellow encrustations and fracture- and cavity-fillings of uranyl mineral(s) in a few rock types like quartz-apatite cataclasite, with the uranophane dominant over pitchblende. In addition, very low-order radioactivity is associated with apatite, zircon, limonite, chlorite and smectite, as indicated by sparse to very sparse alpha tracks recorded on CN films. Other ore minerals identified include sulphide minerals (pyrite, chalcopyrite, pyrrhotite and galena), rutile and martitised magnetite. The U-ore (quartz-apatite cataclasite) comprises ~ 70% apatite, with subordinate amount of quartz, minor biotite and ferruginous material, and accessory zircon and opaque ore minerals. Apatite is present in two modes (i) coarse-grained, sub-rounded to rounded type (0.18-0.66 mm) and (ii) fine-grained (< 0.03 to 0.09 mm) type that occurs as in-fillings along the grain boundaries of the former.

***XRD and florescence studies*:** XRD study on methylene iodide-heavy fraction of quartz-apatite cataclasite confirmed the pitchblende, earlier identified by mineragraphic study, as detailed above. Fluorescence study under UV light on the scratched material from the yellowish green coloured encrustations present on the surface of highly radioactive quartz-apatite cataclasite and apatite-bearing quartzofeldspathic schist showed weak yellowish-green fluorescence. This material on XRD study was identified as *uranophane* [$(Ca(UO_2)_2 Si_2O_7.6H_2O]$.

***Radiometric analysis*:** Amongst the analysed rocks, quartz-apatite cataclasite and quartzofeldspathic schist recorded high radioactivity up to 0.36% U_3O_8 and 0.05% ThO_2.

***Geochemical analysis*:** Eleven whole-rock samples, *viz.,* quartz-apatite cataclasite (2 samples), schists (2), phyllites (2), quartzite (4) and conglomerate (1) were analysed chemically for their major, minor and trace elements, including REE. The chemical analysis of the U-ore (quartz-apatite cataclasite; sample no. GKCS-2B)) that was subjected to mineral processing is as follows:

Major and minor elements, in oxide form (in wt. %): SiO_2: 17.38, Al_2O_3: 1.92, Fe_2O_3: 1.58, FeO: 0.36, MgO: 1.16, CaO: 41.80, Na_2O: 0.14, K_2O:0.46, TiO_2: < 0.01, P_2O_5: 31.34, LoI: 1.20. Trace elements (in ppm): V: 229, Cr: 109, Co: 34, Ni: 67, Cu: 68, Ga: 18, Y: > 1000, Zr: 359, Pb: > 200, U: 2595, Th: 78; REE (in ppm): La: 725, Ce: 1052, Nd: 425, Sm: 85, Eu: 30, Tb: 38, Tm: 13.5, Yb: 83 and Lu: 11.2; ∑REE: 2462.7.

***Mineral Processing*:** The U-ore from Gudarukoppu that was subjected to laboratory-based mineral processing (Sudhakar, 1996) is the 'radioactive quartz-cataclasite' (bulk sample no. GKCS-2B). Megascopically, this U-ore is fine grained, yellowish brown coloured with yellow coloured surface encrustations of uranyl mineral, identified by XRD study as 'uranophane' (see item no. 3 above). Microscopically, it consists of dominant apatite (~ 70 vol. %) with lesser amount of quartz, biotite and still lesser ferruginous material, and accessory zircon and smectite. As noted under the item no. 2 above, apatite occurs in two modes: coarse grained (0.18-0.66 mm) and fine grained (< 0.03-0.09 mm). As the sieve analysis data of the sample (Table 1) and the experiments conducted on it in laboratory indicated that the optimum pre-determined size is -100 mesh (-149 microns), the ore was subjected to comminution by crushing it in a jaw-crusher followed by grinding in a ball mill so as to obtain materials of -100 mesh product. Under physical beneficiation, the –100 mesh material of the sample was subjected to de-sliming and heavy liquid separation, using bromoform. The bromo-heavies were then subjected to magnetic separation, first with a low-powdered hand magnet to remove magnetite and then in a Frantz isodynamic separator at 0.2-0.3 amp to remove left out magnetite (after hand magnet separation) and other magnetic materials. The non-magnetic fraction analysed 46% CaO and 33% P_2O_5. The minerals identified in this non-magnetic fraction are apatite (76%), quartz (23.5%) and biotite + zircon (0.5%). As the ore contains silicate gangue, hydrometallurgy through acid-route was adopted. This procedure comprises sequentially leaching U from the ore, solid - liquid separation, purification by solvent extraction and finally precipitation of U as 'yellow cake'. The experimental procedure adopted under this is as follows:

