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Allanite in Singhbhum Shear Zone, India and Its Implications on the Genesis of REE Mineralization

V. R. Akhila^{1*}, S. Rakesh¹, S.C. Gupta², Atanu Mukherjee¹, Debashis Bhattacharya¹, Kalyan Chakrabarti¹ and D.K. Sinha³

Atomic Minerals Directorate for Exploration and Research,

¹Jamshedpur - 831 002; ²Bengaluru - 560 072; ³Hyderabad - 500 016, India

*E-mail: akhilavr.amd@gov.in

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ABSTRACT

Allanite, being one of the most common REE bearing mineral phases in the multimetallic mineralized domain of Singhbhum Shear Zone, has always attracted attention from researchers. The present paper outlines a detailed petromineralogical study on various textural types of allanites. The allanite is categorized into 6 different types falling under three major categories on the basis of deformation, metamictisation and darkening of pleochroic halos. On the basis of mineral assemblage and probe analysis of allanite it follows that the optical and textural variations are an implication of not only multiple generations of their formation but rather significant variation in nature of hydrothermal fluids as evidenced by the differences in co-crystallized assemblages. They hint at relatively reducing hydrothermal conditions in Singhbhum Shear Zone responsible for REE-U-Th mineralization overprinting earlier event of oxidizing hydrothermal mineralization in which the well-known Th-poor uraninite, crystallized. Majority of the allanite appeared post or at the most syn-tectonic in their formation. The available geochronological data of allanite suggests them to be formed around 1.8 Ga. Considering textural criteria as seen in the present study, it appears that the majority of allanite owing to their undeformed morphology must have formed later to or at the most during waning stages of shearing and hence the minimum age of shearing in SSZ could be considered around 1.8 Ga instead of 1.6 Ga.

INTRODUCTION

Singhbhum Shear Zone (SSZ) is a known repository of radioactive and REE minerals. Uraninite is the major radioactive phase followed by brannerite and thorite, while major REE minerals include monazite, xenotime, allanite and bastnesite (Sarkar, 1982; Rao and Rao, 1983; Pal et al., 2011, 2021). Florencite and hellandite are also reported in this belt. Amongst these allanite deserves a special status as it is the most abundant REE bearing phase within rocks of Singhbhum Shear Zone (SSZ). The present study summarizes the mode of occurrence, textural relationships, available published geochronology to understand its genesis and evolution amongst other U-Th-REE phases in the shear zone.

REGIONAL GEOLOGY

SSZ occurs as a narrow linear belt surrounding the northern

periphery of ellipsoidal shaped Singhbhum Odisha Craton (Fig. 1). The craton, roughly 250 km x 150 km in dimension, hosts Paleoproterozoic granite-greenstone terrain with supracrustal provinces. The units within the cratonic part comprise Older Metamorphic Tonalite Gneiss (OMTG), Older Metamorphic Group (OMG) that occurs within OMTG and Iron Ore Group (IOG). Intrusive into these are the Singhbhum-Bonai-Kaptipada-Mayurbhanj granite, Neoproterozoic mafic dyke swarms, Malantoli, Jagannathpur and Ongarbira volcano sedimentary provinces (Saha, 1994; Bose et al., 2016).

Along the northern periphery of the craton, parts of IOG and Dhanjori Group of rocks occupy their respective basins and Singhbhum Shear Zone grazes through the rocks of Chaibasa Formations of Singhbhum Group, part of metapelites of IOG as well as meta volcano sedimentary sequences of Dhanjori Group of rocks. The SSZ is rich in sulphide and oxide mineral phases many of which are of economic interest. The shear zone is understood to be deep, perhaps reaching upto upper mantle and the hydrotherms activated during the thrusting tectonics probably restricted the mineralization within this structural (domain) discontinuity.

Of the wide range of polymetals in SSZ, uranium and copper are the significant elements. They are known throughout the shear zone with the richness in grade mostly localized around central and eastern sector of the belt. Uraninite is the most abundant uranium bearing mineral with minor proportion of brannerite and coffinite reported. The uranium mineralization, as per present knowledge, is categorized as metamorphite type uranium deposit.

LOCAL GEOLOGY

The study is confined to Gura, Turamdih, Rajdah, Jaduguda, Purnapani, Pathargora, and Bagjata where occurrence of uranium and REE are present (Fig. 1). These areas comprises of metapelitic rocks of Chaibasa Formation of Singhbhum Group, feldspathic schist, conglomerates, metabasic rocks and quartzite of Dhanjori Group. The rocks are sheared and mylonitised and hosts hydrothermal mineral assemblages including uraninite, magnetite, tourmaline, allanite, fluorite, thorite and apatite showing multiple textural variations and deformational features.

ALLANITE- AN UBIQUITOUS MINERAL IN SINGHBHUM SHEAR ZONE

Allanite is a REE bearing member of epidote group of minerals.

