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THE BIRIMIAN GRANITOIDS OF GHANA : A REVIEW

Y. YAO and L.J. ROBB

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by

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ABSTRACT

Palaeoproterozoic granitoids are extensively developed in the Birimian terrain of Ghana. Four granitoid types have been recognized: (1) Belt-type (associated with volcanic-sedimentary "greenstone" belt; (2) Basin-type (associated with Eburean sedimentary basins between the greenstone belt; (3) Bongo-type; and (4) Winneba-type. The former two types are widespread in the Birimian, while the latter two types are only found locally.

Belt granitoids occur as small- and medium-sized massive intrusions emplaced within the greenstone belt volcanics and comprise dioritic to granitic rocks. The granitoids are metaluminous, but their felsic phases are slightly peraluminous. Hornblende is the main ferromagenesian mineral in granitoids of more mafic compositions, whereas biotite dominates in felsic members. By contrast, Basin granitoids outcrop as large batholiths intruded within Eburean sedimentary basins between the major greenstone belts. They are peraluminous tonalite to granite, and their main mafic mineral is biotite. The Bongo granitoids are late, K-rich porphyritic granitoids, while the Winneba granitoids consist of porphyritic granodiorite and granite.

U-Pb isotopic ages of zircon, monazite, and rutile range from 2145 ± 2 to 2179 ± 2 Ma for Belt granitoids, and from 2090 ± 1 to 2125 ± 2 Ma for Basin granitoids, indicating that the major granite types were emplaced during two discrete episodes at least 20 million years apart. Based on geological, petrological, geochemical and isotopic (whole-rock Rb-Sr, Pb-Pb and Sm-Nd) characteristics, it is suggested that the Belt granitoids (including the Bongo type) were derived from a mantle source by partial melting, while the Basin granitoids were generated by mixing of mantle derived magma with crustal material. The Winneba granitoids, however, show derivation from an older sialic basement.

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THE BIRIMIAN GRANITOIDS OF GHANA: A REVIEW

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THE BIRIMIAN GRANITOIDS OF GHANA: A REVIEW

INTRODUCTION

The Palaeoproterozoic Birimian terrain of Ghana is charaterized by five equally spaced volcanic greenstone belts with intervening sedimentary basins, and by widespread outcrops of granitoids that occur intruded within both the greenstone belts and the sedimentary basins. Since the pioneering work of Kitson (1928) the Ghanaian Birimian granitoids have, over the past 70 years, been studied by many geologists (e.g., Junner, 1940; Van Den Berg, 1959; Murray, 1960; Kesse, 1969; Senger, 1975, 1984; Mauer, 1986, 1990; Leube and Hirdes, 1986; Taylor et al., 1988, 1992; Leube et al., 1990; Hirdes et al., 1992, 1993; Zitzmann et al., 1993; Loh and Hirdes, 1996) and a considerable body of data has been accumulated. The object of this review is to summarize the latest ideas on the characteristics and genesis of the Birimian granitoids in Ghana.

With the recent renewal in gold exploration in Ghana, it has become apparent that many Birimian granitoids are hosts to gold mineralization. From both an economic and petrogenetic viewpoint a summary of the characteristics of Birimian granitoids was deemed necessary. For this purpose the senior author carried out reconnaissance investigations of the Ghanaian Birimian granitoids during September and October, 1997, with particular emphasis on mineralized granitoids. In the course of this work, numerous publications as well as unpublished data on the granitoids were collected and synthesized.

The main object of this review is to summarize the geological, petrological, geochemical and radiometric isotope data of the granitoids and to discuss their petrogenesis; in addition, an evolutionary model related to regional crustal accretion will also be presented.

GEOLOGICAL SETTING

The Birimian terrain of Ghana forms the easternmost part of the Man Shield which occupies the southernmost third of the West African Craton. Since 1.7 Ga, the West African Craton has remained stable (Leube et al., 1990).

The Birimian geology of Ghana is characterized by five fairly evenly spaced NE-SW-striking volcanic or greenstone belts, with intervening sedimentary basins between the volcanic belts (Fig. 1). Greenstone-belt rocks are composed mainly of deformed Birimian metalavas and Tarkwaian sediments as well as Belt-type granitoids. The metalavas are basaltic in composition, with minor andesitic, dacitic and rhyolitic rocks (Leube et al., 1986, 1990), and their Sm-Nd whole-rock isochron age is reported to be 2166 ± 66 Ma (Taylor et al., 1988, 1992). The Tarkwaian Group is only found within the volcanic belts and overlies the Birimian volcanics. The Tarkwaian consists of conglomerates, sandstones and slates which were interpreted to be derived from various underlying Birimian rocks and to be deformed by gravity tectonics (Leube and Hirdes, 1986; Leube et al., 1990). The U-Pb isotopic dating on zircon and authigenic rutile from the Tarkwaian Group at Tarkwa suggests a time span of 2132 ± 3 to 2095 ± 10 Ma for its deposition, with a Birimian source area that was 2194 ± 3 to 2155 ± 5 Ma old (Hirdes and Nunoo, 1994).

The intervening Birimian sedimentary basins are composed of dacitic volcaniclastics, wacke and argillitic sediments as well as basin-type granitoids. The basin sediments and volcanic-belt lavas are thought to be contemporaneous lateral facies equivalents (Leube and

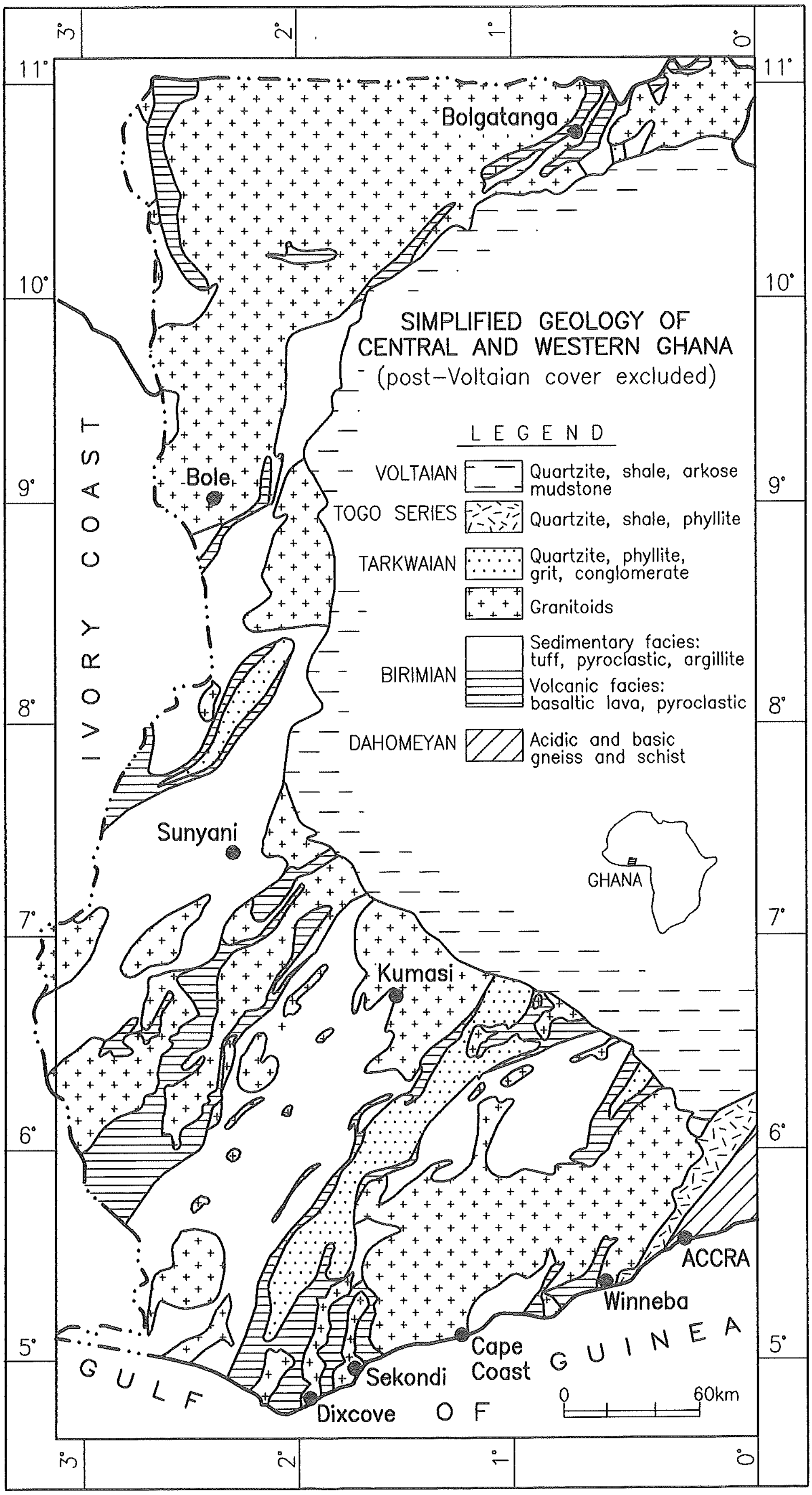


Fig. 1. Simplified geological map of central and western Ghana (after Leube et al., 1990)

Hirdes, 1986; Leube et al., 1990). U-Pb single-grain zircon and monazite ages from the Birimian sediments are between 2184 ± 3 and 2135 ± 5 Ma (Davis et al., 1994), which are comparable with the 2166 ± 66 Ma age of the belt lavas (Taylor et al., 1988, 1992).

Structures of the Birimian Supergroup are represented by a large, asymmetrical, undulating, NE-SW-striking "megasynform". The axis of this megasynform plunges at a low angle and is approximately parallel to the axis of the Ashanti belt. The eastern flank rises sharply to the Pan-African boundary, whereas the western edge dips gently to the SE of the Bole-Navrongo belt. The northeastern extension of the axis, characterized by a gravity high, is approximately in the centre of the Voltaian basin (Leube et al., 1900; Zitzmann et al., 1993).

Granitoids occur extensively in both the sedimentary basins and volcanic belts, and they occupy a large area of the Birimian terrain. A detailed description of their characteristics is summarized below.

THE BIRIMIAN GRANITOIDS OF GHANA

Classification

The Birimian granitoids of Ghana were firstly categorized by Kitson (1928), who recognized three main granite types(Table 1) on the basis of provisional mapping of the Gold Coast. These include: (1) an older biotite granite containing no economic minerals; (2) an older muscovite granite with various associated granites. Pegmatites associated with this type of granite often contain gold, pyrite, cassiterite, molybdenite and rutile; and (3) a younger red granite with various associated granites. Pegmatites associated with this granite contain pyrite and some gold.

Junner (1940) contributed a classic division of the Birimian granitoids dividing the granitoids into two major types: an older granite (G1) and a younger granite (G2). The latter was also referred to as the Dixcove type, whereas the former was defined as the Cape Coast type. Junner (1940) further discussed the relative ages of these two granitoid types and pointed out that the two types were rarely, if ever, seen in contact and, therefore, their relative ages (G1 and G2) could not be determined conclusively.

As summarized by Barning (1976), the Cape Coast type of Junner (1940) corresponds to Kitson's (1928) second granite, whereas the Dixcove type is the same as Kitson's (1928) third type. It is not clear which category of granite was being referred to in Kitson's (1928) first type, but it may be a part of the Cape Coast suite.

The Winneba granite was first recognized by Layton (1958), who described this pluton as a porphyroblastic microcline-biotite adamellite cut by biotite granite. According to Mauer (1986, 1990), the Winneba granite is granodioritic to granitic in composition.

In the mapping of the "Zuarungu" ½° field sheet of NW Ghana, Murray (1960) first distinguished the Bongo granite as a pink, coarse-grained, K-rich hornblende granite and described its geological and petrographic characteristics. He stated that this granite is only confined to a relatively small area in Zuarungu. Murray (1960) did not elaborate upon the relative ages of the Bongo granite. Somewhat later, Mauer (1986) recognized the Banso granite southeast of Kumasi and attributed the phase to the K-rich Bongo type. He suggested that the Banso granite is of post-Tarkwaian age.

In contrast to the above petrographic divisions, Lobjoit (1962) attempted to correlate the Birimian granitoids with orogenesis. Based on the geological and petrographic characteristics of the granitoids in the Wiawso-Bibiani and Axim-Tarkwa-Sekondi areas, he proposed syn- and late-orogenic categories for the Birimian granitoids. However, a lack of temporal relationships between regional orogeny and magmatism meant that this subdivision was largely speculative.

Building on the classification of Junner (1940), however, Bourov and Sharkovsky (1964) as well as Dabowski (1972) proposed a multiple stage evolution for the Cape Coast and Dixcove type granitoids. Based on their field mapping in northwestern Ghana, they recognized three or four lithological phases of the granitoids, which represent different evolutionary stages. Moreover, Dabowski (1972) suggested that the Cape Coast type was synkinematic with respect to regional Birimian deformation, whereas the Dixcove type was postkinematic. This proposal was based on the concept of the Birimian stratigraphy of Junner (1940).

Table 1: Classification of the Birimian granitoids in Ghana

Author	**Year**	**Classification**				
Kitson	1928	Older Biotite granite	Older muscovite granite	Younger red granite		
Junner	1940	Older Cape Coast and Winneba types (G1)		Younger Dixcove type (G2)		
Murray	1960				Bongo K-rich granite	
Lobjoit	1962	Syn-orogenic granite		Late-orogenic granite		
Bourov and Sharkovsky	1964	Cape Coast granitoids (4 phases)		Dixcove granitoids (3 phases)		
Dabowski	1972	Synkinematic multiphases		Postkinematic multiphases		
Barning	1976	Cape Coast granitoids		Dixcove granitoids	Post-Dixcove intrusions	
Kesse	1985	Cape Coast type	Winneba type	Dixcove type	Bongo type	
Mauer	1986	Sedimentary-basin granitoids		Volcanic-belt granitoids	Late K-rich granitoids	Unclassified granitoids
Mauer	1990	Sedimentary-basin granitoids	Winneba granitoids	Volcanic-belt granitoids	Bongo K-rich granitoids	
Leube et al.	1990	Sedimentary-basin type	Winneba type	Volcanic-belt type	Bongo K-rich type	
Hirdes et al.	1993	Basin type		Belt type		

Barning (1976) reviewed classifications of the Birimian granitoids in Ghana, and also accepted the terminology relating to the Cape Coast and Dixcove types of Junner (1940). In mapping of the ¼° field sheet of Kukuom N.E., Barning (1976) recognized three distinct phases of Dixcove type granitoids, which represent an evolution of granitoids from basic to acidic compositions. He also described post-Dixcove intrusions as diabase dykes and quartz veins which intrude and cut both the granitoids and country rocks.

In his book "The Mineral and Rock Resources of Ghana", Kesse (1985) summarized previous divisions of the Birimian granitoids in Ghana and termed them the Cape Coast, Dixcove, Winneba and Bongo types. He described geological and geochemical features of the four granitoid types. Recently, however, comprehensive studies on the Ghanaian Birimian granitoids have been made by German geologists involved in the Germany-Ghana Mineral Prospecting Project. Mauer (1986) reviewed previous granitoid work and made an intensive field investigation of the Birimian granitoids in Ghana. On the basis of their geological setting and geochemistry, Mauer (1986) renamed the granitoids as volcanic-belt, sedimentary-basin, late K-rich and unclassified types. In 1990, Mauer divided the Ghanaian granitoids into volcanic-belt, sedimentary-basin, Winneba and Bongo K-rich types and described petrographic and geochemical features for each of the four granitoid types. He also recognized the I-type characteristics of the four granitoid types. In combination with the Rb-Sr whole-rock isotopic data of Taylor et al. (1988), Mauer (1990) suggested that the Belt, Basin and Bongo granitoids were derived from the partial melting of basaltic material from the mantle, and that the Winneba granitoids were produced by the melting of Archaean protocrustal materials.

At the same time, Leube et al. (1990) summarized the geological and geochemical characteristics of the four granitoid types identified by Mauer (1986, 1990). Based on Rb-Sr, Pb-Pb, and Sm-Nd whole-rock isotope data of Taylor et al. (1988), Leube et al. (1990) suggested that the Basin- and Belt-type granitoids from the Birimian terrain of Ghana have strong mantle affinites and could be compared with the I-type granites of Chappell and White (1974). By contrast, the Winneba granitoid was suggested to have been derived from an Archaean sialic precursor.

In the mapping of areas in central and west Ghana, on a scale of 1:100 000, Hirdes et al. (1993) and Zitzmann et al. (1993) also summarized the geological, petrographical, geochemical and isotopic characteristics of the Belt- and Basin-type granitoids, with special emphasis on their particular study areas.

Finally, Loh and Hirdes (1996) accepted the Belt- and Basin-type categories in their 1:100 000 mapping of areas in southwest Ghana, and gave a detailed geological, petrological, and geochemical description of the Belt granitoids in their study areas.

Petrology

Belt granitoids outcrop within volcanic belts as small- and medium-sized massive plutonic bodies (Fig. 1), comprising diorite, gabbro, tonalite, granodiorite, and granite (s.s.) (Fig. 2a). Several different lithological phases are common within the larger plutons, and metabasalt enclaves are usually found in most of the intrusions, a feature which is consistent with an I-type origin for these granitoids.

Major mineral assemblages of the Belt granitoids are plagioclase-quartz-K-feldspar-hornblende-biotite (Table 2). Plagioclase is typically oligoclase to andesine, and is characterized by saussuritization or sericitization (Mauer, 1990; Leube et al., 1990); K-feldspar is microcline and is sericitized to a less extent; hornblende is defined as hastingsite and in some cases is epidotized; biotite is also partly chloritized (Mauer, 1990). As shown in Table 2, concentrations of plagioclase, hornblende and biotite decrease from mafic to felsic members, whereas quartz and K-feldspar increase. In more mafic plutons, hornblende is the dominant ferromagnesian mineral, with minor biotite, while in more felsic intrusions biotite constitutes the major mafic mineral. Accessory minerals in the various granitoid types are similar, including epidote, apatite, and allanite, with minor zircon, titanite, and opaque minerals.

Basin granitoids are emplaced within basin sediments as large granitoid batholiths, and tend to coincide with the central axes of the sedimentary basins (Leube et al., 1990). They consist of tonalite, granodiorite, and granite (s.s.) (Fig. 2a). Mineral assemblages of the Basin granitoids include plagioclase, quartz, K-feldspar, biotite and muscovite (Table 2). Plagioclase is oligoclase to andesine in composition and K-feldspar is microcline. In contrast to Belt granitoids, saussuritization or sericitization of plagioclase is less well developed (Mauer, 1990). Biotite and muscovite are the main ferromagnesian minerals, and hornblende is rare. The Basin granitoids commonly display foliation indicated by interveining dark-coloured biotite and light-coloured feldspar and quartz. Accessory minerals of the Basin granitoids are similar to those of the Belt granitoids, and comprise epidote and titanite, with minor zircon, apatite, and opaque minerals (Table 2).

Table 2: Mineral assemblages and concentrations of different rock types from the four granitoid types in Ghana (after Mauer, 1990)

Rock type		**Di**	**QG**	**QDi**	**Tn**		**Gd**				**Gr**			
Granitoid type		**VGr**	**VGr**	**VGr**	**VGr**	**BGr**	**VGr**	**BGr**	**WbGr**	**BnGr**	**VGr**	**BGr**	**WbGr**	**BnGr**
Mineral concentrations (vol. %)														
	Pl	69	66	66	59	61	50	48	47	49	40	35	39	35
	Qz	2	6	15	25	25	29	27	26	25	26	28	26	24
	Kf	1		6,5	6	1,5	11	13	18	19	30	31	25	35
Maj.	Hb	18	16	6	2	0,5	2	0,3						
	Bi	5	10	10	7	8	6	5	5	4	2	3	6	3
Min.	Mus				++	3	++	6	1,5	1,5	1	2	3	2
	Ep	3												
	Tau	1												
	Ep		++	++	++	++	++	++		++	++	++		++
	Tt	++		+	+	+	++	++						++
Acc.	Ap	++	++		++		+	++	++	++	-	-	++	+
	Zr						++		+	++		+	++	+
Min.	At				+		+		++	++	++		++	
	OM	-	-	+	-	-	-	-	-	-	-	-	-	-
	Hm		+				-							
	Car		-											

Note: Di=diorite, QG=quartz gabbro, QDi=quartz diorite, Tn=tonalite, GD=granodiorite, Gr=granitoid. VGr=volcanic belt granitoids, BGr=sedimentary basin granitoids, BnGr=Bongo granitoids, WbGr=Winneba granitoids. Maj. Min.=major minerals, Acc. Min.=accessory minerals. Pl=plagioclase, Qz=quartz, Kf=K-feldspar, Hb=hornblende, Bi=biotite, Mus=muscovite, Ep=epidote, Tau=titanaugite, Hm=hematite, Car=carbonates, Tt=tatanite, OM=opaque minerals, Ap=apatite, At=allanite, Zr=zircon. ++: abundant, +: minorly abundant, -: less abundant. VGr=volcanic-belt granitoids, BGr=basin granitoids, BnGr=Bongo granitoids, WbGr=Winneba granitoids.

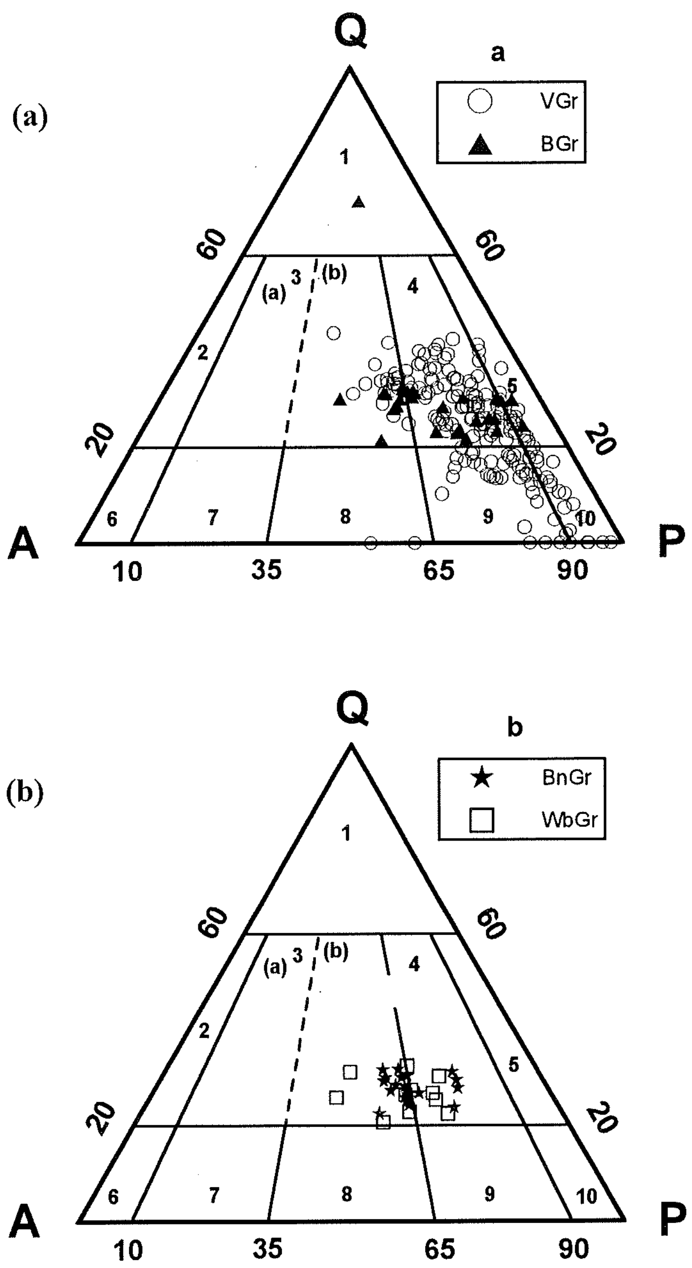


Fig. 2. Triangular QAP diagram (Streckeisen, 1976) showing CIPW normative mineral compositions of Belt and Basin granitoids in a, and Bongo and Winneba granitoids in b from Ghana. Q=quartz, A=alkali feldspar, P=plagioclase. 1=quartz-rich granite, 2=alkali-granite, 3=granite, 3(a)=syenogranite, 3(b)=monzogranite, 4=granodiorite, 5=tonalite/trondhjemite, 6=alkali syenite, 7=syenite, 8=monzonite, 9=monzogranite/ monzogabbro, 10=diorite/ gabbro/ anorthosite. Chemical analyses of the VGr, BGr, BnGr, and WbGr are from Mauer (1990); Hirdes et al. (1993); Loh and Hirdes (1996). Abbreviations as in Table 2. For data see Appendix 1.

