JOURNAL GEOLOGICAL SOCIETY OF INDIA
Vol.91, January 2018, pp.67-75

Geochemistry and Petrogenesis of 2.8 Ga Old Rare Metal Bearing Fertile Granite at Allapatna, Mandya District, Karnataka

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ABSTRACT

This paper reports petrography, geochemistry and Rb-Sr age data on the rare metal bearing Neoarchean fertile (Nb-Ta) granite at Allapatna and elucidates its petrogenesis and role in Nb-Ta-Li-Be mineralization. The Allapatna granite (AG) intrudes the Tonalitic-Trondhjemitic - Granodioritic (TTG) Peninsular Gneiss and analysed SiO_2 (72.3-75.6 wt%), K_2O (4.0-5.7wt%), Na_2O (3.0-4.4wt%), CaO (0.7-1wt%), MgO (0.13-0.25wt%) and K_2O/Na_2O (>1) indicating evolved nature. The presence of muscovite, biotite and garnet in the mode, peraluminous nature and high initial $^{87}Sr/^{86}Sr$ ratio (0.7284±0.0083) attest to their S-type characteristics. Varying Nb/Ta ratio and high Li with moderate abundance of Cs further indicate affinity to Li-Cs-Ta (LCT) type granite-pegmatite system. The AG showing whole rock Rb-Sr isochron age of 2803± 68 Ma, is the oldest reported fertile granite in India parental to rare metal pegmatites hosting Nb-Ta, Be, and Li resources. Partial melting of a mixed source consisting of both basement TTG rocks and metapelites has generated such type of granitic magma. Fractionation of such granitic magma possibly has given rise to the rare metal (Ta-Nb-Li-Be) bearing pegmatites intruding the nearby schist belt.

INTRODUCTION

In many pegmatite fields of the world, the source of rare metals (Li, Nb, Ta and Be) is considered to be fertile granites which are genetically related to the pegmatites (Cerny and Meintzer, 1988; Linen and Cuney, 2005). The fertile granite with respect to lithium-niobium-tantalum of LCT (Li-Cs-Ta) system is characterized by low calcic (CaO), high silicic (SiO_2) and potassic (K_2O), having high Rb, moderate Ba and low Sr content, peraluminous S-type character exhibited by the typical presence of Al rich minerals like muscovite, biotite and garnet. As such, characterization of these granite-pegmatite systems is essential, although in many cases it is difficult or impossible to locate the parental granite (Cerny et al., 1981; Shearer et al., 1987; Breaks and Moore, 1992). The oldest extensive rare metal granite-pegmatite systems are of Kenoran age (2800 Ga) and appear to be characteristic of many shield areas (Cerny, 1991a and b, 2005; Shearer et al., 1987; Breaks and Moore, 1992). These granites are mainly confined to greenstone belts and different hypotheses have been proposed for their origin, ranging from entirely crustal origin to a mixed TTG-supracrustal protoliths (Cerny and Meintzer, 1988).

The schist belts of southern part of Dharwar craton of southern Karnataka, are intruded by numerous rare element (Nb, Ta, Be, Li) pegmatites. The most significant occurrence is at Marlagalla-Allapatna which contains columbite-tantalite, beryl and spodumene (Banerjee et al., 1987, 1994; Sarbajna, 1998). Many stock-like bodies of granite intruded the schist belts and surrounding tonalite-trondhjemite-granodiorite (TTG) gneisses in this area (Fig.1a, b). The AG represents one such granitic body which has been considered to be the possible source for these rare metal pegmatites (Sarbajna and Krishnamurthy, 1996). So far there is no reported Indian example of fertile rare metal granite-pegmatite system of Neoarchean age. In this paper field, petrological, geochemical and Rb-Sr geochronological data on AG are presented to constrain its petrogenesis and possible tectonic setting.

GEOLOGICAL SETTING

The southern Indian Precambrian shield is divided into two blocks, a granite greenstone terrain in the north and granulite terrain in the south (Fig.1a, b). The granite greenstone terrain is classically termed as 'Dharwar craton', which consists of two parts; (1) Western Dharwar craton (WDC) and (2) the younger Eastern Dharwar Craton (EDC) (Swami Nath and Ramakrishnan, 1981; Ramakrishnan, 1994; Naha et al., 1996). However, recently it has been suggested that crust formation in both the western and eastern Dharwar cratons took place over similar time interval of 3.5-2.5 Ga (Maibam et al., 2011).

The WDC comprises 3.4-3.0 Ga 'ancient supracrustals' (Sargur Group) and tonalite-trondhjemite-granodiorite (TTG) basement overlain unconformably by 2.9-2.6 Ga greenstone belts (Radhakrishna and Vaidyanathan, 1997; Chadwick et al., 2000). The EDC is mainly made up of late Archaean (2.6-2.5Ga) TTGs, sanukitoids and granites with interleaved narrow greenstone belts interpreted to be accreted against the WDC (Radhakrishna and Vaidyanathan, 1997; Chadwick et al., 2000; Jayananda et al., 2000; Moyen et al., 2003).

The AG (7 km × 3 km) intrudes the TTG gneisses and the N-S trending Nagamangala schist belt (Sargur) near Mysore-Srirangpatna (Fig. 1b), which comprises fuchsite quartzite, biotite-garnet-quartz schist, banded iron formation and amphibolites with lensoid bands of crystalline limestone, staurolite-mica schist and garnet-sillimanite-biotite gneiss (Fig. 1b). Spinifex-textured peridotitic komatiite was also reported (Srikantappa et al., 1992). Mineral assemblages developed in different lithologies indicate regional greenschist to middle amphibolite facies metamorphism (Sarbajna, 1998).

TTG gneisses represent granitic intrusions in different phases and their remobilization products which have suffered polyphase deformation. Naqvi et al. (1980) have grouped the gneisses of this area into four suites viz. (i) quartzo-feldspathic gneisses, (ii) banded migmatitic gneisses, (iii) paragneisses and (iv) trondhjemite-granodiorite-granite plutons.

Neoproterozoic felsite and dolerite dykes cut across all the older lithologies of the area (Radhakrishna and Vaidyanadhan, 1997). The schist belt is affected by an E-W trending fault along the river Cauvery (Fig. 1b). The Nagamangala belt represents a series of isoclinal folds with axes (F-1) running along a N 15°E-S15° W direction and the pegmatites have intruded along the hinges of these folds (Sarbajna, 1998).