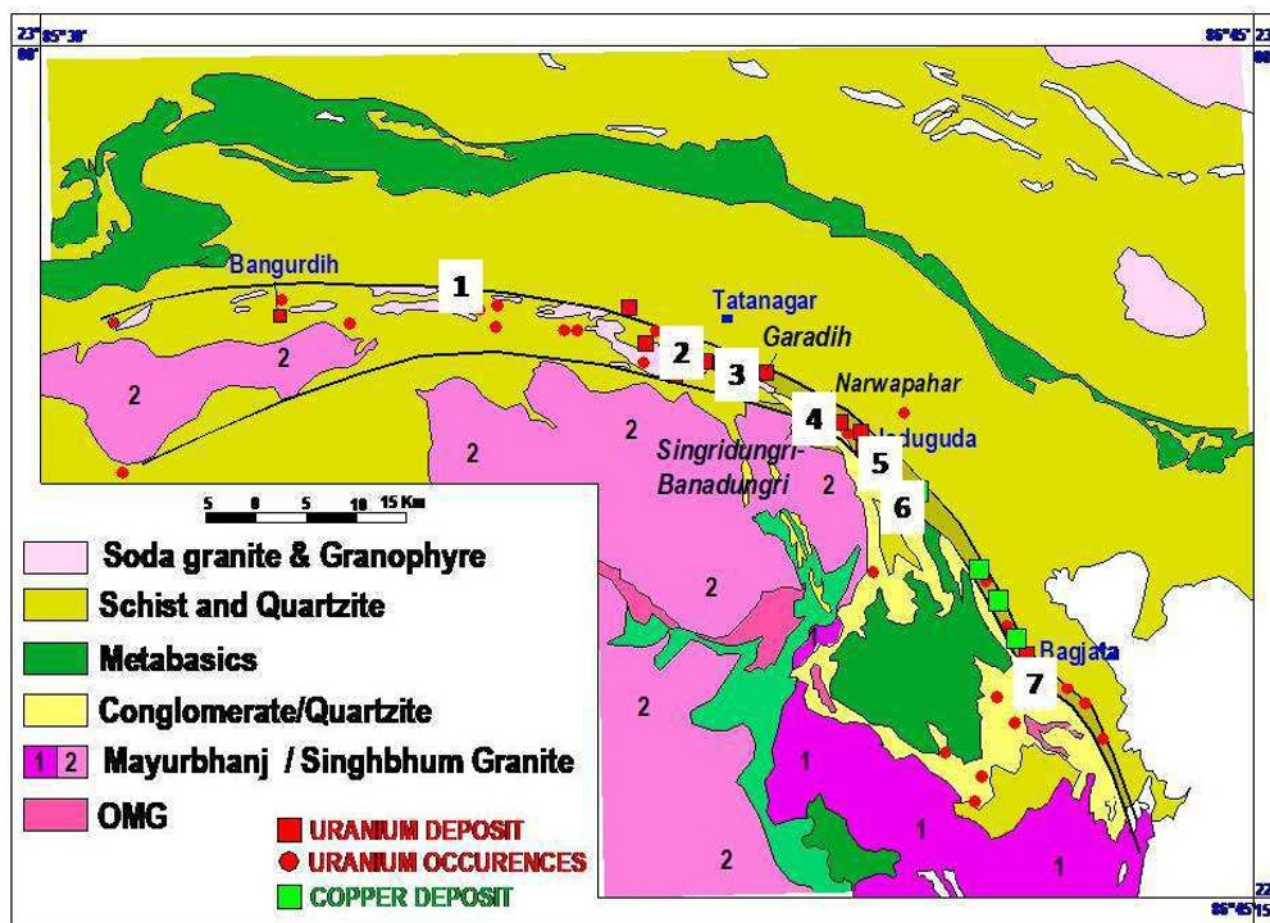


Fig 1. Regional geological map of Singhbhum Shear Zone showing sample locations. 1 - Gura, 2 - Turamdih 3 - Rajdah, 4 - Jaduguda, 5 - Purnapani, 6 - Pathargora, 7 - Bagjata

Epidote group of minerals are sorosilicates comprised of isolated silicon tetrahedra and corner sharing group of two tetrahedra with a structural formula of $A_2M_3(SiO_4)(Si_2O_7)(O,F)(OH)$ in which $A = Ca, Sr, Pb^{2+}, Mn^{2+}, Th, REE^{3+}$, and U , and $M = Al, Fe^{3+}, Fe^{2+}, Mn^{3+}, Mn^{2+}, Mg, Cr^{3+}$, and V^{3+} (Deer et al., 1986). There are two structurally different A sites, A(1) and A(2), with different coordination numbers, and there are three different M sites, M(1), M(2), and M(3), which are all octahedrally coordinated (Dollase 1971).

Allanite can be represented by the idealized formula $CaREEAl_2Fe^{2+}(SiO_4)(Si_2O_7)(O)(OH)$. It typically contains small amounts of Th and U and thus may be used as a geochronometer. In Singhbhum shear zone it has been dated to yield an age of 1.88 Ga (Pal et al., 2011, 2021) which is used to infer the earliest metallogeny in the region. Allanite tends to occur in the last stage of crystallization of mostly felsic rocks causing the inclusion of REE, Th±U elements in the crystal lattice. They also occur as a common hydrothermal phase and occasionally as a detrital mineral in metapelites with source derivation from felsic rocks. Allanite can be formed by the expense of detrital or metamorphic monazite as well (Wing et al., 2003).

Overall four possible modes of formation for allanite have been recognized. They are:

1. Primary (in igneous rocks) 2. Hydrothermal 3. Detrital and 4. Metamorphic

The identification of 1 and 2 are texturally simple where overprinting of later events are absent. However due to the wide range of textural variations displayed by this phase, there are challenges in distinguishing types 2, 3 and 4 especially where multiple events/phases of mineralization and multiple deformation events has taken place.

In the present work involving detailed petrography it is observed that allanite in SSZ falls in hydrothermal category owing to their spatial restriction within the sheared host as well as its association with other similar hydrothermal assemblages.

Allanites in SSZ occur in mylonitised metapelites in Chaibasa Formation of Singhbhum Group and also in mylonitised mafic schists of Dhanjori Group. The host rock varies from sericite-chlorite-quartz schist, quartz-chlorite schist, conglomerates, quartz-biotite schist and feldspathic schist. With such vast distribution, they show great variation in their morphology, extent of metamictisation and strength of pleochroic halos around.

MODE OF OCCURRENCE

In the present study (based on petrography from more than 110 samples) in central and eastern SSZ, allanites are categorized into three major types with a total of six sub types (Table 1),

1. Type 1 is characterized by euhedral nature, metamict core with epidote/clinozoisite rim, colourless to pale brown body colours. The metamict core suggests significant radioactive content or older formation ages or both. Based on the mode of occurrence these are further categorized into two:
 - a) *Type 1a* - These are also having euhedral to fairly subhedral morphology but shows rotational features and pressure shadows defined by biotite-chlorite-quartz. They have fine grained inclusions of phyllosilicates within them suggesting these to be grown in the system and therefore texturally these can be considered as syn-tectonic in origin. These are mostly observed in feldspathic schist (Fig.2a). Pre-tectonic origin is

Table 1. Summary of different textural modes of occurrence of allanite grains in SSZ

