Chapter - 6

URANIUM MINERALISATION
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6.1. INTRODUCTION

As described earlier in Chapter-2, U-mineralisation is confined to several fracture zones in the basement granites which are invaded into gneisses of the study area. In chapter-4 physical properties, mode of occurrence, optical properties both in transmitted light and reflected light microscopes, of various primary as well as secondary u-bearing minerals and other sources of radioactivity, nature and types of various alterations, alteration assemblages, chemical reactions involved in the u-concentration in various fracture zones are described. Based on the geological setting, petrography and geochemistry of host rocks, a genetic model has been proposed and presented.

Thorium free uranium values in the fracture zones range from 0.012 to 0.43 % U$_3$O$_8$. The uranium mineralisation in the fracture zones are hosted by sheared granite, cataclasite and mylonite.

6.2. SOURCE OF URANIUM

The source of uranium are:

(i) Ultrafine pitchblende, coffinite, brannerite and U-Ti complex associated with specular heamatite and limonite.

(ii) Uranium in the adsorbed state on limonite, smectite and chlorite.

(iii) Secondary uranium minerals like autunite and uranophane.

(iv) Apatite, leucoxene, anatase, spene, allanite (V), zircon and monazite as feeble contributor of radioactivity.
6.2.1 RADIOACTIVE MINERALS

There are roughly 150 minerals known to accommodate U in their structure so as to call them uranium minerals. Minerals consisting uranium in tetravalent state are classified as primary uranium minerals and those containing uranium in hexavalent are referred to as secondary uranium minerals. The principal radioactive minerals identified in cataclasite and mylonites in the study area include uraninite and pitchblende. Uranium is also associated with titanium bearing minerals like brannerite, anatase, leucoxene. Phosphate bearing minerals containing uranium are apatite monazite and xenotime. Uranium is also associated with zircon, limonite and pyrite.

6.2.1.1. Uraninite: Uraninite is an oxide of uranium. It is the primary ore mineral of uranium. It is radioactive. Uraninite in its amorphous form is also known as "pitchblende". It’s color is brownish black to black. It’s streak is brownish black or grayish. The luster is submetallic to pitchlike. It doesn’t have any cleavage. It has a hardness of 5.0 - 6.0. It’s specific gravity is 6.5 - 10.0. Some of its distinguishing characteristics are it’s radioactivity, color, luster, specific gravity, and lack of cleavage. It’s chemical classification is an oxide. It’s chemical composition is Uranium Oxide (UO2).

Uraninite occurs as discrete grains in undeformed granite of study area (Fig.6.1a,b &c) as well as fracture fill in the brecciated granite (Fig.6.2). In mylonites (Fig.6.3) and phyllonites (Fig.6.4a & b). It occurs as as euhedral and sub-rounded inclusions in quartz-chlorite-sericite-clay matrix, usually in association with fragmented quartz, uraninite grains are usually found with partly dissolved edges and rimmed by chlorite. Fine grained galena which has probably formed from the radiogenic lead is found disseminated sometimes with uraninite grain. Pitchblende is
formed in the vicinity of the fractured uraninite later to the uraninite under more oxidic conditions. The alteration product was determined as gummite which is reddish seen in crossed Nicols as orange coloured mineral (Fig.6.5a-d). At many places it is intimately associated with specular haematite. (Fig.6.6a &b).

6.2.1.2. Pitchblende: It is amorphous form of uraninite. It is often massive, often colloform, mineral of lower specific gravity and higher water content. It occurs as irregular patches and veinlets in brecciated granite (Fig 6.7), in mylonites (Fig.6.8) and in phyllonites (Fig.6.9). It occurs along the border of uraninite and as fillings along hairline fractures originating at the edge of the uraninite and extending into the matrix. It is also observed to occur as roughly oriented parallel to the foliation, at places both parallel and across the foliation is also seen. Botryoidal pitchblende (Fig.6.10) is seen in some samples from Gondipalle area.

6.2.1.3. Anatase: Anatase is found as the dominant radioactive mineral in some samples. It is mostly found as fracture-filling as accessory mineral and as inclusion in the matrix. It registers sparse alpha tracks. It is also found associated with hematite. In some cases, trace amounts of uraninite are intimately intergrown with anatase in dense concentrations (Fig.6.11a & b).

6.2.1.4. Brannerite: It occurs as anhedral to subhedral (Fig.6.12a to 12e), columnar and needle-shaped crystals in chlorite/sericite matrix. It is brownish black in transmitted light and brownish grey colour and it exhibits yellowish to reddish brown internal reflections in reflected light with approximately 16% reflectivity. In some samples, it contains number of minute pittings on its surface and registers medium dense alpha tracks on CN-85 film.
6.2.1.5. **Leucoxene:** Leucoxene occurs as clusters along fractures in chlorite matrix (Fig. 6.12d) and many times it is closely associated with haematite. It registers sparse alpha tracks on CN-85 film after four days of exposure.

