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Allanite-britholite bearing migmatite gneiss-Amet Granite and intrusive syenite-monzonite rocks of SW Rajasthan, India, and their REE potential

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Allanite and REE bearing minerals are primum fama report from migmatite gneisses, plutonic Amet granite and intrusive alkaline rocks of Rajasthan, and these minerals are important for establishing REE deposit. Allanite taken from host migmatite and granite have been analysed along with host rocks containing REE minerals, both of which contain appreciably high amount of Σ REE and Th. Allanite phases identified are CaO and Ce₂O₃ rich with positive correlation of silica and alumina. As silica proportion decreases and Σ REE increases, allanite changes to britholite and thorite indicating a role of fluid in its crystallization. The chondrite normalized REE in migmatite gneiss and allanite mineral is compatible indicating a primary nature of allanite. The carrier of REE minerals is envisaged as the alkaline intrusives which deposited their REE minerals during ascent of magma from deeper source. Chemico-mineralogical study of Allanite and its hosts suggest possible reaction between a REE bearing fluid rich in P and F brought up by alkaline rocks, and the silicate minerals, mainly biotite and hornblende of the migmatite gneiss and Amet granite. The allanite in migmatite gneiss and granite may prove to be a sumptuous deposit of REE minerals in India, and similar terrains elsewhere.

Introduction

The NW Indian craton of Rajasthan, comprising northwestern edge of the Indian shield consists predominantly of gneiss-granite-amphibolite-metasedimentary rock association of Archaean age, referred to as the Banded Gneissic Complex or BGC (Gupta, 1934; Heron, 1953; Raja Rao, 1970). The gneissic complex served as basement over which the Proterozoic cover rocks of Aravalli and Delhi Supergroup, along with the platformal sediments of Vindhyan Supergroup, were deposited with profound unconformities (Heron, op.cit.; Raja Rao et al., 1971; Prasad, 1984; Sinha Roy, 2000). The BGC basement has stabilized at

about 2500 Ma (Wiedenbeck et al., 1996).

During Archaean-Proterozoic times, the Rajasthan craton witnessed formation of greenstone sequences and granulite gneisses (Mohanty and Guha, 1995; Guha, 2018). The deformational and metamorphic episodes led to crystallisation of migmatite gneisses with several episodes of anatexis melting, and emplacement of several intrusive magmatic plutons (Guha et al., 2018). The greenstone sequences are reworked in later deformations and are a storehouse of several known Pb-Zn-Cu-Au-U deposits in India, e.g., Kayar-Ghugra Pb-Zn deposit, Pur Banera Pb-Zn-Cu deposit (Oza et al., 2017), Agucha Zn-Pb deposit (Gandhi, 2003; Fareeduddin et al., 2014), Rohil (Khetri fold belt) U deposit (Nanda et al., 2009), Rare metal and REE deposit in BGC terrain of Bichun-Nayagaon (Shaji et al., 2011; Yadav et al., 2015). Occurrence of rare minerals, such as, Ecandrewsite has recently been reported from the Khetri fold belt of Rajasthan having its significance in REE and Au-Cu-U search (Neogi et al., 2017).

During course of our investigations on Archaean terrane of SW Rajasthan, India, we discovered *primum fama* widespread occurrence of allanite, which is one of the major REE bearing mineral, around Borana, Mad, Rama and Tikar areas of Rajsamand district of Rajasthan State, India (Fig. 1). In view of present worldwide demands of REE, the detail study of REE bearing minerals is highly required. This new find of REE bearing minerals in migmatite in recoverable resources will be a new emerging domain in India. It was, therefore, decided to study the allanite composition to know the concentration of different REE within it and also to compare the allanite composition of present finding with the composition of allanite commonly occurring worldwide. Allanite (Ca,REE)₂(Fe,Al)₃Si₃O₁₂[OH], is a REE enriched mineral of epidote group, is being first time reported from the migmatite gneisses (Fig. 1b) and their associate alkaline intrusive bodies of Syenite/alkali feldspar syenite (Fig. 1a), and granite, referred to as Amet Granite, in the study area. REE deposits of the world are mainly found in carbonate, as in Africa; Fe-carbonate rocks, or clays as in China deposits (Harmer and Nex, 2016). In Bayan Obo, Inner Mongolia, REE ore in silicate rock is found and the economically exploited minerals are bastnaesite and monazite. Other considerable occurrences of rare earth

Occurrence of REE bearing allanite with its alteration to britholite, thorite along with zircon, titanite, apatite in basement rock migmatite

gneiss (silicate rock) intruded by syenite (alkaline rock), and plutonic Amet Granite in cratonic part of Rajasthan, is unique in its rarity. This new find of allanite, in recoverable profuse quantity, may turn up into a mineable deposit of REE in widespread migmatite gneiss–granite complexes of Rajasthan and elsewhere in similar cratonic terranes of India and the world. In present study, authors tried to find out the behaviour of different rare earth elements within allanite and its host rock; thereby highlighting its origin during possible magmatic crystallisation. The chondrite normalised pattern of Σ REE in allanite vis-a-vis the chondrite normalised pattern of Σ REE in rocks containing these allanite are compared and a compatible relation of Σ REE of rock vis-a-vis the mineral allanite contained within it is observed; indicating allanite of primary magmatic origin (Fig. 20, see also at p.15 line 373–376). Since allanite crystallised in later period of magmatic crystallisation, the compositional variation in allanite REE and host REE is imminent.

Aim of the paper is to establish behaviour of REE in allanite, and the relation between allanite and the host rocks through detailed chemico-mineralogical study of both REE bearing allanite and allanite bearing host rocks, leading to establishment of recoverable REE deposit in migmatite cratonic terrain of Rajasthan, India.

Geological Setting

The NW Indian craton of Rajasthan (also known as Rajasthan craton or Aravalli craton), made up mostly of the Banded Gneissic Complex (BGC), is flanked on the west by the Proterozoic fold belts of the Aravalli and Delhi Supergroup rocks (Heron, 1953) that has attracted the attention of scientists because of its heterogeneous lithological assemblages, tectonic stacking, and early Archaean to mid Proterozoic complex magmatic–metamorphic history. The BGC has been reclassified as the Bhilwara Supergroup (BSG, Raja Rao, 1970; Gupta et al., 1997) which is made up of lithologies of granulite facies Sandmata Complex (SC, 2.29–1.72 Ga; Sarkar et al., 1989; Buick et al., 2006), amphibolite facies Mangalwar Complex (MC, 3.3–2.8 Ga; Gopalan et al., 1990) and greenschist facies Hindoli Group (younger than 2.52 Ga; Dey et al., 2018). The geology of the BSG has been worked out in detail by Guha and Bhattacharya (1995), Mohanty and Guha (1995), Gupta et al. (1997), Chakrabarti et al. (2004), Guha (2018), and specially the geological and petrological details of the migmatite gneisses and its enclosing granite pluton (Amet Granite) north of the present granite pluton (Amet Granite) is dealt in detail by Guha et al. (2018).

Rock Types Containing Allanite

Migmatite gneiss (protolith age 2.75–2.698 Ga, Dharma Rao et al., 2011) is a mixed rock and consists of mainly two parts, leucosome and palaeosome. Leucosome consists of mainly quartz and feldspar (K-feldspar and plagioclase), where as paleosome consists of biotite, amphibole $\pm$ pyroxene $\pm$ garnet. Large body of amphibolite occurs within migmatite gneiss with diffuse boundary near Mad, Rama and Borana areas (Fig. 1). Dispersed grains of primary allanite with light brown alteration rims are found in migmatite gneisses around Borana-Rama-Galyari areas (Fig. 1b). The 1–2 mm to 10 mm size grains of allanite occur along the foliation defined by biotite–muscovite of migmatite gneiss, lying either along the foliation or athwart to it, and

many times pushing across the foliation. The light brown alteration rims around these allanite grains are 1 to 3 mm in thickness.

Amet Granite (1870 ± 200 Ma, Chaudhary et al., 1984) covers large part of the mapped area around Mad (Fig. 1). The Amet Granite is intrusive within the migmatite rock and is considered a product of partial melting of migmatite gneisses of the Mangalwar Complex (Guha, 2018; Guha et al., 2018). This plutonic body is semi-circular with moderately developed foliation in the core part. The peripheral part of the Amet Granite is sheared with development of mylonite zone where garnet and the feldspar phenocrysts are extremely sheared. The western part of this granite body is incised by a longitudinal northeasterly trending major shear zone (Fig. 1). The Amet Granite is medium to coarse grained and is tonalitic in composition, comprising of plagioclase, quartz with small amount of alkali feldspars and hornblende and subordinate amount of biotite. Primary, discrete and euhedral crystals of allanite are seen within this granite.

Amphibolite (2.83 ± 0.05 Ga, Gopalan et al., 1990) occurs as bands of different size and shape within the Amet granite and migmatite gneiss. Some of the amphibolite bands are large enough to be mapped in the present scale. Near Borana and Rama, thick amphibolite bands are exposed which are highly deformed and show multiple folding (Fig. 1). It is a medium grain, dark colour rock consisting of amphibole as dominant mineral with feldspar and minor biotite, apatite, sphene, opaque minerals.

At Chatrawan mata temple, near Borana, younger intrusive plutonic bodies identified as syenite-alkali feldspar syenite (Fig. 1a) are found associated with amphibolite. Nevertheless, these syenite-alkali feldspar syenite are intrusive within the host migmatite gneiss in which amphibolite has intruded migmatite gneiss syntectonically and is folded along with it (Fig. 1). These younger intrusive alkaline plutonic bodies are nonfoliated and extend in the east-west direction which are also marked with numerous criss-cross epidote veins of varying size having dispersed allanite grains. These allanite grains are dark in colour with conchoidal fractures and light brown haloes around it.

