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Review Article

Radioactive Minerals: General Status

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This article presents a brief review on new radioactive mineral occurrences brought to light during the period 2015 to 2019. It is noted that new occurrences are located in extension areas of already known provinces/geological settings, where exploration work is under progress. Uranium mineralization is also intercepted in a new host rock (altered ultramafic suite) in the environs of the Singhbhum shear zone. Uranium oxide reserves have been augmented to more than three lakh tonnes by Atomic Minerals Directorate for Exploration and Research (AMD), Department of Atomic Energy, Government of India.

Introduction

Growth of any country is measured by per capita consumption of energy. To meet ever growing energy requirements, it is necessary to tap energy from all possible sources. However, due to environmental degradations linked with energy production there is progressively increasing demand for clean energy sources. In this regard, nuclear energy finds a vital place as it is a clean energy. Accordingly, there is a growing demand to augment uranium resources to meet increasing applications of uranium as fuel in nuclear power programme of India. This article presents a brief review on notable new radioactive mineral occurrences/prospects brought to light during the period 2015 to 2019. So far, uranium oxide reserves have been augmented by AMD to more than three lakh tones (PIB Delhi, posted on 16 May 2019 12:08PM; pib.nic.in). If some new reported finding during the relevant period is left out, it is unintentional and the author regrets for such an inadvertent omission.

Cuddapah Basin

The Proterozoic Cuddapah basin and its environs are considered as storehouse for different types of uranium deposits (Sinha *et al*., 1996). Granites forming the basement in environs of the Cuddapah basin contain anomalous uranium and thorium (Shrivastava *et al*., 1992; Dhana Raju *et al*., 2002), which are contributed by their various mineral species (Singh and Viswanathan, 2012). Unconformity-related uranium mineralization present in northern part of the Cuddapah basin in and around Lambapur-Peddagattu-Chitrial areas is considered economically viable (Sinha *et al*., 1995, 1996). Recent work by Atomic Minerals Directorate for Exploration and Research (AMD) in northern parts of the Cuddapah basin has brought to light additional zones of uranium mineralization both in basement granites and overlying sedimentary cover rocks, some being located along the unconformity and others either on the basement rocks or in the cover rocks. Salient features of these uranium mineralized areas are summarized below.

Mastipuram area, Wanaparti District, Telangana

New zone in northern parts of the Cuddapah basin has come to light in Mastipuram area, Wanaparti district, Telangana State, where 8 leucogranite-hosted uranium mineralized bodies have been reported (Rajaraman *et al*., 2019). The radioactive

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leucogranites intrude Archaean Peninsular Gneissic Complex (PGC) and occur as NNW-SSE trending linear bodies. Leucogranites, containing orthoclase, microcline, perthite, plagioclase (albite-oligoclase) and quartz (Fig. 1a), show sericitisation and occasional sassuritisation of plagioclase that are marked by the presence of zoisite, clinozoisite, epidote and calcite. Biotite occurs mostly as segregation along interstices of major minerals and alters to chlorite. Allanite (Fig. 1b), sphene, zircon, apatite, magnetite, hematite, ilmenite, pyrite, anatase and goethite occur as accessories.

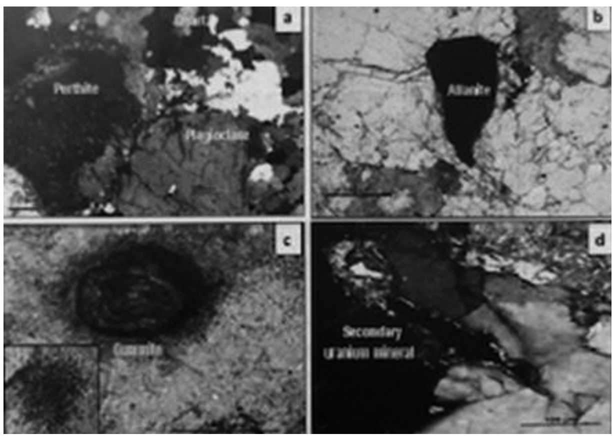

Fig. 1: Microphotographs of leucogranite showing (a) Hypidiomorphic granular texture; (b)Allanite inclusions and radial cracks in its host feldspar; (c) Feldspar-hosted gummite (altered uraninite) and corresponding alpha tracks; and (d) Segregations of secondary uranium mineral along fracture planes (after Rajaraman *et al*., 2019)

