Correct nomenclature for the Angadimogar pluton, Kerala, southwestern India

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The proper usage of modal composition and geochemical classification of granitoids is discussed for assigning a proper nomenclature for the Angadimogar pluton, Kerala, southwestern India. This discussion is mainly aimed at addressing questions concerning the nomenclature of Angadimogar pluton (syenite *vs.* granite). Modal composition and whole-rock XRD data clearly show that the pluton exposed near Angadimogar is a quartz-syenite and its geochemistry is typical of a ferroan, metaluminous, alkali (A-type) granitoid.

1. Introduction

Classification of granitoid rocks involving various criteria has long been a subject of frequent debate and voluminous literature. It can be a confusing exercise involving the minerals present and their relative proportion in the rock (depending largely on the chemical composition of the magma), the texture of the rock (depending largely on the cooling history of the magma), the colour of the rock (depending largely on the minerals present and on their grain size), and the chemical composition of the rock. Granitoid classification schemes have evolved from being genetic (e.g., Chappell and White 1974) and/or tectonic (e.g., Pearce *et al* 1984) in nature to non-genetic and non-tectonic in nature (e.g., Frost *et al* 2001). Controversies surrounding the classification of granitoid rocks are usually due to the usage of different schemes of classification by different workers. Such controversies rarely arise from the quality of geochemical data used. This study however, illustrates an example of misclassification of a granitoid rock due to the incorrect application of poor-quality geochemical data.

Anil Kumar *et al* (2005) reported geochemical data from two plutons (Angadimogar and Kumbdaje) from Kerala, southwestern India, and

suggest that these bodies are granites based on their normative compositions. They apparently question the nomenclature of Angadimogar pluton (syenite *vs.* granite) used by Santosh and Nair (1986). Rajesh (1999) carried out a detailed field, petrographic, geochemical, and isotopic characterization of the Angadimogar pluton. The present paper is based on this work and intends to demonstrate that the pluton exposed near Angadimogar is a quartz-syenite.

2. Study area and field relations

The Neoproterozoic granulite-facies terrain of southwestern India is intruded by a suite of high-K calc-alkalic plutons (metaluminous to slightly peraluminous biotite granites and hornblende-biotite granites) with subsequent widespread alkaline (A-type) plutons (including quartz syenites) and minor garnet-bearing leucogranites (Rajesh 1999, 2000, 2003, 2004). These granitoids, emplaced between ~640 and 500 Ma (figure 1a), were generated in environments of high heat flow and volatile activity, correlative with an extensional tectonic regime (Rajesh 1999, 2003, 2004). The pluton exposed near Angadimogar (figure 1a), northern Kerala, belongs to this suite,

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Figure 1. (a) Generalized geologic map of Kerala, southwestern India, showing the approximate location of granitoids and anorthositic gabbro mentioned in the text. Available ages of granitoids are also given. Inset is a shaded relief image of southern India showing the states of Kerala and Tamil Nadu. (b) Photograph illustrating the pink syenite exposed near Angadimogar, northern Kerala. (c) Modal composition (this study) and normative compositions (reproduced from Anil Kumar *et al* 2005) of the Angadimogar samples in a QAP plot. The three components, Q (quartz), A (alkali (Na–K) feldspar), and P (plagioclase), were recalculated from the modal amounts to sum to 100 per cent (as recommended by IUGS). The plagioclase ratio ($100 \times P/(A + P)$) is also useful to name the rock, as the non-horizontal divisions in the QAP diagram are lines of constant plagioclase ratio.

and is a quartz-syenite composed dominantly of medium- to coarse-grained K-feldspar, with minor amounts of quartz, plagioclase and uniformly distributed ferromagnesian minerals (figure 1b). Greenish amphibole constitutes the principal mafic constituent with minor biotite. This is in contrast to other syenites in southwestern India, where pyroxene constitutes the main mafic mineral. The syenitic body shows variations from a coarse-grained rock rich in pink feldspar, with large hornblende grains and

minor quartz, to a medium- to coarse-grained rock rich in pink K-feldspar, with fine-grained hornblende, to a medium-grained rock rich in grey feldspar, with finer grained hornblende. The syenite is locally cut by thin (< 2 cm) amphibole-bearing veinlets. Pegmatites and aplites cut across the syenite exposures and attest to the presence of late-stage fluids.

