THE ORIGIN OF LATE ARCHAEAN GRANITOIDS IN THE SUKUMALAND GREENSTONE BELT OF NORTHERN TANZANIA: GEOCHEMICAL AND ISOTOPIC CONSTRAINTS.

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ABSTRACT

Granitoids intruding the late Archaean sequences of the Sukumaland Greenstone Belt of northern Tanzania belong to two distinct geochemical suites. Suite 1 is characterised by $Na_2O/K_2O > 1$ (1.04 – 4.67), high Sr/Y (56 – 204) and Ba/Rb ratios (6.1 – 27.1) and low Rb/Sr ratios (0.08 - 0.25). The rocks are enriched in Sr (405 – 1264 ppm) and depleted in Yb (0.17 – 0.93 ppm) and Rb (56 – 132 ppm). On chondrite-normalised REE diagrams, the rocks display highly fractionated patterns characterised by relative LREE enrichment ($(La/Yb)_N$ = 23 – 128 and $(Gd/Yb)_N$ = 3.10 – 8.54) and lower concentrations of the HREE (Yb_N = 0.80 – 4.45). On primitive mantle-normalised spidergrams, Nb and Ti, together with P and Y are depleted relative to adjacent elements. The major and trace element characteristics of Suite 1 are comparable to those of typical Archaean TTG suites and High Silica Adakites (HSA). Suite 2 granitoids are characterised by $Na_2O/K_2O < 1$, low Sr/Y (2.80 – 41.7) and Ba/Rb (0.40 – 8.91) ratios and high Rb/Sr (0.30 – 6.27) ratios. Suite 2 is also characterised by low Sr (53 - 326 ppm) and high Rb (40 - 365 ppm) and Yb (0.44 – 1.36 ppm) contents. Compared to Suite 1, Suite 2 rocks display less fractionated REE patterns ($(La/Yb)_N$ = 15 – 86 and $(Gd/Yb)_N$ = 1.73 – 6.74) and are characterised by higher concentrations of the HREE (YbN = 2.1 – 6.5). On primitive mantle-normalised spidergrams, Suite 2 samples, like those of Suite 1, show relative depletion in Th, Nb and Ti, together with P and Y relative to adjacent elements. Sm-Nd mean crustal residence ages for both suites are indistinguishable and range between 2470 and 2720 Ma with a mean of 2610 ± 35 Ma (2 SE), similar to the emplacement age of 2620 ± 40 Ma. The granitoids are interpreted to have formed by partial melting at the base of a late Archaean thickened sub-arc basaltic crust. Melting to form the Suite 1 granitoids occurred in the eclogite stability field whereas Suite 2 formed by melting at shallower depth in the garnet amphibolite stability field.

INTRODUCTION

Processes of Archaean continental crust formation continue to generate a great deal of interest among earth scientists (Drummond and Defant 1990, Smithies 2000). In particular, much effort has been directed at comparing processes responsible for the formation of Archaean granite-greenstone terranes with those operating in Phanerozoic tectonic settings (Drummond and Defant 1990, Smithies 2000). Central in the debate has been the origin of granitic rocks of the tonalite-trondhjemite-granodiorite (TTG) suite that form a major component of many Archaean terranes. Some workers have interpreted the genesis of TTG in terms of slab melting processes akin to those responsible for the formation of Phanerozoic adakites (Drummond and Defant 1990, Martin 1999, Martin et al. 2005) whose formation is only confined to those areas where, as in the Archaean, young

and warm easy to melt oceanic lithosphere is subducted (Drummond and Defant 1990). Other workers, however, urgue that unlike most Cenozoic adakites, Archaean TTG show no evidence of interaction of the parental magmas with mantle peridotite which is reflected in low SiO_2 contents (as low as 58%), high Mg numbers (as high as 68) and high concentrations of Ni and Cr (Smithies 2000). Thus, they postulate a model for TTG generation in which partial melting of hydrated basalt occurs at the base of magmatically and/or tectonically thickened crust. A similar tectonic setting has been postulated for Phanerozoic Na-rich granitoids that share many geochemical and petrological similarities with Archaean TTG (e.g. Atherton and Petford 1993).

The Tanzania craton of eastern Africa consists of 2.5 – 2.8 Ga granitoids, intruding and flanking a number of greenstone belts in northern Tanzania and western Kenya (Borg and Shackleton 1997). Although forming an important component of the Archaean crust of East Africa, there has been no modern geochemical investigation of the granitoids and their role in the growth and stabilisation of the Tanzania craton. This paper, therefore, presents major and trace element geochemical as well as Nd isotopic data of granitoids from the Sukumaland Greenstone Belt (SGB) sampled along a ~100 km long transect trending roughly north south from Geita to Kahama (Fig. 1). The data are used to constrain the petrogenesis and tectonic setting of the granitoids.

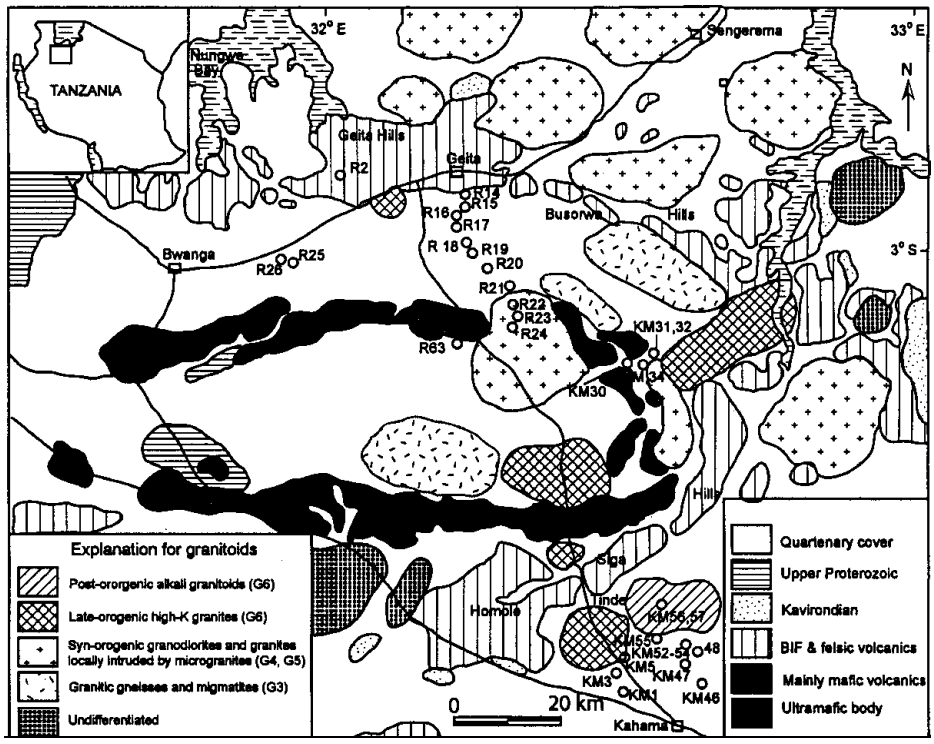

Figure 1: Geological map of the Sukumaland Greenstone Belt (SGB) showing sampling localities (as circles and numbers). The frame in the inset map shows the location of the Sukumaland greenstone Belt.