Mineralised leucogranites contain 0.01 to 0.25% U_3O_8 with negligible to notable amounts of thorium (0.005 to 0.084% ThO_2). Uranium is contributed mainly by gummite (altered uraninite), and schoepite, uranophane and haiweeite (Rajaraman *et al*., 2019). Uraninite occurs as inclusion within feldspar (Fig. 1c), whereas secondary U minerals are present as segregations along fractures (Fig. 1d). Shielded-probe logging of leucogranite outcrops revealed 0.01 to 0.05% eU_3O_8 with mineralized widths of 0.80 m to 10.0 m. Results of initial 10 boreholes indicated highly variable width of mineralized bands (1 to 31 m), with a vertical impact of about 50 m (Rajaraman *et al*., 2019).

Koppugattu-Bamanapalle area, Mahboobnagar District, Telangana

At Koppugattu, the radioactive granite outcrop extends over a total strike length of 50 m along the unconformity and is restricted to basement granite (Mukundan and Parashar, 2016). The samples analysed 0.037 to 0.046% U_3O_8. The radioactivity is contributed by secondary uranium minerals that are observed along the fracture planes, intergranular spaces and also as clusters within the feldspar. U-Ti complex also occurs along the fractures and records medium density alpha tracks. The non-mineralised counterpart of granite also have elevated abundances of radioelements, namely, U (9-21 ppm) and Th (39-46 ppm). In Bamanapalle area, N-S trending intensely altered ferruginised basic dyke, having dimension of 25 m x 2 m, records radioactivity due to uranium, assaying 0.38 to 1.44% U_3O_8. The dyke occurs close to unconformity contact. Basic dyke is coarse-grained, green coloured and contains chloritized fragments containing granular anatase and sphene. Ophitic texture is marked by plagioclase feldspar that is enclosed in chloritized fragments showing varying degrees of alterations. Due to intense fracturing, brecciation and alteration initial fabric of mineralized basic dyke has been obliterated. Fractures have been invaded by felsic material comprising microcrystalline quartz and little amount of feldspar. Hydrothermal activity resulted in formation of chlorite occurring as veins and pseudomorphic replacements of earlier formed minerals retaining their cubic/hexagonal morphology. Radioactivity is contributed by secondary uranium minerals hosted in felsic material, with U also being adsorbed on anatase and hydrous iron oxide (Mukundan and Parashar, 2016).

Kappatralla area, Kurnool District, A.P.

Uranium mineralization is hosted by Gulcheru Formation in Kappatralla area, Kurnool district, A.P., which occurs as outlier above basement granites, over an area of about 3.5 km^2. Mineralisation, with 0.018% to 0.16% (av. 0.058%) U_3O_8, occurs between two NW-SE trending faults (Jain *et al*., 2017a). The non-mineralised granite contains on an average 29 ppm U and 40 ppm Th (Rajaraman *et al*., 2018), which are higher than their contents in average granite. Borehole data revealed correlatable bands recording radioactivity of 0.014-0.19% eU_3O_8 with a thickness of 1.40-4.60 m and depths range of 9.30 m –16.0 m

(Rajaraman *et al*., 2019). The basement granites and overlying sediments bear signatures of hydrothermal activities and attendant enrichment of radioelements in the environments of unconformable contacts.

