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Uranium Geology, Resources and Production in India- A Review

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Abstract: The element uranium, with its inherent high concentration of energy, is the basic raw material for nuclear power plants and it plays a significant role in meeting the energy demand in many countries. It is ubiquitous in nature occurring in varied concentration in almost all types of rocks and in wide-ranging geological environments. In spite of the widespread distribution of uranium, these deposits predominate in certain metallogenic provinces with time-bound characteristics. 67% of the world's uranium resources are confined to only five countries and 66% of world uranium production during the year 2020 came from only three countries. The possibility of using uranium as nuclear weapons makes it a material of strategic importance, and therefore, its availability, in general is influenced by international agreements, accentuated further by 'technology denial' regimes. The International Atomic Energy Agency (IAEA) acts as a global nuclear watch-dog and in many ways promote exploration, production, and use of uranium for several useful purposes for t he mankind. Only a small part of the land mass in the Indian subcontinent is assumed to be geologically favourable for hosting uranium deposits. Major areas of uranium mineralization of the country have been identified in Singhbhum shear zone (Jharkhand), Cuddapah basin (Andhra Pradesh and Telengana), Mahadek basin (Meghalaya), Bhima basin (Karnataka) and Delhi Supergroup of rocks (Rajasthan). India's uranium production centers are located in the state of Jharkhand and Andhra Pradesh.
Keywords: Uranium, India, production, geology, nuclear power.

Introduction

Now-a-day, nuclear power is a significant contributor to the global supply of electricity and is considered as a source of clean and green energy. Uranium is the basic raw material for nuclear power plants. It is a naturally occurring element with two major isotopes - 235U (~0.71%) and 238U (~99.28%) and is regarded as one of the highly concentrated sources of energy. The average concentration of this element on the earth's crust is 2 to 3ppm. Rocks are the only extractable primary source of uranium. The deposits of uranium, like those of other metals do predominate in certain metallogenic provinces and such provinces are of economic significance when uranium values increase due to a certain level of concentration, justifying commercial extraction through mining and processing. There are a number of such uranium provinces in the world, but only a few are of economic significance. The properties of uranium, particularly its solubility, ease of transport and precipitation, lead to the formation of ore deposits in a variety of geological settings. The metallogeny of uranium deposits of the world including those in India exhibit several anomalous features. These include the time-bound character for certain types of deposits, innumerable mineral species and deposit types, spatial restriction of certain types to a few sites (countries), wide variation in concentration etc. Such features in uranium metallogeny can be related to secular variations in the Earth's evolution such as the development of the continental crust and shield areas, formation of life and oxygen levels in the atmosphere, developments of super continents, evolution of land-plant, etc. The possibility of using uranium as nuclear weapons makes it a material of strategic importance and therefore, its availability, in general is influenced by international agreements, accentuated further by 'technology denial regimes'. The International Atomic Energy Agency (IAEA) acts as a global nuclear watch-dog and in many ways promote exploration, production and use of uranium for several useful purposes for the mankind.

Geology and origin of Uranium deposits

The element uranium is present in varied concentration in almost all type of rocks, natural waters including sea water, living organisms and even in extra-terrestrial rocks. The average concentration of uranium in the earth's crust is about 3 ppm in rock (Taylor, 1964), less than 1 ppb in surface water, 0.5 to 10 ppb in groundwater and 1.3 ppb in sea water (Dybeck, 1962; Rogers and Adams, 1969). About 1.3 X 1014 tons of uranium exist in the earth's crust. Igneous rocks with high silica content, such as granite tend to show higher uranium concentration (about 8 ppm), while rocks with less silica and more magnesium, aluminium and iron content may contain less than 1 ppm. Figure1 depicts the order of abundance of uranium in the earth's crust with respect to other elements. The concentration of more than 10 times the average crustal abundance of uranium can be attributed to the distinctive physical and chemical properties. Polyvalence, high chemical reactivity and relative solubility in aqueous solutions of some of the common chemical compounds, as well as the preponderance of uranium compared to some other ore metals, influence its localization in a wide variety of minerals (McKelvey et al., 1955;

Evseeva and Perelman, 1962). Its chemical reactivity, in particular, facilitates deposition in many rock types and minerals of diverse origin and composition. Uranium deposits are formed as a result of igneous, sedimentary, metamorphic and weathering process (Kostov, 1977). The enrichment of uranium in some parts of the earth crust is the result of outward uranium migration as shown in Fig. 2.

