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Criteria to distinguish between regional and contact zone monazite – a case study from Proterozoic North Delhi Fold Belt (NDFB), India

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North Delhi Fold Belt (NDFB) is a part of a NNE-SSW trending Proterozoic mobile belt hosting sulfide mineralization in Khetri Copper Belt (KCB) towards its western margin. It preserves assemblages of amphibolite facies Barrovian metamorphism locally overprinted by a thermal metamorphic event. Monazite (REEPO₄) is developed in both the assemblages. Detailed chemistry and chemical geochronology of monazites in regional and contact metamorphic assemblages depict distinct chemical traits and ages. Two stage growth of metamorphic assemblages at ~1100 Ma and ~920 Ma is recorded. Contact zone monazite grew at ~650 Ma under hydrothermal conditions. It has low thorium and is cerium enriched in comparison to the regional metamorphic monazite. Low Th and high Ce/Th ratio in contact zone monazite is proposed as discriminating criteria between regional and contact metamorphic monazites.

Introduction

Monazite is a natural rare earth element bearing monoclinic phosphate mineral having the general formula REEPO₄. Substitutions are possible on both cationic and anionic sites. Cationic substitutions include trivalent substitutions (e.g. La³⁺ to Gd³⁺), A⁺ to REE³⁺ (e.g. Na, K to REE³⁺), substitution by tetravalent (U⁴⁺, Th⁴⁺) cations for trivalent REE (4 REE³⁺ = 3 B⁴⁺ + ?), coupled substitutions of trivalent REE with divalent and tetravalent cations (2REE³⁺ = A²⁺ + B⁴⁺ wherein A can be Ca and B is often Th in natural monazites) while substitutions on anionic sites can result in transformation to vanadates, arsenates or chromates (Kolitsch and Holstam, 2004). Besides, coupled substitutions on the cationic as well as the anionic groups occur which have been experimentally investigated in the huttonite/thorite-Ce monazite-xenotime (ThSiO₄-CePO₄-YPO₄) system and a miscibility gap between monazite-xenotime and temperature dependence of substitution demonstrated (Seydoux-Guillaume, et al. 2002). Monazite is a common accessory mineral in metamorphic rocks, it strongly influences REE and Th-U budget of these rocks and is highly useful in dating of metamorphic events on account of very low inherited Pb (Copeland et al., 1988). Low rate of Pb diffusion in monazite lattice has been considered suitable of its utility in

deciphering the peak metamorphic conditions (Janots et al, 2008, 2009). Conditions of metamorphism of multiple phases can be ascertained using mineralogical and textural criteria. Monazite composition readjusts to the changing P-T conditions and these variations preserve the evolutionary history of a terrain (e.g. Zhu and O'Nions, 1999; Krenn and Finger, 2007). Studies on control of monazite composition in metamorphic rocks are relatively scarce though monazites developed in contact metamorphic aureole were described as depleted in europium compared to those produced as a product of regional metamorphism (Rosenblum and Mosier, 1983) in a study on monazite grains recovered from the heavy mineral fractions.

Khetri copper belt is the northern most entity of North Delhi Fold Belt (NDFB) comprising two metamorphic series representing two episodes of prograde regional metamorphism i.e. andalusite and sillimanite in the north and kyanite sillimanite in the south separated by an east west trending fault between Dhanota and Chappoli (Dasgupta, 1964, 1968; Lal and Shukla 1975; Sharma 1988). Several models of genesis of ore in NDFB ranging from syn-sedimentary deposition and metamorphism (Sarkar and Dasgupta, 1980; Basu, 1986), hydrothermal (Roy Choudhury and Das Gupta, 1965, Banerjee, 1976) and post-metamorphic Iron oxide-Copper-Gold (IOCG) type (Knight et al., 2002) have been proposed.

In the present work we describe texturally constrained monazite from regional metamorphic as well contact metamorphic association from the rocks of NDFB and discuss control on monazite chemistry in these two situations.

Geological setting

Delhi fold belt has been divided into two parts NDFB and SDFB (Sinha-Roy et al; 1998). North Delhi Fold Belt (NDFB) which is characterized by several fossil grabens, horsts, distributed broadly in three main sedimentation sub-basins (Singh, 1984). From east to west, these are the Bayana- Lalsot, the Alwar, and the Khetri subbasins. Polyphase deformation in the Alwar basin has resulted in complex outcrop patterns with abundant structural duplication. The rocks are folded into appressed upright to isoclinal shallow to moderate plunging NNE-SSW trending antiforms and complementary synforms, which were subsequently refolded on NW-SE and ENE- WSW axial planes, resulting in axial culminations and depressions. Based on the occurrence of andalusite- staurolite-biotite-muscovite association, Sharma (1988) estimated 500-550°C temperature and 3-4 kbar pressure for Alwar basin metamorphism. Monazite bearing samples in the present study are reported from two locations. Khetri copper

mine within the Khetri Copper Belt (KCB) is located ~25 km northwest of Golwa-Gangutana area.

Khetri Copper Belt: The Khetri Copper Belt constitutes the northernmost entity of the Aravalli craton and extends for about 80 km from Singhana (Jhunjhun District) in the NE to Sangarva (Sikar District) in the SW. The belt is further separated into northern and southern parts by the NW-SE striking transverse Kantli Fault (Gupta et al. 1998). Following Heron (1923), Das Gupta (1968) considered that the Khetri Copper Belt is made up of rocks of the Delhi Supergroup, which are further divided into (1) an older psammitic – dominated Alwar Group and (2) a younger pelitic dominated Ajabgarh Group. In contrast, some later studies consider rocks of the Khetri Copper Belt as pre – Delhi (Chakrabarti & Gupta, 1992). The NNE-SSW to NE – SW striking metasedimentary rocks of the northern Khetri Copper Belt consists of feldspathic quartzite with magnetite, banded amphibole quartzite, garnetiferous chlorite schists, mica schists and quartzite, which are folded into a number of regional anticlines and synclines (Das Gupta, 1968). In contrast, Sarkar and Dasgupta (1980) and Sarkar (2000) concluded that these rocks belong to a homoclinal sequence and are part of one limb of a regional fold. The Khetri Copper Belt displays two episodes of prograde regional metamorphism (M_1 and M_2), the andalusite – sillimanite facies in the north and a transition to kyanite – sillimanite facies towards the south, and there is an eastward increase in the grade of metamorphism (Lal

and Shukla, 1975; Lal and Ackermann, 1981). The intrusive rocks in the KCB are largely represented by mafic and granitoid rocks. Ray identified a 170 km long NNE-SSW trending lineament, the albitite line in the region. Besides, minor amount of felsic volcanic have also been reported.

Golwa Gangutana area: The rocks of Alwar and Ajabgarh Groups of Delhi Supergroup are exposed in southern part of Haryana state and adjacent part of Rajasthan. Quartzite and metamorphosed mafic volcanics represent the Pratapgarh Formation of Alwar Group while interbedded calc silicates, metapelites and arenites constitute the Kushalgarh Formation of Ajabgarh Group (Prasad et al., 1994). Metapelites occur as a ~500m thick band of ~6km strike length near Golwa village (Fig. 1) within the core of the refolded synform (Kundu et al., 2004). The emplacement of most of the granitoid plutons was structurally controlled, and they occur in the cores of anticline or parallel to foliation of the country rocks. These plutons have been interpreted as syn- to post- kinematic with respect to different episodes of the Delhi orogeny. Granitic activity in the KCB is considered to have taken place during the culmination of regional metamorphism.

Petrography

Several thin sections of mineralized rock and metapelites from Khetri and Golwa Gangutana were studied using polarizing microscope and scanning electron microscopy (SEM) to select suitable

Fig.1. A geological map of the area around Narnaul, Mahendergarh district, Haryana. (Bhola, 1989). Here, metapelites occur as a ~500 m thick band of ~6 km strike length near Golwa village.

Fig.2. Thin section scale elemental X-ray maps of Al and Fe show presence of zoned as well as unzoned garnets. Porphyroblasts of staurolite and garnet as dominant constituent along with biotite and quartz and sub-ordinate muscovite and plagioclase.

samples for investigating the monazite. Thereafter, one sample from garnet-staurolite schist and one sample from chlorite schist were chosen for detailed analysis. Sample GG-5 was collected from metapelites (garnet-staurolite schist) of Kushalgarh Formation and sample KH-2 was from chlorite schist of Khetri Copper Belt.