Small unmappable intrusive plutonic body of alkali feldspar rich rock monzonite was identified as intrusive body within the Amet Granite near west of Mad. This monzonite is extending in the east-west direction showing intrusive nature with the Amet Granite (Fig. 1c). The monzonite and syenite-alkali feldspar syenite are hitherto not reported from this BSG terrain. Therefore, it is clear from field inter-relations that the syenite-alkali feldspar syenite and the monzonite are intrusive both within the migmatite gneiss and the Amet Granite respectively and its relation with amphibolite is inferred. As amphibolite is syntectonically emplaced within migmatite gneiss and is folded with migmatite, whereas the alkaline rocks are undeformed, it can be said that the alkaline rocks are the latest in its emplacement in the area. Isotopic ages of alkaline rocks are not yet determined.

Dataset and Sample Collection

Samples were collected from the different part as well as different phases of the migmatite gneiss, granites and also from the associated late acidic intrusions to examine mineralogical and chemical variations within the same pluton and also between different granitic phases. Fresh samples containing megascopically visible allanite grains in rock were

Table 1. Whole rock and trace element chemical analysis data of Amet Granite

Sample No.	Amet Granite							
	PCS- 01/08	PCS- 06/08	PCS- 22/08	PCS- 23/08	PCS- 24/08	PCS- 25/08	PCS- 26/08	PCS- 27/08
SiO ₂	69.49	60.1	61.14	59.46	58.9	61.23	58.89	57.19
Al ₂ O ₃	13.86	14.12	13.56	13.74	13.55	13.14	13.52	13.37
Fe ₂ O ₃	1.86	6.2	6.45	6.37	7.08	6.26	7.44	8.62
MnO	0.02	0.04	0.07	0.08	0.09	0.07	0.08	0.1
MgO	0.13	2.48	1.19	1.7	1.47	1.23	2.18	1.68
CaO	1.19	4.31	2.65	3.26	3.84	2.79	3.73	3.78
Na ₂ O	2.58	2	1.83	1.93	2.14	1.94	1.87	2.3
K ₂ O	5.71	2.62	5.99	5.62	4.79	5.8	4.53	4.97
TiO ₂	0.03	1.18	0.88	0.85	1.05	0.87	1.2	1.31
P ₂ O ₅	0.01	0.02	0.34	0.37	0.48	0.35	0.56	0.56
Ba	55	1170	1860	1344	1503	1486	1241	1925
Co	7	31	27	27	30	28	27	26
Cr	<15	58	<15	28	<15	16	45	<15
Cu	<1	8	10	12	10	12	20	16
Ga	25	23	18	18	18	18	21	23
Nb	56	15	33	25	26	32	34	62
Pb	44	9	19	23	19	31	25	16
Rb	455	93	188	168	120	171	133	180
Sc	<3.5	10	10	7	9	7	13	19
Sr	17	260	243	216	267	213	242	267
Th	59	<4	11	7	8	15	<4	24
V	<20	222	60	72	81	63	113	75
Y	260	<5	39	41	43	45	49	57
Zn	11	48	63	59	64	67	87	107
Zr	142	357	427	287	357	413	333	674
Ni	6	31	10	15	7	11	17	3
Be	1.73	3.21	2.19	2.28	1.88	2.41	10.46	2.79
Ge	1.7	1.73	1.42	1.44	1.49	1.45	1.46	1.4
Y	209.3	82.33	56.56	54.39	55.25	58.12	17.17	53.02
Mo	<0.50	1.03	0.98	1.04	0.7	1.13	<0.50	0.64
Sn	2.88	2.2	1.13	1.24	1.2	1.01	1.01	2.31
La	57.37	297.79	121.83	126.19	103.51	154.93	34.28	189.8
Ce	113.9	460.4	202.4	211.7	195.9	258.6	60.7	292.4
Pr	13.58	48.56	25.56	25.05	22.06	33.07	6.08	33.91
Nd	56.31	167.62	99.14	95.49	87.62	126.79	22.75	118.22
Sm	17.23	20.44	15.04	14.03	13.43	18.78	5.27	14.84
Eu	0.43	2.67	5.63	4.68	4.37	5.93	1.01	2.38
Gd	13.51	22.52	12.86	12.79	11.03	15.81	4.39	14.4
Tb	4.78	3.52	2.4	2.24	2.15	2.67	1.09	2.4
Dy	39.22	15.53	11.18	10.45	10.57	11.29	4.81	10.42
Ho	9.31	3.22	2.31	2.19	2.19	2.27	0.65	2.13
Er	24.84	10	6.7	6.54	6.13	7.04	1.35	6.49
Tm	4.69	1.28	0.87	0.86	0.8	0.87	0.13	0.82
Yb	30.74	8.6	5.92	5.64	5.36	5.88	1.29	5.59
Lu	4.47	1.17	0.8	0.78	0.71	0.8	0.17	0.77
Hf	10.56	14.31	15.09	16.99	12.83	22.57	10.03	12.17
Ta	2.37	1.82	1.51	1.6	1.38	2.13	0.86	0.99
W	4.7	0.95	5.52	1.74	2.07	2.65	5.91	0.85
U	10.84	3.53	0.74	1.2	<0.50	1.75	<0.50	2.4

Table 2. Whole rock and trace element chemical analysis data of migmatite, syenite and amphibolite

Sample No.	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MnO	MgO	CaO	Na ₂ O	K ₂ O	TiO ₂	P ₂ O ₅	Ba	Co	Cr	Cu	Ga	Nb	Pb	Rb	Sc	Sr
PCS-11/08	63.24	14.03	4.72	0.06	1.37	2.99	2.97	4.32	0.62	0.24	895	22	18	8	19	36	26	201	6	204
PCS-20/08	57.68	17.72	3.45	0.03	0.07	5.17	6.01	3.21	0.54	0.16	659	24	29	<1	21	71	21	83	5	600
BRS-07/08	68.58	13.36	3.46	0.04	0.45	1.44	2.24	5.67	0.33	0.08	899	42	<15	2	18	36	34	181	<3.5	115
BRS-09/08	57.18	18.4	3.75	0.03	0.02	6.29	4.37	5.52	0.45	0.21	814	18	<15	6	36	90	36	203	11	847
BRS-10/07	59.7	18.59	3.57	0.03	0.08	5.64	7.13	2.26	0.37	0.16	585	29	22	<1	28	42	18	47	5	797
BRS-11/08	47.5	11.48	14.49	0.21	6.51	10.76	2.09	0.42	0.98	0.11	139	57	174	108	22	14	<2	19	48	100
BRS-12/07	68	12.14	2.33	0.03	0.13	4.74	0.4	7.35	0.27	0.08	889	29	<15	3	22	65	26	230	<3.5	351
BRS-13/08	70.97	12.64	2.09	0.03	0.15	2.58	1.46	7.14	0.22	0.07	883	38	<15	3	15	48	36	249	<3.5	196
BRS-14/08	74.12	13.71	0.41	0.02	0.09	0.45	2.9	6.87	0.05	0.02	421	34	<15	<1	10	20	25	212	<3.5	100
BRS-15/08	69.34	14.26	1.65	0.02	0.32	2.26	2.4	7.05	0.27	0.08	744	42	<15	<1	17	27	25	229	<3.5	176
	Th	V	Y	Zn	Zr	Ni	Be	Ge	Y	Mo	Sn	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy
PCS-11/08	37	36	62	56	376	25	3.40	1.60	68.38	1.23	2.10	193.38	303	32.89	118.15	14.82	3.84	14.13	2.64	12.98
PCS-20/08	153	<20	120	<10	438	14	2.24	1.41	55.89	0.80	1.26	113.33	200.08	23.48	89.23	13.50	4.39	11.47	2.19	10.61
BRS-07/08	114	<20	78	23	310	7	2.92	1.7	81	1.61	2.35	600.48	864.51	88.83	278.42	28.84	2.19	36.14	4.85	17.23
BRS-09/08	246	<20	165	<10	567	8	4.46	3.41	138.63	4.8	4.79	467.18	823.93	76.18	254.48	35.61	2.95	32.91	5.23	24.85
BRS-10/07	168	<20	107	<10	373	9	5.17	3.15	117.33	2.78	5.28	380.59	634.33	62.86	212.1	30.81	2.37	26.98	4.4	20.54
BRS-11/08	<4	315	25	107	51	77	0.27	1.38	28.24	1.56	2.68	3.78	10.51	1.4	7.45	2.37	0.86	1.43	0.55	4.75
BRS-12/07	139	<20	123	<10	425	5	1.69	2.6	110.3	1.04	4.63	605.75	949.95	83.97	290.63	35.81	2.34	39.11	5.43	20.47
BRS-13/08	112	<20	102	37	343	5	1.07	1.99	101.33	0.93	2.91	663.07	880.57	94.86	298.53	33.5	2.24	40.12	5.33	19.62
BRS-14/08	36	<20	19	<10	96	6	1.11	1.11	28.5	0.5	2.83	25.3	78.59	5.75	20.75	4.17	0.95	3.52	0.97	6.62
BRS-15/08	34	<20	58	<10	214	10	2.76	1.95	81.14	0.79	4.41	155.5	276.47	27.9	99.05	13.29	2.27	13.39	2.49	13.13
	Ho	Er	Tm	Yb	Lu	Hf	Ta	W	U	ΣREE (ppm)										
PCS-11/08	2.75	7.83	1.08	7.13	0.95	16.75	1.90	2.91	2.29	715.57										
PCS-20/08	2.23	6.43	0.89	5.73	0.78	15.90	1.55	1.38	0.99	484.35										
BRS-07/08	3.45	12.28	1.31	8.85	1.16	16.08	1.82	155.67	4.13	1948.54										
BRS-09/08	5.26	16.85	2.55	16.99	2.39	20.42	3.42	51.12	11.31	1767.35										
BRS-10/07	4.25	13.57	1.96	13.59	1.95	18.1	3.31	53.09	10.41	1410.29										
BRS-11/08	1.09	2.82	0.5	3.3	0.48	2.08	0.09	47.77	<0.50	41.30										
BRS-12/07	4.44	14.81	1.9	13.22	1.84	15.86	3.8	128.08	4.93	2069.67										
BRS-13/08	4.03	14.36	1.69	11.62	1.68	12.55	4.74	122.39	5.19	2071.20										
BRS-14/08	1.42	3.48	0.55	3.56	0.49	6.28	2.75	110.54	4.12	156.12										
BRS-15/08	2.97	8.83	1.38	9.43	1.29	10.27	2.07	133.78	3.61	627.40										

Migmatite: BRS-14, BRS-15, PCS-11/8, Syenite: PCS 20/8, BRS-7/8, BRS- 9/8, BRS-10/8, BRS-12/8, BRS-13/8 Amphibolite: BRS-11/8.