The AG consists of leucocratic pink and grey, medium to coarse grained granitoids. Parallel alignment of biotite grains imparts a crude

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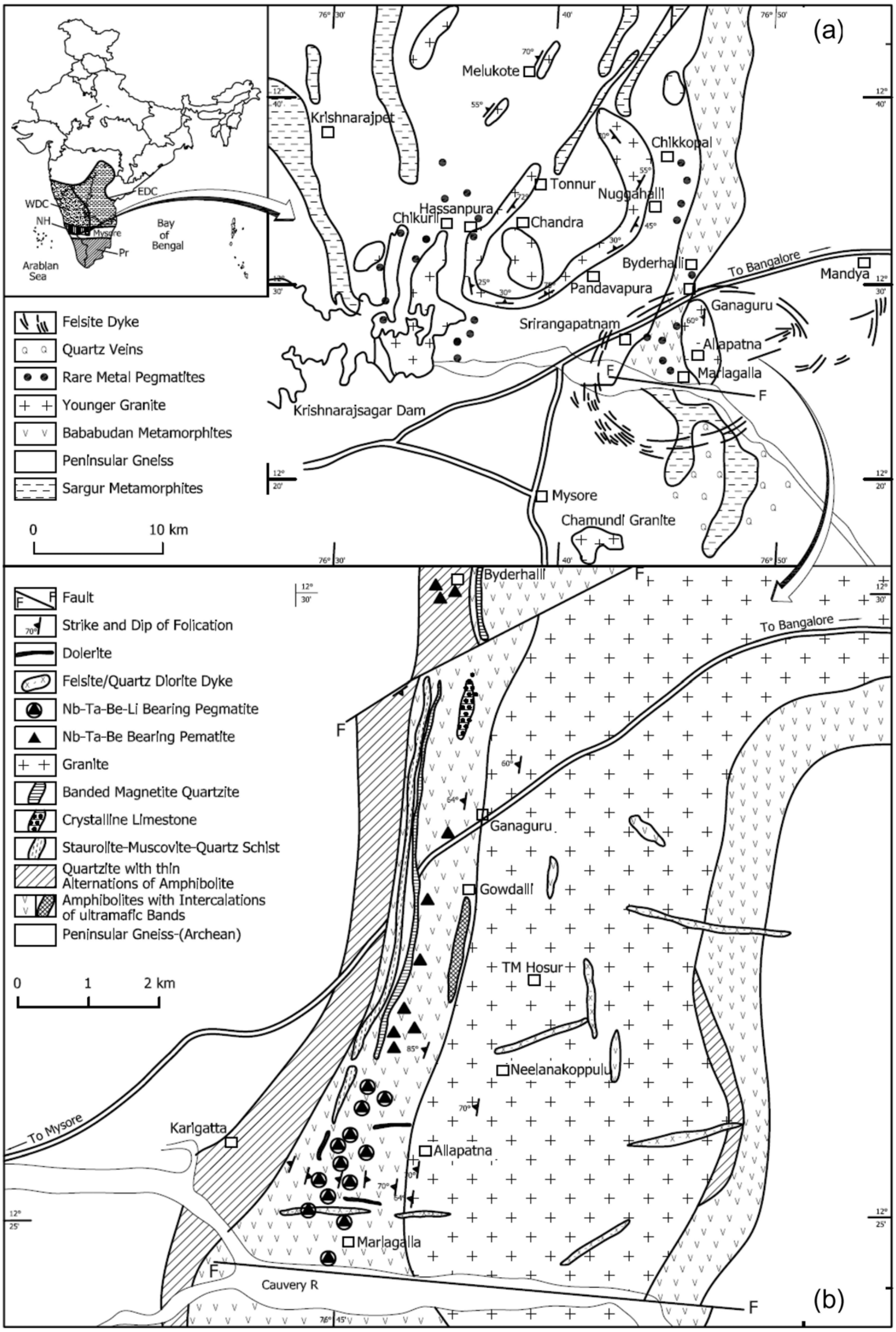

Fig.1. (a) Geological map of part of southern Karnataka (modified after Banerjee et al., 1987). **(b)** Geological map around Marlagalla-Karigatta-Allapatna area, Mandya district, Karnataka (Sarbajna, 1998).

NE-SW trending gneissosity. Relict patches of quartzites occur within AG. Pegmatite and aplite veins are abundant within AG. The pegmatites are simple, unzoned, and homogenous in nature (Sarbajna,1998). The fractionated liquid of AG were responsible for poorly zoned and mineralised Nb-rich columbite-tantalite bearing pegmatites near the contact of AG and the amphibolites. Further fractionation has possibly given rise to complex zoned highly mineralized spodumene-tantalite-alkali beryl rich pegmatites.

PETROGRAPHY

AG is a leucocratic, medium- to coarse-grained (at places pegmatitic) rock showing hypidiomorphic texture. It is two-mica eqigranular granite mainly consisting of quartz, K-feldspar (microcline, orthoclase and microcline perthite) and sodic plagioclase with minor biotite and muscovite. Accessory minerals include garnet, sphene, allanite, zircon, epidote, hornblende, chlorite, apatite, magnetite and ilmenite. Discrete grains of coffinite and gummite have also been

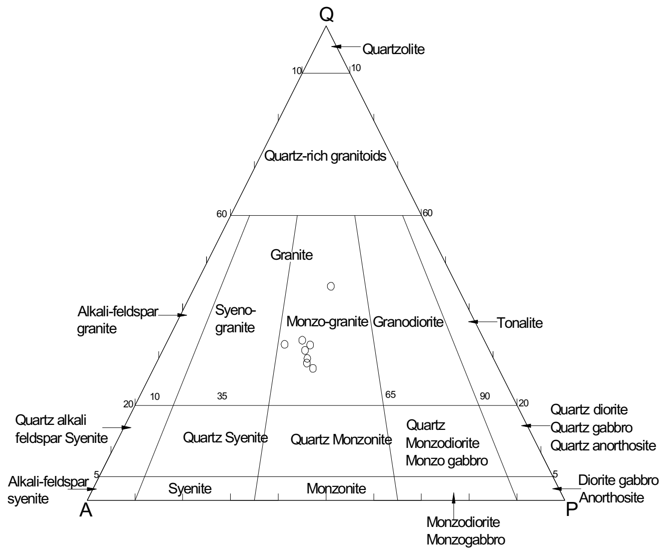

Fig. 2. Allapatna granites, Mandya District, plotted in the QAP diagram of Streckeisen (1976). It can be observed that the granitic rocks are confined to "Monzogranite" sub field within "Granite" field.

identified. The presence of columbite-tantalite along with rutile, anatase and goethite have been confirmed by XRD studies of heavy mineral separates. Subhedral to anhedral crystals of zoned zircon are present as inclusion within perthite crystals. Alteration products in AG include epidote, green biotite, clinozoisite and chlorite. In the quartz-alkali-feldspar-plagioclase feldspar (QAP) diagram of Streckeisen (1976), the AG plot in the field of monzogranite (Fig.2).

GEOCHEMISTRY

Analytical Procedures

Representative fresh, cogenetic and undeformed samples (n=14), weighing about 10-12 kg, were collected from widely distributed locations for both geochemical and geochronological studies. The samples were first cleaned using ultrasonic cleaner, and then dried and powdered with the help of crushers, ball mill and pulverizer to -100 mesh. Finally, the representative powdered samples were ground to -250 to -300 mesh.