5.2.1.6. **Apatite:** Uranium rich apatite that occurs as randomly-oriented prismatic crystals (Fig 6.13a,b,&c) in mineralized cataclasite and mylonites. In Chakrayapeta radioactivity is mainly due to uranium associated with apatite, as it registers sparse alpha-tracks on CN-85 film for seven days of exposure.

Other radioactive minerals identified in the granite cataclasites and mylonites which occur as accessory minerals are monazite, zircon, allanite and sphene.

6.2.1.7. **Monazite:** Monazite is homogeneously distributed within the granite (Fig 6.14a & b). It is about 0.2 mm in diameter, yellowish white to white with vitreous to resinous luster, conchoidal fractures and brittle. It occurs as tabular to irregular fragments with monoclinic crystal shape and low radioactivity. In thin sections, monazite is observed as small sub-transparent mineral inclusions within biotite, feldspar or amphibole and shows some pleochroic haloes. Physical characters observed under ultra violet light show green and yellowish fluorescence colour.

6.2.1.8. **Zircon:** Both unaltered (Fig 6.15a &b) and altered zircon (Fig.6.15c) varieties have been recognized in the granites and cataclasites. Zircon is 0.1 mm diameter in average size, reddish to colourless with vitreous to adamantine luster. It is brittle and exhibits conchoidal fracture, euhedral shape from tetragonal bipiramid to rounded, with 4.7 specific gravity, and records radioactivity. In thin sections, zircon occurs as the inclusion within biotite, amphibole and feldspar. It is transparent, sometimes show zonal structures, weak pleochroic haloes and the shell is metamict.

6.2.1.9. **Allanite:** Allanite is one of the radioactive minerals recorded. It occurs as brittle grains. It shows reddish brown colour and resinous luster. It is sub-translucent
to opaque. It’s size is 1-2 mm in diameter (Fig.6.16), and is radioactive like monazite and zircon. Under transmitted polarized microscope, it shows strong pleochroism; Z = brownish yellow, Y = reddish brown and X = greenish brown. Some allanite grains are altered.

**6.2.1.10. Sphene:** It has been identified both in the granites (Fig.6.17), cataclasites and mylonites.

**6.2.1.11. Limonite.** Uranium also occurs in adsorbed state with limonite (Fig.6.18a & b)
Fig. 6.1a. Photomicrograph of Uraninite in granite 20x, TL, 1N.

Fig. 6.1b. Photomicrograph of Uraninite 50x, TL, 1N.

Fig. 6.1c. Photomicrograph of Uraninite 50x, RL, 1N.
Fig. 6.2. Photomicrograph of Uraninite (U) as fracture filling in granite cataclasite 50x, RL, 1N, Mulapalle area.

Fig. 6.3. Photomicrograph showing skeletal uraninite in mylonite 20x, RL, 1N, Mulapalle area.
Fig. 6.4a Photomicrograph showing replacement of uraninite (U) by Hematite (H) in phyllonite 50x, RL, 1N, Mylonite, Mulapalle

Fig. 6.4b. Photomicrograph of skeletal uraninite grains (U) in quartz rich rock, 50x, RL, 1N, Gondipalle area.
Fig. 6.5a. Photomicrograph showing Uraninite (U) altering to gummite (G) quartz rich rock, 20x, RL, XN, Gondipalle area.

Fig. 6.5b. Photomicrograph showing Uraninite (U) altering to gummite in quartz rich rock, 50x, RL, IN, Gondipalle area.
Fig. 6.5c. Photomicrograph showing Uraninite(U) altering to gummite(G) in quartz rich rock 20x, RL, 1N, Gondipalle area.

Fig. 6.5d. Photomicrograph of uraninite(U) altering to gummite(G) in quartz rich rock 20x, RL, 1N, Gondipalle area.
Fig. 6.6a. Photomicrograph showing replacement of uraninite(U) by hematite(H) in phyllonite, 50x, RL, 1N, Mulapalle area.

Fig. 6.6b. Photomicrograph of alpha tracks(AT) over uraninite (U) in mylonite, 10x, TL, 1N, Mulapalle area.
Fig. 6.7. Photomicrograph of granite with fractures in quartz and botryoidal pitchblende (Pbl) 2x, TL, XN, Gondipalle area.

Fig. 6.8. Photomicrograph showing uraninite with pitchblende in hairline cracks in mylonite 50x, RL, 1N, Mulapalle area.
Fig. 6.9. Photomicrograph of uraninite with pitchblende in hairline cracks in phyllonites 50x, RL, 1N oil, Mulapalle area.