Geological background

In the area south of Lake Victoria (Fig. 1), the Nyanzian Belt is represented by rocks of the Sukumaland Greenstone Belt (Borg et al. 1990). The Sukumaland Greenstone Belt consists of gabbro, pillow basalt and subordinate felsic flows and pyroclastics overlain by a sequence composed predominantly of BIF, felsic pyroclastics and flows and carbonaceous shales metamorphosed to the greenschist facies and locally to the middle amphibolite facies. The relative proportion by volume of the volcanic rocks has been estimated as 40% mafic, 30% andesite and 20% felsic whereas the ratio of sedimentary to igneous rocks has been estimated at 1:8 (Borg and Shackleton 1997). The maximum preserved thickness of the greenstone sequence as estimated using geophysical methods is 5-7 km (Borg and Shackleton 1997).

Numerous granitoids intrude and flank the Nyanzian Greenstone Belts. Borg and Shackleton (1997) estimated a ratio of granite to greenstone in the belt of 4:1 by volume. Earlier studies by Grantham *et al.* (1945) distinguished four different generations of granitoids in the Tanzania craton on the basis of their chemical and petrographic composition and by their tectonic location in relation to the greenstone belts. The first generation (G3) includes granitic gneisses and migmatites, which occupy structurally lower positions than the greenstones. The second generation comprises syn-orogenic granite and granodiorite (G4 and G5) whereas post-orogenic alkali granites and syenite (G6) comprise the youngest generation. Barth (1990) who observed that it was unlikely that a single intrusive differentiation sequence exists for the granitoids in the Tanzania craton proposed an alternative classification in which he subdivided the rocks into a syn-orogenic and a late-kinematic (late or post-orogenic) intrusive cycle. The syn-orogenic cycle comprises of migmatites, foliated and porphyroblastic granites, biotite-hornblende granites, trondhjemites, granodiorites, tonalites, monzonites and quartz diorites with an excess of Na over K (Barth 1990). The late-kinematic cycle comprises biotite granite, microgranite, alaskite, leucogranites and feldspar porphyries (Barth 1990). Thus, this scheme groups the G3 to G5 granites of Grantham et. al. (1945) into a single syn-orogenic suite while maintaining the G6 granites as a distinct post-orogenic suite.

The Na-rich granitoids (equivalent to the G3 suite of Grantham *et al.* 1945), which intrude and flank the greenstone sequences in the Geita area, have yielded a Rb-Sr whole rock isochron age of 2620 ± 30 Ma (initial $^{87}Sr/^{86}Sr$ ratio = 0.7017 ± 4) reported by Bell and Dodson (1981). The supracrustal assemblages in the Sukumaland Greenstone Belt have yielded a Sm-Nd isochron age of 2823 ± 44 Ma reported by Manya and Maboko (2003) for the Nyanzian metabasalts from Rwamagaza. Borg and Krogh (1999) reported single zircon U-Pb ages of 2780 ± 3 and 2808 ± 3 Ma for the Nyanzian rhyolitic pyroclastic rocks from the outer arc of the SGB north to north-west of Kahama.

MATERIALS AND METHODS

Thirty one granitoid samples collected along a ~100 km long N-S trending transect from Geita to Kahama (Fig. 1) were analysed for major elements at the ACME Analytical Laboratories in Vancouver, Canada. Trace elements for a batch of 16 samples were also analysed at the ACME Laboratories. For the major elements and Ba, aliquots of the pulverised samples, mixed with $LiBO_2$ flux, were melted prior to acid digestion and analysis by ICP-OES. All the other elements were analysed using ICP-MS following $LiBO_2$ fusion and acid digestion. Trace elements for the remaining 15 samples were analysed at the Geochemical Laboratory of the University of Dar es Salaam using a Varian Vista MPX ICP-OES as described in Messo (2004). The analytical reproducibility, expressed as the Relative Standard Error of the Mean, obtained from

repeated measurement of the USGS Reference Material W2 is better than 8% for most elements and is typically ~2.5% (n = 10) for most elements except for Er, Gd, Pr and Tm which are accurate to within 10.8, 19.2, 20.0 and 10.5% respectively of their respective certified values.

Fifteen samples were also analysed for Nd isotopic composition as well as Nd and Sm concentrations on a Finnigan MAT 262 thermal ionisation mass spectrometer at the Laboratory for Isotope Geology of the Department of Geology, University of Bergen in Norway. Sm and Nd were separated by specific-extraction chromatography using a modified version of the method described by Richard *et al.* (1976). Sm and Nd were loaded onto a double filament and analysed in static and dynamic modes, respectively. Nd isotopic ratios were corrected for mass fractionation using a $^{146}Nd/^{144}Nd$ value of 0.7219. Sm and Nd concentrations were determined using a mixed ^{150}Nd-^{149}Sm spike. Repeated measurements of Johnson and Mattey NdO_3 standard at the time of the analyses yielded a mean $^{143}Nd/^{144}Nd$ ratio of 0.511102 ± 5 (2σ).

RESULTS

The major and trace element composition of the samples is summarised in Table 1. On the basis of the geochemical data, the granitoids can be subdivided into two distinct geochemical suites. Suite 1 consists of 15 samples with $Na_2O/K_2O > 1$ (1.04 – 4.67). In the area near Kahama, this suite consists mostly of foliated granitoids. Further north, however, granitoids of this suite tend to lack the gneissic foliation. According to the molecular normative Ab – An - Or classification scheme of Barker (1979), the rocks plot in the granite – trondhjemite fields with most samples straddling the boundaries between trondhjemite, tonalite and granodiorite (Fig. 2). The rocks are enriched in Al_2O_3 (13.9 – 17.0, mean = 15.5 weight %) with SiO_2 contents ranging between 66.6 and 74.5 % (mean = 70.5). The combination of high Al_2O_3 and relatively high SiO_2 contents indicates that the rocks are high Al-trondhjemites (Barker 1979) and are compositionally similar to the High Silica Adakites (HSA) of Martin *et al.* (2005).