The Bongo granitoids occur within the Bole-Navrongo Belt of northern Ghana where they intrude Tarkwaian sediments (Mauer, 1986, 1990; Leube et al., 1990). The granitoids are characterized by pink porphyroblastic K-feldspar, including granodiorite and granite (s.s.) (Fig. 2b), and their major minerals are plagioclase, K-feldspar, and quartz, with minor biotite.

Accessory minerals include epidote, titantite, apatite, with minor zircon and opaque minerals (Table 2).

The Winneba granitoids occur only in the vicinity of Winneba town where they intrude basin sediments. The granitoids comprise granodiorite and granite (s.s.) (Fig. 2b), which are commonly cut by late-stage pegmatite veins. Pink porphyritic K-feldspar is characteristic, and biotite dominates as the main mafic mineral. The Winneba granitoids show weak foliation. Their accessory mineals are similar to those of the Bongo granitoids (Table 2).

Major element oxides

Chemical analyses of 235 samples from the four granitoid types are compiled from data in Mauer (1990), Hirdes et al. (1993), and Loh and Hirdes (1996), and are presented in Appendix 1. Average chemical compositions of the Belt, Basin, Bongo, and Winneba granitoids, together with I-type granitoids, are tabulated in Table 3.

Table 3: Average concentrations of major oxides and trace elements of four granitoid types in Ghana (Mauer, 1990; Hirdes et al., 1993; Loh and Hirdes, 1996), together with I-type granitoids from Chappell and White (1992)

Type	I-type granitoids	VGr	BGr	BnGr	WbGr
Number of sample	1074	175	27	10	23
Major oxides (%)					
SiO_2	69,50	66,10	70,32	71,17	69,34
TiO_2	0,41	0,42	0,29	0,24	0,46
Al_2O_3	14,21	15,07	15,15	14,77	15,12
Fe_2O_3	3,01	4,37	2,49	1,75	3,00
MnO	0,07	0,08	0,05	0,03	0,03
MgO	1,38	1,74	0,89	0,55	0,75
CaO	3,07	3,58	1,95	1,64	2,31
Na_2O	3,16	4,38	4,48	4,35	3,82
K_2O	3,48	2,15	2,93	4,23	3,84
P_2O_5	0,11	0,13	0,10	0,08	0,12
Trace elements(ppm)					
Cu	9	27	16	8	9
Pb	19	11	17	24	29
Zn	48	61	54	39	63
Rb	164	61	129	158	110
Sr	235	505	421	624	379
Ba	519	748	683	1174	1018
SC	13	12	7	6	6
V	57	62	22	13	4
Cr	20	35	20	4	7
Co	10	25	18	15	18
Ni	8	21	14	7	6
Nb	11	7	5	5	11
Th	20	7	11	18	30
U	5	3	4	6	6
Zr	150	140	104	119	216
Y	31	21	7	8	14

Note: Abbreviations as in Table 2.

The Belt granitoids show lower SiO_2 and K_2O, but higher Al_2O_3, Fe_2O_3, MgO, CaO, and Na_2O values. By contrast, the Basin granitoids have higher SiO_2, Al_2O_3, and Na_2O, but lower TiO_2, Fe_2O_3, MgO, CaO, and K_2O contents. As listed in Table 3, Fe_2O_3, MgO, CaO, Na_2O, and K_2O are characteristic for each of the four granitoid types. The Belt granitoids have higher Fe_2O_3, MgO, and CaO, but lower Na_2O, and K_2O contents than the Basin granitoids. The Bongo granitoids are characterized by the highest K_2O concentrations in the four types and the Winneba granitoids show lower Na_2O, but higher K_2O and CaO values than the Basin granitoids.

The Belt granitoids exhibit a complete gradation in composition from diorite to granite, whereas the Basin granitoids are much more restricted in compositional range, and are mainly granodioritic to granitic. The Bongo and Winneba granitoids are also granodioritic to granitic in composition. Harker diagrams (Fig. 3) reveal considerable variations in major element chemistry of the Belt- and Basin-type granitoids, with a much more restricted range for the Bongo and Winneba types, the latter undoubtedly related to the fewer samples available.

As shown in Figure 3, SiO_2 concentrations of the Belt granitoids show a wide range from about 45 to 77 % and their TiO_2, Fe_2O_3, MgO, and CaO concentrations gradually decrease with increasing SiO_2 (Fig. 3a-d). Similarly, these oxide concentrations of Basin granitoids also decrease with increasing SiO_2, ranging from about 65 to 74 % (Fig. 3a-d). By contrast, total alkalis (Na_2O+K_2O) of the Belt and Basin granitoids range from 2 to 10 % and from 6 to 10 %, respectively, and they are positively correlated with SiO_2 (Fig. 3e). Both the Bongo and Winneba granitoids show a narrow range of SiO_2 concentrations from 65 to 75 % (Fig. 3f-j), and their TiO_2, Fe_2O_3, MgO, and CaO concentrations decrease with increasing SiO_2 (Fig. 3f-i), but total alkalis contents increase with increasing SiO_2 (Fig. 3 j). The chemical characteristics of the major element oxides suggest a liquid-line-of-descent, perhaps supportive of a typical AFC (assimilation-fractioned crystallization) process.

Molar CaO-Na_2O+K_2O-Al_2O_3 compositions of the four granitoid types are shown in Figure 4, illustrating the peraluminous, metaluminous, and peralkaline fields. Sixty five percent of the samples of Belt granitoids fall in the metaluminous field near the boundary line, while most of the remainder fall on the metaperaluminous boundary. By contrast, all but one sample of the Basin granitoids plot in the peraluminous field just below the boundary line (Fig. 4a). The Bongo granitoids show similarities in aluminous character to the Belt granitoids, while the Winneba granitoids are similar to the Basin granitoids (Fig. 4b).

Figure 5 shows the aluminium saturation index (ASI), expressed as molar $Al_2O_3/(CaO+Na_2O+K_2O)$, for the four type granitoids, which distinguishes between I- and S-type granites (Chappell and White, 1974; 1992). The Belt granitoids have ASI values mainly between 0,8 and 1,1, with an average of 0,96 ± 0,15 (1σ, n=175). Sixty two percent of samples plot in the I-type field, and the others fall in the S-type field near the boundary (Fig. 5a). The S-type field of the Belt granitoids coincides only with the more differentiated phases of the suite and it is therefore suggested that the peraluminous values do not necessarily represent a S-type origin, but merely a fractionation trend.

The Basin granitoids plot in the S-type field near the S- and I-type boundary, with three point in the I-type field (Fig. 5a), and have ASI values of 0.97 to 1,27, with an average of 1.08 ± 0,07 (1σ, n=27). This suggests that the Basin granitoids are S-type granites in the sense of Chappell and White (1992). The Bongo granitoids show an average ASI of 1.00 ± 0,04 (1σ,

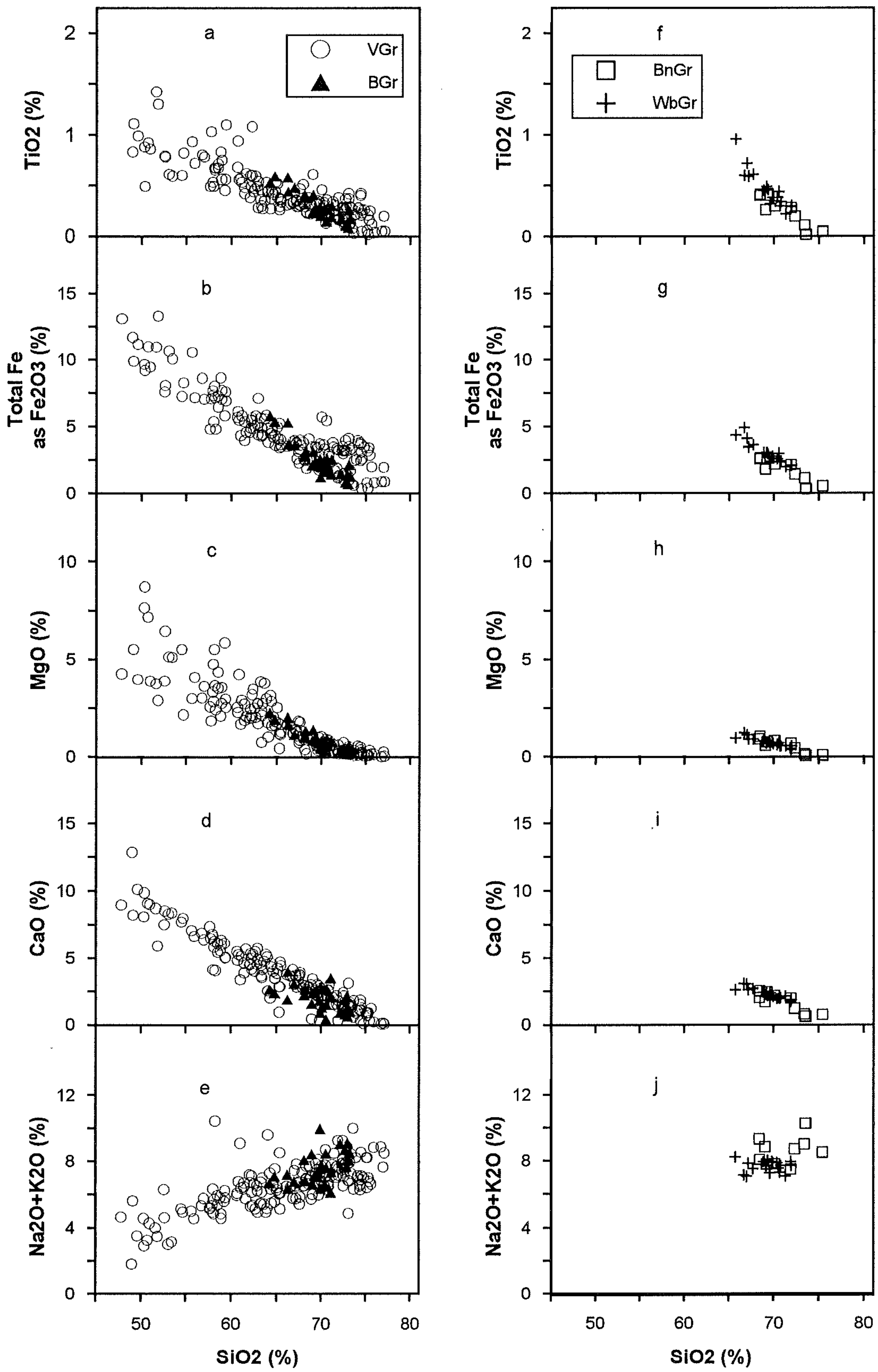
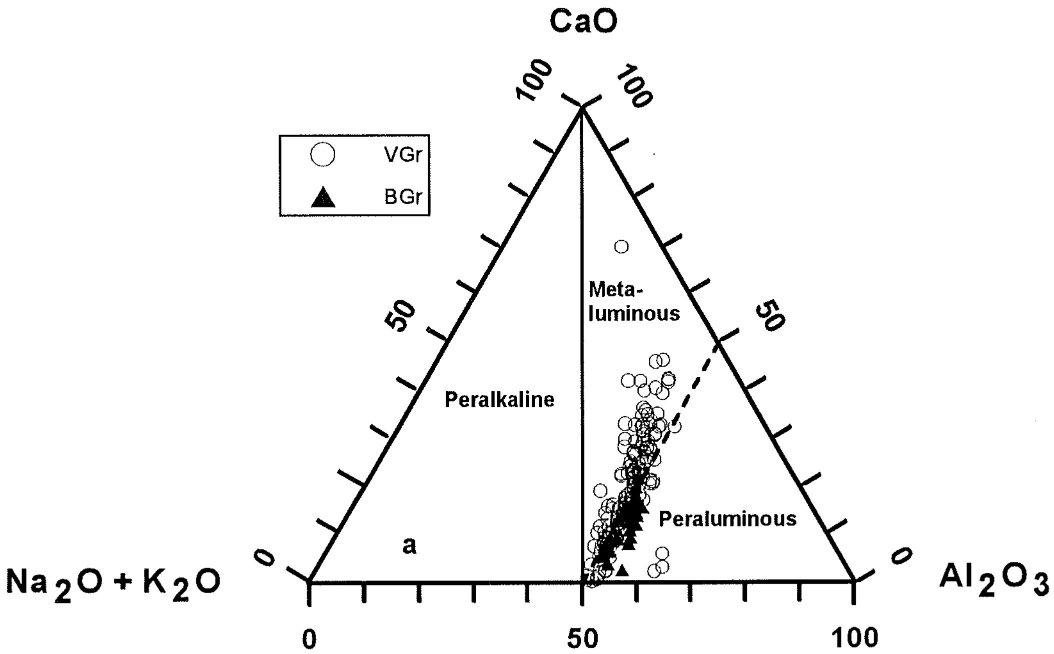


Fig. 3. Harker diagrams displaying the compositions of TiO_2, Fe_2O_3, MgO, CaO and $Na_2O + K_2O$ versus SiO_2 for the four granitoid types from Ghana. Abbreviations as in Table 2 .



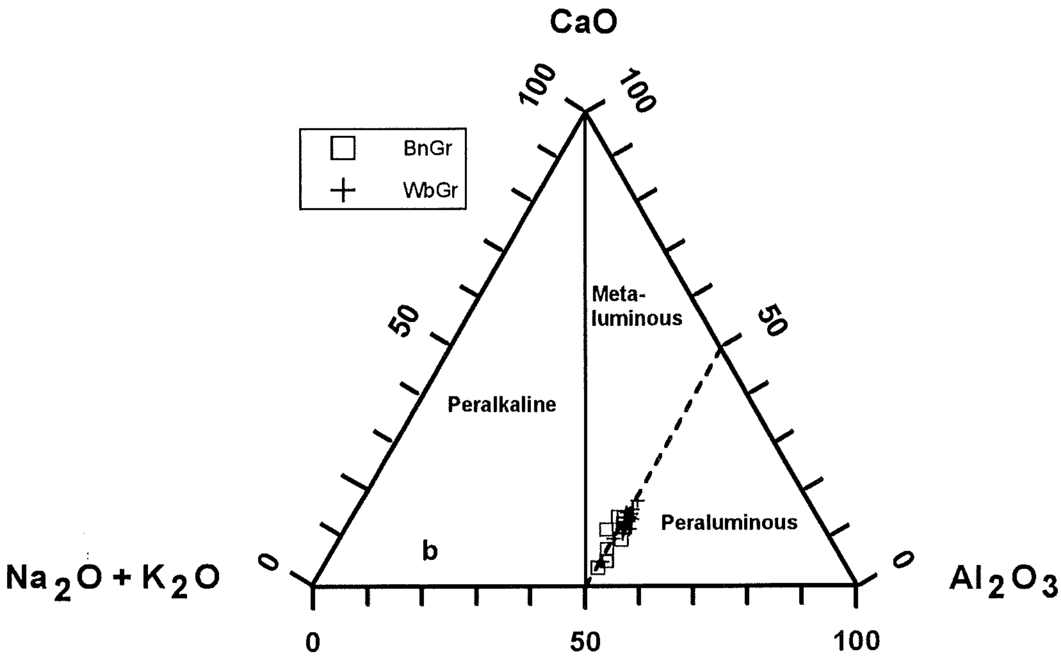
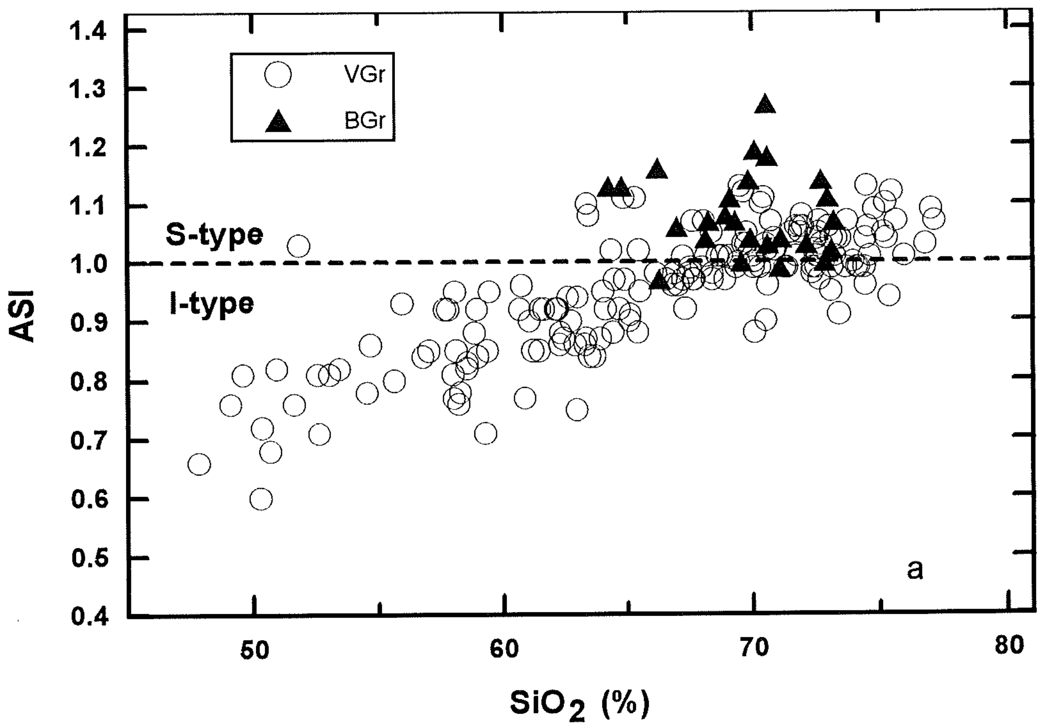


Fig. 4. Ternary diagrams of molar CaO-Na_2O+K_2O-Al_2O_3 compositions for the four granitoid types from Ghana. The original plot is from Witt and Davy (1997). Abbreviations as in Table 2.

(a)



(b)

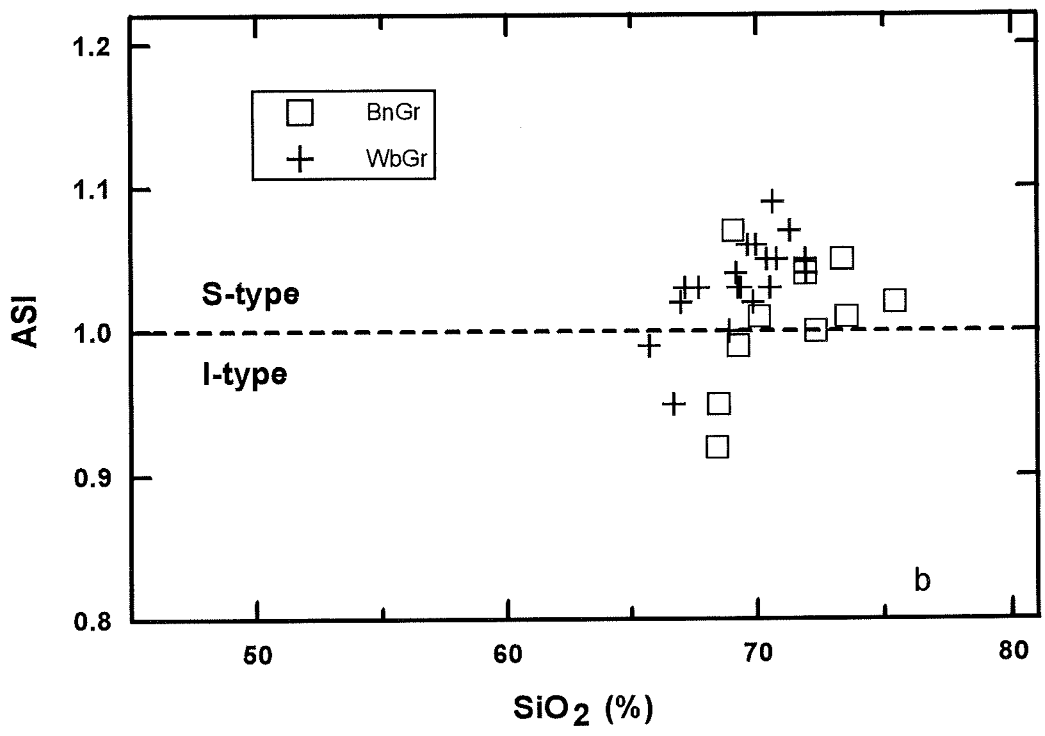
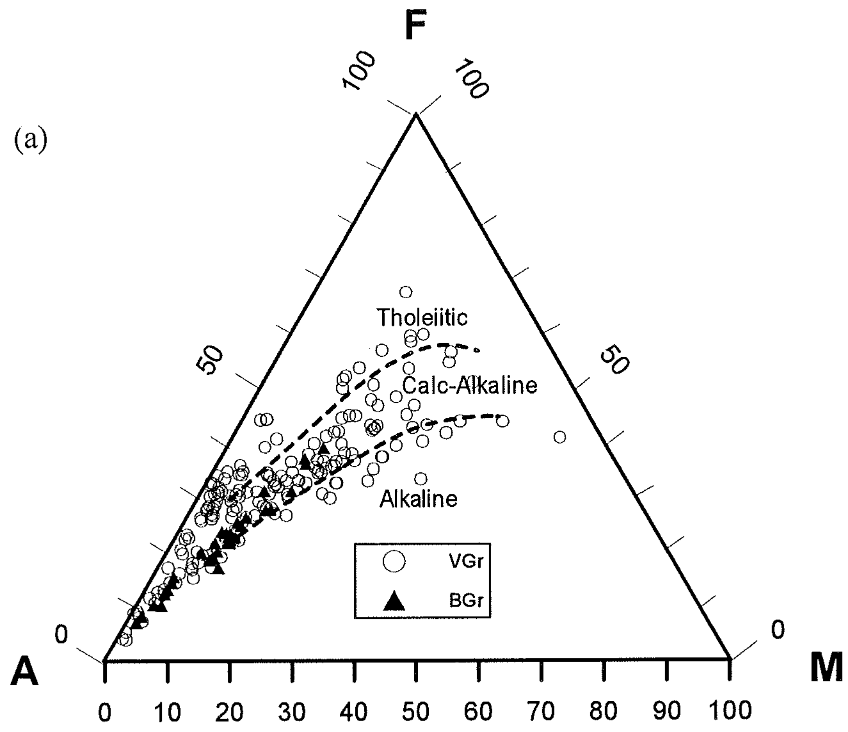


Fig. 5. Aluminium saturation index (ASI) versus SiO_2 diagram showing aluminium saturation index of the four granitoid types from Ghana. ASI=molar $Al_2O_3/(CaO + Na_2O + K_2O)$. The dashed line dividing the I- and S-type granites is at ASI=1 (Chappell and White, 1992).



