

Carbonate-hosted Indian U-deposits – Tummalapalle in the Cuddapah Basin and Gogi-Kanchanakayi in the Bhima Basin: Attributes for their Genetically Divergent U-mineralisation

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Abstract— Amongst the 15 types of U-deposits worldwide in divergent host-rocks, carbonate rocks generally are amongst the least U-bearing in the Earth's crust. In India, two carbonate-hosted U-deposits were hitherto established by the AMD – around Tummalapalle in the Cuddapah basin and Gogi-Kanchanakayi (G-K) in the Bhima basin, with the former having the largest resources but low-grade (U₃O₈: >0.222 Mte, ~0.045%) and the latter with the highest grade but low-tonnage (U₃O₈: ~0.18%, 6,461 te) amongst the Indian U-deposits. Their attributes, drawn from the field and laboratory studies, viz., physiographic and geomorphic province, host-rock of U-mineralisation, stratigraphic setting, nature and extent of mineralisation, grade and tonnage, structural aspects, petro-/mineral-graphy, petro-/ore-mineral-/isotopic-geochemistry, depositional environment, controls of mineralisation, source and type, mineral processing, and possible generation of critical minerals, are presented. From these, the factors responsible for their genetically divergent U-mineralisation, viz., strata-bound, syn-/dia-genetic, phosphatic dolostone-hosted U-deposit at Tummalapalle (and contiguous areas) and structurally-controlled, epigenetic, hydrothermal vein-type, brecciated non-phosphatic limestone-hosted G-K U-deposit are discussed. Based on these, the following guidelines in the prospecting for U in a carbonate region are suggested: after establishing a fertile source for U, phosphatic carbonate rock appears potential for syn-/dia-genetic U-mineralisation, whereas non-phosphatic carbonate rock involved in major structural disturbances is potential for epigenetic U-mineralisation, with reductants of organic matter and sulphides in both cases will enhance the quantity of primary U-minerals and, hence, U-grade.

Keywords— Carbonate-rocks, attributes, syn-/dia-genetic, epigenetic, U-deposits, India.

1. INTRODUCTION

The classifications of U-deposits worldwide mainly follow two alternate approaches: based either on descriptive features of the mineralisation, such as the type of host-rock and orebody morphology or on the genetic aspects of mineralisation (IAEA, 2018). In this regard, the recent classification of U-deposits is that of the OECD (2020). This comprises 15 types and 36 sub-types with 14 classes of U-deposits, based mainly on the host-rock. Carbonate rocks (no. 13 out of 15 types of U-deposits) generally are amongst the least uraniferous substances of the earth's crust due to the transport of U in solution, usually as uranyl bi- or tri-carbonate complex. Out of 1,807 total U-deposits identified so far in the world, only 10 are carbonate type (stratabound-1, cataclastic-8, paleokarst-1), which is the least in number when compared to that of other types (IAEA-TECDOC, 2018). Rocks that are composed almost wholly of carbonate minerals and include only minute traces of other constituents generally contain about 0.0001% (1 gram per ton), or less, of syngenetically deposited

uranium; they are amongst the least uraniferous rocks. The phosphatic constituent in some appreciably uraniferous limestones and dolostones is thought to hold the uranium; detrital constituents and possibly organic matter may hold uranium in other carbonate rocks. Uranium is deposited epigenetically in carbonate rocks under a variety of circumstances, and some of these deposits provide rich ores.

Epigenetically deposited uranium minerals in carbonate host-rocks are found in hydrothermal veins (examples: the Shinkolobwe district, Republic of Congo, and in the Lake Athabaska region, Saskatchewan, Canada; deposits at Tyuya-Muyun and Agalyk in the Uzbekistan, Taboshar in the Tadzhikistan, and the Todilto Limestone, New Mexico, USA), in efflorescent deposits, in cavities of karst terrains, and as peneconcordant deposits in stratified carbonate rocks (Bell, 1960). The Baimadong uranium deposit in the Yangtze Craton, SW China is one of the most representative carbonate-hosted uranium deposits in

China, with U-mineralization being spatial and genetical relationships with black and red alterations (Yanyan Li et al., 2021).

The carbonate-hosted U-deposit in Guizhou, China is controlled by fault and hydrocarbon fluids, and so it can be defined as a structural hydrocarbon-carbonate-type U deposit, with U, Mo, and other metals mainly found in the black rocks in the lower stratum (presumably Niutitang Formation), having migrated together with hydrocarbon fluids in the form of tiny mineral inclusions. The hydrocarbon fluids (containing some brine) caused cracking and differentiation upon entering the fracture zone, at which point the ore-forming materials (U, pyrite, and other metals) were released and precipitated (Lin-Fei Qiu et al., 2022).

In India, the Atomic Minerals Directorate for Exploration & Research (AMD), Department of Atomic Energy has established two carbonate-hosted U-deposits, viz., (i) the large-tonnage (>0.222 million tonnes U₃O₈) and low-grade (~0.045% U₃O₈) syn-/diagenetic U-deposit in the Tummalapalle and contiguous areas along the SW, S, and W margins of the Cuddapah basin in Andhra Pradesh with the U-ore being the 'Uraniferous Phosphatic Siliceous Dolostone' (UPSD) and (ii) the highest grade (~0.18% U₃O₈ amongst the Indian U-deposits, but medium grade internationally) with limited tonnage (7,476 tonnes U₃O₈), structurally-controlled, hydro(epi)-thermal Gogi-Kanchanakayi (G-K) U-deposit in Karnataka with the host-rocks being brecciated, non-phosphatic limestone (above the unconformity; ~70% U₃O₈) and the basement biotite granite (below the unconformity).

In this communication, a brief account of these two U-deposits, with emphasis on their attributes, are presented, the factors responsible for their genetically divergent U-mineralisation are discussed, and based on these a few guidelines are proposed in prospecting for U-mineralisation in a terrain of carbonate-rocks.

2. CARBONATE-HOSTED U-DEPOSIT IN THE TUMMALAPALLE AND CONTIGUOUS AREAS IN THE CUDDAPAH BASIN, ANDHRA PRADESH

The Cuddapah Basin (CB) in the southern part of the state of Andhra Pradesh is India's second largest intracratonic Proterozoic (Purana) basin with a vast potentiality of metallic mineral resources of base metals, iron, and manganese, and non-metallic resources of lime-/dolo-stone, barite, asbestos, phosphorite,

dimensional stones, and diamonds, which have been utilized since a long time (Geological Survey of India [GSI], 1975, 1994; Kurien, 1980; Dutt, 1986; Nagaraja Rao et al., 1987; Ramam, 1999).