Feature	Type 1a	Type 1b	Type 2a	Type 2b	Type 3a	Type 3b
Morphology	Subhedral	Euhedral	Anhedral to sub-rounded	Anhedral	Euhedral to subhedral	Anhedral
Body colour under transmitted light	Colourless to very pale brown	Colourless to very pale brown	Reddish brown	Reddish brown Pale yellow	Colourless	
Halo	Moderate to strong	Strong halo	No halo	No halo	Strong halo	Strong halo
If Metamict or not	Metamict core with epidote rim with sharp grain boundaries for both phases	Metamict core with epidote rim with sharp grain boundaries for both phases	Non metamict	Non metamict often with clusters along with rutile.	Non metamict	Non metamict
Mode of occurrence	Blastic grains with inclusions and pressure shadows	As clusters suspended in biotite-chlorite matrix with haphazard orientation. Foliation truncates its grain boundaries.	Porphyroblasts with sub-rounded morphology with inclusions and rotational features	Disseminated, often as fractured, sometimes aligned parallel to foliation	They occur as fine sized clusters which are either aligned parallel to foliation or forming sub-rounded aggregates with rutile. Their boundaries are diffusive and may grade to clinozoisite	As clusters, shows replacement texture with biotite, often shows skeletal or granular morphology at the contact with biotite
Stratigraphy	Found in feldspathic schist.	Dominantly found in biotite schist of Dhanjori Group. Also in feldspathic schist, sheared conglomerates and biotite-chlorite quartz schists of Chaibasa Formation	Found in qtz-chl-bt bearing schists of Chaibasa Formation	Found in qtz-chl-bt bearing schists of Chaibasa Formation	Found in qtz-chl-bt bearing schist of Chaibasa, feldspathic schist, biotite-schist of Dhanjori (rare)	Found in qtz-chl-bt bearing schist of Chaibasa, feldspathic schist
Associated accessory minerals	Apatite, thorite, ilmenite, rutile	Apatite, uraninite, ilmenite, rutile.	Sphene, epidote, apatite, magnetite, ilmenite, rutile	Sphene, thorite, bastnesite, apatite, ilmenite, magnetite	Uraninite, thorite, uranothorite, clinozoisite, rutile, tourmaline, apatite	Sphene, thorite, uranothorite, monazite, apatite, tourmaline, rutile, magnetite
Temporal relation with shearing based on texture	Syn-tectonic	Post-tectonic	Syn-tectonic	Post-tectonic	Syn to Post-tectonic	Post-tectonic

less probable as the grains maintain their morphology in its highly mylonitised host rock.

- b) *Type 1b* - These tend to occur as clusters (Fig.2b) with perfect euhedral morphology for both metamict core as well as the enveloping epidote. The metamict core as well as the epidote rim shows haphazard alignment of their longer axis suggesting they were not sheared or mylonitised to form a common orientation. They do not show any warping of foliations around them, rather the foliations truncate at the grain boundaries. Therefore texturally these allanite grains can be considered to have formed post the events of formation of the mylonitic foliation, ie post shearing. This type is mostly observed in biotite schist derived from the metabasic rocks of Dhanjori Group. They are also found in feldspathic schistose units occurring in the hangwall side of this biotite schist. It is important to note here that allanites observed in these biotite schist of Dhanjori Group from different sectors of SSZ (Gura, Rajdah, Jaduguda, Purnapani, Pathargora, Bagjata) show post tectonic textures.
2. Type 2 grains are characterised by anhedral nature, absence of both metamictisation and rimming by epidote, reddish brown body colour and very faint to no pleochroic halo around them

(Fig. 2c). Based on the effect of deformation they are further categorized into two:

- a) *Type 2a* - these are coarse grained, show rotational features and porphyroblastic growth like textures with inclusions of biotite, quartz, chlorite and adjacent oxide phases like ilmenite (Fig. 2c). Texturally these appear to be pre-to syn - tectonic in nature.
- b) *Type 2b* - They are mostly seen as fractured and are aligned along foliation planes. Foliation truncate the grain boundaries suggesting their post tectonic growth in the system (Fig. 2d).

Type 2 allanites are mostly seen in chlorite schist of Chaibasa Formation

3. Type 3. These are mostly euhedral to subhedral and are characterised by its absence of metamictisation, but presence of a very strong pleochroic halo. Based on grain size and mode of occurrence, they are classified into two:

- a) *Type 3a* - They occur as clusters of very fine sized grains with euhedral to subhedral morphology and along with rutile aggregates (Fig. 2e). They also form as linear bands parallel to the mylonitic foliation along with uraninite. Their grain boundaries are diffused and often grades to clinozoisite.