The syenite shows an intrusive relationship with the surrounding light coloured, medium- to coarse-grained (sometimes migmatitic) hornblende-biotite

gneiss/biotite-hornblende gneiss, often carrying boudins and bands (concordant as well as discordant) of amphibolites. These ortho-gneisses range in composition from alkali-feldspar-granite with less than 6% modal biotite to tonalite with up to 10% biotite. Hornblende-rich granitoid is much more common than biotite-rich granitoid. Dark greenish-grey coloured, medium grained, orthopyroxene-bearing quartzo-feldspathic charnockite is exposed in the northwestern and southeastern parts of the study area. This rock also contains hornblende and biotite, with occasional garnet.

3. Petrography

For plutonic rocks with less than 90% (by volume) mafic (dark) minerals, the rock name is determined from the relative proportions of quartz, alkali feldspars, plagioclase feldspars, and feldspathoids (nepheline, leucite, etc.). In any classification scheme, boundaries between classes are set arbitrarily; however, if the boundaries can be placed close to natural divisions or gaps between classes, they will seem less random and subjective, and such standards can facilitate universal understanding. The most commonly used scheme was devised by the International Union of Geological Sciences (IUGS) and is based on Streckeisen (1976) (figure 1c). IUGS recommends that if the mineral mode cannot be determined (or difficult to determine) as is often the case for volcanic rocks, then a chemical classification (e.g., total alkali *versus* silica diagram of Le Bas *et al* (1986)) is better. More discussions on this topic can be found in Le Bas and Streckeisen (1991) and Le Maitre *et al* (2002).

Modal analyses (obtained by point counting) of representative samples from the Angadimogar pluton plotted on a Streckeisen (1976) QAP plot indicates that they range in composition from quartz-syenite to quartz-alkali-feldspar-syenite (figure 1c). Whole rock XRD analyses were carried out as part of this study on powdered rock samples from six representative plutons (three granites, one anorthositic gabbro, and two syenites, including the Angadimogar pluton) across southwestern India, using a Philips PW3020 model X-ray diffractometer (housed at Fukuoka University of Education, Japan), using Ni-filtered, $\text{CuK}\alpha$ radiation and a scanning speed of 1°min^{-1} . All the representative whole-rock XRD plots of southwestern Indian granites (e.g., Ezhimala, Ambalavayal, Pathanapuram granites (see figure 1a)) show clear peaks for the main granitic minerals quartz and feldspar (figure 2). On the other hand, Angadimogar syenite whole-rock XRD pattern is similar to that of Puttetti syenite (Rajesh 2003) and Perinthatta anorthositic gabbro (see figure 1a;

Rajesh 2005), with a dominant peak for feldspar (figure 2). The syenite shows a general allotriomorphic texture and consists predominantly of perthitic orthoclase (68–75%), normally zoned plagioclase (6–9%), and a variety of mafic minerals: amphibole (potassian-ferro edenitic hornblende to ferro edenite to ferro actinolite (in the nomenclature of Giret *et al* 1980)), clinopyroxene (diopside (in the nomenclature of Morimoto 1988)), and biotite (annite) (Rajesh 1999). In some samples acmite was found. Quartz occurs as interstitial grains. Magnetite is the main opaque phase and is generally intergrown with ilmenite. Other accessory phases include zircon, allanite, apatite, titanite, calcite, and epidote.

4. Geochemistry

Santosh and Nair (1986), Rajesh (1999) and Anil Kumar *et al* (2005) presented geochemical data on the Angadimogar pluton. Representative major element data from these studies are given in table 1. The syenite has high K_2O (up to 6 wt%). In terms of aluminium saturation index (ASI; Shand 1943) (which is better than A/CNK (molar $\text{Al}_2\text{O}_3/(\text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O})$) in defining peralkaline/metaluminous/peraluminous compositions, as it takes into account the presence of apatite, and is expressed as the molecular ratio of Al, Ca, P, Na and K), Angadimogar syenite samples are clearly metaluminous ($\text{ASI} < 1$ and molecular $\text{Na} + \text{K} < \text{molecular Al}$) similar to quartz-syenites worldwide and different from alkali-feldspar-syenites which are mostly peralkaline (e.g., Eby 1990; Nédélec *et al* 1995; Rajesh 2003). In such rocks (where $\text{ASI} < 1$ and molecular $\text{Na} + \text{K} < \text{molecular Al}$) there is likely to be excess Ca after aluminium has been accommodated in the feldspars. As a result, metaluminous rocks contain calcic phases such as hornblende and augite but lack either muscovite or sodic ferromagnesian phases. This clearly accounts for the mineralogy of the Angadimogar syenite.