During the mid-1980s, U-mineralisation was discovered in the Vempalle dolomite and Pulivendla conglomerate in CB by the GSI (Sinha and Babu, 1986; Sundaram et al., 1989).

The radioactive samples were sent by the GSI to the AMD for determination of their U₃O₈ content and identification of their radioactive minerals, when the present author in July, 1986 has identified discrete pitchblende and coffinite to account for much of U₃O₈ in the samples of carbonate rock.

Since then, intense exploration for U has been carried out by the Scientists of AMD. This sustained exploration has changed the CB from an earlier considered 'Thorium-province' to a major 'Uranium-province' with diverse types of U-deposits, thereby making the CB as 'India's emerging U-hub' (Dhana Raju, 2009) and a 'U-province' (Parihar and Srinivasa Rao, 2012).

Amongst the established U-deposits in CB and its environs, the strata-bound, syn-/diagenetic, carbonate-hosted U-deposit in the Vempalle Formation of the Cuddapah Supergroup along the SW-, S-, and W-margins of CB at Tummalapalle (14.3214° N: 78.2678° E.) and its contiguous areas over a ~160 km long belt (Fig. 1) in the combined Kadapa, Anantapur, and Kurnool districts is unique (Vasudeva Rao et al., 1989; Saraswat et al., 1989; Dhana Raju et al., 1993; Roy and Dhana Raju, 1997, 1999, 2012; Jeyagopal and Dhana Raju, 1998; Rai et al., 2002; Dhana Raju, 2019) due to its giant-size of large tonnage (~0.222 million tonnes U₃O₈ up to 2022, constituting 59% U-resources out of 0.376 million tonnes of uranium oxide, established by the AMD, in India; Sinha, 2022), very low-grade (~0.045% U₃O₈), and rare due to its host-rock being carbonate that is usually considered as unfavourable for U-mineralisation.

After an exploratory mine by the AMD, the Uranium Corporation of India Ltd. (UCIL, a Public Sector Undertaking of the Department of Atomic Energy, Government of India) has been commercially utilizing since 2012 the carbonate-hosted U-deposit in the Tummalapalle – Gadankipalle sector (Fig. 1) by an underground mining and a processing plant, close by to the mine for the extraction of uranium.

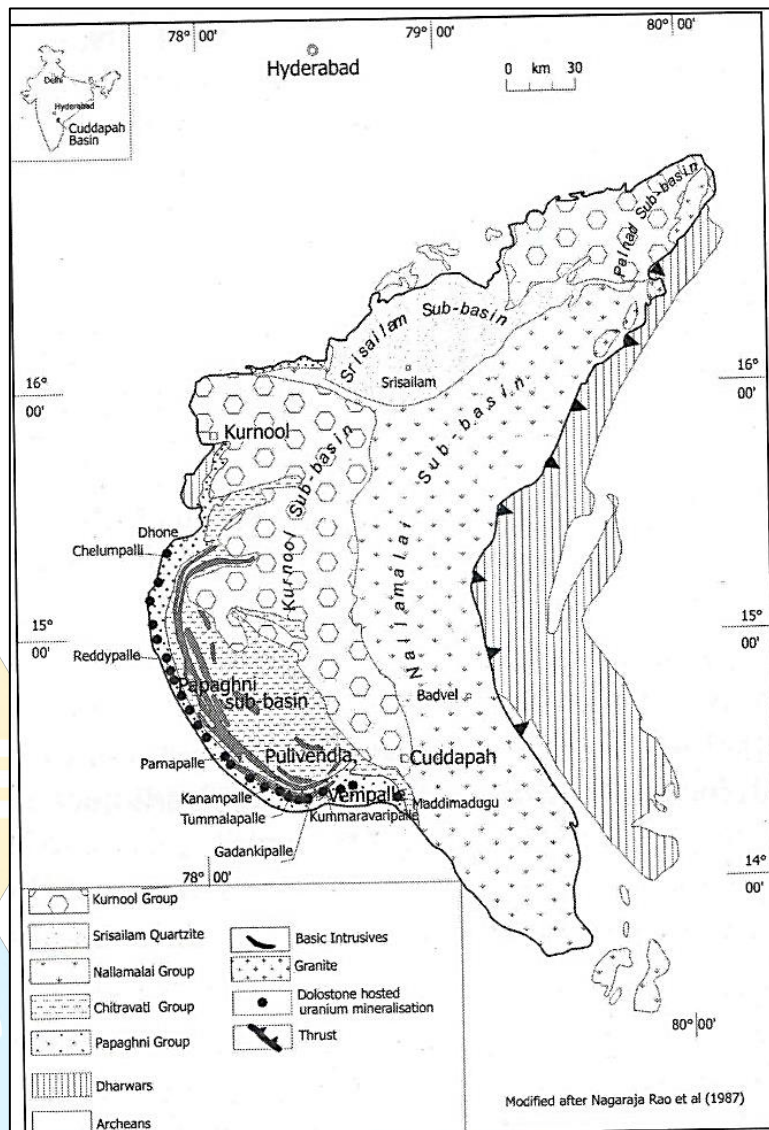


Fig 1. Geological map of the Proterozoic Cuddapah basin, India with locations of the phosphatic dolostone-hosted Uranium-deposit (Credit: Jeyagopal et al., 2012, p. 44).