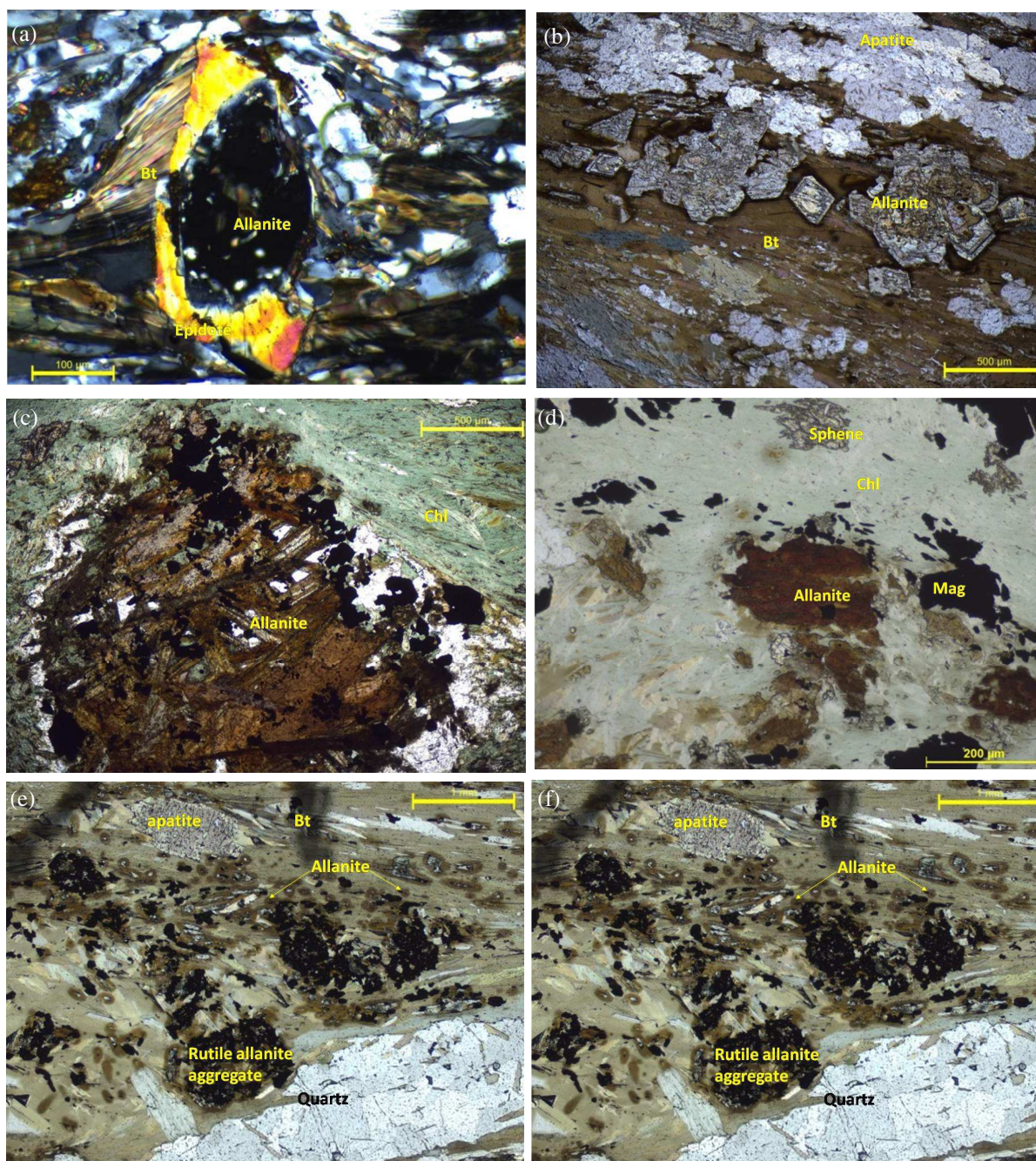


Fig. 2. (a) (Type 1a) Porphyroblastically grown metamictised allanite with inclusions of biotite, chlorite and quartz in feldspathic schist, Pathargora area (TL,air,2n). (b) (Type 1b) Euhedral clusters of allanite with metamict core, showing a strong halo (Biotite Schist), Purnapani area (TL, air, 1n). (c) (Type 2a) Porphyroblastically grown coarse allanite grains with inclusions of quartz, magnetite in chlorite schist, Rajdah (TL, air, 1n). (d) (Type 2b) Anhedral disseminated allanite with no metamictisation and faint/no halo in association with magnetite and sphene (Chl Schist), Rajdah (TL, air, 1n). (e) (Type 3a) Euhedral fine sized transparent allanite grains with strong halo occurs in close association with rutile and also as aggregates within biotite schist, Pathargora (TL, air, 1n). (f) (Type 3b) Anhedral non metamict allanite grains showing extensive replacement with biotite. They cast strong halo in the vicinity, Bagjata.

Occasionally finer sized isolated clusters of these shows inclusions of sulphides as well.

b) *Type 3b* - Allanite show extensive replacement relationships with biotite and in most cases relicts of patches of biotite are observed within the aggregate. They often result in skeletal texture and shows intricate association with phases such as apatite, thorite and monazite. They seem to be hydrothermally formed at the expense of biotite during metasomatism (Fig.2f). Close to the contact of biotite they show granular texture. These are found in Chaibasa Formation as well as in feldspathic schist.

Type 1 category includes allanite with a distinct metamict core rimmed by epidote/clinozoisite. The rimming phase shows radial cracks suggesting the formation of epidote rim prior to metamictisation and the resultant expansion. Whereas Type 2 contains non metamict allanite with feeble to negligible haloes implying their relatively negligible concentration of radioactive elements as well constraints from age. Type 3 with post tectonic textures are non-metamict allanite having very strong radioactive haloes around them. These are therefore relatively younger but with sufficient presence of radioactive elements within them so as to generate haloes. These variations in metamictisation and surrounding halo together with their boundary

Table 2. EPMA analysis of allanite from different sectors of Singhbhum Shear Zone