On the other hand, if $\text{ASI} > 1$, then the rock is corundum-normative and peraluminous. This means that the rock has more Al than can be accommodated in feldspars and that it must have another aluminium phase present. For weakly peraluminous rocks this phase may be aluminous biotite, but for strongly peraluminous granites the phase can be muscovite, cordierite, garnet or an Al_2SiO_5 polymorph. All the 'granite' samples given in Anil Kumar *et al* (2005) are strongly peraluminous (ASI : 1.24–2.25 (Angadimogar); 1.78 (Kumbdaje); see table 1). But the mineralogy of both Angadimogar and Kumbdaje plutons mentioned in Anil Kumar *et al* (2005) (qtz-kfs-plg-bt-pyx-hbl-opaques) includes no Al_2SiO_5

Figure 2. Representative whole-rock XRD plot of Angadimogar syenite compared with that of Ezhimala, Ambalavayal, and Pathanapuram granites, Puttetti syenite, and Perinthatta anorthositic gabbro, southwestern India. The granites show clear peaks for the main granitic minerals quartz and feldspar, while the syenites and anorthositic gabbro show a dominant peak for feldspar. Peaks of other identified minerals are not shown for clarity.

polymorph to characterize the strongly peraluminous nature. One reason for this can be the poor quality of geochemical data used.

Let me address the *quality* of geochemical data given in Anil Kumar *et al* (2005). At a glance the first thing that strikes a granitoid geochemist, is the extremely *low* Na_2O content (0.23–0.65) of *all the rock types* from the study area (7 granite samples from Angadimogar pluton, 1 aplite sample, 3 gneiss samples and 1 charnockite sample from Angadimogar area, and 1 granite sample from Kumbdaje pluton; see table 1) (figure 3). The Na_2O content of these samples were compared with Na_2O contents of granites and syenites from southwestern India (Rajesh 1999, 2000, 2003, 2004), typical A-type granitoids (including quartz-syenites) given in Eby (1990), quartz-syenites from East Greenland, syenites (quartz-syenite to alkali-feldspar-syenite) from Russia, quartz-syenites from Antarctica, and quartz-syenites from Madagascar (see Rajesh 1999, for the references and compilation), typical peraluminous granites (Strong

and Hamner 1981; Nabelek *et al* 1992; Inger and Harris 1993; Searle *et al* 1997), charnockite massifs from southern India (Rajesh and Santosh 2004 and references therein), hbl-bt gneiss/bt-hbl gneiss from central and northern Kerala (Nambiar *et al* 1992; Rajesh 1999), sodic and potassic garnet-biotite gneiss, garnet-biotite-sillimanite gneiss, and cordierite gneiss from southern Kerala (Chacko *et al* 1992), and mafic dykes from southern India (Radhakrishna *et al* 1995) (figure 3). It should be noted that quartz syenites with hornblende as the major mafic mineral (syenites from East Greenland, Russia and Antarctica) have similar Na_2O contents with the Angadimogar syenite samples, while quartz syenites with pyroxene as the major mafic mineral (other syenites from southwestern India and Madagascar) have lower Na_2O contents. A common feature of all these quartz-syenite studies is their modal per cent of quartz (average 10%; sometimes reaching up to ~19%). This is comparable to modal contents used in this study as well as Santosh and Nair (1986).

Figure 3. Na_2O vs. SiO_2 plots illustrating the compositional variance of the data presented in Anil Kumar *et al* (2005) in comparison with representative data from a range of rock types from southern India and elsewhere. The dotted line in each figure represents the upper limit of the data given in Anil Kumar *et al* (2005). None of the rock types have the extremely lower Na_2O content as the samples given in Anil Kumar *et al* (2005).