Major elements were analyzed in chemical laboratory, Atomic Minerals Directorate for Exploration and Research (AMD), Hyderabad. Si, Ti and P were analyzed by spectrophotometer; Na, K by flame photometer; Al, Fe (total), Ca, Mg, Mn, Li by atomic absorption spectrometer (AAS) by a GBC-make Avanta-P spectrometer; Fe^{2+} by titrimetry, Th by ICP-OES and U by fluorimetry. Loss on ignition was determined by heating powdered samples for 2 hours at 950°C. REE, Hf, Ta, Cs, and were analyzed by instrumental neutron activation (INA) technique following the method of Gordon et al. (1968). 100 mg of powdered sample was placed in a quartz vial, heated, sealed and irradiated in a neutron flux of 10^{13} $ns^{-2}cm^{-2}$ for a period of 7 hrs in CIRUS reactor, Bhaba atomic research centre, Mumbai. Gamma ray spectra of activated samples are measured using high purity germanium detector in physics laboratory, AMD, Hyderabad. Percentage of error due to counting statistics at 1 sigma level for La, Ce, Sm and Eu, is reported 10%. Trace elements like Rb, Sr, Ba, Y, Zr, Nb, Cu, Ni contents in these granites are analyzed at XRF laboratory, AMD, Hyderabad using sequential wavelength dispersive x-ray fluorescence spectrometer(Philips-1410). Undiluted, plain pressed pellets of samples and international rock standards of 40 mm diameter were made from 1 g of the ultra-fine rock powder (-200 mesh) using boric acid as backing material at a pressure of 20000 kg/cm^2. Certified reference materials (CRM) like GSP1, G2, GSN, GH, SG1A (USGS); JG1A, JG2 and JG3 (Japan) were used as calibration standards for analysis of major and trace elements by WDXRFS as well as wet chemical techniques. The analytical accuracy is SiO_2±0.8%, TiO_2±3%, Al_2O_3±0.4%, Fe_2O_3±1.0%, FeO±2.5%, MnO ±2.0%, MgO ±1.3%, CaO: ±0.6%, Na_2O and K_2O ±1.6% and P_2O_5 ±6%. For trace elements and REE the accuracy is better than 5% for concentrations <30 ppm and 10% for concentrations < 5ppm.

Isotope analysis was performed in the geochronology and isotope geochemistry laboratory, AMD, Hyderabad by using a multi collector thermal ionization mass spectrometer (TIMS, VG-354). Approximately 200 mg of representative powdered rock sample spiked with tracers enriched in ^{87}Rb and ^{84}Sr were dissolved with 6 ml 48% HF and 2 ml 16M HNO_3 in a Savillex FEP digestion vessel at 150 °C for 48 hrs. Separate powders were dissolved for isotopic ratio measurements of Sr. Trace solutions were calibrated by carefully prepared solutions of Jhonson-Mathew spec pure salt. Sr and Rb contents are determined by isotope dilution mass spectrometry. Ion exchange techniques are used to separate elements for isotope analyses. Rb and Sr are separated using BiO-Rad AG-50*12 cation exchange resin. The total analytical blanks for Rb and Sr were <0.5 and 1 respectively. The Sr isotopic ratio are normalized to $^{86}Sr/^{88}Sr$=0.1194. The SRM987 yielded a mean $^{87}Sr/^{86}Sr$ ratio of 0.710241±23 (n=15). USGS rock standard G-2 has given the following mean values (n=3): Rb=170.0±0.5 ppm, Sr=480.5±1ppm. The analytical errors at 2σ are 2% for $^{87}Rb/^{86}Sr$, 0.05% for $^{87}Sr/^{86}Sr$. The decay constant used is l^{87}Rb=1.42*10^{-11}a-$^{1.}$ The slopes and intercepts were calculated using isoplot programme of Ludwig (1993).

Major and Trace Element Geochemistry

Major and trace elementsincluding REE concentration of AG are given in Table 1, 2 and 3. They are highly fractionated in nature with high but limited range of SiO_2 (72.3-75.6%), Na_2O (3.00-4.38%). K_2O (4.0-5.7%) and with low CaO (0.7-1%), MgO (0.13-0.57%), Fe_2O_3(0.23-0.63%) and FeO (0.57-1.40%). In Harker variation diagrams (Figs. 3, 4) Al_2O_3, CaO, MgO, Ba, Sr and Zr show negative correlation with SiO_2, while CaO and Sr show sympathetic relationship. The negative correlation between CaO and SiO_2indicates plagioclase fractionation which is corroborated by the presence of albite in the coarse grained variety of the granite in place of oligoclase. The AG shows very low contents of FeO, Fe_2O_3, MgO and TiO_2 than the general granitoids. Total iron expressed as FeO ranges from 0.57 to 1.40% and reveals a dominance of Fe^{2+} over Fe^{3+}. MgO content ranges from 0.13 to 0.57%, which exhibits a dispersed variation with SiO_2.

Granites are peraluminous (Fig.5; A/CNK =1.02-1.12) with normative corrundum (0.01 to 1.32 wt %). K_2O/Na_2O ratios vary from 1.03 to 1.88 (avg.1.27). K/Rb ratios in AG range from 89 to 182 with an average of 128 and fall within the field of rare metal fertile granite (Fig 6, 7). This field indicates pegmatitite hydrothermal trend of Shaw (1968) and according to Cerny et al. (1985), it marks a turning point in K/Rb evolution of fertile granites and is characterized by a sharp decrease in the ratio in products of late- and post-magmatic crystallisation. K/Rb vs Rb (Fig. 7) shows a negative correlation indicating enrichment of Rb with fractionation in the residual liquids or fluids of the granite. The most conspicuous relationship that exists between Rb, Ba and Sr in these granites is the enrichment of Rb compared to Ba and Sr, indicating its strongly differentiated character (Fig.8). However, samples plot slightly away from the field boundary due to the higher Sr content, which varies from 85-177 ppm. This trend is also supported by the variable CaO content in these granites. Rb/Sr ratios (Table 2) of AG show a fairly large variation (1.5-4.6) with an average value of 2.6 which is markedly higher than barren granite (0.25). The average ratio (2.6) is, however, lower than the reported value from fertile rare metal granite (5.2; Cerny and Meintzer,

Table 1. Major element analyses and CIPW Norms of Allapatna granite, Mandya district, Karnataka