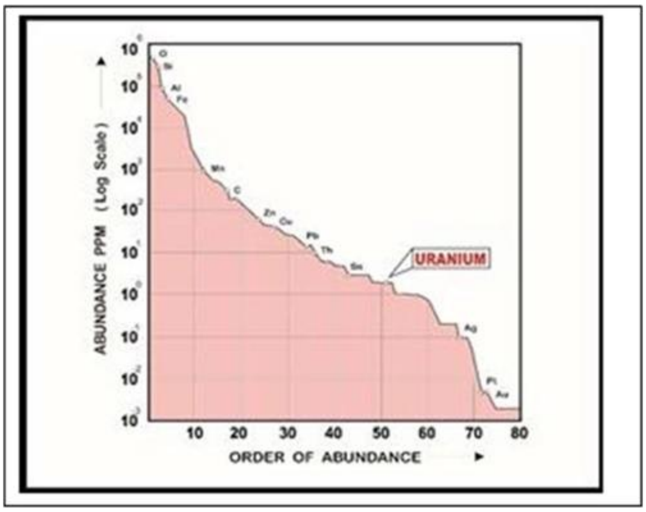

Fig. 1. Relative order of abundance of elements (Robertson et al.,1978).

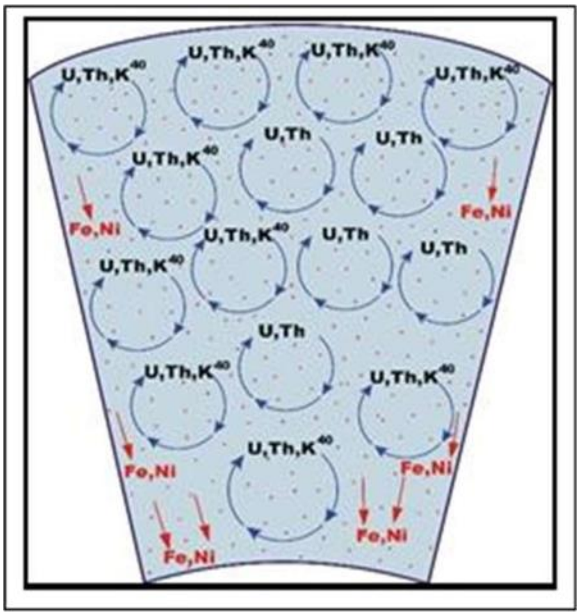

Fig. 2. Upward migration of Uranium (after Simov, 1989).

During the process of accretion of the primordial earth substance, some parts of the accumulated mater were enriched in radioactive metals and the heat produced in these places by radioactivity was higher resulting in upward migration of uranium by convection (Simov, 1984,1989). The formation of uranium deposits in a variety of geological settings – ranging from near- surface, low-temperature, recently-formed environments to deep seated environments at high temperature conditions is related to the source, mode of transportation and causes of precipitation. The localization is mainly controlled by the mechanism of transportation, the physico-chemical conditions and the host rock characteristics (Sarangi and Krishnamurthy, 2008). On the basis of the geological settings and mode of occurrence, the International Atomic Energy Agency has proposed a detailed classification system of world uranium deposits that consists of following 15 major categories (OECD NEA & IAEA, 2020).

1. Sandstone deposits
2. Proterozoic unconformity deposits
3. Polymetallic Fe-oxide breccia complex deposits

9. Metasomatic deposits
10. Surficial deposits
11. Carbonate deposits

4. Paleo-quartz-pebble conglomerate deposits
5. Granite-related
6. Metamorphite
7. Intrusive deposits
8. Volcanic-related deposits
12. Collapse breccia-type deposits
13. Phosphate deposits
14. Lignite and coal
15. Black shale

Of the above types, the Sandstone type, the Proterozoic unconformity type and Polymetallic Fe-Oxide breccia complex type of deposits predominate in share of total world uranium resources. (OECD NEA & IAEA, 2020). The deposits of above 15 types belong to more than one age and a review of their age of formations reveal that specific types are restricted to distinct epochs, exhibiting the time-bound phenomena. This character is considered to be controlled by the physical and chemical environments prevalent during the geological time involved. The Proterozoic period accounts for most of the resources known so far. Considerable resources are also found in Phanerozoic rocks. Most of the changes in the types of uranium deposits through time can be attributed to major changes in the geodynamic evolution of the Earth - in magmatic or fluid fractionation processes, in the composition of the atmosphere, and in the nature of life (Cuney, 2010).

Uranium deposits of India and resources

Uranium exploration in India is carried out by the Atomic Minerals Directorate for Exploration and Research (AMD) under Department of Atomic Energy. The activities were initiatedin 1948 and after nearly 75 years of intense investigation (which includes geophysical, geo-chemical, surface drilling and exploratory mining), five major geological basins of the country have emerged as uranium provinces hosting more than 98% of known uranium resources. (AMD's Issue on 'Uranium Deposits of India', [Eds.] Dhana Raju et al., 2002; Dhana Raju, 2019; Sinha, 2022).