Fig. 6.10. Photomicrograph of botryoidal pitchblende(P) in granite cataclasite, 50x, RL, 1N, Gondipalle area.
Fig. 6.11a. Photomicrograph showing replacement of uraninite(U) by anatase along the fractures in granite cataclasite 20x, RL, XN, Mulapalle area.

Fig. 6.11b. Photomicrograph showing replacement of uraninite(U) by anatase along the fractures in granite cataclasite 20x, TL, XN, Mulapalle area.
Fig. 6.12a. Photomicrograph of opaques identified as brannerite and galena 10X, RL, 1N.

Fig. 6.12b. Photomicrograph of opaques giving high density alpha tracks 10X, TL, 1N.

Fig. 6.12c. Photomicrograph of high density alpha tracks, 10X, TL, 1N.
Fig. 6.12d. Photomicrograph of Brannerite (B) and RA leucoxene (L) in the fracture of granite 10X, TL, 1N.

Fig. 6.12e. Photomicrograph of Brannerite in magnified view under reflected light, 20X, RL, 1N.

Fig. 6.12f. Photomicrograph of Brannerite in magnified view under reflected light 50X, RL, 1N.
Fig. 6.13a. Photomicrograph of apatite (A) associated with chlorite (C) and feldspar (F) 10x, TL, 1N.

Fig. 6.13b. Photomicrograph of allanite (Al) and apatite (Ap) inclusion in plagioclase, 5X, TL, XN.

Fig. 6.13c. Photomicrograph of radioactive apatite (A) inclusion in quartz creating radiation cracks 5x, TL, XN.
Fig. 6.14a. Photomicrograph of monazite (M) in groundmass of chlorite 20x, TL, 1N.

Fig. 6.14b. Photomicrograph of monazite (M) in groundmass of chlorite 20x, TL, XN
Fig. 6.15a. Photomicrograph of radioactive zircon (Z) with chlorite (c), 50x, TL, 1N, oil.

Fig. 6.15b. Photomicrograph of radioactive zircon inclusion in altered feldspar 20x, TL, 1N T.R.Palle area.

Fig. 6.15c. Photomicrograph of euhedral zoned zircon in cataclasite 50X, TL, 1N.
Fig. 6.16. Photomicrograph of allanite with radiation cracks 10x, TL, XN.

Fig. 6.17. Photomicrograph of sphene(S), zircon (Z) with pleochroic halo and chlorite (C) in granite, magnified view, 20X, TL, XN.
Fig. 6.18a. Photomicrograph of limonite having adsorbed uranium 50x, RL, XN.

Fig. 6.18b. Photomicrograph of limonite having adsorbed uranium 50x, RL, 1N.
6.3 ALTERATIONS

The rocks containing the mineralised fracture zones are altered to a lesser or
greater extent. Alterations are generally confined to the fracture zones and do not
extend much laterally away from the contact of the fracture zones. An alteration
index (Ishikowa, 1976) is used to characterise the changes in alterations within the
uraniferous fracture zones. More intense the alterations larger the alterations index. It
is conspicuously seen in Mulapalle area where in unaltered granite, the alteration
index is low which progressively increases and is high (92.44) in the intensely
mylonitised rock. With increase in alteration index the concentration of uranium also
increases. The study of the alterations associated with fracture controlled
mineralisation provides an important insight into the chemical processes responsible
for uranium concentration.

6.3.1. Chloritisation

Chloritisation is one of the most common alteration types seen in structurally
controlled ore deposits. Similarly this type of alteration is characteristically recorded
in fractured controlled type of uranium mineralisation in southwestern margin of
Cuddapah basin. Though this alteration is wide spread, degree of chloritisation varies.
It is characteristically seen in Sundupalle area where chloritisation is the dominant
alteration. Petrographically chloritisation advanced by alteration of biotite and
plagioclase. Chloritization of biotite can be explained by representative reaction
(Neill and Phillips, 1987) as

\[
K\text{AlFe}_3\text{Si}_3\text{O}_{10}(\text{OH})_2 + H^+ + O_2 = Fe_5\text{Al}_2\text{Si}_3\text{O}_{10}(\text{OH})_8^+ + SiO_2 + Fe_3O_4 + K^+
\]