GG-5 is strongly foliated garnet-staurolite schist comprising porphyroblasts of staurolite and garnet as dominant constituent along with biotite and quartz and sub-ordinate muscovite and plagioclase (Fig. 2). Ilmenite, apatite and monazite are present as accessory phases. Schistosity is defined by aligned biotite and muscovite flakes and quartz grains. Staurolite occurs as the coarsest sub-idioblastic to idioblastic poikiloblasts and has inclusions of variable size. Garnet, quartz, micas and ilmenite are present as major inclusions in staurolite. The internal schistosity of staurolite is in continuation with external schistosity indicating it to be post-kinematic. Thin section scale elemental X-ray maps of Al and Fe show presence of zoned as well as unzoned garnets (Fig. 2). Garnet grains are present as inclusions in staurolite as well as in the matrix. Overgrowth as well as diffusion related zoning is inferred in garnets wherein the former appear to be an expression of garnet in two different P-T conditions thereby indicating polyphase metamorphism (Fig. 3). Peak metamorphic conditions (temperature around 645°C and pressure ~ 7 kbar; Kundu et al., 2004) have been reported from this area.

KH-2 is chlorite schist where biotite and chlorite define the foliation. It contains chlorite, biotite, cordierite, muscovite, quartz, garnet and Cu and Fe- sulfides as major metamorphic assemblage.

Fig.3. Overgrowth as well as diffusion related zoning is inferred in garnets wherein the former appear to be an expression of garnet in two different P-T conditions thereby indicating polyphase metamorphism.

Chalcopyrite and pyrrhotite are present as main sulfide phases and occur typically as hydrothermal vein fillings (Fig. 4). Monazite is associated with these hydrothermal veins (Fig. 4). The rock has retrogressed chlorite formed from biotite and garnet. Biotite is of two generations with the earlier being commonly retrogressed to chlorite and the latter occurring at the margins of chlorite in association with cordierite (Fig. 5). This association and texture is inferred as evidence of thermal metamorphism with following operative reaction.

Temperature of ~600°C is inferred for development of cordierite+biotite in a mineralized contact aureole (Whyldal et.al, 2009)

Fig.4. Chalcopyrite and pyrrhotite are present as main sulfide phases and occur typically as hydrothermal vein fillings.

Fig.5. Biotite is of two generations with the earlier being commonly retrogressed to chlorite and the latter occurring at the margins of chlorite in association with cordierite.

Analytical conditions

The monazite analysis work was carried out on a CAMECA SX100 Electron Microprobe at EPMA Laboratory, Geological Survey of India, Faridabad and IIT Khadagpur. The analyses were carried out at 20kV and 200 nA beam current. Pb ($M\alpha$) was measured on LPET and the peak counting time was 300 seconds with background measured on both sides at half the peak time. For uranium, $UM\alpha$ line was used in order to avoid the interference of $ThM\beta$ line. In order to counter the loss of count rate, a peak counting time of 200 seconds (and 200 seconds for background by counting on both sides of the peak) was used for $Um\beta$ line. U and Th were measured on PET. Thorium $M\beta$ peak was also counted for 200 seconds. Rare Earth elements measured included La ($L\alpha$), Ce ($L\alpha$), Nd ($L\beta$), Pr ($L\alpha$), Sm ($L\alpha$), Ho ($L\beta$), Dy ($L\alpha$) and Gd ($L\alpha$). Counting time at peak varied between 40–60 seconds for these elements. Y $L\alpha$ line was used for yttrium and it was counted for 40 seconds on peak. No solution for correcting interference of Y $L\gamma$ on Pb $M\alpha$ could be arrived at using Virtual WDS. The overlap correction procedure for this interference was used. The raw data was corrected using PAP (Pouchoir and Pichoir, 1991) correction method which is inbuilt in software.

Standards used for Pb, U and Th were $Pb_5(PO_4)_3Cl$, UO_2 and ThO_2 and synthetic silica-aluminium glass containing 4% rare earth elements were used as standards for La, Ce, Nd, Pr, Sm, Ho, Dy and Gd. Phosphorus was calibrated with apatite. For yttrium aluminium garnet (YAG) was used. Al and Fe were calibrated using Al_2O_3 and Fe_2O_3 while for silica orthoclase was used. Further details of the analytical procedure are given in Pant *et al.* (2009). Complete analyses of monazite were obtained for chemical dating and the results with Si+P+S value at ~ 1.0 (normalization of cations at 4 O basis) were used for further processing. For individual spot ages, the formulation of Montel *et al.* (1996) was followed, whereas the age probability plots and unmixing of ages were obtained using the software Isoplot3 (v.3.71.09.06.19nx) (Ludwig, 2003). Uncertainties in individual analyses in the data table and in weighted mean ages are quoted at the 95% confidence level (2σ). Electron Microprobe analyses of monazites along with their calculated spot ages are given in Table 1.

Monazite chemistry

Regional metamorphic grains (sample GG-5)

Six monazite grains in the sample were examined out of which grain1 is present as inclusion in staurolite and grains 2, 3, 4, 5 and 6 are present in matrix (Fig. 6). Grain1 is elongated, euhedral with maximum dimension of $\sim 60\mu m$. Grain2 is subhedral with the length $\sim 15\mu m$ while grain3 has length of around $50\mu m$. Both of these matrix grains are deeply embayed. Grain4 is euhedral and rounded with diameter $\sim 30\mu m$ and grain5, which is of similar size is anhedral. Grain 6 is relatively large in size and subhedral (not shown in Fig. 6).

X-ray elemental mapping of U, Th, Ce and Y of two matrix monazite grains (grain 4 and grain5) are shown in Fig. 7 and 8. Black to blue colour in these maps indicates absence of the element while red colour shows higher content of the mapped element. The Ce X-ray maps show that the two matrix monazites are Ce-monazites (Fig. 7a, 8a). Grain 4 is euhedral while grain 5 is anhedral and resorbed. High Th and high Y fragments in this grain (right central part of the X-ray maps; Fig. 8) indicate that these possibly represent remaining parts of a larger grain. The core of the grain4 is Th deficient while rim is Th-rich (Fig. 7b). Similar pattern is visible in grain5 although not with the same prominence. These grains show zoning of Th from core to rim but boundary of zone is irregular. Both grains are U poor and Y rich monazites (Fig. 7 c,d and 8 c,d).

The inclusion and the matrix monazite grains show large compositional variation. Inclusion monazite is depleted in REE as compared to matrix grains while it has higher Th+U than matrix grains (Fig. 9). Grain1 is also depleted in LREE as compared to matrix grains and show higher huttonite content (Fig. 10). All six grains have almost similar Y content but Th/U ratio is significantly higher in grain1 (Fig. 11). Variation between brabantite and huttonite shows that grain 1 has positive brabantite and huttonite component while other grains only have huttonite component (Fig. 12).

In view of two sets of chemically distinct monazites the age data was analyzed in two groups. The spot ages of six grains are shown in Fig. 13. Grain1 represents dominantly one age population and the probability density plot of this grain gives an age of 917 ± 19 Ma

Fig.6. BSE images of inclusion and matrix monazite grains in garnet staurolite schist. Grain1 is present as inclusion in staurolite and grains 2, 3, 4, 5 and 6 are present in matrix.

Fig7. X-ray elemental maps of Ce (a), Th (b), U (c), and Y (d) of grain 4.

Table 1. Chemical analysis of monazites of garnet schist from Golwa Gangutana and Khetri area (Note: Brb- brabantite; hut- huttonite; apfu- atom per formula unit on 40 basis)