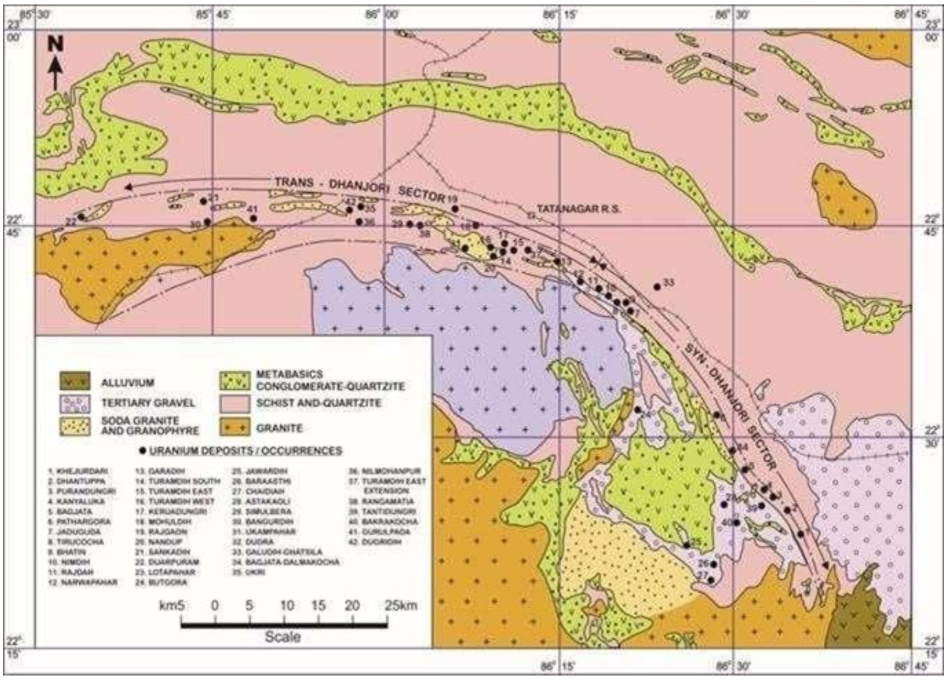

Fig. 3. Uranium occurrences identified in Singhbhum shear zone and adjoining areas (Modified after Bhola et al.,1966).

Singhbhum Shear Zone (SSZ) in Jharkhand

The Singhbhum craton and its adjoining northern mobile belt (Jharkhand and Odisha region) is are separated by a deep-seated crustal furrow – known as Singhbhum Shear Zone (SSZ). It is represented as a zone of intense deformation, basic volcanism and hydrothermal mineralisation. SSZ is known for its rich repository of mineral wealth. In the central and south-eastern part, this zone of intense and deep tectonisation with less than 1 km width gradually widens towards north-west and hosts a number of copper and uranium deposits with associated nickel, molybdenum, bismuth, gold, silver, tellurium, selenium and magnetite. Copper and uranium mineralisation has taken place along the zone of shearing particularly in the central and southeastern sector (Sarkar, 1984). Amongst a score of discoveries in SSZ so far, some significant uranium deposits are Jaduguda, Bhatin, Narwapahar, Garadih, Bagjata, Kanyaluka, Turamdih, Banduhurang, Mahuldih, Bangurdih, etc. (Fig.3).

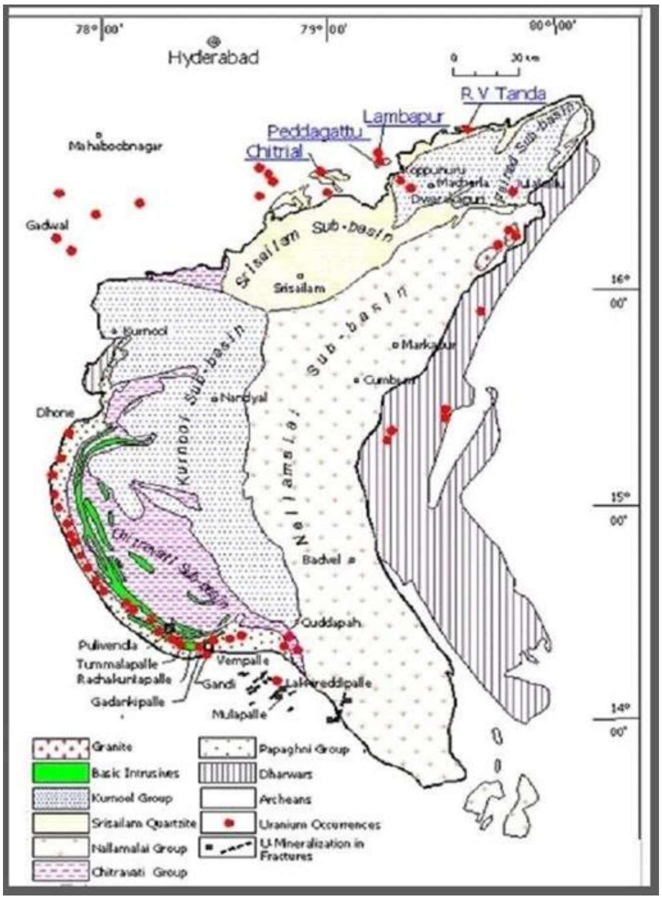

Fig. 4. Uranium occurrences identified in Cuddapah Basin in Andhra Pradesh and Telangana.