3. CARBONATED-HOSTED GOGI – KANCHANAKAYI U-DEPOSIT IN THE BHIMA BASIN, KARNATAKA

The Bhima basin, amongst the Proterozoic (Purana) basins of India, is the smallest (~5,300 sq. km) and youngest (~1.3 Ga; Pandey et al., 2008, 2009). It has become the first-order target for U-exploration by AMD, on the analogy of (i) similar basins in Canada and Australia hosting many large-tonnage and medium-high grade unconformity-type/related U-deposits and (ii) the Proterozoic Cuddapah basin that has become a U-hub/province with diverse types of U-mineralisation, with two of them (Impure carbonate-hosted, giant-size U-deposit in the Tummalapalle, Andhra Pradesh and unconformity-proximal type at Lambapur-Peddagattu-Chitrial-Koppunuru area, Telangana-Andhra Pradesh) being important (Dhana Raju, 2019). The Bhima basin

is a NE-SW trending, S-shaped, Meso-/Neo-proterozoic, epicratonic, extensional basin (Fig. 2a) formed due to gravity faulting. It comprises ~300 m thick, alternating sequence of clastic and carbonate sediments (Janardhana Rao et al., 1975; Kale et al., 1990), with carbonate dominating and serving as resource for the cement industry in the area. The sediments were deposited in a stable, shallow basin in a closed system with a depositional trend of NE-SW and introduction of load from the provenance rocks of Peninsular Gneiss, younger granites, and greenstone belts along the southern edges. The present basin configuration and disposition of its litho-sequence are the resultant of post-depositional, deformation episodes, evidenced by at least nine major faults. Of these, the E-W trending Gogi-Kurlagare dextral fault is extensive

with a strike length of over 20km. Besides, folds formed in a ductile deformational domain are recorded from the Devan Tegnur and Gogi areas (Jayaprakash, 1999).

In the Bhima basin, uranium mineralisation was recorded by AMD along the Kurlagare-Gogi-Gundanhalli (KGG) fault, first near Ukinal (16°45' N: 76°39'59" E) in phosphatic rocks by remote sensing study, and later in potential one with a few outcrops, mainly by gamma-ray logging of shallow borewells dug for drinking water (down to ~30 m) in the village, Gogi (Pandit et al., 1996) (Figs. 2a and b). Near Ukinal, the mineralisation is traceable discontinuously over 2km along the boundary of cherty limestone and shale, and less commonly along minor faults (Achar et al., 1997). At Gogi, the U-mineralisation occurs along the major E-

W trending Gogi-Kurlagare fault (near to the intersection by NE-SW trending reverse fault) in a non-phosphatic, brecciated, siliceous limestone as well as in the deformed basement granite (2504±28 Ma, Sastry et al., 1999) that is equivalent to the Closepet Granite. This fault is traced along strike length in the east up to Kanchanakayi (Fig. 2b). AMD's sub-surface exploration by drilling since May, 1997 has established the Gogi-Kanchanakayi (G-K) U-deposit, with internationally medium-grade but the highest grade in India so far (~0.18%; resource of 6,461 t U₃O₈; Singh, 2022), mainly in the Shahabad Limestone down to ~50 m above the unconformity (ca. 200 m below surface) and less in the basement granitoid (Pandit et al., 2002; Dhana Raju et al., 2002; Dhana Raju, 2019, 2023).

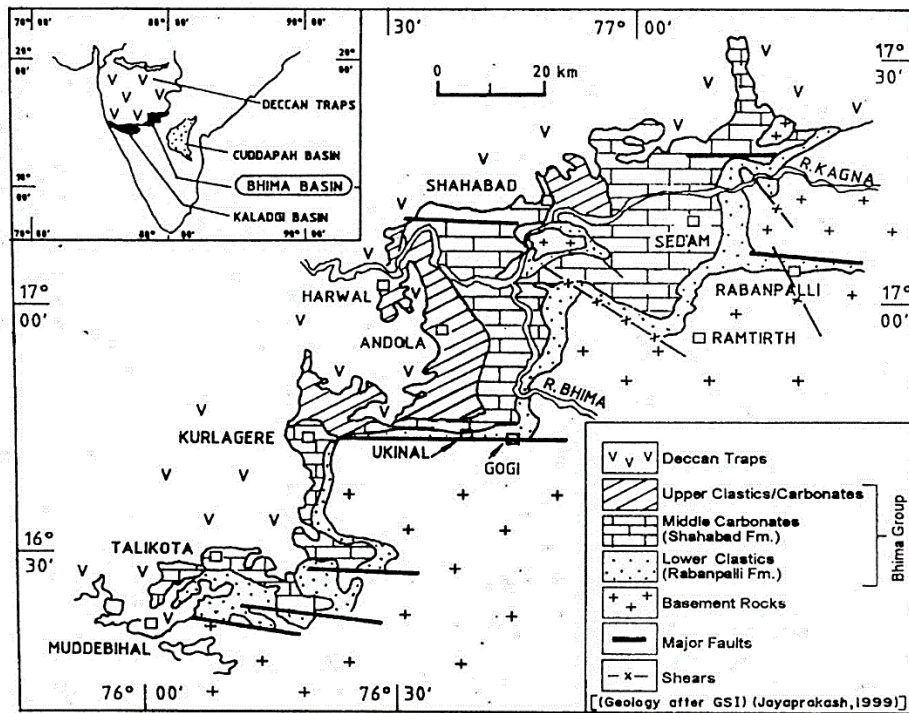


Fig 2a. Geological map of the Meso-/Neo-Proterozoic Bhima basin, India with the limestone-hosted Gogi U-deposit, Yadgir district, Karnataka.

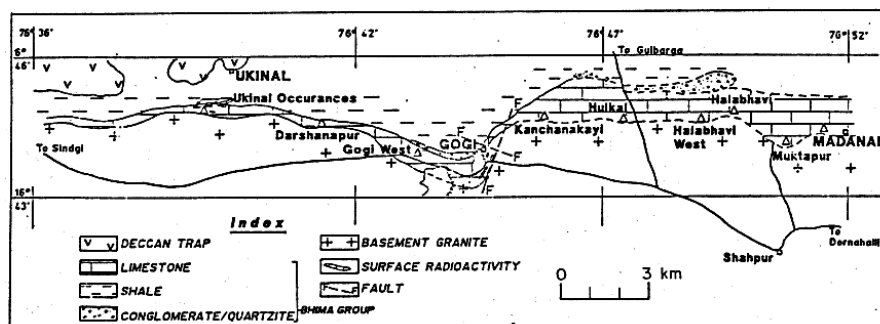


Fig 2b. Geological map of the limestone-hosted Gogi-Kanchankayi (G-K) U-deposit and the same as a satellite U-deposit at Hulkal in the Bhima basin, India.

4. ATTRIBUTES OF THE CARBONATE-HOSTED U-DEPOSITS IN INDIA

Salient attributes of the carbonate U-deposits in the host-rocks of ‘Uraniferous Phosphatic Siliceous Dolostone’ (UPSD) in the Tummalapalle and contiguous areas on

its either side in the Cuddapah basin, Andhra Pradesh, and Non-Phosphatic Limestone of the Gogi-Kanchanakayi area in the Bhima basin, Karnataka are presented in Table 1.