Table 1. Representative major element data of the Angadimogor syenite from Santosh and Nair (1986) and Rajesh (1999). The major element data and normative compositions on rock types from the Angadimogor and Kumbdaje areas from Anil Kumar et al (2005) are reproduced for comparison. No P_2O_5 data was used in the calculation of ASI for data from Anil Kumar et al (2005), as it was not available. In any case, addition of P_2O_5 will only increase the value of ASI. MALI – $Na_2O + K_2O - CaO$; Fe-number – $total\ Fe/(total\ Fe + MgO)$.

Sample No. Rock type Reference Major elements (wt%)	AM-1/2 Syenite	AM-1/4 Syenite Santosh and Nair (1986)	AM-1/7 Syenite Santosh and Nair (1986)	AM-1/9 Syenite	R95091G Syenite	R95091B Syenite Rajesh (1999)	R95091F Syenite Rajesh (1999)	R95091E Syenite
SiO ₂	59.74	62.88	63.46	65.85	61.89	62.27	64.24	65.33
TiO ₂	0.31	0.12	0.16	0.44	0.42	0.38	0.16	0.16
Al ₂ O ₃	18.86	18.86	17.84	16.31	18.34	18.23	17.79	18.53
Fe ₂ O ₃	1.83	1.47	2.48	1.16	4.04	5.61	3.22	3.14
FeO	3.09	1.69	1.29	2.26				
MnO	0.07	0.04	0.05	0.05	0.09	0.13	0.08	0.09
MgO	0.32	0.64	0.32	0.64	0.68	0.47	0.35	0.36
CaO	2.47	1.79	1.57	2.47	1.56	1.60	1.16	1.20
Na ₂ O	6.73	6.35	6.43	6.12	6.87	6.05	6.39	5.97
K ₂ O	5.17	5.05	5.60	3.68	4.55	5.27	5.42	6.25
P ₂ O ₅	0.13	0.02	0.02	0.15	0.18	0.13	0.06	0.08
LOI	0.32	0.33	0.50	0.32	0.41	0.53	0.20	0.29
Others*								
Total	99.04	99.24	99.72	99.45	99.03	100.67	99.07	101.40
ASI	0.90	0.99	0.92	0.89	0.97	0.99	0.97	0.99
MALI	9.43	9.61	10.46	7.33	9.86	9.72	10.65	11.02
Fe-number	0.94	0.83	0.92	0.84	0.86	0.92	0.90	0.90
C.I.P.W. norm								
q		1.25	1.73	10.37	0.85	3.16	3.86	3.79
or	30.95	30.17	33.35	21.94	27.27	31.10	32.40	36.53
ab	47.45	54.32	54.84	52.24	58.95	51.12	54.69	49.96
an	6.06	8.13	3.30	6.22	5.85	7.01	3.89	5.24
C								
di	4.76	0.59	2.01	4.33			1.00	
hy		3.10		2.01	1.72	1.17	0.42	0.89
il	0.60	0.23	0.31	0.84	0.19	0.28	0.17	0.19
ap	0.31	0.05	0.05	0.35	0.42	0.30	0.14	0.09

*Others – No P_2O_5 or LOI data was given in Anil Kumar et al (2005). Instead a column titled ‘Others’ was given; MALI – Modified Alkali Lime Index.

Table 1. (Continued).

[illegible]

Figure 4. (a) Q' vs. ANOR plot for the Angadimogar syenite samples (filled symbols; this study), and 'granite' samples from Anil Kumar *et al* (2005) (open symbols). Inset shows the outlier samples from Anil Kumar *et al* (2005). (b) Normative compositions of granite samples given in Anil Kumar *et al* (2005) compared with similar compositions of 7659 granitic rocks from around the world. Note that about 50% of the analyses fall within only about 5% of the diagram (analyses compiled and plotted courtesy of Roger W Le Maitre, Tasmania).

None of the rock types given in figure 3 have such extremely lower Na₂O content as the samples given in Anil Kumar *et al* (2005). *Even typical peraluminous granites do not have such low Na₂O*. In the absence of data on analytical accuracy and precision in the Anil Kumar *et al* (2005) paper, the only way I can explain the extremely low and similar Na₂O content of granite, gneiss, charnockite, and aplite samples analysed by them is poor data quality. This low Na₂O combined with the high Al₂O₃ content translates to a corundum normative composition and hence a peraluminous rock, but

without an Al₂SiO₅ polymorph to account for the peraluminous composition.