Uranium mineralisation in SSZ is confined to well defined zones of deformation and intimately related to the tectonic, structural and depositional evolution of the area. The richest uranium ore lodes in Jaduguda-Bhatin sector in central part of SSZ are hosted in quartz-granular rock and brecciated quartzite, occurring as veins with associated copper, nickel and molybdenum. Towards the eastern part of SSZ around Bagjata – Kanyaluka area, the mineralisation is found in quartz-biotite-sericite schist. In the western sector from Narwapahar to Turamdih and further west, discrete uranium grains are found disseminated in quartz-chlorite, crushed sericite-chlorite schist and feldspathic schist. Low grade uranium mineralisation in this sector exhibits strata bound character showing concordant to pene-concordant relationship with the host rock. The ore lenses of Turamdih deposit extends westward and coalesce to form a massive ore zone very close to surface at Banduhurang. Mineralisation at Mohuldih is found in tourmaline bearing quartz schist occurring as veins. Uranium deposits in SSZ are of low grade and most of them are of small to medium size (Krishnamurthy, 2006).

Cuddapah basin (Andhra Pradesh and Telangana)

The crescent shaped Cuddapah basin in southern part of Indian sub-continent is known for variety of economic minerals. Exploration for unconformity related, large-tonnage, high grade- uranium deposits began in this basin in 1980's which led to the discovery of two different types of uranium deposits. These are, (a) the unconformity proximal type in the basement granites below the Kurnool Group of sediments at Lambapur and Peddagattu (Sinha et al., 1995) and (b) the stratabound type, dolostone-hosted mineralisation at Tummalapalle (Rai et al., 2002). Cuddapah basin is an important uranium province of the country (Fig. 4). The northern side of the basin in the state of Telengana comprises dominantly of arenaceous and argillaceous rocks of Middle Proterozoic period overlain by Upper Proterozoic calcareous formations. Close to the unconformity (basement granite and its overlying Srisailam quartzites) in the Srisailam outlier, cluster of uranium deposits have been found around Lambapur, Peddagattu, Kuppunur and Chitrial. In the south western margin of the Cuddapah basin in Andhra Pradesh, uranium deposits occur in phosphatic siliceous dolostone of the Middle Proterozoic Vempalle formation. Within the thick pile of carbonate rocks, the mineralized horizon is sandwiched between lower massive dolostone and upper shale. Mineralisation extends over about 60 km length, but the mineable lodes are persistent over about 12 km of length in Tummalapalle-Rachakantapalle - Kanampalle sector near Pulivendla. The lodes are proven to extend up to a depth of about 800 m. This area hosts significant uranium inventory of the country.

