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Geochemistry of Granitoids and Associated Mafic Enclaves in Kalpathri Area of Amgaon Gneissic Complex, Central India

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Abstract

The Amgaon Gneissic Complex (AGC) exhibit well developed gneissic and migmatitic bandings in Bagh River section, south of the Central Indian Shear Zone. It also includes some of the felsic components that are massive and show less deformation. Granitic rocks exposed in Kalpathri area show typical calc-alkaline and peraluminous granite characteristics. It has high-Al TTG composition and was probably derived from partial melting of a mafic source, most likely a garnet bearing amphibolite, leaving a residue free of plagioclase. Basic dykes and sills have intruded the granitoid body, while it was undergoing consolidation. This has caused an excellent case of magma mingling between felsic and mafic magmas. These mafic magmatic enclaves are tholeiitic in nature and show enriched LILE-LREE characteristics with negative anomalies for Nb, Ti, Sr and Eu, commonly observed in continental rift basalts and Precambrian dyke swarms. These characteristics are also observed in the mafic enclaves of the neighboring Dongargarh granite, probably indicating their consanguinity. Deformed mafic enclaves, probably older than this granitoid, are also described from this area. This older mafic component may be a part of the basement AGC. The deformed mafic enclaves have less enriched trace elements characteristics compared to the dominant mafic enclaves of the granitic rocks exposed in Kalpathri area.

Keywords : Geochemistry, granitoids, mafic enclaves, Amgaon Gneissic Complex, Kalpathri area, Central India

Introduction

The Amgaon Gneissic Complex (AGC) constitutes a component of the basement of Central Indian Bastar Craton and is exposed on the southern side of Central Indian Suture Zone (CIS). It comprises migmatites, gneisses, augen gneisses and amphibolite restites, basic and ultrabasic intrusives. The Late Archaean-Palaeoproterozoic supracrustal groups viz. Sakoli, Nandgaon and Khairagarh Groups overlie the AGC. Deccan traps and Quaternary alluvium in turn cover theses supracrustals.

AGC consists of various types of granite gneisses. Some exhibit prominent migmatitic bandings, while in some areas the gneisses show compositional banding between felsic and mafic minerals. In other areas these gneisses are distinctly massive with weak deformation, except for alignment of planer minerals, visible in thin sections.

The granitoids exposed around Kalpathri village, lie within the AGC. It shows little deformation and virtual absence of any kind of gneissic banding. The mafic magmatic enclaves (MME) are present within this granitoid.

This paper deals with the geochemistry and some of the rheological features of the granitoids exposed around Kalpathri area.

Granitoids of Kalpathri

Kalpathri village lies ~ 20 km NE of Amgaon, in southern part the area covered under Toposheet No. 64 C/6. The granitic rocks are well exposed in a quarry lying further 1.5 km west from Kalpathri village (Latitude 21°30' 21', Longitude 80°29'46"; Fig.1).

The granitoids show weak or no gneissic or migmatitic banding, although a few aplitic and pegmatitic veins traverse it. The mafic enclaves occur as meter size swarms in the quarry. They are more in abundance and larger in size towards north-eastern margin, restricted to the top of the granitoid body and decreases towards bottom of the body (Fig.2a). At places, the mafic enclaves are mingled with the felsic component giving a co-genetic appearance. However, in many parts the felsic and mafic components show distinct physical boundaries with no gradation or compositional banding, thus

