URANIUM METALLOGENY WITH SPECIAL REFERENCE TO INDIAN DEPOSITS

A. K. Sarangi* & P. Krishnamurthy**

***Jaduguda Mine, Uranium Corporation of India Ltd., Jaduguda – 830102**

**** Management Training Center, Uranium Corporation of India Ltd., Narwapahar - 832107**

ABSTRACT

Metallogeny of the uranium deposits of the world including India exhibit several anomalous features. These include the time-bound character for certain types of deposits, innumerable mineral species and deposit types (15 types with several sub-types), spatial restriction of certain types to a few countries, namely Australia, Canada and South Africa and three deposit types, namely the unconformity-related, breccia complex and sandstone type containing about 68% of the world uranium resources. Such features in uranium metallogeny can be related to secular variations in the Earth's evolution such as the development of continental crust and shield areas, formation of life and oxygen levels in the atmosphere, developments of super continents, evolution of land-plant and others.

The uneven distribution of deposits through geological time, particularly their predominance during Proterozoic and Phanerozoic Eons are of great relevance to the exploration geologists. 65% of world uranium resources have been identified in deposits falling under Proterozoic, bulk of it (33%) being accounted by the unconformity related-type of deposits found in Canada and Australia. A single deposit of Middle Proterozoic period, termed as 'breccia complex' type with Cu-Au-Ag-Fe-REE and U, as found in the Olympic Dam, South Australia, accounts for 17% of the world resources. Phanerozoic sandstone type of deposits formed in continental fluvial or marginal marine sedimentary environment account for 18 % of the world uranium resources.

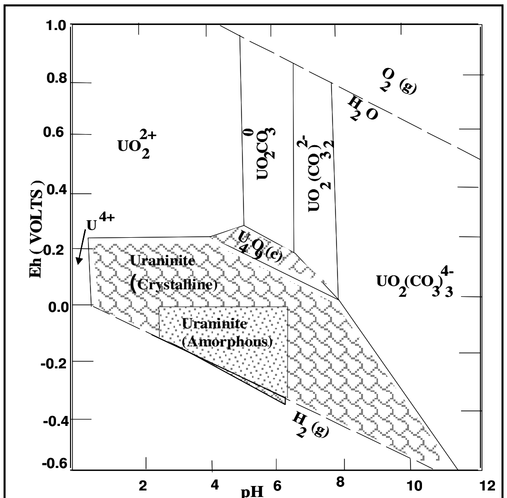
In India, Proterozoic deposits host about 75% of uranium resources and the remaining come from deposits that are hosted in the Phanerozoic sandstones. Most of Indian uranium reserve identified so far, comes from four types. These include three deposit types from the Proterozoic, namely the vein types from the Singhbhum belt, Jharkhand, the unconformity proximal (?) deposits in the northern parts of Cuddapah basin and the strata-bound, dolostone-hosted deposit in the south western margins of the Cuddapah basin, Andhra Pradesh. The fourth resource base includes the Phanerozoic sandstone type deposits of Kylleng-Pyndengsohiong (formerly known as Domiasiat) and Wahkyn in the state of Meghalaya. A number of smaller deposits are known from several other Proterozoic uranium provinces in India and these should lead to larger ore finds in the future.

Key words: Uranium deposits, World, India, Metallogeny

1. INTRODUCTION

Among the heavy metals, the metallogeny of uranium is rather unique and special in many ways. These include processes ranging from physical transport of residual uraninite grains in aqueous, low temperature, stream sediment and deposition in deltaic environments, under oxygen deficient or rich atmosphere to those related to solution or fluid transport at higher temperatures that prevail in late-magmatic, pegmatitic, hydrothermal and medium-grade metamorphic systems. The nuclear renaissance and the continuous rise in uranium price since the start of the new millennia, coupled with world-wide concerns to limit CO_2 emissions have led to renewed interests in uranium exploration and exploitation. It is in this context that we take a fresh look at the metallogeny of uranium with special reference to the Indian context.

Uranium minerals are formed in the earth's continental crustal domains leading to deposits under different geological conditions mentioned above. This diverse mode of occurrence is primarily related to: (a) the mobility of uranium under conditions ranging from acidic to alkaline, (b) the ease of transportation under oxidizing conditions and (c) causes of precipitation (reducing environment) leading to concentration. Though the primary dispersion of uranium is largely a function of its chemical properties, the secondary distribution is controlled by the E_h (redox potential) and pH (hydrogen ion concentration) conditions of the geological environment (see Fig.1). Uranyl ($UO_2\ ^{+2}$) complexes predominate at high fO_2 values whereas sulphate complexes become important in acid solutions. Fluoride complexes dominate in acid to slightly alkaline pH values while carbonate complexes become important at pH > 7 (Romberger, 1984).



Eh-pH diagram in the U-O -CO -H O system at 25°C for PCO =10 atm & U solubility of 10 M (Langmuir, 1978).

Fig. 1

The time-bound character of uranium deposits was first recognized by Roberston et al., (1978) and Toens (1981). However, the concept of uranium metallogeny the world over have undergone a major re-orientation following the major discoveries and the emergence of the class of "Unconformity related uranium deposits" in the well known Athabasca basin, Canada (Sibbald. 1988; Ruzicka, 1996; Jefferson et al., 2003) and the world's largest uranium deposit with copper and gold at Olympic Dam, South Australia (Roberts, 1988). These discoveries were a sequel to decade long geological studies including air-borne surveys both in Canada and Australia following the uranium glut of the 1960s and the intense fillip for uranium exploration as a sequel to the first oil crisis after the Arab-Israeli war of the early 1970s. High grade and large tonnage uranium deposits containing as high as 16-20% uranium with over 50,000 t of U_3O_8 were discovered in the Athabasca basin, Canada (Cigar Lake, MacArthur River and others) below a thick cover of barren sandstones.

Similar deposits, however, with medium grade were discovered in the Pine Creek Geosyncline, Northern Territory, Australia. The discovery of a magnetic-gravity anomaly in the South Australian Precambrian gneissic terrain followed by diamond drilling led to the unearthing of the giant Olympic Dam, poly metallic deposit with 0.05% uranium, termed as the "Breccia complex type", represents the single largest uranium reserve in the world with almost a million tonne of uranium oxide.
The extreme diversity in the geochemistry of uranium coupled with first order changes in earth's crustal evolution has resulted in a plethora of uranium minerals and deposit types. We shall briefly overview the uranium deposits and the metallogeny that caused these deposit types.

2. TYPES OF URANIUM DEPOSITS

Uranium deposits discovered so far and occurring in different geological environments, have been classified by Dahlkamp (1993) in to 15 major types with several sub-types. He also provides geological and other details of selected deposits. IAEA (1996) published an atlas of world deposits with a continent-wise summary of the 582 uranium deposits along with their classification in terms of deposit-types, grade, U_3O_8 reserves, status of exploration, age of the host rocks and others. Accordingly, a uranium deposit is defined as one that contains 500 t of U_3O_8, generally with a cut off of 0.03% U_3O_8 or above. However, when uranium is a co-product as in the case of phosphorites or Au-bearing conglomerates, the grades could be as low as 0.01%. The different deposit types, their abundance and their contribution to the world uranium resources are given in Table 1.
Of the 15 types listed in Table-1, five, namely quartz-pebble-conglomerate type, unconformity related type, vein type, sandstone type and breccia complex type constitute the bulk (90%) of the uranium resources of the world. Among these, the sandstone type predominates in abundance and hold 18% of the world resources whereas the single, breccia complex type, accounts for 17% of the world's resources.

2.1 QUARTZ-PEBBLE CONGLOMERATE TYPE DEPOSITS

This unique type developed as a paleo-placer deposit with detrital uraninite grains formed due to the non availability of oxygen in the earth's atmosphere before the Lower Proterozoic Eon. The Au-U bearing quartz-pebble-conglomerate deposits of the Witwatersrand basin in South Africa and the U-REE bearing placer deposits of Elliot lake deposits in Canada represent the type examples. Both these areas contain some giant deposits (over 50,000 t of U_3O_8). An important pre-requisite for this class is the non-availability of oxygen in the atmosphere for effecting oxidation of the uraninite that had formed in the late Archean, potassic granites and pegmatites. Deep weathering under oxygen poor atmosphere, liberated uraninite and other heavy minerals such as zircon, monazite, magnetite, ilmenite, pyrite, xenotime and others which were transported swiftly in the fluvial to littoral environments forming conglomerates with rapid burial. Au is the main product in South Africa whereas in Canada besides uranium, monazite and xenotime become important co-products. Diagenetic processes within the conglomerate pile resulted in the formation of brannerite ($UO_2.TiO_2$) from rutile and clay was formed from feldspar in the Elliot Lake deposits (Robertson, 1989). Diabase intrusions have induced 'albitite type' signature on the conglomerates and distributed some 25% of the uranium in the Pronto uranium mine, according to Heinrich

(1982). Deep burial of the conglomerates preserved the uraninite from subsequent oxidation as well as erosion.

In South Africa, the conglomerate horizons have been re-worked by geological processes improving the grade from a few tens of ppm to over 100 to 300 ppm. The enormous size of the Witwatersrand basin, spread over 50,000 km^2 with over 8 km thick sedimentary pile, in which the conglomerates or reefs have a thickness varying from 5 – 200 cm (locally become 400 cm). The U/Au ratio in these conglomerates ranges from 6 to 769 (Pretorious, 1974). The exclusive development of such large basins and deposits is taken up for discussion later.

Table-1. A simplified list of different uranium deposits with leading examples along with the share of such deposit types in the uranium inventory (after Dhalkamp, 1993 and IAEA, 1996)

No.	Types	Typical examples	% of total deposits	% of total uranium resources
1	Quartz-Pebble-Conglomerate type	Witwatersrand area, South Africa	3.8	13.0
		Elliot Lake region, Canada		
2	Unconformity related	Athabasca basin, Canada	4.0	33.0
		Alligator river basin, Australia		
3	Vein type (hydrothermal or disseminations)-structurally controlled / stratabound	Beverlodge, Uranium City, Canada	23.7	9.0
		Massif central, France		
		Schwatzwalder, USA		
4	Sandstone type	Oklo, Gabon	42.8	18.0
		Grants, USA		
		Niger		
		Kazakhstan		
5	Breccia complex	Olympic Dam, Australia	0.2	17.0
6	Intrussive	Rossing, Namibia	2.2	10.0
		Bancroft, Canada		
7	Volcanic	Jiang Xi, China	7.4	
		Michelin, Canada		
8	Metasomatites	Ross Adams, USA	2.1	
		Kriverozhsky-Zheltye, Ukraine		
9	Collapse breccia type	Orphan lode and Hack Canyon, Arizona, USA	1.7	
10	Phosphorite	Montpelier, USA	1.7	
11	Black shale	Chattanooga, USA	1.5	
		Ranstad, Sweden		
12	Lignite	Slim Buttes, South Western Williston Basin, USA	3.8	
		Czech Republic		
13	Surficial / Fluvial valley fill	Yeelerie, Australia	2.7	
14	Metamorophic	Forstau, Austria	2.4	
15	Others			

2.2 UNCONFORMITY RELATED TYPE DEPOSITS

At present deposits of this type, spatially related to the Lowe-Middle Proterozoic unconformity are known only from Australia and Canada. The ore zones occur above, along and below the unconformity in Canadian deposits (Athabasca) or mainly found in the Lower Proterozoic rocks below the unconformity as in Australian deposits (Pine Creek Geosyncline). Uranium metallogeny for this group of deposits, as inferred from the case studies of deposits envisages a sequence of events that ultimately led to their formation often with high grades and large tonnage forming giant deposits.