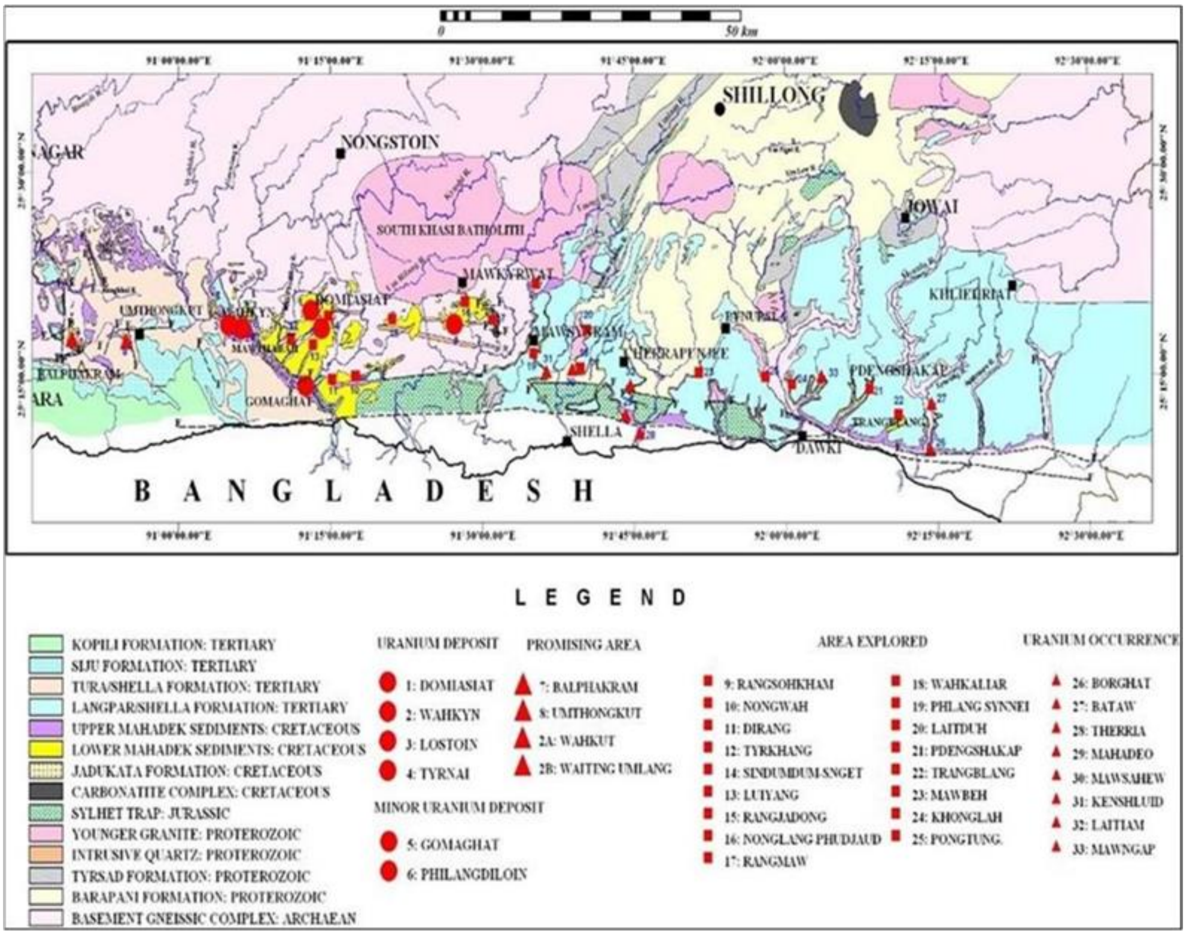

Fig. 5. Uranium occurrences identified in Mahadek Basin in Meghalaya.

Mahadek basin (Meghalaya)

The Mahadek sediments of Cretaceous period (Fig. 5), which host the uranium mineralization lie in the southern part of Shillong plateau bounded by three faults: theDauki fault in the south, Haflong fault in the east and north-east and the Brahmaputra graben in the north. The plateau consists of rocks ranging from Precambrian to Tertiary. The basement consists of Archean gneissic complexes intruded by basic and ultrabasic intrusives with late-phase acidic-granitic bodies. Basic volcanic flow (Sylhet trap) overlies the basement, followed by Upper Cretaceous sediments (Jadukata and Mahadek). Lower Mahadek sandstones are coarse to fine grained, arkosic, and reduced, whereas upper Mahadeks are represented by coarse, arkosic, oxidized sandstone. A large uranium deposit with a tabular to lensoidal orebody has been located at Domiasi at in lower Mahadek sediments. The host rock shows primary sedimentary structures like cross and parallel bedding, horizontal bedding with fining upward. Mineralisation is controlled by palaeochannels and impregnated with carbonaceous matter both in-situ and migratory, as streaks, lumps, dispersion in matrix and pore fillings. The ore zone is tabular with an almost flat dip (~ 50), thickness ranging from a few centimeters to tens of meters (Sen et al., 2002). A number of small to medium size deposits (Wahkyn, Tyrnai, Wahkut, Lostoin, etc.) have also been discovered in the area under similar geological settings.

Bhima basin (Karnataka)

The Bhima basin in the southern Indian plateau towards NW of Cuddapah basin has also emerged as an important uranium province. The basin predominantly comprises of carbonates with minor argillites and arenites. A number of fault zones have been identified in the basin, with trends varying between E-W to NW-SE (Fig. 6). Occurrences of uranium mineralisation have been reported along most of these fault zones associated with deformed Bhima sediments and / or basement granite. Significant uranium mineralisation at Gogi has been discovered almost at the middle of 30 km long East – West trending Kurlagere – Gogi – Gundahalli fault zone at the contact of basement granite and Bhima sediments on its southern margin. This mineralisation is mainly associated with two lithological units - brecciated limestone and sheared granite (Pandit et al., 2002). The continuation of mineralisation of Gogi deposit is further traced towards NE up to Kanchankayi. Some more mineralization is also reported at Hulkul village showing continuity of Kanchankayi block.