Samlpe No.	95/1	95/2	95/4	3A	3D	4A	4D	95/103	95/94	95/95	95/96
SiO_2	72.27	73.93	74.69	73.49	74.26	73.73	74.26	75.59	75.28	73.23	74.16
TiO_2	0.13	0.14	0.11	0.11	0.27	0.17	0.15	0.10	0.10	0.24	0.08
$Al2O_3$	14.48	13.93	13.82	13.90	13.47	14.01	13.53	12.50	12.73	13.62	14.07
Fe_2O_3	0.34	0.55	0.23	0.42	0.63	0.58	0.58	0.27	0.23	0.57	0.28
FeO	1.01	0.93	0.90	0.79	0.57	0.79	0.79	0.72	1.15	1.40	1.01
MnO	0.03	0.03	0.03	0.02	0.02	0.03	0.03	0.01	0.03	0.03	0.03
MgO	0.24	0.25	0.21	0.17	0.17	0.18	0.22	0.18	0.13	0.57	0.14
CaO	1.02	0.96	0.84	0.83	0.80	0.94	0.84	0.67	0.71	1.04	0.67
Na_2O	3.88	4.00	3.88	3.60	3.60	3.60	3.60	3.00	3.86	3.91	4.38
K_2O	5.01	4.53	4.44	4.60	5.00	4.60	4.80	5.65	4.24	4.01	5.02
P_2O_5	0.05	0.05	0.04	<0.05	<0.05	<0.05	<0.05	0.03	0.04	0.15	0.08
LOI	0.15	0.18	0.18	0.27	0.23	0.19	0.15	0.06	0.05	0.07	0.11
Total	**98.61**	**99.48**	**99.37**	**98.2**	**99.02**	**98.82**	**98.95**	**98.78**	**98.55**	**98.84**	**100.03**
K_2O/Na_2O	1.29	1.13	1.14	1.28	1.39	1.28	1.33	1.88	1.1	1.03	1.15
A/CNK	1.060	1.053	1.090	1.120	1.053	1.111	1.070	1.019	1.041	1.076	1.015
A/NK	1.210	1.210	1.210	1.210	1.210	1.210	1.210	1.210	1.210	1.210	1.210
Mg#	24.52	23.81	25.25	20.59	21.03	19.64	23.00	24.97	14.57	34.67	16.50
Q	27.522	30.71	32.52	32.54	32.3	32.7	32.61	34.46	34.17	31.68	27.95
Or	29.55	26.77	26.24	27.18	29.55	27.18	28.37	3.39	25.06	23.7	29.82
Ab	32.83	33.85	32.83	30.46	30.46	30.46	30.46	25.39	32.66	32.09	36.57
An	4.73	3.68	3.91	3.79	3.64	4.34	3.84	3.13	3.26	4.18	4.82
C	0.75	0	0.2	1.24	0.8	0.31	0.01	0.3	0.6	1.32	0.2
Hy	2.01	1.38	1.84	1.38	0.54	1.19	1.33	1.4	2.13	3.18	1.9
Mt	0.49	0.8	0.33	0.61	0.91	0.84	0.84	0.39	0.35	0.83	0.41
Il	0.25	0.27	0.21	0.21	0.51	0.32	0.28	0.19	0.19	0.46	0.15
Ap	0.12	0.12	0.09	0.12	0.12	0.12	0.12	0.07	0.09	0.35	0.19

Table 2. Trace element analyses of Allapatna granite, Mandya district, Karnataka

Sample No.	95/1	95/2	95/4	3A	3C	3D	4A	4B	4D	4E	95/94	95/103	95/95	95/96
Rb	302	253	319	325	228	290	318	270	306	282	373	284	233	405
Sr	177	146	120	104	97	107	108	120	114	113	95	113	152	85
Ba	442	249	232	245	200	200	200	208	262	218	108	297	317	180
Y	26	223	21	39	39	43	30	19	226	47	47	20	46	52
Hf	4	5	4	4.5	3.6	4	4.2	4.3	3.9	3.5	5.3	6	5	5
Zr	161	136	113	135	123	139	114	104	142	127	72	108	178	136
Nb	20	20	26	19	23	19	28	16	20	17	24	28	19	354
Ta	15	15	15	10	15	10	10	10	12	12	10	10	10	20
Sn	4	5	5	4	4	< 2	< 2	13	39	25	5	5	9	10
Cs	5	4	5	5	4	5	5	4	5	5	4	5	4	5
Th	38	42	46	23	19	22	32	22	23	24	44	44	22	22
U	8	9	10	6	10	11	12	11	11	12	6	5	22	22
Pb	32	35	50	49	60	56	54	52	53	49	61	40	46	43
Zn	21	24	54	23	52	29	30	31	37	29	25	14	43	31
Sc	2.5	1.9	2.5	2.9	2.6	2.9	2.4	2.8	2.9	2.9				
Ga	21	23	25	24	25	26	27	28	27	26	31	30	32	33
Li	30	26	46	38		42	41		39		66	20	55	49
Be	12	13	12	11	10	<10	12	11	13	12	10	12	13	12
K/Rb	137	148.6	115.9	117.4	181.8	131.6	119.5	147.4	127	135.6	93.8	165.4	137.3	88.9
K/Ba	93.8	151	159.5	155.1	171.8	208	191	158.7	123.5	122	324.1	158.2	100.9	200
Rb/Sr	1.7	1.73	2.66	3.13	2.4	2.71	2.9	2.25	2.68	2.49	3.92	2.51	1.53	4.56
Ba/Rb	1.46	0.98	0.7	0.75	0.88	0.7	0.63	0.8	0.86	0.77	0.29	1.04	1.36	0.44
Ba/Sr	2.5	1.7	1.93	2.36	2.1	1.9	1.9	1.7	2.3	1.9	2.62	1.14	2.1	2.1
Zr/Hf	40.3	27.2	28.3	30.0	34.0	35.0	27.0	24.0	36.4	36.3	13.5	18	35.6	27.2
Al/Ga	3595	2952	2712	3409		3100	2615		2444		2200	2233	2250	2212
Th/U	4.75	4.7	4.6		4.7		3.9	1.9	1.04	2	7.3	8.8	0.7	
Nb/Ta	1.33	1.33	1.33	1.9	1.53	1.9	2.8	1.6	1.67	1.42	2.4	2.88	1.9	17.7

Table 3. Rare earth element concentration(ppm) of the Allapatna granite, Mandya district, Karnataka

Sample No.	95/1	95/2	95/4	3A	3C	3D	4A	4B	4D	4E	4C	95/94	95/103
La	59	33	35	38	35	38.5	40	32	38.5	42	41	33	18
Ce	109	73	62	70	62	71.5	73	56.5	69	74	76	71	37
Nd	33	23	20	32	28	34	35	26	36	38	31	22	11
Sm	5	5	5	4.8	4.5	4.7	5	3.5	5.2	4.8	5	5	5
Eu	0.50	3.5	0.5	0.8	0.6	0.7	0.8	0.6	0.7	0.65	0.5	0.5	0.5
Gd	5	5	5	5	5	5	5	5	5	5	5	5	5
Yb	1.6	0.5	1.6	2	1.5	2	3.2	1.5	1.6	3.1	3.1	1.9	0.5
Lu	0.5	0.5	0.5	0.35	0.3	0.35	0.5	0.3	0.6	0.5	0.5	0.5	0.5
Total	**213.6**	**143.5**	**129.6**	**152.95**	**136.9**	**156.75**	**162.5**	**125.4**	**156.6**	**168.05**	**162.1**	**138.9**	**77.5**
$(La/Yb)_N$	24.675	14.200	14.662	12.771	15.681	12.938	8.431	14.333	16.130	9.155	8.939	11.703	7.959
$(La/Sm)_N$	7.422	4.160	4.410	4.984	4.887	5.154	5.039	5.765	4.652	5.508	5.168	4.160	2.270
$(Gd/Yb)_N$	2.506	2.573	2.506	2.010	2.681	2.010	1.261	2.681	2.506	1.304	1.304	2.121	2.644
Eu/Eu*	0.306	0.477	0.306	0.500	0.389	0.442	0.491	0.443	0.419	0.406	0.306	0.306	0.306