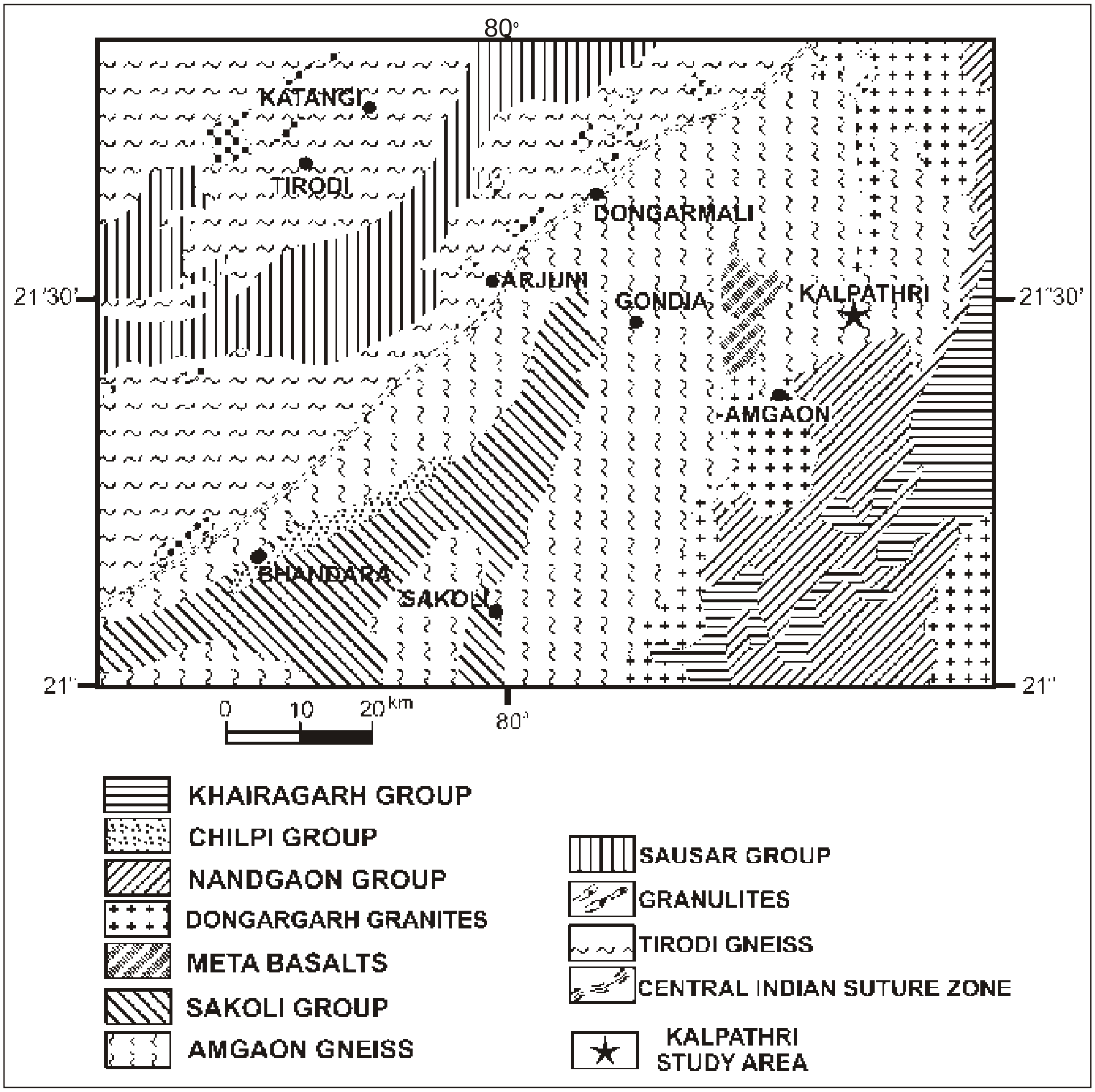

Fig.1. Geological and location map of the study area (modified *after* Yedekar *et al.,* 2003).

limiting possibility of being co-genetic or magma mixing. Field observations overwhelmingly suggest only magma mingling (Wienberg, 1997). The felsic component also shows rhythmic succession of layers (Fig. 2b & 2c), which are defined as Schlieren layering by Cloos (1936). These layers may have been deposited from and partly eroded by flowing magma (Gilbert, 1906).

Interaction of Mafic and Felsic Components

The disruption and peeling off is seen on the peripheries of mafic enclaves associated with felsic component of the granitic rocks of Kalpathri area (Fig. 2b &2c). Such mafic enclaves have been defined as "mafic microgranular enclave" (Didier, 1973) or "microgranitoid enclave" (Vernon, 1983). In this study these enclaves are termed as "mafic magmatic enclaves" as suggested by Barbarin (2005) in a similar outcrop in Sierra Nevada batholith, California and elsewhere. According to Barbarin (2005) as the enclaves are finer grained than the enclosing granitoids, but not essentially microgranular, thus the term "micro" in this case is ambiguous and should be avoided. The term "magmatic" emphasizes the crystallization of these enclaves from magma. Similarly term "mafic" indicates that these enclaves are darker coloured (due to presence of Fe-Mg minerals), than enclosing granitoids, and also distinguishes dark coloured magmatic enclaves from felsic microgranular enclaves, commonly found in granitoids (Didier, 1973). Thus the term "mafic magmatic enclave" has been used in this communication to define the mafic component of outcrop.

The granitoids are relatively fresh and show virtual absence of any kind of deformation except at places due to MME interaction, which appears to be more or less coeval and lack typical gneissic banding. The AGC shows typical gneissic banding in Bagh River section. This suggests that the granitoids of Kalpathri may be younger components of

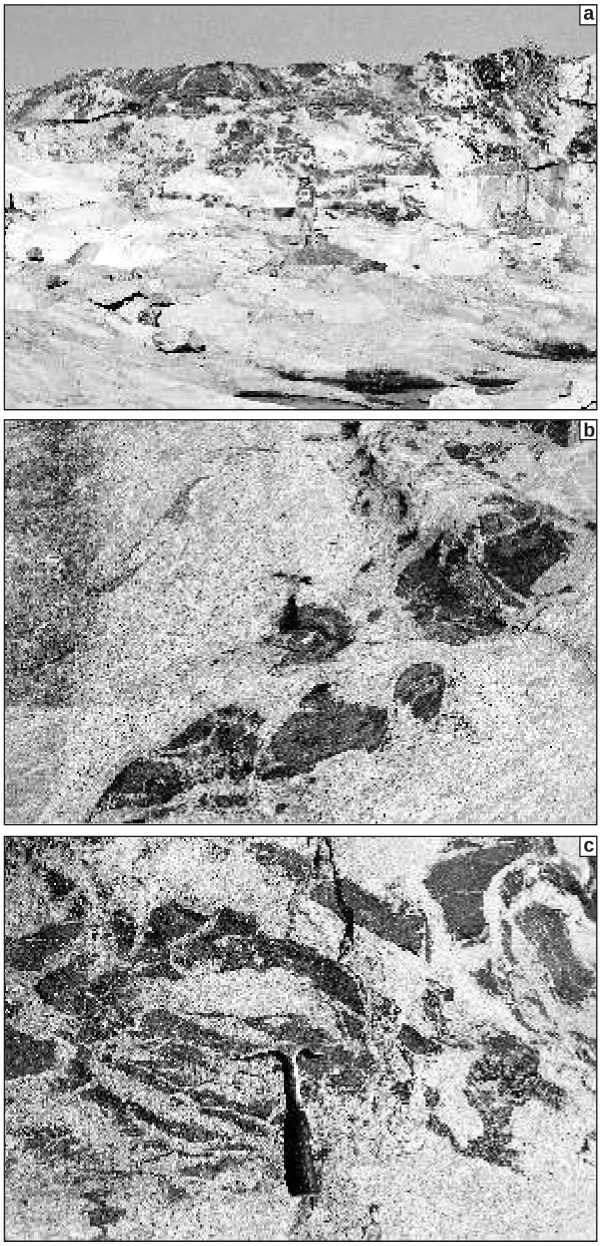

Fig.2. (a) Field photograph showing a section of Kalpathri quarry. Note the size and abundance of mafic magmatic enclaves decreases towards bottom. (b) Field photograph showing schlieren layering in granitoids and rupturing of mafic dyke. In the lower part towards right side ripples or flow banding are clearly visible. (c) Field photograph showing the mingling of mafic and felsic components.

the AGC such as Dongargarh granites that are also massive, which probably formed due to reworking of the pre-existing basement/crustal rocks. However, the Kalpathri granitoids are quite different from Dongargarh granites, as the latter are dominantly pink colored (k-feldspar rich) and much coarser. Thus, they may both be post deformational granitoids but appear to be apparently unrelated.