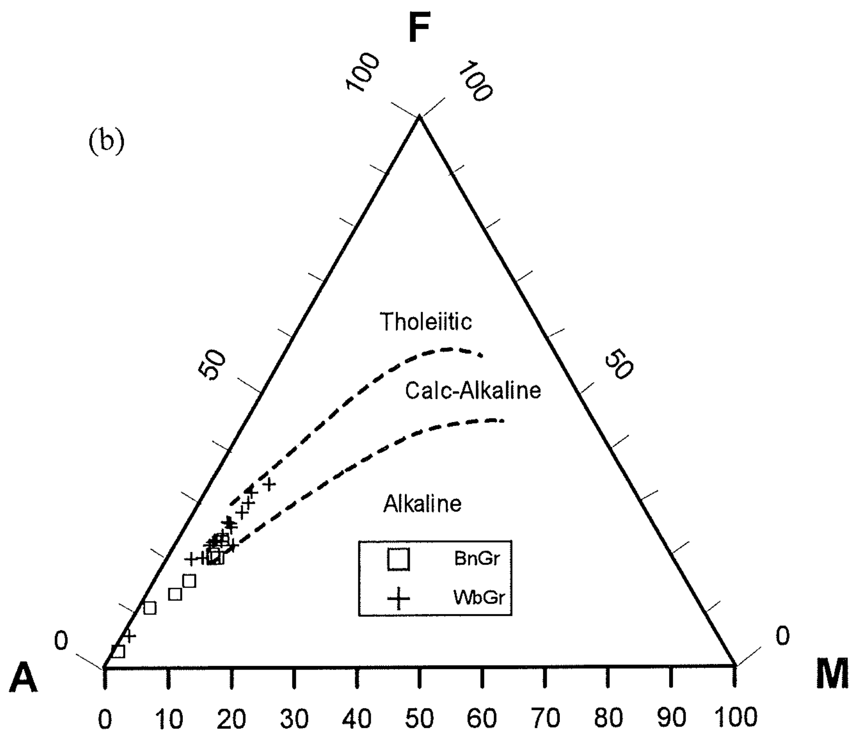


Fig. 6. Ternary AFM plots showing an alkaline trend for the four granitoid types from Ghana. F=total Fe as Fe_2O_3, A=Na_2O+K_2O, M=MgO (molar). The dashed line separating the alkaline, calc-alkaline and tholeiitic fields are from Barker and Arth (1976). Abbreviations as in Table 2.

n=10), with some samples plotting in the S-type field (Fig. 5b). By contrast, the Winneba granitoids show ASI similarities to the Basin granitoids (Fig. 6), ranging from 0,95 to 1.09, with an average of 1,03 ± 0,03 (1σ, n=19). The degree of aluminous saturation for the four granitoid types are further reflected in Figures 8 and 15, which emphasize the petrogenetic differences between Belt and Basin granitoids.

In the AFM ternary plots (Fig. 6), most of samples from Belt granitoids show a calc-alkaline affinity, although a few samples stray into both of the alkaline and tholeiitic fields. The Basin granitoids as well as the Bongo and Winneba granitoids, which are different to the Belt type, plot mainly along the calc-alkaline boundary.

A chemical-mineralogical diagram for plutonic rocks was proposed by Debon and Le Fort (1983), who considered the aluminous and mafic characters of intrusive rocks in terms of two parameters A (Al-(K+Na+2Ca)) and B (Fe+Mg+Ti) calculated in terms of millications per 100 grams, and correlated the two parameters with rock types (Fig. 7). This diagram is divided into six sections which, in turn, subdivide the peraluminous and metaluminous domains in terms of mineral contents. It also separates leucogranitoids at B=38,8 from more typical granitoid complexes (Fig. 7). The metaluminous character of the granitoids indicates a source mainly derived from the mantle or primary crustal material, whereas the peraluminous domain of granitoids is related to derivation from anatexis of continental crust, including metasedimentary precursors (Debon and Le Fort, 1983). Thus, the diagram provides not only chemical-mineralogical associations, but also petrogenetic constraints for granite plutons.

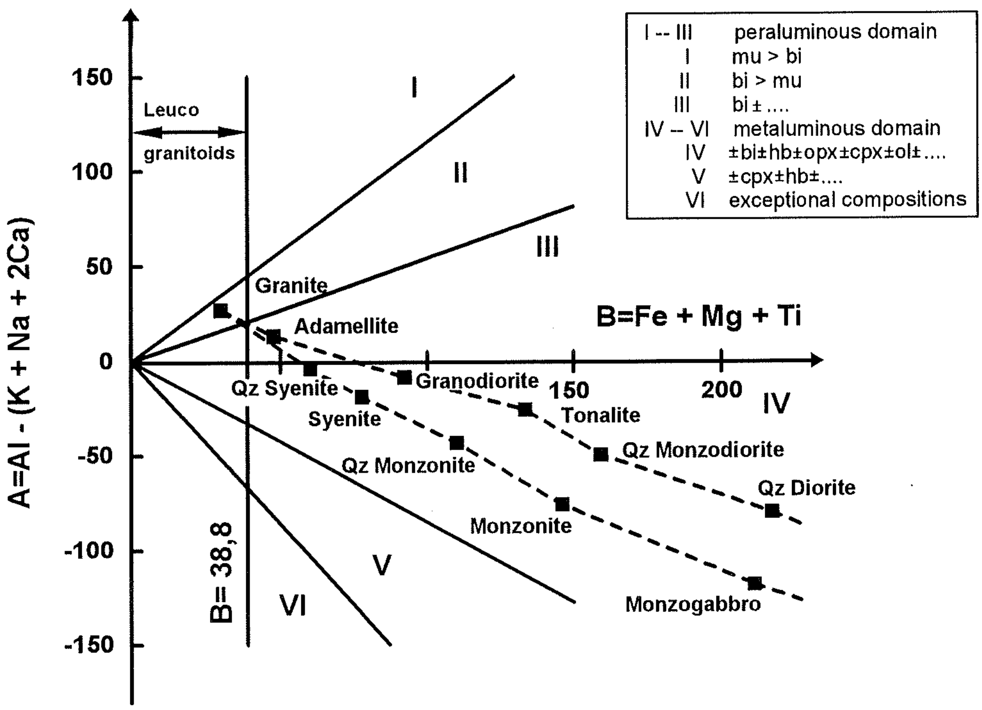


Fig. 7. Petrographic diagram for intrusive rock types on the basis of A (Al-(K-Na-2Ca)) and B (Fe-Mg-Ti) parameters in millications per 100 gram (Debon and Le Fort, 1983).

With the exception of three samples, the bulk of Belt granitoids defines a negative slope on the Debon and Le Fort (1983) diagram (Fig. 8a). seventy per cent of samples plot in the metaluminous field, whereas the others fall in the peraluminous field, the latter reflecting the more fractionated end-member of this series. In contrast, all but three samples of Basin granitoids, fall in the peraluminous field, and define a slightly positive slope (Fig. 8a). The Bongo granitoids are similar to Belt granitoids, while the Winneba granitoids, like the Basin granitoids, fall in the peraluminous domain (Fig. 8b). These indicate that the Belt granitoids (including the Bongo granitoids) are different in their petrogenesis to the Basin granitoids (including the Winneba granitoids). This will be discussed in more detail in a later section.

Trace elements

Birimian granitoids exhibit considerable variations in trace element contents by comparison with the typical ranges exhibited for I-type granites (Chappell and White, 1992). For example, Rb contents in the Belt and Basin granitoids are 103 and 35 ppm lower, repectively, than those in the I-type granitoids (Table 3). For each of the four granitoid types, the Rb, Sr, and Ba contents appear to discriminate them one from the other (Table 3). Belt granitoids are characterized by lower Rb contents than the other three types, whereas Basin granitoids show higher Rb, but lower Sr and Ba contents than Belt granitoids. The Bongo and Winneba granitoids are characterized by higher Ba contents than Belt and Basin granitoids, which is consistent with their higher K_2O contents (Table 3). In addition, Belt granitoids are marked by higher V, Cr, Co, and Ni contents than the other three types, reflecting their more mafic character.

In the ternary Rb-Ba-Sr diagrams (Fig. 9), Belt granitoids display, with the exception of three samples, a continuously differentiated trend from diorite to normal granite. Basin granitoids, however, show a differentiated trend from quartz diorite/granodiorite to anomalous ganite (Fig. 9a). This may be related to their more fractionated nature or to hydrothermal alteration. Similarly, both the Bongo and Winneba granitoids demonstrate a differentiated trend from granodiorite to anomalous granite (Fig. 9b).

The transition elements of the four granitoid types and the Birimian basalts are normalized to the primitive mantle and shown in Figure 10. All the normalized patterns of the granitoids and basalts are similar. The Birimian basalts are characterized by significant depletions in Cr and Ni, and slight depletions in Fe and Co, but enrichment in Sc, Ti, V, Mn, Cu and Zn contents. It is noteworthy that each of the transition elements from Belt granitoids is about three times lower than its corresponding equivalent in the basalts. Except for Zn, the pattern shapes of the Basin granitoids, as well as the Bongo and Winneba granitoids are similar to those of the Belt granitoids, but in all they exhibit a depletion in the transition trace elements, and especially in the case of Cr and Ni contents. Taking into account the geological occurrence of the four granitoid types, it is not surprising that the Belt granitoids and the basalts exhibit a geochemical affinity with one another, possibly suggesting a genetic link. The other three granitoid types are clearly more felsic in composition, thus possibly reflecting a different origin/precursor.

In the tectonic discrimination diagrams of Pearce et al. (1984) (Fig. 11), the overwhelming majority of all the Birimian granitoid samples fall into the fields of "volcanic arc

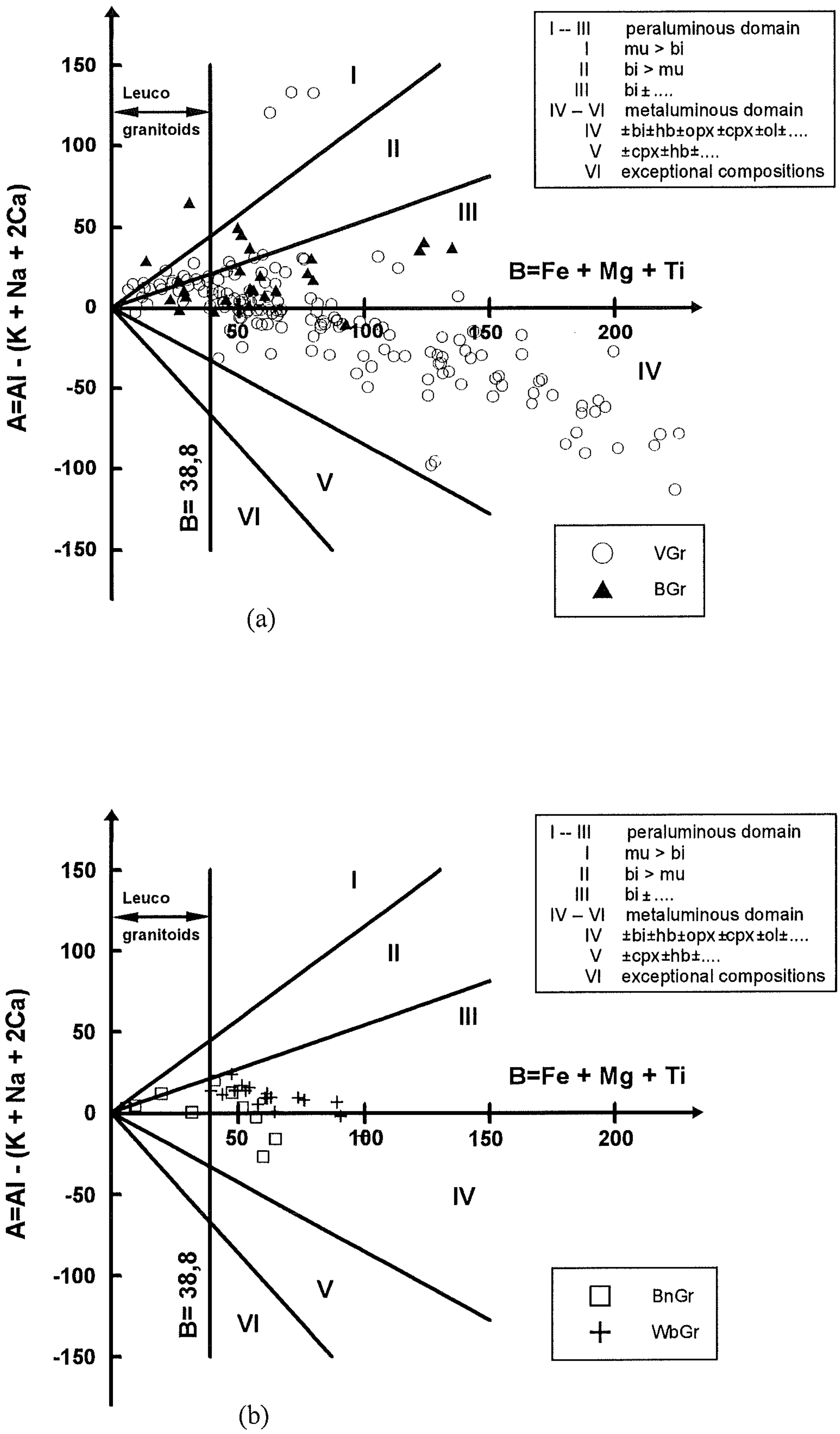


Fig. 8. Petrogenetic diagram showing the nature of the four granitoid types from Ghana (classification scheme after Debon and Le Fort, 1983).

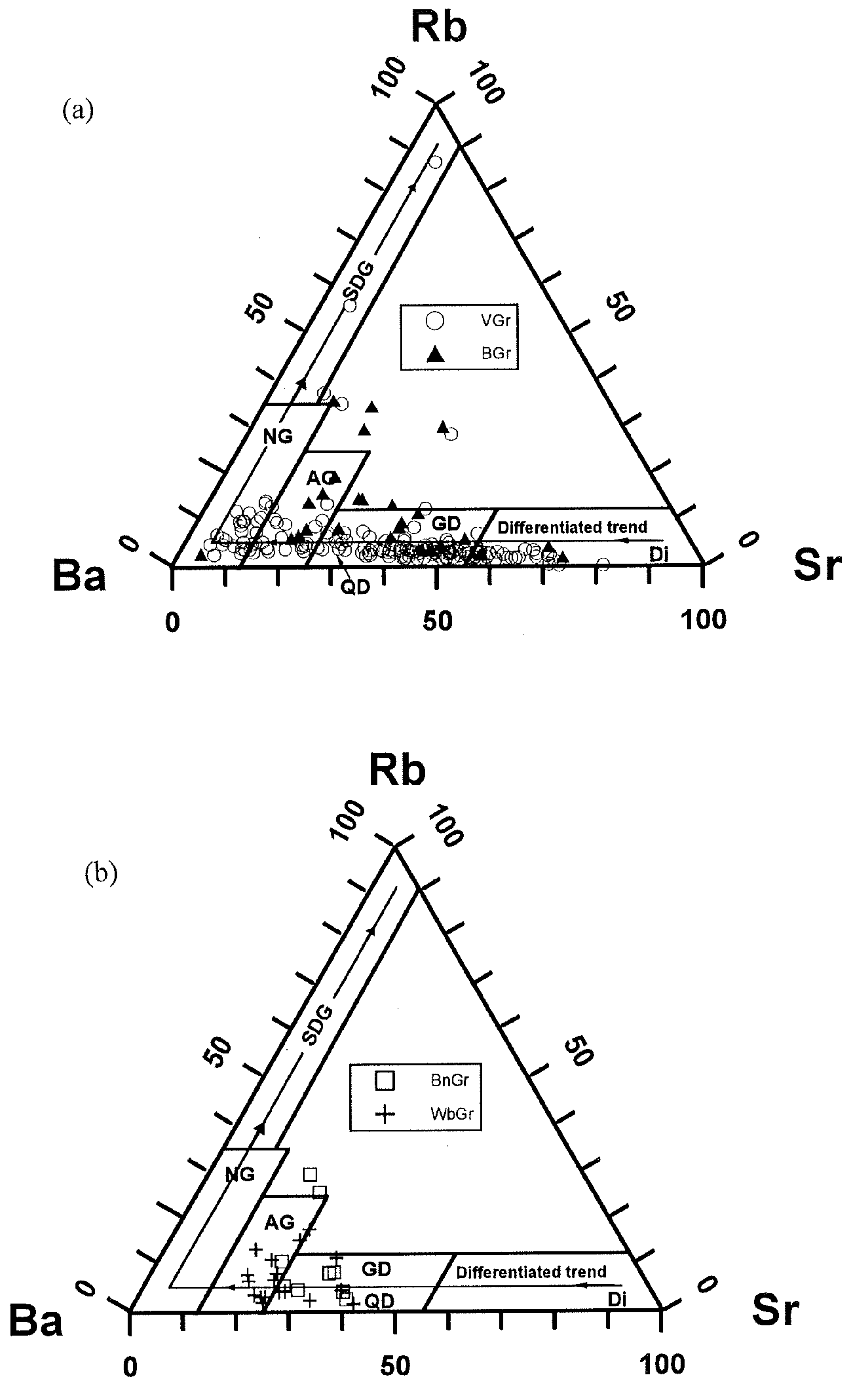


Fig. 9. Ternary Rb-Ba-Sr diagrams (El Bouseily and El Sokkary, 1975) showing differentiated trends of the four granitoid types from Ghana. Di=diorite, QD=quartz diorite, GD=granodiorite, AG=anomalous granite, NG=normal granite, SDG= strongly differentiated granite. Abbreviations as in Table 2.

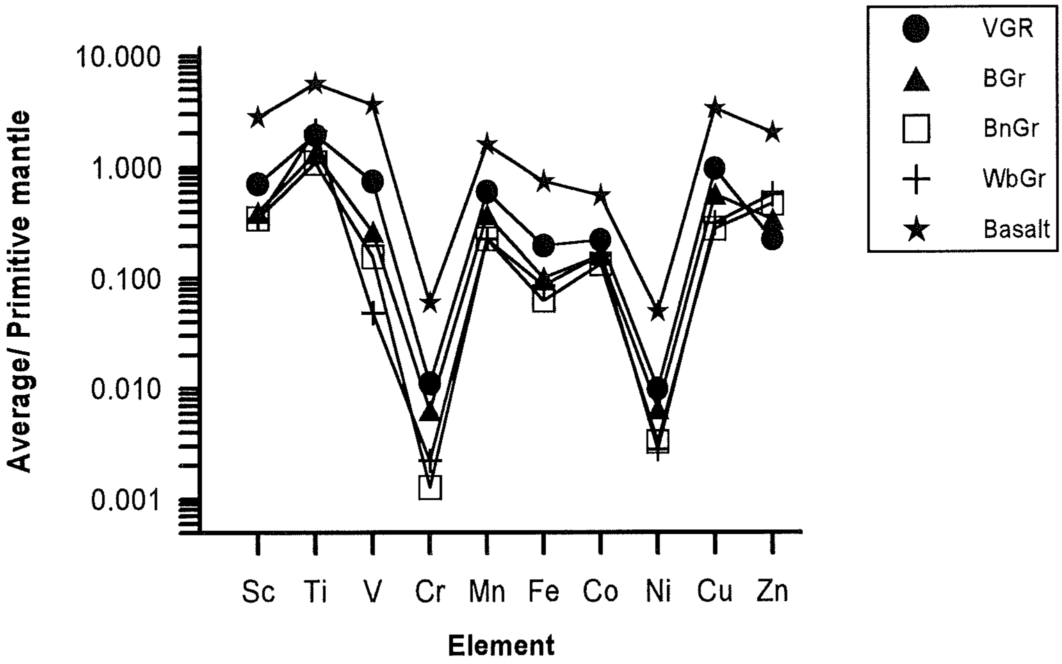


Fig. 10. Normalized abundance patterns of transition elements for the four granitoid types and the Birimian basalts from Ghana. The primitive mantle values for normalization are from Sun (1982) (in Rollison, 1993). Abbreviations as in Table 2.

granitoids" or "syn-collision granitoids". Figure 11(c and d) further discriminate the separation and point to a preference for the former tectonic environment. In a general sense these characteristics confirm the models which envisage the entire Birimian terrain to be the result of juvenile crustal growth and accretion during the Palaeoproterozoic. In detail, however, several models envisage the rift-related setting for the belt-related tholeiitic magmas, with contemporaneous emplacement of Belt granitoids and the late-kinematic intrusion of Basin granitoids for the Birimian terrain (Leube et al., 1990; Hirdes et al., 1993; Zitzmann et al., 1993). This discrepancy may be related to the fact that Pearce-type diagrams, originally designed for Phanerozoic tectonic settings, are not suitable for the Precambrian intrusions in Ghana, which perhaps reflect different crustal growth mechanisms (Mauer, 1986).

Chondrite-normalized REE patterns of eight granitoid samples are shown in Figure 12. The samples were taken from both the Belt and Basin granitoid types and composed mainly of granodiorites. The four samples of Basin granitoids from northern Ghana display steep LREE-rich patterns, with no significant Eu depletion, indicating less differentiated characteristics (Fig. 12a). By contrast, four samples of Belt granitoids (n=2) and Basin granitoids (n=2) from southwestern Ghana are characterized by enriched LREE and prominent negative Eu anomalies and variable LREE contents (Fig. 12b), which suggests a more differentiated character. With respect to the eight samples available, it would appear that the REE patterns of Birimian granitoids reflect their geographic localities rather than the granite types. This supposition needs to be more rigorously tested with additional analyses before it can be deemed to have any meaningful significance.