Suite 1 samples are characterised by high Sr/Y (56 – 204, mean = 124), high Ba/Rb (6.1 – 27.1, mean = 12.9) and low Rb/Sr (0.08 - 0.25, mean = 0.16) ratios. The rocks are also enriched in Sr (405 – 1264 ppm, mean = 634 ppm) and depleted in Yb (0.17 – 0.93 ppm, mean = 0.40 ppm) and Rb (56 – 132 ppm, mean = 92 ppm). On chondrite-normalised REE diagrams (normalising values after Boynton 1984), the Suite 1 rocks display highly fractionated patterns (Fig. 3) as reflected by $(La/Yb)_N$ values of between 23 and 128 (mean = 71, the subscript N refers to chondrite normalised values) and $(Gd/Yb)_N$ values between 3.10 and 8.54 (mean = 5.64). All samples, except R17 which has no anomaly, are characterised by slightly negative Eu anomalies (Eu/Eu* = 0.52 – 0.97, mean = 0.76). The low Yb contents ($0.8 < Yb_N < 4.5$, mean = 1.89) and strongly fractionated REE patterns are also typical of other Archaean TTG suites and contrasts with the less fractionated ($(La/Yb)_N < 20$) and higher Yb contents of post-Archaean granitic rocks (Drummond and Defant 1990). On primitive mantle-normalised spidergrams (normalising values after McDonough and Sun 1995), the High Field Strength Elements (HFSE) Nb and Ti, together with P and Y are depleted whereas Zr and Hf are enriched relative to adjacent elements. Sr is, however, enriched relative to Ce and Nd (Fig. 4).

Table 1: Major (in oxide weight %) and trace (in ppm) element composition of granitoids from the Sukumaland Greeenstone Belt

SUITE 1 GRANITOIDS

Sample	R 2	R 14	R 15	R 16	R 17	R 18	R 19	R 20	R 21	R 21*	R 26	KM30	KM31	KM32	KM34	KM46
Classification	G3	G3	G3	G3	G3	G3	G3	G3	G3	G3	G3	G3	G3	G3	G3	G3
SiO_2	66.63	68.68	69.86	69.84	68.16	71.51	71.76	72.22	70.42	70.41	72.88	67.92	74.46	70.47	70.44	72.95
TiO_2	0.3	0.37	0.28	0.38	0.27	0.23	0.15	0.15	0.27	0.26	0.24	0.41	0.14	0.33	0.32	0.09
Al_2O_3	16.25	16.36	15.22	15.38	17.01	14.95	15.2	15.08	15.39	15.39	14.47	16.53	13.94	15.89	15.45	14.85
Fe_2O_3tot	3.33	2.53	2.51	2.62	2.55	2.08	1.35	1.68	2.24	2.22	2.13	3.12	1.09	2.29	2.09	0.87
MnO	0.08	0.03	0.03	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.04	0.05	0.02	0.03	0.02	0.01
MgO	1.03	0.84	0.54	0.65	0.72	0.4	0.27	0.32	0.53	0.54	0.4	1.22	0.27	0.73	0.67	0.3
CaO	3.07	3.02	2.15	2.08	3.15	1.71	1.64	1.76	2.09	2.1	1.64	3.51	1.32	2.98	2.01	2.14
Na_2O	5.11	5.08	4.49	4.31	5.28	4.22	4.32	4.7	4.97	4.96	4.6	5.28	4.21	5.16	4.45	3.84
K_2O	2.82	1.86	3.16	3.48	1.46	3.16	3.88	3.06	2.69	2.61	2.34	1.13	3.79	1.25	3.59	3.69
P_2O_5	0.15	0.12	0.11	0.13	0.08	0.07	0.05	0.01	0.07	0.09	0.07	0.12	0.03	0.09	0.1	0.01
LOI	0.90	0.80	1.40	0.70	1.00	1.30	1.00	0.70	0.90	1.00	1.00	0.60	0.60	0.50	0.50	0.90
Totals	99.67	99.69	99.75	99.61	99.71	99.66	99.65	99.71	99.6	99.61	99.81	99.89	99.87	99.72	99.64	99.65