North Delhi Fold Belt

Bucharaarea, Jaipur District, Rajasthan

The Proterozoic Delhi Supergroup rocks of North Delhi Fold Belt (NDFB) is one of the prime target for base metals, uranium and other economic mineral prospects. Intensive exploration over the years by AMD helped in identification of uranium mineralisation at various places in Khetri sub-basin of NDFB (Singh *et al*. 1998; Yadav *et al*., 2002; Khandelwal *et al*., 2010, 2018; Singh *et al*., 2013; Padhi *et al*., 2016), which exposes rocks of the Alwar and Ajabgarh Groups that are intruded by granite, pegmatites and quartz veins (Sinha-Roy *et al*., 1998). Radioactivity is known to be contributed by several uranium, thorium, multiple oxide, yttrium and rare-earth-bearing minerals (Singh *et al*., 2012). Ongoing geological and radiometric surveys for uranium has resulted in locating significant new uraniferous zones in Buchara area, Jaipur district, Rajasthan (Patel *et al*., 2018), which also forms a part of the Khetri sub-basin of NDFB. The area around Buchara exposes calc-silicate, mica schist of Ajabgarh Group and pegmatites. Buchara area falls in the hinge zone of Todra-Buchara syncline. The NNE-SSW to NE-SW trending calc-silicate is flanked by mica schist in the east and west. Uranium mineralization associated with calc-silicate is located about a kilometre southwest of Buchara village. Based on radiometric data eight anomalous zones, ranging from 4m x 1m to 68m x 39m in four hillocks, have been recognised (Patel *et al*., 2018). Grab samples (n=12) contain 0.010 to 0.63% U_3O_8. Carbonaceous mica schist is also radioactive due to uranium (0.025% U_3O_8). Uranium is contributed by euhedral aggregates of uraninite, which occur in association with pyrite (Fig. 2a). The host-rock calc-silicate is albitised, and also contains subordinate amounts of tremolite, diopside, wollastonite, scapolite, sphene and graphite (Patel *et al*., 2018).

The association of uranium mineralisation with albititic alteration and sulphides indicates epigenetic nature of uranium mineralisation. The fault/fracture system related to polyphase deformational episodes in NDFB appear to have played an important role in the repeated circulation of uranium bearing hydrothermal fluids causing remobilisation and reconcentration of uranium along weak planes (Fig. 2b). Prevalence of reducing environment, as revealed by the presence of sulphides and carbonaceous schist, might have been responsible for precipitation of uranium from hydrothermal fluids.

Chhotanagpur Granite Gneissic Complex

Chhotanagpur Granite Gneissic Complex (CGGC) is an ENE–WSW trending terrain in the eastern part of Central Indian Tectonic Zone (CITZ) and covers an area of about 80,000 km^2. It is bounded by the Singhbhum mobile belt in the south, the Gangetic alluvium in the north and by the Rajmahal basalt in the northeast. In the west, CGGC is separated from CITZ by younger Gondwana sediments. The terrain consists mostly of gneisses and migmatites with numerous metasedimentary enclaves of varying metamorphic grade which are in turn intruded by