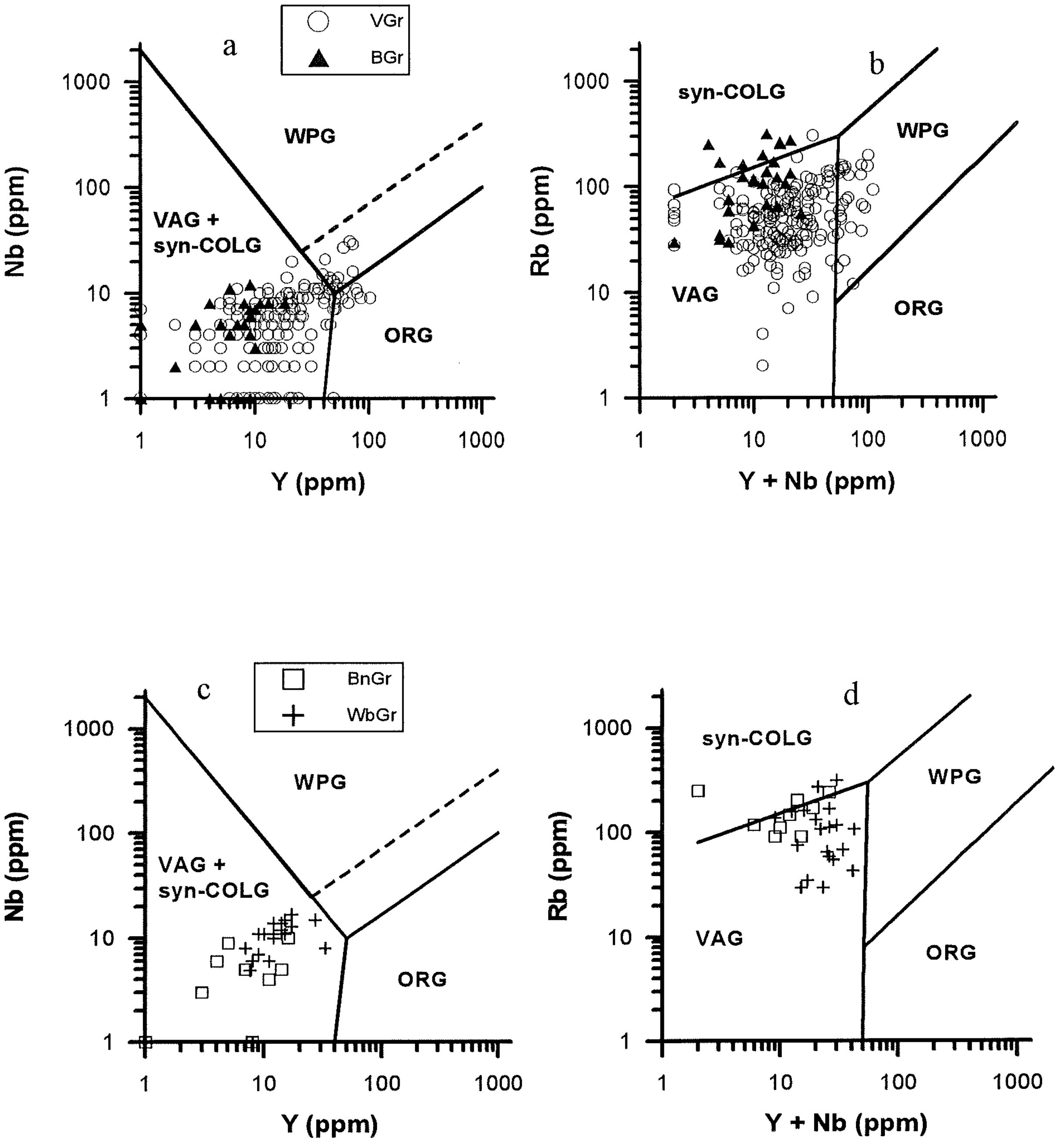


Fig. 11. Nb-Y and Rb-Y+Nb diagrams (Pearce et al., 1984) showing the tectonic settings of the four granitoid types from Ghana. OGR=ocean-ridge granites, syn-COLG=syn-collisional granites, VAG=volcanic-arc granites, WPG=within-plate granites. Abbreviations as in Table 2.

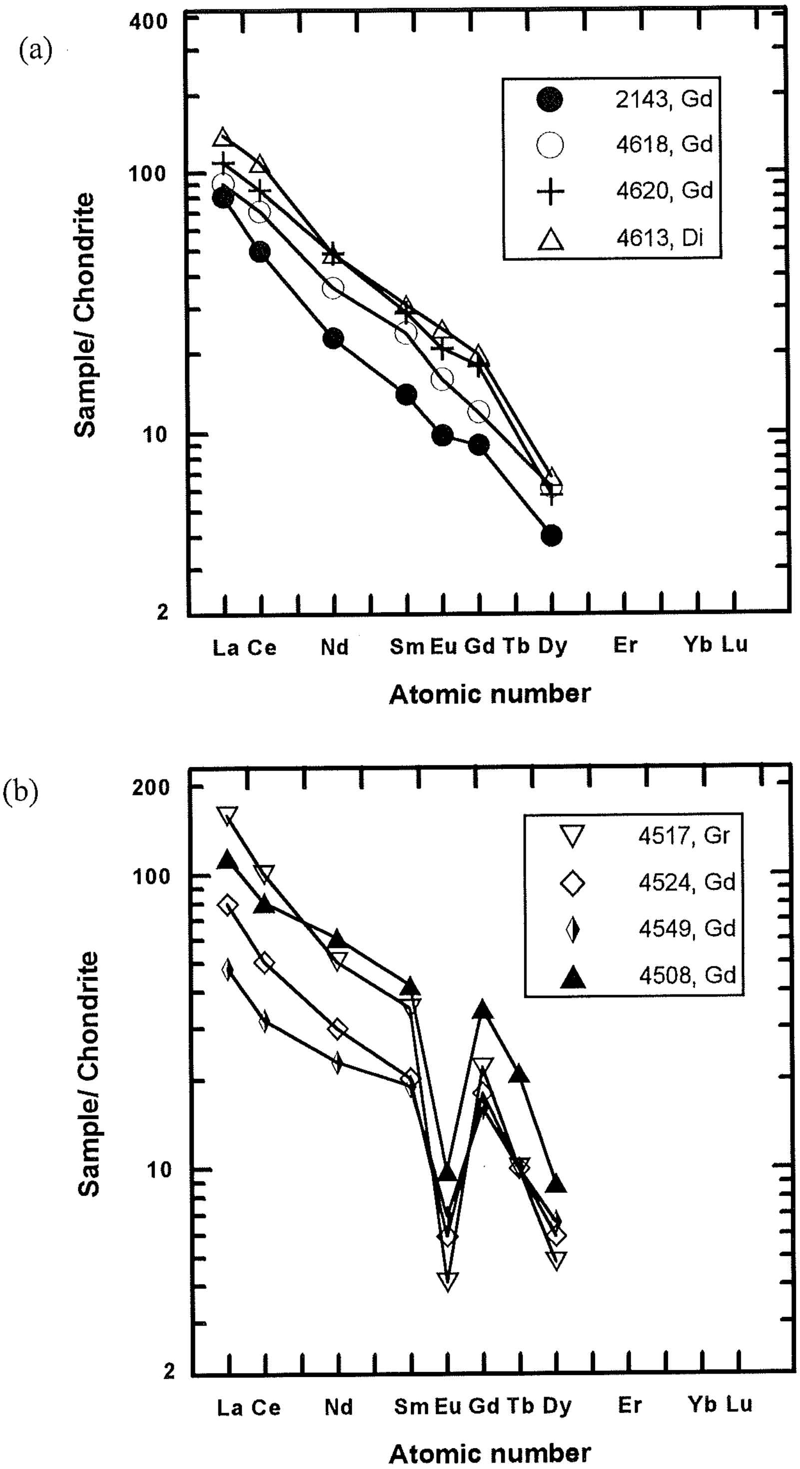


Fig. 12. Chondrite-normalized REE patterns of Belt and Basin granitoids from Ghana. a: Basin granitoids from the Upper West region of northwestern Ghana and Bolgatanga of northeastern Ghana; b: Belt granitoids (4549 and 4508) and Basin granitoids (4517 and 4524) from southwestern Ghana. Di=diorite, Gd=granodiorite, Gr=granite. Data source is from Mauer (1986).

Isotopic ages

Previous attempts to derive the relative ages of the Cape Coast (G1) and Dixcove (G2) granitoids were carried out by Junner (1940), based on the degree of foliation of the two granitoid types. However, as Junner (1940) himself discussed, this was not conclusive since contact relationships between the two granitoid types were seldom if ever observed.

Many attempts to isotopically date the Birimian granitoids in Ghana have been carried out over past 40 years. According to the summary of Agyei (1988), the earliest isotopic dating work was undertaken by Schillibeer and Watson (1954), who obtained a K-feldspar separate from a pegmatite east of Konogo which gave a K-Ar age of 1851 ± 120 Ma. Since then, many isotopic age determinations using the K-Ar and Rb-Sr systems on biotite, K-feldspar and whole-rock granitoids from the Birimian terrain of Ghana have been reported (Priem et al., 1966; Holmes and Cahen, 1967; Tungarinov and Vernaskiy, 1967; Agyei, 1977; Vechette and Attoh, 1982; Agyei and Armstrong, 1986; Agyei et al., 1987; Taylor et al., 1988, 1992; Chalokwu et al., 1997). Most of the data confirm, in a general way, the Palaeoproterozoic age of the Birimian terrain, but are characterized by large errors and imprecision.

Taylor et al. (1988, 1992) reported isotopic dating results of Rb-Sr, Sm-Nd and Pb-Pb whole rocks on the four major Brimian granitoid types and volcanic-belt lavas. Most of the results on the granitoid ages were not well documented due to large uncertainties (Appendix 2). Chalokwu et al. (1997) reported K-Ar ages of muscovite and biotite from pegmatites and granites at the Mankwadzi district, southeast Ghana. Three muscovite separates from pegmatites yielded ages of 1909 ± 13, 1965 ± 13 and 2019 ± 14 Ma, whereas a biotite separate from a Cape Coast granite gave an age of 1907 ± 14 Ma. These K-Ar isotopic ages are better constrained than previously reported Rb-Sr and K-Ar isotopic results of mineral separates and whole-rock granitoids (Appendix 2). However, the K-Ar ages of Chalokwu et al. (1997) are still some 100 Ma younger than those of U-Pb zircon and monazite dating for the Cape Coast granitoids reported by Hirdes et al. (1992), Zitzmann et al. (1993), and Loh and Hirdes (1997), which are now regarded as reasonably definite indications of the age of the various components comprising the Birimian terrain of Ghana.

Figure 13 shows the Rb-Sr and K-Ar isotopic ages of Basin granitoids available to date. The Rb-Sr and K-Ar isotopic ages span a similar wide range from 1620 to 2261 Ma, with an average of 1938 ± 136 Ma (1σ, n=26), and from 1649 to 2184 Ma, with an average of 1932 ± 137 Ma (1σ, n=43), respectively. These data are now considered as thermochronometers and reflect the variable re-setting of isotopic systems by thermal perturbations and/or progressive cooling through the blocking temperatures that apply to the different host minerals and isotopic systems.

Age relationships between major granitoid types and the Birimian and Tarkwaian rocks had not been established with any precision until the work of Hirdes et al. (1992), who first reported U-Pb zircon, monazite and rutile isotopic ages for Belt and Basin granitoids. Two samples of Belt granitoids gave ages of 2172 ± 2 Ma (Ashanti belt) and 2179 ± 2 Ma (Sefwi belt), while another two samples of Basin granitoidsed yield ages of 2116 ± 2 Ma (Kumasi basin) and 2088 ± 1 Ma (Sunyani basin). In contrast to the traditional concept that Basin granitoids are older than Belt granitoids, the results of Hirdes et al. (1992) indicated that the Belt granitoids are some 60 to 90 Ma older than the Basin granitoids. The Belt granitoid ages

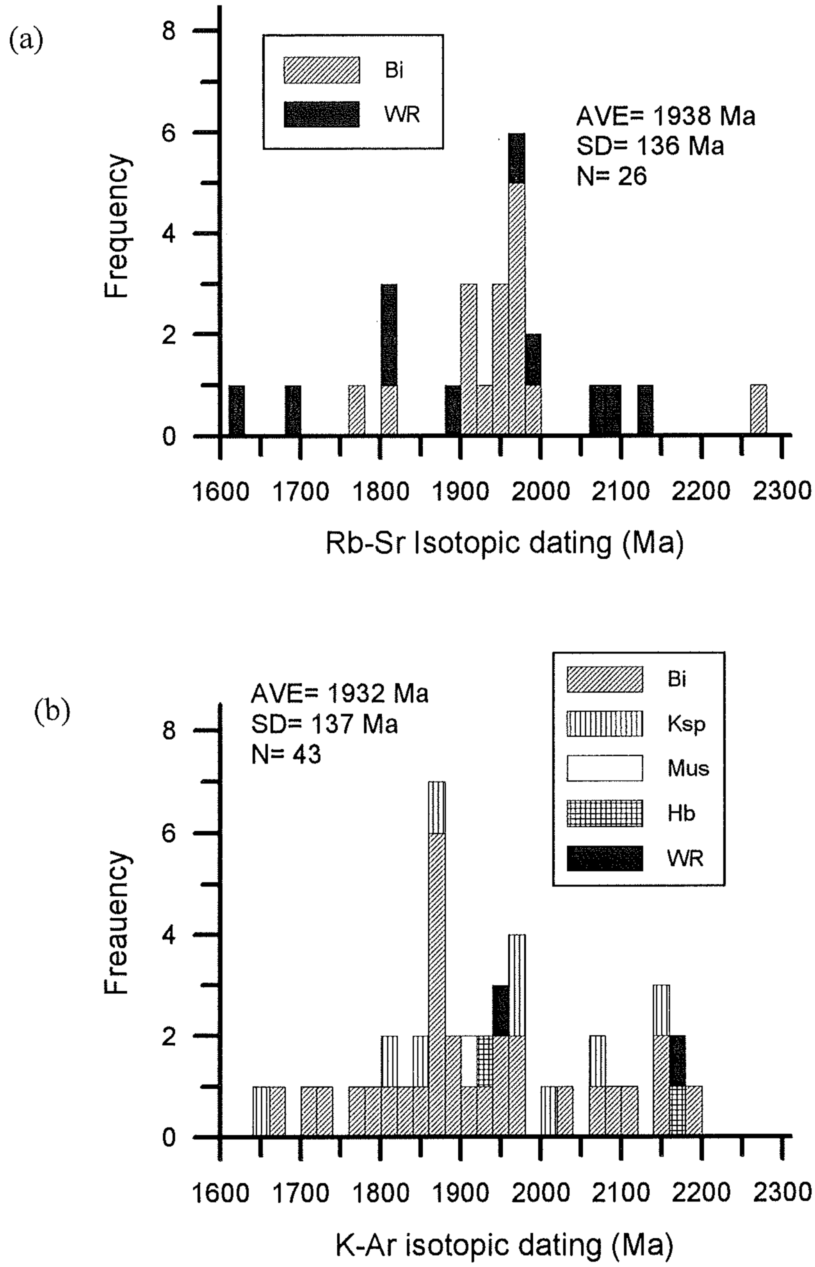


Fig. 13. Histograms of Rb-Sr and K-Ar isotopic ages for Basin granitoids from Ghana. For data see Appendix 2.

are comparable with the 2166 ± 66 Ma age for belt tholeiites obtained by Taylor et al. (1988, 1992), thus confirming the earlier suggestion that Belt granitoids and volcanics are coeval and part of the same igneous event (Hirdes et al., 1992). Spacially, Belt granitoids are intimately associated with metabasalts within the volcanic belts; furthermore, an early pre-deformation emplacement of Belt granitoids is also indicated by their absence within Tarkwaian sediments, as well as by extensive retrograde alteration and shearing of these plutons (Hirdes et al., 1992).

Zitzmann et al. (1993) has also reported U-Pb zircon isotopic dating for four Birimian granitoids in their map area in western Ghana. The ages are 2145 ± 2 Ma for the Dome pluton, marginal to the Bui belt; 2125± 2 Ma in the Maluwe basin; 2092 ± 2 Ma in the Sunyani basin; and 2090 ± 1 Ma for a Cape Coast granite near Elmina.

U-Pb monazite and rutile isotopic ages of the Basin-type granitoids at Ayanfuri and Yanmensakrom near Obuasi, from the easternmost margin of the Kumasi basin, were reported to be between 2086 ± 4 (rutile) and 2105 ± 3 Ma (monazite), and between 2098 ± 7 (rutile) and 2105 ± 3 Ma (monazite), respectively (Oberthür et al., 1994).

Most recently, in the mapped area of the southern Cape Coast basin and the Ashanti belt, some U-Pb zircon and monazite dating for Basin and Belt granitoids was also reported by Loh and Hirdes (1997). The ages of Belt granitoids in the southern Ashanti belt range from 2153 ± 5 to 2174 ± 2 Ma (4 samples), whereas the ages in the Cape Coast basin are between 2102 ± 1 and 2104 ± 3 Ma (2 samples). These results of Zitzmann et al. (1993), Oberthür et al. (1994), and Loh and Hirdes (1996) indicate that the Belt granitoids are 20 to 90 Ma older than the Basin granitoids, which agrees well with the data of Hirdes et al. (1992).

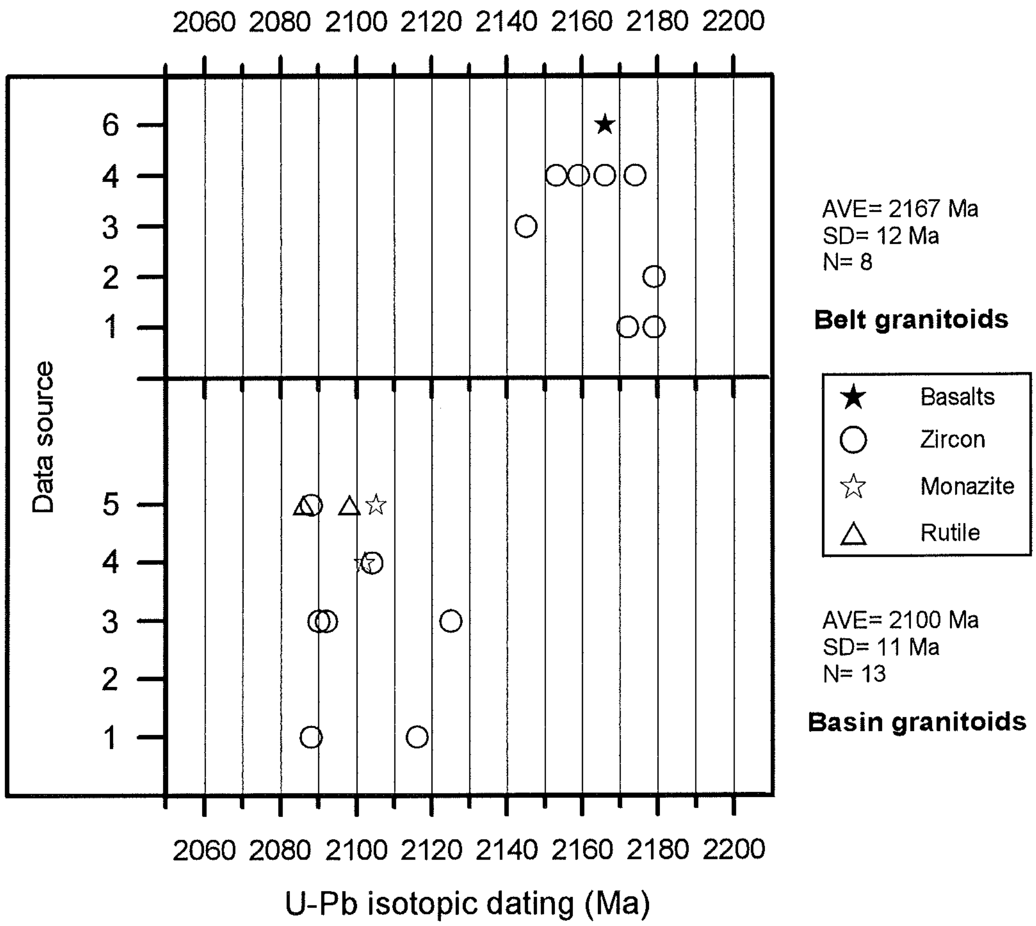


Fig. 14. Diagram of U-Pb zircon, monazite and rutile isotopic ages for Belt and Basin granitoids from Ghana. Also shown is the Rb-Sr isochron age of belt basalts. Data source: 1: Hirdes et al. (1992); 2: Hirdes et al. (1993); 3: Zitzmann et al. (1993); 4: Oberthür et al. (1994); 5: Loh and Hirdes (1996); 6: Taylor et al. (1988, 1992).

All the high-precision U-Pb isotopic ages available for Belt and Basin granitoids are presented in Appendix 2 and plotted in Figure 14. This diagram shows two quite separate age groups: one from 2145 ± 2 to 2179 ± 2 Ma, with an average of 2167 ± 12 Ma (1σ, n=8) for the Belt granitoids, and the other from 2086 ± 4 to 2125 ± 2 Ma, with an average of 2100 ± 11 Ma (1σ, n=13) for the Basin granitoids. The former group is consistent with the belt basalt ages of 2166 ± 66 Ma (Taylor et al., 1988, 1992), suggesting contemporaneous relationships between the Belt granitoids and belt basalts (Hirdes et al., 1992; Zitzmann et al., 1993). The latter group is clearly late-kinematic and postdates Tarkwaian sedimentation, thus representing a minimum age for the Eburnean deformation event (Hirdes et al., 1992). The age differences between the Basin granitoids were interpreted to be either a compositional evolution of Basin granitoids or a progressive accretion of belt terranes (Hirdes et al., 1992). However, the ages of Belt granitoids are remarkably different from belt to belt: 2153 to 2174 Ma in the Ashanti belt; 2179 Ma in the Sefwi belt; and 2145 Ma in the Bui belt, which suggests an evolution towards younger ages in Belt granitoids from the southeast to the northwest. If it can be confirmed, this trend would argue in favour of a mechanism of progressive accretion of belt terranes over an interval of some 100 million years between circa 2080 to 2180 Ma.

Summary

The Belt, Basin, Bongo and Winneba granitoids from the Birimian terrain in Ghana are readily defined in terms of their geology, petrology, geochemistry and isotopic characteristics, and these are summarized in Table 4. The data are mainly compiled from Mauer (1986, 1990), Leube et al. (1990), Hirdes et al. (1992), and Taylor et al. (1992).

The Belt granitoids (including the Bongo type) are dioritic to granitic in composition, with hornblende as the dominant ferromagnesian mineral in the more mafic rocks and biotite in the more felsic phases. In accordance with these mineralogical characteristics, the Belt granitoids are dominantly metaluminous. Deuteric and hydrothermal alteration of minerals is common. By contrast, the Basin granitoids (including the Winneba type) exhibit a more restricted compositional range and are granodioritic to granitic. They are marginally peralumious and their mafic minerals are mainly biotite, with minor muscovite. The Basin granitoids usually show foliation and the alteration of minerals is weak.

Both the Belt and Basin granitoids, except for the Winneba type, have low $^{87}Sr/^{87}Sr$ initial ratios (0,7014 to 0,7017) and model-μ values (7,84 to 8,00) indicating derivation from a mantle source. The high-precision U-Pb isotopic ages reveal that the Belt granitoids are 20 to 90 Ma older than the Basin granitoids. The age differences between the Belt and Basin granitoids may reflect a progressive accretion of belt terranes.

Discussion

Relationship between chemical and mineralogical compositions

The relationship between the chemical and mineralogical compositions of the four granitoid types, together with the mantle-derived (MD), fertile sediment (FS), and “mimimum melt“ (MM) compositions, is shown on ACF diagrams (Chappell and White, 1992) in Figure 15. The diagram displays the major mineral phases occurring in intrusive rocks, and the peraluminous and metaluminous fields, which are separated by a line (aluminium saturation index: ASI=1) joining anorthite (An) and hypersthene (Hyp). According to Chappell amd

White (1992), I-type granitoids occupy the metaluminous field, and are characterized by hornblende, whereas S-type granitoids tend to lie in the peraluminous field.