5. Normative compositions and the nomenclature of Angadimogar pluton

Anil Kumar *et al* (2005) calculate normative compositions from their geochemical data and plot it in the QAP diagram of Streckeisen (1976) (see figure 1c). It is quite clear from figure 1(c) that plotting normative compositions and modal

compositions of the same pluton in the QAP plot can lead to a significant difference in nomenclature. Streckeis and Le Maitre (1979) put forward the Q' – ANOR method, which is approximately equal to that of the modal QAP diagram of IUGS, for usage with normative compositions. In the Q' – ANOR plot (figure 4a) samples from this study plot in the syenite field, while most of the 'granite' samples from Anil Kumar *et al* (2005) plot out of the fields covered by the diagram (see inset in figure 4a). This uncertainty of the normative compositions of the 'granite' samples is further visible in figure 4(b), where they are compared with normative compositions of 7659 granitic rocks from around the world (compiled and plotted by Le Maitre).

6. Proper classification of the Angadimogar pluton

Granitoid classification is problematic as the same mineral assemblage (quartz-feldspar-ferromagnesian minerals) can be achieved by a number of processes. A major drawback of the IUGS classification scheme is that it ignores compositional variations apart from those that affect the feldspar abundances. Because of this complexity, petrologists have relied upon geochemical classifications to distinguish between various types of granitoids. This study utilizes the geochemical classification of Frost *et al* (2001) based on Fe-number, modified alkali lime index, and ASI. Accordingly Angadimogar syenite is ferroan, alkalic, and metaluminous, typical of alkali (A-type) granitoids (figure 5). Data from Anil Kumar *et al* (2005) subjected to similar geochemical discrimination suggests that the Angadimogar pluton is magnesian to ferroan, calcic, and peraluminous (Kumbdaje is magnesian, calcic, and peraluminous) (figure 5). Interestingly, Frost *et al* (2001) points out that magnesian, calcic, and peraluminous compositions are shown by diorites, quartz diorites, and tonalites, while *there is no known granitoid rock with ferroan, calcic, and peraluminous compositions*.

7. Concluding remarks

Experimental results indicate that the partial melts generated deep in the crust are closer to syenite than granite in composition (e.g., Huang and Wyllie 1975). Low initial $^{87}\text{Sr}/^{86}\text{Sr}$ isotope ratio (0.7032 ± 0.0008 ; Santosh and Nair 1986; Rajesh 1999) and estimated (using Al-in-Hbl geobarometry; Rajesh 1999) pressure conditions of ~ 8 kbar for the Angadimogar syenite translates to a deep crustal depth. The Angadimogar quartz-syenite

Figure 5. $\text{Fe}^*/(\text{Fe}^* + \text{MgO})$ vs. SiO_2 and $\text{Na}_2\text{O} + \text{K}_2\text{O} - \text{CaO}$ vs. SiO_2 plots for the Angadimogar syenite samples, and 'granite' samples from Anil Kumar *et al* (2005).

belongs to the ~ 640 – 500 Ma granitoid magmatic activity along southwestern India (Rajesh 1999, 2000, 2003, 2004). It has all the geochemical characteristics of alkali (A-type) granitoids. Similar quartz-syenites have been reported from different continental fragments (Arabian shield (Harris 1985), Madagascar (Nédélec *et al* 1995), East Antarctica (Zhao *et al* 1995)), placed adjacent to India in a supercontinent framework.

The absence of any mineral (muscovite, cordierite, corundum, andalusite, tourmaline, topaz, garnet, cordierite, sillimanite) characteristic of peraluminous rock does not correlate with the peraluminous compositions presented for samples from the Angadimogar pluton (as well as Kumbdaje pluton) by Anil Kumar *et al* (2005). The mafic mineralogy (hornblende, clinopyroxene, biotite) of Angadimogar syenite is clearly characteristic of a metaluminous rock. Thus the syenite–granite nomenclature issue raised by Anil Kumar *et al* (2005) for the Angadimogar pluton (as well as Kumbdaje pluton) is just an artifact of using questionable geochemical data, and the improper usage of normative compositions in the QAP diagram.

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