Oxide wt.%	Jaduguda (Type 1b and 2a)								Pathargora (Type 3a)								Purnapani (Type 1a)		
	G1(150µm)				G2(300µm)				G1		G1	G1		G2		G1	G2	G3	
	Type 1b				Type 2a				(600µm)		(200µm)	(2.5mm)		(600µm)		(250µm)	(200µm)	(150µm)	
	P1	P2	P3	P4	P1	P2	P3	P4	P1	P2		P1	P2	P1	P2	P1	P2	P3	
SiO ₂	36.27	35.95	38.13	37.57	34.49	38.84	35.28	37.79	35.06	37.33	34.33	32.58	32.81	33.23	32.01	30.444	27.85	28.93	
TiO ₂	0.11	0.14	0.13	0.06	0.21	<0.01	0.11	0.05	0.06	0.04	0.08	0.33	0.09	0.15	0.17	0.134	0.127	0.072	
Na ₂ O	0.23	0.27	0.25	0.18	<0.01	<0.01	<0.01	<0.01	0.02	0.05	0.11	0.05	0.02	<0.01	0.01	na	na	na	
K ₂ O	0.1	0.17	0.08	0.11	<0.01	<0.01	<0.01	<0.01	0.01	0.03	<0.01	0.01	<0.01	<0.01	0.01	na	na	na	
CaO	11.47	11.45	12.74	12.03	11.59	16.2	14.29	17.23	12.59	14.25	12.2	10.59	10.88	10.92	10.85	11.443	11.38	11.38	
MgO	na	na	na	na	na	na	na	na	<0.01	<0.01	0.02	0.08	0.13	0.14	0.05	0.423	0.34	0.29	
MnO	<0.01	<0.01	<0.01	<0.01	<0.01	0.05	<0.01	0.07	<0.01	<0.01	0.08	<0.01	<0.01	<0.01	<0.01	0	0	0	
FeO	9.85	8	9.18	9	13.32	11.89	13.17	11.77	11.34	10.08	11.69	12.23	11.96	12.54	13.06	12.722	11.77	13.38	
PbO	0.08	<0.01	0.04	<0.01	<0.01	0.03	0.04	<0.01	0.04	0.04	0.04	0.08	0.04	<0.01	<0.01	na	na	na	
Al ₂ O ₃	13.92	13.83	13.84	16.12	14.88	19.59	16.44	19	17.72	18.94	18.22	15.17	16.36	15.81	15.6	19.596	19.13	17.51	
P ₂ O ₅	0.05	0.05	<0.01	0.08	<0.01	<0.01	<0.01	<0.01	0.24	0.43	0.05	0.06	0.28	0.03	<0.01	0.202	0.29	0	
Y ₂ O ₃	0.71	0.96	1.41	0.53	<0.01	2.06	0.56	2.3	0.08	0.44	0.2	0.02	<0.01	<0.01	<0.01	0.345	0.20	0.049	
La ₂ O ₃	4.47	4.09	3.04	4.16	5.09	1.75	2.7	1.74	4.05	3.38	3.86	5.23	4.84	5.62	5.8	4.515	4.90	5.39	
Ce ₂ O ₃	9.39	8.49	5.52	8.55	9.76	2.93	5.66	2.58	9.39	6.93	8.26	10.98	10.43	11.2	11.04	10.236	10.79	10.85	
Pr ₂ O ₃	1.7	1.61	1.06	1.5	1.91	0.61	1.11	0.46	1.48	0.96	1.11	1.32	1.53	1.45	1.34	1.398	1.54	1.56	
Nd ₂ O ₃	4.18	3.83	3.05	3.82	4.03	1.77	3.12	1.29	4.39	3.12	3.89	4.87	4.99	4.54	4.42	4.629	4.56	4.6	
Sm ₂ O ₃	0.88	0.9	1.01	0.85	0.87	0.85	1.09	0.59	0.83	0.59	0.7	0.87	0.84	0.79	0.81	0.85	0.77	0.99	
Eu ₂ O ₃	na	na	na	na	na	na	na	na	0.02	<0.01	<0.01	0.07	0.01	0.04	<0.01	0.161	0.14	0.18	
Gd ₂ O ₃	1.06	1.05	1.28	0.93	1.01	1.28	1.16	0.89	0.93	0.78	0.89	0.98	1.09	0.94	0.98	nd	nd	nd	
Tb ₂ O ₃	na	na	na	na	na	na	na	na	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	nd	nd	nd	
Dy ₂ O ₃	<0.01	0.13	0.23	<0.01	<0.01	0.42	<0.01	0.29	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	nd	nd	nd	
Ho ₂ O ₃	na	na	na	na	na	na	na	na	<0.01	0.02	<0.01	0.01	<0.01	<0.01	<0.01	nd	nd	0.004	
Er ₂ O ₃	0.06	0.08	0.28	<0.01	0.13	0.18	0.18	0.23	0.01	0.1	0.02	0.1	0.04	<0.01	0.01	nd	0.084	0.016	
Tm ₂ O ₃	na	na	na	na	na	na	na	na	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	nd	nd	nd	
Yb ₂ O ₃	<0.01	<0.01	0.07	<0.01	<0.01	<0.01	<0.01	0.03	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.037	nd	0.045	
Lu ₂ O ₃	0.06	0.05	0.05	0.03	<0.01	0.04	<0.01	0.07	0.04	<0.01	0.04	0.06	0.02	<0.01	<0.01	0.028	0.038	0	
ThO ₂	1.18	0.77	1.19	0.61	0.07	<0.01	<0.01	<0.01	0.09	0.48	0.88	0.62	0.46	<0.01	<0.01	0.096	0.057	0	
UO ₂	0.1	0.21	0.23	0.04	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.05	<0.01	0.04	0.01	<0.01	0.03	0	0	
Total	95.92	92.05	92.81	96.19	97.39	98.53	94.99	96.42	98.37	97.98	96.74	96.3	96.87	97.39	96.17	98.871	95.476	96.78	
RE ₂ O ₃	21.79	20.24	15.59	19.84	22.8	9.82	15.03	8.17	21.13	15.88	18.77	24.49	23.8	24.57	24.4	21.854	22.824	23.63	
(ThO ₂ +UO ₂)	1.28	0.98	1.42	0.65	0.075	<0.01	<0.01	<0.01	0.09	0.48	0.93	0.62	0.5	0.01	<0.01	0.126	0.057		

relationship with mylonitic foliation suggest there are more than one episode of formation of allanite involving hydrotherms with variable chemistry and these episodes are mostly syn to post shearing in nature since the foliation truncates the grain periphery in most cases. In type 2a morphology is sub rounded and there is presence of inclusions of surrounding phases. In type 1a the morphology is euhedral to subhedral morphology with presence of oriented inclusions of phyllosilicates. Thus texturally type 2a and type 1a suggest a syn tectonic formation in the host environment. Rest of the categories clearly shows their formation post the development of mylonitic foliation associated with shearing in SSZ. Based on the relative frequency of occurrence amongst the studied samples, it follows that pre to syn tectonic allanites are very rare and limited in occurrence. Most likely it appears that majority of the allanite in SSZ starts their formation in the waning stages of shearing and their formation outlasted the deformation pretty longer resulting in the dominance of post tectonic allanite within SSZ. This is especially true for allanite phases in biotite schists of Dhanjori Formation where the aluminium from biotite is reported to have aided in the formation of allanite suggesting the prerequisite of biotite for the formation of allanite (Pal et al, 2011, 2021). It is to be noted that from the biotite schist derived from the sheared metabasites of Dhanjori Formation collected from areas like Rajdah, Jaduguda, Purnapani, Pathargora, Kendadih and Kusumbari areas along the SSZ, the Type 1b dominate and rest of the textural categories of allanite are usually found in the Chaibasa Formation and feldspathic schist suite.

MINERAL CHEMISTRY OF ALLANITES

In the central sector (Rajdah area), allanite of type 2a shows association with thorite which occur as vein as well as discrete grains in biotite chlorite schist. The vein form of thorite along with bastnesite and sphene cross cuts the rock and as well as the mega crystals of hydrothermal magnetite suggesting this to be the youngest event. Presence of uranothorite associated with the cluster of thorite grains in apatite bearing chlorite feldspathic schist is also observed in this area.

In Jaduguda sector, allanite occurs as subhedral grains of variable size (150-300 μm) falling in category Type 1a in biotite quartz chlorite schist often showing inclusions of magnetite and flakes of biotite. X-ray elemental mapping indicates enrichment of Ce and depletion of Ca in the core. Whereas, the rim shows depletion of Ce (Fig. 3a). Analyses show variable RE_2O_3 (8.17-22.80 wt.%), SiO_2 (34.49-38.84 wt.%), high and variable CaO (11.45-17.23 wt.%), FeO (8.00-13.32 wt.%) and Ce_2O_3 (2.58-9.76wt.%). Epidote rimming allanite shows altered nature.

In the eastern sector of SSZ, in Pathargora area, allanite of type 1b, 3a and 3b are found in feldspathic schist while of type 3a are found in albite veins cross cutting them. Allanite grains of type 3a show ThO_2 rich monazite, apatite and uranothorite as inclusions (Fig 3b). Skeletal anhedral allanite are present occasionally at places and occurs in association with albite, biotite, chlorite and ilmenite (Fig 3c). Allanite-thorite-uranothorite-apatite-monazite assemblage is common in feldspathic schist and overlying Chaibasa metapelites in Pathargora.