*Table 1. Attributes of the Carbonate-hosted U-deposits of India: Tummalapalle (Andhra Pradesh) and Gogi-Kanachanakayi (Karnataka)**

Attributes	A - Tummalapalle	B - Gogi-Kanchanakayi (G-K)
1. Physiographically distinctive geomorphic province	Paleo- to Neo-Proterozoic, Intra-cratonic (Purana) Cuddapah basin	Meso- to Neo-Proterozoic, Intra-cratonic (Purana) Bhima basin
2. Host-rock of the U-deposit	Uraniferous Phosphatic Siliceous Dolostone (UPSD)	Non-phosphatic, brecciated, siliceous Limestone (70% U3O8) & less U in deformed Basement Biotite Granite
3. Stratigraphic setting of the Host-rock of the U-deposit	UPSD underlined by Red Shale-Massive Dolostone-Polymictic Conglomerate-Grey Shale & overlain by Sedimentary Breccia-Red Shale-Cherty Dolostone-Basic Flows	Archean/Proterozoic Basement Crystallines → Bhima Group of Sediments (~300m; Rabanpalli Clastics → Shahabad Limestone → Hulkal Shale-Silt → Katamdevarahalli Limestone → Harwal Shale) → Deccan Trap
4. Nature & Extent of Host-rock of the U-mineralisation	Strata-bound, homogenous, & stroma-tolite-bearing, well-bedded, compact, fine-grained, and laminated; strike-length: ~160km (Maddimadugu, Kadapa district in SE to Chelumpalli, Anantapur district in NW) with a max. width of 3km, and better grade & development in the central portion, viz., Tummalapalle-Gaddankipalle sector; outcrops of massive dolostone, UPSD & shale occur in the valley portion, bordered by the ridges of the Gulcheru Quartzite to their west & cherty dolostone to their east. In the underground: two bands – hanging (av. thickness:2.3m) & footwall (av. thickness:1.75m) – with a vertical separation of 1-5m; both bands show isotropic character along & across the strike in terms of grade & thickness; depth of the ore: >270m from the surface	Shahabad brecciated limestone plus deformed basement Biotite Granitoid (~2.5 Ga) within a post-sedimentary tectonized zone Sub-surface exploration established (i) at Gogi: total of 5 ore lodes – 3 hosted by brecciated limestone (as hang-wall and footwall bands for a strike extension of 2km, with both ends still open) and 2 in granite cataclasite –, mostly confined to the brecciated zones & fracture systems associated with the E-W trending Gogi-Kurlagare fault; (ii) another deposit in Kanchankayi block: located ~2.5km NE of Gogi deposit in its geologic contiguity at the tectonic contact between basement granite and Bhima

		se-diments along the Gogi-Kurlagare fault zone, with U-mineralisation host-ed by pyritiferous and brecciated lime-stone distributed and (iii) Hulkal block: fracture zone in the eastern part of Kanchanakayi over a strike-length of 300m; exploration is in progress
5. Grade & Tonnage of U-resources (U3O8)	~0.045% and 0.376 million tonnes (up to the year, 2022)	~0.18% in the G-K deposit & ~0.15% in the Hulkal block; & ~7,000 tonnes
6. Structural aspects	Sedimentary: Primary: Stratification, current bedding, graded bedding, ripple marks, mud cracks and pelloids; Secondary: Stylolites, concretion structures, secretion, and fracture-filling; Organo-sedimentary: Oncolite-, colenia- & columnar-types	3 sets of major lineaments: NNW-SSE to NW-SE, oldest, cut-across by NE-SW to ENE-WSW & E-W to WNW-ESE in the south of central part of the Bhima basin and 3 fracture zones: (i) E-W trending Kurlagare-Gogi fault, (ii) intersection of the ENE-WSW lineament & the Wadi fault, and (iii) E-W trending Hunsigi-Devathkal fault with intense shearing & spatially close to the younger granitoid; In the sub-surface, the U-ore body is in the form of intricate network of veins, veinlets, and fracture-fillings within the brecci-ated limestone & tectonised granitoid
7. Petrography of the Host-rock(s) for U-mineralisation	UPSD samples show concentric & alter-nate lamellae of collophane & micrite dolomite-rich layers with poorly sorted silicate clasts (10-20%, comprising larger quartz [0.15-0.39 mm], smaller microcline and plagioclase [0.05-0.20 mm, An10-30] and intra-clasts of impure dolostone [3-4.5 mm]), all set in a cement consist-ing of ferroan dolomite (secondary, with precursor phase of high-Mg calcite) & ultrafine collophane; ore minerals: oxid-es & sulphides; at places, UPSD admix-ed with clay, sericite & limonite; effects of intruding magmatic basic rocks on UPSD: contact met. with development of hornfels, marble, magnetite-/epidote-ana-tase-chalcedony-bearing dolostone, dep-letion of U & formation of wollastonite, chalcedony & secondary U-minerals	(i) Limestone: light to dark grey coloured, fine-grained, compact, and brecciated; contains ferroan calcite (~60-70% primary and secondary; fractured, micritic & less sparry, turbid; chert (detrital quartz), migra-tory organic/carbonaceous matter (OM), clays (illite, smectite), sulphides and limonite with a little rhomb-shaped dolomite; and (ii) Biotite granite-granodiorite: pink/ grey, deformed, cataclastic texture,

