

A-type granites: geochemical characteristics, discrimination and petrogenesis*

Joseph B. Whalen¹, Kenneth L. Currie¹, and Bruce W. Chappell²

¹ Geological Survey of Canada, 601 Booth Street, Ottawa, K1A 0E8 Canada

² Department of Geology, The Australian National University, G.P.O. Box 4, Canberra, A.C.T. 2600, Australia

Abstract. New analyses of 131 samples of A-type (alkaline or anorogenic) granites substantiate previously recognized chemical features, namely high SiO₂, Na₂O + K₂O, Fe/Mg, Ga/Al, Zr, Nb, Ga, Y and Ce, and low CaO and Sr. Good discrimination can be obtained between A-type granites and most orogenic granites (M-, I and S-types) on plots employing Ga/Al, various major element ratios and Y, Ce, Nb and Zr. These discrimination diagrams are thought to be relatively insensitive to moderate degrees of alteration. A-type granites generally do not exhibit evidence of being strongly differentiated, and within individual suites can show a transition from strongly alkaline varieties toward subalkaline compositions. Highly fractionated, felsic I- and S-type granites can have Ga/Al ratios and some major and trace element values which overlap those of typical A-type granites.

A-type granites probably result mainly from partial melting of F and/or Cl enriched dry, granulitic residue remaining in the lower crust after extraction of an orogenic granite. Such melts are only moderately and locally modified by metasomatism or crystal fractionation. A-type melts occurred world-wide throughout geological time in a variety of tectonic settings and do not necessarily indicate an anorogenic or rifting environment.

Introduction

Granitoid rocks may be divided into those generated during evolution of fold belts (orogenic) and those associated with uplift and major strike-slip faulting (anorogenic). Anorogenic or A-type granites, first defined by Loiselle and Wones (1979), and discussed by Collins et al. (1982), have recently received much attention (Anderson 1983; Anderson and Thomas 1985; Whalen and Currie 1984; Whalen 1986a; Jackson et al. 1984; Harris and Marriner 1980; Collier 1982; Imeokparia 1985) because of their economic potential and tectonic significance. We further document and substantiate the chemical characteristics of A-type granites based on new chemical analyses of 131 samples and 17 recently published analyses (Collins et al. 1982). We also present trace element plots which facilitate the identification of A-type granites, and discuss their petrogenesis and tectonic significance.

Offprint requests to: J.B. Whalen

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Granite classifications and A-type granites

Chappell and White (1974) proposed a genetic subdivision of granitic rocks into those extracted from sedimentary protoliths (S-types) and those extracted from igneous protoliths (I-types). Subgroups of I-type granites include those derived from recycled, dehydrated continental crust (A-type: Loiselle and Wones 1979; Collins et al. 1982) and those derived directly from melting of subducted oceanic crust or overlying mantle (M-type: White 1979; Pitcher 1983; Whalen 1985). In felsic granites (SiO₂ > 74 wt.%), the restite component (refractory source residue) is minimal and the chemical and mineralogical composition of different granite types converge. Such granites are difficult to classify because the ability of the I- and S-type classification to distinguish different granite types is thought, in part, to reflect a signature given to the magma by a restite component (White and Chappell 1977).

A quite different type of granite classification can be constructed by statistical analyses of large numbers of chemical analyses of granites from well defined tectonic settings (Pearce et al. 1984; Brown et al. 1984). This approach leads to discrimination diagrams which can be utilized in identifying the tectonic settings of other granite suites. As applied to mafic volcanic rocks (Pearce and Cann 1973; Floyd and Winchester 1975), this approach has gained quite wide acceptance, but its application to granitoid rocks is still at an early stage of development. Pearce et al. (1984) have indicated that they can, on the basis of Nb, Y, Ta, Yb and Rb trace element data, discriminate between syn-collision, volcanic-arc, ocean ridge and within-plate type granites. Brown et al. (1984), using a different data set, group granitoid rocks into primitive, calcic arc granitoids, normal calc-alkaline continental arc granitoids, mature alkali-calcic arc granitoids and back-arc/anorogenic alkaline granitoids. We show that both the chemical/mineralogical classification pioneered by Chappell and White (1974) and discrimination classifications based on trace elements produce a well-defined group corresponding to A-type granites.