	Grain 1								Grain 2								Grain 3							
DataSet/Point	1/1.	2/1.	1/1.	2/1.	3/1.	4/1.	5/1.	6/1.	3/1.	4/1.	5/1.	6/1.	7/1.	8/1.	9/1.	7/1.	8/1.	9/1.	10/1.	11/1.	12/1.	13/1.	14/1.	
Al ₂ O ₃	0.34	0.07	0.09	0.05	0.06	0.08	0.05	0.07	0.00	0.00	0.03	0.01	0.06	0.00	0.00	0.00	0.00	0.04	0.00	0.01	0.00	0.04	0.02	
SiO ₂	1.38	1.30	1.33	1.07	1.32	0.68	1.28	1.82	0.24	0.26	0.37	0.35	0.91	0.27	0.35	0.33	0.32	0.39	0.30	0.29	0.33	0.50	0.55	
P ₂ O ₅	27.94	29.32	29.90	30.77	28.54	30.29	28.77	28.53	31.79	31.58	30.67	31.83	32.75	31.15	31.01	30.35	30.64	28.74	30.56	30.03	29.70	28.67	28.91	
CaO	2.58	2.75	2.35	2.43	2.82	1.74	2.66	2.60	0.98	0.64	0.57	0.66	0.64	0.68	0.68	0.65	0.63	0.66	0.68	0.59	0.64	0.78	0.90	
FeO	0.15	0.10	0.29	0.20	0.28	0.11	0.06	0.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
Y ₂ O ₃	1.78	1.61	1.51	1.70	2.13	1.57	1.58	1.73	2.15	1.34	1.15	1.43	1.60	1.35	1.52	1.21	1.25	1.32	1.18	1.21	1.25	1.62	1.35	
La ₂ O ₃	10.86	10.88	11.29	11.43	9.80	12.52	11.52	10.39	13.65	15.39	15.40	14.80	14.81	15.11	14.88	16.14	15.92	15.18	15.43	15.91	15.78	14.76	15.01	
Ce ₂ O ₃	20.96	20.70	21.83	21.72	19.68	24.10	21.34	20.09	27.01	28.78	29.01	28.54	28.86	28.55	28.52	28.75	28.56	28.02	28.57	28.67	28.59	26.93	27.21	
Pr ₂ O ₃	2.40	2.45	2.53	2.58	2.56	2.86	2.62	2.43	3.25	3.29	3.30	3.31	3.37	3.25	3.30	3.19	3.13	3.07	3.18	3.19	3.14	3.17	3.07	
Nd ₂ O ₃	9.10	8.99	9.40	9.54	9.38	10.51	9.29	9.06	12.21	11.77	12.00	12.38	12.28	12.04	12.15	11.07	11.07	11.28	11.60	11.20	11.24	11.41	11.05	
SmO	1.66	1.67	1.81	1.82	1.89	1.92	1.74	1.78	2.10	1.86	1.84	2.01	1.92	1.90	1.89	1.70	1.88	1.88	1.94	1.81	1.87	1.92	1.83	
Gd ₂ O ₃	1.40	1.32	1.62	1.60	1.69	1.64	1.40	1.44	1.51	1.37	1.35	1.39	1.26	1.36	1.33	1.37	1.48	1.46	1.52	1.46	1.45	1.61	1.47	
Dy ₂ O ₃	0.49	0.56	0.58	0.60	0.69	0.59	0.50	0.57	0.71	0.49	0.42	0.49	0.53	0.50	0.55	0.48	0.56	0.56	0.52	0.54	0.53	0.63	0.54	
Ho ₂ O ₃	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.00	0.00	0.00	0.02	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00		
PbO	0.67	0.74	0.69	0.67	0.73	0.44	0.71	0.77	0.25	0.17	0.15	0.17	0.16	0.18	0.17	0.18	0.17	0.18	0.18	0.16	0.16	0.21	0.22	
ThO ₂	16.13	16.76	15.40	15.07	17.25	9.68	16.58	18.45	3.63	2.63	2.22	2.72	1.98	2.79	2.58	2.89	2.81	3.02	3.03	2.57	2.64	3.62	4.67	
UO ₂	0.45	0.43	0.50	0.44	0.51	0.39	0.41	0.44	0.72	0.36	0.28	0.29	0.40	0.36	0.39	0.39	0.41	0.43	0.36	0.37	0.38	0.49	0.39	
Total	98.30	99.64	101.09	101.67	99.32	99.12	100.50	100.32	100.27	99.93	98.76	100.36	101.54	99.53	99.33	98.68	98.83	96.23	99.07	98.02	97.71	96.38	97.17	
Age (Ma)	889	938	936	944	900	937	913	895	969	1031	1071	1068	1098	1047	1029	972	955	938	987	983	944	911	859	
Age err	30	30	31	32	29	38	30	28	54	79	92	82	89	76	76	71	71	66	72	77	73	58	53	
Formula	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	
Ca	0.111	0.115	0.097	0.099	0.120	0.073	0.112	0.110	0.040	0.026	0.024	0.027	0.025	0.028	0.028	0.027	0.026	0.029	0.029	0.025	0.027	0.034	0.039	
Fe	0.005	0.003	0.009	0.006	0.009	0.004	0.002	0.005	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	
Sm	0.024	0.024	0.025	0.025	0.027	0.027	0.025	0.025	0.029	0.026	0.026	0.028	0.026	0.027	0.026	0.024	0.026	0.028	0.027	0.026	0.027	0.028	0.027	
Pb	0.007	0.008	0.007	0.007	0.008	0.005	0.007	0.008	0.003	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	
Al	0.016	0.003	0.004	0.002	0.003	0.004	0.002	0.003	0.000	0.000	0.001	0.000	0.003	0.000	0.000	0.000	0.000	0.002	0.000	0.000	0.000	0.002	0.001	
Y	0.038	0.034	0.031	0.034	0.045	0.032	0.033	0.036	0.044	0.027	0.024	0.029	0.031	0.028	0.031	0.025	0.026	0.029	0.025	0.025	0.027	0.035	0.029	