		fractures filled with calcite & less flu-orite, fertile (10-110ppm U); quartz, sodic plagioclase, microcline, chlori-tized/epidotized biotite & hornblende; accessory zircon, apatite, allanite, sulphides, anatase, ilmenite, limonite & OM
8. Mineragraphy of the Ore Minerals	<p>U-minerals: Pitchblende, coffinite; U-Ti/Si complex as stringers & inclusions in quartz clasts; uranophane as surficial coatings and adsorbed U (~20%), associated with collophane, anatase, and carbonaceous/clayey matter;</p> <p>Sulphides: Pyrite (framboidal & disseminated; partial to complete goethitization in surface samples), molybdenite, galena, chalcopyrite, bornite, digenite & covellite;</p> <p>Oxides: Magnetite, ilmenite, leucoxene, and goethite</p>	<p>In Limestone: U-minerals: Coffinite & pitchblende, with minor contribution in OM, anatase, clays & chert, and labile U along grain boundaries of minerals; pitchblende is of 2 generations, with earlier rimmed by coffinite due to coffinitization & later replaces coffinite; OM is a low-rank, migratory, bituminous variety with textures like meshwork, stringers, veins etc., & occurs as large globular aggregates & contains pockets of clay, chert, and U-minerals; Sulphides: Dominant pyrite; minor marcasite, chalcopyrite & galena. U-minerals occur as veins, veinlets & fracturing-fillings</p>
9. Petrochemistry of the Host-rock for U-mineralisation (wt. %)	<p>SiO₂:0.77-27.68, TiO₂:0.01-0.33, Al₂O₃: 0.83-3.82, Fe₂O₃:0.13-1.87, FeO:0.57-1.47, MnO:0.01-0.34, MgO:4.61-17.89, CaO:22.47-31.69, Na₂O:0.19-0.94, K₂O: 0.14-1.96, P₂O₅:0.80-28.58, UO₂:0.01-0.39 & CO₂:2.90-37.20; (ppm) Mo:<10-1260, V:17-1520, Cr:<25-84, Cu:36-670, Pb:<5-613, Ni:11-33,</p>	<p>Limestone: CaO: 40-50, SiO₂: 7-19, Al₂O₃: 1.2-3.6, Fe₂O₃: 0.3-4.3, FeO: 0.3-0.7, MgO: 0.6-1.4, Na₂O: 0.2-0.8, K₂O: 0.4-1.1, P₂O₅: 0.04-0.42, CO₂: 32-39, U₃O₈: 0.013-1.68 (ppm): V: 58-1143, Cr: <25-433, Co: <10-129, Ni: 9-77, Cu: 9-105, Mo: <5-721, Ag: <2-62</p>
10. Ore Mineral Geochemistry (EPMA, wt.%) (Partial analysis with	<p>Pitchblende: UO₂:77.26-86.92, ThO₂:0.00-0.03, PbO:1.7910.36, ΣRE₂O₃:0.25-0.55</p> <p>Coffinite: UO₂:63.21- 81.33, ThO₂:0.00-0.08, PbO:0.13- 5.63, ΣRE₂O₃:0.31-1.20; U-Si Complex: UO₂:46.94-60.92, ThO₂:0.00-0.11, PbO:0.00-7.91, ΣRE₂O₃:0.32-0.71</p> <p>U-Si-Ti complex: UO₂:47.91-71.14, ThO₂:0.00-0.11, PbO:3.03-7.91, ΣRE₂O₃:0.24-0.44</p>	<p>Limestone: Pitchblende: UO₂ 79.37-87.22, ThO₂ 0.00-0.09, PbO 3.88-6.98, & ΣRE₂O₃ 0.20-0.96;</p> <p>Coffinite: UO₂ 70.68-84.65, ThO₂ 0.00-0.10, PbO 0.65-12.16, & ΣRE₂O₃ 0.08-0.61;</p>

important radicals)	Euhedral pyrite: S:52.55, Fe:45.40, Cu:0.105, Ni:0.07, Co:0.02, As:1.345, Ag:0.04; Framboidal pyrite: Fe:46.76, Cu:0.025, Ni:0.085, Co:0.03, As:0.045, Ag:0.03; Collophane: MgO:0.35, CaO:49.13, P2O5:40.25	Sulphides: Pyrite, euhedral: 51.81-53.90 S, 45.52-47.50 Fe, 0.00-0.34 Co, 0.00-0.25 Ni, 0.00-0.12 Cu, 0.00-0.13 Zn, 0.02-0.71, 0.00-0.22 Ag; Pyrite, framboidal: 51.10-53.42 S, 44.15-47.31 Fe, 0.00-2.2 Co, 0.00-1.47 Ni, 0.00-0.94 Cu, 0.02-2.68 As, 0.00-0.22 Se, 0.00-0.32 Ag; Galena: 12.38-13.07 S, 0.09-0.60 Fe, 0.00-0.04 Co, 0.00-0.06 Ni, 0.00-0.09 Cu, 81.51-85.75 Pb, & 0.00-0.08 Au; Chalcopyrite: 34.51-36.36 S, 29.08-30.76 Fe, 0.08-0.62 Co, 0.03-0.28 Ni, 28.59-34.12 Cu, , 0.00-1.18 Ag; Organic Matter (OM): OM: 0.00-14.57 UO ₂ , 0.00-0.03 ThO ₂ , 0.00-1.80 PbO, 0.00-0.25 Pr ₂ O ₃ , 0.00-0.11 Nd ₂ O ₃ , 0.00-0.11 Er ₂ O ₃ ;
11. Stable-isotopic Geochemistry of the Host-rock for U-mineralisation	$\delta^{13}\text{CPDB}$: +0.08 to -0.87‰; $\delta^{18}\text{OPDB}$: -7‰ to -14‰; $^{234}\text{U}/^{238}\text{U}$ activity ratio: 0.7	(i) $\delta^{18}\text{O}$: -6.38 to -7.17‰; the presence of original microbial texture & Proterozoic marine life indicate minimum diagenetic alteration. (ii) $\delta^{13}\text{C}$: 3.8‰; high positive values indicate burial of a large mass-fraction of isotopically light organic carbon.
12. Radio-isotopic age of the U-mineralisation	1.9-2.0 Ga, Pb-Pb (Pb SL)	1308 ± 49 Ma (Pb-Pb); Minimum age of U-mineralisation: ~1.3 Ga
13. Depositional environment of the U-mineralisation	Mixed marine- & fresh-water, inter-tidal environment with a minimum Eh of -0.2 to -0.3 volts and a pH between 7 & 8, and a temperature of <150°C	Gradual up-section decreases to ~1‰ $\delta^{13}\text{C}$ suggests transgression & mixing of isotopically heavy coastal water (~4‰) with global Dissolved Inorganic Carbon reservoir (~0‰); low salinity (15 wt.% NaCl eq.) of hydrothermal fluids; 100-200°C; Eh: -0.35 to 0.6 V; pH: 0.25 to 11