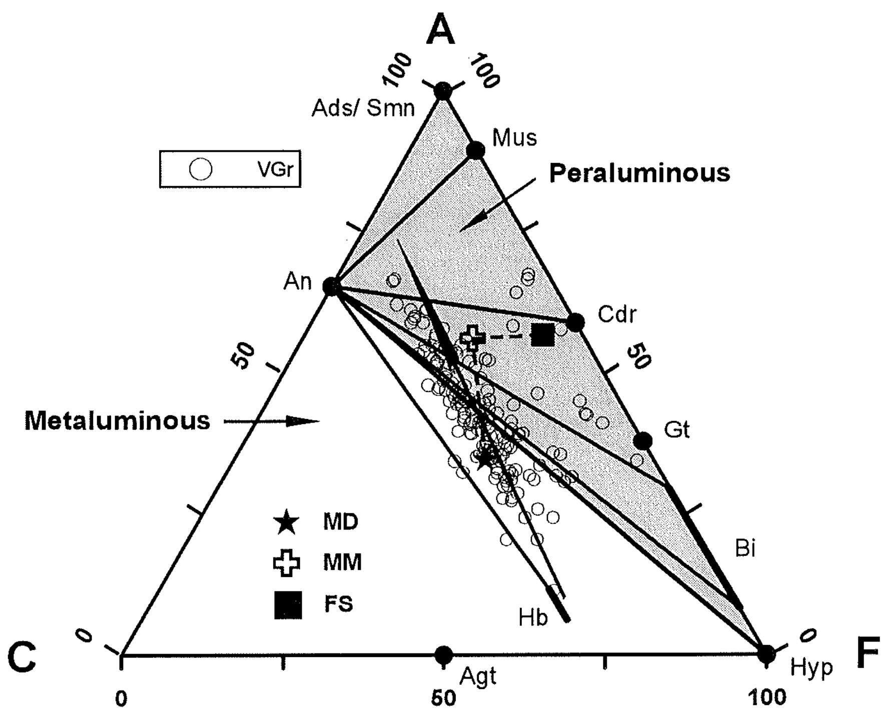
As shown in Figure 15a, 62 % of the samples of Belt granitoids plot within the metaluminous area, which is defined by An-Hb-Bi end-members, with the remainder fully within the peraluminous field defined by An-Bi-Mus. This is consistent with the petrographic observations whereby mineral assemblages in the Belt granitoids comprise plagioclase-quartz-K-feldspar-hornblende-biotite for the mafic end-member rocks, but plagioclase-quartz-K-feldspar-biotite for the more felsic phases. The samples plot around the composition of mantle-derived granitoids (MD) and define a trend (see arrow in Fig. 15) which can be extrapollated away from the hornblende composition, suggesting that fractionation of amphibole may have been largely responsible for the variation of compositions within the Belt granitoids. Chappell

Table 4: Characteristics of Belt, Basin, Winneba and Bongo granitoids of the Birimian terrain in Ghana (compiled from Mauer, 1986, 1990; Leube et al., 1990; Hirdes et al., 1992; Taylor et al., 1992).

Content	Belt granitoid	Basin granitoid	Winneba granitoid	Bongo Granitoid
Geological setting	Volcanic belt	Sedimentary basin	Sedimentary basin	Bole-Navrongo belt
Occurrence	Small to medium-sized plutons, stocks	Large batholiths, small stocks	Batholith	Small stock
Rock type	Diorite to granite	Tonalite to granite	Granodiorite to granite	Granodiorite to granite
Mafic mineral	Hornblend > biotite	Biotite > Hornblende	Biotite	Biotite
Mineral alteration	Pronounced retrograde	Little alteration	Little alteration	Retrograde
Foliation	Locally foliation	Foliation	Foliation	No Foliation
Shearing	Shearing	Locally shearing	No shearing	Shearing
Contact aureole	Up to a few tens of meters	Extensive contact-metamporphic aureoles	Contact-metamor-phic aureoles	A wide metasomatic zone
Aluminous index	0,96 ± 0,15 (175)	1,08 ± 0,07 (27)	1,03 ± 0,03 (19)	1,00 ± 0,04 (10)
K_2O (%)	2,13	2,58	3,89	4,12
Na_2O (%)	4,53	4,37	3,77	4,58
CaO (%)	3,24	2,19	2,30	1,94
Au (ppb)	2,6 (26)*	1 (6)*	18 (1)+	No data
Rb (ppm)	53	112	152	136
Sr (ppm)	488	454	375	109
Ba (ppm)	770	706	1041	1683
Affiliation	With tholeiites	Not with tholeiites	Sialic older crust (?)	With tholeiites
$^{87}Sr/^{86}Sr_i$	0,7017 ± 8	0,7014 ± 3 to 0,7017 ± 2	0,7040 ± 32	0,7017 ± 3
Pb-Pb model μ	7,84	7,85 to 8,00		8,4
IεNd	+2,0	+3,7	-5,4	+2,0
Petrogenesis	Partial melting of mantle basalts	Mixing of mantle matters with the crust	Anatexis of an older sialic crust (?)	Partial melting of mantle basalts
U-Pb age (Ma)	2145 ± 2 to 2179 ± 2	2086 ± 4 to 2125 ± 2	2600 (Sm-Nd model)	1968 ± 49 (Rb-Sr)

Note: *: number of sample available. +: Martin and Khoun (1996).

(a)



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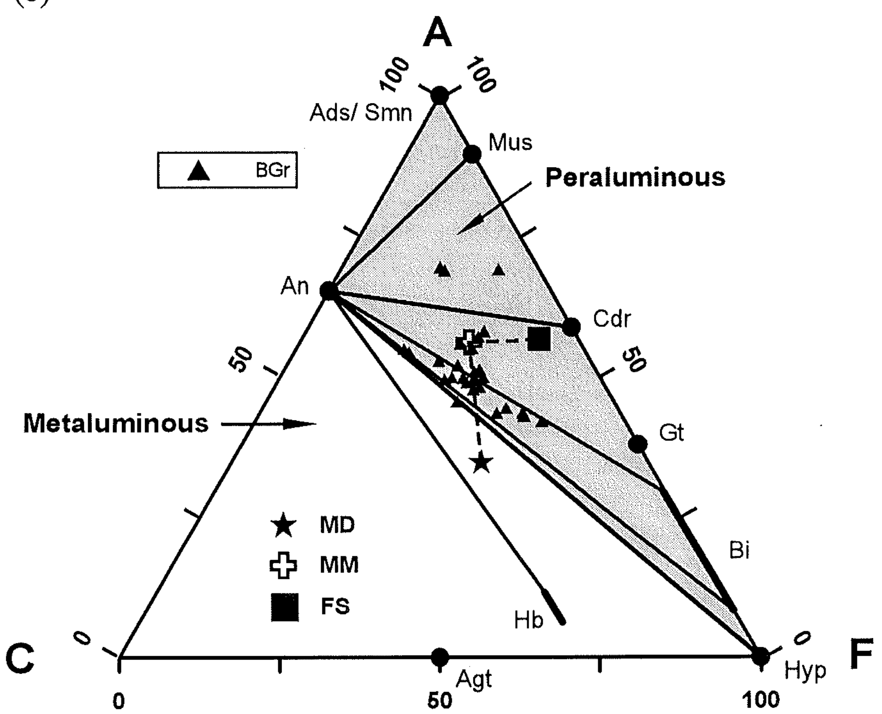
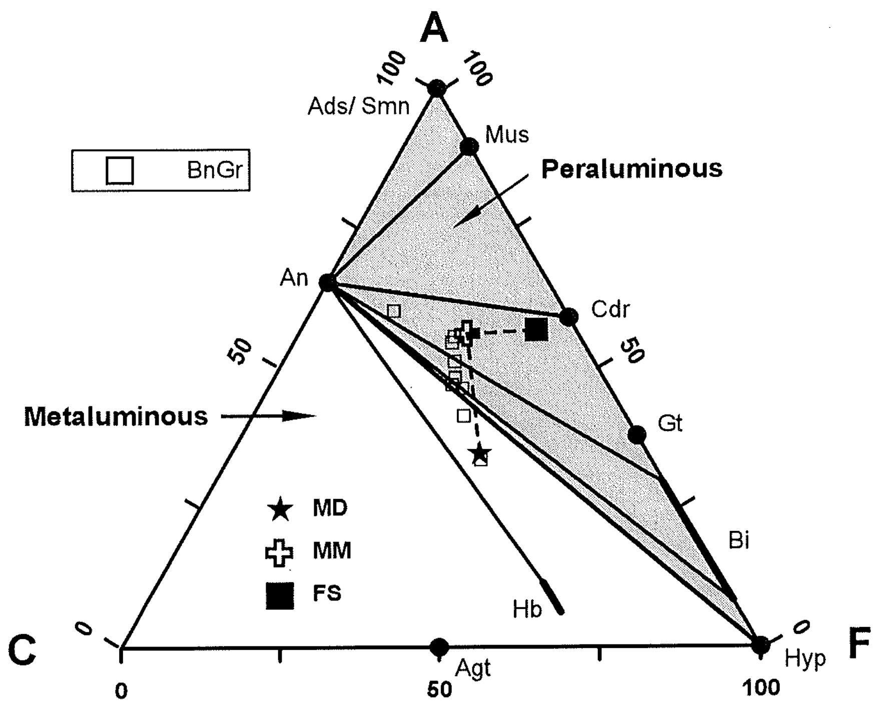


Fig. 15. ACF diagrams (Chappell and White, 1992) showing the relationship between chemical and mineralogical compositions of the four granitoid types from Ghana. Also shown are source rocks of granitoids. A=Al-Na-K; C=Ca; F=Mg+Fe (molar). Ads=andalusite, An=anorthite, Agt=augite, Bi=biotite, Hb=hornblende, Cdr=cordierite, Gt=garnet, Hyp=hypersthene, Mus=muscovite, Smn=sillimanite. MD=mantle-derived, MM= "mimimum" melt, FS=fertile sediment. For interpretation see text.

(c)



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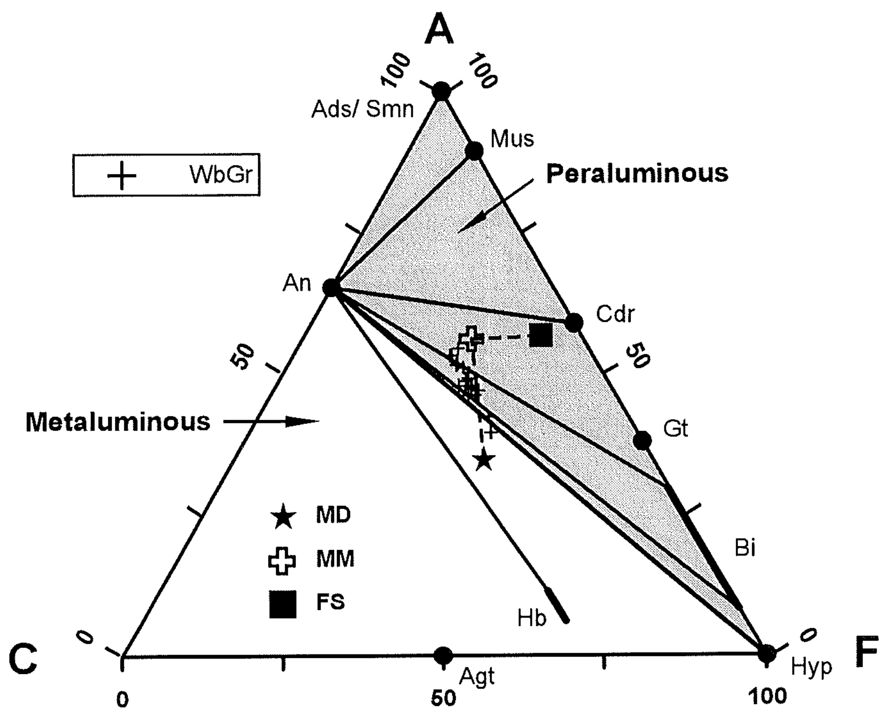

Fig. 15. (continued).

and White (1992) suggested that fractional crystallization of a mantle-derived melt could produce a compositional range along the line from the MD to the mimimum melt (MM) point, a feature which is compatible with the Belt granitoid trend.

All but one sample of the Basin granitoids fall in the peraluminous field near the boundary between the metaluminous and peraluminous fields, and overlap the field of the Belt granitoids, suggesting a similar source and/or origin. Moreover, most of the Basin granitoid samples are distributed near the mimimum melt point and have a more limited compositional range (Fig. 15a). The lack of compositions between the MM and FS line suggests that the Basin granitoids could not be derived from a sedimentary source, a feature which is also consistent with their low $^{87}Sr/^{86}Sr$ initial ratios and low model-μ values, which reflect juvenile additions (Hirdes et al., 1992; Taylor et al., 1992). It is therefore suggested that the Basin granitoids may be S-type in origin, but where melt compositions by crustal anatexis have been contaminated by addition of a more juvenile magma, possibly from a mantle source.

The Bongo and Winneba granitoids are similar to the Belt and Basin granitoids in the ACF diagram (Fig. 15b), respectively, indicating similar petrogenetic processess corresponding to the Belt and Basin granitoids.

Petrogenesis

The four granitoid types discriminate among the petrographic and geochemical characteristics as well as the radiometric isotope dating and the distinct isotope values, thereby indicating petrogenetic differences to the Birimian granitoids. The Belt granitoids demonstrate affinities with the volcanic-belt basalts. The metaluminous character, as well as the low $^{87}Sr/^{86}Sr$ initial ratios (0,7017) and model-μ values (7,84) (Taylor et al., 1988, 1992) indicate derivation from a mantle source. However, relatively high Al_2O_3, K_2O amd Ba compositions exclude the direct mantle derivation of the Belt granitoids by differentiation of basaltic magmas (Mauer, 1990; Leube et al., 1990). It is, therefore, suggested that the Belt granitoids formed by partial melting of basaltic magmas through crystallization of the melt. This also agrees with the following facts: (1) the most mafic gabbro/diorite within a Belt granitoid is spacially limited in amount; (2) plagioclase granites generated by differentation of mantle sources have not been reported in the Birimian terrain of Ghana; and (3) more felsic granites can be produced by sequences of partial melting from much more mafic material (Chappell and White, 1992, and references therein).

The Basin granitoids are peraluminous, indicating derivation from anatexis of continental crust (Debon and Le Fort, 1983). However, the low $^{87}Sr/^{86}Sr$ ratios (0,7014 to 0,7017) and low model-μ values (7,85 to 8,00) (Taylor et al., 1988, 1992) of the Basin granitoids are not suitable for the anatectic model. By contrast, the isotopic data suggest derivation from a mantle source. However, the direct mantle derivation is excluded in terms of the geochemical-mineralogical character of the Basin granitoids. It is suggested that the Basin granitoids are compatible with S-type granites (Chappell and White, 1992) and were generated by the "minimum" melt of crustal materials with addition of a mantle source. The peraluminous character may result from large-scale contamination of the ascending granitoid magmas by first-cycle assimilated intermediate to acidic volcanic basin sediments (Leube et al., 1990). The relative geochemical "primitiveness" of the early Proterozoic Birimian sediments may be responsible for the fact that the Basin sediments keep their low Sr and model μ values (Leube et al., 1990).

The slight peraluminous character of the Bongo granitoids may reflect either contamination of the crust or compositional evolution from mafic to felsic end-member phases. The latter is not supported by the petrographic characteristics. The high K_2O contents need more K-rich sources, and this is not provided by direct mantle materials. Considering their low $^{87}Sr/^{86}Sr$ ratios and model-μ values (Table 4), it is suggested that the Bongo granitoids were derived from mantle, but contaminated by crustal material. The relatively high $^{87}Sr/^{86}Sr$ values (0,704) and model-μ values (8,40) of the Winneba granitoids (Table 4), together with their petrographic and geochemical characteristics, indicate that the Winneba granitoids were derived from a crustal source, possibly associated with an older Archaean crust precursor (Leube et al., 1990; Taylor, et al. 1992).

Association of Birimain granitoids with gold mineralization

Over 20 gold-mineralized granitoids are currently known within the Birimian terrain in Ghana and these comprise both Belt- and Basin-type granitoids. Gold mineralized Basin type granitoids occur within the eastern Kumasi basin, especially in a belt of about 4 to 6 km west of the Ashanti belt, while mineralized Belt-type granitoids occur within the Ashanti belt, the Asankrangwa belt, and the southernmost part of the Bole-Navrongo belt. These cover a wide area over the southwest and west-central parts of Ghana. Mineralized rock types are dioritic to granitic in composition; mafic minerals are hornblende, biotite and muscovite, which vary clearly in the composition of individual intrusions. It would seem at least at this stage, therefore, that gold mineralization within granitoids is largely independent of granitoid types (Yao and Robb, 1998).

Two types of gold mineralization can be clearly identified within the Birimian granitoids: the first is related directly to quartz veins and stockworks, whereas the second is a more disseminated zoning related to the altered parts of granitoids. In general, quartz veins are about 2 to over 100 cm thick. They usually cut granitoids and wall rocks, and show deformation, which suggests an influence by regional deformation on mineralization at a late stage, or the high-temperature solid-state deformation during the cooling of intrusions. Within quartz veins, ore minerals consist of disseminated pyrite ± arsenopyrite ± pyrrhotite ± native gold. The altered parts of granitoids comprise an alteration mineral assemblage of sericite, chlorite, quartz, pyrite ± arsenopyrite ± pyrrhotite ± tourmaline, suggesting mesothermal physico-chemical fluid circulation and mineralization. Both types of gold mineralization occur together in each mineralized granitoid. The gold occurs in both the free state and enclosed in sulphides (mainly pyrite). The average gold grade is about 1,5 to 3,5 g/t, with a large variation of gold grade in individual mineralized granitoid bodies. The cross-cutting relationships among quartz veins, intruded granitoids, alteration selvages and shearing and deformation zones indicate that the gold mineralization is post-granitoid emplacement and syn- or subsequent to an event of regional shearing and may be associated with late-stage magmatism, or regional metamorphism, or both (Yao and Robb, 1998). The controls of gold mineralization within the Birimian granitoids of Ghana are currently the object of further study.

A tectonic model for the Belt and Basin granitoids

Based on the geological characteristics and isotopic dating of the Birimian terrain in Ghana, sequences of the geological events and gold mineralization are summarized in Table 5. The data are mainly compiled from Hirdes et al. (1992, 1993); Zitzmann et al. (1993); Oberthür et al. (1994); Hirdes and Nunoo (1994); and Loh and Hirdes (1996). Corresponding to these events, a modified evolutionary model for the Belt and Basin granitoids is presented in Figure

16. This model is similar to that of Zitzmann et al. (1993), but it summarizes all isotopic dating of the Birimian rocks available at present and is mainly involved in the Belt and Basin granitoids. The three-stage evolution of the events is described as follows:

Stage I: after attenuation and near-complete destruction of sialic crust, rifting, at sites of parallel, evenly-spaced lineaments or zones of crustal weakness was developed and tholeiitic lavas extended into the rifts. Large volumes of the basalt erupted and volcanic ridges formed at 2166 ± 66 Ma (Taylor et al., 1988, 1992). At the same time, volcanoes grew above the sea level and volcaniclastic sediments were deposited in a slightly subsiding basin in the interval between about 2135 ± 5 to 2184 ± 3 Ma (Leube et al., 1990; Oberthür et al., 1994; Hirdes and Nunoo, 1994). During the volcanism, Belt granitoids were emplaced within the basalt pile in the interval between 2145 ± 2 Ma (Bui belt) to 2179 ± 2 Ma (Sewfi belt) (Hirdes et al., 1992, 1993; Zitzmann et al., 1993).

Table 5: Sequences of geological events and gold mineralization in the Proterozoic terrain of Ghana (Hirdes et al., 1992, 1993; Zitzmann et al., 1993; Oberthür et al., 1994; Hirdes and Nunoo, 1994; Loh and Hirdes, 1996)

Seq-uence	Tectonic	Volcanism	Intrusion	Sedimen-tation	Gold miner-alization	Isotopic age (Ma)
9					Gold miner-alization	1876 ± 42 to 1893 ± 43 (K-Ar)
8			Dolerite dykes			
7			Bongo K-rich granitoids			1968 ± 49 (Rb-Sr)
6			Emplacement of Basin granitoids			2086 ± 4 to 2125 ± 2 (U-Pb)
5	Deformation (SE-NW com-pression) and regional meta-morphism					ca. 2100 Ma (Main Reef/ Tarkwa/Ashanti Belt)
4					Gold miner-alization	2116 ± 2 to 2132 ± 3 (U-Pb) to 2224 ± 20 (Pb-Pb)
3				Deposition of Takwaian conglome-rates		2095± 10 to 2132 ± 3 (U-Pb)
2	Uplift erosion					
1		Birimian volcanics (tholeiitic basalts)	Emplacement of Belt grani-toids (comag-matic)	Vocanic sediments (later phase equivalent)		Basalts (Rb-Sr): 2166 ± 66; Granitoids (U-Pb): 2145 ± 2 to 2179 to 2; Sediments (U-Pb): 2135 ± 5 to 2184 ± 3.