Field observations indicate that these granitoids are result of some small scale, local phenomenon, involving melting and reworking of pre-existing crustal rocks and intruded by mafic dyke/sill during crystallization of the granitoid body, resulting in mingling and formation of mafic magmatic enclaves. There are minor units of the mafic bodies that show some sort of deformation in the form of foliation. These bodies occur as fragmented and boudinaged units enclosed in massive granitoids with little deformation. This observation indicate presence of two types of mafic enclaves, the minor one being older than the granitoid from Kalpathri area (sample GS-42), that was picked by the invading Kalpathri granitoid magma and the more dominant type (sample MN-7) with no deformation, being nearly coeval to the Kalpathri granitoid.

Geochemistry of Mafic Magmatic Enclaves

Major Elements

Major, trace and REE data of four samples of granitoids and two mafic magmatic enclaves samples from Kalpathri along with two mafic enclaves samples from Dongargarh granite are presented in Table 1. As analyses of only two samples (MN-7 and GS-42) of mafic magmatic enclave is available, no Harker plot is shown, but two samples (X-3 and X-11) of mafic enclaves from Dongargarh granites are plotted for comparison. On AFM plot (Fig.3a), these enclaves follow tholeiitic trend. On total alkali (K_2O+Na_2O) *vs.* SiO_2 plot (Le Bas *et al.*, 1986; Le Maitre, 1989; Fig.3b), the mafic magmatic enclave of Kalpathri granitoids plots on boundary of basaltic andesite and basaltic trachy andesite, whereas enclaves from Dongargarh granites ranges from andesitic to dacitic composition.

Trace and Rare Earth Elements

The variation of trace element ratios of Nb/Y with Zr/TiO_2*10000 after Winchester and Floyd (1978) is shown in Fig.3c, where Nb/Y acts as an alkalinity index and Zr/TiO_2 ratio acts as a differentiation index. In this diagram, mafic enclave from Kalpathri area plots in basalt field and mafic enclaves from Dongargarh granites fall in andesitic field.

Multi-element plot of these enclaves normalized by primitive mantle (Sun and McDonough 1989) is shown in Fig.3d. This plot shows an excellent match between the enclave MN-7 of Kalpathri and X-3 and X-11 of Dongargarh granite, similar observation is made from chondrite normalized plot (Fig.3e), of these enclaves. In contrast GS-42 of the Kalpathri area, which appears to be older than the granitoid (as indicated by well developed foliations) has very different multi-element and rare earth element patterns compared to the other mafic samples from Kalpathri and Dongargarh (Fig.3d & 3e). Thus, the field observation of the possibility of at least two types of mafic enclave within the Kalpathri granitoids is supported by trace and rare earth element geochemistry.

Table 1: Representative major element (in wt %) and trace element (in ppm) analyses of granitoids and mafic enclaves of Kalpathri

Sample Type	GS43 Kalpathri Granitod	GS45 Kalpathri Granitod	GS46 Kalpathri Granitod	GN-9 Kalpathri Granitod	MN-7 MME	GS42 Mafic Enclave	X3 Mafic Enclave Dongargarh	X11 Mafic Enclave Dongargarh
SiO_2	72.8	71.7	70.7	72.0	53.5	47.0	66.1	57.5
TiO_2	0.08	0.12	0.08	0.05	1.17	1.68	0.50	0.54
Al_2O_3	15.5	15.7	15.4	14.6	13.6	13.1	11.6	13.6
Fe_2O_3	1.08	1.34	1.07	0.59	11.10	14.32	6.42	8.81
MnO	0.01	0.02	0.01	0.01	0.23	0.21	0.11	0.20
MgO	0.08	0.28	0.22	0.04	4.26	5.00	1.05	5.62
CaO	1.43	1.64	1.70	1.93	8.12	11.72	2.61	4.62
Na_2O	4.19	4.81	4.70	4.72	4.44	3.65	4.39	4.03
K_2O	5.22	3.59	3.83	3.31	0.87	0.78	3.05	2.71
P_2O_5	0.02	0.04	0.02	0.01	0.20	0.19	0.11	0.06
LOI	1.08	0.35	1.12	1.01	1.81	1.43	2.88	1.05
SUM	101.49	99.53	98.89	98.30	99.30	99.07	98.82	98.77
Trace Elements								
V				3	206		63	76
Cr				20	256		27	167
Sc				2	25	48	11	12
Co				2	34		52	29
Ni				14	112		5	119
Cu				1	465		350	23
Zn				12	167		187	225
Ga				49	26		19	18
Pb				19	20		23	14
Th	39	3	3	4	22	2	2	3
U	11	2	1			2	1	1
Rb	165	99	96	79	14	9	122	235
Sr	692	1366	938	483	547	202	68	99
Ba	2397	3219	2397	935	246	95	918	385
Y	10	8	3	5	80	57	49	166
Zr				125	91		207	139
Nb	10	4	1	6	39	10	21	22
La	16.10	19.06	10.93	9.70	50.00	11.81	53.74	35.92
Ce	28.65	32.34	16.57	15.90	138.40	30.30	108.25	105.00
Pr	3.32	3.59	1.72	1.60	19.46	4.77	19.50	16.60
Nd	10.23	11.53	5.53	6.20	73.70	19.93	76.10	68.80
Sm	2.95	3.47	1.98	2.00	16.72	5.29	16.00	15.11
Eu	1.27	1.69	1.12	0.80	2.68	1.42	2.02	1.71
Gd	1.29	1.32	0.51	0.90	14.63	4.97	14.81	13.85
Tb	0.19	0.18	0.07	0.10	2.05	1.04	2.24	2.08
Dy	1.31	1.15	0.39	0.80	11.23	8.59	12.34	11.39
Ho				0.09	2.33		2.51	2.27
Er	0.76	0.56	0.21	0.30	6.39	4.49	6.74	5.92
Tm				0.04	1.00		1.02	0.87
Yb	1.16	0.76	0.34	0.50	6.65	6.25	6.45	5.44
Lu	0.21	0.13	0.07	0.08	0.95	0.90	0.95	0.75

Geochemistry of Granitoids

Major Elements

On AFM plot (Irvine and Baragar, 1971), granitoids of Kalpathri follow typical calc alkaline trend while MME's plot in calc-alkaline and tholeiitic fields (Fig.3a). On An-Ab-Or classification diagram of Barker (1979), granitoids of Kalpathri plot in the granite field (Fig.4a). A/CNK values for the granitoid samples range between 0.98 to 1.05, indicating these granites are peraluminous and are of I-type origin *i.e.* they might have been derived by partial melting of pre-existing igneous rocks (Chappell and White, 1974) (Fig.4b). This suite has medium to high K, calc-alkaline characteristics as K_2O shows positive correlation with silica content (Fig.5).