<p>14. Controls of U-mineralisation</p>	<p>Lithology, phosphate as an impurity, permeability-porosity barrier, sedimentary structures, reducing environment, fertile granitoid provenance to its west and south; mixed marine- and fresh-water, inter-tidal environment</p>	<p>(i) Fertile, basement biotite granitoid; (ii) Structurally weak & disturbed zones; (iii) Presence of weak & permeable zones (iv) Reductants: OM & sulphides; (v) Impervious cover-rocks; and (vi) Dyke in the basement granitoid as a source of heat & S, and to remobilize U in the basement</p>
<p>15. Source & Type of U-mineralisation/depot</p>	<p>Fertile granitoids in the S & W environs of the Cuddapah basin; Stratabound, syn-/diagenetic & impure carbonate-hosted along the SW, SE, and W margins within the Cuddapah basin</p>	<p>Fertile basement granitoid (20-24 ppm U); structurally-controlled, hydro(epi)-thermal, vein-type within the Shaha-bad Limestone [~70%] & basement, deformed biotite granitoid, along the S-margin of the Bhima basin</p>
<p>16. Mineral Processing of the Ore for extraction of U</p>	<p>Multi-stage operations of alkaline pressure leaching, using Na₂CO₃ & NaHCO₃ as leachants & industrial oxygen as an oxidant, resulting ~75% leachability of U</p>	<p>Alkaline process: Na₂CO₃-NaHCO₃ leaching, using O₂ as oxidant; solid-liquid separation & ppt. of Sodium Di-Uranate” (at 50°C & 6h reaction-time) assayed 82% U₃O₈, with 97% ppt. efficiency & ~78% over all recovery</p>
<p>17. Possible extraction of Critical Minerals from the U-ore</p>	<p>REEs, V, Mo, Co, Ni, Cu, Ag, and phosphate as value-added by-products from its U-phases, sulphides & collophane</p>	<p>REEs, Ni, Co, Cu, Ag, Au, and As from the Ore & Gangue minerals</p>
<p>*18. The above information & data were compiled from the References, in the alphabetical order, given in columns 2 & 3</p>	<p>Anand Rao et al. 2022; Bhattacharyya et al. 1997; Dhana Raju 2019, In press; Dhana Raju et al. 1993, 2001; Jeyagopal 1993; Jeyagopal & Dhana Raju 1998; Jeyagopal et al. 2008, 2012; Rai et al. 2015; Roy 1993; Roy & Dhana Raju 1997, 1999, 2012; Roy et al. 1990; Sreenivas & Chakravartty 2015; Suri et al. 2010; Vasudeva Rao et al. 1989</p>	<p>Absar et al. 2018; Achar et al. 1997; Bincy et al. 2011; Dhana Raju 2019, 2023; Dhana Raju et al. 2002; Janar-dhana Rao et al. 1975; Jayaprakash 1999; Latha et al. 2012; Pandey et al. 2008, 2009; Pandit 2002; Pandit et al. 2002; Pandit & Dhana Raju 2008; Patnaik et al. 2016; Raza et al. 2018; Sastry et al. 1999; Sinha, 2022; Sree-nivas & Chakravartty 2015</p>

5. DISCUSSION

Based upon the attributes of the carbonate-hosted U-deposits of Tummalapalle (and contiguous areas) in the Cuddapah basin and Gogi-Kanchanakayi in the Bhima basin (Table 1), the factors responsible for U-mineralisation in them are discussed in the following.

5.1. Tummalapalle (and contiguous areas) U-deposit:

5.1.1. Source of U and major impurity of silicate clasts in the U-ore of UPSD: Based upon the field setting of the deposit (Fig. 1) and the attributes (items in Table 1: A-7, 15), its source of both U and the impurity of detrital silicate clasts of quartz and feldspars is most probably the crystalline granitic provenance to the south and west of the deposit. Petrographic and geochemical characterisation of these granitic rocks has shown that they comprise 3 phases: (a) the dominant phase I - Peninsular Gneiss that is heterogeneous having migmatitic contact with schist belt, oldest (>3 Ga), syntectonic with xenoliths of basic rocks (amphibolite etc.), fractured, high-Ca, sodic, metaluminous (A/CNK: 0.9-1.1), Na-metasomatically affected 'hornblende granodiorite' of 'magnetite series' and possibly of I-type with barren nature for U (<5 ppm); (b) phase II is younger, possibly the equivalent of the ~2.5 Ga Closepet Granite, homogeneous, consists of grey and pink variants, present as ridges intrusive into the Phase I, late-tectonic, fractured, low-Ca, potassic, strongly peraluminous (A/CNK: 1.1-1.31), fractionated '1 or 2 mica granite' of the 'ilmenite series' and possibly of S-type with fertile nature for U (~10 to 36 ppm, av. ~15 ppm); and (c) phase III - leuco-microgranite with very less areal extent, occurs as mounds or hillocks in the Phase II, youngest, homogeneous, intrusive, post-tectonic, low-Ca, moderately sodic, moderate to strongly peraluminous (A/CNK: 1.06-1.3), less fractionated, and fertile for U (up to 118 ppm) with a little secondary U-minerals, confined mostly to fracture zones within the phase II (Dhana Raju et al., 2001). Thus, the characterisation of the provenance granitic rocks points out that the source for U and the silicate clasts is most probably the fertile Phase II - Mica granitoid, equivalent to the ~2.5 Ga Closepet Granite.

5.1.2. Role of Phosphate impurity and Lithology:

Phosphate, the essential and second most impurity in the UPSD (Table 1: A-14) has played a key role in the U-mineralisation, as evidenced by: (a) the phosphatic carbonate rock is exclusively U-mineralised, whereas the non-phosphatic carbonate rocks like the underlying massive dolostone and overlying cherty dolostone, with reference to UPSD in the stratigraphic sequence (Table

1: A-3, 4), are non-mineralised and, hence, the U-mineralisation is 'strata-bound' (Table 1: A-4) with a lithological control; (b) in the alternating layers of phosphate (pH: 7-7.5) and carbonate (pH: 8.0) in the UPSD (Table 1: A-4, 7) U-mineralisation is preferably associated with the former; and (c) positive correlation of U₃O₈ with P₂O₅ with 'r value' of 0.979 (Rai et al., 2011; Roy and Dhana Raju, 2012).

5.1.3. Role of Organic Matter (OM) and Sulphides:

Mineragraphic studies (Table 1: A-8) have demonstrated the intimate relationship between OM and U as well as OM with framboidal pyrite. It appears that the Ca-phosphate and OM have helped in the initial syngenetic fixing of U (Table 1: A-8, 15), as indicated by the presence of pitchblende with collophane and adsorbed U on organic matter. OM, together with sulphides, also helped to reduce U₆₊ to U₄₊ for precipitation of primary U-minerals of pitchblende and coffinite. Further diagenesis within a reducing environment have resulted in localisation of primary minerals along major diagenetic and sedimentary weak zones such as the carbonate-phosphate contact, clast boundaries, micro-stylolites, fibrous dolomite-rich cavities, and dolo-micritic pelloids (Table 1: A-6) (Roy and Dhana Raju, 2012). Hence, the U-mineralisation is designated as 'strata-bound, syn-/dia-genetic' type (Table 1: A-16).