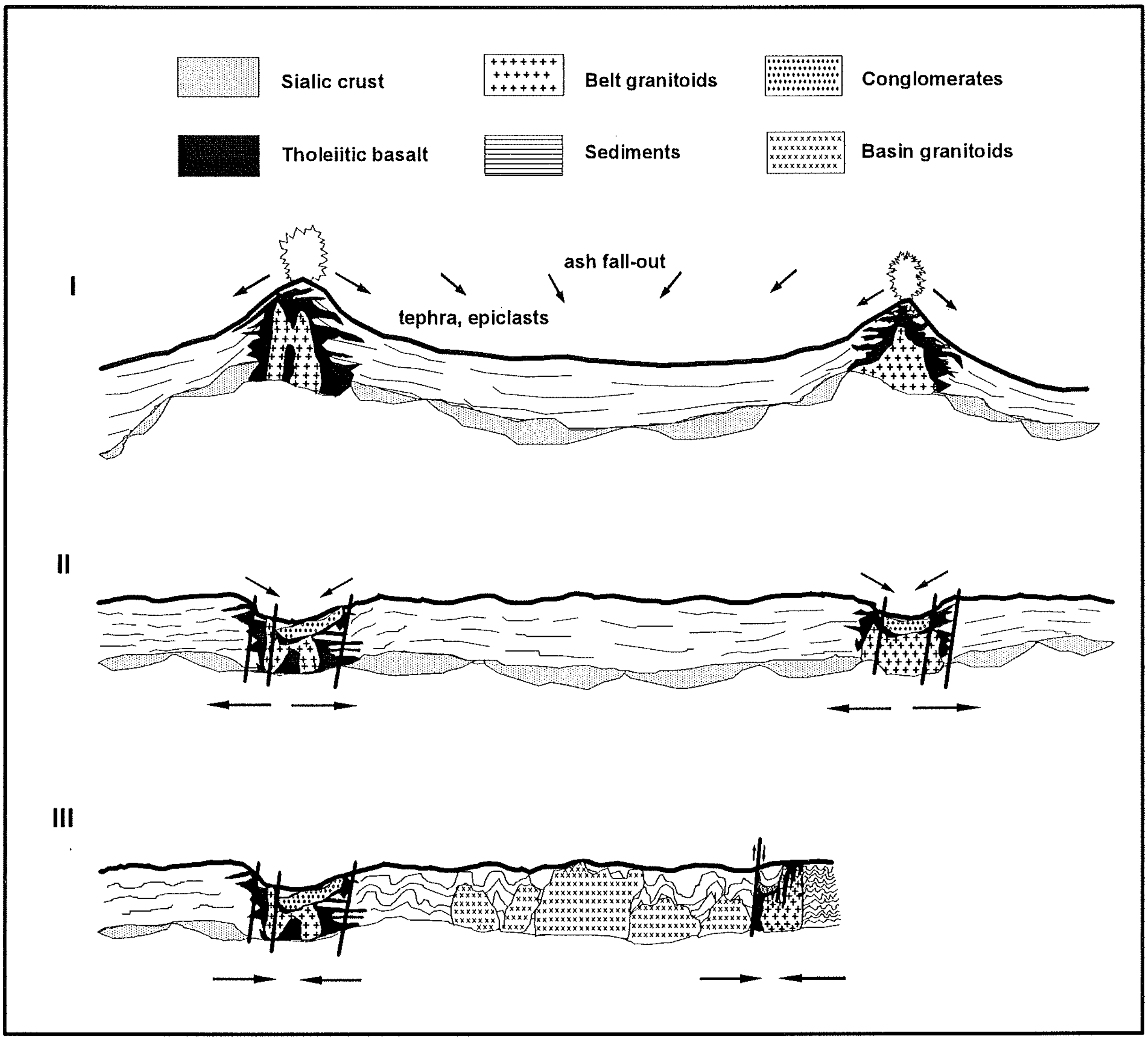

Fig. 16. A schematic tectonic-evolutionary model for the Belt and Basin granitoids from the Birimian terrain in Ghana (modified from Hirdes et al., 1993).

Stage II: the Birimian terrain was uplifted and underwent erosion after the volcanic activity and Belt granitoid intrusion ceased. Due to SE-NW extentional tectonics, intermontane grabens formed within the volcanic belts and the clastic sediments of the Tarkwaian Group were derived from eroded Birimian crust between about 2095 ± 10 and 2132 ± 3 Ma (Oberthür et al., 1994; Hirdes and Nunoo, 1994). The first stage of gold mineralization at Ashanti was formed syntectonically at 2132 ± 3 to 2116 ± 2 Ma. The Pb-Pb model age of about 2100 Ma from Pb isotopes of lead sulphides from quartz veins at Ashanti could represent the best estimate of the mineralization age, and a Pb-Pb secondary isochron age of 2224 ± 20 Ma from Pb isotopic compositions of arsenopyrite could define an estimate of the maximum age of sulphide mineralization in the host rocks (Oberthür et al., 1994).

Stage III: due to progressive accretion of belt terrains, the lateral compression from SE towards the NW shortened the crust, and the Birimian terrain was folded, faulted, and regionally metamorphised to greenschist facies at about 2100 Ma (Hirdes et al., 1993). This event is responsible for the shear-related gold mineralization at Ashanti (Oberthür et al., 1994).

The Basin granitoids intruded within basin sediments as large batholiths at 2086 ± 4 Ma (Kumasi Basin) to 2125 ± 2 Ma (Maluwe Basin) (Hirdes et al., 1992; Zitzmann et al., 1993). Subsequently, the post-kinematic K-rich Bongo granitoids were locally emplaced within the Bole-Navrongo belt. Mafic sills and dykes, the latter post-dating the Bongo granitoids, were also emplaced into the Birimian terrain (Hirdes et al., 1993). A second stage of gold mineralization, coinciding with this tectono-magmatic activity, was produced at 1876 ± 42 to 1893 ± 43 Ma, as suggested by the K-Ar dating of muscovite from the sediment-hosted ores. This may reflect either cooling from the mineralization event or a younger hydrothermal event (Oberthür et al., 1994). The gold mineralization hosted within the Basin granitoids may be correlated with this event in age, but this is not shown in Figure 16.

CONCLUSIONS

The four granitoid types from the Birimian terrain in Ghana are distinct in terms of their geological, petrological, geochemical and isotopic characteristics. The Belt granitoids are mainly of a metaluminous character. By contrast, the Basin and Winneba granitoids show peraluminous characteristics, while the Bongo granitoids have an aluminous saturation index of around 1.0. These indicate different petrogenetic processes for the four granitoid types. Taking into account the geochemical-mineralogical features and whole-rock Rb-Sr, Pb-Pb, and Sm-Nd isotopic data, it is, therefore, suggested that the Belt granitoids are compared with I-type granites and were derived from the partial melting of mantle material. By contrast, the Basin granitoids are comparable to S-type granites and were most probably derived from a "minimum" melt of crustal origin with possible contamination by a mantle-derived source. The Bongo grantioids show I-type characteristics and were probably formed by the partial melting of mantle-derived sources with addition of crustal materials, while the Winneba granitoids are S-type granites derived from an older Archaean precursor.

The U-Pb isotopic dating data indicate that the Belt granitoids were formed at 2145 ± 2 to 2179 ± 2 Ma, and are comagmatic with the Birimian basalts, whereas the Basin granitoids were emplaced at 2086 ± 4 to 2125 ± 2 Ma, were late-kinematic, and post-dated the Tarkwaian sedimentation. The Belt granitoids are 20 to 90 Ma older than the Basin granitoids. The age differences between both the Belt and Basin granitoids reflect a progressive accretion of belt terrains from the southeast to the northwest of Ghana. The Bongo grantioids are late K-rich plutons and formed at 1986 ± 49 Ma.

Gold mineralization hosted within the Belt and Basin granitoids occurs as quartz veins (stockworks) and altered selvages, and appears to be independent of granitoid type. Mineral assemblages of quartz veins and alteration zones comprise pyrite ± arsenopyrite ± pyrrhotite ± native gold + sericite + chlorite + quartz ± tourmaline, which suggests mesothermal physico-chemical fluid circulation and mineralization. The gold mineralization is post-granitoid emplacement and syn- or subsequent to an event of regional shearing, and may be associated with late-stage magmatism or regional metamorphism or both. In the light of the regional geological evolution, two stages of gold mineralization within the Birimian terrain of Ghana are suggested, one is associated with regional metamorphism at about 2100 Ma, and the other a younger hydrothermal event related to magmatism at about 1900 Ma.

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APPENDICES

Appendix 1: Chemical analysis of volcanic belt granitoids from the Birimian terrain of Ghana (from 1: Mauer, 1990; 2: Hirdes et al., 1993; 3: Loh and Hirdes, 1996)

Belt granitoids

		Oxides (%)												Trace elements (ppm)															
Sample	Ref.	SiO2	TiO2	Al2O3	Fe2O3	MnO	MgO	CaO	Na2O	K2O	P2O5	LOI	Sum	Cu	Pb	Zn	SC	Rb	Sr	Ba	V	Cr	Co	Ni	Zr	Nb	Th	U	Y
4612	1	62.28	1.08	15.63	5.64	0.08	2.00	4.20	4.16	2.96	0.49	0.95	99.47	19	8	86	13	86	841	1444	1	19	12	1	301	14	16	1	19
4593	1	62.12	0.60	17.04	4.87	0.07	2.44	4.58	5.28	1.43	0.49	0.75	99.67	13	1	65	12	37	1127	823	49	13	17	5	126	5	7	1	8
4594	1	63.89	0.53	15.03	5.84	0.09	2.98	5.31	3.98	0.94	0.15	0.66	99.40	20	1	33	21	24	577	672	83	20	32	33	133	5	1	1	14
4597	1	71.50	0.22	14.78	1.72	0.02	0.40	1.51	3.81	4.65	0.07	0.74	99.42	5	21	45	5	188	310	883	11	5	13	52	157	11	22	5	13
4598	1	72.97	0.16	14.04	1.34	0.04	0.21	0.90	3.47	5.40	0.04	0.89	99.46	1	27	41	5	302	126	434	12	1	21	1	134	9	26	4	24
4600	1	64.87	0.53	16.91	3.62	0.06	1.59	3.49	5.25	2.29	0.22	0.59	99.42	7	15	66	10	93	709	507	12	7	16	13	172	1	9	1	14
4601	1	60.66	0.68	17.52	5.66	0.09	2.54	5.54	4.74	1.18	0.20	0.63	99.44	15	1	73	20	31	818	606	80	15	28	16	110	7	8	1	11
4603	1	69.72	0.24	15.87	1.77	0.03	0.58	2.13	4.98	3.12	0.08	0.71	99.23	20	19	43	5	93	691	1563	4	20	5	19	167	1	10	4	1
4613	1	62.26	0.60	15.82	5.47	0.08	3.18	5.01	4.60	1.51	0.19	0.83	99.55	32	9	62	20	42	813	651	38	32	29	8	136	14	17	8	19
1507	1	75.45	0.25	11.92	2.85	0.06	0.33	0.32	4.80	1.96	0.03	0.91	98.88	48	48	28	5	41	102	1416	20	48	0	9	276	11	16	4	60
1560	1	74.79	0.26	12.49	3.49	0.06	0.05	0.11	6.46	0.56	0.03	0.90	99.20	1	34	32	8	12	61	241	24	1	0	8	297	8	16	3	66
1566	1	74.48	0.26	12.70	3.08	0.02	0.17	0.31	5.79	1.06	0.03	1.11	99.01	1	45	21	6	17	74	448	7	1	0	12	275	15	17	1	39
1650	1	75.36	0.16	11.02	3.41	0.05	0.07	0.95	4.35	2.64	0.02	1.20	99.23	7	34	41	3	38	54	679	6	7	0	6	313	16	13	5	72
1672	1	70.07	0.46	11.42	5.70	0.09	0.36	1.96	3.66	3.10	0.10	2.21	99.13	14	22	64	12	67	68	932	13	4	0	41	340	10	18	6	79
1677	1	73.40	0.28	12.24	3.36	0.06	0.23	1.48	5.27	1.99	0.05	0.88	99.24	1	32	41	8	33	124	931	6	1	0	8	303	1	14	4	49
1678	1	62.96	0.54	15.32	7.11	0.10	1.70	4.95	3.63	1.29	0.13	1.31	99.04	23	1	59	14	36	305	648	88	23	0	6	155	3	8	8	12
1679	1	50.92	0.86	18.79	9.44	0.14	3.88	9.02	3.20	1.06	0.10	1.75	99.16	29	6	68	25	28	412	298	188	29	0	1	30	10	11	9	11
1680	1	70.59	0.36	12.79	5.44	0.08	0.46	2.25	4.32	1.97	0.07	0.83	99.16	19	24	71	7	52	130	852	20	19	0	27	252	5	14	7	42
1719	1	59.36	0.56	15.51	7.57	0.11	2.96	5.04	4.30	1.91	0.21	1.36	98.89	17	15	81	16	48	1139	1260	124	17	0	17	106	6	16	7	25
1725	1	66.80	0.33	15.67	3.87	0.07	1.21	3.68	4.58	1.94	0.12	0.80	99.07	8	34	62	12	45	878	683	65	8	0	25	102	6	16	10	18
1726	1	67.21	0.36	15.64	3.78	0.07	1.28	3.59	4.50	1.99	0.13	0.68	99.23	1	27	73	12	51	875	731	64	1	0	10	104	3	14	5	15
2097	1	61.44	0.42	14.69	3.96	0.05	1.87	3.92	5.12	1.54	0.13	5.75	98.89	7	18	40	12	35	431	439	49	7	30	13	96	1	6	1	10
2105	1	68.38	0.35	15.38	2.86	0.04	1.01	2.96	4.96	1.94	0.10	1.46	99.44	11	9	49	7	51	485	505	36	11	28		126	1	8	1	10
2111	1	70.43	0.25	14.93	1.97	0.04	0.18	2.19	4.42	2.08	0.08	3.13	99.70	33	8	34	5	56	262	593	20	33	22		102	4	9	5	6
2112	1	68.14	0.29	15.09	2.46	0.03	0.37	2.93	4.54	1.96	0.09	3.66	99.56	15	12	51	5	61	406	528	20	15	20		113	1	6	5	10
2119	1	69.44	0.25	15.79	2.08	0.03	0.61	2.25	5.66	2.19	0.08	0.96	99.34	15	22	53	6	61	772	851	39	15	14		106	1	7	1	6
2127	1	67.04	0.43	14.93	3.97	0.07	1.40	3.04	3.50	3.95	0.13	1.00	99.46	63	8	48	11	91	480	841	51	63	23		138	3	12	1	14
2133	1	68.89	0.30	15.42	2.58	0.05	0.93	3.04	4.87	2.25	0.09	1.24	99.66	15	16	45	6	60	783	809	34	15	8		86	1	10	4	7
4501	1	74.10	0.28	11.81	3.97	0.08	0.55	1.06	4.24	2.75	0.03	0.48	99.35	1	5	115	9	59	119	1099	1	1	3		268	7	6	4	49
4502	1	52.57	0.79	18.73	7.59	0.11	3.88	7.53	4.87	1.40	0.34	1.51	99.32	27	7	78	20	37	1203	698	87	27	44		109	3	15	1	17
4504	1	54.53	0.60	17.06	7.24	0.11	5.51	7.70	4.18	0.93	0.26	1.45	99.57	20	5	71	21	26	1192	457	94	20	42		43	1	16	5	9
4505	1	72.48	0.15	14.37	1.47	0.02	0.31	0.86	4.64	4.60	0.06	0.64	99.60	16	18	23	5	86	419	506	26	16	18		121	8	21	4	5
4506	1	64.10	0.45	16.70	3.83	0.07	1.02	2.56	5.45	4.13	0.23	0.93	99.47	8	21	62	8	122	1034	958	27	8	16		207	8	20	7	21
4507	1	72.71	0.37	12.44	3.98	0.11	0.28	0.98	3.87	3.65	0.06	0.98	99.43	8	10	90	15	74	245	1601	1	8	11		235	12	7	4	52
4508	1	73.07	0.42	12.07	4.11	0.10	0.41	1.46	4.75	2.07	0.07	0.95	99.48	1	6	83	17	44	165	834	1	1	22		239	5	1	1	46
4509	1	61.46	0.48	16.22	5.35	0.07	2.71	4.64	3.92	2.52	0.12	1.96	99.45	8	6	73	15	70	295	551	47	8	24		107	3	7	3	13
4511	1	73.71	0.21	13.47	2.47	0.04	0.33	1.84	4.28	2.03	0.04	1.19	99.61	1	17	40	8	49	140	1059	1	1	16		162	8	11	1	50
4512	1	73.22	0.29	12.97	3.26	0.06	0.32	1.71	4.17	2.63	0.04	0.96	99.63	8	11	69	8	63	77	936	1	8	12		285	9	8	4	85
4513	1	70.51	0.13	15.57	1.73	0.03	0.52	1.97	5.50	2.25	0.03	1.06	99.30	1	9	34	4	67	748	1150	21	1	7		64	1	8	1	1
4514	1	62.07	0.38	17.07	4.59	0.08	1.99	4.52	4.75	2.41	0.20	1.48	99.54	55	6	57	17	68	1049	1078	60	55	32		101	6	19	8	13
4515	1	66.14	0.31	16.15	3.52	0.07	1.66	3.80	4.72	1.74	0.10	1.33	99.54	13	1	52	14	50	639	784	53	13	16		100	4	13	4	10
4540	1	61.62	0.62	17.70	4.57	0.05	2.06	5.71	4.76	0.97	0.14	1.18	99.38	35	1	60	13	23	433	268	33	35	30		182	4	8	1	9
4541	1	57.64	0.49	19.61	4.79	0.05	2.56	7.38	4.31	0.83	0.05	1.70	99.41	30	1	38	21	28	344	306	90	30	34		102	1	1	5	8
4542	1	71.70	0.25	15.35	1.90	0.03	0.43	2.18	5.23	1.79	0.06	0.75	99.67	1	1	48	5	56	633	652	15	1	13		121	1	15	4	1
4547	1	61.17	0.53	15.74	5.81	0.11	2.90	5.17	4.04	2.33	0.27	1.41	99.48	41	15	73	18	52	935	1214	120	41	26		118	5	11	1	19
4548	1	63.33	0.46	15.54	4.93	0.09	2.33	4.47	4.30	2.43	0.22	1.35	99.45	48	20	66	17	70	912	1070	64	48	31		118	4	11	4	19
4549	1	64.47	0.43	16.17	4.74	0.08	1.59	4.60	4.33	1.13	0.13	1.78	99.45	38	11	53	11	30	463	372	56	38	29		91	5	6	1	18
4550	1	70.02	0.21	15.00	2.27	0.05	1.05	2.76	4.70	2.16	0.07	1.23	99.52	11	12	40	7	57	693	710	36	11	21		78	4	10	1	9
4551	1	70.55	0.19	15.25	1.89	0.05	0.89	2.43	5.17	1.88	0.06	1.13	99.49	12	14	34	6	51	727	869	28	12	18		78	4	9	5	6
4552	1	66.55	0.32	15.72	3.57	0.07	1.61	3.66	4.53	1.88	0.11	1.43	99.45	20	13	54	13	55	598	761	63	20	21		91	5	1	3	9
4553	1	67.67	0.34	15.57	3.60	0.06	1.34	3.96	4.64	1.20	0.10	1.16	99.64	16	12	59	9	31	495	482	37	16	30		93	5	1	1	9
4554	1	65.45	0.36	16.93	3.65	0.07	1.14	4.76	4.36	0.75	0.17	1.75	99.39	79	9	57	8	17	765	547	39	79	16		98	1	1	4	8
4567	1	62.71	0.59	16.01	5.81	0.09	2.03	5.52	3.94	1.18	0.10	1.59	99.57	26	7	58	19	35	288	520	80	26	33		113	1	6	5	20
4568	1	58.98	0.75	15.62	7.67	0.11	3.55	6.38	3.66	0.89	0.15	1.71	99.47	30	1	69	27	28	327	437	103	30	36		126	1	1	7	21
4569	1	74.42	0.21	12.98	2.45	0.03	0.36	1.87	4.06	2.22	0.04	0.81	99.45	11	13	35	7	62	121	950	6	11	8		164	4	13	1	31
4571	1	74.60	0.23	12.50	2.58	0.04	0.25	1.29	4.19	2.92	0.03	0.96	99.59	13	15	46	8	78	56	983	4	13	18		233	9	10	5	58
4572	1	75.63	0.12	12.77	1.97	0.03	0.14	1.23	4.41	2.21	0.02	0.79	99.32	8	24	31	4	58	144	898	3	8	6		140	4	1	4	13
4576	1	75.13	0.06	13.62	0.81	0.02	0.08	0.90	4.38	3.83	0.16	0.63	99.62	6	24	32	5	105	99	599	16	6	9		45	5	9	4	10

Appendix 1. (continued)