The formation of this class of deposits following the QPC types has been related to several first order features in the evolution of the crust that influenced the metallogeny. These include the formation of super continents and development of intracratonic or pericratonic basins, protracted period of weathering or laterisation and regolith formation as a sequel to crustal stability and the development of first generation, solution transported uranium following the oxygenation of the atmosphere. The influence of mantle-related magmatic processes such as emplacement of anorogenic rift related granites, alkaline rock-carbonatite complexes, kimberlites and flood basalt provinces, however, are poorly understood. The development of Mesoproterozoic basin with a thick sequence of continental sandstones that provided the cover to the Paleoproterozoic basins seems to have provided the twin benefit of not only protecting the deposits from erosion but also provided uraniferous solutions that could percolate down and migrate along the unconformity and below and on encountering reductants can precipitate the uranium. Thus, this group of deposits is rather special and in Canada many of them are below 500 m of cover rocks.

2.3 BRECCIA COMPLEX TYPE DEPOSIT

This deposit type represented by a single deposit, namely, Olympic Dam in the Stuart shelf, South Australia is unique in several ways. It is located within the Middle Proterozoic Roxby Down granite (anorogenic, A-type) in the form of a boat-like structure of c. 30 km^2 area. The granite forms the basement over which c. 350 m of clast-rich sediments formed. Granite brecia and other polymictic breccias developed as a consequence of phreato-magmatic activity related to the Hiltaba suite volcanic and plutonic activity. Ore zones occur in a variety of brecciated rocks namely, granite breccias (matrix-poor), hematite-granite breccias and hematite breccias (matrix-rich) which often show transitional features. U and Cu mineralisation occur both in strata-bound and transgressive litho-units. Ores average 0.05% U, 1.6% Cu and 0.6g/t of gold (Roberts, 1988).

2.4 VEIN TYPE DEPOSITS

This type constitutes the second most important group forming 23.7% of the known deposits and including 10% of the world’s resources. Vein types predominate in the Paleozoic period with some 86 deposits followed by the Proterozoic and Archean which host 36 deposits.

Metallogeny of the major vein type deposits include granite-hosted, (Margnac, Peny and others in the Limousin province, France), peri-granitic in close proximity in the contact metamorphic envelope (deposits in Pribram district, CSFR) and hosted in meta-sediments unrelated to granite bodies, often carrying other metals besides uranium such as the St. Jaochimsthal or Jaochimov in CSFR, with Ag, Co, Ni and Bi (Dahlkamp,1993). The first two types are invariably related to the Hercynian orogeny (300-350 Ma).

There are other vein type deposits which do not show any direct relation to granites like those of Schwartzwalder (Front Range, USA), Shinkolobwe, Katanga Copper Province (Zaire) and others. Metallogenesis in these deposits appear to be sedimentary-metamorphic in origin often involving shear-induced remobilization and structure-controlled. Thus vein type deposits show extreme diversity in their metallogenesis. A variety of alteration features such as silicification, chloritization and hematitization are common to these deposits (Rich et al., 1977).

2.5 SANDSTONE TYPE DEPOSITS

This group includes the maximum number of deposits, some 250 out of a total of 582 deposits known. They also show a prominent time-bound feature as 240 deposits belong to the Phanerozoic, especially the Mesozoic (101) and Cenozoic (104), when land plant debris and the humates generated from them became a potential reductant in continental sediments. The remainders occur in the Proterozoic or of unknown age. Several variants of this type of deposit, based on the nature of the reductant and the shape of the ore bodies have been recognized in the Phanerozoic mainly from the western US. The most important Proterozoic sandstone type occur in the Franceville basin in Gabon which of course, in many respects resemble those of the Phanerozoic types.

2.6 URANIFEROUS BLACK SHALE AND PHOSPHORITES TYPE DEPOSITS

Syngenetic uranium in low concentrations (50 – 300 ppm) occur in these types of deposits typically in three distinct time periods. Black shale hosted uranium is confined to the Paleozoic. The phosphorites, typically developed during Mesozoic and Cenozoic, as exemplified by the deposits of Florida, USA, carry uranium that substitutes in carbonate-apatite for calcium. However, because of their large volume, uranium becomes important as a co-product.

2.7 COLLAPSE BRECCIA PIPE TYPE DEPOSITS

This unique type of solution collapse, breccia pipes are known only from the north western Arizona, USA. They are of solution and collapse origin and are composed of Mississippian to Lower Triassic continental to marginal marine limestones, mudstones and sandy to silty sediments (Dahlkamp, 1993). They display a very heterogeneous mineralisation with both uranium (pitchblende and coffinite) and sulphides, arsenides, sulfo-arsenides, oxides, carbonates and sulphates of Fe, Cu, Ni, Co, Mo, Pb, Zn and Ag. Minor to trace elements include Au, Cd, Sb, Se, and V. There is considerable diversity among the pipes. The temperature of mineralisation as inferred from fluid inclusion studies of the sulphides range from 54 to 173^0 C. The age of mineralisation based on U-Pb data on pitchblende range from 260 to 140 Ma, typically within the Paleozoic.

2.8 SURFICIAL (CALCRETE) TYPE DEPOSITS

Carnotite (U-K-Vanadate) bearing, calcrete (surficial, duricrusted, playa sediments) of Yeelirrie, Australia represents this type of deposit with no comparable deposits so far found elsewhere. A uranium-rich granite basement (up to 80 ppm but mostly 3-8 ppm), with a deep (up to 250 m) weathered mantle (lateritic type under humid climate), followed by an arid climate, when evaporation far exceeded the precipitation (15 to 1) have been inferred to be important pre-requisites for this type. A very low drainage gradient (0.001) and a very large catchment area provided U, K and V. Absence of pedogenic calcrete and organic matter, helped in fixing the U largely brought in to the system as uranyl carbonate complex. Different aspects of this carnotite mineralisation have been discussed in great detail by Arakel (1988).

2.9 METASOMATITE TYPE DEPOSITS

Deposits of this type predominantly occur in the Proterozoic (11 out of the 12 deposits known) and include structurally deformed metasediments or granites that have been subjected to metasomatism, mostly of the sodic-type. Examples include the Krivorozhysky-Zheltye Vody deposit in Ukraine hosted in metasediments and the Ross Adams, USA deposit formed in metasomatised granites with alkai pyroxenes and or amphiboles (Dahlkamp, 1993).

2.10 INTRUSIVE TYPE DEPOSITS

Uranium mineralisation hosted in intrusive granite or pegmatite facies or alkali syenite or carbonatite belong to this group. The type example for the intrusive granite or alaskite related type include the Rossing deposit, located in the Namib desert of Namibia. The alaskites, both syn-and late-tectonic are part of the Damara orogenic belt formed during the Cambrian at c. 468 Ma. Uraninite occurs mainly as disseminations within the alaskite, termed as the 'porphyry type' (Berning et al., 1976).

As we have seen so far, except for the Phanerozoic sandstone types, majority of the other types occur in the Proterozoic rocks. The Proterozoic also hosts some of the 'giants' with over 50,000 t of U_3O_8 at single localities. The special conditions that prevailed during the Proterozoic thus become important in understanding the uranium metallogeny.

3. TIME-BOUND CHARACTER OF URANIUM DEPOSITS

An appraisal of all known uranium deposits of the world and their ages reveals a striking feature of the uranium metallogeny, namely their formation in five well defined epochs from early Proterozoic to Recent (Fig. 2). These epochs apparently coincide with the major phases of secular crustal evolution such as cratonisation of the continental crust, oxygenation of the atmosphere, supercontinent formation and others indicating a closer link between them.

The pre -2800 Ma is the period of formation of lithosphere, the crust being enriched with lithophile elements like uranium besides Th, Zr, Nb, Ta, Y, REE and others. During the 2800-2200 Ma, the erosion of stable crust led to formation of sedimentary sequences with detrital uraninite, since there was no oxygen in the atmosphere to oxidize the uraninites. Uraniferous pyritic conglomerate and gold bearing carbonaceous seams formed in the fluvial regimes that developed peripheral to the cratons. The QPC type belongs to this time band, the older one (2500 Ma) being the Witwatersrand in South Africa whereas the younger one (2200 Ma) is from Canada represented by the Elliot Lake deposits (Dahlkamp, 1993).

The period from 2200 Ma to 1200 Ma is one of super continent formation, represented by large stable cratons as well as formation of intra cratonic basins. The appearance of oxygen in the atmosphere as a result of photosynthesis and photo-dissociation of water under the effect of ultraviolet light enabled an oxygenic atmosphere as at present. Consequent oxidation of uranium led to chemical transportation (U^{+6}) superseding the mechanical transportation (U^{+4}) and subsequent re-precipitation in tetravalent stage under reducing conditions. Availability of substantial amounts of organic matter led to the formation of syn-sedimentary or strata bound uranium deposits. This long period is also characterized by orogenic events resulting in repeated influx of uranium associated with granitic injections and development of mobile belts hosting thick pile of sedimentary volcanic piles. With such geological settings, the unconformity between the Lower-Middle Proterozoic apparently formed the most favorable trap for some of the extraordinarily high grade mineralization (see Table-2). A unique, amazingly large multi-metallic deposit with low uranium content, breccia complex type as at Olympic Dam, South Australia is believed to be the summative effect of multiple tectonic events of this period in a very favorable geological setting.