5.1.4. Permeability-porosity barrier: The stratigraphic sequence of UPSD (Table 1: A-3) with UPSD underlined by the assemblage of red shale-massive dolostone-polymictic conglomerate-grey shale and overlined by the assemblage of sedimentary breccia-red shale-cherty dolostone points to the permeability and porosity provided by conglomerate and breccia, whereas shales, both below and above the UPSD, created the barrier to confine the U-bearing solutions within the carbonate rocks and thereby helped the association of syngenetic U more with phosphate and less by OM (Table 1: A-8, 15).

5.1.5. Biogeochemical control: Abundant stromatolitic assemblages in the UPSD (Table 1: A-6 and 8) point to the possible role of stromatolite-building micro-organisms (algae and cyanobacteria) in the rhythmic precipitation of phosphate and formation of biogenic framboidal pyrite. Sulphate reduction by sulphate-reducing bacteria, which were thriving on the OM-based nutrient produced algae had a major effect on this rhythmic precipitation of carbonate and phosphate. Physico-chemical conditions (pH of 7 to 9 and Eh of -

0.25 to -0.55 volts) (Table 1: A-13), deduced from the experimental results of Krumbein and Garrels (1952), responsible for algae-activity (OM) is conformable with high-Mg calcite from which dolomite was formed, colophane, pyrite, and U-minerals (Roy and Dhana Raju, 1997, 2012).

5.1.6. Depositional environment of UPSD: This is identified as the mixed marine- and fresh-water, inter-tidal environment with a minimum Eh of -0.2 to -0.3 volts and a pH between 7 and 9, and <150°C temperature of U-mineralisation, as indicated by the association of carbonate-sulphides-OM-U-phases, brought out by petrographic, mineragraphic, and stable isotopic attributes (Table 1: A-7, 8, 11), with the experimental studies cited above. Stratigraphic position, sedimentary structures like ripple marks, mud-cracks, and stromatolites, process of dolomitization from high-Mg calcite, association with colophane and silicate clasts indicate a shallow marine inter-tidal depositional environment for UPSD, with silicate clasts and U brought by fresh-water from the provenance rocks of granitoids (some are fertile for U), and carbonate and phosphate from the marine-water (Table 1: A-13). The massive impure dolostone, mineralised UPSD, and shale occur in the valley portion, bordered by the ridges of resistant older Gulcheru Quartzite to their west and younger cherty dolostone to their east (Table 1: A-4) with a large resource (0.222 Mte) of mineralisation extending to a strike continuity of ~160 km close to the S and W margins of the Cuddapah basin (Table 1: A-4) (Roy and Dhana Raju, 1997; Jeyagopal and Dhana Raju, 1998), which is having an arcuate length of 440km and maximum width of ~145 km in the middle (Nagaraja Rao et al., 1987).

5.1.7. Transition from oxygen-deficient to oxygenated environment: The Cuddapah Supergroup stands at the transition between the oxygen-deficient, azoic in the Archaean period and oxygenated, Ediacaran fauna-bearing Proterozoic period. The base of Papaghi sub-basin, the oldest of all the sub-basins in the Cuddapah basin, has the well documented the Great Oxidation Event (GOE) with repeated oxidising (oxygen-dominant) and reducing (oxygen-deficient) environment, and the carbonate sediment-hosted uranium mineralisation, probably, suggests the transition between the reducing and oxygenic environments, corresponding to this GOE in south Indian Peninsula (Jeyagopal, A.V.; Personal Communication, 2023).

Finally, the tectonic events inferred from sea-level changes, cyclic sedimentation (Jeyagopal et al., 2008), sequence stratigraphy, sea floor spreading etc., appear to have played the key role in the strata-bound, syn-/diagenetic U-mineralisation (Jeyagopal et al., 2012) of the phosphatic carbonate-hosted Tummalapalle (plus contiguous areas) U-deposit. From this deposit, apart from U, some critical minerals in notable contents like REEs, V, Mo, Co, Ni, Cu, Ag, and phosphate may be generated as value-added by-products from its U-phases, sulphides, and colophane, as indicated by their petrochemistry and mineral chemistry (Table 1: A-9, 10, 17) (Dhana Raju, in press).

5.2. Gogi-Kanchanakayi (G-K) U-deposit

5.2.1. Source of U for the G-K U-deposit: Along the southern margin of the Bhima basin, the basement granitoids occur (Figs. 2a and b) that comprise the barren (for U: 3-4 ppm) Archaean Peninsular Gneiss (PG) and fertile (20-24 ppm U), younger granitoid (equivalent of ~2.5 Ga Closepet Granite) (Items in Table 1: B-3, 15). Regional geo-structural mapping by remote sensing techniques in the Gogi area revealed 3 sets of major lineaments, viz., NNW-SSE to NW-SE, NE-SW to ENE-WSW, and E-W to WNW-ESE, with the first set, representing the trends of greenstone belts, being the oldest, which is cut across by other two sets. The impress of these 3 lineaments is best over the PG in the south of the central part of the Bhima basin and, incidentally, this sector has a large proportion of the younger, fertile granitoid (Achar et al., 1997). Spatially, this sector is near to the Gogi-Kurlagare (K-G) major fault (Fig. 2a) along which the Gogi U-deposit in the basin hosted by limestone (~70% U) occurs (Table 1: B-2, 15), with the sediments in the basin unconformably underlined by the basement granitoids. Hence, it is most probable that the source of U in the Shahabad limestone of the G-K deposit is from the fertile, younger basement granitoid that is also the host for lesser part of the U-mineralisation (~30%) in the Gogi deposit.