A-type granites exhibit chemical analyses characterized by high SiO₂, Na₂O + K₂O, Fe/Mg, F, Zr, Nb, Ga, Sn, Y, and REE (except Eu) contents and low CaO, Ba, and Sr (Loiselle and Wones 1979; Collins et al. 1982; White and Chappell 1983). Mineralogically these granites contain annite-rich biotite and/or alkali amphiboles and commonly sodic pyroxene. Mafic minerals generally crystallized late

in the solidification history, typically occurring as interstitial grains or clots. The feldspar is mainly alkali feldspar, commonly albite-orthoclase solid solutions or intergrowths. Micrographic intergrowths of quartz and alkali feldspars are very common. Textural evidence, which is supported by experimental work (Clemens et al. 1986), suggests that most A-type granites formed from relatively high temperature, water undersaturated, completely molten (i.e. restite-free) magmas. A-type granites characteristically form part of highly contrasting mafic-salic associations with evidence for mixing between the two magma types (Whalen and Currie 1984). Plutons were emplaced at high level, and volcanic equivalents of the plutonic rocks are common. A-type granites exhibit mineralization by Sn, Mo, Bi, Nb, W, Ta, and F (Collins et al. 1982; Pitcher 1983). A-type suites are currently considered to represent the final plutonic event in both orogenic belts and the rift-related anorogenic magmatism of shield areas. Such granites occur world-wide and throughout geologic time, at least from Proterozoic to Recent.

Geochemistry of A-type granites

This paper is based on 148 analyses of A-type granites compared to 1569 analyses of I- and S-type granites from the Lachlan Fold Belt of Australia (White and Chappell 1983 and unpublished data) and 17 analyses of M-type granites from New Britain (Whalen 1985). All trace element analyses were carried out by B.W. Chappell in the Department of Geology, The Australian National University (see Appendix). Of the A-type analyses, 131 are new. These consist of 72 samples from the Topsails igneous terrane, western Newfoundland (Whalen and Currie 1983a, b, 1984; Whalen et al. in press), two samples from the Seal Island Bight complex, northern Newfoundland (Taylor 1979), one sample from the Saint Lawrence granite, southeastern Newfoundland (Teng and Strong 1976), 5 samples from the Welsford complex, southern New Brunswick (Jackson 1968), 15 samples from the Evisa Complex of Corsica (Bonin et al. 1978), 11 samples from the Shira complex, one of the most peralkaline and oldest (200 Ma) of the Younger Granite complexes in Nigeria (Bowden 1982, pers. com.) and 25 samples from nine recently recognized A-type granite suites of the Lachlan Fold Belt, S.E. Australia. In addition, we have used 17 published analyses from two other A-type granite suites of the Lachlan Fold Belt (Collins et al. 1982). We compare these 148 A-type granite analyses with fractionated felsic granites: the possibly I-type Ackley granite, eastern Newfoundland (6 analyses) (Whalen 1983) and the S-type Sandy Cape granite, western Tasmania (5 analyses). All the raw analytical data and the chemical plots in this paper are included in Whalen et al. (1987), copies of which are available from the senior author. By contrasting A-type granites with fractionated granites of other types and average M-, I- and S-type granite compositions, we aim to expand and clarify the chemical characterization of A-type granites outlined by Collins et al. (1982).

Means plus standard deviation data for M-, I- and S-type granites are presented in Table 1. A-type granites tend to have higher SiO₂ than the other granite types. In granitic rocks, the content of many elements is directly correlated with SiO₂ content. Therefore to aid comparisons, we have included means for the most felsic I- and S-type granites in Table 1. Comparison between I-, S- and A-type granite

averages indicates that for a given SiO₂ content, A-type granites contain higher abundances of Fe and K + Na, and highly charged cations such as Ga, Nb, Y, Zr and REE and also Zn and lower abundances of Al, Mg, Ca and V. These granites characteristically have enriched, relatively flat to somewhat HREE depleted (Ce/Yb_N = 2.2 to 5.5) chondrite normalized REE patterns with significant negative Eu anomalies (Hermes et al. 1981; Collins et al. 1982; Jackson et al. 1984; Whalen unpublished data). High Ga/Al values appear to be particularly diagnostic of A-type granites. Plots of this ratio against major (Fig. 1) and trace (Fig. 2) element data readily distinguish A-type granites from M-, I- and S-type granite compositions, although a plot of agpaite index against Ga/Al (Fig. 2f) indicates that this distinctive character is most pronounced for strongly alkaline to peralkaline analyses and less so for subalkaline analyses. High quality Ga data are rare in the published literature, although Ga can be readily determined in silicate samples by X-ray fluorescence spectrometry with no significant interferences and a detection limit of 0.6 ppm (Norrish and Chappell 1977).