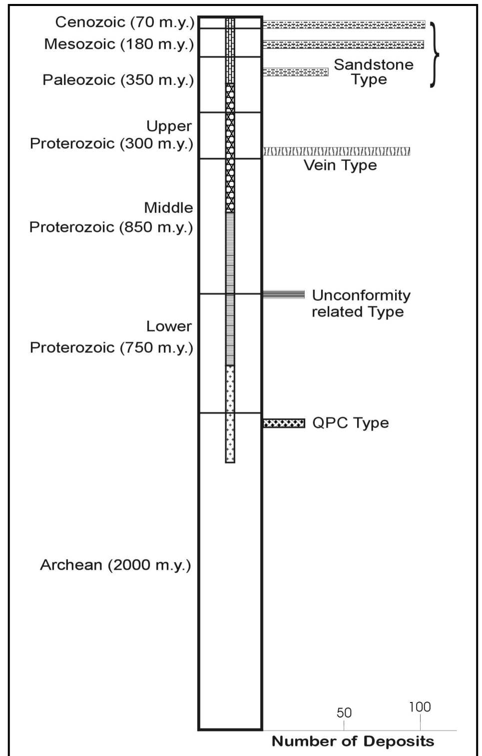


Fig. 2 **Time bound characteristics of uranium deposits (Modified after Simov, 1979)**

Table 2. **List of some giant uranium deposits of the Proterozoic (Modified after Bray et al, 1987)**

No.	Deposit	Area	U_3O_8 in tonne	Grade in % U_3O_8	Type
1	Cigar lake	Athabasca basin, Canada	1,58,000	18.58	Unconformity related
2	Key lake		> 89,100	2.88	Unconformity related
3	McArthur lake		2,45,000	18.4	Unconformity related
4	Ranger	Alligator River basin, Australia	98,300	0.21	Unconformity related
5	Jabiluka		2,03,800	0.39	Unconformity related
6	Olympic Dam	Australia	9,96,000	0.05	Breccia complex

The period of 1200 Ma to 400 Ma is marked with events like continental splitting, orogeny, subsequent metamorphism, increased amounts of organic material (non-plant origin) in the oceans etc. The mineralization during this period is viewed as the product of tectonic, hydrologic and diagenetic process leading to the formation of some nine types of deposit such as vein, granitic intrusive, black shale and others.

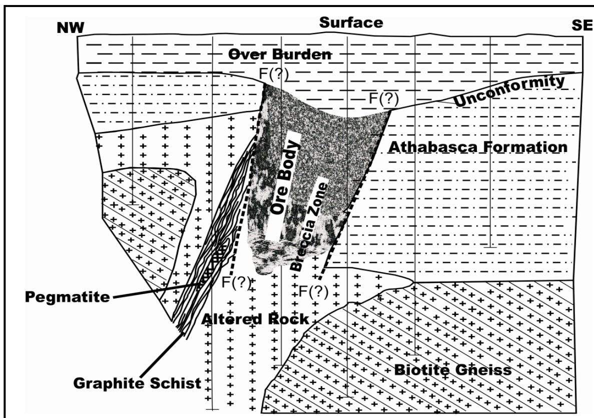
The post-400 Ma period is largely represented by continental collision, formation of subduction zones, magmatism, deformation, metamorphism, sedimentation, evolution of land based flora and fauna etc. Uranium mainly derived from granitic highland provenance during this period moved into the sedimentary sequence through oxygenated water. Land-plant derived organic matter provided the reducing conditions and the favorable sedimentary basins became the host for sand stone type of deposits. This group includes 250 deposits most of them belonging to the Phanerozoic, emphasizing the important role played by land derived plant debris in the sedimentary pile that acted as sources of reductants.

Phosporite and volcanogenic uranium deposits become important during the Mesozoic and Cainozoic. In addition, surfacial and coal-associated uranium assumes importance during Cenozoic.

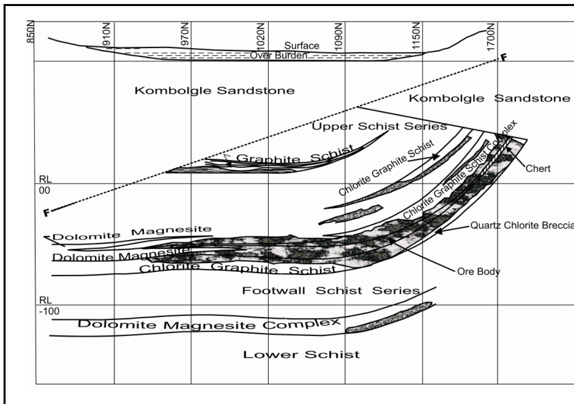
3.1 URANIUM DEPOSITS IN THE PROTEROZOIC EON

The Proterozoic Eon, spanning over 40% earth's history account for 68% of world uranium resources. This predominance can be related to numerous first order changes or features either singly or in combination that have directly or indirectly influenced the metallogeny of many elements including uranium (see Discussions).

The Lower-Middle Proterozoic, unconformity-related deposits, as represented by the Canadian and Australian examples show close similarity on many aspects but still have distinct differences (see Fig. 3 and Table 3). Some of the salient differences between them include the older age of the Australian deposits, the absence of cover rocks in Australia, their lower temperature of formation, monometallic nature and their lower grades compared to the Canadian deposits.



Not to Scale



Not to Scale

Fig. 3 **Geological section Key lake orebody, Athabasca, Canada** | **Geological section of Jabiluka orebody, Pine Creek Geosyncline, Australia**

Table 3. Salient features of the unconformity-related type deposits of Australia and Canada (after Krishnamurthy, 1996).

Salient Features	**Australia, Pine Creek Geosyncline, Northern Territory**	**Canada, Athabasca Basin, Saskatchewan**
Spatial relation of the unconformity	Between Carpentarian (Lr.Ptz.) and Kombolgie (Mid, Ptz,) formed after 1688 Ma (Owenpelli dolerite)	Between the Aphebian Wollaston domain (Lr.Ptz.) and the NeoHelikian (Mid. Ptz.) Athabasca Group
Age of primary mineralisation	c. 1750 – 1650 Ma	c. 1540 – 1240 Ma
Age of remobilisation	c. 920 – 1480 Ma	c. 450 – 990 Ma
Nature of host rocks	Lr.Ptz. rocks: Graphitic schists, carbonate rocks often chloritised. Mid.Ptz. rocks: None known at present	Lr.Ptz.: variety of meta pelites (graphitic); also gneisses and calc-silicate rocks. Mid.Ptz.: regolith, sandstone & conglomerate
Structural control of ore zones	Normal & reverse faults; Collapse breccias related to carbonate rocks	Faults (normal & reverse), mylonite & fractures
Location of ore zones	Below the unconformity in Lr. Ptz. rocks	Below, along and above the unconformity
Dimensions of ore body (length, thickness, width in metres)	230-1000, 10-300, 85-400	40-2150, 20-110, 20-900
Ore grade	0.1% to 1.0 % U_3O_8	0.1% to 20% U_3O_8 (Cigar Lake-16%; MacArthur -20%)
Associated metals	Except Kyntyre, all are mono-metallic with U only	Many of them polymetallic with Ni, As, Co, Au, Pb & others.
Uranium minerals	Uraninite, coffinite & variety of pitchblende ± brannerite; variety of secondary minerals at Koongara	Uraninite, coffinite and pitchblende; secondary minerals present up to a depth of 100 m (e.g. Rabbit lake & Eagle Point)
Temperature of formation	75 to 160^0 C	135 to 225^0 C
Alteration features	Chloritic and clay (illite, kaolinite); Mg-chlorite dominant; alteration haloes upto 200 m wide; hematitisation, silicification and tourmalinisation	Clay (illite, kaolinite) and chlorite (Mg-rich); hematitisation, silicification and tourmalinisation
Reserves	A total of 3,30,600 t of U in 7 deposits	A total of 4,09,700 t of U in 18 deposits

The gigantic, multi-metallic (Cu-Au-U) Olympic Dam deposit formed during the Middle Proterozoic is apparently related to many of the crustal evolution features so unique to Proterozoic Eon (see Discussions). Hosted in the Middle Proterozoic granite covered by thick sediments (see Fig. 4), this group of 'breccia complex' type deposits has been recognized to belong to a larger group of multi-metal deposits termed as the 'iron oxide-breccia complex' characterised by Cu-U-Au-REE-Ag association that develops in continental, rift-related environments with alkali granites and related rock association (Oreskes and Hitzman, 1997). Thus regions with Proterozoic, rift-related magmatism, especially alkali granite, iron-rich carbonatite suite and related syenitic rocks become important for possible locale of such deposits.

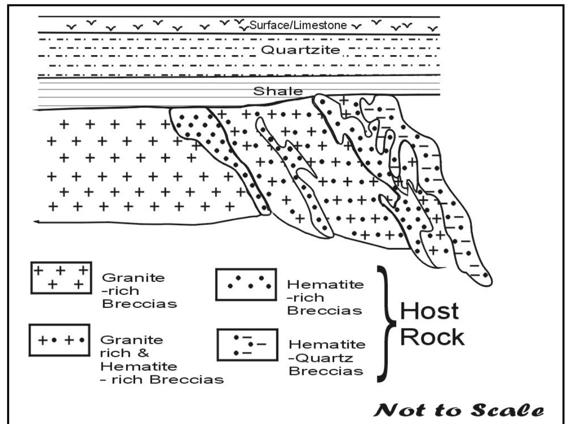


Fig. 4 **Geological section of Olympic Dam orebody, Australia**

Apart from the above giant deposits, metasomatite deposits and a significant number of vein and intrusive types are also confined to the Proterozoic time-band.