Major oxides values are in %; REE and trace element values are in ppm.

Table 3. REE and silicate analysis chemical data (EPMA) of five samples

35-8 (Migmatite)											
Sample Name											
Point No.	1 / 1	2 / 1	4 / 1	5 / 1	11 / 1	7 / 1	12 / 1	8 / 1	9 / 1	10 / 1	14 / 1
Na ₂ O	0.02	0.03	0.15	0.11	0.03	0	0	0.03	0.06	0.05	0.04
MgO	0.31	0.34	0.18	0.31	0.57	0.16	0.21	0.02	0.12	0.04	0.14
CaO	11.1	11.6	14.2	12	9.58	7.65	7.22	0.22	27.5	28.4	27.67
MnO	0.29	0.33	0.46	0.15	0.46	0	0	0.02	0.15	0.11	0.14
FeO	15.4	14.9	11.6	8.99	15.67	1.22	1.92	0.43	2.06	1.21	2.15
SmO	0.21	0.15	0.34	0.15	0.19	0.7	0.67	0	0.02	0.03	0.05
EuO	0	0	0	0	0	0	0	0.03	0.02	0.01	0
PbO	0.09	0.13	0.05	0.07	0.07	0	0.01	4.81	0	0.01	0.03
Al ₂ O ₃	14.3	14.8	16.9	17.8	12.9	6.56	6.7	0.02	5.73	3.54	5.81
La ₂ O ₃	8.94	8.41	6.3	4.38	9.68	16.82	17.1	0.05	0	0	0
Ce ₂ O ₃	11.1	10.7	8.44	5.25	12.14	24.51	22.61	0.04	0.4	0.09	0.33
Pr ₂ O ₃	1.26	1.18	0.88	0.46	1.11	2.34	1.93	0	0.11	0	0
Nd ₂ O ₃	2.38	2.32	2.11	1.14	2.41	7.03	6.87	0.09	0.34	0.02	0.39
Gd ₂ O ₃	1.2	1.13	0.92	0.54	1.15	2.86	2.7	0.14	0.17	0	0.15
Tb ₂ O ₃	0	0	0	0	0	0	0	0	0	0	0
Dy ₂ O ₃	0.12	0.11	0.05	0	0.05	0.27	0.31	0.29	0.23	0.17	0.12
Ho ₂ O ₃	0.03	0	0	0	0	0.06	0.09	0	0.11	0	0.11
Er ₂ O ₃	0	0	0	0	0	0.03	0.02	0	0.12	0.08	0
Tm ₂ O ₃	0	0	0	0	0	0.01	0.02	0	0.06	0.07	0.04
Yb ₂ O ₃	0.13	0.2	0	0	0	0	0	0	0.2	0.11	0.07
Lu ₂ O ₃	0.09	0.01	0	0.02	0.04	0.07	0	0.04	0.04	0.05	0.12
SiO ₂	30.5	31.7	33.2	39.6	29.95	10.31	10.01	18.48	30.6	30.3	30.59
TiO ₂	0.81	0.89	0.35	0.21	1.28	0.39	0.41	0.14	28.8	33.7	29.04
ZrO ₂	0	0	0	0	0	0	0	0	0	0	0
ThO ₂	1.5	1.81	2.18	0.8	1.49	3.58	3.15	70.11	0.08	0	0.07
UO ₂	0	0.09	0.03	0.14	0.01	0.13	0.23	0	0.04	0.01	0.01
P ₂ O ₅	0	0	0	0	0	0	0	0	0	0	0
Total	99.6	101	98.4	92.1	98.78	84.7	82.18	94.96	96.9	97.9	97.07
Comment	allanite	allanite	allanite	allanite	allanite	britholite	britholite	thorite	titanite	titanite	titanite
PCS 1-8 (Amet Granite)											
Sample Name											
Point No.	1 / 1	2 / 1	4 / 1	5 / 1	6 / 1	7 / 1	8 / 1	9 / 1	10 / 1	12 / 1	11 / 1
Na ₂ O	0.03	0.01	0.02	0	0.04	0.04	0.02	0.01	0.02	0.02	0.01
MgO	0.37	0.15	0.27	0.18	0.35	0.28	0.13	0.24	0.09	0	0.01
CaO	14.3	19.4	18.1	19.8	15.3	15.4	19.7	18.9	20.6	27.8	23.3
MnO	0.31	0.19	0.24	0.28	0.28	0.19	0.19	0.15	0.26	0.13	0.17
FeO	13.2	12.1	12.3	12.3	12.5	12.9	12	12.1	11.8	1.09	12.2
SmO	0.25	0.14	0.19	0.09	0.46	0.26	0.17	0.09	0.05	0.07	0
EuO	0	0	0	0.09	0	0	0	0	0.06	0.04	0.1
PbO	0	0	0.02	0.01	0.02	0	0	0.04	0.07	0	0
Al ₂ O ₃	18.5	21.5	20.2	21.2	20.8	19.3	22	21.8	21.9	2.13	23.4
La ₂ O ₃	6.12	2.37	2.22	2.18	4.01	4.06	2.12	3.78	1.54	0	0
Ce ₂ O ₃	8.75	3.24	4.27	3.09	7.4	7.48	3.05	4.38	2.09	0.13	0.04
Pr ₂ O ₃	0.93	0.28	0.59	0.38	1.1	0.97	0.16	0.34	0.06	0	0
Nd ₂ O ₃	2.87	1.54	2.17	1.27	3.27	3.27	1.41	1.09	0.78	0.12	0
Gd ₂ O ₃	0.78	0.32	0.54	0.36	0.79	1.03	0.4	0.33	0.38	0.02	0
Tb ₂ O ₃	0	0	0	0	0	0	0	0	0	0	0
Dy ₂ O ₃	0.08	0.09	0.15	0	0.13	0.1	0.08	0	0.2	0	0.18
Ho ₂ O ₃	0.03	0.01	0.03	0.02	0.06	0.08	0	0	0	0.07	0

Table 3. Continued

PCS 1-8 (Amet Granite)											
Sample Name											
Point No.	1 / 1	2 / 1	4 / 1	5 / 1	6 / 1	7 / 1	8 / 1	9 / 1	10 / 1	12 / 1	11 / 1
Er ₂ O ₃	0	0	0.02	0	0	0	0	0	0	0.11	0
Tm ₂ O ₃	0	0.06	0	0	0	0	0	0	0	0	0
Yb ₂ O ₃	0.13	0.07	0.05	0	0	0	0	0.14	0.07	0	0.03
Lu ₂ O ₃	0	0	0.1	0.04	0	0	0.02	0.01	0	0.03	0
SiO ₂	33.2	35.1	34	35	36.1	33	36	35.2	35.6	29.6	36.9
TiO ₂	0.18	0.17	0.19	0.2	0.17	0.16	0.14	0.16	0.12	35	0.1
ZrO ₂	0	0	0	0	0	0	0	0	0	0	0
ThO ₂	0.14	0.12	0.04	0.06	0.04	0.03	0.05	0.09	0.05	0	0
UO ₂	0.05	0	0	0	0.02	0.06	0.04	0.09	0	0	0.01
P ₂ O ₅	0	0	0	0.01	0	0.02	0	0.01	0.01	0.02	0
Total	100	96.9	95.6	96.5	103	98.6	97.7	98.9	95.8	96.4	96.4
Comment	allanite	allanite	allanite	allanite	allanite	allanite	allanite	allanite	allanite	allanite	epidote
55B-8 (syenite/alkali feldspar syenite)											
Sample Name											
Point No.	2 / 1	5 / 1	7 / 1	1 / 1	3 / 1	4 / 1	8 / 1	6 / 1			
Na ₂ O	0.45	0.03	0.00	0.07	0.13	0.06	0.03	0.00			
MgO	0.28	0.01	0.03	0.10	0.16	0.11	0.09	0.01			
CaO	11.99	55.54	55.86	7.13	8.42	26.79	27.14	0.00			
MnO	0.27	0.11	0.01	0.00	0.00	0.21	0.20	0.00			
FeO	10.03	0.00	0.04	4.77	6.02	1.82	1.79	0.11			
SmO	0.26	0.00	0.02	0.67	0.83	0.00	0.00	0.04			
EuO	0.00	0.00	0.00	0.00	0.00	0.06	0.05	0.00			
PbO	0.06	0.00	0.00	0.04	0.06	0.01	0.06	0.05			
Al ₂ O ₃	17.17	0.00	0.00	8.71	8.92	8.46	8.25	0.01			
La ₂ O ₃	4.45	0.03	0.01	13.24	10.10	0.00	0.00	0.00			
Ce ₂ O ₃	6.97	0.01	0.01	18.22	16.00	0.14	0.09	0.03			
Pr ₂ O ₃	0.78	0.00	0.00	2.11	2.02	0.00	0.00	0.00			
Nd ₂ O ₃	1.76	0.00	0.09	5.50	5.29	0.00	0.01	0.03			
Gd ₂ O ₃	1.05	0.00	0.05	2.13	2.12	0.15	0.00	0.00			
Tb ₂ O ₃	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00			
Dy ₂ O ₃	0.47	0.26	0.00	0.35	0.46	0.33	0.22	0.14			
Ho ₂ O ₃	0.08	0.00	0.00	0.12	0.11	0.00	0.09	0.00			
Er ₂ O ₃	0.00	0.14	0.00	0.00	0.09	0.07	0.17	0.00			
Tm ₂ O ₃	0.03	0.04	0.00	0.19	0.19	0.00	0.00	0.13			
Yb ₂ O ₃	0.06	0.00	0.00	0.00	0.12	0.23	0.19	0.13			
Lu ₂ O ₃	0.00	0.00	0.00	0.00	0.00	0.09	0.05	0.00			
SiO ₂	34.79	0.08	0.10	17.60	20.02	29.83	30.38	31.18			
TiO ₂	0.33	0.02	0.02	0.18	0.25	24.64	25.43	0.03			
ZrO ₂	0.00	0.00	0.00	0.00	0.00	0.00	0.00	59.99			
ThO ₂	1.77	0.00	0.03	3.56	5.77	0.00	0.05	0.08			
UO ₂	0.08	0.01	0.01	0.06	0.13	0.04	0.00	0.09			
P ₂ O ₅	0.00	38.40	37.72	0.00	0.00	0.00	0.00	0.35			
Total	93.13	94.68	94.00	84.75	87.21	93.04	94.29	92.40			
Comment	allanite	apatite	apatite	britholite	britholite	titanite	titanite	zircon			