La	0.161	0.157	0.160	0.160	0.143	0.180	0.167	0.151	0.191	0.217	0.221	0.207	0.202	0.215	0.212	0.233	0.229	0.228	0.222	0.232	0.232	0.221	0.223	
Ce	0.308	0.297	0.308	0.302	0.286	0.344	0.307	0.289	0.376	0.403	0.414	0.397	0.390	0.403	0.404	0.413	0.408	0.418	0.408	0.415	0.417	0.401	0.402	
Pr	0.035	0.035	0.035	0.036	0.037	0.041	0.038	0.035	0.045	0.046	0.047	0.046	0.045	0.046	0.046	0.046	0.044	0.046	0.045	0.046	0.046	0.047	0.045	
Nd	0.130	0.126	0.129	0.129	0.133	0.146	0.131	0.127	0.166	0.161	0.167	0.168	0.162	0.166	0.168	0.155	0.154	0.164	0.162	0.158	0.160	0.166	0.159	
Gd	0.019	0.017	0.021	0.020	0.022	0.021	0.018	0.019	0.019	0.017	0.017	0.017	0.015	0.017	0.017	0.018	0.019	0.020	0.020	0.019	0.019	0.022	0.020	
Dy	0.006	0.007	0.007	0.007	0.009	0.007	0.006	0.007	0.009	0.006	0.005	0.006	0.006	0.006	0.007	0.006	0.007	0.007	0.007	0.007	0.007	0.008	0.007	
Ho	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	
Si	0.055	0.051	0.051	0.041	0.053	0.026	0.050	0.071	0.009	0.010	0.014	0.013	0.033	0.011	0.014	0.013	0.013	0.016	0.012	0.012	0.013	0.020	0.022	
Th	0.147	0.149	0.135	0.130	0.156	0.086	0.148	0.165	0.031	0.023	0.020	0.024	0.017	0.024	0.023	0.026	0.025	0.028	0.027	0.023	0.024	0.034	0.043	
U	0.004	0.004	0.004	0.004	0.005	0.003	0.004	0.004	0.006	0.003	0.002	0.002	0.003	0.003	0.003	0.003	0.004	0.004	0.003	0.003	0.003	0.004	0.003	
P	0.948	0.972	0.975	0.990	0.958	0.999	0.958	0.949	1.024	1.023	1.012	1.024	1.023	1.018	1.015	1.007	1.012	0.991	1.010	1.006	1.001	0.987	0.987	
Total	2.015	2.001	1.999	1.994	2.012	1.998	2.009	2.003	1.992	1.990	1.997	1.990	1.984	1.994	1.996	1.999	1.996	2.010	1.999	2.001	2.004	2.011	2.009	
2Ca	0.222	0.230	0.194	0.198	0.240	0.146	0.224	0.220	0.080	0.052	0.048	0.054	0.050	0.056	0.056	0.054	0.052	0.058	0.058	0.050	0.054	0.068	0.078	
(Th+U+Pb)-Ca	0.047	0.046	0.049	0.042	0.049	0.021	0.047	0.067	0.000	0.002	0.000	0.001	-0.003	0.001	0.000	0.004	0.005	0.005	0.003	0.003	0.002	0.006	0.009	
D	0.994	0.977	0.963	0.957	0.996	0.968	1.000	0.980	0.966	0.960	0.971	0.955	0.927	0.968	0.970	0.981	0.974	1.007	0.980	0.984	0.994	1.006	1.002	
XBrb	0.223	0.235	0.201	0.207	0.241	0.151	0.224	0.224	0.083	0.054	0.049	0.057	0.054	0.058	0.058	0.055	0.053	0.058	0.059	0.051	0.054	0.068	0.078	
Xhut	0.047	0.047	0.051	0.044	0.049	0.022	0.047	0.068	0.000	0.002	0.000	0.001	-0.003	0.001	0.000	0.004	0.005	0.005	0.003	0.003	0.002	0.006	0.009	
XLREE	0.658	0.639	0.657	0.652	0.626	0.738	0.668	0.627	0.807	0.853	0.875	0.846	0.825	0.857	0.856	0.871	0.861	0.884	0.864	0.877	0.882	0.863	0.856	
XHREE	0.025	0.024	0.028	0.027	0.031	0.028	0.024	0.026	0.029	0.023	0.022	0.023	0.021	0.023	0.024	0.024	0.026	0.027	0.026	0.026	0.026	0.030	0.027	
XYPO ₄	0.131	0.129	0.134	0.135	0.134	0.151	0.131	0.130	0.172	0.168	0.172	0.176	0.175	0.171	0.173	0.158	0.158	0.163	0.165	0.161	0.161	0.165	0.159	
Th/U	36.750	33.750	33.750	32.500	31.200	28.667	37.000	41.250	5.167	7.667	10.000	12.000	5.667	8.000	7.667	8.667	6.250	7.000	9.000	7.667	8.000	8.500	14.333	
Th (ppb)	143.54	149.17	137.06	134.08	153.50	86.134	147.55	164.22	32.342	233.89	19.785	24.244	17.657	24.813	22.953	257.56	25.044	26.913	26.958	22.864	23.504	32.244	41.518	
U (ppb)	3.942	3.810	4.364	3.828	4.505	3.458	3.616	3.854	6.353	3.168	2.490	2.534	3.546	3.194	3.458	3.405	3.599	3.766	3.159	3.229	3.379	4.312	3.405	
Ce/Sm	12.833	12.375	12.320	12.080	10.593	12.741	12.280	11.560	12.966	15.500	15.923	14.179	15.000	14.926	15.538	17.208	15.692	14.929	15.111	15.962	15.444	14.321	14.889	
Ca+Si/(Th+U+Pb)	0.151	0.148	0.133	0.125	0.155	0.091	0.146	0.162	0.046	0.034	0.037													