(Biotite) (Chlorite)
6.3.2. Phosphatisation

Phosphatisation is a characteristic alteration seen in Chakrayapeta and Payalopalle fracture zones. This alteration is predominantly recorded in the fractures developed immediately in the vicinity of thick quartz reefs. The distribution of high fracture density around quartz reefs may suggest some tectonic links between quartz reefs and fractures, which may have initiated or reactivated the fracture systems. Regional fracturing together with hydraulic fracturing generated a highly porous domain which prompted the development of mineralised body. Higher concentration of \( \text{P}_2\text{O}_5 \) in Chakraytapeta and Payalopalle than at Sundupalle, Mulapalle areas suggest active fluids have higher phosphate content than the other areas. This may be due to \( \text{P}_2\text{O}_5 \) content (av. 1.68%) in the granites hosting these fractures. Deficiency of \( \text{SiO}_2 \) and enrichment of \( \text{P}_2\text{O}_5 + \text{CaO} \) (Apatite) in the fractured rock suggest fluids had a pH varying from neutral to slightly alkaline which was favourable for apatite deposition. The degree of apatitisation progress with desilicification of the rock. This is very well indicated in Chakrayapeta. Oxidizing conditions are well marked by heamatite (\( \text{Fe}_2\text{O}_3 \)) development. It is very probable that reduction of \( \text{U}^{4-} \) by oxidation of \( \text{Fe}^{2+} \) plays an important role in precipitation of uranium together with apatite.

6.3.3. Haematitisation

Some degree of haematitisation occurs together with most other alteration features in all the mineralised fracture zones throughout the study area. The first effect of haematitisation is slightly reddening of the feldspars and transformation of biotite to chlorite. Within the mineralised fracture zone, the degree of haematitisation increases with the increase of the uranium content.

Heamatitisation occurs either as fine bands or as matrix binding quartz framework. Heamatite breccia occurring in the fault zone consist of fragments of wall rock
crystals of K-feldspars, quartz and biotite in a fine grained matrix of heamatite and hydrated iron oxide. The competency of breccia is dependent on amount of silica present in the matrix. Breccias with more siliceous matrix are hard and ore consisting of hydrated Fe oxide are soft. The samples with intense heamatite alterations show a pronounced increase in Fe$_2$O$_3$ / FeO ratio. Studies of U versus Fe$_2$O$_3$ indicate that the higher uranium contents have more Fe$_2$O$_3$ content. The uranium enrichment in heamatite rich rock occupying fracture zones suggest genetic link between uranium and haematitisation.

Close spatial association of haematitisation with phosphatisation and sericitisation in mineralised portions indicates a probable direct genetic link among these alterations processes.

The three major sources of iron released during alteration were: (1) primary iron bearing silicates (e.g. biotite, hornblende), (2) magnetite, which is an important accessory phase in the granite and (3) titanite. The oxidation of ferrous iron could locally lead to fluids depleted in oxygen (oxygen used up in hematite precipitation). This process may have resulted in the development of a geochemical environment conducive to the precipitation of U$^{4+}$ minerals (uraninite, pitchblende). The large extent of altered rocks and the abundant presence of Fe$^{3+}$-bearing minerals associated with the uranium ore suggest that the deposition of uranium minerals was a response to the reduction of the ore-bearing fluid by direct interaction with ferrous iron bearing silicate (biotite and chlorite). A similar scenario was proposed for Australian deposits by Wilde et al., (1989). In addition to Fe$^{2+}$ phyllosilicates, pre-uranium pyritization significantly contributed to the reducing capacity of the host rock.
6.3.4. Sericitisation

Sericitic alterations are characteristically seen in fractures developed in highly differentiated microcline bearing granites in areas of Mulapalle, Burjupalle and Pulikinta. Sericitic alterations are controlled by intense micro fracturing and sericite occurs in salvages around quartz veinlets. Sericitic alterations have much higher K$_2$O (average = 8.65%) and slightly higher SiO$_2$ (x =75%). It is highly deficient in Na$_2$O. The complete disappearance of Na$_2$O in all the alteration types seen in uraniferous fracture zones can be related to complete destruction of Albite. MgO remains fairly constant in all sericitic alteration. The Mg bearing minerals identified are chlorite and smectite. In Mulapalle area sericitic alterations show high Fe$_2$O$_3$ thereby having a close association with hematitisation. Sericitic rich zones with higher Fe$_2$O$_3$ record a better concentration of uranium (0.17% eU$_3$O$_8$ x 3.00m).

Two possible reactions responsible for the formation of the mineral assemblage of sericitization (Neill and Phillips, 1987) include;

Hydrolysis of alkali feldspar:

$$(K,Na)AlSi_3O_8+H^+=KAl_3Si_3O_{10}(OH)_{2}(nH_2O) +NaAlSi_3O_8 + SiO_2 + Na^+$$

Breakdown of plagioclase:

$$(Ca,Na)Al_2Si_2O_8+CO_2+H_2O= Ca_2Al_3Si_3O_{12}(OH) + NaAlSi_3O_8 + O_2$$

6.3.5. Silicification

In most of the cases the zones of silicification are within or in close proximity of the mylonite zones. The least altered fracture zone rock is pink or grey coloured granite. With intensity of deformation and mylonitisation, this develops into a fine grained dark coloured rock (mylonite) which is closely associated with zones of
silicification. In its more silicified form rock is massive, very hard and has clouded white colour. Silicification also develops simultaneously with the associated alterations like chloritisation of biotite and sericitisation of feldspars.