		Oxides (%)												Trace elements (ppm)															
Sample	Ref.	SiO2	TiO2	Al2O3	Fe2O3	MnO	MgO	CaO	Na2O	K2O	P2O5	LOI	Sum	Cu	Pb	Zn	SC	Rb	Sr	Ba	V	Cr	Co	Ni	Zr	Nb	Th	U	Y
4605	1	67.96	0.51	15.19	3.83	0.05	1.07	2.79	4.17	3.15	0.16	0.66	99.54	12	15	65	11	88	452	1064	24	12	23	8	198	8	12	1	14
4611	1	60.85	0.56	14.72	5.49	0.10	4.22	5.29	3.77	3.00	0.28	1.29	99.57	28	8	72	19	78	1085	1212	61	28	33	52	155	4	8	5	16
0024	2	70.52	0.20	14.51	1.72	0.04	0.72	1.99	5.52	3.17	0.10	0.63	99.12	21	22	36	3	75	904	1213	31	26	114	16	66	5	3	3	9
6107	2	49.08	1.11	17.62	9.89	0.15	5.52	8.22	4.09	1.51	0.48	1.94	99.61	39	3	107	23	35	989	668	194	76	42	43	135	3	7	3	24
6112	2	75.25	0.02	13.71	0.38	0.05	0.05	0.93	4.56	3.65	0.02	0.83	99.45	4	17	10	3	75	56	396	8	8	10	3	30	8	3	3	6
6124	2	69.60	0.24	16.47	2.01	0.02	0.69	3.06	5.63	1.11	0.07	0.66	99.56	9	3	52	6	31	639	506	23	8	10	3	125	3	3	3	3
6125	2	68.05	0.32	16.69	2.57	0.03	0.92	2.98	5.56	0.94	0.09	1.31	99.46	10	3	54	6	29	671	395	45	17	33	3	143	6	8	7	7
6126	2	70.71	0.21	15.69	1.72	0.03	0.55	2.21	5.24	1.91	0.06	1.19	99.52	13	17	49	3	52	615	766	28	8	10	8	94	2	3	3	8
6128	2	70.05	0.25	15.68	1.82	0.02	0.50	2.22	5.91	1.80	0.08	1.09	99.42	13	8	31	4	44	658	597	8	8	10	3	115	2	3	3	5
6129	2	67.50	0.31	17.06	2.26	0.03	0.73	3.67	5.72	1.02	0.08	0.99	99.37	12	3	44	6	28	505	370	39	8	10	3	145	3	3	3	5
6160	2	71.90	0.38	13.49	3.25	0.14	0.60	1.36	4.44	2.70	0.12	1.16	99.54	4	10	89	11	78	409	876	28	8	10	3	187	9	14	3	40
6168	2	75.21	0.21	12.49	3.19	0.09	0.10	0.70	5.51	0.92	0.04	1.01	99.47	7	3	54	6	20	88	277	8	8	10	3	238	8	3	3	40
6178	2	77.15	0.05	12.39	0.89	0.01	0.03	0.05	4.13	4.35	0.00	0.43	99.48	10	9	35	3	155	16	106	8	27	10	3	126	31	12	3	68
6179	2	76.78	0.05	12.66	0.88	0.01	0.01	0.08	4.60	4.26	0.01	0.33	99.67	4	14	17	3	128	35	180	8	8	10	3	117	27	18	7	60
6226	2	75.95	0.04	12.60	0.81	0.02	0.13	0.21	4.55	4.28	0.02	0.58	99.19	5	17	32	3	196	15	15	8	8	71	3	85	29	14	3	72
6323	2	47.82	2.33	15.49	13.09	0.21	4.25	8.98	3.68	0.95	0.42	1.91	99.13	265	3	112	31	20	421	279	277	19	259	30	192	21	8	3	41
6338	2	73.12	0.37	13.13	3.52	0.03	0.53	3.14	4.00	0.85	0.10	0.66	99.45	34	3	46	3	31	281	470	23	8	63	3	261	4	14	3	7
6358	2	58.27	0.67	16.84	4.81	0.07	2.40	4.08	5.38	5.04	0.45	1.01	99.02	27	19	81	8	93	1816	1800	77	40	82	34	167	3	8	3	29
6374	2	73.65	0.03	14.18	0.59	0.01	0.06	0.60	4.35	5.64	0.02	0.54	99.67	13	22	8	1	134	181	155	16	8	114	3	29	5	3	3	2
6514	2	57.01	0.78	17.16	7.03	0.11	3.60	6.39	4.36	1.39	0.33	1.49	99.65	25	3	81	17	35	1038	775	138	47	33	29	126	7	6	3	22
6528	2	50.34	0.49	16.23	9.19	0.15	8.72	9.88	2.59	0.32	0.28	1.38	99.57	60	3	91	27	4	968	221	166	274	47	146	20	2	3	3	10
6529	2	50.28	0.88	13.17	9.66	0.15	7.66	8.12	4.01	0.54	0.28	4.66	99.41	50	3	89	34	15	359	159	233	262	33	81	53	2	5	3	14
6571A	2	48.97	0.83	7.44	11.69	0.21	14.86	12.85	1.05	0.75	0.12	0.86	99.63	25	3	92	74	7	133	165	289	617	55	125	23	2	3	3	18
5671B	2	50.68	0.92	14.62	10.97	0.19	7.18	9.09	2.35	0.90	0.35	2.39	99.64	37	7	100	40	25	792	414	276	192	53	50	43	9	3	3	17
6565	2	72.37	0.22	12.70	3.52	0.18	0.28	1.46	3.68	3.78	0.02	0.95	99.16	4	3	132	4	92	294	2086	8	23	10	3	227	9	8	3	102
6586	2	77.02	0.20	10.98	1.95	0.02	0.25	0.15	2.74	4.88	0.02	1.24	99.45	10	39	57	5	65	61	1185	20	8	10	3	261	10	3	3	13
6588	2	74.43	0.42	11.78	3.69	0.10	0.23	1.56	4.08	2.53	0.07	0.51	99.40	12	8	85	16	52	199	1012	8	8	10	3	241	7	6	3	51
6526	2	55.94	0.72	17.66	7.15	0.11	4.07	6.66	3.66	0.88	0.20	2.46	99.51	15	3	73	16	22	781	418	155	69	42	41	64	4	3	3	10
6536	2	58.54	0.67	15.94	6.41	0.10	4.34	6.11	3.92	1.44	0.22	1.88	99.57	18	9	78	17	32	877	593	114	125	43	87	69	6	3	3	13
6637	2	52.63	0.78	16.16	8.05	0.13	6.46	8.55	3.95	0.64	0.33	1.63	99.31	17	8	99	22	11	1344	542	172	207	48	150	31	2	3	3	13
6624	2	57.77	1.03	18.21	7.05	0.10	1.84	6.47	4.27	0.89	0.26	1.54	99.43	16	3	77	27	30	475	336	24	8	21	3	165	10	3	3	19
6628	2	73.10	0.12	14.61	0.99	0.02	0.23	1.61	4.58	3.29	0.02	0.91	99.48	9	16	22	1	89	313	1101	8	8	10	3	79	2	3	3	4
6632	2	71.93	0.16	15.14	1.25	0.03	0.14	0.34	5.92	3.33	0.03	1.23	99.50	4	11	46	3	62	413	1316	16	19	10	3	96	4	3	3	4
6562	2	67.60	0.47	16.30	3.29	0.03	0.86	3.73	4.46	0.97	0.12	1.76	99.59	11	3	45	7	31	392	357	42	15	10	9	195	2	3	3	22
6563	2	70.00	0.27	15.82	1.94	0.03	0.66	2.50	5.69	1.63	0.08	0.89	99.51	11	6	37	3	37	662	602	24	8	10	3	115	4	3	3	3
6629	2	71.99	0.17	15.10	1.34	0.03	0.28	1.82	5.04	2.50	0.03	1.10	99.40	4	13	34	3	69	466	708	20	8	10	3	78	2	5	3	3
7054	2	72.61	0.13	14.93	1.37	0.03	0.38	1.49	5.29	2.32	0.05	0.79	99.39	17	14	44	1	50	347	913	17	8	10	3	78	2	3	3	8
7062	2	74.18	0.28	12.11	3.78	0.09	0.09	1.06	4.66	2.47	0.03	0.65	99.40	8	7	99	6	67	175	981	8	8	10	3	273	9	3	3	51
7064	2	74.39	0.40	11.55	3.79	0.09	0.50	1.09	4.66	1.85	0.07	0.94	99.33	9	17	88	14	36	173	840	8	8	10	3	218	10	3	3	45
7068	2	51.62	1.42	16.93	10.95	0.17	3.74	8.73	3.52	0.48	0.15	1.94	99.65	140	3	89	36	9	231	203	296	8	50	26	92	2	3	3	31
7080	2	61.03	0.57	17.88	4.33	0.07	1.67	3.38	6.77	2.30	0.31	0.98	99.29	15	11	78	9	83	1562	707	60	8	23	14	169	9	13	8	21
L299	3	71.86	0.17	15.53	1.14	0.01	0.29	1.89	5.32	2.36	0.02	0.96	99.55	1	15	26	2	51	715	1215	16	1		1	100	1	13	1	1
L289,2	3	73.42	0.08	14.39	0.70	0.02	0.21	1.34	3.92	4.53	0.03	1.07	99.71	1	21	12	4	109	426	1110	1	1		10	56	1	1	1	9
L289,3	3	74.52	0.05	14.07	0.37	0.01	0.12	1.14	3.55	4.99	0.02	0.62	99.46	1	18	11	1	96	513	1689	1	3		1	61	4	1	1	1
L300,1	3	72.59	0.11	15.16	0.96	0.02	0.22	2.20	4.87	2.23	0.04	1.22	99.62	46	18	17	3	57	267	880	11	1		9	69	5	12	7	5
L298,0	3	72.49	0.19	14.71	1.52	0.02	0.73	2.43	4.77	1.72	0.05	1.02	99.65	11	1	28	4	48	617	860	13	32		21	116	1	1	1	1
L298,1	3	58.10	0.67	14.76	8.00	0.13	5.52	5.84	2.51	2.33	0.10	1.77	99.73	11	14	89	23	102	339	374	148	129		123	98	1	15	1	15
L299,0	3	69.08	0.61	15.75	2.59	0.03	1.02	3.48	4.89	1.10	0.16	0.65	99.36	245	8	46	4	47	736	672	39	1		1	230	7	1	1	7
A146,0	3	67.62	0.31	14.57	4.01	0.09	1.77	3.79	4.06	1.35	0.07	1.93	99.57	15	21	47	12	40	388	427	74	32		24	87	1	1	1	13
A147	3	67.21	0.35	15.38	3.83	0.09	1.39	3.73	4.04	1.71	0.09	2.02	99.84	24	1	44	9	44	427	389	65	1		18	85	5	1	1	24
L183	3	64.00	0.44	16.32	4.89	0.09	1.74	5.13	4.12	1.02	0.13	2.00	99.88	22	1	53	11	28	495	351	87	25		32	83	1	1	1	11
L184	3	62.18	0.49	16.45	5.43	0.09	2.10	5.36	4.31	0.97	0.14	2.20	99.72	51	10	64	15	28	545	359	86	27		36	88	7	1	1	17
L187	3	72.79	0.29	12.96	3.16	0.07	0.28	1.10	3.96	3.93	0.05	1.06	99.65	14	20	83	6	150	112	1020	1	15		9	276	14	1	1	46
L33	3	53.44	0.59	16.40	10.06	0.12	5.12	8.38	2.44	0.72	0.09	2.38	99.74	142	1	68	27	20	522	204	278	103		96	54	1	1	1	9
L33,0	3	53.05	0.61	15.96	10.65	0.13	5.13	8.32	2.29	0.72	0.06	2.33	99.25	151	4	73	24	18	527	211	279	113		98	64	5	1	1	9
L459	3	72.34	0.28	12.95	3.21	0.06	0.26	1.40	3.98	3.87	0.05	0.93	99.33	31	16	56	6	133	125	1219	1	1		1	296	11	11	4	45
L460	3	71.28	0.34	13.44	3.82	0.07	0.27	1.53	4.10	3.69	0.06	0.82	99.42	1	17	78	8	127	150	1355	16	1		1	344	14	8	6	54
L463	3	54.67	0.82	19.12	8.25	0.11	2.15	8.01	4.06	0.87	0.13	1.13	99.32	41	5	114	20	25	392	447	146	1		18	91	6	1	1	20

Appendix 1. (continued)

Sample	Ref.	Oxides (%) SiO2	TiO2	Al2O3	Fe2O3	MnO	MgO	CaO	Na2O	K2O	P2O5	LOI	Sum	Trace elements (ppm) Cu	Pb	Zn	SC	Rb	Sr	Ba	V	Cr	Co	Ni	Zr	Nb	Th	U	Y
L464	3	70.28	0.33	13.92	3.66	0.06	0.67	2.15	4.08	3.17	0.08	0.92	99.32	1	10	59	9	122	222	979	25	8		1	216	11	8	1	36
L466	3	69.62	0.35	14.84	3.47	0.06	0.33	1.58	4.04	3.45	0.07	1.57	99.38	1	13	61	9	133	149	1058	15	1		1	307	13	11	4	43
L467	3	69.48	0.33	14.81	3.39	0.06	0.52	1.77	3.82	3.35	0.08	1.77	99.38	11	14	53	7	136	189	998	20	1		1	239	11	8	5	33
L468	3	70.32	0.30	14.67	3.32	0.06	0.77	2.27	3.89	2.65	0.09	0.84	99.18	1	14	51	6	116	270	770	24	1		1	157	7	1	1	25
L469	3	70.84	0.24	14.72	2.78	0.06	0.66	2.65	4.08	2.45	0.08	0.85	99.41	1	11	47	5	97	384	848	24	1		1	122	7	1	4	16
L47	3	58.01	0.49	15.11	7.32	0.12	4.75	6.64	3.72	1.21	0.15	2.14	99.66	66	1	71	24	34	668	479	160	127		30	73	1	1	1	15
L470	3	70.83	0.24	14.42	2.94	0.08	0.72	2.58	4.00	2.70	0.08	0.78	99.37	18	14	42	6	103	349	915	17	4		1	131	8	1	1	16
L471	3	55.63	0.93	16.31	10.56	0.16	2.98	7.09	3.69	1.29	0.23	0.50	99.37	14	20	94	25	44	340	489	156	1		15	140	6	1	1	26
L472	3	49.57	0.99	19.55	11.15	0.17	3.97	10.14	3.29	0.21	0.08	0.27	99.39	57	20	142	32	2	527	194	213	1		29	24	3	1	1	9
L473	3	71.36	0.31	13.51	3.48	0.06	0.64	2.06	3.94	3.22	0.08	0.75	99.41	29	10	112	8	125	194	977	12	1		1	217	10	11	5	35
L474	3	73.94	0.22	12.74	2.55	0.06	0.16	0.90	3.86	4.34	0.04	0.61	99.42	49	26	60	5	158	79	1063	12	1		1	267	11	11	6	48
L476	3	72.56	0.26	13.06	3.20	0.05	0.36	1.32	3.86	3.91	0.06	0.80	99.44	10	22	79	5	157	121	858	11	9		1	270	11	11	6	77
L477	3	72.50	0.28	13.10	3.16	0.07	0.27	1.30	4.02	3.88	0.06	0.70	99.34	1	18	60	7	143	124	1168	1	1		1	281	12	9	3	43
L478	3	72.62	0.27	12.81	3.25	0.07	0.27	1.38	3.94	3.84	0.05	0.79	99.29	26	19	77	8	143	122	1181	6	4		1	281	13	12	1	49
L479	3	71.71	0.30	13.61	3.36	0.07	0.36	1.57	4.08	3.57	0.07	0.69	99.39	1	16	66	7	139	149	1011	6	1		1	265	11	11	4	36
L480	3	69.33	0.34	14.96	3.50	0.06	0.74	2.61	4.37	2.89	0.09	0.58	99.47	13	16	56	8	114	293	887	40	1		1	179	11	9	1	27
L481	3	72.43	0.25	13.31	2.99	0.08	0.24	1.15	4.01	4.07	0.05	0.81	99.39	1	15	99	5	151	119	1261	17	1		1	266	10	8	4	53
L482	3	58.92	0.56	16.80	7.02	0.14	2.74	6.02	3.79	1.04	0.17	2.21	99.41	66	7	76	20	31	549	267	120	15		15	67	6	1	3	15
L96	3	67.44	0.29	15.56	3.13	0.07	1.82	3.33	4.66	2.00	0.10	1.28	99.68	11	1	48	7	51	761	771	61	44		28	89	1	1	1	1
A118	3	58.05	0.49	15.95	5.35	0.63	2.83	4.14	4.22	2.08	0.20	5.55	99.49	20	15	86	15	57	576	771	106	52		43	129	5	1	1	10
A138	3	51.83	1.30	16.78	13.28	0.26	2.88	5.93	3.03	0.44	0.55	3.27	99.55	10	1	109	40	14	516	326	34	17		18	64	1	1	1	24
A139,0	3	69.84	0.34	15.84	3.71	0.09	0.47	0.34	3.49	3.08	0.09	2.27	99.56	22	10	43	8	82	484	1077	66	20		5	104	10	1	1	11
D10	3	64.41	0.37	15.16	4.48	0.09	2.84	4.39	4.37	1.93	0.14	1.12	99.30	1	6	60	13	59	818	702	88	102		29	106	8	7	1	13
L224	3	62.88	0.49	15.07	5.21	0.09	2.71	4.55	3.90	2.61	0.23	1.62	99.36	81	10	62	15	85	793	1048	123	50		1	110	20	9	6	21
L260	3	67.30	0.29	16.01	2.60	0.04	1.07	2.85	6.84	0.98	0.07	1.62	99.67	62	1	17	7	28	479	427	26	20		23	90	1	1	1	1
L353,0	3	68.60	0.38	15.00	4.09	0.08	1.02	2.87	4.38	2.26	0.08	0.74	99.50	1	10	71	9	90	245	1068	38	5		6	189	9	1	1	26
L353,1	3	57.97	0.53	16.77	7.65	0.15	3.32	6.82	4.66	0.64	0.10	0.86	99.47	36	1	102	29	15	364	470	66	24		25	156	7	1	1	21
L354	3	69.76	0.31	15.04	2.90	0.05	0.98	2.97	4.31	1.65	0.07	1.62	99.66	53	16	49	4	60	356	985	31	13		21	111	11	1	1	7
L387	3	58.20	0.65	15.03	7.15	0.15	3.65	6.29	3.71	1.97	0.24	2.44	99.48	318	11	92	21	50	763	665	161	53		27	115	9	12	1	20
L407	3	64.66	0.41	15.44	4.20	0.09	2.02	4.02	4.27	2.27	0.18	2.05	99.61	15	1	63	12	60	968	981	89	41		27	100	8	1	1	12
L490	3	62.58	0.47	15.85	5.06	0.10	2.49	4.02	4.13	2.50	0.22	1.73	99.15	44	7	74	14	70	891	984	105	31		15	118	8	10	1	12
L491	3	73.28	0.13	14.25	1.69	0.04	0.14	1.35	4.77	3.16	0.03	0.63	99.47	1	10	22	4	108	176	1162	14	1		1	140	10	7	7	35
L494	3	65.41	0.37	15.27	4.03	0.07	1.68	2.88	5.23	3.26	0.11	1.03	99.34	1	8	53	12	83	609	794	97	28		12	112	8	1	1	15
L495	3	56.77	0.80	17.60	8.59	0.17	3.01	6.89	4.72	0.59	0.16	0.60	99.90	30	6	112	27	17	369	469	123	33		18	125	7	1	5	21
L496	3	58.84	0.83	16.71	8.63	0.16	2.07	5.59	4.70	1.08	0.17	0.67	99.45	60	9	117	21	31	341	624	84	17		12	297	9	1	1	29
L504	3	68.38	0.23	15.39	2.53	0.06	1.08	2.66	4.88	2.83	0.10	1.13	99.27	1	12	36	7	53	931	1355	61	12		7	88	6	1	1	9
L505	3	68.77	0.22	15.60	2.44	0.06	1.01	2.42	4.78	2.87	0.09	1.06	99.32	1	16	42	7	73	880	1291	56	16		1	85	7	1	1	1
L507	3	63.42	0.44	16.28	4.41	0.09	2.12	3.57	3.37	2.76	0.21	2.52	99.19	43	9	63	12	71	765	1114	100	26		12	126	10	10	5	20
L508	3	65.08	0.52	14.13	4.96	0.10	2.52	3.88	3.36	2.90	0.25	1.49	99.19	33	9	68	14	60	713	1228	99	25		14	138	9	11	3	21
L509	3	65.11	0.38	15.72	4.10	0.08	1.75	4.27	4.58	1.82	0.14	1.33	99.28	37	14	63	12	48	868	800	74	23		9	114	8	5	1	14
A157	3	58.53	0.71	15.08	7.26	0.13	3.51	5.45	3.79	2.13	0.21	2.50	99.30	75	16	84	22	57	556	848	148	86		34	137	7	1	1	17
L246	3	66.87	0.34	15.96	3.61	0.08	1.18	4.17	4.51	1.25	0.14	1.18	99.29	68	8	65	8	28	686	637	61	10		1	95	8	1	1	10
L255	3	65.50	0.34	16.55	3.51	0.08	1.27	4.46	4.92	1.18	0.14	1.81	99.76	69	1	64	8	24	665	617	56	17		24	97	7	1	1	10
L293,0	3	70.90	0.21	15.26	2.22	0.06	0.84	2.98	4.63	1.83	0.07	0.54	99.54	1	1	43	3	53	629	675	35	8		1	85	7	1	1	6
L317	3	68.35	0.24	15.56	1.85	0.04	0.16	2.51	4.97	1.97	0.08	3.82	99.55	19	18	68	4	52	260	826	28	21		15	51	9	1	1	6
L332	3	60.73	0.94	17.16	6.10	0.08	2.27	4.86	4.56	1.50	0.22	1.24	99.66	25	1	87	22	45	636	1122	124	44		30	212	8	1	1	19
L337	3	59.44	1.10	17.08	6.89	0.09	2.53	5.08	4.38	1.42	0.28	0.98	99.27	1	7	103	25	35	667	882	132	34		13	264	12	1	1	27
L385	3	64.84	0.44	16.20	4.37	0.09	1.82	3.52	3.85	1.70	0.13	2.73	99.69	30	16	65	11	40	560	688	82	19		29	76	7	1	1	11
L447	3	65.30	0.29	17.84	5.23	0.05	0.43	0.96	4.89	1.18	0.16	3.21	99.54	1	1	59	7	27	889	397	61	6		6	115	5	1	1	10
L452	3	63.35	0.30	16.50	4.30	0.07	0.74	3.68	4.25	1.18	0.16	4.76	99.29	63	6	95	9	24	796	441	66	1		8	119	6	1	1	11
L453	3	65.29	0.26	15.91	3.43	0.05	1.17	2.89	4.57	1.44	0.15	4.19	99.35	1	1	42	7	32	479	548	65	1		1	119	5	5	1	12
L455	3	68.93	0.30	16.31	3.48	0.02	0.95	0.46	4.41	1.31	0.07	3.41	99.65	21	10	49	12	33	555	499	55	8		6	179	7	1	1	9
L69	3	59.27	0.45	13.88	5.80	0.12	5.86	6.13	4.42	1.16	0.17	2.11	99.37	36	12	68	20	25	750	719	118	400		127	75	6	1	1	10
L73	3	63.68	0.35	14.42	5.56	0.13	3.77	4.79	4.60	0.80	0.08	1.67	99.85	20	1	62	18	16	294	211	96	127		77	61	1	1	1	7
L73,0	3	63.27	0.36	14.71	5.64	0.09	3.86	4.68	4.62	0.83	0.09	1.35	99.50	1	1	55	17	17	369	308	102	114		60	69	7	1	1	9
L209	3	62.42	0.44	15.45	4.85	0.08	3.47	5.34	3.97	1.36	0.16	1.72	99.26	86	7	69	14	31	815	638	88	138		54	107	6	1	1	11
L424	3	62.94	0.28	14.93	4.39	0.09	2.74	5.78	4.82	1.38	0.09	2.05	99.49	12	1	65	14	26	794	612	95	107		36	47	1	1	1	6
L98,0	3	63.46	0.27	15.22	4.35	0.09	2.72	4.16	5.17	1.80	0.11	1.81	99.16	47	1	62	14	38	659	682	92	116		13	61	5	1	1	6
L98	3	64.34	0.27	15.05	4.48	0.09	3.14	2.00	5.70	1.56	0.10	2.83	99.56	56	24	67	14	38	388	612	106	207		64	53	1	1	1	7

Appendix 1. (continued)