Ni	7.7	7.5	12.5	9	7	6.5	6.3	9.8	8.4	8.8	8.7	11.37	6.3	3.6	5.97	1.34
Co	5	5.3	4.1	4.5	4.7	3.9	2.6	2.2	4.2	4	3.6	8.28	1.41	5.05	4.34	2.62
Rb	84.7	100	110	106	56	103	116	103	76	74.3	73.1	78.8	132	61.5	99.3	101
Sr	737	465	551	620	603	490	457	405	689	669	449	866	562	761	1264	565
Ba	1717	609	1131	1694	418	1265	1330	829	976	973	587	703	940	960	2156	2732
Nb	7.7	3.47	5.91	6.54	3.82	2.13	2.54	2.89	3.3	3.33	5	5.27	4.22	4.45	3.6	2.5
Zr	144	167	152	212	98.8	139	108	87.6	113	110	139	144	111	146	179	77.5
Hf	4.1	3.8	4	4.8	2.4	3.5	3	2.4	3	3.1	3.9	3.22	3.64	3.65	4.18	2.58
Y	13.1	2.7	9.2	7.9	3.7	2.4	3	2.8	4.2	4	5.9	9.8	5.45	8.74	7.17	6.02
Pb	16.2	3.59	9.91	13.1	6.87	8.16	11.9	9.12	7.2	7.62	6.41	18.22	28.59	16.36	22.54	11.33
Th	14.2	8.6	13.5	22	6.7	7.6	7.6	7.2	9.1	9.1	7.8	2.13	0.54	1.67	1.41	0.26
La	46.3	38	45.3	89	29.4	32.3	27.9	18.8	34	32.8	25.7	29.92	21.17	21.54	55.15	24.24
Ce	87.1	61.7	78.6	158	50.9	57.5	47	31	64	61.6	54	56.9	44.1	41.8	111	44.2
Pr	10.3	6.02	8.63	16.3	5.67	5.68	5.03	3.47	7.21	7.18	5.29	7.26	5.22	5.51	13.99	4.45
Nd	37.2	18.7	27.8	50.1	18.2	17.6	15.4	11	24.4	24.6	18.3	23.14	18.14	19.3	41.56	14.96
Sm	5.9	2.3	4.1	5.8	2.4	2.2	2.2	1.7	3.1	3.2	2.9	5.87	4.44	4.19	11.08	4.35
Eu	1.39	0.52	0.84	0.89	0.73	0.51	0.44	0.36	0.7	0.68	0.69	1.02	0.63	1.02	1.51	0.61
Gd	4.79	1.8	3.66	4.66	2.02	1.8	1.78	1.47	2.28	2.27	2.45	2.17	1.86	2.48	3.09	1.24
Tb	0.54	0.18	0.41	0.31	0.19	0.16	0.16	0.16	0.21	0.23	0.26	0.39	0.25	0.36	0.3	0.21
Dy	2.55	0.65	1.89	1.41	0.87	0.6	0.7	0.72	0.93	0.97	1.32	1.53	0.7	1.39	1.21	1.07
Ho	0.44	0.09	0.32	0.28	0.13	0.08	0.09	0.1	0.14	0.13	0.2	0.29	0.12	0.28	0.31	0.1508
Er	1.19	0.27	0.81	0.58	0.35	0.27	0.29	0.28	0.41	0.37	0.52	0.54	0.315	0.77	0.45	0.2625
Tm	0.17	0.05	0.12	0.09	0.05	0.05	0.05	0.05	0.05	0.05	0.09	0.11	0.04	0.08	0.07	0.03
Yb	0.93	0.2717	0.57	0.52	0.2717	0.17	0.21	0.21	0.3	0.3	0.43	0.5643	0.1881	0.64	0.59	0.1672
Lu	0.17	0.04	0.09	0.09	0.04	0.03	0.03	0.04	0.05	0.05	0.08	0.08	0.02	0.06	0.07	0.02
Na_2O/K_2O	1.81	2.73	1.42	1.24	3.62	1.34	1.11	1.54	1.85	1.90	1.97	4.67	1.11	4.13	1.24	1.04
K/Rb	276.4	154.4	238.5	272.5	216.4	254.7	277.7	246.6	293.8	291.6	265.7	119	238.5	168.6	300	303.6
Rb/Sr	0.11	0.22	0.2	0.17	0.09	0.21	0.25	0.25	0.11	0.11	0.16	0.09	0.23	0.08	0.08	0.18
Ba/Rb	20.27	6.09	10.28	15.98	7.46	12.28	11.47	8.05	12.84	13.1	8.03	8.91	7.13	15.59	21.7	27.08
Sm/Nd	0.16	0.12	0.15	0.12	0.13	0.13	0.14	0.15	0.13	0.13	0.16	0.25	0.24	0.22	0.27	0.29
Sr/Y	56.3	172.2	59.9	78.5	163	204.2	152.3	144.6	164	167.3	76.1	88.4	103.2	87	176.3	93.9
Eu/Eu*	0.80	0.78	0.66	0.52	1.01	0.78	0.68	0.70	0.81	0.77	0.79	0.87	0.67	0.97	0.79	0.80
La/YbN	33.6	94.3	53.6	115.4	73.0	128.1	89.6	60.4	76.4	73.7	40.3	35.7	75.9	22.7	63.0	97.7
Gd/YbN	4.16	5.35	5.18	7.23	6.00	8.54	6.84	5.65	6.13	6.11	4.60	3.10	7.98	3.13	4.23	5.98