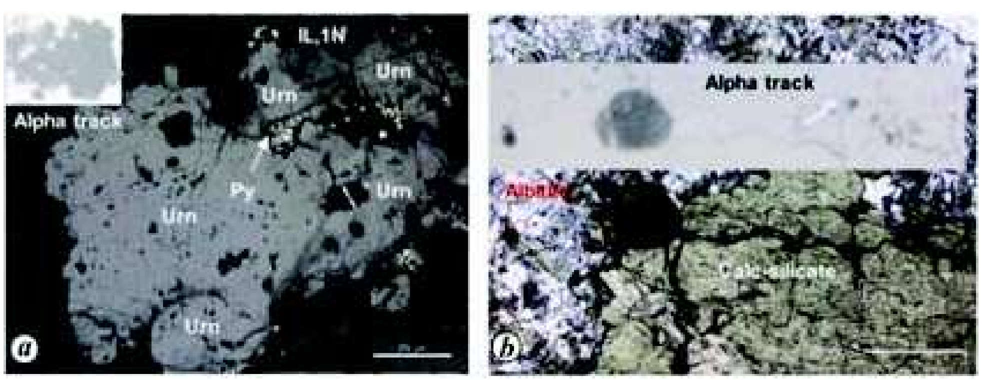

Fig. 2: Microphotograph of (a) Aggregates of uraninite grains (and associated pyrite) alongwith corresponding very dense alpha tracks on CN-85 film; and (b) occurrence of uraninite along fractures of calc-silicate rock (after Patel *et al*., 2018). Urn = Uraninite; Py = Pyrite

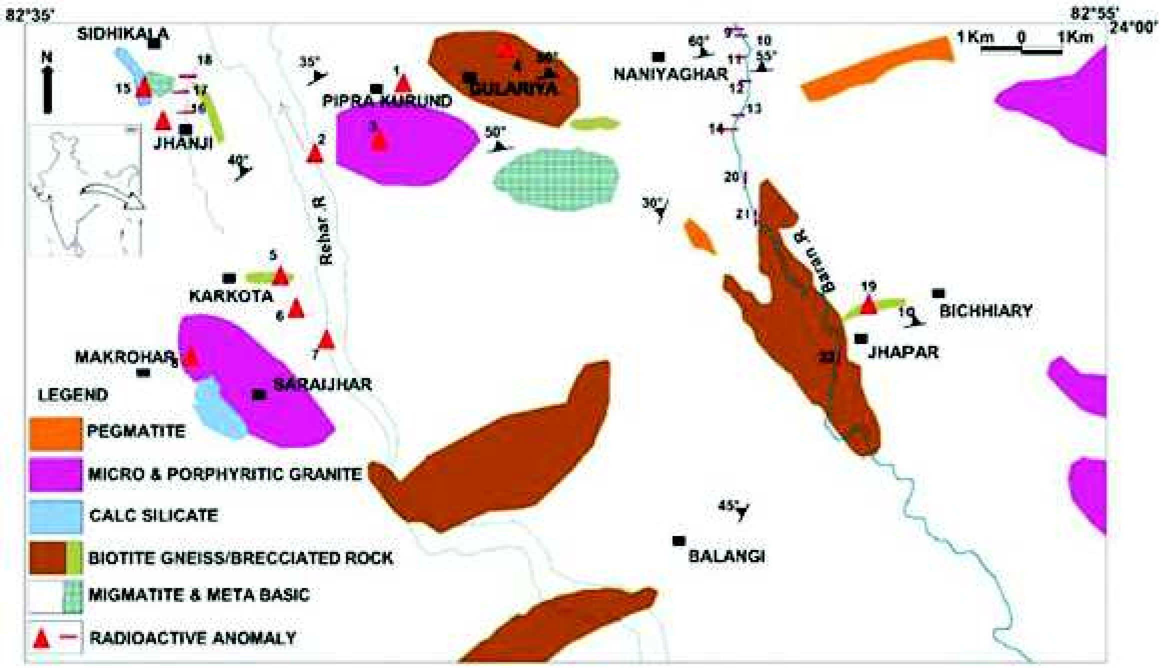

Fig. 3: Map showing various geological units in northern part of Surguja district with locations of radioactive migmatites near Naniyaghar-Jhanji (after Ajay Kumar *et al.*, 2019)

metabasic, an orthositic and granitic plutons. Exploration efforts resulted in location of uranium mineralization in the central Sarguja shear zone, Binda-Nagnaha, Gularia, Belda, Jhapar, Bichhiari, Mahuli, Rasgandha, Naktu, Kudar, Nawatola, Lakhar, Sirsoti, Kudri, Kundabhati, Jaurahi and Anjangira areas, U being hosted mainly in pegmatoid leucosome mobilizate (PLM) and granitic bodies within the migmatite of CGGC (Saxena *et al*. 1990; Bhattacharya *et al*., 1992; Sinha *et al*., 1992; Khandelwal and Tiwari, 1996; Mahendra Kumar *et al*., 1998; Singh *et al*., 1999; Bidwai *et al*., 2013). In these areas uranium is contributed by various radioactive mineral assemblages (Singhand Viswanathan, 2011). Subsurface exploration by AMD indicated low-grade, low-tonnage of U-mineralisation in the area in parts of Sonbhadra district of Uttar Pradesh (Parihar, 2014).