A-type granite suites in which peralkaline granites are rare or absent exhibit relatively little variation in Ga/Al, Zr, Nb, Ce, Y and Zn. For example, the Gabo and Mumbulla A-type suites of the Lachlan Fold Belt appear remarkably homogeneous (Collins et al. 1982) (see Fig. 2). Suites which contain peralkaline granites (Topsails, Welsford, Evisa and Shira) exhibit moderate to strong variations. The well documented Topsails igneous suite (Whalen and Currie 1983a, b, 1984; Whalen 1986b; Whalen et al. in press) exhibits a main intrusive phase of coarse-grained arfvedsonite-aegirine granite of Early Silurian age (analysis TB129 in Table 2) with which are associated contemporaneous, marginal, fine- to medium-grained intrusive phases varying from peralkaline, hypersolvus, amphibole +/–clinopyroxene granite through subsolvus, amphibole–biotite granite and biotite +/–amphibole granite (samples TB37, 69, 97 and 72 in Table 2). Associated syenites (samples TB124 and 68 in Table 2) and subvolcanic, peralkaline, quartz-K-feldspar porphyry intrusions (samples TB90 in Table 1) also occur. Hybrid intrusive rocks of intermediate composition, formed by mixing between granitic and basaltic magmas (Whalen and Currie 1984) have not been included in these plots. The more alkaline intrusive phases contain distinctly higher concentrations of Zr (Fig. 3), Nb, Ce, Y, Zn and Ga/Al, whereas biotite-bearing phases and many of the syenites exhibit a spectrum of values, the lower end of which approaches the values exhibited by Lachlan I- and S-type granites. In the granite classification based on zircon morphology (Pupin 1980), the A-type granites of the Topsails terrane fall in the alkaline and hyperalkaline syenites and granites field (Whalen et al. in press). A few samples, in the absence of associated more alkaline phases could be difficult to identify chemically as A-type granites.

The Evisa complex of Corsica shows similar subsolvus subalkaline and hypersolvus peralkaline trends (see Figs. 1 and 2, Table 2 and Bonin et al. 1978). This association of subalkaline and strongly alkaline phases shows the importance of considering the full compositional range of a granite suite, since peralkaline phases clearly demonstrate the A-type nature of the suite, despite the presence of ambiguous phases. Data for a suite of Proterozoic anorogenic granites from the Davis Inlet-Flowers Bay area of Labrador (Collerson 1982) exhibit a range in Ga/Al and Zr (Fig. 4)