3.2 URANIUM DEPOSITS IN PHANEROZOIC EON

This period dominated by sandstone type of deposits constitutes about 43% of the total deposits discovered so far and contains about 18% of the world uranium resources (see Table 1). These deposits, defined as epigenetic concentrations of uranium minerals are wide spread in continental and marginal-marine rocks from Ordovician to Tertiary ages. However, the largest resources are in rocks of Permian, Jurassic and Tertiary period with typical occurrences in Mesozoic and Tertiary formations of Colorado Plateau in USA, Carboniferous sandstones in Nigeria, Permian and Createaceous sandstones of Central Asia Kazakhstan, Uzbekistan), Argentina etc. (IAEA, 1996). Most favourable lithologies are alternating horizons of clay and sandstone containing carbonaceous matter. (See Fig. 5)

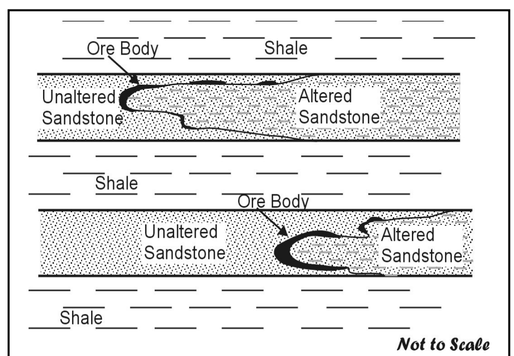


Fig. 5 **Geological section of Sandstone type deposit at Shirley Basin, USA**

The genesis of sandstone type of deposits is primarily linked with sedimentation, hydrological-geochemical regime and geotectonic evolution of the basin, as outlined below (Adams and Saucier, 1981).

a) A land mass with fertile granite, volcanic tuffs and other litho units over large areas bordering basins subjected to extensive erosion and peneplanation provide an ideal provenance for sandstone type of deposits. The depositional basins constituting clasts or detritus rich in uranium also intermittently receive uraniferous solutions that migrate within the basal layers.

b) The climatic conditions (warm, humid with high rain-fall) support luxurious growth of plant and organic matters thereby playing an important role in the geo-chemical fixation of uranium. The role of H_2S and sporadically distributed pyrite from organic matter present in host rock is also significant.

c) Tectonics also play the dominant role in the dispersal and concentration of uranium. Periodic upliftment of provenance exposes fresh areas for erosion and leaching. The upliftment of post-depositional basin rejuvenates hydrodynamics influencing the mineralization process. Subsidence of the basin after formation of deposits protect the mineralization from further groundwater action

4. INDIAN URANIUM DEPOSITS

Uranium exploration, spanning over 50 years within the 3.28 million square km area in the Indian shield has brought out the presence of uranium deposits of all major types in different geological settings. (See Fig. 6).

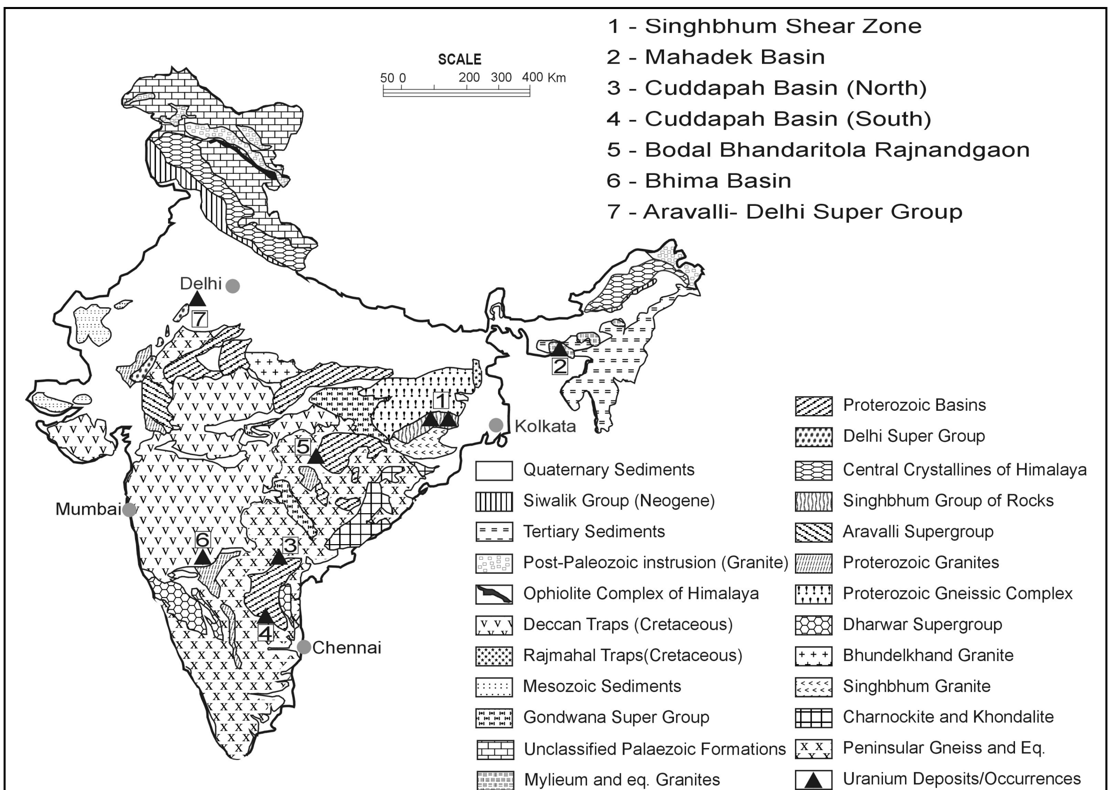


Fig. 6 **Geological map of India (GSI, 1995) showing uranium deposits / occurrences**

A number of basins, notably the Proterozoic basins hold considerable promise for the possible presence of some of the major types, such as the unconformity related type based on preliminary geological analogy. However, an in-depth geological scrutiny should reveal closer similarity, if any, between the Proterozoic basins and their Australian or Canadian counterparts. Uranium potential of India thus remains to be fully evaluated.

Of the uranium resources estimated so far, the Proterozoic Eon accounts for nearly 75% of the reasonably assured resources, bulk of it coming from the vein type deposits in Singhbhum Shear Zone (SSZ), Jharkhand (53%) and a smaller amount (7%) from the unconformity-related (sensu lato) and strata-bound type deposits in Cuddapah basin, Andhra Pradesh (16%). Sandstone type uranium deposits of Phanerozoic Eon in Mahadek basin (Meghalaya) account for about 17% of the resources (see Fig. 7).

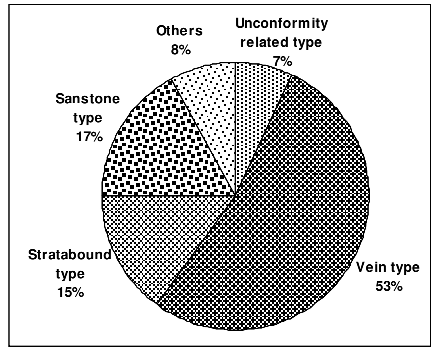


Fig. 7 **Distribution of Indian uranium resources**

4.1 PROTEROZOIC URANIUM DEPOSITS OF INDIA

Proterozoic rocks account for about 64% (exposed and buried) of the Indian subcontinent represented by the craton-mobile belt shear zone as in the Singhbhum shear zone and some 13 basins including the Purana and their peripheral parts.

Among the areas that have been explored, spectacular successes have been achieved in only two areas namely the Singhbhum shear zone in Jharkhand and the Cuddapah basin area in Andhra Pradesh..

Most part of uranium resources have been located in Singhbhum Shear Zone (vein type deposits) distributed in eleven deposits that occur within a stretch of about 70 km. In the Cuddapah basin, two different types - unconformity related (sensu lato) and stratabound types have been located in two different geological settings. We shall briefly describe the metallogeny of these two areas.

4.1.1 Singhbhum shear zone

The Proterozoic metasediments of the Singhbhum Shear Zone (SZZ), a zone of intense and deep tectonisation in the eastern part of India hosting a number of vein type uranium deposits such as Jaduguda, Bhatin, Narwapahar and Turamdih is the only uranium production center of the country (See Fig. 8). Other mines like Bagjata, Banduhurang and Mohuldih in this area are being added to production in recent years.

This shear zone extending in arc shape over a length of 160 km is a site of acid and basic magmatism and hydrothermal metasomatic activity. Rocks on both sides of the shear zone belong to two contrasting ages – Archean and Proterozoic rocks in the south (sediments, basic intrusions and batholithic Singhbhum granite) and a thick pile of metasediments in the north. The rocks along the shear zone have undergone varying grade of metamorphism exhibiting different level of chloritisation, biotitisation, sericitisation and feldspathisation (Dunn and Dey, 1942; Bhola et al., 1965; Sarkar and Saha, 1983; Sarkar, 1984 and others).

Metallogenesis of uranium in this area is linked with the Singhbhum granite as the main geo-chemical provenance. The origin of Singhbhum granite (3000 – 2900 Ma) is attributed to the partial melting of pre-existing crustal rocks (Sarkar and Saha op. cit). The weathering of Singhbum granite started before (during ?) lower Proterozoic period (non-availability of oxygen) and the sediments derived from this granitic craton led to the syngenetic deposition of some detrital uraninite (uranium in the tetravalent stage) within the thick pile of sediments dipping towards north and northeast flanking the Singhbhum granite (Rao and Rao, 1983). Along the cratonic margin of Singhbhum granite, basic rocks (now represented as chlorite schists and epidiorites) were also emplaced forming an inter-layered basic volcanic and sedimentary pile. With gradual availability of oxygen in the atmosphere, detrital uranium was solubilised (hexavalent state), transported into solution through favorable pathways and precipitated where it came in contact with reductants.

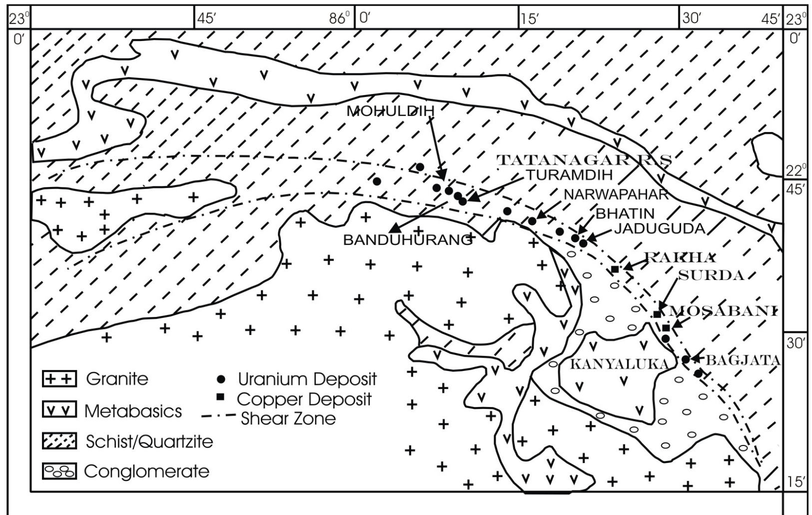


Fig. 8 **Geological map of Singhbhum Shear Zone (After Dunn & Dey, 1942)**

The Singhbhum orogenic cycle (2000 Ma), represented by regional metamorphism, emplacement of basic rocks, tectonic activities like shearing etc. helped in concentration of uranium in favourable structural and / or lithological traps. Emplacement of basic rocks supplied heat to enrich the circulating water with uranium, introduced sulphides (Cu, Ni etc) and provided the geo-chemical control for uranium deposition in the vicinity. The tectonic activity like shearing and post-shearing folding has helped in continued remobilization and concentration of uranium minerals in structural traps.