In Purnapani area, the biotite schist of Dhanjori Group shows profuse development of Type 1a allanites in association with apatite (Fig.3d). Allanite as well as apatite shows inclusions of flaky biotite suggesting their post tectonic growth. Within the euhedral boundary of allanite phase defined by metamict zone, the Ce mapping shows diffused morphology suggesting leaching of Ce (Fig.3e). This probably resulted through the interaction of fluids along radial fractures in enveloping epidote developed during metamictisation and seemed to have caused relatively less radioactive elemental concentration contrary to what is expected. This suggests the mineral system was open to fluid-rock interactions. EPMA data of allanites

from areas viz Jaduguda, Pathargora and Purnapani falling under the category of Type 1a, 1b, 2a and 3a are outlined for comparison in Table 2.

Overall there is a variation in the contents of total REE, radioactive elemental concentration as well as Ca, Fe, Al suggesting varying conditions of their formation. For Type 1a average concentration of radioactive elements (U+Th) is the highest amongst the analysed allanite types corroborating their metamict nature and strong halo. Whereas for Type 2a the average radioactive concentration is almost negligible corroborating to its non-metamict nature and feebly pleochroic (halo), it shows the least total REE content amongst the three types analysed using EPMA probably suggesting either impoverishment of REE in the hydrotherms or the simultaneous crystallisation of other REE bearing phases. Based on the presence of bastnesite and REE bearing thorite-uranothorite in the vicinity of phase, the latter seems more probable. A comparative table showing in the range of values of REE_2O_3 as well as total ThO_2+UO_2 is given Table 3.

It is understood from the mineral chemistry that there is mutual multiple substitutions amongst Al-Fe, Si-REE-Ca elemental groups. The presence of REE and radioactive elements which controls the strength of halo (in addition to time) is a function of the chemistry of parent hydrotherms as well as the crystallization of associated phases which can act as a sink for them. Apparently this appears to be the reason for the absence of halo and metamictisation in Type 2 allanites which shows an association of phases such as sphene, thorite, bastnesite and apatite.

DISCUSSION

Allanite is known to be a main REE bearing mineral in the uraniferous zones/bands of SSZ and is reported to be associated with uraninite, apatite, monazite, florencite as per published literature (Pal et al, 2011, 2021). Present study brings out a *hitherto unreported spatial association of allanite with thorite (Fig. 4a), uranothorite, monazite (Th rich), apatite along with ilmenite, rutile, fluorite and rare bastnesite, high Th-uraninite, uraninite-ilmenite worm like intergrowth textures suggesting variable physico chemical conditions for their formation.*

It is known that geochemically, under oxidizing conditions U is quite mobile especially in comparison with Th and hence the crystallization of Th poor uraninites signifies conditions of high oxygen fugacity. In SSZ, an earlier reducing event followed by relatively oxidizing event is mentioned following the probe analysis of allanite and its rim in published literature (Pal et al., 2011). Crystallisation of thorite, uranothorite, REE minerals and thorium rich uraninite suggests higher reducing conditions in which separation of U and Th did not take place effectively. In such conditions, presence of complexes like F , CO_3 and Cl , enhances the co mobility of U-Th along with REEs. In this context, the mineral assemblage and subsequent textural studies postulates the possibility of relatively reducing conditions overprinting preexisting oxidizing ones in which Th poor uraninites crystallized earlier. In association with allanites of Type 2 and Type 3 the following observations are made:

1. Presence of rare Th rich uraninite is recently identified in SSZ (Unpublished data of AMD, Kudada and Jaduguda sector, Central SSZ). In Jaduguda uranothorite is found associated with allanite of type 2 and 3.
2. Thorite and uranothorite is found within shear zone but in different spatial levels as compared to uraniferous zones. On a regional scale it appears to be cross cutting the uraniferous bands suggesting later origin. In central sector, high Th value zones occur footwall to uranium bands while in SE sector they occur on the hangwall side.
3. In SSZ, the sheared rocks shows the presence of grains having