In these plots samples from parts of AGC are plotted to

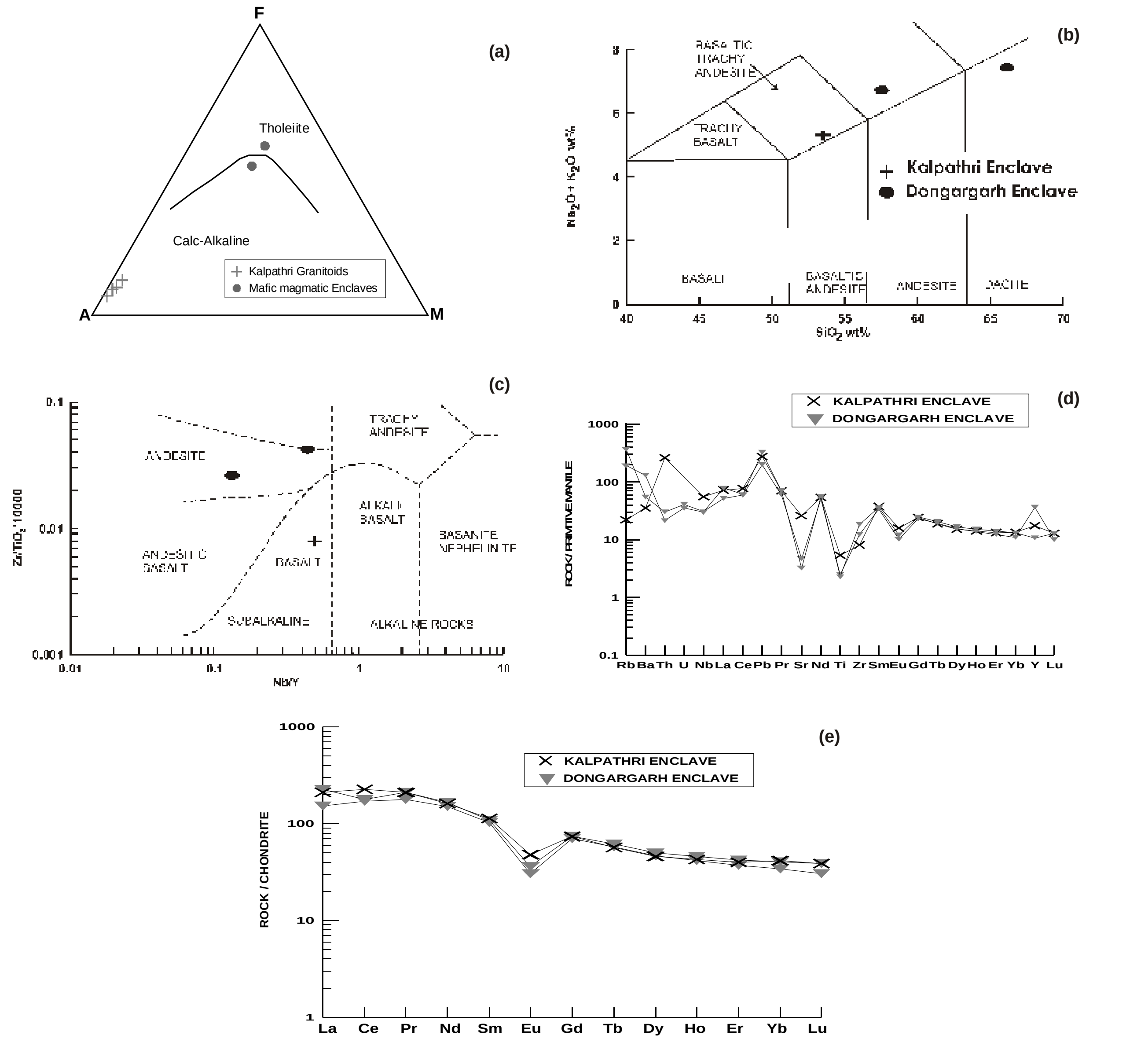

Fig.3. (a) Alkali (Na_2O+K_2O) - FeO^T - MgO (AFM) plot (Irvine and Baragar, 1971) of granitoids and mafic enclaves. (b) Total Alkali (Na_2O+K_2O wt %) *vs.* SiO_2 wt % (*after* Le Bas *et al.*,1986; Le Maitre, 1989). (c) Nb/Y *vs* Zr/TiO_2*10000 (*after* Winchester and Floyd, 1978). (d) Primitive mantle normalized multi-element plot of mafic magmatic enclave from granitoids of Kalpathri and Dongargarh granite. (e) Chondrite normalized REE plot for mafic magmatic enclaves from granitoids of Kalpathri and Dongargarh granites.

see its correlation with granitoids of Kalpathri (Fig.5). The AGC samples are granite gneisses of banded or migmatitic variety. Petrologically none of the granitoid samples from Kalpathri area resemble similar to AGC samples, owing to their near massive and non-foliated character.

Geochemical comparison indicates that there is not much difference within the AGC pluton irrespective of the magnitude of the deformation.