chosen and thin polished sections were prepared for EPMA studies. Five thin polished sections of allanite bearing migmatite gneiss (1 no.), Amet granite (2 no.) and syenite-alkali feldspar syenite (2 no.) were studied for their silicate and REE content and analysis of mineral

phases (Table 3). Cation proportions of the minerals studied (five samples) are given in Table 4 and mineral formula calculated on the basis of 13 O for allanite for the same five samples is given in Table 5. Total 18 rock samples were collected for silicate and REE analysis

Table 3. Continued

Sample Name	20-8 (syenite/alkali feldspar syenite)						
Point No.	1 / 1.	2 / 1.	5 / 1.	3 / 1.	4 / 1.	6 / 1.	
Na ₂ O	0.01	0.02	0.03	0.1	0.41	0.07	
MgO	0.17	0.18	0.07	0.96	0.01	0.09	
CaO	13.3	10.05	15.66	0.15	0.62	27.51	
MnO	0.37	0.44	0.49	0.08	0.08	0.22	
FeO	13.02	14.7	12.23	1.56	0.5	1.3	
SmO	0.23	0.33	0.21	0	0.01	0.08	
EuO	0	0	0	0.1	0	0.08	
PbO	0.07	0.03	0.11	3.94	3.35	0	
Al ₂ O ₃	18.57	15.81	20.44	1.7	0.15	7.34	
La ₂ O ₃	5.8	8.53	3.93	0.09	0	0	
Ce ₂ O ₃	8.27	11.97	5.49	0.01	0	0.09	
Pr ₂ O ₃	0.66	1.31	0.64	0	0.19	0	
Nd ₂ O ₃	2.58	3.36	1.85	0	0	0	
Gd ₂ O ₃	1.08	1.32	0.81	0	0.11	0	
Tb ₂ O ₃	0	0	0	0	0	0	
Dy ₂ O ₃	0.17	0.3	0.2	0	0.21	0.19	
Ho ₂ O ₃	0	0	0.12	0	0.1	0.1	
Er ₂ O ₃	0	0	0	0	0.1	0.17	
Tm ₂ O ₃	0.02	0	0	0.18	0.01	0	
Yb ₂ O ₃	0.16	0.1	0	0	0	0.1	
Lu ₂ O ₃	0.04	0.01	0.06	0	0	0	
SiO ₂	33.22	31.19	34.67	18.1	18.58	30.6	
TiO ₂	0.24	0.31	0.18	0.08	0.03	28.33	
ZrO ₂	0	0	0	0	0	0	
ThO ₂	1.38	0.87	2.07	73.35	58.36	0	
UO ₂	0	0.05	0.16	0	20.69	0	
P ₂ O ₅	0	0	0	0.04	0	0	
Total	99.36	100.88	99.42	100.44	103.51	96.27	
Comment	allanite	allanite	allanite	thorite	thorite	titanite	
Sample Name	PCS 2-8 (Amet granite)			Sample Name	PCS 2-8 (Amet granite)		
Point No.	1 / 1.	2 / 1.	3 / 1.	Point No.	1 / 1.	2 / 1.	3 / 1.
Na ₂ O	0.02	0.18	0	Dy ₂ O ₃	0.07	0	0
MgO	0.16	0.21	0	Ho ₂ O ₃	0	0.13	0.05
CaO	19.73	17.39	23.37	Er ₂ O ₃	0	0	0
MnO	0.21	0.2	0.26	Tm ₂ O ₃	0	0.01	0.03
FeO	11.82	11.61	12.43	Yb ₂ O ₃	0.01	0	0.05
SmO	0.22	0.49	0	Lu ₂ O ₃	0.08	0	0
EuO	0	0	0.07	SiO ₂	36.21	36.07	37.07
PbO	0.05	0.07	0	TiO ₂	0.1	0.23	0.09
Al ₂ O ₃	21.77	20.35	23.1	ZrO ₂	0	0.19	0
La ₂ O ₃	1.59	1.79	0	ThO ₂	0.04	0.15	0
Ce ₂ O ₃	2.69	3.11	0	UO ₂	0.03	0.02	0.03
Pr ₂ O ₃	0.23	0.57	0	P ₂ O ₅	0	0	0.02
Nd ₂ O ₃	1.67	2.21	0.04	Total	97.04	95.59	96.61
Gd ₂ O ₃	0.34	0.61	0	Comment	allanite	allanite	epidote
Tb ₂ O ₃	0	0	0				

Table 4. Cation proportions of allanite calculated from EPMA chemical data

Sample Name	20-8					35-8			55B-8
Point no	1 / 1	2 / 1	5 / 1	1 / 1	11/1	2 / 1	4 / 1	5 / 1	2/1
Mineral	Alln	Alln	Alln	Alln	Alln	Alln	Alln	Alln	Alln
SiO ₂	33.22	31.19	34.67	30.48	29.95	31.71	33.19	39.64	34.79
TiO ₂	0.24	0.31	0.18	0.81	1.28	0.89	0.35	0.21	0.33
ZrO ₂	0	0	0	-0.17	-0.2	-0.1	-0.01	-0.14	0
ThO ₂	1.38	0.87	2.07	1.5	1.49	1.81	2.18	0.8	1.77
UO ₂	0	0.05	0.16	0	0.01	0.09	0.03	0.14	0.08
SnO ₂	0	0	0	0	0	0	0	0	0
Al ₂ O ₃	18.57	15.81	20.44	14.27	12.9	14.8	16.93	17.75	17.17
Fe ₂ O ₃	0	0	0	0	0	0	0	0	0
V ₂ O ₃	0	0	0	0	0	0	0	0	0
Y ₂ O ₃	0	0	0	0	0	0	0	0	0
Ce ₂ O ₃	8.27	11.97	5.49	11.09	12.14	10.73	8.44	5.25	6.97
La ₂ O ₃	5.8	8.53	3.93	8.94	9.68	8.41	6.3	4.38	17.17
Pr ₂ O ₃	0.66	1.31	0.64	1.26	1.11	1.18	0.88	0.46	0.78
Nd ₂ O ₃	2.58	3.36	1.85	2.38	2.41	2.32	2.11	1.14	1.76
Sm ₂ O ₃	0	0	0						0
Gd ₂ O ₃	1.08	1.32	0.81	1.2	1.15	1.13	0.92	0.54	1.05
Dy ₂ O ₃	0.17	0.3	0.2	0.12	0.05	0.11	0.05	0.07	0.47
FeO	13.02	14.7	12.23	15.36	15.67	14.91	11.62	8.99	10.03
ZnO	0	0	0	0	0	0	0	0	0
MnO	0.37	0.44	0.49	0	0	0	0	0	0.27
MgO	0.17	0.18	0.07	0.31	0.57	0.34	0.18	0.31	0.28
CaO	13.3	10.05	15.66	11.05	9.58	11.59	14.18	11.95	11.99
SrO	0	0	0	0	0	0	0	0	0
PbO	0.07	0.03	0.11	0.09	0.07	0.13	0.05	0.07	0.06
Na ₂ O	0.01	0.02	0.03	0.02	0.03	0.03	0.15	0.11	0.45
K ₂ O	0	0	0	0	0	0	0	0	0
P ₂ O ₅	0	0	0	0.04	0	0.01	0.07	0.08	0
Si	3.051	3.009	3.065	3.003	3.021	3.044	3.107	3.569	3.127
AlIV	0	0	0	0	0	0	0	0	0
Sum_T	3.051	3.009	3.065	3.003	3.021	3.044	3.107	3.569	3.127
AlVI	2.008	1.796	2.128	1.656	1.533	1.673	1.866	1.882	1.818
Fe3	0	0	0	0	0	0	0	0	0
Ti	0.017	0.022	0.012	0.06	0.097	0.064	0.025	0.014	0.022
Mg	0.023	0.026	0.009	0.046	0.086	0.049	0.025	0.042	0.038
V	0	0	0	0	0	0	0	0	0
Fe ₂	1	1.186	0.904	1.266	1.322	1.197	0.91	0.677	0.754
Sn	0	0	0	0	0	0	0	0	0
Zn	0	0	0	0	0	0	0	0	0
Zr	0	0	0	-0.08	-0.01	-0.05	0	-0.06	0
Mn	0.029	0.036	0.037	0	0	0	0	0	0.021
Y	0	0	0	0	0	0	0	0	0
Ca	1.309	1.039	1.483	1.167	1.035	1.192	1.422	1.153	1.155
Sr	0	0	0	0	0	0	0	0	0
Th	0.029	0.019	0.042	0.034	0.034	0.04	0.046	0.016	0.036
U	0	0.001	0.003	0	0	0.002	0.001	0.003	0.002
Sn	0	0	0	0	0	0	0	0	0
Ce	0.278	0.422	0.178	0.4	0.448	0.377	0.289	0.173	0.229
La	0.196	0.303	0.128	0.325	0.36	0.297	0.217	0.145	0.569
Pr	0.022	0.046	0.021	0.045	0.041	0.041	0.03	0.015	0.026
Nd	0.085	0.116	0.058	0.084	0.087	0.079	0.07	0.037	0.056
Sm	0	0	0	0	0	0	0	0	0
Gd	0.033	0.042	0.024	0.039	0.038	0.036	0.029	0.016	0.031
Dy	0.005	0.009	0.006	0.004	0.002	0.003	0.002	0.002	0.014
Na	0.002	0.004	0.005	0.004	0.006	0.006	0.027	0.019	0.078
Pb	0.002	0.001	0.003	0.002	0.002	0.003	0.001	0.002	0.001