Table 1 Contd...

	Grain 4										Grain 5										Grain 6									
DataSet/Point	15 / 1.	16 / 1.	17 / 1.	18 / 1.	19 / 1.	20 / 1.	21 / 1.	22 / 1.	23 / 1.	24 / 1.	25 / 1.	26 / 1.	27 / 1.	28 / 1.	29 / 1.	30 / 1.	31 / 1.	32 / 1.	33 / 1.	34 / 1.	35 / 1.	36 / 1.	37 / 1.	38 / 1.						
Al ₂ O ₃	0.04	0.01	0.05	0.01	0.00	0.00	0.00	0.03	0.01	0.01	0.01	0.00	0.10	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.01	0.01	0.03	0.00						
SiO ₂	0.40	0.25	0.23	0.34	0.42	0.22	0.26	0.25	0.25	0.21	0.27	0.20	0.43	0.21	0.25	0.25	0.22	0.22	0.24	0.20	0.26	0.20	0.22	0.20						
P ₂ O ₅	30.64	30.97	31.30	30.98	31.04	31.14	30.94	30.10	31.32	31.54	32.20	31.43	31.51	30.93	31.51	30.69	31.18	30.75	30.87	30.86	30.74	30.97	30.68	31.28						
CaO	0.56	0.46	0.49	0.51	0.55	0.37	0.32	0.28	0.45	0.55	1.12	0.59	1.03	0.74	0.37	0.36	0.41	0.42	0.40	0.47	0.47	0.32	0.50	0.41						
FeO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00						
Y ₂ O ₃	1.36	1.79	1.74	1.18	1.37	1.34	1.76	1.78	1.17	1.13	1.10	1.42	1.07	1.52	1.35	1.16	1.53	1.49	1.42	1.67	1.28	1.15	1.23	1.53						
La ₂ O ₃	16.25	17.01	17.04	16.73	16.02	17.14	17.34	17.40	18.26	18.74	16.54	18.09	17.43	17.45	17.16	17.45	16.85	16.76	16.92	16.50	16.78	17.07	16.75	16.66						
Ce ₂ O ₃	28.78	29.50	29.52	29.03	28.76	29.79	29.81	29.83	30.69	30.70	29.37	29.88	29.88	29.62	29.78	30.03	29.46	29.34	29.49	29.21	29.41	30.10	29.41	29.54						
Pr ₂ O ₃	3.12	3.09	3.08	3.11	3.18	3.23	3.17	3.07	3.11	3.11	3.13	3.08	3.07	3.13	3.13	3.22	3.19	3.22	3.20	3.22	3.19	3.26	3.17	3.22						
Nd ₂ O ₃	10.88	10.53	10.53	10.84	11.05	10.75	10.50	10.39	10.32	10.08	10.94	10.05	10.34	10.38	11.02	10.83	11.11	11.15	10.97	11.13	11.00	11.21	10.98	11.25						
SmO	1.65	1.49	1.47	1.68	1.78	1.56	1.46	1.49	1.35	1.28	1.69	1.37	1.46	1.48	1.55	1.51	1.59	1.66	1.56	1.63	1.57	1.54	1.54	1.66						
Gd ₂ O ₃	1.28	1.11	1.07	1.24	1.36	1.09	1.07	0.96	0.85	0.80	1.27	0.86	0.91	1.04	1.09	0.92	1.17	1.22	1.17	1.17	1.09	1.07	0.98	1.21						
Dy ₂ O ₃	0.46	0.50	0.53	0.45	0.50	0.46	0.52	0.52	0.33	0.34	0.43	0.42	0.38	0.44	0.47	0.40	0.49	0.51	0.47	0.52	0.41	0.39	0.41	0.51						
Ho ₂ O ₃	0.01	0.03	0.01	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.01	0.01	0.00	0.04	0.00	0.00	0.02	0.03	0.00	0.04	0.00	0.00	0.00	0.00						
PbO	0.18	0.12	0.13	0.18	0.17	0.13	0.10	0.10	0.08	0.08	0.17	0.13	0.11	0.12	0.12	0.11	0.12	0.13	0.13	0.13	0.15	0.11	0.16	0.11						
ThO ₂	2.68	1.13	1.24	2.42	2.57	1.55	0.75	0.69	0.56	0.46	2.41	1.01	1.42	1.19	1.87	1.78	2.00	2.12	2.05	2.00	2.57	1.73	2.62	1.59						
UO ₂	0.32	0.33	0.36	0.36	0.34	0.28	0.36	0.37	0.18	0.19	0.35	0.45	0.25	0.33	0.16	0.13	0.16	0.17	0.16	0.24	0.14	0.11	0.23	0.16						
Total	98.59	98.30	98.77	99.04	99.12	99.05	98.42	97.28	98.90	99.21	101.00	98.98	99.37	98.61	99.82	98.85	99.49	99.18	99.02	98.98	99.06	99.23	98.89	99.34						
Age (Ma)	1107	1176	1180	1113	1067	1143	1204	1201	1506	1627	1077	1179	1101	1184	1113	1173	1086	1094	1131	1042	1133	1171	1059	1139						
Age err	82	118	112	84	81	112	131	131	233	248	85	110	122	119	117	128	109	105	111	99	98	134	88	127						
Formula	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)						
Ca	0.023	0.019	0.020	0.021	0.023	0.015	0.013	0.012	0.018	0.023	0.045	0.024	0.042	0.031	0.015	0.015	0.017	0.018	0.017	0.020	0.020	0.013	0.021	0.017						
Fe	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000						
Sm	0.023	0.021	0.020	0.024	0.025	0.022	0.020	0.021	0.019	0.018	0.023	0.019	0.020	0.021	0.021	0.021	0.022	0.023	0.022	0.023	0.022	0.021	0.022	0.023						
Pb	0.002	0.001	0.001	0.002	0.002	0.001	0.001	0.001	0.001	0.001	0.002	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.002	0.001	0.002	0.001						
Al	0.002	0.000	0.002	0.000	0.000	0.000	0.000	0.002	0.000	0.000	0.000	0.000	0.004	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000						
Y	0.028	0.037	0.036	0.024	0.028	0.028	0.036	0.038	0.024	0.023	0.022	0.029	0.022	0.031	0.027	0.024	0.031	0.031	0.029	0.035	0.026	0.024	0.025	0.031						
La	0.234	0.244	0.242	0.239	0.228	0.245	0.249	0.254	0.259	0.265	0.229	0.257	0.245	0.250	0.242	0.251	0.240	0.240	0.242	0.236	0.241	0.244	0.241	0.237						
Ce	0.411	0.420	0.417	0.412	0.407	0.422	0.424	0.432	0.433	0.431	0.404	0.421	0.417	0.421	0.418	0.429	0.416	0.418	0.419	0.416	0.419	0.427	0.420	0.417						
Pr	0.044	0.044	0.043	0.044	0.045	0.046	0.045	0.044	0.044	0.043	0.043	0.043	0.043	0.044	0.044	0.046	0.045	0.046	0.045	0.046	0.045	0.046	0.045	0.045						
Nd	0.151	0.146	0.145	0.150	0.153	0.148	0.146	0.147	0.142	0.138	0.147	0.138	0.141	0.144	0.151	0.151	0.153	0.155	0.152	0.154	0.153	0.155	0.153	0.155						
Gd	0.017	0.014	0.014	0.016	0.017	0.014	0.014	0.013	0.011	0.010	0.016	0.011	0.011	0.013	0.014	0.012	0.015	0.016	0.015	0.015	0.014	0.014	0.013	0.015						
Dy	0.006	0.006	0.007	0.006	0.006	0.006	0.006	0.007	0.004	0.004	0.005	0.005	0.005	0.005	0.006	0.006	0.006	0.006	0.006	0.007	0.005	0.005	0.005	0.006						
Ho	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000						
Si	0.015	0.010	0.009	0.013	0.016	0.009	0.010	0.010	0.009	0.008	0.010	0.008	0.016	0.008	0.009	0.010	0.008	0.009	0.009	0.008	0.010	0.008	0.009	0.008						
Th	0.024	0.010	0.011	0.021	0.023	0.014	0.007	0.006	0.005	0.004	0.021	0.009	0.012	0.010	0.016	0.016	0.018	0.019	0.018	0.018	0.023	0.015	0.023	0.014						
U	0.003	0.003	0.003	0.003	0.003	0.002	0.003	0.003	0.002	0.002	0.003	0.004	0.002	0.003	0.001	0.001	0.001	0.001	0.001	0.002	0.001	0.001	0.002	0.001						
P	1.011	1.019	1.022	1.017	1.016	1.020	1.018	1.009	1.022	1.024	1.025	1.023	1.017	1.016	1.022	1.013	1.018	1.011	1.015	1.015	1.013	1.017	1.013	1.021						
Total	1.995	1.994	1.992	1.992	1.992	1.991	1.993	1.999	1.993	1.993	1.995	1.993	2.000	1.989	1.995	1.992	1.996	1.994	1.995	1.994	1.993	1.993	1.995	1.992						
2Ca	0.046	0.038	0.040	0.042	0.046	0.030	0.026	0.024	0.036	0.046	0.090	0.048	0.084	0.062	0.030	0.030	0.034	0.036	0.034	0.040	0.040	0.026	0.042	0.034						
Th+U+Pb)-Ca	0.006	-0.005	-0.005	0.005	0.005	0.002	-0.002	-0.002	-0.010	-0.016	-0.019	-0.010	-0.027	-0.017	0.003	0.003	0.003	0.003	0.003	0.001	0.006	0.004	0.006	-0.001						
D	0.969	0.968	0.962	0.965	0.963	0.965	0.968	0.981	0.964	0.964	0.963	0.965	0.963	0.978	0.957	0.973	0.966	0.975	0.968	0.975	0.972	0.967	0.974	0.963						
XBrb	0.047	0.039	0.042	0.044	0.048	0.031	0.027	0.024	0.037	0.048	0.093	0.050	0.087	0.063	0.031	0.031	0.035	0.037	0.035	0.041	0.041	0.027	0.043	0.035						
Xhut	0.006	-0.005	-0.005	0.005	0.005	0.002	-0.002	-0.002	-0.010	-0.017	-0.020	-0.010	-0.028	-0.017	0.003	0.003	0.003	0.003	0.003	0.001	0.006	0.004	0.006	-0.001						
XLREE	0.863	0.875	0.867	0.869	0.858	0.883	0.884	0.898	0.897	0.895	0.846	0.878	0.866	0.880	0.876	0.898	0.876	0.882	0.880	0.875	0.880	0.893	0.881	0.877						
XHREE	0.023	0.020	0.021	0.022	0.023	0.020	0.021	0.020	0.015	0.014	0.021	0.016	0.016	0.019	0.020	0.017	0.021	0.021	0.022	0.022	0.019	0.019	0.018	0.021						
XYPO ₄	0.156	0.151	0.151	0.155	0.159	0.153	0.151	0.150	0.147	0.143	0.153	0.143	0.146	0.147	0.158	0.155	0.158	0.159	0.157	0.158	0.157	0.160	0.157	0.161						
Th/U	8.000	3.333	3.667	7.000	7.667	7.000	2.333	2.000	2.500	2.000	7.000	2.250	6.000	3.333	16.000	16.000	18.000	19.000	18.000	9.000	23.000	15.000	11.500	14.000						
Th (ppb)	23.825	10.083	10.991	21.493	22.899	13.750	6.675	6.158	4.984	4.076	21.422	8.953	12.593	10.546	16.678	15.868	17.835	18.850	18.209	17.791	22.890	15.432	23.344	14.177						
U (ppb)	2.789	2.921	3.132	3.168	2.983	2.490																								