Trace Elements

Trace element variations for selected elements against silica content are shown in Fig.6. The samples of granitoid from Kalpathri area show large variations in Rb, Ba and Sr for restricted SiO_2 abundances. In the case of Nb, Yb and to some extent Th a weak positive trend is discernible. The restricted SiO_2 contents and the scatter in the range of trace element contents discount any major role for crystal fractionation during consolidation of this suite. Comparison with granitoids of AGC show that the granitoid of Kalpathri lies well within the range defined by AGC, with expected degree of scatter.

Multi-elements patterns normalized to primitive mantle values of Sun and McDonough (1989) are shown in Fig.7. It shows clear enrichment of LILEs and Sr and distinct negative anomalies for Nb and Ti, whereas Y and Yb do not show any significant enrichment.

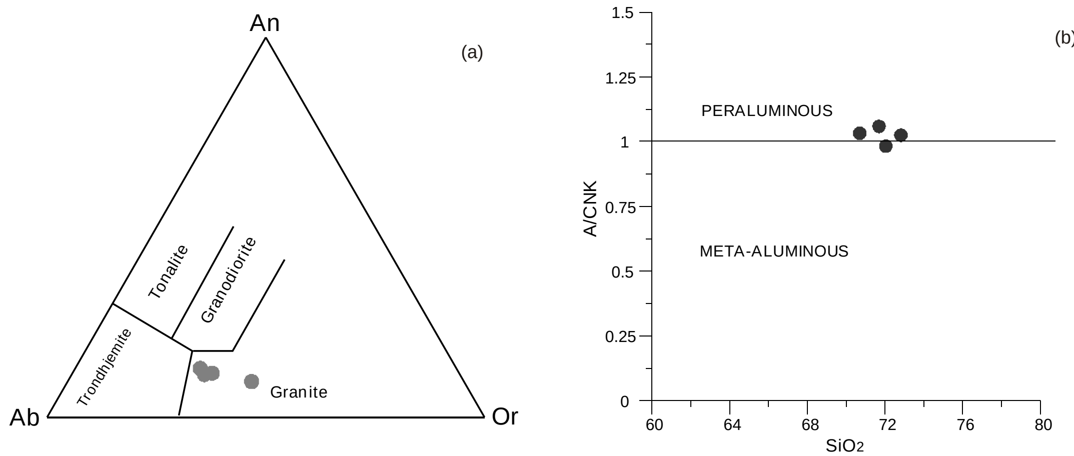

Fig.4. (a) An-Ab-Or classification diagram of granitoids of Kalpathri (*after* Barker (1979) . (b) A/CNK vs. SiO_2 plot granitoids of Kalpathri, indicating their peraluminous nature.

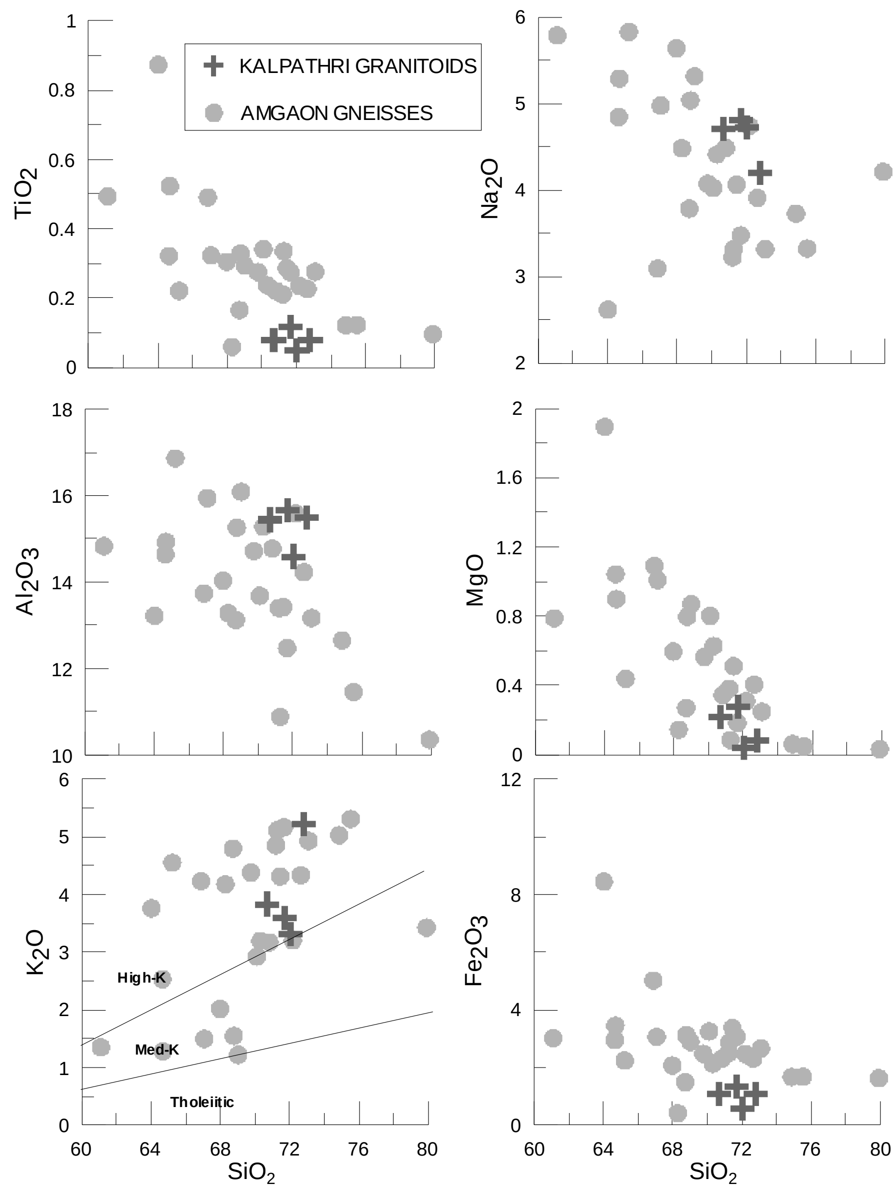

Fig.5. Harker diagrams showing variation of major oxides against SiO_2. Data for samples from other parts of AGC is also shown for comparison.