Baranand Gabala River Sections, Singrauli District, M.P.

Current radiometric surveys revealed additional areas of uranium mineralization associated with migmatites along Baran and Gabala River sections in south-eastern part of Singrauli district of Madhya Pradesh (Ajay Kumar *et al*., 2019). Nine radioactive migmatite bands have been recognized in upstream direction along Baran River section having dimensions from 5m-100m to 1.5m-10m (Fig. 3). Similarly in Gabala river section, three radioactive bands of migmatite are exposed having dimension of 3 m-35 mX0.5 m-15 m.U content ranges from 93 ppm to 534 ppm with an average of 235 ppm (Ajay Kumar *et al*., 2019). Radioactivity is mostly due to uraninite, and is confined to leucosome part of migmatite (Fig. 4a). Normally, uraninite occurs in the form of inclusions within the feldspar. It is brownish and encircled by radiation rims adjacent to biotite (Figs. 4a, 4b, 4c, 4f, 4g, 4h and 4i). Commonly, uraninite is euhedral to sub-hedral, isotropic, dull grey colour under reflected light, partially encircled by fine size pyrite with radiation cracks in host mineral. Fine-grained gangue minerals are present as inclusions within the uraninite (Figs. 4d and 4e). Chemical age of single uraninite grain from Gabala river indicated that it is 792Ma old (Ajay Kumar *et al*., 2019).

Karjawan nala, Balrampur District, Chhattisgarh

Pegmatoidal migmatite-hosted mineralization in CGGC terrain is reported along the Karjawan nala in Balrampur district, Chhattisgarh, which falls in periphery of a granite pluton near Dugru (Samanta *et al*. 2018). Here uranium localization is linked with