* Duplicate analysis

Table 1 continued……

SUITE 2 GRANITOIDS

Sample	R22	R23	R 24	R 25	R63	KM1	KM3	KM3*	KM5	KM47	KM48	KM52	KM53	KM54	KM55	KM56	KM57
Classification	G4	G4	G4	G5	G4	G4	G4	G4	G4	G4	G4	G4	G4	G4	G6	G6	G6
SiO_2	73.13	71.94	71.46	60.04	67.60	74.50	70.68		73.09	70.45	66.98	68.45	67.55	74.75	74.47	74.01	72.68
TiO_2	0.20	0.23	0.28	0.36	0.40	0.14	0.23		0.16	0.45	0.53	0.58	0.58	0.22	0.11	0.19	0.25
Al_2O_2	13.82	13.89	14.43	20.00	13.90	12.71	15.26		14.36	14.89	15.57	14.19	14.69	12.83	13.22	12.74	13.26
Fe_2O_3tot	2.00	2.33	2.69	3.21	2.86	1.38	2.01		1.33	2.31	3.37	3.52	3.63	1.80	1.02	1.80	2.29
MnO	0.08	0.07	0.06	0.06	0.04	0.04	0.05		0.04	0.03	0.05	0.05	0.05	0.02	0.03	0.04	0.06
MgO	0.32	0.55	0.70	1.86	1.41	0.21	0.35		0.22	0.73	0.70	0.76	0.78	0.33	0.15	0.16	0.29
CaO	1.07	1.41	1.99	0.54	2.84	1.03	1.49		1.15	2.19	1.90	2.05	2.08	1.15	0.93	0.56	0.72
Na_2O	3.82	3.75	3.93	5.00	3.20	3.56	4.33		3.99	4.23	4.09	3.97	3.96	3.23	4.08	5.29	5.48
K_2O	4.29	4.20	3.61	6.85	4.52	5.55	4.32		4.54	3.34	5.61	4.75	5.30	5.13	5.10	4.51	4.37
P_2O_5	0.07	0.07	0.08	0.08	0.11	0.01	0.04		0.02	0.10	0.14	0.17	0.18	0.01	0.01	0.01	0.03
LOI	0.90	1.30	0.60	1.70	3.30	0.70	1.00		0.90	1.10	0.90	1.20	1.00	0.40	0.80	0.60	0.50
Totals	99.70	99.74	99.83	99.70	100.18	99.83	99.76		99.80	99.82	99.84	99.69	99.80	99.87	99.92	99.91	99.93
Ni	8.80	8.20	9.40	8.40	12.90	5.00	3.27	2.88	3.33	5.47	3.83	3.13	4.37	0.93	3.33	1.53	2.98
Co	2.90	3.70	4.60	5.30	7.60	1.55	3.17	2.97	0.90	4.59	5.49	5.49	5.62	1.93	0.31	1.21	2.83
Rb	199	254	215	365	40	159	140	162	267	120	289	215	259	116	293	331	353
Sr	161	196	250	194	136	99	158	166	126	315	319	326	321	176	112	53	74
Ba	924	547	576	937	287	379	662	679	416	1066	808	675	718	882	475	133	266
Nb	8.81	11.30	10.60	14.90	4.20	5.87	9.37	9.48	12.81	6.68	19.10	23.64	24.29	4.62	13.16	35.47	28.41
Zr	133	122	144	268	144	114	150	150	121	267	355	398	321	169	114	405	199
Hf	4.00	4.10	4.30	7.20	3.10	3.34	4.47	3.94	3.58	5.80	8.01	9.59	7.72	3.98	3.30	9.79	5.54
Y	13.60	15.30	14.40	12.80	6.20	6.34	14.90	16.13	20.16	7.55	20.66	24.25	24.93	8.59	9.31	18.68	19.89
Pb	14.60	13.20	12.80	10.40	2.10	29.02	20.38	21.73	29.80	15.26	28.37	33.55	24.55	18.84	24.68	49.35	30.30
Th	20.40	20.70	23.30	36.30	2.80	0.65	0.98	1.02	0.72	2.26	2.54	2.94	3.19	0.98	0.48	1.09	1.24
La	52.10	31.00	37.10	56.20	21.00	28.73	37.49	39.46	28.93	44.29	87.08	98.13	73.48	69.04	21.34	46.07	98.15
Ce	90.7	55.4	65.5	96.5	38.0	51.9	73.1	75.9	57.4	83.5	175.5	206.0	161.5	135.4	39.2	100.5	150.8
Pr	9.42	6.43	7.52	10.70	4.40	3.97	6.41	6.71	5.04	7.17	16.62	19.08	16.14	12.48	2.58	6.87	12.00
Nd	29.90	21.90	24.30	33.00	17.00	17.38	27.37	28.99	22.62	25.28	57.39	68.50	57.85	43.59	12.74	22.27	39.23
Sm	4.40	3.90	3.90	4.90	2.50	5.05	7.53	7.67	5.66	7.69	17.34	20.33	16.05	13.38	3.73	8.69	14.85
Eu	0.66	0.61	0.75	0.57	0.78	0.45	0.72	0.81	0.41	0.70	1.34	1.35	1.45	1.05	0.30	0.45	0.72
Gd	3.90	3.31	3.27	3.91	2.20	1.67	3.53	3.65	4.51	3.14	6.09	6.51	6.05	3.12	2.73	6.81	5.45
Tb	0.46	0.46	0.46	0.49	0.20	0.25	0.40	0.39	0.43	0.31	0.31	0.38	0.30	0.39	0.23	0.33	0.38
Dy	2.24	2.51	2.36	2.38	1.30	1.51	2.38	2.56	2.75	2.12	3.25	3.71	3.74	1.47	1.28	2.08	2.85
Ho	0.44	0.48	0.49	0.46	0.20	0.32	0.37	0.37	0.42	0.48	0.58	0.72	0.63	0.32	0.27	0.34	0.49
Er	1.22	1.27	1.27	1.27	0.50	0.84	0.80	0.82	0.89	1.09	1.47	1.43	1.49	0.80	0.50	1.05	1.07
Tm	0.20	0.24	0.20	0.16	0.10	0.13	0.13	0.13	0.13	0.10	0.14	0.15	0.15	0.14	0.07	0.13	0.13
Yb	1.12	1.36	1.28	0.79	0.50	0.78	0.69	0.69	0.79	0.57	0.73	0.88	0.86	0.81	0.44	0.82	0.77
Lu	0.21	0.25	0.24	0.12	0.10	0.09	0.10	0.10	0.13	0.07	0.11	0.12	0.13	0.12	0.06	0.13	0.12
Na_2O/K_2O	0.90	0.90	1.10	0.70	0.71	0.60	1.00	-	0.90	1.30	0.70	0.80	0.70	0.60	0.80	1.20	1.30
K/Rb	179	137	139	156	466	289	256	221	141	232	161	183	170	367	145	113	103
Rb/Sr	1.24	1.30	0.86	1.88	0.30	1.62	0.89	0.98	2.12	0.38	0.91	0.66	0.81	0.66	2.62	6.27	4.81
Ba/Rb	4.64	2.15	2.68	2.57	2.11	2.38	4.72	4.19	1.56	8.91	2.80	3.14	2.77	7.60	1.62	0.40	0.75
Sm/Nd	0.15	0.18	0.16	0.15	0.15	0.29	0.28	0.26	0.25	0.30	0.30	0.30	0.28	0.31	0.29	0.39	0.38
Sr/Y	11.80	12.80	17.40	15.20	21.94	15.50	10.60	10.30	6.30	41.70	15.40	13.40	12.90	20.50	12.00	2.80	3.70
Eu/Eu*	0.49	0.52	0.64	0.40	1.02	0.47	0.43	0.47	0.25	0.44	0.40	0.36	0.45	0.50	0.29	0.18	0.24
La/YbN	31.4	15.4	19.5	47.7	28.3	24.8	36.6	38.6	24.6	52.4	80.3	75.4	57.8	57.5	32.8	38.1	85.6
Gd/YbN	2.81	1.96	2.06	3.97	3.55	1.73	4.13	4.27	4.58	4.45	6.72	5.98	5.70	3.11	5.02	6.74	5.69

* Duplicate analysis

The second suite consists of 16 samples which are characterised by $Na_2O/K_2O < 1$ (except samples R24, KM3, KM47, KM56 and KM57, which have ratios between 1.10 and 1.30). On the Ab-An-Or diagram, Suite 2 rocks plot mainly in the granite field except for one sample that plots in the trondhjemite field (Fig. 2). Compared to Suite 1, Suite 2 rocks have lower Na_2O (mean = 4.12 wt %) and higher K_2O (mean

= 4.65 wt %) contents. They are also characterised by low Sr/Y (2.80 – 41.7, mean = 14.4), low Ba/Rb (0.40 – 8.91, mean = 3.23) and high Rb/Sr (0.30 – 6.27, mean = 1.67) ratios. Compared to Suite 1, these rocks also have low Sr (53 - 326 ppm, mean = 187 ppm), high Rb (40 - 365 ppm, mean = 222 ppm) and high Yb (0.44 – 1.36 ppm, mean = 0.82 ppm) contents. K/Rb ratios range between 103 and 466 (mean = 203) and are generally lower than in the suite 1 samples.