6.4. CONCENTRATION OF URANIUM

The first phase of concentration of uranium in the granite is primary syngenetic uraninite occurring as fine-sized inclusions in quartz, biotite and amphiboles.

The second phase is during deformation where remobilization of primary uranium took place leading to the development of fracture controlled uranium mineralisation. During metamorphic phase, uranium present in inclusions, was remobilized and precipitated as uraninite (II) in the fractures associated with either iron oxide and pyrite.

The third and major phase of concentration of uranium is during intense fracturing and hydrothermal activity, wherein uranium phases such as uraninite, brannerite and U–Ti ± Fe complex occur as discrete grains and veins filling fracture planes. The fourth phase is of concentration of U in the zone of oxidation.

Secondary uranium minerals occur as encrustations of yellow, green, on the granite and fractures planes in the shear zone up fracture planes. Labile uranium occurs as very fine-sized submicroscopic material around grain margins of both rock forming as well ore minerals in the host rock and along very fine fractures, and as adsorbed uranium on Fe and Ti oxides.

Uranium mineralisation is associated with alterations like haematitisation, chloritisation, sericitisation, silicification and phosphatisation. Petrographic evidence indicates that both alteration and uranium mineralization were episodic in nature, suggesting that mineralized cataclastic zones acted as channel-ways within which
hydrothermal fluids flowed cyclically during deformation. The cyclical nature of this processes may reflect the action of a "suction-pumping" mechanism (e.g. Sibson, 1987) triggered by abrupt drops in elastic strain following brittle rupture events. This mechanism has been suggested as an important process in the formation of many other epithermal, fault hosted ore bodies including the vein hosted Schwartzwalder deposit in Colorado and breccia-hosted uranium deposits of Salamanca Spain (Wallace and Karlson, 1985; Wallace and Whelan, 1986, and Both et al., 1994).

It is proposed that intense cataclasis and brecciation associated with the fault helped oxidizing (meteoric?) fluids cyclically circulated through the fault zone during epithermal processes. After leaching the uranium from the source rocks the uranium enriched fluids may have been channeled into the zone of brecciated granites and mylonites. Where fluid bearing fracture zones intersected these reducing iron rich lithologies, uranyl complexes in the fluid would react and lead to the precipitation of the ore assemblages. Uranium ore assemblage consisting of uraninite and pitchblende, and the abundance of titanium bearing uranium minerals like brannerite, anatase and phosphate bearing minerals like apatite and absence of calcite in the primary uranium ore assemblage, indicates that, early in the mineralization process uranium was probably transported primarily as phosphate, oxides and/or fluoride complexes depending on the pH of the solution.
6.5. PROPOSED GENETIC MODEL FOR GRANITE-MYONITe HOSTED FRACTURE/SHEAR CONTROLLED URANIUM MINERALISATION IN THE STUDY AREA

The essential requirement for any mineralizing system are suitable uranium source, suitable fluids and fluid pathways and effective reducing mechanisms (Skirrow et al., 2009). The proposed model of ore formation of granite hosted-fracture controlled type of uranium mineralisation associated with cataclasite and mylonites in areas around Lakkireddipalle in Kadapa district consist of following four stages:

1) Evolution of favourable granite that acted as both source and host of the ore.

2) Development of fractures in granites.

3) Mobilization of uranium in response to multiphase dislocation metamorphism and the associated alterations.

4) Precipitation of uranium in the fracture zones being a suitable structural trap.

The first step in the formation of granite-hosted fracture controlled mineralisation is the generation of highly evolved granites (Fig.6.19). The highly evolved nature of granites is documented by (1) higher content of incompatible elements such as U (32 ppm), Th (10-60 ppm), Ce (10-306 ppm, av.71 ppm), La 12-96 ppm, av.32 ppm), high Rb/Sr ratio (0.19 – 15, av 5.19). The chemistry of these granites shows that, they are weak (Molar Al₂O₃/Na₂O + K₂O + CaO, 1.05 – 1.18) to strongly peraluminous (Molar A/CNK, 1.29 – 1.86). The main processes of controlling U enrichment in peraluminous granites is partial melting, magmatic
differentiation, hydrothermal and meteoric alteration (Fredrich et al., 1986). The granites in the study area are considered to be homotaxial with Closepet granites. These granites are considered to be generated by partial melting of their protolith i.e. the Peninsular gneisses.