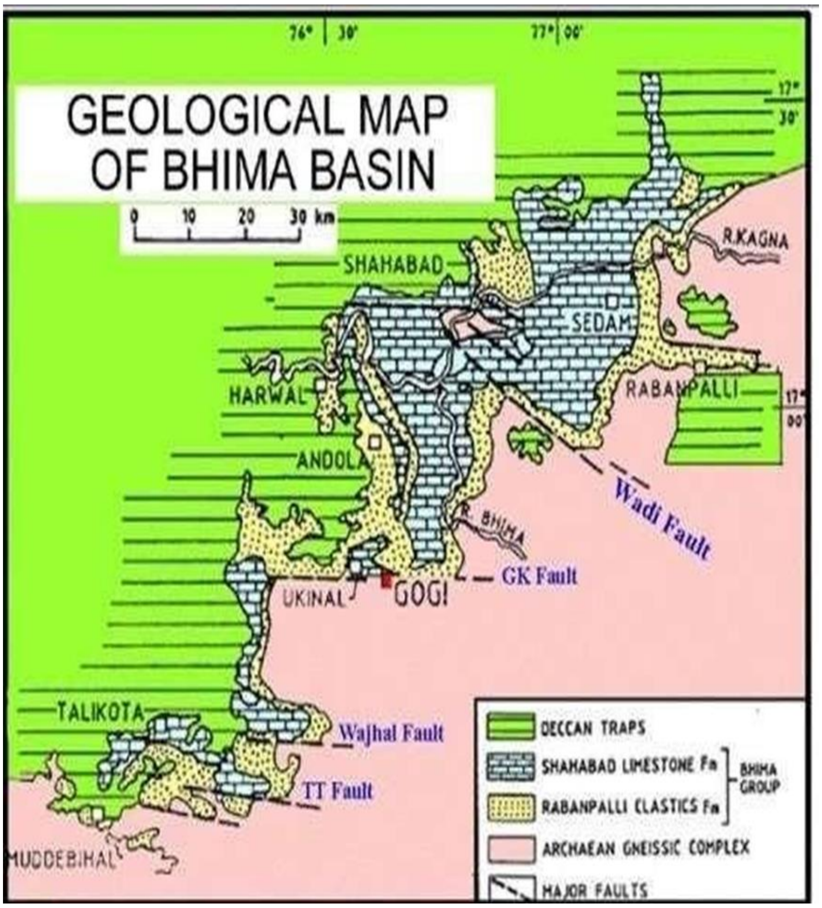

Fig. 6. Uranium occurrences identified in Bhima Basin in Meghalaya.

North-Delhi Fold belt (Rajasthan)

The Southern part of the Khetri sub-basin (the albitised zone) of North-Delhi Fold Belt in Rajasthan has recently been known as a large inventory of uranium mineralisation (Fig.7). The mineralized bands are found along the sheared contact between quartzite and quartz-biotite-chlorite- hornblende-graphite schist (carbonaceous?) of Azabgarh metasediments at Rohil – Ghateswar area that extends for about 20 km following NNE-SSW trend. This structurally weak zone has served as a favourable locale for uranium concentration being activated/reactivated during different phases of deformation, metamorphism and igneous activity. The mineralisation is associated with hydrothermal activities and controlled by shears, faults / fractures. A number of vertical to sub-vertical poly- metallic uranium lodes have been located in this area with associated copper, molybdenum, nickel andcobalt. The host rock exhibits wall rock alteration represented by silicification, chloritization and albitization. (Khandelwal et al., 2010). Uranium mineralisation was also located in Precambrian black shales at Umra during '50s. However, these lenses were found very discontinuous showing erratic uranium concentration.

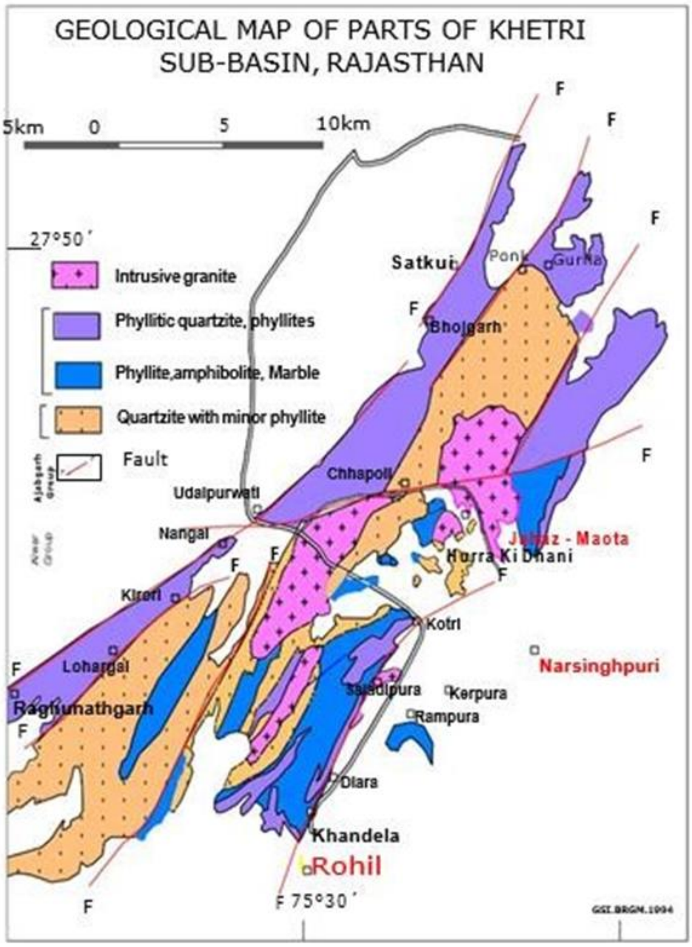

Fig. 7. Uranium occurrences identified in North Delhi Fold Belt (parts of Khetri sub basin) in Rajasthan.