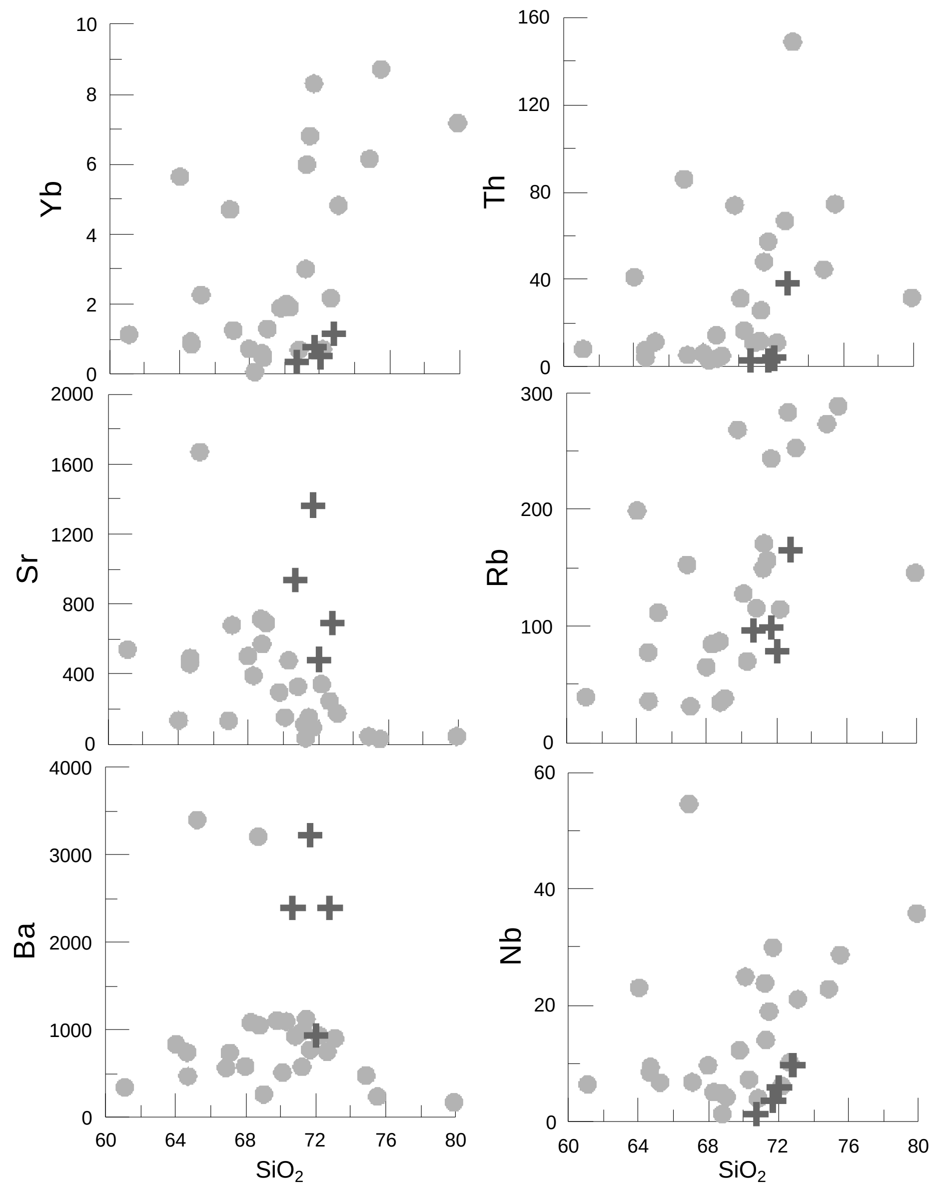

Fig.6. Harker diagrams showing variation of trace elements in Kalpathri granitoids against silica.

Rare Earth Elements

Chondrite normalized REE pattern for KPG is shown in Fig.8, normalizing values after McDonough and Sun (1995). The patterns show the samples are LREE enriched and HREE depleted, with prominent positive Eu anomaly. Positive Eu anomaly indicates accumulation of feldspars during consolidation of Kalpathri granitoid magma.

$(La/Yb)_N$ ratio ranges from 9 to 22 and Yb_N is between 3-7 with an average of 15.32 and 4.29 respectively.

Implications of the Geochemical Results

Major oxides and normative plots shows that the granitoid of Kalpathri have calc-alkaline, peraluminous granitic character with I-type granite origin. Trace and rare earth elements data for the granitoid samples from Kalpathri, presented hitherto indicate the possibility of presence of TTG like component in the pluton.

Barker (1979) and Drummond and Defant (1990) have defined TTG as having Al_2O_3 contents >15% at 70 % SiO_2, Sr > 300 ppm, Y <20 ppm, Yb <1.8 ppm and Nb = 10 ppm. The averages for granitoid from Kalpathri, for the same parameters are Al_2O_3 ~15.29% at SiO_2 ~71.81%, Sr ~870 ppm, Y ~6 ppm, Yb ~0.7 ppm and Nb = 5 ppm. Comparative data is also presented in Table 2.

Along with these one of the most significant features indicating presence TTG suite is the presence of prominent positive Eu anomaly (Fig.8). The positive Eu anomaly is interpreted as absence of plagioclase in the residual source

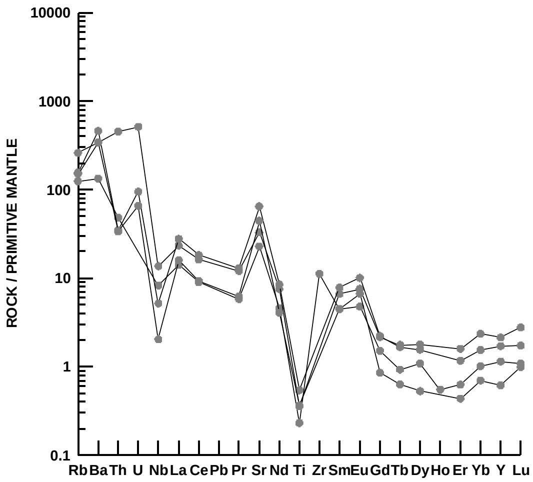

Fig.7. Multi-element plot of granitoids of Kalpathri normalized to primitive mantle values of Sun and McDonough (1989).