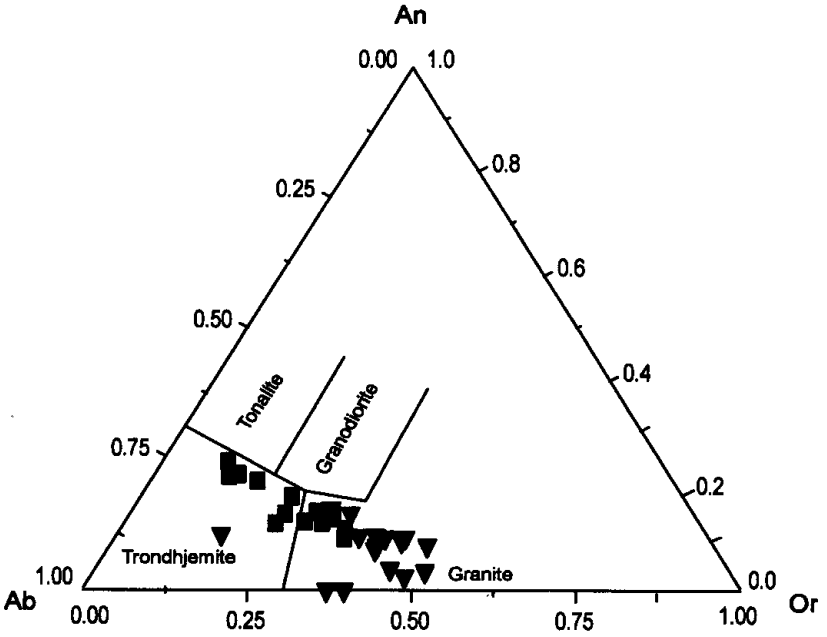

Figure 2: Classification of the SGB Suites 1 (filled triangles) and 2 (filled triangles) granitoids according to their molecular An-Ab-Or composition. Note the granitic to trondhjemitic character. The field boundaries are as defined by Barker (1979).

Suite 2 rocks generally display less steep chondrite-normalised REE patterns (Fig. 5). $(La/Yb)_N$ values range between 15 and 86 with a mean value of 44, significantly lower than the corresponding Suite 1 values. The rocks are characterised by higher concentrations of the HREE compared to Suite 1 samples as revealed by Yb_N values of between 2.1 and 6.5 (mean 3.90). On primitive mantle-normalised spidergrams, Suite 2 samples, like those of Suite 1 show relative depletion in Th, Nb and Ti, together with P and Y whereas Zr and Hf are enriched relative to adjacent elements. Unlike Suite 1 samples, however, Suite 2 rocks are depleted in Sr relative to Ce and Nd (Fig. 6).

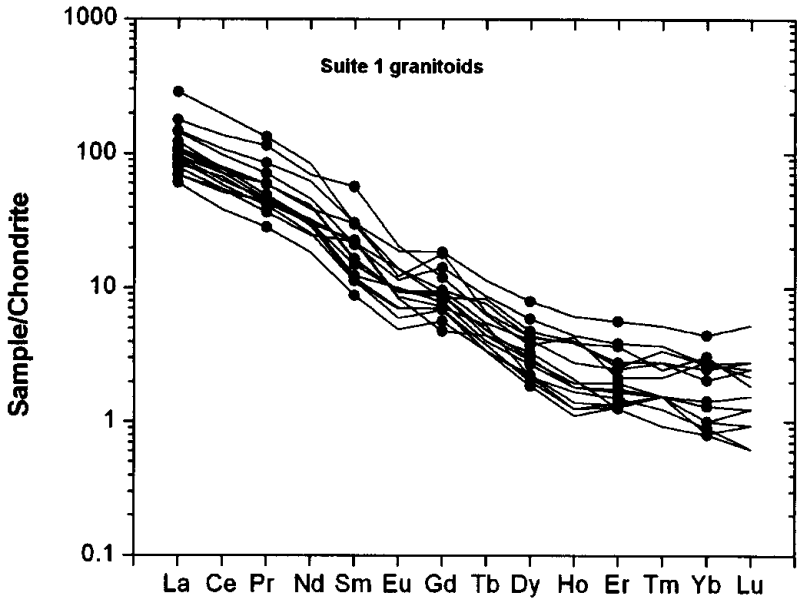

Figure 3: Chondrite-normalised REE diagrams for the Suite 1 granitoids.

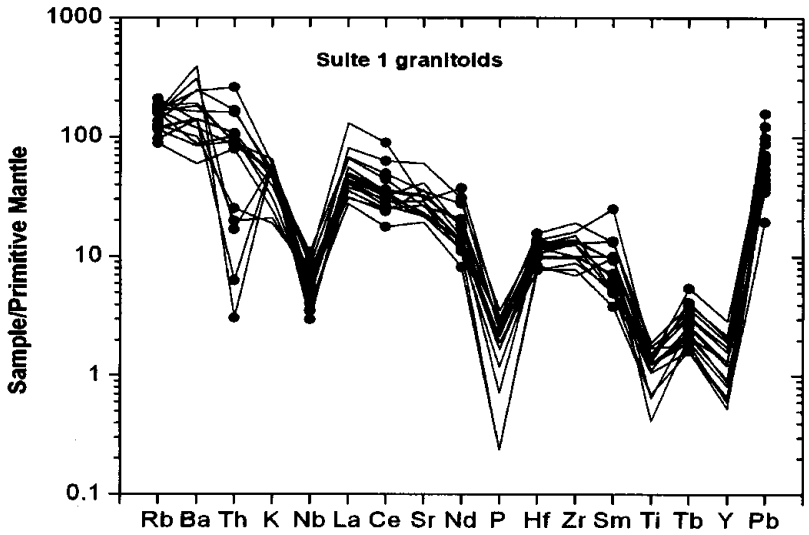

Figure 4: Primitive Mantle-normalised spidergrams for the Suite 1 granitoids.

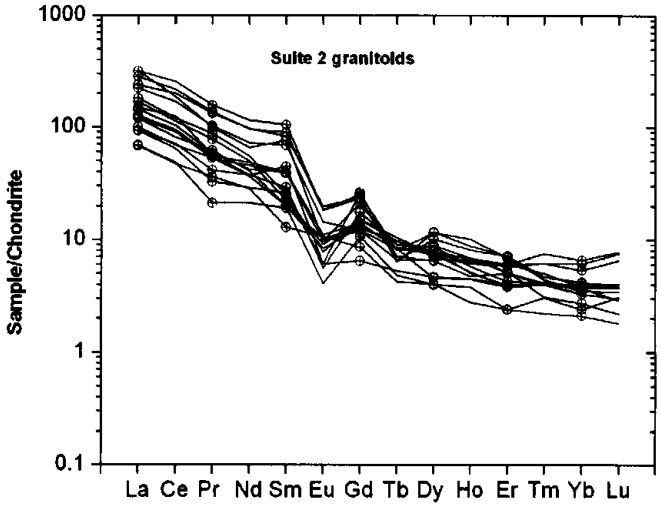

Figure 5: Chondrite-normalised REE diagrams for the Suite 2 granitoids.