Other known areas of Uranium occurrences

In addition, some small uranium deposits / occurrences have also been reported in the Chhotanagpur Gnessic Complex (CGC) of Eastern Indian Shield, Bodal - Bhandaritola in Chhattisgarh occurring in Nandgaon group of Dongargarh supergroup and in Gondawana sandstones around Motur near Betul in Madhya Pradesh. Shear controlled hydrothermal mineralisation has also been located to a lesser extend in the Barahbhum thrust belt and has also been reported in Gangpur mobile belt in adjoining areas of Singhbhum craton. But no major discovery has so far been made in these areas. Further, quartz-pebble-conglomerate type uranium mineralisation has been traced in the Singhbhum craton south of the Singhbhum shear zone at the base of Iron ore group of rocks in the Badampahar- Gorumahisani basin and in Dharwar group of rocks in Karnataka. In these areas, uranium mineral uraninite occurs as fine grains closely associated with sulphide rich matrix within conglomerates (auriferous at places).

Uranium Resources of India

As on February, 2021, a total of 3,50,438 tons (t) in situ U_3O_8 (2,97,170t U) uranium resources have been established in forty-four (44) uranium deposits located in Andhra Pradesh, Telangana, Jharkhand, Meghalaya, Rajasthan, Karnataka, Chhattisgarh, Uttar Pradesh, Uttarakhand, Himachal Pradesh and Maharashtra. Of these, Andhra Pradesh account for 57%, Jharkhand 23%, Meghalaya 6%, Telangana 5%, Rajasthan 4%, Karnataka 2% and remaining in other states (DAE, 2021). Indian uranium deposits are of low-grade and the country has a modest uranium resource base. It is expected that future investigations adapting novel exploration strategies along with improvements of techniques focused towards deep-seated uranium mineralization shall enhance the uranium resource of the country.

Uranium production centres in India

Uranium ore mining in India is accomplished through conventional underground and open pit mining. The mined-out ore undergoes processing which includes crushing and grinding, leaching (either in acidic or alkali medium depending on the host rock chemistry), filtration, concentration and purification of the solution and product precipitation. The final product, in the form of uranium concentrate (called Yellow-cake) is sent to Nuclear Fuel Complex, Hyderabad for further processing. Uranium industry of India started in 1967 with the formation of Uranium Corporation of India Ltd. (UCIL) under Department of Atomic Energy. Jaduguda mine and mill (formerly in Bihar and now in Jharkhand) is first production center of the country. Later, with the discovery of deposits in other areas, efforts were made to open new deposits in different parts of the country. Presently, the uranium ore mining and processing in India are confined to only two areas (Gupta and Sarangi, 2010; Sarangi, 2014).

Singhbhum Shear Zone in Jharkhand

Uranium mining in SSZ started in 1968 with the commissioning an underground mine and ore processing plant at Jaduguda. Later on, with the increasing need of uranium for the growing atomic energy program of the country, other deposits were taken up for development in this area. Presently, UCIL is operating six underground mines and one open pit mine in Singhbhum Shear Zone. All these mines are located within 25km of Jaduguda. Jaduguda underground mine was initially explored with the development of a few adits as entry into the orebody. Regular mining operations started with the sinking of a vertical shaft. This was followedby commissioning of Bhatin mine in 1986, Narwapahar mine in 1995, Turamdih mine in 2003, Bagjata mine in 2008 and Mohuldih mine in 2013. New mines at Narwapahar, Turamdih, Bagjataand Mohuldih adopt decline method of entry and use of track less equipment. Vertical shaft provides access to deeper levels for ore and men & material hoisting. Ore extraction in underground uranium mines of UCIL is generally carried out by horizontal cut-and- fills method of stopping with site-specific modifications and introduction of newer equipment with a view for better safety, improved ore recovery and less dilution. Banduhurang, the first opencast uranium mine of the country was commissioned in 2009.Uranium ore produced from these mines are processed in two central plants located at Jaduguda and Turamdih. Jaduguda plant was commissioned in 1968 and had undergone expansion in phases to treat the ore of Bhatin, Narwapahar and Bagjata mines. Turamdih plant was commissioned in 2009 to treat the ore of Turamdihand Banduhurang mines. Ore from Mohuldih mine is also fed to this plant. Both the uranium processing plants in SSZ in Jharkhand follow conventional way of processing the ore through acid leaching route because of siliceous nature of host rock.