Table 1 Contd...

DataSet/Point	Contact monazite Grain (Cm) from chlorite schist																			
	1/1.	2/1.	3/1.	4/1.	5/1.	6/1.	7/1.	8/1.	9/1.	10/1.	11/1.	12/1.	13/1.	14/1.	15/1.	16/1.	17/1.	18/1.	19/1.	20/1.
Al ₂ O ₃	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SiO ₂	0.21	0.16	0.21	0.19	0.18	0.43	0.19	0.16	0.14	0.25	0.22	0.15	0.15	0.15	0.16	0.34	0.15	0.15	0.16	0.16
P ₂ O ₅	30.15	29.77	29.56	30.00	29.48	28.80	29.51	29.30	29.60	28.74	28.06	29.18	29.38	29.45	29.04	28.84	29.07	29.17	29.58	29.52
CaO	0.15	0.13	0.15	0.15	0.16	0.24	0.15	0.08	0.07	0.11	0.15	0.09	0.11	0.11	0.10	0.12	0.07	0.08	0.20	0.06
FeO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Y ₂ O ₃	1.39	1.46	1.40	1.39	1.44	1.31	0.85	0.78	0.76	0.89	0.76	0.84	0.89	0.77	1.00	0.79	0.80	0.79	1.35	0.86
La ₂ O ₃	15.72	15.15	15.48	15.83	15.07	15.26	16.30	16.37	16.88	16.39	16.38	16.10	16.46	17.16	16.00	16.23	16.24	16.53	15.49	16.12
Ce ₂ O ₃	30.43	30.09	30.43	30.47	30.25	29.93	31.39	31.70	31.19	31.00	31.20	31.82	31.05	31.66	30.86	31.44	31.40	31.47	30.53	31.53
Pr ₂ O ₃	3.45	3.51	3.39	3.45	3.45	3.47	3.43	3.41	3.42	3.35	3.34	3.58	3.40	3.34	3.48	3.45	3.38	3.31	3.48	3.37
Nd ₂ O ₃	13.48	13.83	13.60	13.66	13.66	13.24	13.44	13.20	12.92	13.01	13.11	13.32	13.13	12.97	13.44	13.25	13.18	13.17	13.43	13.36
SmO	2.59	2.84	2.75	2.70	2.66	2.68	2.46	2.54	2.30	2.28	2.34	2.36	2.30	2.22	2.57	2.37	2.33	2.34	2.56	2.43
Gd ₂ O ₃	1.65	1.70	1.59	1.55	1.68	1.61	1.32	1.30	1.26	1.35	1.24	1.31	1.27	1.28	1.43	1.19	1.26	1.29	1.48	1.36
Dy ₂ O ₃	0.43	0.45	0.42	0.43	0.40	0.40	0.26	0.31	0.26	0.34	0.30	0.27	0.34	0.31	0.38	0.30	0.25	0.28	0.39	0.28
Ho ₂ O ₃	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PbO	0.03	0.03	0.02	0.02	0.03	0.03	0.01	0.02	0.02	0.03	0.02	0.02	0.03	0.02	0.02	0.01	0.02	0.01	0.04	0.01
ThO ₂	0.10	0.10	0.07	0.00	0.18	0.12	0.09	0.11	0.06	0.07	0.14	0.09	0.09	0.05	0.10	0.08	0.05	0.05	0.15	0.09
UO ₂	0.27	0.31	0.26	0.28	0.27	0.27	0.17	0.19	0.19	0.27	0.18	0.17	0.31	0.20	0.25	0.19	0.19	0.18	0.26	0.19
Total	100.04	99.53	99.32	100.12	98.90	97.78	99.57	99.47	99.08	98.07	97.44	99.29	98.90	99.70	98.82	98.60	98.37	98.82	99.09	99.34
Age (Ma)	585	696	581	500	601	662	501	589	674	596	679	681	612	533	596	430	598	391	787	413
Age err	214	207	227	212	202	223	302	306	333	238	321	343	215	296	243	281	325	291	236	262
Formula	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)
Ca	0.006	0.005	0.006	0.006	0.007	0.010	0.006	0.003	0.003	0.005	0.006	0.004	0.004	0.005	0.004	0.005	0.003	0.003	0.008	0.002
Fe	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Sm	0.035	0.038	0.037	0.036	0.036	0.037	0.034	0.035	0.031	0.032	0.033	0.032	0.031	0.030	0.035	0.033	0.032	0.032	0.035	0.033
Pb	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Al	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Y	0.029	0.031	0.029	0.029	0.030	0.028	0.018	0.017	0.016	0.019	0.017	0.018	0.019	0.016	0.021	0.017	0.017	0.017	0.028	0.018
La	0.226	0.220	0.226	0.228	0.220	0.226	0.238	0.240	0.247	0.244	0.247	0.237	0.242	0.251	0.236	0.240	0.240	0.243	0.226	0.235
Ce	0.434	0.434	0.440	0.436	0.439	0.440	0.454	0.461	0.453	0.458	0.467	0.464	0.452	0.459	0.452	0.461	0.461	0.460	0.442	0.457
Pr	0.049	0.050	0.049	0.049	0.050	0.051	0.049	0.049	0.049	0.049	0.050	0.052	0.049	0.048	0.051	0.050	0.049	0.048	0.050	0.049
Nd	0.188	0.194	0.192	0.191	0.194	0.190	0.190	0.187	0.183	0.187	0.192	0.190	0.187	0.183	0.192	0.190	0.189	0.188	0.190	0.189
Gd	0.021	0.022	0.021	0.020	0.022	0.022	0.017	0.017	0.017	0.018	0.017	0.017	0.017	0.017	0.019	0.016	0.017	0.017	0.019	0.018
Dy	0.005	0.006	0.005	0.005	0.005	0.005	0.003	0.004	0.003	0.004	0.004	0.003	0.004	0.004	0.005	0.004	0.003	0.004	0.005	0.004
Ho	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Si	0.008	0.006	0.008	0.007	0.007	0.017	0.007	0.006	0.006	0.010	0.009	0.006	0.006	0.006	0.006	0.014	0.006	0.006	0.006	0.006
Th	0.001	0.001	0.001	0.000	0.002	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.000	0.001	0.001	0.000	0.001	0.001
U	0.002	0.003	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.003	0.002	0.002	0.002	0.002	0.002	0.002	0.002
P	0.996	0.992	0.989	0.993	0.990	0.980	0.988	0.985	0.993	0.981	0.972	0.984	0.990	0.987	0.984	0.979	0.987	0.987	0.991	0.990
Total	2.001	2.004	2.006	2.004	2.005	2.010	2.007	2.008	2.003	2.010	2.017	2.009	2.005	2.008	2.009	2.011	2.007	2.007	2.006	2.005
2Ca	0.012	0.011	0.013	0.013	0.013	0.020	0.012	0.007	0.006	0.009	0.013	0.008	0.009	0.009	0.008	0.010	0.006	0.007	0.017	0.005
(Th+U+Pb)-Ca	-0.003	-0.002	-0.003	-0.004	-0.002	-0.006	-0.004	-0.001	0.000	-0.001	-0.003	-0.001	-0.001	-0.002	-0.001	-0.003	-0.001	-0.001	-0.004	0.000
D	0.780	0.793	0.792	0.784	0.797	0.800	0.782	0.782	0.762	0.782	0.797	0.788	0.775	0.771	0.789	0.785	0.778	0.776	0.793	0.777
XBrb	0.016	0.014	0.016	0.016	0.017	0.026	0.016	0.009	0.008	0.012	0.016	0.010	0.012	0.012	0.011	0.013	0.008	0.008	0.021	0.006
Xhut	-0.003	-0.002	-0.004	-0.005	-0.003	-0.008	-0.005	-0.001	-0.001	-0.002	-0.004	-0.002	-0.001	-0.003	-0.001	-0.003	-0.001	-0.002	-0.006	0.000
XLREE	0.954	0.959	0.965	0.960	0.962	0.966	0.982	0.990	0.979	0.987	1.006	0.992	0.978	0.988	0.985	0.990	0.988	0.989	0.963	0.982
XHREE	0.005	0.006	0.005	0.005	0.005	0.005	0.003	0.004	0.003	0.004	0.004	0.003	0.004	0.004	0.005	0.004	0.003	0.004	0.005	0.004
XYPO ₄	1.024	1.023	1.018	1.022	1.020	1.008	1.006	1.002	1.009	1.000	0.989	1.002	1.009	1.003	1.005	0.995	1.004	1.003	1.019	1.008
Th/U	0.356	0.335	0.293	0.011	0.676	0.440	0.547	0.576	0.320	0.265	0.817	0.547	0.296	0.241	0.407	0.451	0.253	0.292	0.583	0.487
Th (ppb)	0.846	0.898	0.649	0.026	1.610	1.041	0.827	0.952	0.534	0.631	1.273	0.818	0.801	0.427	0.881	0.729	0.418	0.445	1.335	0.818
U (ppb)	2.402	2.710	2.244	2.464	2.411	2.393	1.531	1.672	1.689	2.411	1.575	1.513	2.737	1.795	2.191	1.636	1.672	1.540	2.314	1.698
Ce/Sm	12.486	11.272	11.744	12.012	12.090	11.860	13.552	13.243	14.419	14.456	14.173	14.354	14.367	15.178	12.756	14.079	14.292	14.308	12.649	13.775
Ca+Si/(Th+U+Pb)	2.386	1.579	2.596	2.786	1.657	4.529	2.913	2.200	2.270	3.010	2.852	2.383	1.523	2.529	1.906	5.419	2.679	2.852	1.537	2.422
REE+P+Y	1.983	1.988	1.988	1.987	1.987	1.979	1.991	1.995	1.992	1.992	1.998	1.997	1.991	1.995	1.995	1.989	1.995	1.996	1.987	1.993
Th+U+SI	0.011	0.010	0.011	0.010	0.011	0.021	0.010	0.009	0.008	0.013	0.012	0.008	0.009	0.008	0.010	0.016	0.008	0.008	0.010	0.009
Y (ppm)	10957	11566	11044	10997	11344	10341	6707	6178	6028	7031	5996	6628	7039	6115	7892	6225	6312	6225	10673	6762
Si+P	1.004	0.999	0.997	1.000	0.997	0.997	0.995	0.992	0.999	0.991	0.981	0.990	0.996	0.993	0.990	0.992	0.993	0.993	0.997	0.996
U+th+LREE+HREE	0.962	0.969	0.973	0.968	0.971	0.975	0.988	0.996	0.985	0.995	1.013	0.997	0.986	0.994	0.993	0.996	0.994	0.995	0.971	0.988
Ca+Si	0.014	0.012	0.0																	

Table 1 Contd...