6.5.1. URANIFEROUS GRANITE

The term “uraniferous granite” is applied to only to those granites which contain at least twice the Clarke value. Since the Clarke value for uranium in granite is 4 ppm of U, a uraniferous granite would therefore contain 8 ppm U or more. The presence of associated uranium mineralization should not by itself warrant describing the granite as uraniferous (Darnley, 1982).

Background uranium contents of the unaltered, unmineralized granite in the area under investigation ranges from 20 to 32 ppm. The normal uranium content for granite is considered to be 4 ppm (Rogers and Adams, 1969; Cuney, 1978). These averages suggest that the granites of southwestern margin of Cuddapah basin contains five to eight times as much uranium as the average granite i.e. rocks. The high uranium contents for these granites are normal as uranium contents tend to increase with increasing silica and alkali contents in differentiated suites (Stuckless and Nkomo, 1978). Most of the granites are high in silica and alkalies (Table 3). Uranium occurs in the primary minerals like thorite, zircon, allanite, monazite, xenotime, sphene, and apatite. These minerals may be the source for U that may have been remobilised and concentrated in the fracture zones developed in these granites.

Strongly peraluminous granitic liquids can be generated by partial melting of amphibolitic source rocks (Patin~o Douce and Beard, 1995). Thus, granites with at least
one geochemical characteristic similar to S types (strongly peraluminous chemistry) can be derived through partial melting of nonsedimentary metaluminous protoliths.

Based on the geochemical characteristics of these granites such as (high A/CNK and K/Na, positive Rb and Th anomalies, negative Eu anomalies, etc.), it is suggested (Subba Rao et. al. (1992a & b) that some of the Dharwar Craton biotite-bearing granites formed by anatexis of a TTG-like source (either the old Peninsular Gneisses, or the younger “Krishnagiri-type” TTG).

6.5.2. FRACTURING OF GRANITE AND DEVELOPMENT OF CATACLASITE AND MYLONITE

The second step in the formation of granite hosted fracture controlled uranium mineralization in the study area was initiated by the deformation of granites i.e. fracturing (Fig.6.20). Fractures dissecting this granitic terrain on a regional scale is documented by the LANDSAT imageries (Drury, 1984). Based on the detailed geological mapping by AMD, three set of fractures identified are NW - SE, NNE - SSW and ENE - WSW trending fractures. Among these the ENE – WSW is closely spaced and more deformed. Incidentally most of the identified uraniferous fractures are ENE - WSW trending. Intensity of deformation is documented by the development of cataclasites and mylonites.

The mylonitisation is due to the compression. The essential controls of mylonite formation are temperature confining pressure, differential stresses and rock properties (rock chemistry, mineralogy, grain size etc.). In mylonitisation due to the comminution of the rock in the mineral structure and rock texture are totally destroyed. During this mechanochemical metamorphism, mechanical initiation of
chemical reaction results in remobilisation of the constituents released due to comminution of grains.

Detailed geological mapping of the deformed granites indicate development of mylonites right from millimeter scale (Fig 6.21), centimeter scale (Fig 6.22a & b) to meter scale (Fig.6.23a & b). Uranium mineralisation is recorded in the mylonites irrespective of its thickness. It has been found that concentration of uranium in the mylonites is directly related to the intrinsic uranium concentration in the granites.

6.5.3. MECHANISMS OF URANIUM REMOBILISATION/TRANSPORT

The uranium content of potential sources is only one factor in generating a U-bearing ore fluid. In hydrothermal systems where uranium is scavenged from rock sources, a critical factor in the effectiveness of the mineral system is the leachability or availability of U for possible transfer from mineral to fluid. Whether or not the source minerals are effectively leached in clearly dependant on the presence of fluids with suitably high uranium solubility, which in turn is a function of permeability evolution, fluid/rock ratios, etc.

Any pore fluid present in the fracture zone during deformation would have been important to both the chemical and mechanical processes. Some of the mineral reactions accompanying mylonitization involved hydration. Lack of significant amounts of carbonate minerals in the fracture zones suggests the fluid was predominantly H₂O. A large volume of water must have been introduced into the zone during mylonitization because, the required water was not present in the unmylonitized granitoid rocks of the investigated area.
Models of ore-forming processes require high porosity and permeability of potential source/host rocks. Intense fracturing of the granites and development of cataclasites and mylonites along the fracture zone presents a interconnected system for mobility of hydrothermal solutions. The continuation of hydrothermal convection requires the presence of open fractures in the granite. Porosity and permeability have also been introduced during the alterations like chloritisation of biotite (Kogure and Banifield, 2000). Granite plutons with high radioelement content generates heat that can drive hydrothermal convection (Fehn et al., 1978).