The development of uranium mining technology in Singhbhum Shear Zone of Jharkhand has come a long way progressively adopting appropriate technologies. New mines are being planned with provision to automate all strenuous mining activities avoiding direct handling of radioactive ore. Underground ventilation system, strata control measures etc. are being simulated before field trial and implementation. The bulk ore assaying system with automatic grade estimation, unique to uranium mining industry is undergoing continuous improvement. Similarly, uranium ore processing and tailings management practices have undergone many improvements with utmost consideration on maximising the recovery, minimising the discharge of effluents and maximising the recovery of by-products (Sarangi, 2018).

South Cuddapah Basin in Andhra Pradesh

The SW part of the Cuddapah basin which hosts the lion's share of uranium resources of the country, is now the new center of uranium production activities. Presently, it hosts one of the largest uranium production facilities of the country at Tummalapalle in the Kadapa district. This deposit extends over a strike length of 6.6 km. There are two ore bands in this zone, fairly continuous and parallel, separated by a lean zone of 1.5 m to 3 m width and extend down-dip at 150 to 180 up to a depth of 600m. The two bands are tabular, stratabound and non-transgressive in nature with little variation in grade and thickness along strike and dip. The ore bands are in carbonate host rock.

Several studies were made to develop the orebody at Tummalapalle with an aim to produce the ore at an early date, minimise the cost of production and dilution through optimum level of mechanization and maximize the ore recovery. The entry into this underground mine has been established through a central decline at 9º gradient along the apparent dip of ore body. Two more declines, 15 m apart on both sides and parallel to the central decline are also developed. The central decline is provided with aconveyor for ore transport and other two parallel declines are used as service path for movement of men and materials. The advance strike drives (ASDs) are developed in the strike direction. Size of the panels, ore extraction and size of rib pillars are planned on the basis of competency of host and wall rocks, width of orebody and parting between two lodes. The equipment under use for development includes low profile jumbo drill, rock bolter, low profile loader, dozer and dump truck. The ore processing technology in the plant at Tummalapalle is based on alkali leaching because of the high carbonate content in host rock. This technology has been developed after extensive laboratory and pilot plant studies. The fine-grained nature of minerals within competent host rock has necessitated to carry out leaching under high pressure-temperature conditions. Development of indigenous technology to process the carbonate-hosted ore of Tummalapalle is an exemplary achievement in uranium industry of the country in recent years (Suri, 2010; Gupta and Sarangi, 2008; Sreenivas and Chakravarthy, 2015).

Future uranium production facilities in India

With adequate uranium resources already established in different parts of the country, efforts have been initiated to construct new production facilities (mine and mill) at Rohil in Rajasthan, Gogi in Karnataka, Kanampalle in Andhra Pradesh etc. Small deposits of SSZ in Jharkhand namely, Garadih, Bangurdih, Kanyaluka, etc. hold the promise for new underground mines. Large resources have also been established in the adjoining areas of existing uranium mines at Narwapahar in SSZ in Jharkhand and Tummalapalle in Andhra Pradesh with the potential for new mines or expansion of existing operations.

Conclusion

Uranium ore deposits present the most extreme diversity of concentration processes from the Archean to the Recent. The fractionation and deposition mechanisms of diverse types in varied geological settings are still under intense study, but most of these findings confirm that a large part of the deposits is hosted in Archean-Paleoproterozoic rocks with anomalous concentration of uranium. However, a thorough understanding on parameters of uranium fractionation processes and their variation throughout Earth's history may provide a better insight. Interest on uranium geology and its exploration started in India after the formation of Atomic Energy Commission in 1948. These activities are carried out by Atomic Minerals Directorate for Exploration and Research (AMD) under Department of Atomic Energy. During last 75 years, almost all geological basins of the country have been thoroughly investigated with major findings in four Proterozoic basins (Singhbhum Shear Zone, Cuddapah basin, Bhima basin and North Delhi Fold Belt) and one Phanerozoic basin (Mahadek basin). Unfortunately, Indian deposits are small to medium in size and low grade. Mining of these deposits and processing of ore on commercial considerations have always remained a challenge in our country. The technology for extraction of uranium has been under continuous advancement not only to be cost competitive but also to meet the need for nuclear programme of the country. Emphasis has been laid on augmentation of resources through modern techniques of uranium exploration, innovative ways of uranium production, setting-up new production centers, etc. The growth of this sector in our country has largely been made possible with the involvement of reputed research organisations, educational institutions, manufacturing industry, consultants, scientists and experts ensuring appropriate balance of technological, economic, environmental and social aspects.

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