Table 4. Continued

Sample Name	PCS 1-8								
Point No.	1 / 1	10 / 1	11 / 1	12 / 1	2 / 1	4 / 1	5 / 1	6 / 1.	7 / 1
Mineral	Alln	Alln	Alln	Alln	Alln	Alln	Alln	Alln	Alln
SiO ₂	33.17	35.6	36.88	29.55	35.1	33.97	34.95	36.11	32.99
TiO ₂	0.18	0.12	0.1	35.01	0.17	0.19	0.2	0.17	0.16
ZrO ₂	0	0	0	0	0	0	0	0	0
ThO ₂	0.14	0.05	0	0	0.12	0.04	0.06	0.04	0.03
UO ₂	0.05	0	0.01	0	0	0	0	0.02	0.06
SnO ₂	0	0	0	0	0	0	0	0	0
Al ₂ O ₃	18.45	21.93	23.42	2.13	21.52	20.15	21.2	20.83	19.31
Fe ₂ O ₃	0	0	0	0	0	0	0	0	0
V ₂ O ₃	0	0	0	0	0	0	0	0	0
Y ₂ O ₃	0	0	0	0	0	0	0	0	0
Ce ₂ O ₃	8.75	2.09	0.04	0.13	3.24	4.27	3.09	7.4	7.48
La ₂ O ₃	6.12	1.54	0	0	2.37	2.22	2.18	4.01	4.06
Pr ₂ O ₃	0.93	0.06	0	0	0.28	0.59	0.38	1.1	0.97
Nd ₂ O ₃	2.87	0.78	0	0.12	1.54	2.17	1.27	3.27	3.27
Sm ₂ O ₃									
Gd ₂ O ₃	0.78	0.38	0	0.02	0.32	0.54	0.36	0.79	1.03
Dy ₂ O ₃	0.08	0.2	0.18	0	0.09	0.15	0	0.13	0.1
FeO	13.18	11.84	12.23	1.09	12.12	12.25	12.27	12.47	12.9
ZnO									
MnO	0.31	0.26	0.17	0.13	0.19	0.24	0.28	0.28	0.19
MgO	0.37	0.09	0.01	0	0.15	0.27	0.18	0.35	0.28
CaO	14.3	20.58	23.26	27.83	19.44	18.11	19.82	15.31	15.39
SrO	0	0	0	0	0	0	0	0	0
PbO	0	0.07	0	0	0	0.02	0.01	0.02	0
Na ₂ O	0.03	0.02	0.01	0.02	0.01	0.02	0	0.04	0.04
K ₂ O	0	0	0	0	0	0	0	0	0
P ₂ O ₅	0	0.01	0	0.02	0	0	0.01	0	0.02
Si	3.023	3.063	3.058	2.52	3.043	3.043	3.04	3.09	2.998
AlIV	0	0	0	0.214	0	0	0	0	0.002
Sum_T	3.023	3.063	3.058	2.734	3.043	3.043	3.04	3.09	3
AlVI	1.98	2.222	2.287	0	2.197	2.126	2.172	2.099	2.065
Fe ₃	0	0	0	0	0	0	0	0	0
Ti	0.012	0.008	0.006	2.246	0.011	0.013	0.013	0.011	0.011
Mg	0.05	0.012	0.001	0	0.019	0.036	0.023	0.045	0.038
V	0	0	0	0	0	0	0	0	0
Fe ₂	1.004	0.852	0.848	0.078	0.879	0.918	0.893	0.892	0.98
Sn	0	0	0	0	0	0	0	0	0
Zn	0	0	0	0	0	0	0	0	0
Zr	0	0	0	0	0	0	0	0	0
Mn	0.024	0.019	0.012	0.009	0.014	0.018	0.021	0.02	0.015
Y	0	0	0	0	0	0	0	0	0
Ca	1.396	1.897	2.066	2.543	1.806	1.738	1.847	1.404	1.499
Sr	0	0	0	0	0	0	0	0	0
Th	0.003	0.001	0	0	0.002	0.001	0.001	0.001	0.001
U	0.001	0	0	0	0	0	0	0	0.001
Sn	0	0	0	0	0	0	0	0	0
Ce	0.292	0.066	0.001	0.004	0.103	0.14	0.098	0.232	0.249
La	0.205	0.049	0	0	0.076	0.073	0.07	0.126	0.136
Pr	0.031	0.002	0	0	0.009	0.019	0.012	0.034	0.032
Nd	0.093	0.024	0	0.004	0.048	0.069	0.039	0.1	0.106
Sm	0	0	0	0	0	0	0	0	0
Gd	0.024	0.011	0	0.001	0.009	0.016	0.01	0.022	0.031
Dy	0.002	0.006	0.005	0	0.003	0.004	0	0.004	0.003
Na	0.005	0.003	0.002	0.003	0.002	0.003	0	0.007	0.007
Pb	0	0.002	0	0	0	0	0	0	0
K	0	0	0	0	0	0	0	0	0
OH	0	0	0	0	0	0	0	0	0

Table 4. Continued

Sample Name	PCS 1-8		PCS 2-8	
	8/1	9/1	1/1	2/1
Mineral	Alln	Alln	Alln	Alln
SiO ₂	36.02	35.2	36.21	36.07
TiO ₂	0.14	0.16	0.1	0.23
ZrO ₂	0	0	0	0.19
ThO ₂	0.05	0.09	0.04	0.15
UO ₂	0.04	0.09	0.03	0.02
SnO ₂	0	0	0	0
Al ₂ O ₃	22	21.78	21.77	20.35
Fe ₂ O ₃	0	0	0	0
V ₂ O ₃	0	0	0	0
Y ₂ O ₃	0	0	0	0
Ce ₂ O ₃	3.05	4.38	2.69	3.11
La ₂ O ₃	2.12	3.78	1.59	1.79
Pr ₂ O ₃	0.16	0.34	0.23	0.57
Nd ₂ O ₃	1.41	1.09	1.67	2.21
Sm ₂ O ₃	0	0		
Gd ₂ O ₃	0.4	0.33	0.34	0.61
Dy ₂ O ₃	0.08	0	0.07	0
FeO	11.99	12.05	11.82	11.61
ZnO	0	0	0	0
MnO	0.19	0.15	0.21	0.2
MgO	0.13	0.24	0.16	0.21
CaO	19.69	18.9	19.73	17.39
SrO	0	0	0	0
PbO	0	0.04	0.05	0.07
Na ₂ O	0.02	0.01	0.02	0.18
K ₂ O	0	0	0	0
P ₂ O ₅	0	0.01	0	0
Si	3.071	3.024	3.097	3.17
AlIV	0	0	0	0
Sum_T	3.071	3.024	3.097	3.17
AlVI	2.209	2.203	2.193	2.106
Fe ₃	0	0	0	0
Ti	0.009	0.01	0.006	0.015
Mg	0.017	0.031	0.02	0.028
V	0	0	0	0
Fe ₂	0.855	0.866	0.845	0.853
Sn	0	0	0	0
Zn	0	0	0	0
Zr	0	0	0	0.008
Mn	0.014	0.011	0.015	0.015
Y	0	0	0	0
Ca	1.799	1.739	1.808	1.637
Sr	0	0	0	0
Th	0.001	0.002	0.001	0.003
U	0.001	0.002	0.001	0
Sn	0	0	0	0
Ce	0.095	0.138	0.084	0.1
La	0.067	0.12	0.05	0.058
Pr	0.005	0.011	0.007	0.018
Nd	0.043	0.033	0.051	0.069
Sm	0	0	0	0
Gd	0.011	0.009	0.01	0.018
Dy	0.002	0	0.002	0
Na	0.003	0.002	0.003	0.031
Pb	0	0.001	0.001	0.002

through XRF and ICPMS methods. Out of these, eight samples were of Amet Granite (Table 1), three samples of migmatite gneiss, six rock samples of syenite-alkali feldspar syenite and one sample of amphibolite (Table 2).

Analytical Methods

The samples thus collected were crushed, sieved, coned and quartered, then analysed for major, trace and REE at Chemical Lab of G.S.I, Western Region, Jaipur, India. Major and trace elements were analysed, using PANalytical Axios model X-ray fluorescence (XRF) spectrometers. The rock powder was ground to -200 mesh size, pressed with binder Perspex in 5% Acetone at 20 ton P and pressed to form pellets. The instrument is calibrated with standards of granite and other rocks and the sample pellets were then run against standards calibrated.