Possible migration of major elements such as Si, K and Fe as suggested by the whole-rock chemistry data, also points to the presence of a fluid with a high relative pressure, a fluid present as a distinct phase spread throughout a small volume of interconnected pore space. The pore space may have been maintained dynamically as microcracking was an important deformation mechanism. No medium other than a pore fluid for large scale chemical diffusion in the zone seems reasonable. The fluid phase may have been localized in the mylonite zone of the fracture zone and may not have present during the entire period of deformation. This may be the reason for localized uranium concentration along the fracture zones.

Tectonic force may be one of the important driving forces for migration of fluids (Skirrow et al., 2009). The main media for remobilization, mechanochemical metamorphism may be waters occupying fractures. The process that have governed the liberation of uranium to the depositional sites could be, metamorphic secretion (Boyle, 1982) and alteration of biotite to chlorite (Renard, 1974). Mobilisation of uranium might have also been initiated by carbonate, phosphate, halide and
hydroxide complexes. This is manifested by presence of mineral phases associated with uranium in the mylonites. Uranium is transported in oxidizing fluids as soluble uranyl complexes ($U^{VI}$) which include $UO_2^{2+}$ and uranyl carbonate, fluoride, phosphate, and sulfate complexes (Hostetler and Garrels, 1962; Rich et al., 1977; Langmuir, 1978). The relative abundances of the complexing species, the pH, and (probably) the temperature of the fluid determines which uranyl complex(es) is dominant, although the effect of temperature on the solubility of the various species is not well known.

The mechanical energy during faulting and shearing can be converted into heat required for formation of the hydrothermal system. The heat would have been dissipated by fluids expelled toward the surface through the fracture and breccia system. The hydrothermal solutions driven by regional tectonism used the fault zones and fracture zones of the host granites as pathways. While moving, the hydrothermal solutions may have further leached uranium and other elements from the host rocks, and finally became mineralizing fluids. This is evident by extensive deuteric alteration like chloritization of biotite, argillization of orthoclase and microcline. It was also observed under microscope the presence of accessory minerals like zircon, sphene, monazite, apatite, allanite, xenotime, etc. in the altered granite. Liberation of uranium and other metallic elements from the structure of the primary accessory minerals and biotite and subsequently concentrated in the ores has been reported (Cuney .M, 1978). This process is a critical step which makes the uranium more readily leachable by later hydrothermal solutions.

The widespread alteration and associated U redistribution in rocks along the fracture zones in these granites all along the southwestern margin of the Cuddapah basin
indicate that a hydrothermal system was operational. Limited extent of uranium mineralized lenses suggests migration (probably on the scale of millimeters to centimeters) of uranium through the hydrothermal system was active for only a relatively short period and in many episodes.

The data presented in this study suggest that the fluid was sufficiently oxidizing to transport uranium efficiently and show definitely that sources of leachable uranium are present in these granites. Potential reducing agents, e.g., ferrous and sulfide ions were present in the fluids and could effectively reduce soluble uranyl complexes at potential sites of pitchblende deposition.

6.5.4. PRECIPITATION OF URANIUM

Uranium precipitation can be controlled by many factors, including a decrease in temperature and pressure, mixing, boiling, and degassing of fluids, decrease in pH, or a decrease in oxygen fugacity (Evert et al., 1997). Moreover, sorption and subsequent reduction of uranium species on the surface of silicates or hydroxides of iron may play a substantial role in uranium immobilization. Precipitation of uranium in requires reduction of $U^{VI}$ to $U^{IV}$. Reducing mechanisms for $U^{VI}$ in oxidizing solutions can be grouped into two broad catagories namely (a) carbon based reductants and (b) inorganic reductions. Main inorganic reductants include oxidation of $Fe^{2+}$ to $Fe^{3+}$.

Fractures are important for both transportation of fluid and precipitation of ore minerals. The deep circulating uranium-bearing waters were heated by the regional tectonism, with an elevated geothermal gradient from radioactive decay of U, Th and K in the granites (Birch, 1954; Fehn et al., 1978) and especially intrusion of the basic dikes
which have recorded large variation in ages ranging from 650 to 1879 Ma (Rao et al., 1995).

The uranium mineralization is formed by precipitation of uranium and associated metallic elements from the hydrothermal fluids in fractures and brecciated zones. Factors that may have played a part in deposition of pitchblende and associated uranium minerals from the fluids are: the temperature gradient away from the heat source, the fluid - rock interaction (alterations), and mixing of the hydrothermal fluids with shallow meteoric water in the breccias and related fracture system. Ore deposition apparently occurred during post-faulting discharge and was followed by hydrothermal self-sealing and repetition of brecciation and mineralization processes. Hydrothermal alteration accompanying the deposition of uranium in the granite hosted fracture zones consists of chloritization, hematitization, silicification, sericitisation and phosphotisation. Alteration exists as narrow zones, 0.1–1.0 cm wide, and disseminated in the host granites (Zakaulla et al., 1998).