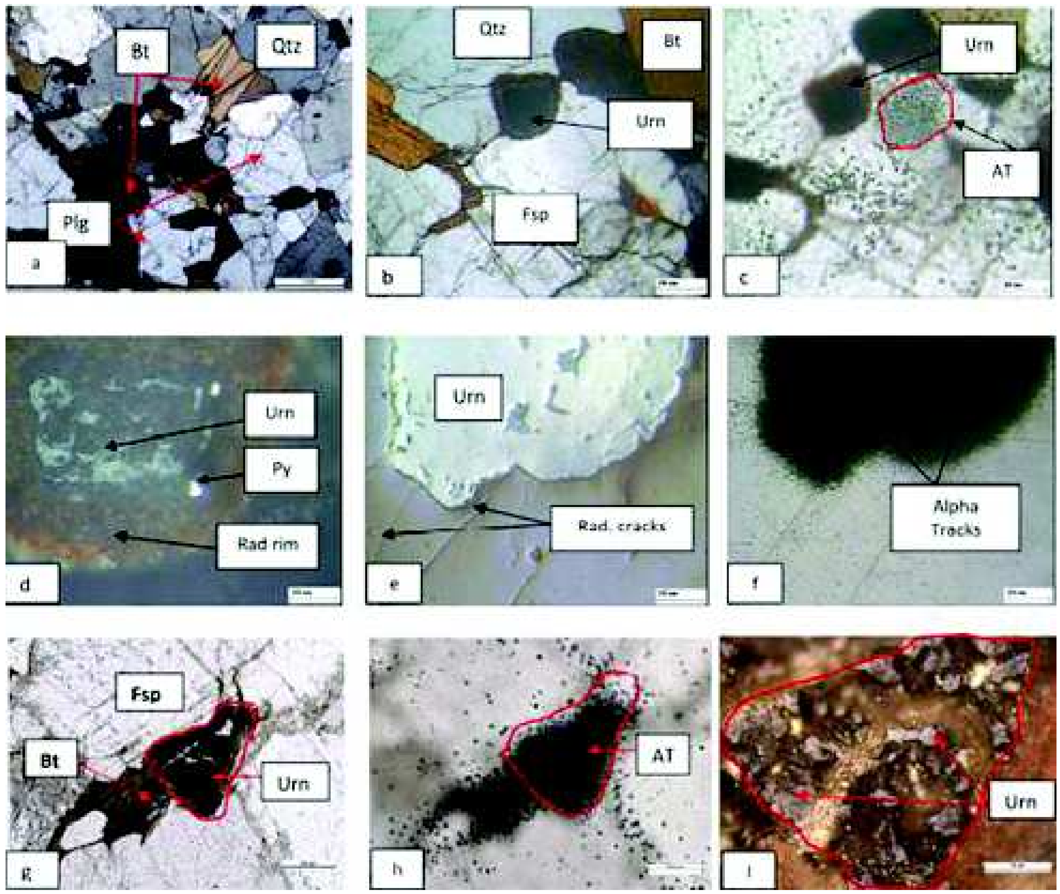

Fig. 4: (a) Radioactive migmatite leucosome near Baran River section comprising quartz (Qtz), plagioclase feldspar (Plg) and biotite (Bt); (b) Uraninite (Urn) inclusions encircled by radiation rim around it in feldspar (Fsp); (c) Feldspar comprising euhedral uraninite (Urn) inclusion, encircled by radiation rim around it, with alpha tracks (AT) in migmatite of Baran River section; (d) Euhedral uraninite (Urn), under reflected light, being encircled by radiation rim (Rad rim) around it with a few tiny pyrite (Py) grains in migmatite leucosome in Baran river; (e) Polished slab of migmatite from Gabala River Section of Jhanji area showing light grey uraninite (Urn) within feldspar; (f) CN-film showing very high density alpha tracks corresponding to uraninite shown in Fig. 3e; (g). Uraninite adjacent to biotite enclosed within the feldspar; (h). High density alpha tracks on CN-film corresponding to uraninite with low density tracks corresponding to adsorb U over biotite flake including weathered portions of feldspar shown in Fig.3g; and (i) Migmatite-hosted uraninite under higher magnification showing alteration and leaching of uranium (after Ajay Kumar *et al*., 2019)

NNW-SSE trending fractures. The radioactivity is contributed mainly by uraninite, brannerite and uranophane.

Karke and Chundi, Garhwa District, Jharkhand

Radioactive outcrops of migmatite and younger intrusive granite occurring within CGGC terrain are observed at about 20 km in north-western part of Garhwa town, Jharkhand. Radiometric surveys and geological mapping in the area revealed presence of uranium mineralization at Karke and Chundi. Mineralisation at Karke is associated with leucosomal part of migmatite, whereas at Chundi it is confined to younger granite and pegmatite (Kushwaha *et al*., 2018; Porwal *et al*., 2019). A total of 9 uranium bearing lenses have been identified over 1000m long and 30m wide area in Karke. Radioactive samples (n=17) assayed up to 0.20% U_3O_8 (av.0.034% U_3O_8) with negligible thorium. The main uranium minerals identified in the mineralised rock are euhedral uraninite and brannerite (Kushwaha *et al*., 2018). In Chundi area, U mineralized younger granite and associated pegmatite occur as linear bodies trending roughly E-W, having width from 0.50m to 25m. Here, in addition to euhedral uraninite and brannerite, secondary uranium minerals are also reported from the mineralized granite and pegmatite (Porwal *et al*., 2019).