1988). Enrichment of Rb and depletion of Sr seem to be the key factor in influencing the ratio. Negative Eu anomaly in the chondrite normalized REE plot (Fig.9) and decrease of Ca and Sr suggest such fractionation schemes within granites to enrich them in Rb and related alkali elements. Distribution of upper crust normalized trace and rare earth elements in AG, average fertilie granite (Cerny and Meintzer, 1988) and high calcic normal granite (Turekian and Wedephol, 1963) in spidergram (Fig. 10) shows positive anomaly of Nb, Ta, Li, Pb, U, Rb and Th. Similarly, the critical ratios like K/Rb, Ba/Rb, Rb/Sr, Al/Ga in AG, average fertile granite (Cerny and Meintzer, 1988) and high calcic normal granite ofTurekian and Wedephol (1963) have also been plotted (Fig.11). The diagram shows positive anomaly of Rb/Sr and K/Ba whereas K/Rb, Ba/Rb, Al/Ga, Zr/Hf and Nb/Ta show negative anomaly. The enrichment of the rare metals as well as variations in the observed critical ration indicates the fractionated character of these granites.

The characteristic trace elemental concentrations and critical ratios of fertile granites reported by Cerney and Meintzer (1988) have been given in the Table 4 for comparison with AG. The AG contains high contents of Rb, Ga, Zr, Th, Li, Nb and Ta and relatively lesser amounts of Cs and Sn than the average rare metal fertile granite. The Nb content in these granites range from 16-28 ppm with an average of 21ppm except in one sample (354 ppm). Maximum values of Nb (354 ppm) with higher Li (49ppm), Zr (136 ppm), Ta (20 ppm) are associated with coarse grained granite sample collected from the eastern fringe of the AG nearer to spodumene-tantalite bearing pegmatites of Marlagalla. Rb content shows an increase with decreasing Sr, and thus the Rb/Sr ratios attain maximum values of 4.6 which strongly indicate its highly differentiated character. Such fertile granites show depletion in Ba, the Ba/Rb ratios provide further insights into the fractionating scheme of the AG. Ba/Rb ratios are distinctly lower (0.29 to 1.46; av. 0.83) in AG and are lower than the known values from barren granite (3.8) and the fertile granite (1.68) emphasizing the enrichment of Rb and depletion of Ba. Ba/Sr ratios in AG range from 1.14 to 2.62 with an average of 2.702. Thus it appears that Sr depletion in AG has been less drastic implying a rather limited role of Ca bearing phases such as plagioclase from these granites. $Al/Ga*10^4$ ratios of the AG range from 2200-3595 with an average of 2695, which is lower than the barren granite (4820) but higher than the fertile granite (2080). Such differences in Ga contents in the granite could be partly explained by the effect of Al rich source viz. metapelite or high Al gneisses which contain higher Ga, may in all probability

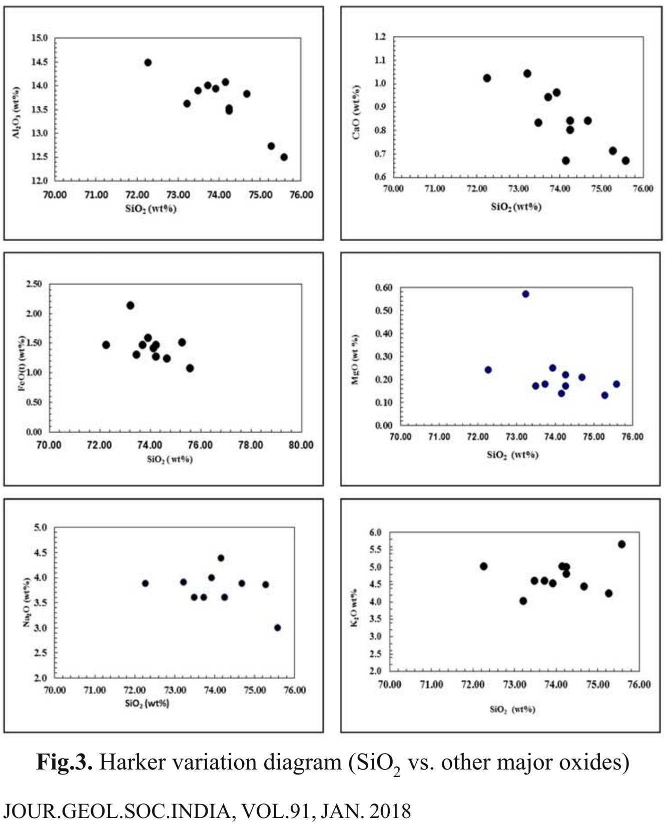

Fig.3. Harker variation diagram (SiO_2 vs. other major oxides)

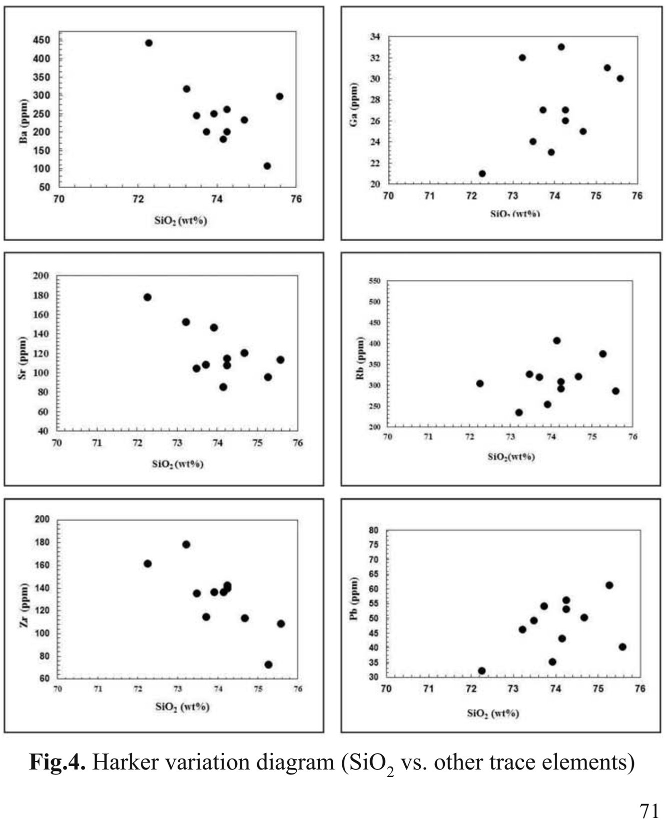

Fig.4. Harker variation diagram (SiO_2 vs. other trace elements)