100 g of -100 mesh size sample-powder of the U-ore was taken with 66.66 ml distilled water in a 400 ml beaker and kept on a hot plate, maintaining a temperature of 45°C with proper stirring arrangement. 10 ml of H_2SO_4 (180 kg/ton) and 50 g each of MnO_2 and $FeSO_4$ were used to maintain the required oxidation-reduction potential for dissolution of U. Series of hot agitation experiments were conducted with different parameters, as shown in Table 2. A maximum U-leachability of 78% was achieved for the U-ore under mineral processing study. The leached residue analysed 0.064% U_3O_8, starting from a feed assay of 0.285% U_3O_8. The leach liquor contained U with contaminants like Fe^{3+}, Fe^{2+}, V, Mn, Ca, Mg, Ti, silicic acid and others. As precipitation of U from such leach liquor will yield a product with a very low U_3O_8 content, a purification step was needed, whereby the U content of the liquor is not only increased by several factors but also most of the impurities will be removed. For such purification, 'solvent extraction' was adopted, using solvents like alamine 336, other secondary amines and alkyl phosphoric acid to extract U from sulphate solution, as per the procedure and equation (1), given earlier under item no. 10 of the 'Materials and Methods' section. This 'extraction' stage was followed by 'stripping' stage during which U was removed in the aqueous phase, as per the equation (2) (see under item no. 10 of the 'Materials and Methods' section). Usually 5% solution of the extractants used in alcohol is usually added to prevent formation of emulsion during shaking. An extraction time of 1-2 minutes at O: A (Organic : Aqueous) of 1:5 during extraction and 2:1 to 5:1 during stripping yielded high efficiency. Finally, U was precipitated as 'yellow cake' by addition of magnesium oxide that is having advantages like increased safety in handling and transportation of the solid MgO, and rapid filtration of product, as against sodium hydroxide. The operation of 'precipitation' was carried out in a beaker, followed by vacuum filtration. Yellow cake (Magnesium Di-Uranate, MDU) analysing 70% U_3O_8 was obtained in the present investigation. Material balance was calculated based on 1 kg U-ore containing assumed 0.3% U_3O_8, ignoring evaporation during leaching and maximum leachability of U (78%) into 666 ml of solution leached residue that assayed 0.064% U_3O_8. The flow sheet adopted for processing the U-ore (quartz-apatite cataclasite) under study, as detailed above, is given in Fig. 2.

DISCUSSION

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

***Parental rock for U-mineralisation*:** The Gudarukoppu area, being adjacent to the highly disturbed E and SE margins of the Cuddapah basin, was subjected to intense deformation, metamorphism and metasomatism, which made it almost impossible to get un-deformed/un-metamorphosed granitoid, parental to the U-mineralisation in the area. Out of such deformed granitoids, the one with the least imprints of deformation and metamorphism was taken as the nearest representative of the original un-deformed granitoid. Characteristics of such sample like GKCS-3 from Gudarukoppu indidcate that the original granitoid in the area is a biotite granite and per-aluminous in nature, with normative corundum of > 3% and A/CKN ($Al_2O_3/CaO+K_2O+Na_2O$) > 1.1. Its relatively high U content(17 ppm against crustal average of 4 ppm), lesser Th content (15 ppm, comparable with crustal average of 16 ppm) and Th/U value of < 1 against crustal value of 3.5 to 4 all indicate that it is a *fertile granitoid* from the point of U, which is also *parental* to the U-mineralization in the area.

Host Rocks for U-mineralization: Radioactivity, mostly due to U, in the Gudarukoppu area is almost restricted to quartz-apatite cataclasite and apatite-bearing biotite quartzofeldspathic schist, which are the deformed, metamorphosed and K-Mg-Fe-P-B metasomatised variants of parental granitoid that was affected by the basic rocks of the Kandra basic volcanics (amphibolites, hornblende schist and tremolite actinolite schist) resulting to de-silicification of the granitoid. Thus, the rocks of quartz-apatite cataclasite and apatite-bearing biotite quartzofeldspathic schist are the de-silicified products of fertile granitoid affected by the Kandra volcanics and also constitute the *host rocks* for the recorded U-mineralization in the area. The U-ore, subjected to mineral processing, is quartz-apatite cataclasite.