Table 1. Average compositions of various granite types

No of samples	1 M-type 17		2 I-type 991		3 S-type 578		4 Felsic I-type 421	5 Felsic S-type 205	6 A-type 148	Range	
	\bar{x}	1 σ	\bar{x}	1 σ	\bar{x}	1 σ	\bar{x}	\bar{x}	\bar{x}	1 σ	
SiO ₂	67.24	4.34	69.17	4.47	70.27	2.83	73.39	73.39	73.81	3.25	(60.4 79.8)
TiO ₂	0.49	0.16	0.43	0.19	0.48	0.18	0.26	0.28	0.26	0.18	(0.04 1.25)
Al ₂ O ₃	15.18	1.12	14.33	1.06	14.10	0.70	13.43	13.45	12.40	1.40	(7.3 17.5)
Fe ₂ O ₃	1.94	0.77	1.04	0.60	0.56	0.37	0.60	0.36	1.24	1.13	(0.14 8.7)
FeO	2.35	1.02	2.29	1.12	2.87	1.09	1.32	1.73	1.58	1.07	(0.33 6.1)
MnO	0.11	0.04	0.07	0.03	0.06	0.03	0.05	0.04	0.06	0.04	(0.01 0.24)
MgO	1.73	1.68	1.42	1.00	1.42	0.76	0.55	0.58	0.20	0.24	(<0.01 1.6)
CaO	4.27	1.15	3.20	1.65	2.03	0.85	1.71	1.28	0.75	0.60	(0.08 3.7)
Na ₂ O	3.97	0.57	3.13	0.58	2.41	0.46	3.33	2.81	4.07	0.66	(2.8 6.1)
K ₂ O	1.26	0.41	3.40	0.92	3.96	0.64	4.13	4.56	4.65	0.49	(2.4 6.5)
P ₂ O ₅	0.09	0.03	0.11	0.06	0.15	0.05	0.07	0.14	0.04	0.06	(<0.01 0.46)
Trace elements (ppm)											
Ba	263	121	538	234	468	182	510	388	352	281	(2 1530)
Rb	17.5	4.5	151	62	217	89	194	277	169	76	(40 475)
Sr	282	108	247	178	120	42	143	81	48	52	(0.5 250)
Pb	5	2	19	8	27	5	23	28	24	15	(2–141)
Th	1.0	0.3	18	7	18	5	22	18	23	11	(<1 87)
U	0.4	0.2	4	3	4	3	5	6	5	3	(<1 23)
Zr	108	32	151	46	165	44	144	136	528	414	(82 3530)
Nb	1.3	0.4	11	4	12	4	12	13	37	37	(11 348)
Y	22	10	28	12	32	25	34	33	75	29	(9 190)
Ce	16	4	64	19	64	17	68	53	137	58	(18 560)
Sc	15	8	13	7	12	6	8	8	4	5	(<1 22)
V	72	49	60	43	56	30	22	23	6	10	(<1 79)
Ni	2	2	7	9	13	9	2	4	<1	1	(<1 11)
Cu	42	62	9	14	11	8	4	4	2	3	(<1 19)
Zn	56	29	49	19	62	20	35	44	120	101	(11 840)
Ga	15.0	1.5	16	2	17	2	16	17	24.6	6.0	(14.0 49.5)
K/Rb	598		187		151		177	137	229		
Rb/Sr	0.06		0.61		1.81		1.36	3.42	3.52		
Rb/Ba	0.07		0.28		0.46		0.38	0.71	0.48		
Ga/Al	1.87		2.1		2.28		2.25	2.39	3.75		
A.I.	0.52		0.62		0.59		0.74	0.71	0.95		

\bar{x} mean; 1 σ one standard deviation. 1 Samples with SiO₂ > 57%, Uasilau-Yau Yau complex, New Britain (Whalen 1985); 2 I-type granites with SiO₂ > 57 wt.%; 3 S-type granites; 4 Felsic I-type granites; 5 Felsic S-type granites; 6 A-type granites, this study. I- and S-type granite analyses from the Lachlan Fold Belt (B.W. Chappell, unpublished data)

and also Y, Nb and Zn values which almost equals that of our data base with relatively low values exhibited by the subsolvus and non-alkaline hypersolvus granite phases and high values by the peralkaline phases. Some of the subsolvus granites represent dykes, probably formed by volumetrically minor anatexis of host rocks at the contacts of an anorthosite massif (Hill 1982). Even excluding these samples, the suite as a whole clearly displays trends and values very similar to those in the Topsails suite. Representative analysis of subalkaline and peralkaline granite phases of the Younger Nigerian granites given by Imeokparia (1985) include Ga, Zr, Nb, Y and Zn data. These data exhibit relatively high Ga/Al values for subalkaline biotite granites and even higher values for peralkaline granites (Fig. 4), comparable to those obtained by us from the peralkaline Shira complex. We are uncertain whether Nigerian A-type granites are characterized by particularly high values of Ga/Al and highly charged cations, or whether analytical differences exist between our data and those of Imeokparia (1985).

Other data sets for A-type granites, though they lack Ga data, exhibit similarities to ours. Data for Zr, Nb, Ce, Y and Zn from Proterozoic A-type granites in Saudi Arabia give high values (Harris and Marriner 1980; Jackson et al. 1984), similar to those found by us. A summary paper by Anderson (1983) on North American anorogenic granites indicates high (Na₂O + K₂O), (Na₂O + K₂O)/CaO and FeO*/MgO values in these granites. Values for these ratios in our samples (Fig. 1) are similar to the representative analyses given by Anderson (1983), though our samples are mainly more alkaline. Anderson (1983) suggested that peralkaline granites of Proterozoic age were rare in North America, but a number of spectacular examples are now known [Lac Brisson (Currie 1985), Blachford Lake (Davidson 1982), Flowers Bay (Collerson 1982)]. Paleozoic New England A-type granites, which are restricted to the eastern "Avalon" terrane, exhibit high REE, Zr, Nb, Y and Zn values (Buma et al. 1971; Hermes et al. 1981; Hermes and Zartman 1985; Hermes pers. com.), similar to our A-type granite data.