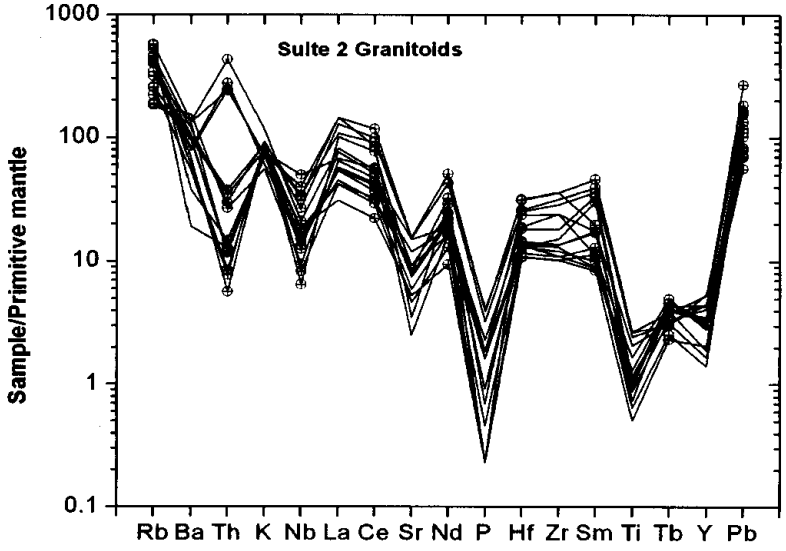

Figure 6: Primitive Mantle-normalised spidergrams for the Suite 2 granitoids.

Emplacement and crustal formation ages

Nd isotopic data from 15 samples (10 from Suite 1 and 5 from Suite 2 granitoids) are presented in Table 2. Also shown in Table 2 are Nd depleted mantle mean crustal residence ages (T_{DM}) calculated assuming a linear evolution model for the mantle together with present day $^{143}Nd/^{144}Nd$ and $^{147}Sm/^{144}Nd$ mantle values of 0.513114 and 0.222, respectively (Michard *et al.* 1985). The T_{DM} ages range between 2470 and 2710 Ma with a mean of 2610 ± 35 Ma (2 SE). Nine samples (R15, R16, R17, R18, R19, R20 from Suite 1; R23, R24 and R63 from Suite 2), however, define a more restricted T_{DM} range, between 2610 and 2650 Ma, with a mean of 2632 ± 11 Ma. The mean T_{DM} age

of 2610 ± 35 Ma is indistinguishable from the Rb-Sr isochron age of 2620 ± 30 Ma ($(^{87}Sr/^{86}Sr)_{initial}$ = 0.7017 ± 4) previously obtained by Bell and Dodson (1981) for granitoids from the Geita area. Calculated initial ε_{Nd} values assuming a 2620 Ma emplacement age range between –0.66 and 3.58 but cluster between 0.28 and 0.84 (mean = 0.53 ± 0.11) for the samples yielding a tight cluster in T_{DM} ages. The remaining 6 samples can be divided into two groups: the two Suite 1 samples, R2 and R21, yield negative ε_{Nd} values (-0.66 and –0.80, respectively) and T_{DM} ages of 2708 and 2703 Ma. The latter are slightly older than the ~2630 Ma age of the 9 samples, which define a tight T_{DM} cluster. The remaining four samples (R14, R22, 25 and R26) yield ε_{Nd} values of between 1.69 and 3.58 and T_{DM} ages of between 2470 and 2570 Ma, younger than the samples with mean crustal residence ages of ~2630 Ma.

The similarity of the emplacement age to the mean crustal residence ages indicates that these granitoids represent late Archaean juvenile additions to the continental crust. The juvenile nature of the granitoids is also consistent with the low initial $^{87}Sr/^{86}Sr$ ratio (0.7017 ± 4). Samples R2 and R21 which yield negative ε_{Nd} values (-0.66 and –0.80 respectively) and slightly older T_{DM} ages (2708 and 2703 Ma) may indicate slight contamination of ~2640 Ma juvenile granitoid melt by older crustal material. On the other hand, the four samples (R14, R22, 25 and R26) which yield ε_{Nd} values between 1.69 and 3.58 and T_{DM} ages of between 2470 and 2570 Ma may indicate derivation from a slightly younger protolith. Samples R14 and R26 belong to geochemical Suite 1 whereas samples R22 and R25 belong to Suite 2 suggesting that there is no significant difference in the mean crustal residence ages of the two suites. This is also true for the nine samples that define a tighter cluster in T_{DM} ages.

Table 2: Sm-Nd isotopic data for granitoids from the Sukumaland Greenstone Belt

Sample	Classification	Nd (ppm)	Sm (ppm)	$^{143}Nd/^{144}Nd$	$^{147}Sm/^{144}Nd$	T_{DM}	ε(2.62)
R 2	G3 , Suite 1	36.07	5.95	0.510921 ± 7	0.099	2708	-0.66
R 14	G3 , Suite 1	24.4	3.26	0.510810 ± 6	0.08	2467	3.58
R 15	G3 , Suite 1	32.81	5.12	0.510875 ± 6	0.094	2648	0.28
R 16	G3 , Suite 1	44.67	5.44	0.510531 ± 6	0.073	2634	0.48
R 17	G3 , Suite 1	15.88	2.14	0.510658 ± 7	0.081	2640	0.38
R 18	G3 , Suite 1	18.51	2.24	0.510527 ± 7	0.073	2627	0.62
R 19	G3 , Suite 1	12	1.67	0.510729 ± 7	0.084	2621	0.74
R 20	G3 , Suite 1	13.86	2.11	0.510845 ± 7	0.092	2638	0.44
R 21	G3 , Suite 1	21.07	2.76	0.510560 ± 6	0.079	2703	-0.8
R 26	G3 , Suite 1	27.27	4.6	0.511154 ± 6	0.101	2466	3.17
R 22	G4, Suite 2	24.45	3.64	0.510874 ± 7	0.09	2566	1.69
R 23	G4, Suite 2	16.08	2.83	0.511115 ± 6	0.106	2614	0.84
R 24	G4, Suite 2	24.87	4.11	0.510990 ± 7	0.1	2630	0.6
R 25	G5, Suite 2	31.6	4.69	0.510878 ± 5	0.089	2554	1.89
R 63	G4 , Suite 2	14.46	2.22	0.510857 ± 7	0.092	2641	0.4