Jaduguda, almost at the central part of this belt is the first uranium deposit to be discovered in the country and is in operation for the last 40 years. Several other deposits – namely Bhatin, Narwapahar, Turamdih and Banduhurang are being operated and a few more – Bagjata and Mohuldih are being developed.

The principal lithological units in these deposits are meta-sediments exhibiting different level of chloritisation, biotitisation, sericitisation and feldspathisation etc (varying grade of metamorphism). Uranium lodes extend as thin veins from surface following the general trend of the schistosity with fairly uniform persistence both along strike and dip (Sarkar, 1984; Mahadevan, 1988; Sinha et al., 1990). Ore bodies are vein-like sub-vertical in the eastern sector (Bagjata and Jaduguda) whereas in the western sector (Turamdih and Banduhurang) they tend to be stratiform to strata-bound (Mahadevan, 1988). Superimposition of three deformational episodes, within an asymmetric synform, have given rise to the coalescing of mineralized zones. (See Fig. 9). The enormous thickness of orebody at shallower depths at Banduhurang can possibly be attributed to tight folding and plastic flowage at the time of metasomatism associated with tectonism (Pandey et al., 1994). The orebody at Banduhurang is amenable to opencast mining.

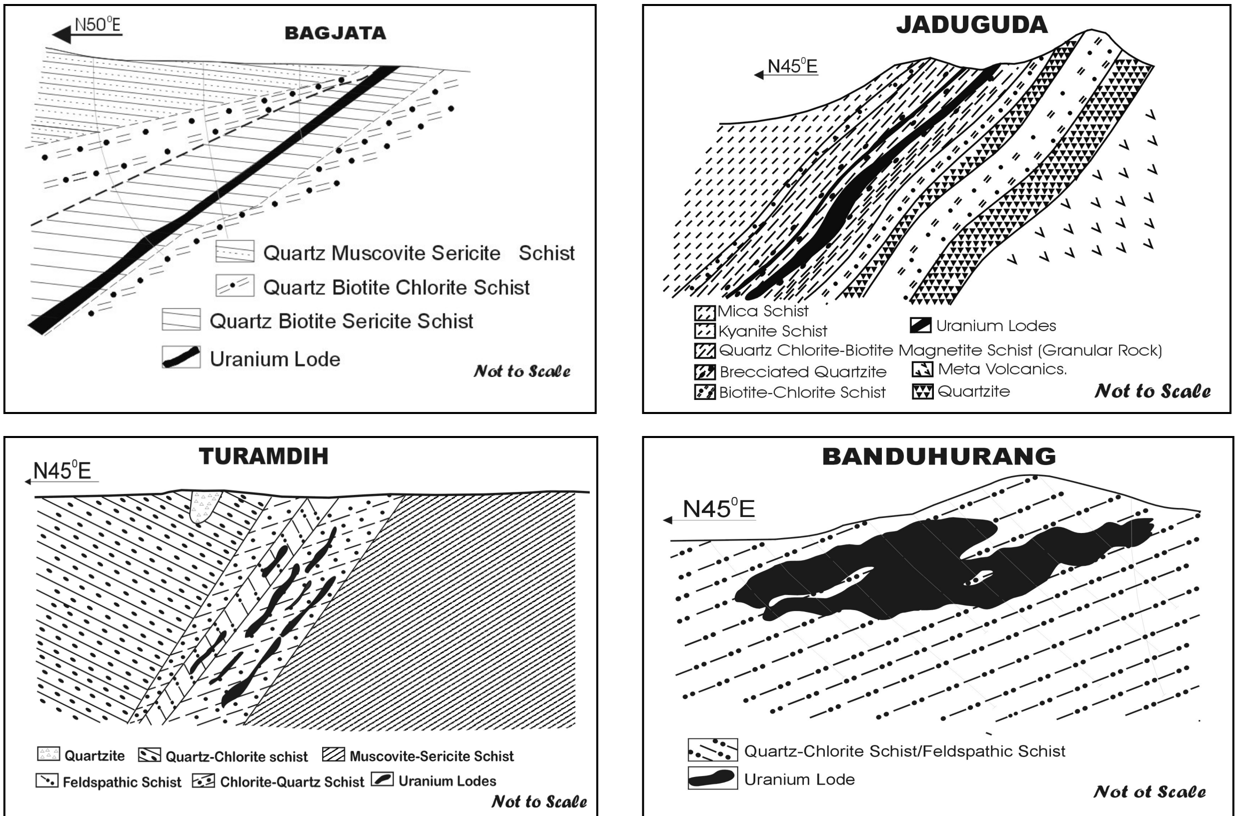


Fig. 9 **Geological section showing orebody at Bagjata, Jaduguda, Turamdih and Banduhurang**

4.1.2 Cuddapah basin

Exploration for seeking unconformity related, large-tonnage, high grade-uranium deposits began in the 1980s by AMD which led to the discovery of two different types, previously unknown. These include the unconformity proximal type in the basement granites below the Kurnool Group sediments (Lambapur and Peddagattu: Sinha et al., 1995) and the strata-bound, dolostone-hosted (Tummalapalle: Rai et al., 2002) type in Cuddapah Basin in Andhra Pradesh, establishing it as an important uranium province.

The northern side of crescent shaped Cuddapah basin comprises dominantly of arenaceous and argillaceous rocks of Middle Proterozoic period overlain by Upper Proterozoic calcareous formations. The Srisailam formation, basement of which comprises Archean gneiss and younger granites (2268±32 Ma to 2482±70 Ma) forms a prominent plateau in the NW side of Cuddapah basin.

Close to the unconformity (basement granite and its overlying Srisailam quartzites) in the Srisailam outlier, cluster of uranium deposits have been found with mineable scale reserves established at Lambapur, Peddagattu, Kuppunur and Chitrial. These deposits are being planned for development soon. The mineral chemistry suggests hydrothermal nature, the mineralization embracing both basement granite, dissected by fractures, basic dykes and vein quartz and the unconformably overlying quartzites. The ore zones at Lambapur, Peddagattu and Chitrial below the Srisailam quartzite outliers (Kurnool Group) are predominately restricted to basement granite within fractures. Marine transgressions have been clearly indicated by such overlap of younger sediments of the basin on to the granite basement. The Kuppunuru deposit is hosted in the Banganpalle quartzites of the Kurnool Group, within the Palnadu sub-basin, overlying the Srisailam quartzites separated by an unconformity. Here, mineralisation occurs both within the quartzite above the unconformity as well as below the unconformity within the granites as at Lambapur (Jeyagopal et al., 1996). (See Fig. 10)

Uranium mineralization in these two formations occur in higher stratigraphic levels of the Cuddapah basin, and the metallogeny may be related to -

a) Regolith formation in the basement over protracted period of sedimentation of the Cuddapah Supergroup (c. 10 km thick) followed by marine transgression during the formation of the Kurnool Group.

b) Subsequent uplift, diagenesis and solution activity along the unconformity probably gave rise to formation of the uranium deposits with some micro-organism derived carbonaceous or graphitic matter.

The mineralisation close to the unconformity, though implies the distinct genetic relationship, the geological settings and genetic model differ with those of Athabasca deposits in Canada and Pine Creek Geosyncline in Australia. They lack the typical meta-sediments of the Lower Proterozoic basins with carbonaceous components so typical in Canada and Australia.

However, the Nallamalai Group, below the Kurnool Group, comprises carbonaceous shales intruded by the Ipuru granitic dome (Cumbam Formation intruded by granites of 1575±20 Ma with Cu-Pb-Zn mineralisation at Agnigundala). The geological settings between the Cuddapah Supergroup and the Kurnool Group, according to Saxena (2004) is conducive for hosting classical unconformity type deposits in the Cuddapah basin.

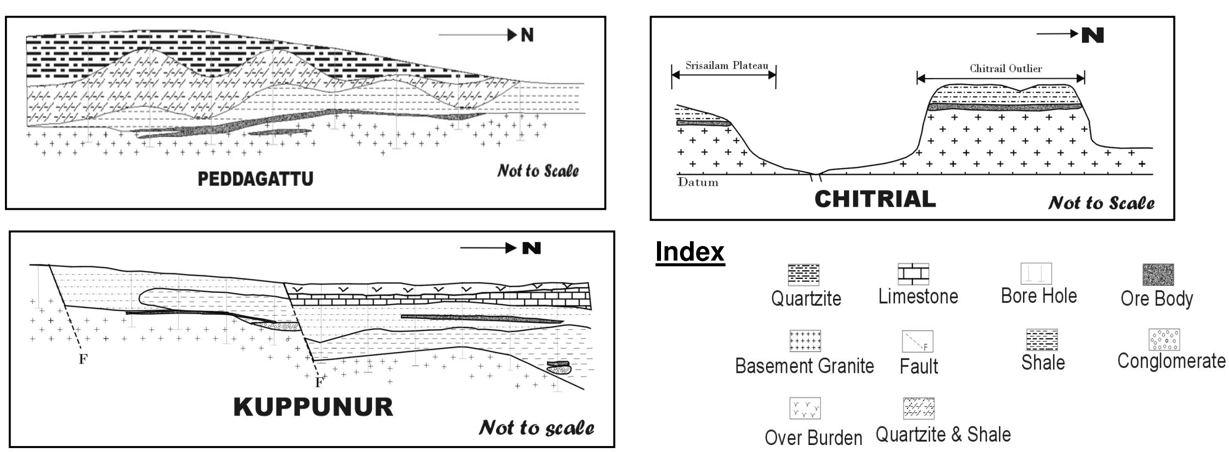


Fig. 10 **Geological sections showing orebody at Peddagattu, Chitrial and Kuppunur**

In the south western margin of the Cuddapah basin, uranium deposits occur in phosphatic siliceous dolostone of Middle Proterozoic Vempalle formation of Papagni Group. Within the thick pile of calcareous rocks, the mineralized horizon is sandwitched between lower massive dolostone and upper shale and cherty dolostone with intermittent intraformational conglomerate (See Fig.11). Mineralisation extends over 60 km length, but the mineabale lodes are persistent over 6.6 km length at Tummalapalle-Rachakantapalle sector near Pulivendla. Presence of secretionary structures, oolites and stromatolites favour diposition of biogenic material during sedimentation in an inter-tidal mud-flat environment (Roy et al., 2002). Fertile basement granites bordering the Cuddapah basin is believed to be the source for uranium. Other ore forming factors are influx of oxygen during mid Proterozoic leading to chemical liberation and concentration by biochemical reduction under euxenic conditions. The algal debris might have provided the nutrients for micro-organisms to produce H_2S. The H_2S and the organic matter could have created the necessary reducing environment for the formation of pyrite and precipitation of uranium in these sediments.