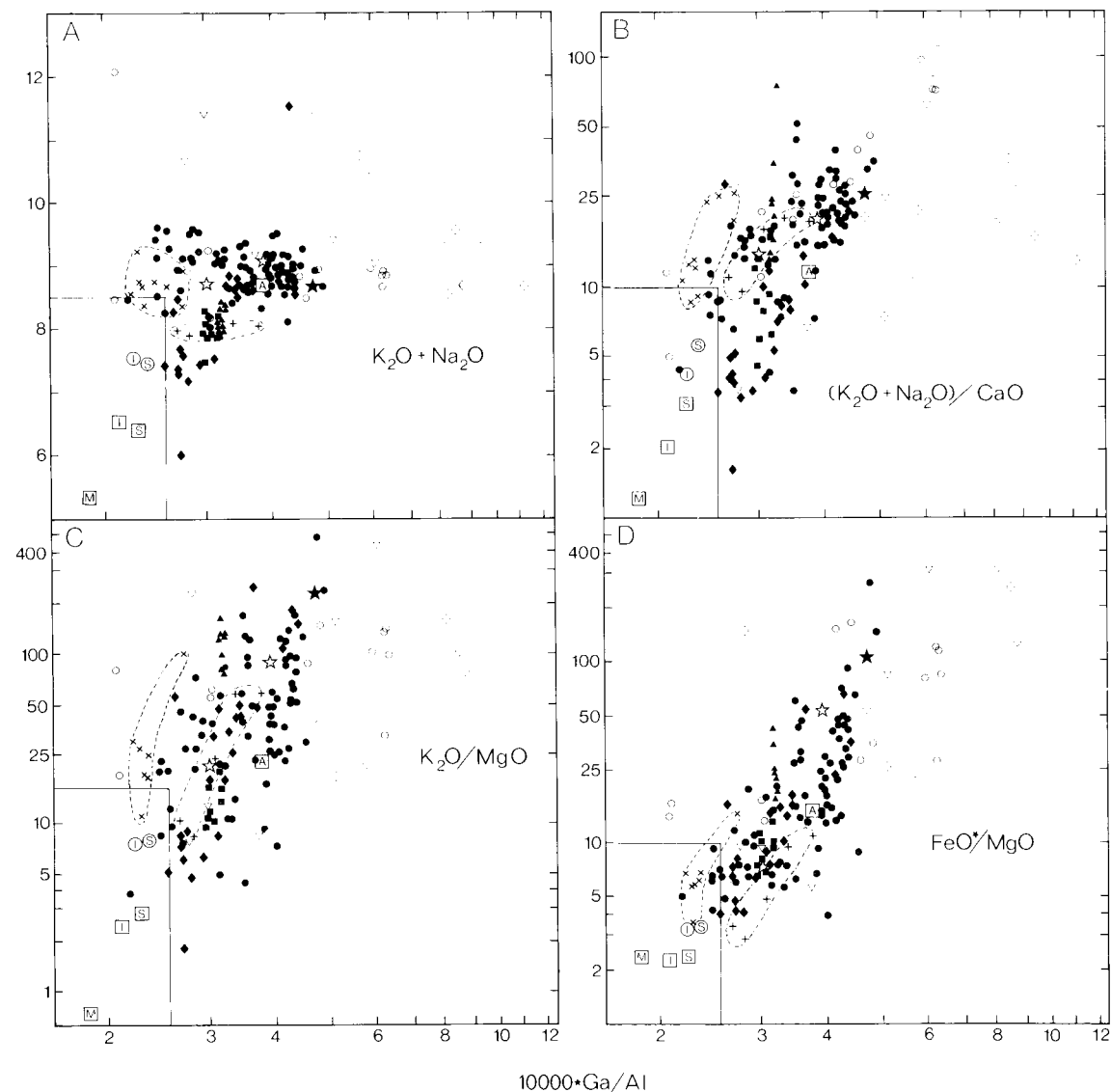


Fig. 1A–D. $10000 \cdot \text{Ga}/\text{Al}$ versus $(\text{K}_2\text{O} + \text{Na}_2\text{O})$, $(\text{K}_2\text{O} + \text{Na}_2\text{O})/\text{CaO}$, FeO^*/MgO and $\text{K}_2\text{O}/\text{MgO}$ plots of various A-type granites and also, for comparison purposes, the fields of two fractionated felsic granites (*dashed outlines*) and I-, S- and M-type granites (*rectangular boxes*) (see averages in Table 1). The coordinates of the latter fields are $X=2.6$, $Y=8.5$ (A) 10 (B), 16 (C) and 10 (D). Symbols used are: ● Topsails suite; ☆ Seal Island Bight granite; ★ St. Lawrence granite; ▽ Welsford complex; ◊ Shira complex, Nigeria; ○ Evisa complex, Corsica; × Ackley granite, fractionated I-type (?) granite, Lachlan Fold Belt; + Sandy Cape granite, fractionated S-type granite; ▲ Mumbulla suite; ■ Gabo suite; ◆ Other Lachlan A-type granites; □ I-type granite average; ⊞ S-type granite average; ⊙ felsic I-type granite average; ⊚ felsic S-type granite average; ⊠ A-type granite average, this study; ⊞ M-type granite average from New Britain, P.N.G.

Chemical discrimination of A-type granites

We suggest that by utilizing plots of Ga/Al versus certain major and trace elements (Figs. 1 and 2), with the fields formed by M-, I- and S-type granites, it is possible to clearly distinguish between A-type granites and these other granite types. If Ga data are not available, plots of $\text{Zr} + \text{Nb} + \text{Ce} + \text{Y}$ versus major element ratios (Fig. 5) such, as FeO^*/MgO and $(\text{K}_2\text{O} + \text{Na}_2\text{O})/\text{CaO}$, are almost equally effective in identifying A-type granites. The fields in Figs. 1, 2 and 5 generally include two standard deviations from the M-, I- and S-type granite averages (see Table 1). Discrimination is best for more alkaline granite compositions. Although subalkaline compositions in some suites tend to give values

which overlap with compositions of other granite types, the presence of more alkaline compositions in many suites clearly identify them as A-type (e.g., Topsails, Welsford and Evisa). As most of these diagrams employ elements (Al, Fe, Mg, Ga, Zr, Nb, Ce and Y) which have been found to be relatively insensitive to low to moderate degrees of alteration (Pearce and Cann 1973; Floyd and Winchester 1975; Bourne 1986), they should be equally effective for both fresh and altered granitic rocks.

There is a problem with the classification of felsic non-peralkaline granites for they could represent highly fractionated I- or S-type granites. In Table 2 (suites 7 and 8), variously fractionated compositions from the I-type (?) Ackley and S-type Sandy Cape granites are presented. These highly