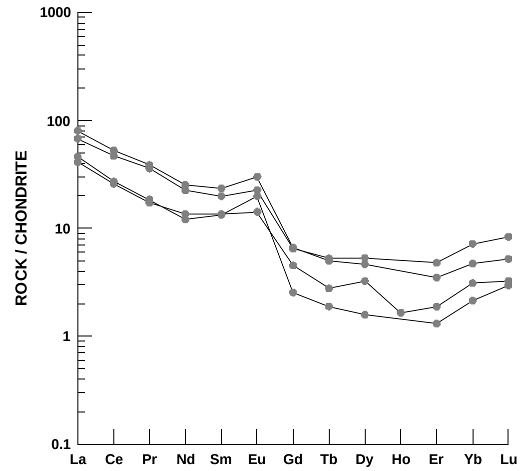

Fig.8. Chondrite normalized REE plot for granitoids of Kalpathri. Normalizing chondritic values after McDonough and Sun (1995).

Table 2: Comparison of average TTG (Drummond and Defant, 1990) and average of granitoids of Kalpathri (present study)

TTG	KPG (n=4)	
Al_2O_3	>15%	~ 15.29%
SiO_2	~70 %	~ 71.81%,
Sr	>300 ppm	~ 870 ppm
Y	<20 ppm	~ 6 ppm
Yb	<1.8 ppm	~ 0.7 ppm
Nb	= 10 ppm	~ 5 ppm

(Clemens *et al.*, 2006). This lack of plagioclase in the source also explains the observed high amount of Sr in these rocks.

Similarly, the depletion of HREE is interpreted as partitioning of these elements in restitic garnet present in the residue. The Yb_N value of Archaean amphibolites is ~ 12 (Gao *et al.*, 1998), whereas the granitoid from Kalpathri area have average Yb_N value of 4.29, indicating their HREE depleted nature.

The $(La/Yb)_N$ *vs.* Yb_N plot (Fig.9a) shows the fields of Archaean TTG and Post Archaean granitoids as proposed by Martin (1993) and partial melting curves of various restitic compositions from Drummond and Defant (1990). Granitoid from Kalpathri area have very low Yb_N and high $(La/Yb)_N$ ratio and fall clearly within Archaean granitoids field. Regarding partial melting curves two samples plot on 25% garnet amphibolite curve and the other two plots on the 10% garnet amphibolite curve, though all these samples show almost similar degrees of partial melting.

The Sr/Y *vs.* Y plot (Fig.9b) also shows the curves for eclogite and 10% garnet amphibolite derived by partial melting two different sources *viz.* Archaean mafic composite and MORB. Here granitoid samples from Kalpathri follow

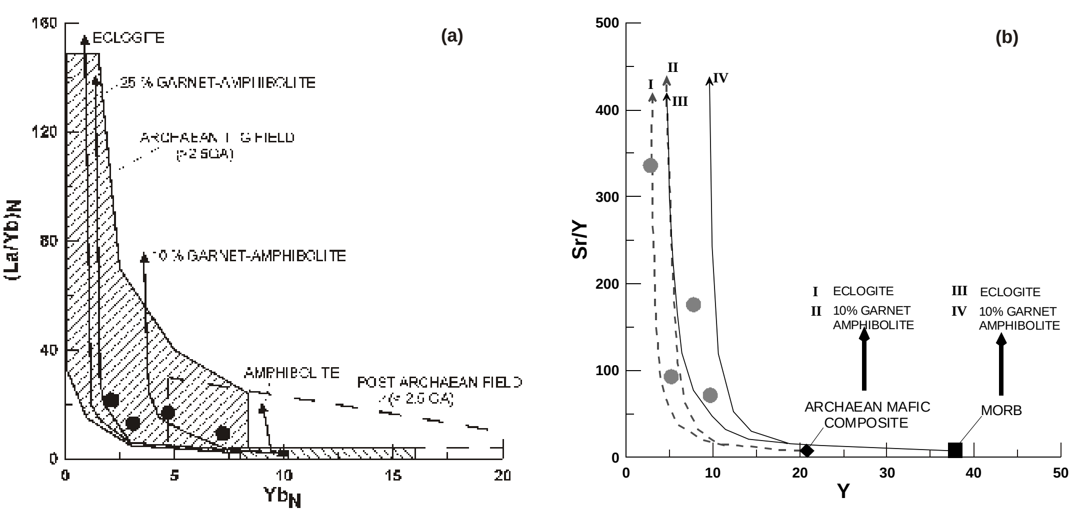

Fig.9. (a) $(La/Yb)_N$ *vs* Yb_N plot showing Archaean TTG field (shaded) and Post Archaean granitic fields after Martin (1993), partial melting curves are from Drummond and Defant (1990), and range of MORB values (dark shading). Granitoids of Kalpathri follow melting curves of 25% and 10% garnet bearing amphibolite. (b) Sr/Y *vs* Y (ppm) plot with basalt partial melting curves leaving either 10% garnet amphibolite or eclogite residue (Drummond and Defant, 1990).

eclogite residue curve having either MORB or Archaean mafic composite as source.

Discussion

The synthesis of geochemical data and major, trace and REE plots have clearly shown that granitoids of Kalpathri belong to high-Al TTG composition and were derived from partial melting of a mafic source, most likely a garnet bearing amphibolite, forming a residue free of plagioclase.

This poses an important question for their petrogenesis *i.e.* what was the source of protolith and in what conditions the mafic protolith has given rise to these rocks.

Drummond and Defant (1990) in their studies of TTG suites world over have confirmed that the partial melting of hydrous mafic rocks in lower crust, in subduction environment was responsible for development of TTG suites. They have listed three major hypotheses in this regard (i) partial melting of mantle, (ii) fractional crystallization of basaltic magma and (iii) partial melting of basaltic source material. They have subsequently shown that the first two processes are unviable and it is the partial melting of a hydrous MORB/basalt like material that gives rise to TTG melts, leaving residue of variable composition between eclogite to amphibolite.