Ores were mainly formed by direct precipitation of mineralizing solutions or through fluid-rock interaction. The spatial variation of mineralization in the fracture zones therefore reflects an essential relationship between fault movement, fluid flow and subsequent ore deposition. Field investigations (both surface and subsurface data) have shown that fluid flow is seldom distributed uniformly along individual fractures, but rather is localized within segments where permeability is highest. These segments are basically dilational and have governed the localization and geometry of the mineralized zone.
The presence of secondary uraniferous minerals (Fig.6.24a & b) in small fractures and microcracks and in association with altered mafic minerals indicates that uranium migrated through an extensive, interconnected, network of fractures and microcracks. Some of it eventually precipitated during the sealing of the microcracks. The uranium was presumably deposited contemporaneously with the crack sealing and the formation of secondary minerals, rather than after they were deposited. These minerals, which are phosphates and carbonates and other associated secondary sulfides, and hydrous silicates, suggest the presence of an H₂O - P fluid phase with minor concentrations of sulfur.

Destabilization of soluble uranyl complexes by reduction of U⁶⁺ to U⁴⁺ is one of the possible mechanism for fixing uranium (Speer et al., 1981). The close spatial association of chlorite, illite and haematite with uranium mineralisation in different fracture zones suggests that Fe⁺² derived from silicates of the host granite have played a major role in precipitation of uranium. This has been reported by Alexendre et. al., (2005) during his studies of uranium mineralisation in Athabasca Basin in Canada. He proposed that Fe⁺² liberated through chloritisation of biotite or illitisation of hornblende could have acted as reductant and the reactions suggested are;

K(Mg,Fe)₃AlSi₃O₁₀(OHF)₂ + H + H₂O + Mg³⁺ => Mg₂(Al,Fe)₃Si₃O₁₀(OH)₈ + K + SiO₂ + Fe⁺²

Biotite                                                                                     Chlorite

U⁺⁶ + 5H₂O + 2Fe⁺² = UO₂⁺ + Fe₂O₃ + 10H⁺

Chloritisation of biotite also results in increase of porosity and permeability due to volume loss and the voids development in the structure due release of K in the biotite structure.
(Kogure and Banifield, 2000). Similar primary mechanism of oxidation of ferrous to ferric iron for the reduction of $U^{+6}$ to $U^{+4}$ was suggested in granites from the Liberty Hill pluton (Speer et al., 1981) and at the Geevor Tin Mine, Cornwall, England (Caruso et al., 1982). The same mechanism was suggested (Rich et al., 1977) for the spatial and temporal association of hematite with pitchblende common in many hydrothermal uranium deposits.

Association of sulphides like pyrite as well as other sulfide minerals in the uraniumiferous fracture zones indicates that their role in reduction and precipitation of $U^{+4}$ (Garrels and Christ 1965; Langmuir 1978). A more likely mechanism for the reduction of uranyl carbonate ions involves sulfide minerals can be explained according to the following reaction:

$$UO_2\left(CO_3\right)^{2-} + Fe^{+2} + 2 H_2S(aq) \rightarrow UO_2 + FeS_2 + 2 H_2O + 2 CO_2.$$  

Cuddapah Basin and its environs are characterized by five different types of uranium deposits. The sequence of events responsible for the mineralisation in the basement granites and in the sediments of the Cuddapah Basin around Lakkireddipalle area are indicated by schematic diagram (Fig. 6.25).
Field photographs showing model of the evolution of uraniferous fracture zones in study area

Fig. 6.19. Field photograph of an exposure of uraniferous granite in the study area

Fig. 6.20. Field photograph of an exposure showing development of fractures in the uraniferous granite of the study area
Fig. 6.21. Field photograph showing fracturing of the uraniferous granite and beginning of mylonite formation in the study area
Fig. 6.22a. Field photograph showing deformed granite with development of centimeter scale mylonite in the study area

Fig. 6.22b. Field photograph of closeup view of deformed granite showing development of mylonite on centimeter scale in the study area
Fig. 6.23 a. Field photograph showing development of mylonites on meter scale in T. Sundupalle fracture zone.

Fig. 6.23 b. Field photograph showing development of mylonites on meter scale in Mulapalle fracture zone.
Fig. 6.24a & b. Field photographs showing concentration of secondary U- minerals in small fractures in the study.
Fig. 6.25. Proposed model of U-enrichment in and around Cuddapah Basin from Archaean to Proterozoic