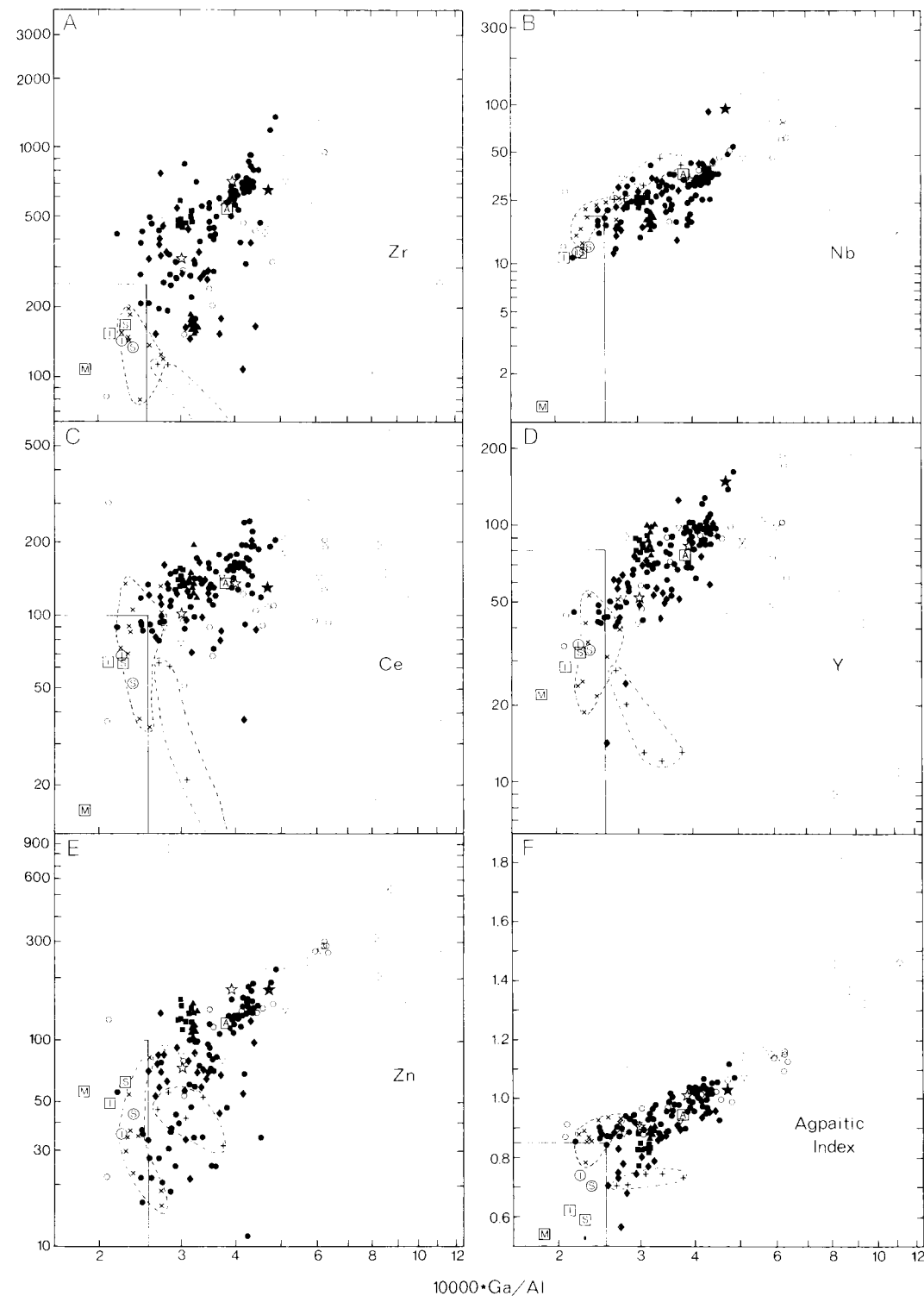


Fig. 2A–F. $10000 \cdot \text{Ga}/\text{Al}$ versus Zr, Nb, Ce, Y, Zn and agpaitic index plots of various A-type granites and also, for comparison purposes, the fields of two fractionated felsic granites (*dashed outlines*) and I-, S- and M-type granites (*rectangular boxes*). The coordinates of the latter fields are $X=2.6$, $Y=250$ (A), 20 (B), 100 (C), 80 (D), 100 (E) and 0.85 (F). Symbols as in Fig. 1

fractionated felsic granites have geochemical characteristics which overlap those for typical A-type granites in Figs. 1, 2 and 5. Trace element variations from these suites, such as colinear increasing Rb, Rb/Sr, Rb/Ba, Ga/Al and Nb with decreasing Ba, Sr, Zr, Y and Ce indicate that their similarities to A-type granites are the product of extensive

crystal fractionation (see Whalen 1983). In contrast, most A-type granites do not exhibit evidence of strong fractionation. High contents of highly charged cations in A-type granites are not necessarily accompanied by high Rb/Sr or Rb/Ba values (see Tables 1 and 2). There may, however, be considerable variation in these ratios within individual