Mineragraphy of the U-mineralization**:** The ore minerals in the U-mineralized cataclasite and schist cited above are pitchblende and uranyl mineral (uranophane), associated with traces of sulphides like pyrite, chalcopyrite, pyrrhotite and galena, and oxides like martitised magnetite and limonite. In this ore, 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 and apatite, whereas uranophane occurs as encrustations and cavity-fillings on the surface of the radioactive rocks. The pitchblende-bearing rocks contain plenty of apatite and less of biotite-tourmaline, which indicate that the formation of pitchblende took place possibly during the K-Mg-Fe-P-B metasomatism during the de-silicification stage. The presence of U^{6+}-bearing uranophane and pitchblende in which part of U is in the U^{6+} form, indicates that the area is potential for U-mineralization with a distinct possibility of depth-wise continuity of the primary U-mineralization in the form of uranous (U^{4+}) phases in a reducing environment.

Type of U-mineralization**:** The (a) association of pitchblende with the volatile-rich minerals like apatite, biotite and tourmaline, (b) its form as vein-lets and along weak planes, (c) its relatively higher oxidation state of 'U' (U^{6+}) and (d) presence of uranophane filling cavities and fractures in the rock, all point out that the U-mineralization is of low-temperature, remobilized, epigenetic, hydrothermal vein-type that appears to be a consequence of regional deformation-metamorphism-metasomatism, which affected the area to different degrees within the structurally weak major shear zone.

Mineralogical Alterations**:** The important mineralogical alterations that have direct bearing on the U-mineralisation in the study area are biotitisation and apatitisation. The sources for such extensive biotitisation appear to be more than one with 'K' from parental granitoid and 'Mg-Fe' from basic rocks of the adjoining NSB as well as Dharwrian basic schists, while large scale structural disturbances could have facilitated movement of volatiles like H_2O, F and Cl. The source for apatitisation is still uncertain. However, the reported high P_2O_5 content (> 2%) in some of the amphibolites of NSB, with their precursor low-K tholeiitic magma from a P- and REE-enriched mantle (Satyanarayana *et al.* 1994), suggests the possibility of the amphibolites being a possible source for P.

Controls and Guides for U-mineralisation**:** The following are the major controls of U-mineralization in the area: (a) structure in the form intense shearing resulting in much deformation, manifested by cataclasite and mylonite; (b) lithology, with the host rock for U-mineralization being variants of fertile granitoid like cataclasite and schist; (c) metamorphism of the greenschist to epidote-amphibolite facies and K-Mg-Fe-P-B metasomatism; and (d) alterations mainly biotitisation and lesser sericitisation. The guides for U-mineralization are: (a) zones of volatile-rich activity; (b) high concentration of secondary minerals like biotite and apatite; and (c) pockets of sulphide-concentration and vein quartz.

Mineral Processing**:** A maximum leachability of 78% U was achieved in the laboratory for the U-ore of quartz-apatite cataclasite, using 180 kg/ton of H_2SO_4 and 50 g each of MnO_2 and $FeSO_4$. The relatively low leachability of this U-ore, in spite of its easily leachable minerals like pitchblende and uranophane, and high acid consumption, are ascribed to high content of phosphate (~ 32%) in the form of apatite. This necessitates some pre-concentration of the ore by flotation or some other suitable technique to separate apatite for increasing the leachability of U with less acid consumption. Furthermore, the leaching of this ore was complicated due to its very low content of iron and, hence, needs addition of some iron compound like FeS_2 for maintaining Eh. As the U-ore contains high content of ∑REE (0.25%), especially LREE (*cf.* ~ 2% in the apatite from apatite-magnetite veins in the Narasingarajapuram area, Visakhapatnam district, AP; Panda *et al.*, 2015), it will be fruitful to extract the REEs from apatite as a bi-/co-product during mineral processing. This operation will reduce substantially the cost of mineral processing of the U-ore, due to high price of REEs that are much sought after for their use in many high-tech industries like lasers, superconductors, electronics, ceramics, fibre optics, nuclear, defence, metallurgy and electric vehicles (Dhana Raju and Venkat Reddy, 2016). All these suggestions for future work require an in-depth and comprehensive mineral processing study on the U-ore from the area under study, both on laboratory- and pilot plant-scale, which, however, is beyond the scope of the present investigation.

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 field work and Mr. K. Muniyappa for studies in the Mineral Technology Lab., SR.

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