DataSet/Point	Contact monazite Grain (Cm) from chlorite schist																			
	21 / 1.	22 / 1.	23 / 1.	24 / 1.	25 / 1.	26 / 1.	27 / 1.	28 / 1.	29 / 1.	30 / 1.	31 / 1.	32 / 1.	33 / 1.	34 / 1.	35 / 1.	36 / 1.	37 / 1.	38 / 1.	39 / 1.	40 / 1.
Al ₂ O ₃	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SiO ₂	0.17	0.16	0.15	0.16	0.18	0.24	0.16	0.17	0.16	0.18	0.17	0.17	0.20	0.18	0.16	0.16	0.18	0.18	0.16	0.24
P ₂ O ₅	29.71	29.72	30.22	30.11	30.40	30.64	30.64	30.80	30.46	30.58	30.79	31.05	30.46	30.66	30.80	30.51	30.06	30.60	30.65	30.86
CaO	0.09	0.10	0.09	0.08	0.07	0.11	0.11	0.09	0.08	0.10	0.10	0.10	0.33	0.26	0.07	0.38	0.25	0.12	0.14	0.21
FeO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Y ₂ O ₃	0.90	0.86	0.80	0.80	0.83	0.90	0.74	0.63	0.80	0.86	0.65	1.02	0.91	0.91	0.73	0.88	0.89	0.86	1.18	0.86
La ₂ O ₃	16.37	16.19	16.78	16.21	16.61	16.72	16.30	16.98	16.63	16.40	16.46	15.62	15.96	15.51	16.36	16.28	16.06	16.30	15.44	16.42
Ce ₂ O ₃	31.09	31.29	31.21	31.59	31.48	30.95	30.75	31.79	31.01	30.83	31.47	30.65	29.90	29.91	30.76	30.30	30.31	30.46	29.99	30.82
Pr ₂ O ₃	3.36	3.50	3.44	3.38	3.57	3.52	3.39	3.54	3.35	3.50	3.39	3.53	3.33	3.38	3.39	3.42	3.37	3.46	3.51	3.37
Nd ₂ O ₃	13.31	13.39	12.94	13.54	13.07	13.12	13.47	12.89	13.04	12.96	13.09	13.75	13.08	13.22	13.30	12.53	12.84	12.93	13.30	12.84
SmO	2.54	2.41	2.37	2.52	2.44	2.48	2.49	2.20	2.41	2.32	2.29	2.66	2.42	2.50	2.49	2.30	2.33	2.34	2.62	2.42
Gd ₂ O ₃	1.40	1.34	1.31	1.37	1.27	1.49	1.42	1.18	1.42	1.34	1.17	1.48	1.27	1.34	1.34	1.29	1.27	1.46	1.51	1.39
Dy ₂ O ₃	0.32	0.34	0.32	0.29	0.31	0.32	0.27	0.24	0.28	0.29	0.26	0.35	0.31	0.23	0.28	0.34	0.31	0.32	0.36	0.29
Ho ₂ O ₃	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PbO	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02	0.01	0.02	0.01	0.03	0.05	0.06	0.02	0.05	0.02	0.04	0.02	0.01
ThO ₂	0.05	0.14	0.10	0.09	0.05	0.09	0.16	0.09	0.06	0.08	0.24	0.03	0.99	1.27	0.21	0.99	0.15	0.17	0.21	0.11
UO ₂	0.26	0.18	0.23	0.17	0.20	0.32	0.24	0.13	0.20	0.25	0.11	0.26	0.21	0.25	0.20	0.23	0.18	0.43	0.20	0.17
Total	99.58	99.64	99.99	100.33	100.49	100.93	100.15	100.75	99.91	99.69	100.20	100.68	99.41	99.67	100.11	99.65	98.22	99.66	99.28	100.02
Age (Ma)	506	485	621	739	565	612	512	741	450	516	442	698	636	704	612	631	729	648	529	440
Age err	241	276	274	361	306	211	238	454	281	246	322	268	152	131	270	148	315	162	234	279
Formula	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)	4 (O)
Ca	0.004	0.004	0.004	0.003	0.003	0.004	0.005	0.004	0.004	0.004	0.004	0.004	0.004	0.014	0.011	0.003	0.016	0.010	0.005	0.006
Fe	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Sm	0.035	0.033	0.032	0.034	0.033	0.033	0.033	0.029	0.032	0.031	0.031	0.035	0.032	0.034	0.033	0.031	0.032	0.031	0.035	0.032
Pb	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000
Al	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Y	0.019	0.018	0.017	0.017	0.017	0.019	0.015	0.013	0.017	0.018	0.013	0.021	0.019	0.019	0.015	0.018	0.019	0.018	0.024	0.018
La	0.238	0.235	0.242	0.233	0.238	0.238	0.233	0.241	0.239	0.235	0.235	0.221	0.229	0.222	0.233	0.234	0.234	0.234	0.222	0.234
Ce	0.449	0.452	0.446	0.452	0.448	0.437	0.436	0.449	0.442	0.439	0.445	0.431	0.427	0.425	0.436	0.432	0.438	0.434	0.427	0.435
Pr	0.048	0.050	0.049	0.048	0.050	0.049	0.048	0.050	0.047	0.050	0.048	0.049	0.047	0.048	0.048	0.048	0.048	0.049	0.050	0.047
Nd	0.187	0.188	0.180	0.189	0.181	0.181	0.186	0.177	0.181	0.180	0.181	0.189	0.182	0.183	0.184	0.174	0.181	0.179	0.185	0.177
Gd	0.018	0.018	0.017	0.018	0.016	0.019	0.018	0.015	0.018	0.017	0.015	0.019	0.016	0.017	0.017	0.017	0.017	0.019	0.019	0.018
Dy	0.004	0.004	0.004	0.004	0.004	0.004	0.003	0.003	0.004	0.004	0.003	0.004	0.004	0.003	0.003	0.004	0.004	0.004	0.005	0.004
Ho	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Si	0.007	0.006	0.006	0.006	0.007	0.009	0.006	0.006	0.006	0.007	0.007	0.007	0.008	0.007	0.006	0.006	0.007	0.007	0.006	0.009
Th	0.000	0.001	0.001	0.001	0.000	0.001	0.001	0.001	0.000	0.001	0.002	0.000	0.009	0.011	0.002	0.009	0.001	0.001	0.002	0.001
U	0.002	0.002	0.002	0.001	0.002	0.003	0.002	0.001	0.002	0.002	0.001	0.002	0.002	0.002	0.002	0.002	0.002	0.004	0.002	0.001
P	0.992	0.992	0.999	0.995	0.999	1.000	1.006	1.005	1.004	1.007	1.008	1.009	1.005	1.008	1.009	1.005	1.005	1.007	1.010	1.008
Total	2.004	2.004	1.999	2.001	1.999	1.997	1.994	1.995	1.996	1.994	1.993	1.992	1.995	1.991	1.992	1.996	1.997	1.993	1.992	1.993
2Ca	0.008	0.008	0.008	0.007	0.006	0.009	0.009	0.007	0.007	0.008	0.009	0.008	0.028	0.021	0.006	0.032	0.021	0.010	0.011	0.017
(Th+U+Pb)-Ca	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.002	-0.001	-0.001	-0.001	-0.001	-0.003	0.003	0.001	-0.005	-0.007	0.001	-0.002	-0.006
D	0.773	0.776	0.758	0.771	0.759	0.757	0.756	0.747	0.753	0.751	0.749	0.761	0.769	0.767	0.748	0.769	0.764	0.754	0.762	0.752
XBrb	0.010	0.011	0.010	0.009	0.008	0.012	0.012	0.010	0.009	0.011	0.012	0.011	0.036	0.028	0.008	0.041	0.027	0.014	0.015	0.023
Xhut	-0.001	-0.002	-0.001	-0.001	-0.001	-0.001	-0.001	-0.002	-0.001	-0.001	-0.001	-0.002	-0.004	0.004	0.001	-0.006	-0.009	0.001	-0.003	-0.008
XLREE	0.975	0.976	0.966	0.974	0.966	0.957	0.955	0.962	0.960	0.952	0.954	0.944	0.934	0.930	0.951	0.935	0.949	0.946	0.938	0.943
XHREE	0.004	0.004	0.004	0.004	0.004	0.004	0.003	0.003	0.004	0.004	0.003	0.004	0.004	0.003	0.003	0.004	0.004	0.004	0.005	0.004
XYPO ₄	1.011	1.010	1.016	1.012	1.016	1.019	1.021	1.018	1.020	1.024	1.021	1.030	1.024	1.027	1.024	1.023	1.023	1.025	1.034	1.026
Th/U	0.205	0.770	0.435	0.517	0.238	0.303	0.700	0.727	0.280	0.312	2.181	0.124	4.813	5.305	1.028	4.309	0.859	0.391	1.048	0.672
Th (ppb)	0.453	1.219	0.863	0.774	0.409	0.836	1.450	0.809	0.489	0.667	2.144	0.275	8.837	11.311	1.824	8.775	1.352	1.468	1.833	1.005
U (ppb)	2.244	1.601	2.006	1.513	1.742	2.789	2.094	1.126	1.768	2.164	0.994	2.244	1.856	2.156	1.795	2.059	1.592	3.801	1.768	1.513
Ce/Sm	12.992	13.795	13.996	13.311	13.708	13.240	13.144	15.326	13.647	14.101	14.585	12.245	13.148	12.688	13.112	14.013	13.837	13.854	12.184	13.508
Ca+Si/(Th+U+Pb)	2.291	2.157	1.878	2.467	2.998	2.375	1.656	3.107	2.561	2.383	2.066	2.434	0.697	0.515	1.662	0.569	2.248	1.222	1.604	3.624
REE+P+Y	1.990	1.990	1.986	1.989	1.986	1.980	1.980	1.983	1.984	1.980	1.979	1.979	1.963	1.960	1.979	1.963	1.976	1.975	1.977	1.973
Th+U+SI	0.009	0.009	0.009	0.008	0.009	0.013	0.010	0.008	0.008	0.010	0.010	0.009	0.018	0.020	0.010	0.017	0.010	0.012	0.010	0.012
Y (ppm)	7126	6818	6320	6288	6589	7126	5870	4977	6312	6770	5127	8050	7205	7181	5767	6944	7039	6802	9322	6770
Si+P	0.999	0.998	1.005	1.002	1.006	1.010	1.012	1.012	1.010	1.014	1.015	1.016	1.013	1.015	1.015	1.011	1.012	1.014	1.016	1.018
U+th+LREE+HREE	0.982	0.983	0.973	0.980	0.972	0.964	0.962	0.967	0.966	0.958	0.961	0.951	0.949	0.946	0.958	0.950	0.956	0.955	0.946	0.949
Ca+Si	0.010	0.011	0.010	0.010	0.010	0.014	0.011	0.010	0.010	0.011	0.011	0.011	0.022	0.018	0.009	0.022	0.018	0.012	0.012	0.018
U+Th+Pb	0.003	0.003	0.003	0.002	0.002	0.004	0.004	0.002	0.002	0.003	0.0									