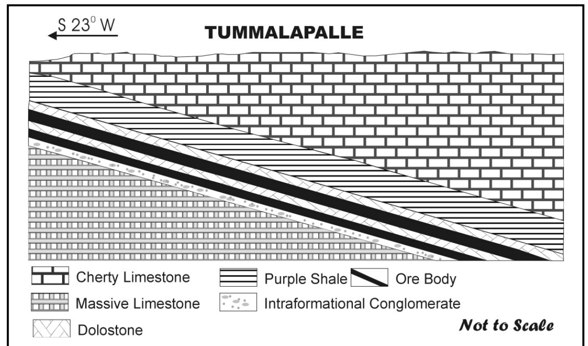


Fig. 11 **Geological section showing orebody at Tummalapalle**

4.1.3 Other Proterozoic uranium deposits and provinces

In addition to the Proterozoic uranium deposits/metallogeny described so far, there are a number of significant metallogenic provinces both in the Peninsular shield and the Central crystallines of Lesser Himalaya (which is said to be the part of the northern extension of the peninsular shield). They host smaller deposits, often in contiguous areas (See Table -4).

Table 4. **Some examples of small uranium deposits of India.**

Deposit & Location	Host rocks and age relations	Remark	References
Bodal-Bhandaritola, Rajnandgaon district, Chhattishgargh	Nandgaon Group of Dongargargh Supergroup; Late Archean-Early Proterozoic	Meta basalt-meta rhyolite hybrids, sheared; hydrothermal	Krishnamurthy et al., 1988.
Jajawal, Sarguja, Chhattishgargh	Central Surguja Crystallines equivalent to Chhotanagpur granite gneiss; Lower-Middle Proterozoic	Shear controlled, granite-pegmatite hosted.	Saxena et al., 1998.
Rohil-Gateshwar, Rajasthan	Biotite schists and albitites, Aravalli Supergroup; Lower Proterozoic	Metasomatite related	Yadav et al., 2002
Gogi, Karnataka	Limestones of Bhima basin and granitoids of the basement,	Fracture-controlled, vein-type;	Pandit et al., 2002;

In addition, a number of smaller deposits (< 500 t U_3O_8) and significant occurrences belonging to the Proterozoic period have been discovered, evaluated and reported from both the Peninsular shield and the Himalayan orogen and the details are available in several publications (Saraswat et al., 1988; Rajendra Singh, 1994).

4.2 PHANEROZOIC URANIUM DEPOSITS OF INDIA

The Phanerozoic basins of India mainly comprise – Mahadek formations in Meghalya, Gondwana basins in Central India and Siwaliks in the foothills of Himalayas. Of all three basins, minable, sandstone type uranium deposits have been located only in the Cretaceous sediments in Mahadek basin of Meghalaya.

4.2.1 Mahadek basin

The Mahadek sediments of Cretaceous period, which host the uranium mineralisation lie in the southern part of Shillong plateau bounded by three faults – Dauki fault in southern side, Haflong fault in east and north-east and Brahmaputra graben in north. The plateau consists of rocks ranging from Precambrian to Tertiary. The basement consists of Archean gneissic complex intruded by basic and ultra basic 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 tabular to lensoidal orebody has been located at Kyelleng-Pyndengsohiong (formerly known as Domiasiat) in lower Mahadek sediments which has been planned for development soon. Deposited in fan, braided rivers of typical proximal facies, the host rock shows primary sedimentary structures like cross bedding, parallel and horizontal bedding with fining upward. Mineralisation is controlled by palaeochannels and impregnated with carbonaceous matter both in-situ and migratory type, as streaks, lumps, dispersion in matrix and pore fillings. The ore zone is tabular with almost flat dip (~ 5^0), thickness ranging from a few centimeters to tens of meters (Sen et al., 2002).

The discovery and proving of Wahkhyn deposit, located c.10 km to the west of Kyelleng-Pyndengsohiong under similar geological settings has substantially added to the uranium inventory of this region. (See Fig.12)

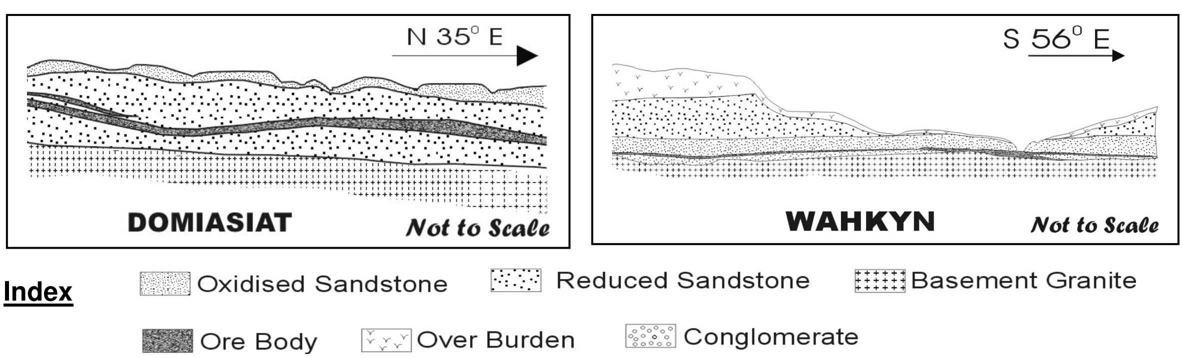


Fig. 12 **Geological sections showing orebody at Domiasiat and Wahkyn**

4.2.2 Other Phanerozoic uranium deposits

A few low grade, small tonnage occurrences have been located in the Siwalik basin in foothills of the Himalayas (Swarnkar et al., 2002). However, at present, because of their small size and low grade, they do not hold any promise for commercial scale mining operations.

Discovery of uranium shows in the Gondawana sandstones around Motur near Betul in Madhya Pradesh opened up the potential of this basin for uranium during the early 1970s. However, subsequent exploration did not show the potential in delineating any ore body (Sarswat et al., 1988).

5. DISCUSSIONS

As we have seen, uranium metallogeny appears to be distinctly time-bound with certain types of deposits unique to specific geological and stratigraphic domains as for example the QPC and unconformity types. Spatial restriction or the non-discovery of such types elsewhere, however, is less precise since it depends on other aspects like the knowledge base on the geology of the region, availability of skills, resources and exploration inputs etc. Nevertheless, we discuss the overall features of uranium metallogeny of the world with special reference to the Indian scenario.

5.1 CERTAIN UNIQUE FEATURES OF EARTH'S EVOLUTION DURING THE PROTEROZOIC EON AND THEIR BEARING ON URANIUM DEPOSITS

The Proterozoic Eon, representing some 40% of earth's history includes several major first order changes in crustal evolution (Condie, 1989 & 1992). These are:

1. Cratonisation of continental areas with emplacement of K-rich granitoids during Late Archean period leading to crustal thickness of c.40 km leading to lithosphere stability.
2. Formation of supercontinents such as Laurentia and Pangea .
3. Oxyatmoversion during the early stages of Paleo-Proterozoic.
4. Development of first generation solution-transported-uranium from pristine sources and presence of higher abundances of CO, SO and Fe^{+3} in the peri-continental sea manifested by sediments rich in carbonates and cherts.
5. Development of abundant microorganisms and algae leading to proliferation of stromatolites and biogenic sediments such as carbonates and cherts.
6. Emplacement of layered igneous complexes including anorthosites.
7. Formation of first generation mafic dyke swarms and continental flood basalts
8. Development of epi-cratonic basins with continental to marginal marine environments of sedimentation and volcanism.
9. Major development of anorogenic, rift-related magmatism such as alkaline rocks, carbonatites and kimberlites involving mantle metasomatism and other large-ion lithophile element enrichment processes including uranium in the upper mantle.
10. Development of Cordileran type geosynclines during Meso-Neo Proterozoic period.
11. Formation of rift-related geosynclines of global dimension and the recognition of operation of the Wilson cycle tectonics.
12. Appearance of ophiolitic association indicating former position of suture or subduction zones or mid-oceanic ridge setups.

The data provided in Table-1 and Table-2 emphasizes the contribution of two deposit types, namely the unconformity related (33%) and the breccia complex (17%) together constitute 50% of the world uranium resources and therefore warrants a special discussion.

The metallogeny of these deposits involves a series of processes that cumulatively aid in their formation. Cratonisation of shield areas during late Archean period with K-rich granitoids and higher abundances of radio elements had set the stage for a major source of uranium. With the oxyatmoversion during the early stages of Proterozoic, the intra-cratonic basins continued to receive uranium from late-Archean cratons (K-rich granitoids) through solution along with uraniferous clasts. The volume of uranium transported is likely to be enormous as the basins were of first generation to receive uranyl ion (U^{+6}) in solution. Subsequently, formation of supercontinents provided good stability leading to the development of large regolith or lateratisation and augmented the source areas for uranium thus enabling large volume of rocks subjected to solution activity and dissolution of uranium from dispersed sources. The system provided suitable pathways and traps (unconformity of Lower-Middle Proterozoic) for movement of uranium bearing solution. A variety processes under oxygen rich conditions like adsorption (clay, carbonaceous matter, Fe^{+2} oxide etc) and reduction (Fe^{+2} bearing minerals, H_2S evolving bacteria / biogenic systems / graphite / carbon / gaseous hydrocarbon / hydrogen) enabled mobile uranium to get fixed forming ore minerals. Further enhancement in supply of uranium has been interpreted by descending solution from the Meso-Proterozoic cover rock (sandstones) which encountered the graphite rich host rocks in the basement. Thus, the culmination and successive combination of these processes had given rise to giant uranium deposits at or near the unconformity contact between Lower and Middle Proterozoic rocks as found in the Athabasca basin in Canada and the Alligator river basin in Australia.

The discovery of uranium at Olympic Dam in 1975 came as a big surprise since the geophysical exploration within the tough or graben developed over the Middle Proterozoic Roxby Down granite covered by sediments, was aimed mainly for buried base metal deposits related to the Gowler Range volcanics. Uranium metallogeny at Olympic dam is part of the larger Gawler Range volcanics, more specifically to the Hiltaba Suite volcanic and plutonic activity of which the Roxby Downs granite breccias and hematite breccias are the major host rocks. According to Haynes et al., (1995), a large hydrothermal breccia complex and eruption crator developed due to phreatic and phreatomagmatic activity. The emplacement of the high level, Roxby Downs granite into such a system led penecontemporaneously to hydrothermal activity and ore formation. Oxidised ground waters carried Cu, U, Au and most of the S from the provenance into the complex where it encountered Fe, F, Ba and CO_2 from below. The persistence of such fluid mixing events over a protracted period of time led the huge deposit as per the model of Haynes and others.