The rocks samples were analysed for their silicate and REE chemistry at the GSI WR, Jaipur, NABL accredited (ISO/IEC17025: 2005) chemical laboratory. The standards used are made of solution from SRMs which are run to calibrate the instrument. The different SRM used are as follows: BE-N (basalt), DR-N (diorite), SY-3 (syenite), GS-N (granite).

Five thin polished sections of allanite bearing migmatite gneiss and monzonite-syenite/alkali feldspar syenite were studied by EPMA at National Centre of Excellence in Geoscience Research (NCEGR), GSI, Bengaluru, India for detailed mineral chemistry. These 5 no. samples were carbon coated (up to 60 nm) and analyzed for silicate chemistry and for REE.

Silicate and Oxide Settings for Epma

Silicate and oxide mineral phase analyses were performed using a CAMECA SX-100 electron microprobe analyser. The EMP is equipped with five wavelength dispersive spectrometers (WDS), e.g., WDS 1 (TAP crystal), 2 (PET crystal) and 4 (TAP crystal) built-in with low-pressure detectors, and WDS 3 (LPET crystal) and WDS 5 (LIF) built-in with high pressure detectors (all detectors use P-10 gas). Poly-propylene separation windows are used with WDS 1, 2 and 4 and Mylar windows are used with WDS 3 and 5. Calibration, overlap correction and quantifications are performed with the CAMECA SX-100 Peak Sight-Geo Quanta software package. Pulse-height analysers (PHAs) adjusted by selecting the differential auto mode for all the elements. Matrix effects are eliminated by using the X-PHI correction method proposed by Merlet (1992, 1994). Silicate and oxide phase are analysed using 15 kV acceleration voltage and 15 nA beam current with 1 µm size beam. The signals used are Na Ka, Si Ka, Mg Ka, Al Ka, K Ka, Ca Ka, Ti Ka, Cr Ka, Fe Ka, Mn Ka for calibration of elements using natural standards for Na, Si, Ca, K, Fe, Mg, Mn, synthetic standards for Al, Ti, Cr. Standards used are jadeite for Na, wollastonite for Si, Ca, diopside for Mg, corundum for Al, orthoclase for K, rutile for Ti, chromite for Cr, haematite for Fe and rhodonite for Mn. The counting time for peak measurement 10s and with half of the peak measurement time allotted for background measurement. Precision of probe analysis is ± 1% for total analysis and 0.5% S.D. individual element wise.

Table 5. Mineral formula of allanite based on 13 (O,OH) for five EPMA analysed samples

Sample Name	Mineral Formula
35-8	1/1. Ca _{1.164} Ce* _{0.894} Th _{0.034} Mn _{0.024} Al _{1.648} Fe _{2+1.262} Ti _{0.06} Mg _{0.045} Si _{2.996} O ₁₂ (OH) –0.004 Na replaced Ca
	11/1. Ca _{1.031} Ce* _{0.971} Th _{0.034} Mn _{0.039} Al _{1.525} Fe _{2+1.316} Ti _{0.97} Mg _{0.085} Si _{3.007} O ₁₂ (OH) –0.006 Na replaced Ca
	2/1. Ca _{1.189} Ce* _{0.832} Th _{0.039} Mn _{0.027} Al _{1.668} Fe _{2+1.194} Ti _{0.064} Mg _{0.049} Si _{3.036} O ₁₂ (OH) –0.006 Na replaced Ca
	4/1. Ca _{1.419} Ce* _{0.635} Th _{0.046} Mn _{0.036} Al _{1.863} Fe _{2+0.908} Ti _{0.025} Mg _{0.025} Si _{3.101} O ₁₂ (OH) –0.027 Na replaced Ca
	5/1. Ca _{1.152} Ce* _{0.386} Th _{0.016} Mn _{0.011} Al _{1.881} Fe _{2+0.677} Ti _{0.014} Mg _{0.042} Si _{3.568} O ₁₂ (OH) –0.019 Na replaced Ca
PCS 1-8	1/1. Ca _{1.306} Ce * _{0.647} Th _{0.003} Mn _{0.024} Al _{1.98} Fe _{2+1.004} Ti _{0.012} Mg _{0.05} Si _{3.023} O ₁₂ (OH) –0.005 Na replaced Ca
	10/1. Ca _{1.897} Ce * _{0.158} Th _{0.001} Mn _{0.019} Al _{2.222} Fe _{2+0.852} Ti _{0.008} Mg _{0.012} Si _{3.063} O ₁₂ (OH) –0.003 Na replaced Ca
	2/1. Ca _{1.806} Ce * _{0.248} Th _{0.002} Mn _{0.014} Al _{2.197} Fe _{2+0.879} Ti _{0.011} Mg _{0.019} Si _{3.043} O ₁₂ (OH) –0.002 Na replaced Ca
	4/1. Ca _{1.738} Ce * _{0.321} Th _{0.001} Mn _{0.018} Al _{2.126} Fe _{2+0.918} Ti _{0.013} Mg _{0.036} Si _{3.043} O ₁₂ (OH) –0.003 Na replaced Ca
	5/1. Ca _{1.847} Ce * _{0.229} Th _{0.001} Mn _{0.021} Al _{2.172} Fe _{2+0.893} Ti _{0.013} Mg _{0.023} Si _{3.04} O ₁₂ (OH)
	6/1. Ca _{1.404} Ce * _{0.518} Th _{0.001} Mn _{0.02} Al _{2.099} Fe _{2+0.892} Ti _{0.011} Mg _{0.045} Si _{3.09} O ₁₂ (OH) –0.007 Na replaced Ca
	7/1. Ca _{1.499} Ce * _{0.557} Th _{0.001} Mn _{0.015} Al _{2.065} Fe _{2+0.98} Ti _{0.011} Mg _{0.038} Si _{2.998} O ₁₂ (OH) –0.007 Na replaced Ca
	8/1. Ca _{1.799} Ce * _{0.223} Th _{0.001} Mn _{0.014} Al _{2.209} Fe _{2+0.855} Ti _{0.009} Mg _{0.017} Si _{3.071} O ₁₂ (OH) –0.003 Na replaced Ca
	9/1. Ca _{1.739} Ce * _{0.311} Th _{0.002} Mn _{0.011} Al _{2.203} Fe _{2+0.866} Ti _{0.01} Mg _{0.031} Si _{3.024} O ₁₂ (OH) –0.002 Na replaced Ca
55 B-8	2/1. Ca _{1.155} Ce * _{0.925} Th _{0.036} Mn _{0.021} Al _{1.818} Fe _{2+0.754} Ti _{0.022} Mg _{0.038} Si _{3.127} O ₁₂ (OH) –0.078 Na replaced Ca
20-8	1/1. Ca _{1.309} Ce * _{0.619} Th _{0.029} Mn _{0.029} Al _{2.008} Fe _{2+1.00} Ti _{0.017} Mg _{0.023} Si _{3.051} O ₁₂ (OH) –0.002 Na replaced Ca
	2/1. Ca _{1.09} Ce * _{0.938} Th _{0.019} Mn _{0.036} Al _{1.796} Fe _{2+1.186} Ti _{0.022} Mg _{0.026} Si _{3.009} O ₁₂ (OH) –0.004 Na replaced Ca
	5/1. Ca _{1.483} Ce * _{0.415} Th _{0.042} Mn _{0.037} Al _{2.128} Fe _{2+0.904} Ti _{0.012} Mg _{0.009} Si _{3.065} O ₁₂ (OH) –0.005 Na replaced Ca
PCS 2-8	1/1. Ca _{1.808} Ce* _{0.204} Th _{0.001} Mn _{0.015} Al _{2.193} Fe _{2+0.845} Ti _{0.006} Mg _{0.02} Si _{3.097} O ₁₂ (OH) –0.003 Na replaced Ca
	2/1. Ca _{1.637} Ce* _{0.263} Th _{0.003} Mn _{0.015} Al _{2.106} Fe _{2+0.853} Ti _{0.015} Mg _{0.028} Si _{3.17} O ₁₂ (OH) –0.031 Na replaced Ca

Ce* is Ce + Total REE in allanite

REE Settings for Epma

REE phase analyses were performed using a CAMECA SX-100 electron microprobe analyser at above mentioned laboratory of GSI. The EMP is equipped with five wavelength dispersive spectrometers (WDS), e.g., WDS 1 (TAP crystal), 2 (PET crystal) and 4 (LIF crystal) built-in with low-pressure detectors, and WDS 3 (LPET crystal) and WDS 5 (LIF) built-in with high-pressure detectors (all detectors use P-10 gas). Polypropylene separation windows are used with WDS 1, 2 and 4 and Mylar windows are used with WDS 3 and 5. Calibration, overlap correction and quantifications are performed with the CAMECA SX-100 Peak Sight-Geo Quanta software package. Pulse-height analysers (PHAs) are adjusted by selecting the differential auto mode for all the elements. Matrix effects were eliminated by using the X-PHI correction method proposed by Merlet (1992, 1994). REE phase are analysed using 20 kV acceleration voltage and 20 nA beam current with 1 µm size beam. The signals used are Si Ka, Ca Ka, Na Ka, P Ka, Al Ka, Ti Ka, Fe Ka, Y La, La La, Ce La, Pr Lb, Nd Lb, Sm La, Eu La, Gd La, Tb La, Dy Lb, Ho La, Er La, Tm La, Yb La, Lu La, Pb Ma, Th Ma, U Mb, Nb La, Ta La for calibration of elements using natural standards for Si, Ca, P, Fe, Pb, synthetic standards for Al, Ti, REE, Y, U, Th. Standards used are wollastonite for Si, Ca, apatite for P, corundum for Al, haematite for Fe, albite for Na, Pb on crocoite, synthetic glass standards for REE, U, Th and 100% metal standards for Nb, Ta. The counting time for peak measurement is 10s and with half of the peak measurement time allotted for background measurement.