5.2.2. Structural Aspects: These played a major control for the U-mineralisation in the G-K deposit. Apart from the 3 sets of major lineaments in the area described above, the NW-SE and NE-SW to ENE-WSW shear systems in the region are known for the occurrence of vein-type U-mineralisation in the Raichur granitoid (Chopra and Jagannadha Rao, unpublished rep., Southern Region, AMD, 1989). Probably, these major shear systems could have acted as conduits for the migration of U-bearing solutions that originated from the younger, fertile granitoid. Apart from these, the

following 3 fracture zones were identified as the first-order target areas in the central Bhima basin, viz., (i) E-W trending major K-G fault (Fig. 2a); (ii) intersection of the ENE-WSW lineament and the Wadi fault between Alur and Bhimanahalli; and (iii) the E-W trending Hunsigi-Devathkal fault with intense shearing and spatially close to the younger, fertile granitoid (Table 1: B-6). These disturbances, caused by the above structural elements, affected the basin, basin-sediments, and basement rocks. Reactivation of the regional faults led to remobilization – transportation, as uranyl tri-carbonate complex, and precipitation of U in reducing (OM- and sulphide-rich) zones. Intense close-spaced folding and repeated reactivation of faults led to poly-episodic U-mineralisation, as demonstrated by two phases of pitchblende, with the earlier phase got coffinitized and later phase replacing coffinite (Table 1: B-8). These structural aspects led to the U-mineralisation in the form of intricate network of hydrothermal veins, veinlets, and fracture-fillings within the brecciated limestone and tectonised granitoid (Table 1: B-6), as seen in the sub-surface by drill-cores (Pandit, 2002; Pandit et al., 2002).

5.2.3. Permeable and weak zones: These are illustrated by the unconformity between the basement granitoids and their overlying sediments of the Bhima basin, fractures, and zones of brecciation, which facilitated the easy mobility for U-bearing solutions from the younger, fertile, granitoid (Table 1: B-14) to precipitate U-phases in the reductant-rich zone.

5.2.4. Reductants of Sulphides and Organic Matter (OM): The sulphides include dominant pyrite with 3 modes, viz., coarse euhedral-subhedral grains replaced by OM that fills fractures, framboidal, and reticulate pattern along the grain-boundaries of calcite, with minor marcasite, chalcopyrite, and galena. The OM is a low-rank, migratory bituminous variety with textures like meshwork, stringers, veins etc., and occurs as large globular aggregates. It contains pockets of clay, chert, and U-minerals (Table 1: B- 7, 8, 10). These sulphides and OM have played an important role for U-mineralisation by acting as reductants (Table 1: B-14) to reduce the soluble U^{6+} in the uranyl tri-carbonate complex to insoluble U^{4+} present in the U-phases of coffinite and pitchblende (Dhana Raju et al., 2002).

5.2.5. Dyke rocks: Dolerite dyke activity in the basement granitoids might have acted as the heat source and created the necessary geothermal gradient for the remobilisation and precipitation of U in the reducing

environment. Besides, the dyke rocks acted as a source of sulphur (Table 1: B-14).

5.2.6. Depositional conditions of U-mineralisation:

From the assemblage of major minerals of brecciated limestone (calcite, chert) and its constituent major U-minerals (pitchblende and coffinite), OM, and pyrite (Table 1: B-7, 8, 10) vis-à-vis the experimental results of Krumbein and Garrels (1952), it can be deduced that the most probable range of Eh and pH conditions of U-mineralisation are -0.2 to -0.3 volts and 7-8, respectively (Table 1: B-13). This mineral assemblage is typical of a low-temperature formation (<200°C), which is corroborated by the framboidal pyrite, occasional marcasite, low-rank bituminous OM (Table 1: B-8) and Th-poor/free pitchblende and coffinite (Table 1: B-10). The association of pitchblende, organic carbon, and pyrite in the hydrothermal U-mineralisation of G-K deposit vis-à-vis the experimental studies (cited from Rich et al., 1978) indicate a log fO₂ of -62 to -68 log fCO₂ ~ -2 and log fS₂ -14 to -18, with transportation of U most probably as Uranyl Tri-Carbonate (UTC) complex at pH of 7.2 to 8 (Dhana Raju, 2019).

Thus, the above factors brought out by the attributes of G-K U-deposit (Table 1: B) point out that the carbonate-hosted U-deposit in the Gogi-Kanchanakayi area in Bhima basin is structurally-controlled, epigenetic, hydrothermal vein-type (Table 1: B-15). Below the unconformity between the basin-sediments and crystalline rocks, the same type in a lesser proportion (~30%) occurs in the basement biotite granitoid that acted both as source (for the above carbonate-hosted U-deposit) and host for U-mineralisation. From the G-K U-deposit, hosted both by limestone and granitoid, a few critical minerals, viz., Rare Earth Elements (REEs), Ni, Co, Cu, Ag, Au, & As occur in notable contents in the host-rocks and more so from their U-minerals and sulphides (Table 1: B-9, 10, 17), and these may be generated as value-added products, after an in-depth R&D in mineral processing and related fields (Dhana Raju, 2023).

6. CONCLUSIONS

1. Amongst the 15 types of U-deposits worldwide, carbonate rocks generally are amongst the least U-bearing in the Earth's crust. Out of 1,807 total U-deposits identified so far in the world, only 10 are carbonate type.
2. In India, two carbonate-hosted U-deposits were hitherto established by the AMD – around Tummalapalle (and contiguous area) in the

Cuddapah basin and Gogi-Kanchanakayi (G-K) in the Bhima basin, with the former having the largest resources but low-grade (U₃O₈: >0.222 Mte, ~0.045%) and the latter with the highest grade but small tonnage (U₃O₈: ~0.18%, 6,461 te) amongst the Indian U-deposits.

3. Attributes of the above two carbonate U-deposits, such as physiographic and geomorphic province, stratigraphic setting, nature and extent of host-rock, source and type, grade and tonnage, structural aspects, petro-/mineral-graphy, petro-/ore mineral-/isotopic-geochemistry, depositional environment, controls of mineralisation, mineral-processing, and possible extraction of critical minerals are presented.
4. Amongst these attributes, the factors responsible for the genetically divergent U-deposits, namely (i) strata-bound, syn-/dia-genetic type in the phosphatic dolostone of Tummalalpalte and (ii) structurally-controlled, epigenetic, hydrothermal vein-type in the non-phosphatic limestone in the G-K area are discussed.
5. Based on the above, the following guidelines in prospecting for U in a carbonate-region are suggested: after establishing a fertile source for U, phosphatic carbonate rock is potential for syn-/dia-genetic U-mineralisation, whereas non-phosphatic carbonate rock involved in major structural disturbances is potential for epigenetic U-mineralisation, with reductants of organic matter and sulphides in both cases will enhance quantity of primary U-minerals and, hence, the grade of U.

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