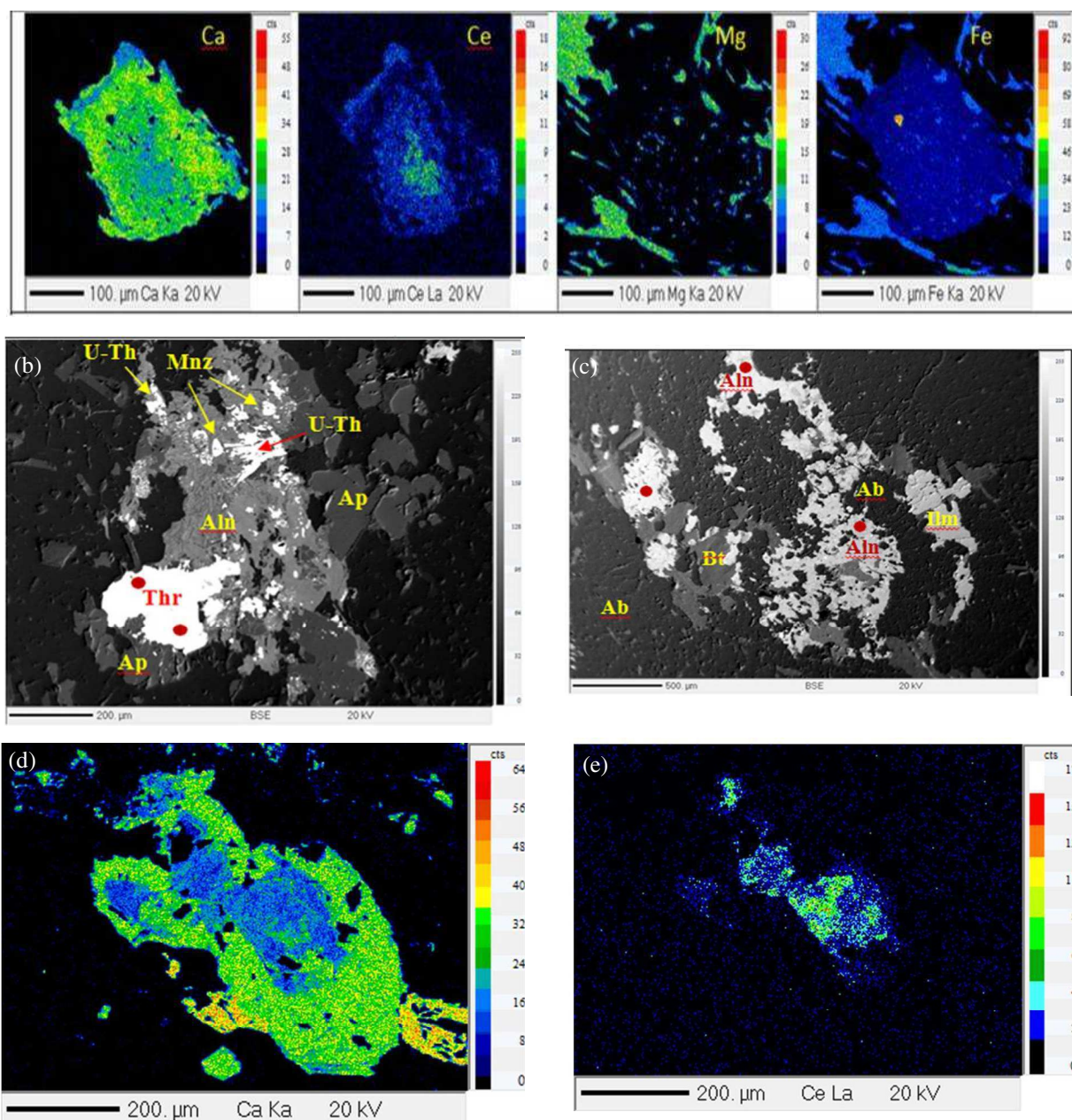


Fig. 3. (a) X-ray scan map of Allanite grains of Type 1a in biotite quartz schist, Jaduguda area showing enrichment of Ce and depletion of Ca in the core. Another similar cycle of Ce enrichment and Ca depletion is seen repeated towards the rim. The Mg and Fe mapping reveals the minute inclusions of phyllosilicates and magnetite suggesting its syn-tectonic growth in the system. (b) BSE image shows presence of two tiny anhedral discrete monazite (Mnz) (ThO_2 rich) inclusions within allanite (Aln) [Type 3a] in association with uranothorite (U-Th). A very coarse grain of thorite (Thr) with irregular margin is also observed in association with apatite (Ap). (c) BSE image of skeletal allanite (Type 3a) in association with albite (Ab), biotite and ilmenite in albite injection, Pathargora. (d) X-ray scan mapping of Type 1a allanite that is rimmed by epidote. The grain shows its close association with apatite (having high Ca values) in biotite schist and inclusions of biotite flakes suggesting its post tectonic growth in Purnapani area. (e) X-ray scan Ce-mapping of Type 1a allanite shows the diffused boundaries suggesting Ce mobility possibly suggesting a high influx of hydrothermal activity.

Table 3. Range of values of selected chemical variables for different types of allanites in SSZ

Allanite type	Type 1a	Type 1a	Type 2a	Type 3a	Type 3a
Area	Jaduguda	Purnapani	Jaduguda	Pathargora	Dumurdiha
Range of REE conc. %	15.97-19.37	21.85-23.63	8.17-15.03	15.88-24.57	21.04-25.92
Range of ($\text{UO}_2 + \text{ThO}_2$)	0.65-1.42	0.00-0.12	bdl	Bdl – 0.93	Bdl – 0.42
CaO	11.45-12.74	11.38-11.44	11.59-17.23	10.59-14.25	8.92-11.36
FeO	8.00-9.85	11.77-13.38	11.77-13.32	10.08-13.06	15.09-16.93
Al_2O_3	13.83-16.12	17.51-19.72	14.88-19.59	15.17-18.94	10.24-13.68
SiO_2	35.95-38.13	27.85-30.44	34.49-38.84	32.01-37.33	28.8-31.99

rutile at the core rimmed by ilmenite along periphery suggesting change in physico chemical environment from oxidizing to reducing (Fig. 4b).

4. Presence of fluorite in the fine fractures and intergranular spaces of metapelites implying F-bearing complexes in the later hydrothermal system (Fig. 4c). Such fluorite bearing horizons show presence of worm like intergrowth of uraninite-ilmenite (Fig. 4d) and neoformed biotite flakes with sagenitic texture suggesting high temperature hydrotherms (Fig. 4e). In high temperature regime Ti is found in significant proportion in biotite which later exsolved to create sagenitic texture. Besides, U-Ti mobility is significant in high temperature conditions. These zones show abundance of type- 3 allanites.

5. Replacement of apatite by microcrystalline calcite (Fig. 4f) and presence of bastnesite in the vicinity puts forth a possible local presence of carbonate bearing complexes in hydrothermal fluids associated with REE and type 2 allanites as observed in the samples.

On the basis of such mineral assemblages and the inter relationship between the phases within the broad radioactive zone of Singhbhum Shear Zone, it can be suggested that the hydrotherms carrying Th, REE, F, CO_3 complexes with relatively reducing conditions overprinted the Th poor uraninite metallogeny.

The occurrence of different types of allanites classified on the basis of metamictisation, haloes and textural features suggests varying physico chemical conditions of their crystallisation. This, along with