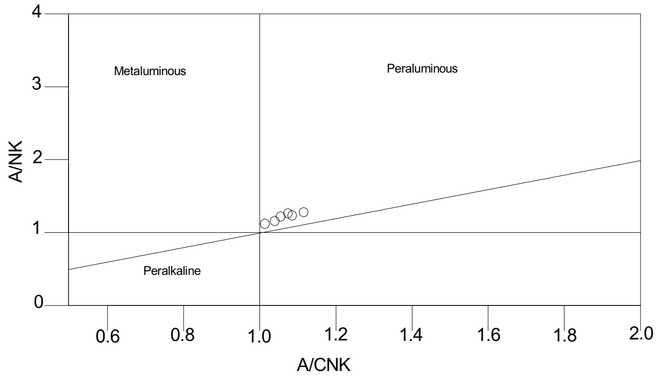

Fig.5. A/CNK vs. A/NK binary plot (after Shand, 1943) for AG

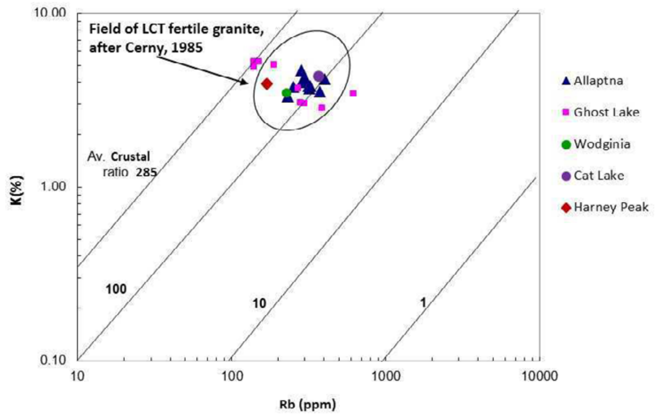

Fig.6. Variation in K versus Rb for the raremetal fertile AG, GhostLake batholith, Superior Province , NW Ontario, Canada (Breaks and Moore, 1992); Lac du Bonnet biotitite leuco granite, Cat Lake Winnipeg River, Manitoba, Canada (Cerny et al., 1981); Harney Peak two mica leuco granite, Iron Creek, Black Hills, South Dakota(Cerny, 1982); Numbana leuco granite, Wodgina district, western Australia (Blockley, 1980).

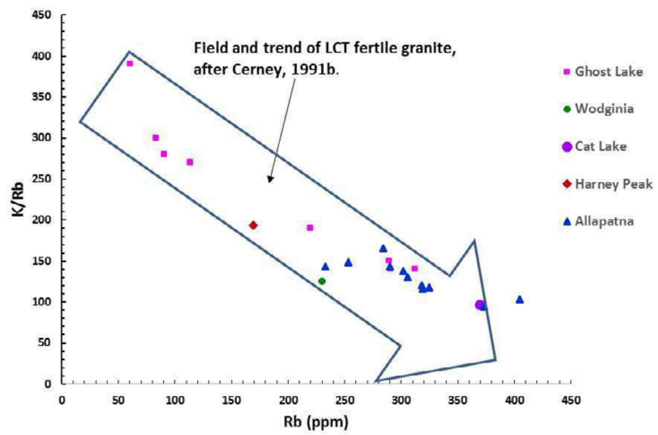

Fig. 7. K/Rb vs. Rb binary plot after Cerney, 1991b. Fertile granites of Ghost lake, Canada, Wodgnia, Australia, Cat Lake, Canada, Harney Peak, USA along with presently studied granites.

an inherited feature from the source.Hf and Zr abundances in this granite are relatively lower compared to barren granite but higher than the fertile granite. The Zr/Hf ratio provides a measure of the differentiated character of the granite and shows a fairly large spread (13.5 to 40.3; av. 29.50) indicating that AG is a fairly well differentiated supporting the Rb/Sr data presented earlier. Nb/Ta ratios of AG show restricted range (1.33-2.89) except one sample shows 17.7. Such ratio is distinctly lower than the fertile and barren granites, and exhibit Ta-rich nature (Table 4). The consequence of

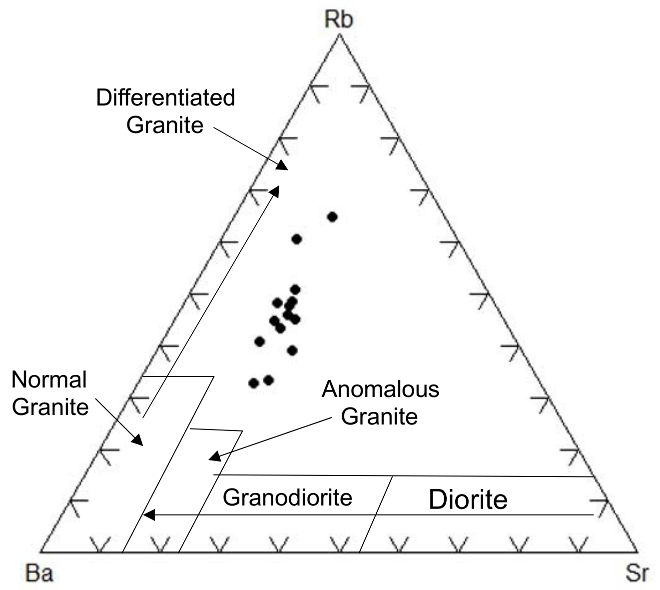

Fig.8. Rb-Ba-Sr covariation triangular diagram (Bouseley and Sokkary, 1975) for AG

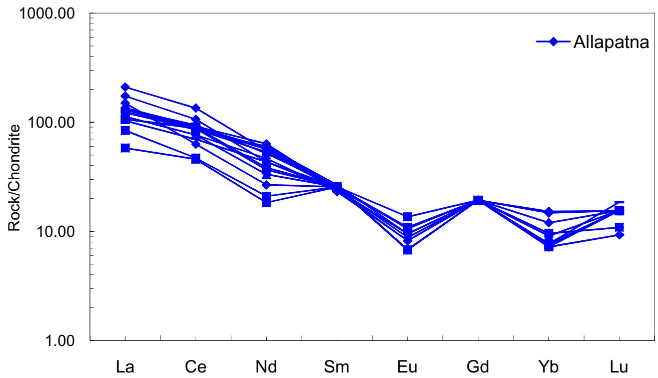

Fig.9. Chondrite normalized (Boynton, 1984) REE plot for AG.