Basin granitoids

Sample	Ref.	Oxides (%) SiO2	TiO2	Al2O3	Fe2O3	MnO	MgO	CaO	Na2O	K2O	P2O5	LOI	Sum	Trace elements (ppm) Cu	Pb	Zn	SC	Rb	Sr	Ba	V	Cr	Co	Ni	Zr	Nb	Th	U	Y
4517	1	72.12	0.17	13.67	1.45	0.02	0.35	0.93	3.22	5.83	0.06	1.83	99.65	6	25	24	5	272	96	391	1	1	19	1	127	12	27	6	9
4522	1	73.20	0.17	14.21	1.27	0.01	0.32	1.00	4.04	4.49	0.06	0.56	99.33	22	23	46	3	161	206	641	6	1	13	5	104	5	13	1	3
4523	1	66.21	0.58	15.20	5.30	0.07	2.02	1.91	3.31	3.87	0.12	0.84	99.43	20	17	70	18	133	395	1411	49	51	14	33	157	8	14	4	13
4524	1	64.21	0.53	16.29	5.79	0.05	2.25	2.66	4.19	2.45	0.11	0.95	99.48	31	11	92	17	138	550	744	76	97	24	52	90	5	10	1	8
4528	1	72.84	0.13	14.35	1.36	0.01	0.31	2.14	3.99	3.65	0.02	0.69	99.49	1	27	17	5	68	220	522	21	1	6	1	104	4	18	11	9
4531	1	68.91	0.23	16.42	2.12	0.07	0.84	1.59	5.72	2.70	0.07	0.83	99.50	1	10	69	6	314	374	351	23	13	13	13	80	3	12	9	10
4532	1	69.27	0.28	16.25	2.42	0.02	0.99	2.44	5.41	1.74	0.07	0.79	99.68	11	11	52	7	59	602	588	17	17	14	16	98	1	6	4	5
4534	1	69.54	0.25	16.02	2.23	0.02	0.92	2.68	6.14	0.91	0.07	0.80	99.58	1	5	60	6	30	566	400	23	21	28	19	91	5	9	4	1
4545	1	70.08	0.26	15.77	2.04	0.02	0.83	1.31	4.27	3.52	0.11	0.91	99.12	10	16	46	6	168	325	648	18	24	28	8	101	1	9	1	4
4546	1	71.10	0.30	14.38	2.54	0.02	0.81	2.10	3.65	3.69	0.17	0.61	99.37	9	11	59	5	107	324	1252	12	5	16	9	115	5	20	4	7
4615	1	68.11	0.41	15.97	2.79	0.03	0.99	2.24	4.65	3.41	0.14	0.66	99.40	12	17	67	5	117	680	998	2	8	23	8	160	5	12	1	5
4616	1	71.07	0.19	15.85	1.44	0.02	0.79	3.51	5.29	0.82	0.06	0.55	99.59	5	1	21	2	30	1043	363	18	15	21	12	59	1	10	1	1
4617	1	66.97	0.48	16.49	3.62	0.05	1.13	3.10	4.71	2.05	0.20	0.68	99.48	14	14	63	9	65	772	872	41	11	11	6	139	8	11	1	8
4618	1	64.76	0.59	16.33	5.36	0.07	1.91	2.39	4.45	2.61	0.14	1.03	99.64	31	9	83	16	107	477	656	49	57	27	41	127	8	13	1	11
4619	1	86.67	0.09	5.97	1.08	0.13	0.33	0.56	1.52	2.01	0.03	0.81	99.20	28	6	22	5	55	73	1759	13	1	9	8	112	8	11	1	18
2114	1	69.91	0.28	15.59	2.47	0.02	0.80	2.89	5.11	1.22	0.09	1.24	99.62	9	6	44	7	35	552	215	16	8	29	6	119	1	11	3	4
2131	1	73.11	0.26	13.71	2.16	0.05	0.58	1.22	4.51	3.52	0.08	0.35	99.55	27	19	50	7	112	286	956	36	14	21	1	86	4	8	1	6
2145	1	66.27	0.44	16.26	3.67	0.05	1.65	4.01	4.69	1.65	0.12	0.66	99.47	8	1	53	9	43	558	582	27	19	17	27	113	1	10	1	9
4577	1	68.23	0.39	16.29	3.14	0.03	1.33	2.68	5.25	1.54	0.09	0.70	99.67	17	10	61	9	75	639	511	34	35	19	17	105	1	1	3	5
4578	1	69.08	0.41	15.58	3.12	0.03	1.39	2.37	4.53	2.07	0.10	0.83	99.51	24	17	60	10	123	431	508	1	38	23	25	110	1	8	6	7
4579	1	69.82	0.27	16.01	2.61	0.03	0.73	1.82	4.69	2.84	0.05	0.80	99.67	8	30	56	7	122	316	471	7	14	14	10	143	7	12	8	9
4580	1	70.58	0.28	15.35	2.66	0.03	0.94	2.74	5.35	1.09	0.08	0.56	99.66	7	18	62	7	32	694	498	24	16	16	13	105	1	9	4	4
4581	1	70.57	0.27	15.55	2.14	0.02	0.83	1.50	4.03	3.57	0.12	0.96	99.56	16	22	48	7	170	318	656	11	17	16	11	93	6	10	12	9
7018	2	70.53	0.15	15.62	1.62	0.45	0.33	0.41	4.25	4.21	0.10	1.76	99.43	50	41	102	1	198	265	947	20	18	10	20	68	8	9	6	4
8909	2	69.88	0.20	15.63	1.21	0.01	0.43	0.93	4.64	5.31	0.19	1.03	99.46	26	22	50	3	248	264	750	21	8	45	6	85	2	15	5	2
6079	2	72.95	0.09	15.15	0.72	0.01	0.13	0.63	4.75	4.33	0.09	0.75	99.60	23	39	41	1	260	154	339	8	23	10	3	53	7	3	6	10
6080	2	72.69	0.11	15.26	0.82	0.01	0.15	0.79	4.60	4.10	0.11	0.76	99.40	21	37	47	1	252	181	413	8	8	10	3	59	11	8	3	6

Bongo granitoids

Sample	Ref.	SiO2	TiO2	Al2O3	Fe2O3	MnO	MgO	CaO	Na2O	K2O	P2O5	LOI	Sum	Cu	Pb	Zn	SC	Rb	Sr	Ba	V	Cr	Co	Ni	Zr	Nb	Th	U	Y
45331	1	71.90	0.28	14.92	2.15	0.03	0.68	1.99	4.57	2.91	0.08		99.51	15	12	41	4	118	468	784	16	3	16	7	123	3	13	5	3
45332	1	73.52	0.02	14.48	0.34	0.01	0.05	0.64	3.66	6.61	0.01		99.34	1	31	6	3	250	222	499	27	1	9	5	12	1	12	4	1
45333	1	70.08	0.30	15.11	2.19	0.03	0.82	2.19	4.46	3.35	0.08		98.61	12	21	40	5	111	511	1335	4	10	10	8	120	6	8	1	4
45334	1	69.04	0.26	16.25	1.81	0.03	0.58	1.72	4.50	4.34	0.07		98.60	10	19	37	5	204	432	1232	9	1	27	11	101	9	12	4	5
4595	1	69.23	0.40	15.30	2.64	0.03	0.76	2.47	4.45	3.35	0.12		98.75	10	12	55	7	91	553	1250	23	3	8	1	107	4	15	4	11
4596	1	73.35	0.11	13.75	1.15	0.04	0.15	0.81	3.43	5.57	0.03		98.39	1	34	30	5	240	155	415	2	1	23	5	103	10	29	9	16
2126	1	72.32	0.20	14.32	1.45	0.03	0.44	1.23	4.69	4.02	0.08		98.78	8	40	34	4	147	581	1016	13	1	31	1	112	5	19	12	7
2135	1	68.38	0.40	14.79	2.58	0.04	0.90	2.05	4.16	5.16	0.20		98.66	9	22	51	9	171	1446	2197	13	12	1	12	227	5	33	7	14
2141	1	68.45	0.41	15.31	2.66	0.04	1.05	2.54	4.90	3.19	0.16		98.71	8	23	59	8	91	1248	1837	12	6	9	13	167	1	22	5	8
4602	1	75.41	0.05	13.49	0.55	0.02	0.07	0.78	4.67	3.84	0.01		98.89																

Winneba granitoids

Sample	Ref.	SiO2	TiO2	Al2O3	Fe2O3	MnO	MgO	CaO	Na2O	K2O	P2O5	LOI	Sum	Cu	Pb	Zn	SC	Rb	Sr	Ba	V	Cr	Co	Ni	Zr	Nb	Th	U	Y
4526	1	68.87	0.45	15.16	3.04	0.03	0.83	2.43	3.76	4.18	0.11	0.76	99.62	1	26	71	6	272	382	879	4	3	11	9	202	11	30	4	10
4527	1	69.61	0.32	15.73	2.40	0.03	0.69	2.40	4.72	2.53	0.07	1.13	99.63	1	24	58	6	161	460	767	1	2	9	1	168	7	15	6	9
4624	1	70.37	0.38	14.72	2.60	0.02	0.62	1.95	3.46	4.42	0.11	0.60	99.25	10	36	57	7	133	299	1221	1	1	21	1	240	11	46	1	9
4625	1	71.90	0.29	14.44	2.09	0.02	0.37	1.75	3.48	4.47	0.06	0.69	99.56	1	33	51	4	138	257	828	1	5	23	1	163	1	16	5	8
4626	1	65.70	0.96	15.46	4.36	0.03	0.96	2.65	3.25	4.99	0.25	0.65	99.26	12	36	88	6	68	473	1523	1	17	9	10	450	17	44	6	17
4627	1	67.12	0.59	15.88	3.48	0.03	0.91	2.64	3.75	4.10	0.16	0.75	99.41	22	34	72	7	314	394	1617	1	9	11	10	308	15	41	8	15
4628	1	67.67	0.61	15.51	3.65	0.04	0.91	2.73	3.55	3.98	0.15	0.54	99.34	9	24	74	5	59	416	1276	1	5	24	1	243	12	40	6	14
4629	1	69.83	0.38	15.10	2.78	0.03	0.73	2.24	3.87	4.06	0.11	0.53	99.66	8	33	58	5	30	373	744	4	10	9	8	165	11	26	9	12
4630	1	71.93	0.30	14.43	2.10	0.03	0.54	1.87	3.73	3.99	0.08	0.48	99.48	1	41	56	5	168	263	654	7	1	28	6	149	14	33	7	12
4631	1	70.50	0.44	14.45	3.00	0.04	0.70	2.01	3.82	3.74	0.12	0.53	99.35	7	34	69	6	107	301	877	17	8	18	9	220	10	35	6	12
4632	1	69.15	0.49	15.13	3.05	0.04	0.68	2.24	3.74	3.97	0.13	0.66	99.28	21	28	68	5	117	328	948	1	9	26	6	233	13	36	9	17
4633	1	70.62	0.30	15.46	2.36	0.03	0.56	1.97	4.87	2.44	0.08	0.70	99.39	1	17	68	6	30	674	935	1	1	13	6	129	8	11	1	7
4634	1	69.23	0.47	15.09	3.04	0.03	0.76	2.39	3.46	4.22	0.13	0.64	99.46	8	29	63	7	65	376	961	1	3	10	6	218	11	34	6	14
4635	1	66.95	0.72	15.50	4.14	0.04	1.13	3.06	3.49	3.57	0.17	0.66	99.43	17	28	71	9	107	365	1068	2	14	21	10	254	15	38	6	27
4636	1	70.76	0.34	14.86	2.41	0.02	0.56	2.03	3.74	3.99	0.09	0.68	99.48	1	31	54	7	55	315	850	21	5	9	5	180	14	32	5	14
4637	1	69.94	0.38	15.05	2.62	0.02	0.67	2.12	3.35	4.52	0.10	0.74	99.51	11	30	52	6	35	384	1190	6	1	21	5	184	6	33	7	11
4639	1	69.34	0.46	15.07	2.94	0.03	0.75	2.17	3.55	4.47	0.10	0.64	99.52	8	27	62	6	112	316	1238	3	3	22	6	239	11	40	4	15
4640	1	66.67	0.60	15.08	4.92	0.07	1.22	3.10	4.34	2.80	0.13	0.60	99.53	16	15	64	13	43	244	852	1	20	37	11	261	8	14	6	33
4641	1	71.28	0.22	15.20	2.01	0.04	0.57	2.14	4.62	2.45	0.06	0.80	99.39	7	18	44	6	75	589	910	6	13	23	6	99	6	12	5	8

Appendix 2. Isotopic dating data of the Birimian granitoids from Ghana

No.	Location	Rock type	Category	Material	Rb-Sr (Ma)	K-Ar (Ma)	Pb-Pb (Ma)	Sm-Nd (Ma)	U-Pb (Ma)	Error (Ma)	Initial ratio of 87Sr/86Sr	μ value	leNd leNd	Note	Ref.
1	Gomoa Assin 5*20' N, 0*48' W	Gd	BGr	Bi	1915					70				AIR	2
2	Gomoa Assin 5*20' N, 0*48' W	Gd	BGr	Bi	1925					70				AIR	2
3	Awutu 5*30' N, 0*30' W	Di	BGr	Bi	1978					79				AIR	2
4	Awutu 5*30' N, 0*30' W	Di	BGr	Bi	1973					70				AIR	2
5	Kumasi	Gr	BGr	WR	2073					29	0.7037			Isoc	5
6	Nsawam 5*48'54" N, 0*21'10" W	Gr	BGr	WR	1996					43	0.7022				7
7	Nsawam 5*48'54" N, 0*21'10" W	Gr	BGr	WR	1819					42					7
8	Tema 5*37'16" N, 0*00'16" W	Gr	BGr	WR	2495					15	0.7010			AIR	7
9	Tema 5*37'16" N, 0*00'16" W	Gr	BGr	WR	2487					5	0.7016			BEM	7
10	Tema 5*37'16" N, 0*00'16" W	Gr	BGr	WR/Ksp	2261					662	0.7200			WR/Ksp line	7
11	Cape Coast area	Mig	BGr	Bi	1772					60	0.7025			BEM	7
12	Cape Coast area	Mig	BGr	Bi	1905					67	0.7010			AIR	7
13	Cape Coast area	Mig	BGr	Bi	1903					67	0.7024			BEM	7
14	Cape Coast area	Mig	BGr	WR/Bi	1898					48	0.7020			15 pt Isoc	7
15	Cape Coast area	Mig	BGr	WR/Bi	1974					28	0.1017			13 pt Isoc	7
16	Dziga-Kope 6*16'24" N, 0*57' W	BG	BGr	WR	2835					135	0.7010				7
17	Dziga-Kope 6*16'24" N, 0*57' W	BG	BGr	WR	2683					262	0.7014				7
18	Near Nsawa 5*00'N, 0*22' W	GG	BGr	WR/Bi	1624					35	0.7022				7
19	Cape Coast area 5*06'54" N, 1*24'32" W	Mig	BGr	Pl/Ksp	1803					49	0.7030			Ksp/Pl line	7
20	Cape Coast area 5*06'54" N, 1*24'32" W	Mig	BGr	Pl/Ksp/Bi	1680					111	0.7033			3 pt isoc	7
21	Cape Coast area 5*09'18" N, 1*17'43" W	Mig	BGr	Bi	1961					86	0.7010			AIR	7
22	Cape Coast area 5*09'18" N, 1*17'43" W	Mig	BGr	Bi	1960					86	0.7023			BEM	7
23	Cape Coast area 5*09'18" N, 1*17'43" W	Mig	BGr	Bi	1989					45					7
24	Cape Coast area 5*10'31" N, 1*18'59" W	Mig	BGr	Bi	1978					64	0.7010			AIR	7
25	Cape Coast area 5*10'31" N, 1*18'59" W	Mig	BGr	Bi	1979					64	0.7023			BEM	7
26	Cape Coast area 5*10'31" N, 1*18'59" W	Mig	BGr	Bi	1815					151	0.7010				7

Appendix 2. (continued)

No.	Location	Rock type	Category	Material	Rb-Sr (Ma)	K-Ar (Ma)	Pb-Pb (Ma)	Sm-Nd (Ma)	U-Pb (Ma)	Error (Ma)	Initial ratio of 87Sr/86Sr	μ value	IeNd IeNd	Note	Ref.
27	Cape Coast area 5*10'31" N, 1*18'59" W	Mig	BGr	Bi	1956					94	0.7010			AIR	7
28	Cape Coast area 5*10'31" N, 1*18'59" W	Mig	BGr	Bi	1954					94	0.7023			BEM	7
29	Kumasi 6*8' N, 2*34' W	Gt	BGr	WR	2086					40	0.7017				8
30	Cape Coast	Gt	BGr	WR	2216					72	0.7015				8
31	Kumasi, Upper West, Dixcove	Gt	BGr+VGr	WR	2106					59	0.7014				8
32	Dixcove	Gt	VGr	WR	1891					314	0.7018				8
33	K-rich granite, Sefwi belt	Gt	VGr	WR	2122					22				Isoc	12
34	Granite, Sewfi belt,	Gr	VGr	WR	2263					98	0.7009			Isoc	12
35	Banso	Gt	BnGr	WR	2081					25	0.7012				8
36	Bongo	Gt	BnGr	WR	1968					49	0.7019				8
37	Bongo	Gt	BnGr	WR	1968					49					9
38	Winneba	Gt	WbGr	WR	2021					143	0.7041				8
39	E of Konongo	Pm	BGr	Ksp		1851				120					1
40	Gomoa Assin 5*20' N, 0*48' W	Gd	BGr	Bi		1939				40				AIR	2
41	Awutu 5*30' N, 0*30' W	Di	BGr	Bi		1964				40				AIR	2
42	E of Konongo	Pm	BGr	Ksp		1649				120					3
43	3 km NE of Boku	Pm	BGr	Bi		1972									4
44	3 km NE of Boku	Pm	BGr	Ksp		1970									4
45	Boku-Techiman	Gr	BGr	Mus		2145									4
46	Boku-Techiman	Gr	BGr	Ksp		2067									4
47	N. Banda Nkwanda	Gd	BGr	Bi		1703									4
48	1 km E of Kalba	Pm	BGr	Bi		1802									4
49	South of Gruppe	Gr	BGr	Bi		1732									4
50	E of Bole 9*03' N, 2*28' W	Di	BGr	Hb		1930									4
51	13,7 km E. of Siripe	Gr	BGr	Ksp		1870									4
52	29 km E of Malawe	Pm	BGr	Bi		1949									4
53	29 km E of Wagawaga 8*41' N, 2*02' W	Pm	BGr	Bi		1674									4
54	Nof, Mandri	GG	BGr	Bi		2184									4
55	Nof, Mandri	GG	BGr	Ksp		1802									4
56	Nsawam 5*48'54" N, 0*21'10" W	Gr	BGr	WR/ Bi		1944				45					7
57	Cape Coast area 5*09'17" N, 1*17'43" W	Gr	BGr	Bi		1833				5					7
58	Cape Coast area	Mig	BGr	Bi		1879				45					7
59	Cape Coast area	Mig	BGr	Bi		1880				45					7
60	Sokode, Btoe/Ho 6*34'12" N, 0*24'12" W	BG	BGr	Bi		2034				50	0.7077			WR/Bi line	7

Appendix 2. (continued)

No.	Location	Rock type	Category	Material	Rb-Sr (Ma)	K-Ar (Ma)	Pb-Pb (Ma)	Sm-Nd (Ma)	U-Pb (Ma)	Error (Ma)	Initial ratio of 87Sr/86Sr	μ value	leNd leNd	Note	Ref.
61	Sokode, Btoe/Ho 6*34'12" N, 0*24'12" W	BG	BGr	WR		2176				44	0.7030			3 pt Isoc	7
62	60 km NW of Kumasi 7*0'41" N, 1*57'58" W	CG	BGr	Bi		2144				11					7
63	60 km NW of Kumasi 7*0'41" N, 1*57'58" W	CG	BGr	Bi		2144				7					7
64	20 km NW of Kumasi 6*09'06" N, 0*07' W	CG	BGr	Bi		2070				10					7
65	20 km NW of Kumasi 6*09'06" N, 0*07' W	CG	BGr	Bi		2112				8					7
66	20 km NW of Kumasi 6*09'06" N, 0*07' W	CG	BGr	Bi		2085				14					7
67	20 km NW of Kumasi 6*09'06" N, 0*07' W	CG	BGr	Hb		2169				26					7
68	Cape Coast area 5*10'31" N, 1*18'50" W	Mig	BGr	Bi		1877				13					7
69	Cape Coast area 5*10'31" N, 1*18'50" W	Mig	BGr	Bi		1850				13					7
70	Cape Coast area 5*10'31" N, 1*18'50" W	Mig	BGr	Bi		1861				21					7
71	Cape Coast area 5*10'31" N, 1*18'50" W	Mig	BGr	Bi		1867				15					7
72	Cape Coast area 5*10'31" N, 1*18'50" W	Mig	BGr	Bi		1897				15					7
73	Near Nsawa 5*00'N, 0*22' W	GG	BGr	Bi		1787				45					7
74	Cape Coast area 5*10'31" N, 1*18'59" W	Mig	BGr	Bi		1942				47					7
75	Cape Coast area 5*10'31" N, 1*18'59" W	Mig	BGr	Bi		1863				45					7
76	Cape Coast area 5*10'31" N, 1*18'59" W	Mig	BGr	Bi		1876				45					7
77	Cape Coast area 5*10'31" N, 1*18'59" W	Mig	BGr	Bi		1774				60	0.7010			AIR	7
78	Mankwadzi, Ejisiman Hill	Pm	BGr	Mus		1909				13					10
79	Mankwadzi, Ejisiman Hill	Pm	BGr	Mus		1965				13					10
80	Mankwadzi, Ejisiman Hill	Pm	BGr	Mus		2019				14					10
81	Cape Coast	Gt	BGr	Bi		1907				13					10
82	Kumasi	Gt	BGr	WR			2114			52					8
83	Upper West	Gt	BGr	WR			2095			+87 -92					8
84	Kumasi, Upper West, Dixcove	Gt	BGr+VGr	WR			2102			+42 -43		7.86			8
85	Cape Coast	Gt	BGr	WR			1984			+60 -62		7.99			8

Appendix 2. (continued)

No.	Location	Rock type	Category	Material	Rb-Sr (Ma)	K-Ar (Ma)	Pb-Pb (Ma)	Sm-Nd (Ma)	U-Pb (Ma)	Error (Ma)	Initial ratio of 87Sr/86Sr	μ value	IeNd IeNd	Note	Ref.
86	Winneba	Gt	WbGr	WR			2173			+107 -115		8.4			8
87	Cape Coast granite	Gr	BGr	WR				2430		5	0.5095			5 pt isoc	6
88	Cape Coast	Gt	BGr	WR				2336		+203 -115			+3,7		8
89	Kumasi, Upper West, Dixcove	Gt	BGr+VGr	WR				2175		145			+2,7		8
90	Winneba	Gt	WbGr	WR				2600						Model	8
91	Granite, Sewfi belt, 6*8' N, 2*34' W	Gt	VGr	Zircon					2179	2					11
92	Dixcove 4*47'28" N, 1*56'43" W	Tn	VGr	Zircon					2172	2					11
93	Near Nyinasia, Ashanti belt 4*57'24" N, 1*42'9" W	Gd	VGr	Zircon					2179	2					12
94	Maluwe Gr, Dome pluton, Bui-belt margin	Gr	VGr	Zircon					2145	2					13
95	Quarry, Sekondi	Gd	VGr	Zircon					2159	9					15
96	Quarry, Sekondi	Gd	VGr	Zircon					2174	2					15
97	Ashanti belt	QA	VGr	Zircon					2166	3					15
98	Ashanti belt	QA	VGr	Zircon					2153	5					15
99	Kumasi 6*24'44" N, 2*14'54" W	Tn	BGr	Zircon					2116	2					11
100	Sanyani 7*3'50" N, 2*39'21" W	Gt	BGr	Zircon					2088	1					11
101	Migmatite , Maluwe basin north of Banda Nkwanta	Mig	BGr	Zircon					2125	2					13
102	Granite, Sunyani basin, south of Wenchi	Gr	BGr	Zircon					2092	2					13
103	Granite, Cape Coast basin, near Elmina	Gr	BGr	Zircon					2090	1					13
104	Cape Coast	Gt	BGr	Zircon					2088	1					14
105	Ayanfuri	Gt	BGr	Monazite					2105	3					14
106	Ayanfuri	Gt	BGr	Rutile					2086	4					14
107	Yanmensakrom, Obuasi	Gt	BGr	Monazite					2105	3					14
108	Yanmensakrom, Obuasi	Gt	BGr	Rutile					2098	7					14
109	Cape Coast	GG	BGr	Monazite					2102	1					15
110	Cape Coast	GV	BGr	Zircon					2104	3					15
111	Cape Coast	GV	BGr	Zircon					2104	3					15

Note: Pm=pegmatite, Gd=granodiorite, Di=diorite, Gr=granite, Mig=migmatite, BG=biotite gneiss, CG=calcic gneiss, GG=granite gneiss, QA=quartz arenite, GV=granitoid vein, Tn=tonalite, Gt=granitoid. BGr=basin granitoid, VGr=volcanic granitoid. Bi=biotite, Ksp=K-feldspar, Pl=plagioclase, Mus=muscovite, Hb=hornblende, WR=whle rock. AIR=assumed initial ratio, Isoc=isochron, BEM=bullk earth model. pt=point. Ref.=reference.
1: Schillibeer and Watson (1964); 2: Priem et al. (1966); 3: Holmes and Cahen (1967); 4: Tugarinov and Vernadskiy (1967); 5: Vechette and Attoh (1982); 6: Agyei and Armstrong (1986); 7: Agyei et al. (1987); 8: Taylor et al. (1988); 9: Hiedes et al. (1988); 10: Chalokwu et al. (1997); 11: Hirdes et al. (1992); 12: Hirdes et al. (1993); 13: Zitzmann et al. (1993); 14: Oberthur et al. (1994); 15: Loh and Hirdes (1996). References 1 to 7 in Agyei (1988).