Such melting of hydrous mafic crust is possible in arc environments but TTGs are also formed as a result of partial melting of under plated basalt in lower crustal zones (Drummond and Defant, 1990; Martin, 1993 and Condie, 2005). The tectonic setting can be constrained on the basis of geochemical data as the melting in arc environment would require ascending magma to interact with overlying mantle wedge and hence will acquire signatures like higher MgO, Mg#, Cr and Ni contents. But in case of flat subduction or lower crustal melting, no such interaction is possible thus such suites have lower contents for these elements. The granitoids of Kalpathri have average MgO content varying from ~1 to 0.2 wt% and Mg# ranges from 10 -26. Presently data for Ni and Cr for these samples is not available.

The granitoids of Kalpathri are plotted on the $(La/Yb)_N$ *vs* Yb_N plot (Fig.9a) that follow 25% to 10 % garnet bearing amphibolite curve and on Sr/Y *vs* Y (ppm) plot (Fig.9b), follow the melting curve of eclogitic residue derived either from Archaean mafic composite or MORB source. Both plots suggest approximately 25% partial melting for the Kalpathri granitoids.

The mafic magmatic enclaves show striking similarity with the enclaves present in Dongargarh granites. Though in field granitoids of Kalpathri, show no clear relationship or contact with Dongargarh granites. But in the geological map (Fig.1), Dongargarh granites lies just north of granitoid out crop of Kalpathri area and towards the south Nandgaon group is exposed. According to Sarkar *et al.* (1981) and Divakara Rao *et al.* (2000) the mafic enclaves of Dongargarh granites belong to Nandgaon group. Thus it may be possible that during the crustal reworking event, which probably gave rise to Dongargarh granites and Kalpathri granitoids, pre-existing basement rocks, consisting of Amgaon Gneissic complex, may have been remobilized too. During this event, basic dyke or sill traversed through the still solidifying Granitoid from Kalpathri area body causing mingling of the basic and felsic components (Fig 2c). This can also partly explain the absence of any deformation in KPG. Presence of minor mafic enclaves with pre-existing foliation indicate possibility of existence of mafic component within the older basement rocks such as Amgaon Gniessic Complex basement in this area.

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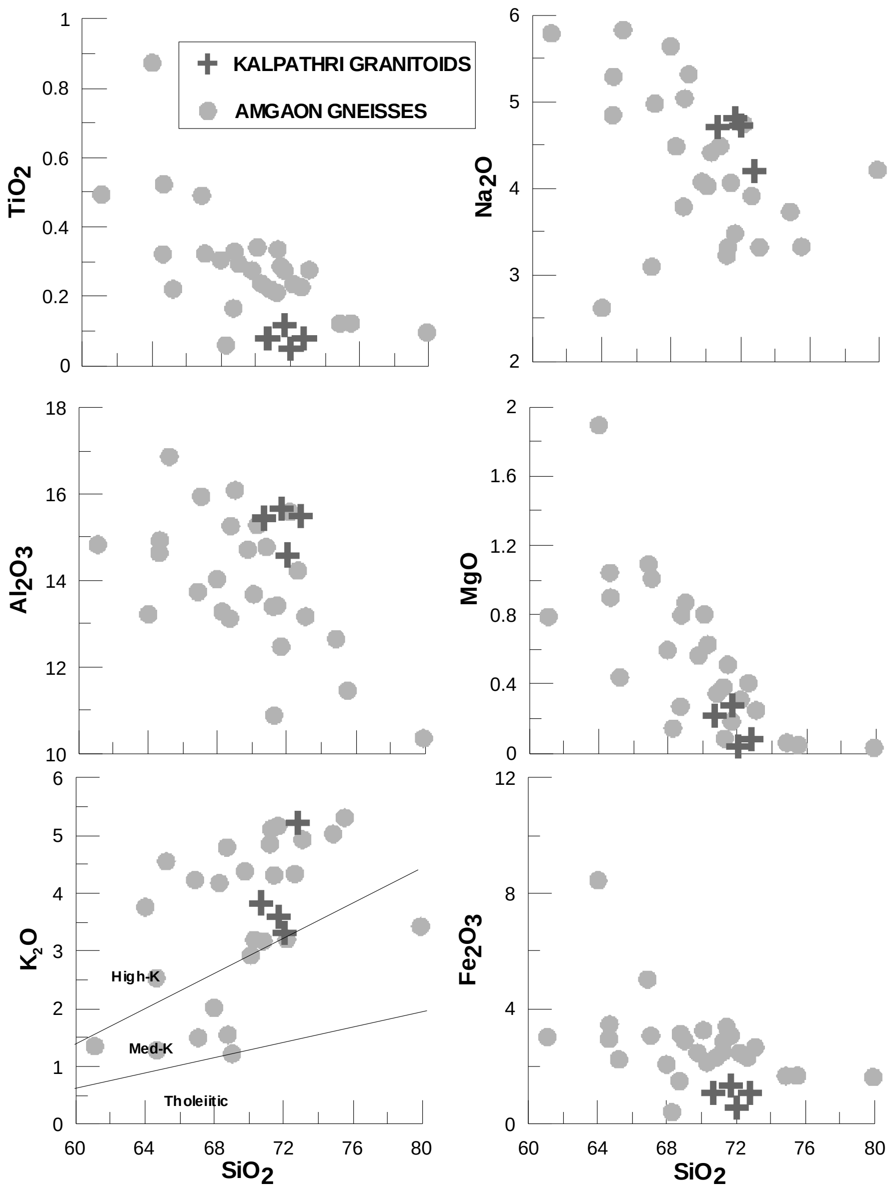

KALPATHRI GRANITOIDS
AMGAON GNEISSES
TiO2
Na2O
Al2O3
MgO
K2O
Fe2O3
High-K
Med-K
Tholeiitic
SiO2
SiO2