Table 4. Major, minor oxides and trace element contents and ratios of AG along with average trace element abundances of a fertile granite and a granite from South Kanara

	1		1	2	n	3
SiO_2	74.08	Rb	299.85	305	121	53
TiO_2	0.15	Sr	118.77	44	121	188
$Al2O_3$	13.64	Ba	242.92	307	102	360
Fe_2O_3	0.43	Y	64.23	41	102	10
FeO	0.91	Zr	126.85	89	114	155
MnO	0.03	Nb	47.23	19	54	10
MgO	0.22	Ta	12.62	18	14	na
CaO	0.85	Sn	10.67	4	114	na
Na_2O	3.76	Cs	4.62	3	109	na
K_2O	4.72	Th	30.85	38	124	na
P_2O_5	0.06	U	11.08	13	118	na
LOI	0.15	Ga	27.08	38	99	na
		K/Rb	131.94	159		528.4
		Rb/Sr	2.66	5.2		0.28
		Ba/Rb	0.83	1.68		6.79
		Al/Ga	2702	2080		na
		Th/U	4.04	4.52		na
		Nb/Ta	2.98	5		na

1. Allapatna granite, average of 11 samples for major oxides and 14 samples for trace elements (present work)
2. Average trace elements for fertile granite (Cerney and Meintzer, 1988, Table 4, p. 189)
3. Trace element abundances of a granite from South Kanara (Balasubramanian, 1978, Tables 1,2 and 3); na :Not available

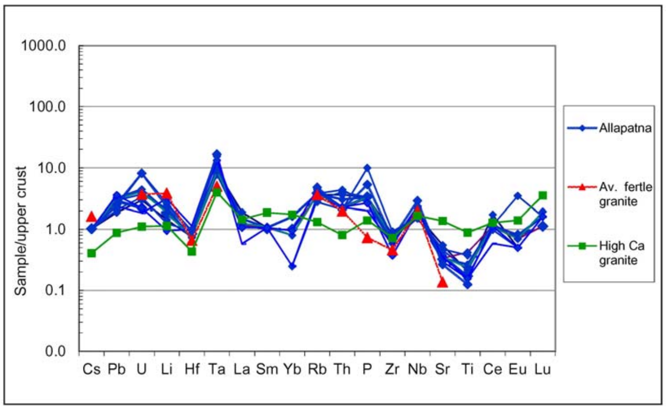

Fig.10. Upper crust normalised rare elements in peraluminous AG, average rare element fertile granite (Cerny and Meintzer, 1988) and high calcic granite (Turekian and Wedephol, 1963). Values of Upper continental Crust are from Taylor and Mclenon (1995)

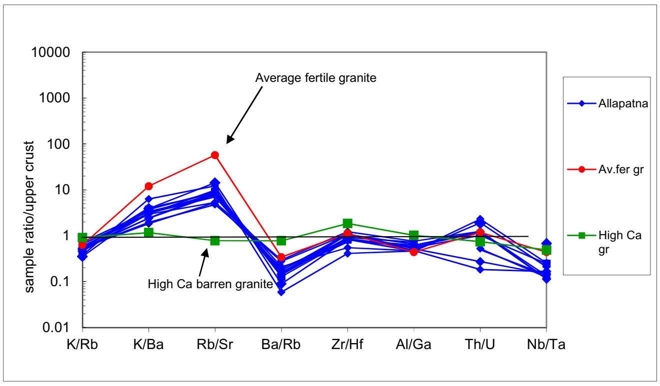

Fig.11. Upper crust normalised elemental ratios in peraluminous AG, average rare element fertile granite (Cerny and Meintzer, 1988) and high calcic granite (Turekian and Wedephol, 1963). Values of Upper continental Crust are from Taylor and Mclenon (1995)

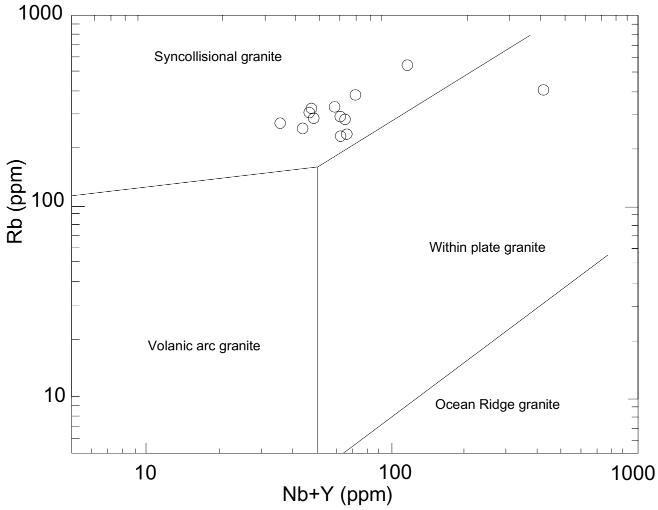

Fig. 12. Tectonic discrimination diagram (Nb+Y vs Rb) (Pearce et al, 1984) for the AG.

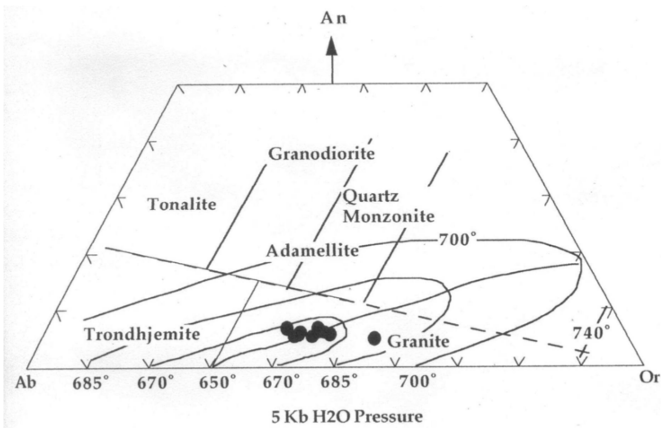

Fig. 13. Normative An-Ab-Or variation of AG. Plotted granitoids fields after O'Conner , 1965. Also shown are the curves of the experimentals of granitic melts at different temperatures and P_{H_2O} of 5 kbar as cited in Winckler, 1964.

granite differentiating to give rise to rare metal pegmatites with Nb-Ta bearing mineral is thus fully supported.

In Rb vs (Y + Nb) tectonic discrimination diagram of Pearce et al. (1984), the AG samples plot in the syn-collisional granite field (Fig.12) except one sample fall within plate granite field due to high Nb concentration.

The total REE abundances of AG vary from 77 to 214 ppm with an average of 148 ppm (n=13) which is comparable to the rare metal fertile granite (160) reported by Cerny and Meintzer (1988). The chondrite normalized REE patterns (Fig. 9) of AG samples show fractionated LREE (La_N/Lu_N = 93.6), flat HREE and strong negative Eu anomaly (Eu/Eu* = 0.31- 0.50, average of 0.39) indicating removal of plagioclase during fractionation of the granite or its retention in the residue phase after the partial melting of the source. In the normative An-Ab-Or triangular diagram (Winkler, 1967) for assumed P_{H_2O} = 5kb, the granites define a very narrow composition field close to the cotectic line (Fig. 13) approximating minimum melt composition. However, AG is not a single feldspar or hypersolvous granite since there are presence of perthites indicating subsolidous transformations.

Rb-Sr GEOCHRONOLOGY

Rb-Sr isotopic data for thirteen whole rock samples of AG are given in Table 5. AG yield an isochron age of 2803 ± 68 Ma with an initial $^{87}Sr/^{86}Sr$ ratio of 0.7284 ± 0.0083 and MSWD of 0.61 (Fig.14). The high initial $^{87}Sr/^{86}Sr$ ratio indicate a crustal source for the AG. Based on field relations, petrographical, mineralogical and geochemical considerations it has been shown that the rare metal pegmatites of Marlagalla represent the residual fluids or liquid derived from the fertile AG through a process of differentiation (Sarbajna, 1998) and thus they would be of similar age or slightly younger than them, but still well within the late Archaean period i.e. between 3000-2500 Ma.