5.2 ENIGMA OF SPATIAL EXCLUSIVENESS OF CERTAIN URANIUM DEPOSITS

The preferential concentration of some specific types of uranium deposits in certain parts of the globe, like Australia, Canada, South Africa, leads to an unequal distribution of deposits with diverse association of other minerals still remains an enigma. Some examples are cited below.

a) Quartz-pebble-conglomerate type uranium deposits of South Africa contain appreciable gold, whereas the same of Elliot lake region in Canada lacks gold but contain significant quantities of yttrium and thorium.

b) Unconformity related type of deposits with widely varying grades are only known from the Athabasca basin in Canada and Alligator river basin in Australia.

c) Breccia complex type typified by Olympic Dam deposit is unique to Australia only.

Absence of such typical deposits, both in terms of quantity and quality of ore, in analogous terrains elsewhere in the world clearly suggest that there must be some first order differences between these terrains and others. These may include the importance of provenance in terms of area as well as other conducive deposit-making requirements. An analysis of the aerial proportion of Archean and Proterozoic rocks from different continents reveal large variation (See Table-5). Such terrains must have formed the provenance for the three types of deposits mentioned above.

Table 5. **Areal proportion of exposed and buried (sub-Phanerozoic) Precambrian crust by continent and Eon / Era (After Goodwin, 1996).**

Continent	**Area in thousand km^2**	**Late (0.6-1.0 Ga)**	**Middle (1.0 -1.7 Ga)**	**Early (1.7 - 2.5 Ga)**	**Archean (>2.5 Ga).**
Africa	28,381	75	6	7	12
North America	19,474	4	30	49	17
South America	18,419	52	33	10	5
Antarctica	10.632	37	38	5	20
Europe	9,507	45	11	20	24
Asia(Excl. India)	8,033	46	30	21	3
Australia	7,657	15	55	20	10
India	3,837	47	15	2	36
Total	105,936	43	22	21	14

It can be seen that the North American continent has the maximum development of Early Proterozoic strata followed by Asia, Australia and Europe. India has the least development of Early Proterozoic rocks. Australia shows the maximum development of Middle Proterozoic rocks. Both North America and Australia exhibit maximum development of both the Middle and Early Proterozoic rocks (about 79 -75 %) and thus seem to correlate with larger number of deposit types with richer grades and larger tonnage. Africa shows the least development of Early and Middle Proterozoic rocks.

The anomalous presence of several other metals such as gold, nickel, Pt, Cr, and others may be related to heterogeneities introduced in the mantle and crustal regions of these continents during the formation of the earth and its early stage of evolution. In addition, the intensity of other processes operating over the length of time contributing towards the formation of deposits may have also been different.
Furthermore, the enterprise to seek new mineral deposits stems from research and developments in the fields of exploration, preceded by the preparation of good geological maps –an essential pre-requisite to any mineral exploration campaign with a high rate of success.

5.3 INDIAN SCENARIO FOR NEW DISCOVERIES

We have seen that uranium deposits can be quite varied in terms of their types and genesis and comparisons become difficult. Nevertheless the broad guidelines for deposit search in terms of source, mobility and sink need to be evaluated in any terrain that is being taken up for survey. Uranium metallogeny in India during the Precambrian include three major time spans, namely 2900 – 2600 Ma., 1600 – 1400 Ma and 1200 – 9 Ma (Mahadevan, 1987).
Indian continent has a large development of Archean terrain (See Table-5) and hence the discovery of economically viable QPC type deposits seem to have better prospects. Although extensively developed in Karnataka (Pandit et al., 2002), Jharkhand, Orissa and Rajasthan (Mahadevan, 1986), sizable deposits have still eluded so far. According to Mahadevan (1987), in Karnataka, the formation of extensive development of volcanism during this period inhibited clastic sedimentation of conglomerates. We need to look more critically the stratigraphic sequences and also infer from geophysical studies the nature of rock types within a basin.

The Proterozoic metallogeny of uranium is of paramount importance to the exploration geologists since five major types are represented with over 42% of the uranium resources. The unconformity related type and Proterozoic sandstone type, however seem to stand better chances as indicated by deposits so far proved in the Cuddapah basin as well as indications of anomalies from other basins.
An important aspect that needs to be resolved in this context is the demarcation of Lower Proterozoic supracrustals below the Purana basins in the Indian shield so that we have first order similarities to search classical unconformity related type of deposits as found in Athabasca in Canada or Pine Creek in Australia. As has been indicated by Krishnamurthy (1996) that the eastern margins of the Chhatishgargh basin-Eastern Ghat province rocks (with graphictic lithlogies) in western Orissa provide one such favourable scenario. Saxena (2004) opined that the unconformity between the Nallamalai Group (Cumbam shales with carbonaceous matter) and the Kurnool Group (Banganpalle quartzite) constitutes a conducive set up.
Breccia complex type deposit, akin to the Olympic Dam, requires intrcratonic, rift-related environments with A-type granite / bimodal magmatism and / or alkalic rock associations (Oreskes and Hitzman, 1997). Several areas in the Indian shield have signatures for such metallogeny. These include the North Singhbhum mobile belt (Krishnamurthy et al., 2004), West Siang (Dhirendra Kumar et al., 1997) and in the Sakoli basin (Rajagopalan and Hansoti, 1997).

The albitite belt of Rajasthan with numerous uranium occurrences (Yadava et al., 2002) represents a potential belt for new discoveries. Structure-controlled, vein type, often related to intrusive rocks, both acid and alkaline rocks represents a major area of search since metallogeny in this group involves both metamorphic fluids as well as late magmatic or pegmatitic stage. Proterozoic terrains with evidences of such geologic evolution become important.

Cretaceous uraniferous sandstone occurrences in the Mahadek basin in Garo Hills, west of the presently known deposits, have opened up new areas for exploration. Sandstone deposits in the Gondwana and Permian basins in central and western India need to be re-looked interpreting the available data. The Miocene sandstones of Siwalik is yet to give a sizable deposit, in spite of the numerous shows and smaller tonnages like Astotha hold (Swarnkar et al., 2002).

Surficial occurrences of anomalous uranium concentrations (with an average of 0.27% U_3O_8) known from Lalburra between the Lematas / basement crystallines and the Deccan Trap cover represent an unusual type (Hansoti et al., 1994). Such unusual types must be critically examined.

Thus, uranium metallogeny and deposits, in spite of a rich knowledge base, still eludes the rigors of classification and grouping. Such defiance is both a challenge and opportunity to generate additional resource bases for this wonder metal.

6. CONCLUSIONS

Uranium is one of the few elements that forms deposits in varied environments and in a wide variety of rocks. The present study has led to the following inferences on uranium metallogeny.

1. Uranium metallogeny is distinctly time-bound for two deposit types, namely the QPC (Late Archean-Early Proterozoic unconformity) and the unconformity-related (Early-Middle Proterozoic unconformity). However, for some of the other types, either there is a preponderance or exclusiveness of certain types over others. For example, the breccia complex and the metasomatite types in the Proterozoic, vein types in the Proterozoic and Paleozoic, collapse breccia pipe type in the Paleozoic, black shale type in the Paleozoic, phosphorite in the Mesozoic and Cenozoic, the sandstone type in the Mesozoic and Cenozoic and the surficial types in the Recent.
2. The spatial restriction of some of the giant types, such as the Quartz-Pebble Conglomerate (QPC) to South Africa and Canada and the unconformity-related types to Australia and Canada, however, is an enigmatic feature that may be related to mantle heterogeneity, unusually large size of the Late Archean and lower Proterozoic rocks in these countries.
3. Based on uranium exploration case studies, the geological knowledge base in these countries for mineral exploration including uranium, appear to be more focused, systematic and advanced compared to other countries, with appropriate development of skills and matching exploration inputs. If other countries match them in these approaches, there may be new discoveries which may negate the present status of ‘exclusiveness’ with respect to certain deposit types. However, the relation of such

exclusiveness of certain deposit types being related to special attributes to the crustal segments of the earth is still not well constrained.

4. The extreme diversity exhibited by the geochemistry of the uranium, coupled with the source-mobility-sink trinity appears to influence the deposit types as well as the grade-tonnage relations of a particular type. The formation of uranium deposit is thus attributed to well-recognised geological processes ranging from cratonisation, evolution of the atmosphere, plate tectonic processes including orogenesis.
5. At present 75% of the Indian uranium resources come from deposits hosted in the Proterozoic rocks (vein types, strata-bound and unconformity related types deposits) and 17% are hosted in Cretaceous rocks (sandstone type deposits) of Mahadek basin.
6. Uranium metallogeny is thus both a challenge and opportunity since there is considerable diversity in deposit types and chances are bright that new types will be discovered.

7. ACKNOWLEDGEMENTS

The authors would like to thank Shri Ramendra Gupta, Chairman & Managing Director, UCIL for the constant encouragement to think differently so as to face the challenges of uranium resource management both in the short and long term. Kind permission given by the C&MD, UCIL to present this technical paper under the aegis of MGMI, Jamshedpur chapter is also thankfully acknowledged.

8. REFERENCES

Adams, S.S., and Saucier, A.E. (1981).Geology and recognition criteria for uraniferous humate deposits, Grants mineral region, New Mexico.UA-DOE GJBX-2(81), 225 p.

Arakel, A.V. (1988). Carnotite mineralisationin inland drainage areas of Australia. In: Gableman, J.W. (Editor).Unconventional uranium deposits. Ore Geology Reviews, Vol. 3, pp.289 – 311**.**

Berning, J., Cooke, R., and Hiemstra, S.A.(1976). The Rossing uranium deposit. Econ. Geol, Vol.71, pp.351-368.

Bhola, K.L., Rama Rao. Y.N., Suri Sastry, C., and Mehta, N.R. (1965).Uranium mineralisation in Singhbhm Thrust Belt, Bihar, India. Econ.Geol., Vol. 61, pp. 152-173.

Bray, C.J., Spooner, T.C., Hall, C.M., York, D., Bill, T.M., and Krueger, H.W. (1987). Laser probe 40Ar/39Ar and conventional K/Ar of illites associated with the McClean unconformity-related uranium deposits, north Saskatchewan, Canada. Can. Jour. Earth Sci., Vol. 24, pp.10-23.

Condie, K.C. (1989). Plate Tectonics and Crustal Evolution. Pergamon Press Third Edition.

Condie, K.C. (1992). Proterozoic Crustal Evolution. Edited volume, Developments in Precambrian Geology, 10,. Elsevier, Amsterdam

Dahlkamp, F.J.(1993).Uranium Ore Deposits. Springer-Verlag, Berlin. 460 p.