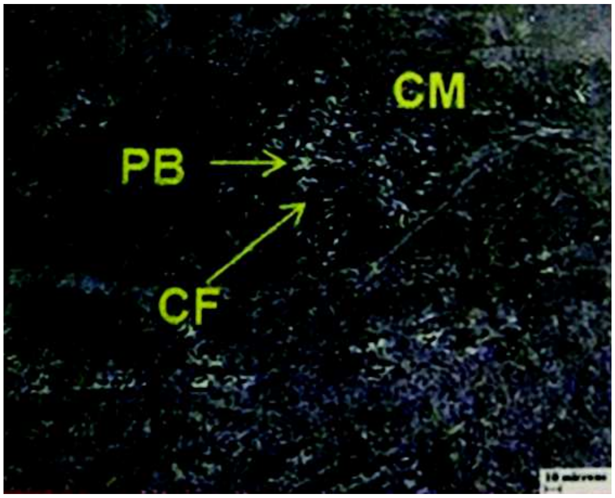

Fig. 5: **Microphotograph of Motur Formation showing carbonaceous matter (CM) hosting coffinite (CF) and pitchblende (PB) in Kachhar-Dharangmau track (after Jain *et al*., 2017b, 2018)**

Satpura-Gondwana Basin

Kachhar-Dharangmau, Betul District, M.P.

Uranium mineralisation at various places associated with Satpura-Gondwana is known since early 1970s (Virnave, 1991; Singh *et al*., 1993). Exploration inputs in the basin around Polapathar, Mansinghpura, Bodhipani and nearby areas established perched type uranium mineralisation. Renewed efforts have brought to light additional areas of uranium mineralisation hosted in Motur Formation around Kachhar-Dharangmau and Jhiriyadol-Handipani, Betul district, M.P. adjoining to earlier known areas (Jain *et al*., 2017b). Palaeocurrent analysis revealed a predominant NW direction of palaeoflow (Viravane, 1991; Jain *et al*., 2017b). Concentration of uranium appears to have been controlled by NW flowing palaeocurrent (Jain *et al*., 2017b). Enrichment of uranium with depth is apparent in response to varying degree of oxidation (Jain *et al*., 2017b). In oxidised zone in shallow level U concentration is low, which increases with depth. It is supported by a gradual decrease of Th/U ratios with increasing depth, with contribution of almost entire radioactivity being due to U in and around reduced zone and redox front (Jain *et al*., 2017b). Intrinsic U was mobilised from oxidised zone, taken in to solution in the direction of paleoflow, e.g., NW and precipitated at depth at redox front analysing up to 2.76% U_3O_8. At redox front the sandstone is grey coloured, and contains carbonaceous matter, which hosts U minerals, pitchblende and coffinite (Jain *et al*., 2017b, 2018; Fig. 5). A host of secondary minerals identified (Jain *et al*., 2018) include tyamunite $[Ca(UO_2)_2V_2O_8.8H_2O]$, meta-tyamunite $[Ca(UO_2)_2(VO_4).2\text{-}5H_2O]$ and metastudtite $(UO_4.2H_2O)$.

Singhbhum Shear Zone, Jharkhand

Uranium exploration in Singhbhum shear zone (SSZ) in under progress since 1950s. In fact this is the only area from where regular mining for uranium is going on since middle of the 20th century. In SSZ, bulk of the U mineralization is hosted in quartz-chlorite schist, besides chlorite-sericite-quartz schist and to some extent in feldspathic schist, all belonging to Dhalbhum Formation of Neoarchaean-Palaeoproterozoic age (Sarkar, 1984; Mahadevan, 1988a, b; Sinha *et al*., 1990; Pandey *et al*., 1994). Recently, uranium mineralization has been intercepted in a new geological setting around Kudada-Turamdih deposits in the environs of Singhbhum shear zone. U mineralization is stated to be of hydrothermal type and is hosted in altered rock of ultramafic suite (Akhila *et al*., 2018). Like uranium mineralization in other areas of SSZ, in this area also U mineralization is polymetallic (Sinha *et al*., 2019).

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