The age of 2803±68 Ma for the AG is the oldest age reported in India for fertile granites parental to rare metal pegmatites with Li-Cs-Ta (LCT) type characters hosting Nb-Ta, Be, and Li resources (Sarbajna, 1998). Rare metal bearing pegmatites and fertile granites of similar late Archean ages are known from Canada, Australia (Breaks and Moore, 1992; Cerny, 2005).

DISCUSSION

Based on detailed petrographic and geochemical features, these granitoids have been shown to possess the following salient characteristic features, which have a bearing on its genesis. (1) fertile character both in terms of mineralogy, major, minor and trace element geochemistry including REE; (2) peraluminous and S-type nature, exhibited by the typical presence of muscovite, biotite and garnet in the mode and presence of corundum in the norm, high initial $^{87}Sr/^{86}Sr$ ratio (0.7284±0.0083), (3) varying Nb/Ta ratio and high Li with moderate abundance of Cs further indicating their affinity to LCT type granite-pegmatite system (Cerny, 1991a; Sarbajna and Krishnamurthy, 1996) (4) syn- to post-collisional regime of emplacement within the Peninsular gneiss for AG.

Table 5. Rb-Sr isotope data on Allapatna granite, Mandya district, Karnataka

Sample No.	Rb	Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
AG-1	287	156	5.47	0.95001
AG-2	224	112	5.96	0.97078
AG-3	283	103	8.25	1.0630
AG-4*	340	114	8.95	1.1153
AG-5	312	104	8.98	1.0937
AG-6*	286	95	9.06	1.1072
AG-7	299	96	9.37	1.1127
AG-8*	328	104	9.47	1.1002
AG-9	335	101	10.0	1.1379
AG-10	330	96	10.3	1.1464
AG-11	320	96	10.4	1.1416
AG-12	309	89	10.5	1.1548
AG-13	320	90	10.8	1.1641

Age = 2803±68 Ma; Initial Ratio = 0.7284±0.0083;
MSWD: 0.61, * = Points deleted

The genesis of such granites has been dealt by a number of workers (Cerny and Meintzer, 1988; Cullers etal., 1981; Cerny, 1991a). Metapelites and metaturbidites sequences which commonly host the LCT bearing systems at lower amphibolite facies have been traditionally considered to be the major or sole protolith at deeper levels because of the relative enrichment in LCT elements. However, the number of reliably documented examples is rather few (eg. Manaslaleuco granite and Harney granite, Cerny, 1991a). Most of the fertile granites of Archaean period have been shown to be derived from a mixed basement from supracrustal protoliths (e.g. Yelllow Knife, Harney Peak granite, Meintzer, 1987). As yet there is no reported Indian example pertaining to such fertile granite systems.

A significant role for the basement in the development of LCT signature at the beginning from low degree partial melts which get enhanced by subsequent fractionation has been postulated by Cerny (1991a) and London (1987). In the present context the possible sources for the AG could be (a) metabasic rocks (b) Peninsular gneiss, and (c) metasedimentary rocks. The field relation of the AG such as its sharp contacts with the country rocks, presence of pegmatite veins and absence of intermediate rocks like diorite point out that these granitic rocks could not be a product of fractional crystallization of magma.

The next probable source could be the Peninsular gneiss. The southern Karnataka region contains extensive granodiorite-granite suite of rocks (the South Kanara batholith) with vast areas of migmatitic gneissic complex (the South Kanara gneissic complex; Balasubramanyan, 1978). This gneissic complex comprises banded biotite gneiss, streaky biotite gneiss and granitic gneiss. The mean

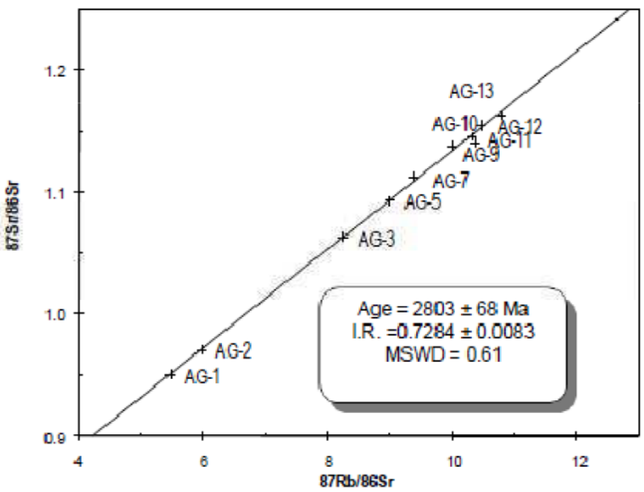

Fig. 14. Rb-Sr isochrones diagram for AG.

composition of the gneisses as found by Balasubramanyan (1978) is poorer in iron, calcium, magnesium and it also shows high abundances of SiO_2 (68.88%), Al_2O_3 (14.65%) and Rb (90 ppm), Ba (290 ppm), Nb (10 ppm), La (30 ppm), and Pb (11.6 ppm). Based on geochemical data of these gneisses, it is postulated that partial melting of such tonalitic granodioritic geneisses could also result in the formation of fertile Allapatna type granites during late Archaean period.

The presence of Al-rich minerals such as garnet, muscovite in the mode and corundum in the norm together with high $^{87}Sr/^{86}Sr$ ratios (0.7284 ± 0.0083) and the S-type character of the AG further suggests the possible involvement of the supracrustal rocks especially the Al-rich types (eg. metapelites). Although such a scheme satisfies the LCT type signature of the granite pegmatite system, the S-type features remain only partly explained from the point of view of parental sources. Higher initial $^{87}Sr/^{86}Sr$ ratios (0.7284 ± 0.0083) of the studied granite is higher than the contemporary mantle. The REE abundances in the AG and the chondrite-normalised REE pattern with REE enrichment together with a pronounced negative Eu anomaly further seem to corroborate, the involvement of K and Al rich metasedimentary pelitic sources as has been proposed for similar granites from Bastar, Madhya Pradesh, India (Ramesh Babu, 1990; Ramesh Babu et al., 1993) and other areas (Linnen and Cuney, 2005).

From the above discussions, it can be concluded that the AG in all probability was derived from partial melting of an undepleted granodiorite tonalite gneiss. Such a melt had chemical features somewhat akin to LCT type granite pegmatite systems but still inadequate to explain the abundances of Li and Nb and other elements. Involvement of a metasedimentary pelitic protolith has also been suggested from both mineralogical and chemical (REE and $^{87}Sr/^{86}Sr$ ratios) data. The fractionation of such fertile granite might have given rise to the rare metal bearing pegmatites.

Acknowledgements: The authors are thankful to Dr. A.K. Rai, Director, AMD for giving permission to publish this research paper. The authors are also thankful to Additional Director (R&D) and Head MPG Group for their encouragement and support.

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(Received: 27 December 2016; Revised form accepted: 9 May 2017)