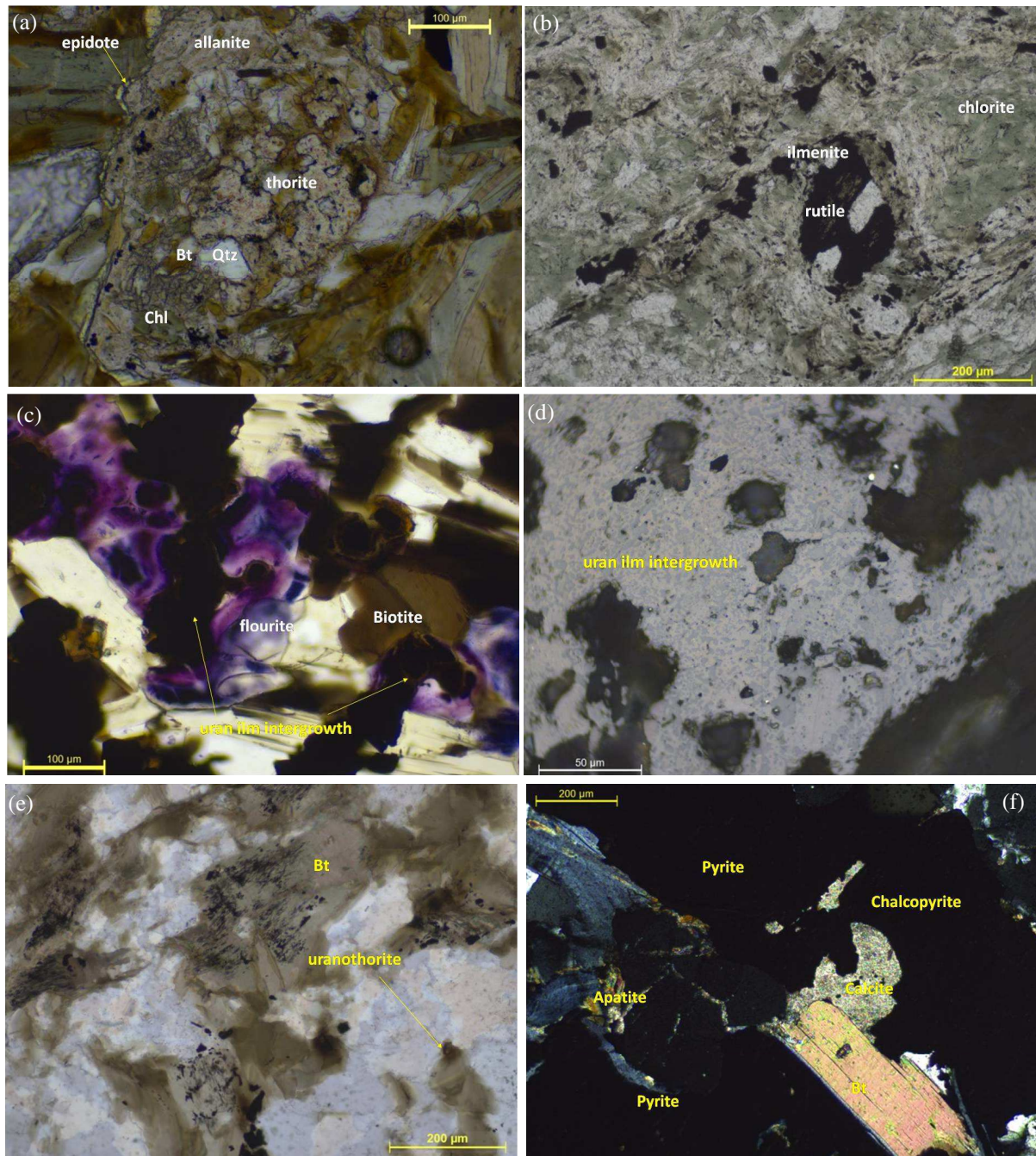


Fig. 4. (a) Thorite with inclusions of quartz magnetite and phyllosilicates gradually transforming to allanite. Pathargora (TL, air, 1n). (b) Rutile at the core replaced by ilmenite showing porphyroclastic texture in quartz chlorite schist, Turamdih (TL, air, 1n). (c) Uraninite intergrown with ilmenite in association with muscovite-biotite-quartz schist, Pathargora (TL, air, 1n). (d) Uraninite (dark grey) forming a typical 'worm' like morphology with ilmenite. (e) Neoformed biotite exhibiting sagenitic texture i.e. exsolution flakes of ilmenite within biotite-quartz-schist, Jaduguda, (TL, air, 1n). (f) Apatite replaced by microcrystalline calcite in feldspathic schist, Pathargora, (TL, air, 2n).

the EPMA data on various allanites and its association with other REE-Th-U bearing phases suggests that dominant formation of allanite occurred in a syn – to post- tectonic manner in an environment of relatively higher temperature and relatively decreased oxygen fugacity. The categorization of allanites resulted thus not only because of different generations but rather due to variation in mineral chemistry as a function of co-crystallised assemblages like apatite, monazite, uranorthorite, thorite, bastnesite.

The available geochronological data places earliest allanite and monazite at 1.88Ga, earliest uraninite at 1.82 Ga, earliest apatite and magnetite at 1.95Ga and sulphides at 1.766 Ga (Pal et al., 2011, 2021, Johnson et al., 1993). Minerals such as apatite, magnetite and uraninite show multiple textural and morphological patterns suggesting their pre- to post- tectonic formations in various episodes. However as the dominant texture of allanite in SSZ is of post tectonic (with very rare syn tectonic) nature as revealed in the present study, the available age for the initial formation of allanite (Pal et al, 2011, 2021) as 1.88 Ga has wide implications. It points to a possibility that since allanites being the most syn tectonic are formed around 1.88 Ga, the initiation of the shearing must have occurred prior to this period. Attention is also invited here on the fact that the oldest age (1.8 Ga) is analyzed on a uraninite grain showing subhedral nature (Pal, et al., 2013) which is quite unusual for the grains supposedly present in the mylonitised host rocks, it can be explained if we attribute that shearing occurred prior to 1.8 Ga. Therefore 1.88 Ga analysed on allanite and monazite in the published literature may be considered the age of shearing or at least as a waning stage of the shearing process in SSZ. At the same time, as the allanite mineral system in itself is open, this has to be still an under estimation of age only.

The assumption made above also follows that the shearing span is much prolonged (1.88 Ga to 1.6 Ga which continued till 1.0 Ga during which the basin closure is envisaged) than what was earlier considered and hence cyclic changes in physico chemical conditions from reducing to oxidizing and again to reducing are not unexpected. In the present study on allanites and its associated mineralogy, it seems that apart from the well-known relatively oxidizing conditions responsible for the majority of uraninite formation, there is a more reducing event with higher temperature resulting in REE-Th mobilization in SSZ manifested in the form of formation of thorite, uranorthorite, allanite, monazite, apatite, fluorite and bastnesite indicating a relatively reducing hydrothermal conditions occasionally marked by the presence of fluorine and carbonate complexes. The preexisting uraninite might have contributed to U also to this later event and therefore the system as a whole was highly open to elemental exchanges. This clearly cautions us against the pitfalls in using chemical ages in SSZ which in this case is bound to be an under estimation.

CONCLUSIONS

Allanite is observed as the ubiquitous REE bearing mineral found within the mylonitised metapelites of Singbhum Shear Zone.

Allanites in SSZ can be categorised into three major categories and total six subtypes on the basis of the presence or absence of

metamictisation, relative strength (darkening) of pleochroic halos, textural relationship with host rock's mylonitic foliation. The broad categorization based on the optical properties is corroborated by the variability in its association with other minerals as well as its mineral chemistry.

Multiple generations of allanite are possible in SSZ and there seems to be relatively reducing hydrothermal conditions in which Th-U-REE fractionating might not have been effective resulting in the assemblages of allanite-thorite-Th bearing uraninite-Th bearing monazite-uranorthorite.

Textural evidence of post tectonic occurrence for majority of the allanites are observed in the present study. Considering the reported age of allanite as 1.8Ga, the waning stages of shearing event in SSZ could be considered 1.8Ga.

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