Fig.8. X-ray elemental maps of Ce (a), Th (b), U (c), and Y (d) of grain5. Note resorbed nature of the grain especially in the Th and Y maps which indicate that originally this grain was larger with the high Th and higher Y fragments on right central part of the X-ray maps being part of the same grain.

Fig.9. A plot of Th+U+Si versus P+Y+REE. Note: Segregation of contact monazite at one end. Inclusion monazite is depleted in REE as compared to matrix grains while it has higher Th+U than matrix grains.

Fig.10. A plot of X_{LREE} versus X_{HUT} . Note: Contact monazite grains value occurs on the extreme end of LREE showing enrichment. Grain1 is depleted in LREE as compared to matrix grains and show higher huttonite content.

Fig.11. A plot of X_{YPO_4} versus Th/U. Note: All six grains have almost similar Y content but Th/U ratio is significantly higher in grain1 and contact monazite grain has highest Y content and lowest Th/U.

Fig.12. A plot of Variation between brabantite and huttonite. Note: grain 1 has positive brabantite and huttonite component while other grains only have huttonite component. It has lower brabantite content comparative to grain1 but it is higher than matrix grains.

Fig.13. BSE image of six monazite grains annotated with the spot ages.

Fig.14. Probability density plot of grain 1 gives an age of 917 ± 19 Ma.

(Fig. 14). The point age data of grains 2, 3, 4, 5 and 6 gives two distinct age populations that are 941 ± 23 Ma and 1100 ± 20 Ma (Fig. 15). The older age constitutes 75% of the ages while the younger age is within the range of age estimated from the inclusion grain. The ages of 1506 and 1627 Ma are from a grain which is anhedral and altering and the low Th in respect of these points possibly reflects open system for this element.

Contact zone monazite (Sample KH-2)

Monazites in this sample are comparatively of larger size. The analyzed grain is anhedral with irregular grain boundary and has length $\sim 200 \mu\text{m}$. Monazite is unzoned and distinctly different from all monazites of garnet-staurolite schist. This grain is enriched in LREE while it is depleted in huttonite content (Fig.10). It has strikingly higher X_{YPO_4} than other monazites while it has Th/U content close to 0 (Fig.11). It has lower brabantite content comparative to

Fig.15. Probability density plot of grains 2, 3, 4, 5 and 6 gives two distinct age populations that are, 941 ± 23 Ma and 1100 ± 20 Ma.

Fig.16. Elemental map of Th, Ce, U and Y of contact monazite grain.

grain1 but it is higher than matrix grains (Fig. 12). It also shows highest value of P+Y+REE which signifies its enrichment in REE (Fig. 9). Fig.16 shows the elemental mapping of Th, Ce, U and Y which shows grain is also a Ce- monazite but has higher Ce content comparative to other monazites. The most significant character about this monazite is that it is significantly depleted in Th content (Fig. 16).

A 40 point's average on 2σ level gives the statistically analyzed age around 649 ± 40 Ma (Fig.17).

Discussion

Several modes of monazite formation have been proposed which

Fig.17. A 40 point's average on 2σ level gives the statistically analyzed age around 649 ± 40 Ma.

Fig.18. A plot of Thorium (a), Cerium (b), and Lead (c) variation versus age of seven monazite grains.

include heterogeneous reaction (which include the solid state growth or recrystallization under changed pressure-temperature conditions or metamorphic growth), precipitation from fluids, dissolution and/or reprecipitation under fluid influx (hydrothermal mode), annealing etc. and in hydrothermal influenced growth it often partially or totally resets the U-Th-Pb systematic (Spear and Pyle, 2002; Ayers et al. 2006). Precipitation of REE and monazite growth in contact aureoles has been attributed to fluid mobilization (Rasmussen et al. 2001; Rasmussen and Fletcher, 2002). As in this study monazite has been occasionally used to date the hydrothermal event (Ayers et al., 2006; Rasmussen et al., 2007). Since there is strong control of fluids in monazite growth during contact metamorphism, chemical distinctions

between monazite formed dominantly by solid state transformation and that in a contact aureole can be expected. Ayers et al. (2006) noted lower Si, Th, Pb and U and higher REE in monazite proximal to the contact zone in the Birch Creek Pluton aureole in eastern California which they attributed to the dissolution and reprecipitation of monazite by the infiltrating fluids which was corroborated by the oxygen isotope compositions of the proximal and distal monazites. Thus, besides temperature fluids appear to strongly influence the monazite chemistry in contact metamorphic setting. It has been noticed that the brabantite component increases away from a contact metamorphism aureole (Ayers et al. 2006). Th (or U)+Ca = 2REE represent the brabantite substitution. A plot of brabantite versus huttonite shows that monazite from contact zone of KCB and regional metamorphic monazite from Golwa- Gangutana area are chemically distinct (Fig. 12). The huttonite content is lowest in contact monazite. The nature of zoning in two types of monazite is also different. Grain 4 and grain 5 of matrix show patchy and partial zoning which are possibly due to partial resetting of the U-Th-Pb systems (Townsend et al., 2000; Ayers et al. 2006, 2013) or due to recrystallization during retrograde metamorphism. The composite monazite from the lowest grade portion of the contact aureole present in south central Maine (Wing et al., 2003) also show similar trend as of contact monazite of KCB. The composite monazites are zoned monazite with inclusion free core and inclusion rich rim which is a result of recrystallization to varying degrees (Wing et al., 2003).

All monazites of both samples are Ce-rich (Table 1). However significant and contrasting chemical variations are clearly distinct and three sets of monazite compositions can be identified. Since, three age domains are indicated the Ce, Th and Pb values are plotted against age (Fig. 18) to assess the chemical variations. Inclusion grain1 has highest Ce and matrix grains 2,3,4,5 and 6 in the garnet staurolite schist contain lower Th (Fig. 18a). The two outlier values of 1506 and 1627 Ma are not considered on account of very low Th and it is inferred that these either represent a detrital component or disequilibrium composition. These two ages are from rim area of grain 5 which is anhedral and appears to be resorbed. The monazite from the contact mineralized zone (Khetri) plots distinctly with lowest Th. Behavior of Ce is inverse of the Th concentration with the contact monazite having highest Ce (Fig. 18b). Pb plot mirrors the Th behavior (Fig. 18c). In view of this, Ce/Th can be considered as a function to segregate the three composition domains. The Ce/Th values of grain 1 range from 1.75-4.00 while that of the matrix grains of the garnet staurolite schist vary from 10-70 (excluding the outliers) with most of the values between 20-40 while the contact monazite shows much higher ratios (>240) of these two elements (Table 1).

The inclusion monazite (grain 1) and the younger age of the matrix monazites provide a well constrained age of 920-940 Ma which is close to the age of the peak regional metamorphism in the area (Pant et al., 2008). The metamorphic conditions for the Barrovian metamorphism have been estimated to be $550^{\circ}\pm 50^{\circ}\text{C}$ and 550° – 650°C with pressure range of 300 to 500MPa during M1 and M2 phases, respectively (e.g. Sarkar and Dasgupta, 1980; Lal and Ackermann, 1981; Sharma, 1988; Kundu et al., 2004; Pant et al. 2008). Formation of cordierite and biotite as a contact metamorphic effect in Khetri and its association with the Cu-sulfide deposit suggests mineralization to be hydrothermally controlled. Chemical dating of monazite indicates age of ~650Ma for this mineralization. Association of chemically distinct monazite in this well constrained contact metamorphic assemblage shows that the monazite formed in such

setting can be distinguished using Ce/Th ratios in comparison to the monazites of the regional metamorphic assemblages.

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