Petrography

Migmatite gneiss (protolith age 2.75–2.698 Ga; Dharma Rao et al.,

2011) essentially consists of quartz, plagioclase, and orthoclase and less amount of microcline as major minerals, having biotite, sodic hornblende and garnet (at places) as subordinate or minor minerals. Allanite, epidote, sphene, magnetite, ilmenite and zircon are the accessory minerals in migmatite gneiss. Allanite occurs as discrete, primary, euhedral crystals overprinting and pushing aside the major foliation (S₂) defined by biotite-amphibole and quartzofeldspathic minerals, thereby suggesting that it formed as a result of reaction between a REE bearing fluid rich in P and F and the silicate minerals (Fig. 2, 4) (see, Arden and Halden, 1999). The proportion of plagioclase and orthoclase is varying regionally and perthitic texture is very common in migmatite gneiss. Some cluster of mafic minerals like sodic hornblende and biotite is associated with mafic bands of migmatite gneiss. Biotite, represented by Fe-Mg rich annite, in migmatite gneisses are seen to form by breakdown of muscovite + quartz assemblage above the granite melting curve. The migmatite gneiss serves as host for the intrusive Amet granite and the monzonite-syenite-alkali syenite rocks.

Petrographically, Amet Granite (1870 ± 200 Ma; Chaudhary et al., 1984) is mainly composed of plagioclase, quartz, and alkali feldspars as the major constituent and hornblende with minor amount of biotite as minor constituents and sphene, epidote, allanite and magnetite as accessory minerals. Garnet porphyroblast is also present within the Amet granite. Both primary and secondary biotite is present within the Amet granite. The primary biotite is Annite compositionally and is aligned along the foliation plane and secondary biotite is haphazardly oriented. The secondary biotite is formed due to the metamorphism of amphiboles.

Syenite-alkali feldspar syenite is predominantly composed of alkali feldspar with small amount of plagioclase and more than 5% quartz, whereas monzonite is predominantly composed of alkali feldspar and

Figure 2. 35-8-borana allanite with 1 set cleavage parallel to 100 or 010 suggesting the mineral is not altered (Molloy, 1959). Note rim of britholite (darker brown) around allanite core (lighter brown).

Figure 3. BSE image of same grain (35-8) with point 11-Allanite core, 12- Allanite rim, 13- outer rim Allantite (alteration).

Figure 4. Allanite grain with radial expansion cracks. PPL X10.

Figure 5. Sample 20-8 (syenite) Allanite-epidote in a groundmass of k-feldspar. Allanite rimmed by britholite or thorite; centre of epidote (Epi) is having glass appearance (thorite). One big allanite on left side. PPL X 10.

Figure 6. BSE image of sample 35-8. Core portion is allanite, britholite (white part) with a white grain of scheelite at NW and NE parts, & thorite in centres alteration. Points 2-rim of allanite, 3- alteration part, 4-REE mineral, 5 & 6-alteration part, 7-britholite with scheelite, 8-Kf, 9-Bi, 10, 11, 15-titanite, 12-iron phase, 13-Bi. (yellow points are REE analysed).

plagioclase with less than 5% quartz. Action of fluid is noticeable as foliation parallel replacement of Amet granite by monzonite is seen which may be due to magma mixing (Fig. 1c). The ages of these intruded rocks (Syenite/alkali feldspar syenite and monzonite) are not yet known but logically they are supposed to be little younger in age than the Amet Granite as it intruded and replaced the granite.

Allanite occurs both as discrete crystals as well as irregular segregations, whereas britholite occurs only as irregular masses forming rims in allanite crystals. The allanite with its britholite rim, typically share sharp contacts with host silicate minerals k-feldspar, plagioclase, biotite, sodic amphibole (Fig. 2, 3 and 8). BSE images of allanite show both normal growth induced magmatic zoning and complicated internal zoning consisting of patchwork of variable domains in brightness (Fig. 3, 6 and 7). Petrography also reveals presence of zoned allanite euhedral crystals (Fig. 2 and 4) with peripheral rims of britholite and titanite and core of allanite. Radial cracks developed not due to radioactive decay, but these are expansion cracks due to alteration from allanite to britholite–thorite (Fig. 4). Apatite, zircon, titanite, britholite, thorite, U-bearing minerals are identified through EPMA studies (Fig. 8). Apatite is seen to be enclosed in allanite (Fig. 8). Epidote changing to allanite rimmed by britholite is seen in Fig. 5 wherein big grains of allanite are forming in the core of epidote.

Geochemistry and Mineralogy

Geochemical Characterisation

The whole rock analysis has been given in Table 1 and 2. The TAS diagram (Fig. 9, Cox et al., 1979) shows that the migmatite gneiss falls in granitic field whereas syenite and amphibolite fall in their respective fields and a crystallisation trend from migmatite gneiss–Amet granite–syenite is observed.

The chemical analyses of the migmatite gneiss indicate that they all have more than 66% SiO₂ and hence classified as acidic suite (Carmichael et al., 1974). Their mean Al₂O₃ concentration is 14.0% classifying them as low-Al gneisses (Monrad, 1983). Their Al₂O₃/Na₂O+K₂O ratio is less than 3.4 pointing to their sub-alkaline nature (Bose, 1989). A/CNK–A/NK diagram (Fig. 10) of Shand (1943) also discriminate these rocks as metaluminous. In the Na₂O Vs K₂O diagram (Fig. 11) of Smith (1982), all our samples of Amet granite plot in the field of S-type granites. In A/CNK–A/NK diagram of Shand (1943) all the samples of Amet granite fall in Metaluminous field (Fig. 10).

The chemistry of the migmatite gneiss indicates a calc alkaline nature and the syenite-alkali feldspar syenite intrusives having alkaline nature,

Figure 7. Sample 20-8 BSE image showing points (Yellow) 1 & 2-allanite core, 3 & 4-thorite, 5-allanite rim.

thereby indicating a genetic correlation between the migmatite gneiss and the alkaline intrusives. In the Na-K-Ca triangular diagram after Barker and Arth, (1976), these rocks show trondhjemitic characteristics (Fig. 12). These rocks are metaluminous when plotted in Shand's diagram (Shand, 1943).

Zr and Th is moderate to high in migmatite gneiss, Amet Granite and alkali intrusives. Σ REE value (Table 2) is low to moderate in migmatite gneiss (156.12 to 627.40 ppm) and high in syenite-alkali feldspar syenite (1410.29 to 2071.20 ppm) which may indicate that the carrier of the REE mineral allanite-britholite is alkaline intrusive syenite-alkali feldspar syenite which deposited their REE content in migmatite gneiss along and across foliations and micro shear (Fig. 2 and 13). The Zr, Y, La, Ce values increase with release of silica in the system, whereas values of Rb, Sr, Ni, Cr, Ba, decrease from syenite-alkali feldspar syenite to Amet granite and migmatite with increase of silica (Table 1 and 2). This is consistent with crystallisation of mafic phases in early stages of magmatic crystallisation. The feldspars of these rocks when plotted in Ab-An-Or diagram (Fig. 14) show feldspars of monzonite as of albite composition and alkali feldspar syenite of orthoclase composition. The mineral composition of biotite of Amet Granite and migmatite gneiss falls in the field of annite thereby indicating higher X_{Fe} content (Fig. 15).

Mineral Chemistry

Total silicate and REE values and of five samples containing allanite, analysed by EPMA, are given in Table 3. The analysis indicates the presence of mineral phases as allanite, britholite, thorite, titanite, apatite, zircon, as major phases and minor scheelite and Uranium-bearing phase in the samples. The cation proportion of the allanite calculated for these five samples is given in Table 4 and the mineral formula of allanite calculated on the basis of 13 (O, OH) is given in Table 5. The composition of allanite ranges from $Ca_{1.031}Ce^{*}_{0.971}Th_{0.034}Mn_{0.039}Al_{1.525}Fe^{2+}_{1.316}Ti_{0.97}Mg_{0.085}Si_{3.007}O_{12}(OH)$ to $Ca_{1.897}Ce^{*}_{0.158}Th_{0.001}Mn_{0.019}Al_{2.222}Fe^{2+}_{0.852}Ti_{0.008}Mg_{0.012}Si_{3.063}O_{12}(OH)$, where Ce^{*} is $Ce + \text{total of other REE values}$. The mineral phase identified, thus, is allanite (Ce), the allanite phases being CaO and Ce_2O_3 rich (see Table 1). Silica and alumina show positive correlation in allanite. As the silica proportions decreases and total REE increases (Table 3), allanite changes to britholite (sample 35-8, 55B-8) and also thorite (sample 20-8). Therefore, with release of SiO_2 , total REE increases. Some grains of scheelite and uranium mineral phase are also identifiable.