Dhirendra Kumar, Saravanan, B., Sinha, K.K., and Dwivedy, K.K.(1997). Iron oxide (U-Cu-Au-REE) type mineralisation in the Proterozoic metasediments of Arunachal Pradesh, Exploration and Research for Atomic Minerals, Vol. 10, pp.15-23.
Dunn, J.A., and Dey, A.K. (1942).The geology and petrology of eastern Singhbhum and surrounding areas. Mem. Geol. Surv. India, No. LXIX, Pt. 2.
GSI (1995).Geological Survey of India, Geological map, 1:500,000. GSI, Kolkata.
Goodwin, A. (1996). Principles of Precambrian Geology. Academic Press, Harcourt Bruce Publishers.
Haynes, D.W., Cross, K.C., Bills, R.T., and Reed, M.H. (1995). Olympic Dam Ore Genesis: a fluid mixing model. Econ. Geol., Vol. 90, pp. 281-307.
Hansoti, S.K., Kamlesh Kumar., and Duddalwar, A.B. (1994). Geology and uranium mineralisation in Deccan Trap-Lameta-Crysltalline basement at Lalbarra, Mandla district, Madhya Pradesh. Exploration and Research for Atomic Minerals, Vol. 7, pp. 15-23.
Heinrich, E.W. (1982). Hydrothermal alterations of conglomerate uranium ores at Elliot Lake, Ontario, Canada. In: Ore Genesis, the state-of-the-art, Springer Verlag, Berlin, pp. 16-24.
IAEA, (1996). World distribution of uranium deposits. Guide book to accompany IAEA Map. IAEA, Vienna, 223 p.
Jefferson, C.W., Thomas, D.J., Gandhi, S.S., Ramaekers, P., Delaney, G., Brisbin, D., Cutts, C., Portella, P., and Olson, R.A. (2003). Unconformity associated uranium deposits. EXTECH IV, Final volume. Geological Survey of Canada, Current Research, pp.1-33.
Jeyagopal, A.V., Kumar, P., and Sinha, R.M. (1996). Uranium mineralisation in the Palnad sub-basin, Cuddapah Basin, Andhra Pradesh, India. Current Science, Vol. 71 (12), pp. 957-958.
Krishnamurthy, P. (1996). Are Early-Middle Proterozoic unconformity related uranium deposits unique to Australia and Canada?: an appraisal with special reference to India. Exploration and Research for Atomic Minerals, Vol. 9, pp. 1- 40.
Krishnamurthy, P., Hoda, S.Q., Sinha, R.P., Banerjee, D.C., and Dwivedy, K.K. (2000). Economic aspects of carbonatites of India. Jour. Asian Earth Sci., Vol. 18, pp. 229 – 235.
Krishnamurthy, P., Chaki, A., Sinha, R.M., and Singh, S.N. (1988). Geology, geochemistry and genesis of metabasalt, metarhyolites and the associated uranium mineralisation at Bodal, Rajnandgaon district, Madhya Pradesh and implications for uranium exploration in central India. Exploration and Research for Atomic Minerals, Vol.1, pp.13-39.
Krishnamurthy, P., Nagar, R.K., Bagchi, A.K., and Gupta, R.K. (2004). Geophysical surveysfor concealed uranium depositsin the north Singhbhum mobile belt. Exploration and Research for Atomic Minerals, Vol. 15, pp.25-31.
Langmuir, D. (1978). Uranium solution –mineral equilibria at low temperatures with applications in sedimentary ore deposits. Geochim. Cosmochim. Acta, Vol. 42, pp. 547-569.
Mahadevan, T.M. (1986). Space-time controls in Precambrian uranium mineralisation in India. Jour. Geol. Soc. India., Vol. 27, pp. 47-62.

Mahadevan, T.M. (1988). Metallogeny—concepts, constraints and prospects in India. Indian Jour. Geol., Vol.59, pp.81-116.

Mahadevan, T.M. (1988). Characterisation and genesis of Singhbhum uranium province., India. In: Recognition of Uranium Provinces. IAEA-TC-450.5/18, Vienna, pp.337-369.

Oreskes, N. and Hitzman, M.W. (1997). Amodel for the origin of Olympic Dam type deposits. In: Mineral Deposit modeling. (Edts.) Kirkham et.al., Geol. Assoc. Canada, Spl. Paper 40, pp.615-674.

Pandey, P., Pramod Kumar, and Upadhyay, L.D. (1994). Uranium deposits of Turamdih-Nandup area, Singhbhum District, Bihar and their spatial relationship. Exploration and Research for Atomic Minerals, Vol.7, pp.1-13.

Pandit, A. (2002). Uranium occurrences In the quartz pebble conglomerates of Karnataka. Exploration and Research for Atomic Minerals, Vol. 14, pp. 131-146.

Pandit, A., Natarajan., and Dhan Raju, R. (2002). Exploration for uranium in the Bhima basin in parts of Karnataka. Exploration and Research for Atomic Minerals, Vol., 14, pp. 59-78.

Pannerselvam, A., and Suryanaraya Rao, S. (1996). Geology and uranium mineralosation of the Proterozoic potassic alkali syenite from Rasimalai, North Arcot Ambedkar district, Tamil Nadu, India. Exploration and Research for Atomic Minerals, Vol. 9, pp. 1-14.

Pretorius, D.A. (1981). Gold and uranium in quartz pebble conglomerates. Econ. Geol, 75thAnniversary Volume, pp.117-138.

Rajagopalan, V. and Hansoti, S.K. (1997). Sakoli basin and surrounding areas: a favourable terrain for iron-oxide type uranium mineralisation in Central India. Exploration and Research for Atomic Minerals, Vol. 10, pp.25-40.

Rajenda Singh, (1994). Constraints and prospects of uranium exploration in Himalya. Exploration and Research for Atomic Minerals, Vol. 7, pp.51-67.

Rajendra Singh , Govind Singh, Sandeep Hamilton, and Mohanty, R. (1997). Lithological and tectonic control of uranium mineralisation in the Lower Proterozoic metasediments at Umra, Udaipur district, Rajasthan, India. Exploration and Research for Atomic Minerals, vol. 10, pp.1-13.

Rao, N.K., and Rao, G.V.U. (1983). Uranium mineralisation in the Singhbhum shear zone, Bihar. IV. Origin and geological time frame. Jour. Geol. Soc. India, Vol. 24, pp.615-627.

Rich, R.A., Holland, H.D., and Peterson, U. (1977). Hydrothermal uranium deposits. Elsevier, New York, 264 p.

Robertson, D.S., Tilsley, J.E., and Hogg, G.M. (1978).The time-bound character of uranium deposits. Econ. Geol., Vol. 55, pp. 659-694.

Roberts, D.E. (1988). The Olympic Dam Copper-Uranium-Gold deposit. IAEA, TC-450.5/11, Vienna. pp.263-271.

Romberger, S. B., (1984). Transport and deposition of uranium in hydrothermal systems at temperatures up to 300 C: geological implications. pp. 12-22. In: De Vivo, B et. al., (Edts.) . Uranium geochemistry, mineralogy, geology, exploration and resources. IMM, London.

Rai ,A.K.,Zakaulla, S., Jeyagopal, A.V., Vasudeva Rao. M., Nagabhushana, J.C. and Varadaraju, H.N. (2002). Uranium mineralisation in the southwestern part of the Cuddapah basin, Andhra Pradesh. Exploration and Research for Atomic Minerals, Vol. 14, pp.79-94.

Ruzicka, V. (1996). Unconformity-associated uranium. pp.199-212. In: Geology of Canadian Mineral Deposit Types. Vol. 8, Eckstrand, O.R., et al., (Edts.), Geological Survey of Canada.

Sarkar, S.N., and Saha, A.K. (1983). Structure and Tectonics of the Singhbhum –Orissa iron ore craton, eastern India. In: Recent Researches in Geology, Hindustan Publishing Corporation, Delhi, India., Vol.10, pp. 1-25.

Sarkar, S.C. (1984). Geology and ore mineralisation of the Singhbhum copper-uranium belt, eastern India. Jadavpur Univ., Kolkata, India.

Saraswat, A.C., Krishnamurthy, P.,and Mahadevan, T.M.(1988). Uranium provinces of the Indian subcontinebt and surroundings. IAEA-TC-543/4, Vienna. pp. 39-57.

Saxena, V.P. (2004). Targetting 'classical unconformity' type uranium deposits in the Palnad sub-basin (Andhra Pradesh)-necessity for gepphysical research. Exploration and Research for Atomic Minerals, Vol.15, pp.1-11.

Saxena, V.P., Bahukhandi, N.K., Reddy, S.V.S., Sabot, H.K., and Verma, S. C. (1998).Uranium mineralisation in Surguja Crystalline Complex, Madhya Pradesh, India-a review for evolving new exploration strategy. Exploration and Research for Atomic Minerals, Vol. 11, pp.61-75.

Sen, D.B., Sachan, A.S., Padhi, A.K., and Mathur, S.K. (2002). Uranium exploration in the Cretaceous Mahadek sediments of the Meghalaya Plateau. Exploration and Research for Atomic Minerals, Vol. 14, pp. 29-58.

Sibbald, T.I.I (1988). Geology and genesis of the Athabasca basin uranium deposits. In: Recognition of uranium provinces, IAEA,, Vienna, pp.61-105.

Simov, S.D. (1979). Uranium epochs. In: Uranium Deposits in Africa: geology and exploration, IAEA, Vienna, pp.191-204.

Sinha, R.M., Shrivastava, V.K., Sharma, G.V.G., and Parthasarathy, T.N. (1995). Geological favourablity for unconformity related uranium deposits in northern parts of the Cuddapah basin: evidences from Lambapur uranium occurrence, Andhra Pradesh, India. Exploration and Research for Atomic Minerals, Vol. 8, pp.111-126.

Sinha, K.K., Das, A.K., Sinha, R.M., Upadhyaya, L.D., Pandey, P., and Shah, V.L. (1990). Uranium and associated copper-nickel-molybdenum mineralisation in the Singhbhum shear zone, Bihar, India. Exploration and Research for Atomic Minerals, Vol. 3, pp.27-43.

Swarnkar, B.M., Umamaheshwar, K., Srinivasan, S., and Kothari, P.K. (2002). Exploration for sandstone type uranium mineralisation in the northern Himalaya, India. Exploration and Research for Atomic Minerals, Vol. 14, 1-27**.**

Toens, P.D. (1981).Uranium provinces and their time-bound characteristic. Trans. Geol. Soc, S Afr., Vol. 1, pp.293-312.

WMC, (2000). Western Mining Corporation Ltd., 2000, Annual Report.

****