DISCUSSION

The relatively low Rb contents even at high SiO_2 values suggest that both Suite 1 and Suite 2 rocks crystallised from little differentiated magmas. Granitoids with a major element composition similar to the Geita rocks can be generated by partial melting of hydrated basalt which has been transformed into eclogite or garnet amphibolite (Arth and Hanson 1972, Drummond and Defant 1990, Rapp *et al.* 1991, Martin 1999, Smithies 2000). Experimental studies further indicate that partial melting of hydrated low K-tholeiite under water undersaturated conditions can produce high Al_2O_3 granitoids, similar to the Geita rocks, over a wide range of PT conditions leaving a hornblende and garnet-rich residue (Wolf and Wyllie 1989, Rapp *et al.* 1991, Rapp and Watson 1995). The Al_2O_3 rich nature of the samples can, therefore, be used to infer their formation by partial melting of hydrated basalt at pressures sufficiently high to stabilise hornblende as a residue phase. Melting in the presence of hornblende as a residue phase can also explain the low to moderate K/Rb ratios (137 – 360) because of the greater affinity of hornblende for K relative to Rb (Arth and Hanson 1972). In the absence of hornblende, melting would produce a liquid which is highly enriched in K resulting in granitoids with high K/Rb ratios (>550 - 650, Drummond and Defant 1990).

The highly fractionated REE patterns as well as the low Y contents further indicate the presence of residual garnet in the sources of both Suites 1 and 2 (Martin 1999). The lower Y content of Suite 1 samples relative to that of Suite 2 most likely reflects relatively higher modal abundance of garnet in its source. The high Sr contents of Suite 1 rocks (mean = 616 ppm), high Ba (mean = 1079 ppm), coupled with the lack of significant Eu anomalies (mean Eu* = 0.8) suggests that plagioclase fractionation was not an important process. This suggests an origin of the Suite 1 granitoids by partial melting of hydrated basalt in the absence of plagioclase as a residue phase. This suggests formation of the granitoids by partial melting of a hornblende eclogite rather than an amphibolite.

In contrast to Suite 1 rocks, the Suite 2 rocks are characterised by lower Sr (mean = 174 ppm) and Ba (mean = 587 ppm) contents as well as prominent negative Eu anomalies (mean = 0.5) suggesting significant fractionation of plagioclase during their petrogenesis. Given the relatively low Rb contents even at high SiO_2 values indicative of crystallisation of the rocks from little differentiated magmas, this suggests an origin of the Suite 2 granitoids by partial melting of a source in which plagioclase was a residual phase. This further indicates that the rocks were formed by partial melting of garnet amphibolite rather than hornblende eclogite. As amphibolites tend to have lower modal abundances of garnet than eclogites, formation by partial melting of amphibolite also explains the relatively higher abundance of Y and other HREE in Suite 2 samples.

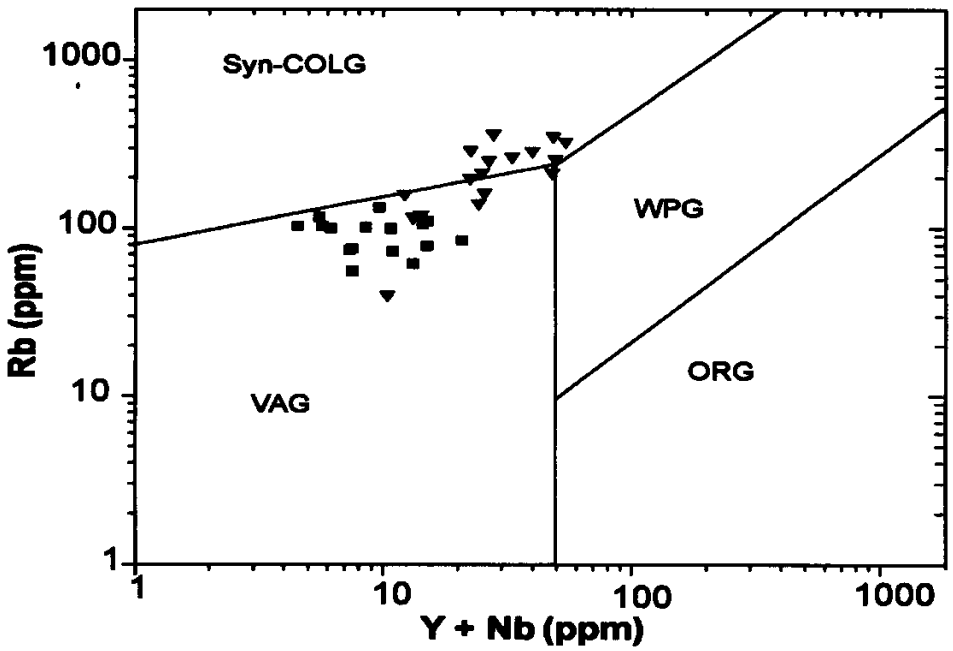

Figure 7: Rb *versus* Y + Nb discrimination diagrams (After Pearce *et al.* 1984) for the SGB Suites 1 (filled squares) and Suite 2 (filled triangles) granitoids.

Geodynamic setting of melting

The samples are plotted on the Rb *versus* Y+Nb tectonic discrimination diagram of Pearce *et al.* (1984) on Fig. 7. All Suite 1 samples plot as volcanic arc granites whereas most of the Suite 2 samples plot as syn-collisional granites with a few plotting in the volcanic arc field. This, together with the prominent negative Nb and Ti anomalies which are characteristic of both Suites 1 and 2 suggest a convergent margin setting for the granitic magmatism in the Sukumaland Greenstone Belt. The similarity of the mean crustal residence ages of the two suites of granitoids further indicates that the magmatism occurred at more or less the same time with the main geochemical difference between Suite 1 and Suite 2 being the depth of melting. To explain the convergent margin setting as well as the over all geochemical characteristics of the rocks, it is proposed that the two suites formed by partial melting at the base of a thickened sub-arc basaltic crust composed of the Nyanzian tholeiites. Melting to form the Suite 1 granitoids occurred at greater depth in the eclogite stability field whereas Suite 2 samples formed by melting at shallower depth in the garnet amphibolite stability field.

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