From thin section study it is seen that allanite is growing over epidote and other silicate minerals (Fig. 5). More total wt% of EPMA data may be related to interference of some elements in allanite because of

Figure 8. Sample 55B-8-BSE image showing points (yellow) 1, 2 & 3-allanite (REE rich white part), 4-titanite, 5-apatite in allanite, 6-zircon, 7-apatite, 8-titanite.

its development from fluid action on epidote thereby crystallising allanite and other REE minerals. Core part of allanite changes to britholite as white rim (Fig. 6) which is REE rich britholite (Ce rich, Table 3), an alteration of allanite. Decrease in MnO is also related to increase in La and Ce making alteration of allanite to britholite. In one sample PCS 1/8, FeO is 1.09%, SiO₂ 29.55%, but britholite could not form as SiO₂ did not move out of the system. As the percentage of FeO increases, different rims of REE minerals are formed as evident from petrographic and EPMA studies (Fig. 2, 3, 4, and 6). FeO is more in allanite than britholite and thorite in this case (sample 35/8, Table 3). Increase in total REE and with release of SiO₂ from system, allanite changed to britholite and thorite indicating role of fluid in this case. Another important observation is that Ca+LREE replaces Mn+HREE (Fig. 16). As HREE (Gd+Dy) increases, Mn also increases (Fig. 17); and as Ca increases, Mn decreases (Fig. 18) indicating a direct replaceable relation between Ca, Mn, HREE and LREE. The chondrite normalised pattern of Σ REE in allanite vis-a-vis the chondrite normalised pattern of Σ REE in migmatite gneiss containing these allanite are compared in Fig. 20 which shows a compatible relation of Σ REE of rock vis-a-vis the mineral allanite contained within it, indicating primary allanite. Migmatite host shows a flat pattern with significant negative Eu anomaly (Fig. 20) as is expected in Achaean-Proterozoic rocks, and is

explained as original source character of magma (Sun and Nesbitt, 1978). Since allanite crystallised in later period of magmatic crystallisation, when volatile rich fluid containing REE, rare earth metal and many such ore minerals of U, Ti of significance crystallise; the compositional variation in allanite REE and host REE is imminent. This observation, therefore, indicates primary nature of allanite of study area.

The Al₂O₃-Fe₂O₃- Σ REE diagram (Fig. 19) indicates that the allanite of study area are falling in intracontinental field, which indicates crystallisation of allanite in consonant with the tectonic setting of migmatite gneisses and granites of the Rajasthan craton (See Hoshino et al., 2005).

Discussion

Magma genesis and assimilation (mixing) of deeper crustal rocks is a possible hypothesis, but mingling or comingling of magma is more plausible in this case (Kumar, 2014) as the migmatite gneiss which is a granitic gneiss, is trondhjemitic in nature (Fig. 12); is replaced or intruded by pulses of syenite-alkali feldspar syenite rocks containing epidote dikes and veins, with thoroughly dispersed primary allanite grains in the rocks. The age of migmatite gneiss is 2.75–2.698 Ga

Figure 9. TAS diagram of syenite (asterisk), Amet Granite (filled circle), Migmatite (filled square), Amphibolite (triangle) after Cox et al. (1979).

Figure 10. A/CNK vs A/NK diagram after Shand (1943). Symbols as in Fig. 9.

whereas the syntectonically emplaced amphibolite within it is 2.83 ± 0.05 Ga. The intrusive plutonic Amet Granite is 1870 ± 200 Ma. Chronologically, migmatite gneiss is the oldest crust which was intruded syntectonically by mafic rocks (now amphibolite), and finally by a melt generated from migmatite gneiss as the Amet Granite pluton. The syenite-alkali feldspar syenite and monzonite dikes intruded last in succession cutting across all rock types in study area.

The minerals epidote and also allanite are seen in the alkaline rocks ubiquitously. The mineral composition of epidote is $\text{Ca}_2(\text{Al}_2, \text{Fe})(\text{SiO}_4)(\text{Si}_2\text{O}_7)\text{O}(\text{OH})$ and is an end member of solid solution series with clinozoisite. Members of the epidote mineral group have a crystal structure that consists of isolated and paired silica tetrahedrons. They share a generalized chemical composition of $\text{A}_2\text{M}_3(\text{Si}_2\text{O}_7)(\text{SiO}_4)\text{O}(\text{OH})$. "A" is a pairing of calcium, manganese, strontium, lead, or sometimes a REE. "M" is usually aluminum pairing with iron, magnesium, manganese, or vanadium. Now here in the present case, Ca is paired with Ce, Th and Mn, and Al is paired with Mg and Fe (Table 5); thereby allanite is formed in profuse in the alkaline rocks during magmatic crystallisation itself. The more the silica released from the system, new species as britholite and thorite have formed indicating a role of fluid in its crystallisation (Mueller and Saxena, 1977). The chondrite normalized REE in migmatite gneiss and allanite mineral is compatible (Fig. 20), thus indicating a primary nature of allanite in the host. Therefore, it is envisaged that the carrier of the REE mineral is alkaline intrusive syenite/alkali feldspar syenite rocks which deposited their REE minerals during ascent of alkaline magma in semi-consolidated state in migmatite gneiss along and across foliations and micro shears, due to reaction between a REE bearing fluid rich in P and F brought up by alkaline rocks, and the silicate minerals, mainly biotite and sodic hornblende of the migmatite gneiss (Fig. 2) and Amet granite (Fig. 13) (cf., Arden and Halden, 1999).

Field evidences of syenite-alkali feldspar syenite impregnating migmatite gneiss and amphibolite (syntectonically intruded in migmatite, and pre syenite) as dikes, sills and veins; and the petrographic study indicated that the syenite-alkali feldspar syenite acted as carriers of the REE bearing mineral phases from deep crustal source at higher temperatures. The syenite-alkali feldspar syenite magma is derived from deeper crustal source since it is not oxidised as seen petrographically as well as the chemical

Figure 11. K_2O/Na_2O diagram of Amet Granite. Symbols as in Fig. 9.

data indicating negative Eu anomaly. Higher temperature of the fluid or magma is indicated by the fact that the granite melting curve has been crossed in migmatite gneiss through the breakdown reaction of Muscovite + Quartz $\rightarrow$ Al_2SiO_5 + K-feldspar + Biotite + H_2O . Absence of primary muscovite and presence of biotite in the migmatite gneiss is an indicator of these phenomena where the emplacement of the

Figure 12. K-Na-Ca diagram of migmatite gneiss, Amet granite, syenite-alkali feldspar syenite and amphibolite. Symbol as in Fig. 9.

syenite-alkali feldspar syenite magma can be considered above the Muscovite + Quartz stability curve (Winkler, 1974). The role of fluid in magmatism and allanite mineral crystallisation is also indicated by reaction between a REE bearing fluid rich in P and F brought up by alkaline rocks, and the silicate minerals biotite and sodic hornblende of the migmatite gneiss (Fig. 2) and Amet granite (Fig. 13) (Arden and

Figure 13. Sample PCS 02-08 BSE image showing epidote containing allanite having reaction relation with biotite and feldspar in ground-mass. Aln (allanite), Bt (biotite), Plg (plagioclase).

Figure 14. Plot of plagioclase and k-feldspar analysis of syenite (asterisk), monzonite (star), Amet Granite (filled circle), Migmatite (filled square).

Figure 15. Plot of biotite of Amet Granite (filled circle), Migmatite (filled square).

Figure 16. Plot of Mn+HREE vs Ca+LREE of allanite analysis. Filled triangle of sample PCS 1-8 (Amet Granite) and filled square of sample 20-8 (syenite/alkali feldspar syenite).

Halden, op.cit.); and also leaching out of silica from the system with concomitant enrichment of REE. The REE bearing fluid impregnated the migmatite gneiss along and across foliation planes and micro

Figure 17. Plot of Mn versus HREE of allanite analysis. Filled triangle of sample PCS 1-8 (Amet Granite) and filled square of sample 20-8 (syenite/alkali feldspar syenite).

Figure 18. Plot of Mn versus Ca of allanite analysis. Filled triangle of sample PCS 1-8 (Amet Granite) and filled square of sample 20-8 (syenite/alkali feldspar syenite).

Figure 19. Al_2O_3 - Fe_2O_3 - ΣREE plot of allanite of migmatite gneiss, syenite-alkali feldspar syenite and Amet granite of studied area. The curved lines indicate the three groups of different kinds of occurrence of allanite (after Hoshino et al., 2005).

shears after the migmatite was crystallised. These REE bearing minerals were deposited in a conducive environment within the migmatite gneiss and Amet granite because of their (the hosts) suitable bulk

Figure 20. REE pattern of allanite versus migmatite gneiss. Red circles are allanite; Black squares are migmatite.

composition. All the cracks observed surrounding allanite grains in migmatite are expansion cracks due to change from allanite to britholite and metamictisation is not observed. This is unique in its genesis as because such large quantity of REE minerals allanite-britholite-thorite-zircon-titanite-apatite is not reported from intrusive syenite-alkali feldspar syenite and migmatite gneiss of the basement rocks of Rajasthan, having a large aerial extension. This report is, thus, important from REE mineral target prospecting point of view also for the Meso to Neo Archaean basement rocks of Rajasthan; and this may trigger similar finds elsewhere in India and in the world in a similar tectonic and petrological set up.

Conclusions

Allanite-britholite REE bearing migmatite gneisses, Amet Granite with its intrusive syenite-alkali feldspar syenite of the cratonic terrain of Rajasthan, India, is reported *primum fama*, having recoverable deposit of REE minerals. Allanite being an important REE mineral; in view of present worldwide demands of REE, this new find of REE bearing minerals in migmatite gneiss in recoverable resources will be a new emerging domain in India leading to search for REE minerals in similar terrain of India and elsewhere in the world. Concentration and the composition of REE in allanite of present finding and its host rocks; its comparison with the composition of allanite commonly occurring worldwide, established a direct relation between REE bearing allanite-britholite and its host migmatitic gneiss and other rocks as discussed above. It was established by chemico-mineralogical details of Allanite and petrochemical study of its host rocks that allanite originated from the deep-seated lower crustal intracontinental magmatic rocks syenite-alkali feldspar syenite, which were the carriers of REE minerals; deposited their REE content within the host migmatite gneiss and the Amet granite along foliations, micro shears and grain boundaries in a

possible peritectic condition.

In view of the large scale demands of REE, this huge quantity of recoverable REE bearing allanite from migmatitic gneiss and granite host rocks may prove to be a sumptuous deposit of REE minerals in India and similar terrains of the world.

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