Table 2. Representative analyses of A-type and fractionated other type granites

Suite unit sample	1 A TB124	1 A TB68	1 B TB37	1 B TB69	1 C TB97	1 D TB72	1 E TB129	1 F TB90	2 A TB44	3 A TB139	4 A 74100	4 B 7483	4 C 7478	5 A SH125
SiO ₂	67.15	71.90	76.15	74.25	74.45	76.85	75.45	76.20	73.75	76.35	63.40	70.77	74.77	64.00
TiO ₂	0.98	0.46	0.09	0.24	0.24	0.15	0.23	0.18	0.22	0.13	0.69	0.38	0.16	0.68
Al ₂ O ₃	13.55	13.75	12.55	13.30	13.10	11.55	11.95	10.75	12.20	11.10	16.90	13.33	10.55	13.70
Fe ₂ O ₃	1.77	1.54	0.16	0.57	0.56	1.41	0.59	1.72	0.92	0.98	1.60	0.88	1.33	3.20
FeO	4.05	1.00	1.05	0.95	1.20	0.80	1.80	1.30	1.90	1.30	3.10	2.25	2.15	4.50
MnO	0.14	0.05	0.02	0.02	0.05	0.02	0.06	0.07	0.09	0.06	0.14	0.06	0.06	0.23
MgO	0.92	0.58	0.06	0.20	0.23	0.03	0.08	0.02	0.05	0.02	0.50	0.52	0.01	0.28
CaO	2.49	1.22	0.50	0.67	0.70	0.31	0.49	0.25	0.44	0.33	1.82	1.32	0.14	1.52
Na ₂ O	4.74	4.32	4.17	3.72	4.20	4.00	4.11	3.96	4.52	3.94	5.65	4.35	4.37	6.10
K ₂ O	3.88	4.73	4.77	5.28	4.80	3.99	4.61	4.58	4.42	4.64	5.74	4.46	4.53	5.18
P ₂ O ₅	0.26	0.09	ND	0.02	0.03	ND	0.02	ND	0.01	ND	0.13	0.06	ND	0.14
S	0.03	0.01	0.01	0.01	0.01	ND	ND	0.02	0.06	0.02	ND	ND	ND	0.02
CL	0.04	0.02	0.02	0.06	ND	0.03	0.02	0.01	0.03	0.04	0.01	0.04	0.04	0.02
F	0.06	0.06	0.19	0.09	0.06	0.04	0.06	0.07	0.08	0.22	0.03	0.11	0.18	0.08
H ₂ O	0.60	0.60	0.40	0.45	0.40	0.35	0.40	0.30	0.40	0.40	0.60	0.50	0.50	0.50
CO ₂	0.10	0.05	0.10	0.10	0.05	0.20	0.20	0.05	0.15	0.20	0.20	0.05	0.20	0.10
rest	0.19	0.18	0.10	0.13	0.16	0.20	0.21	0.30	0.23	0.21	0.16	0.20	0.32	0.29
Total	100.95	100.56	100.34	100.06	100.24	99.93	100.28	99.78	99.47	99.94	100.67	99.28	99.31	100.54
Trace Elements (ppm)														
Ba	410	550	26	340	530	455	575	14	615	34	400	230	14	610
Rb	74	150	301	174	117	103	75	193	118	311	60	188	319	82
Sr	150	87	4.5	38.0	43.0	20.0	13.5	3.0	11.5	7.0	67	62	2.0	41.0
Pb	14	19	32	14	17	4	13	37	17	29	7	18	32	17
Th	9.5	26.5	32.0	31.5	21.0	20.5	9.5	31.0	13.0	37.0	3.5	31.5	40.0	14.0
U	3.0	5.5	10.0	6.0	4.0	5.5	2.5	8.0	3.5	11.0	1.5	5.0	10.5	3.5
Zr	462	369	175	251	301	630	630	1340	675	655	465	600	1370	890
Nb	21	18	41	18	24	39	18	54	33	97	32	48	109	114
Y	60	48	77	47	67	125	67	159	83	149	42	99	100	82
Ce	112	89	96	91	139	169	139	200	135	131	78	146	147	206
Sc	9	5	1	3	2	ND	ND	ND	1	ND	8	4	ND	5
V	43	23	ND	6	7	ND	1	ND	ND	ND	4	19	ND	7
Mn	900	345	175	190	320	165	445	440	655	470	1050	475	505	1610
Ni	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	2	ND
Cu	5	3	ND	ND	ND	ND	1	2	ND	3	6	6	2	5
Zn	116	35	33	20	58	11	107	215	173	181	86	81	281	231
Ga	25.0	18.0	21.5	19.5	22.5	26.0	25.0	28.0	25.5	28.0	27.0	26.5	34.5	37.0
K/Rb	435	262	132	252	341	322	510	197	311	124	794	197	118	524
Rb/Sr	0.5	1.7	66.9	4.6	2.7	5.2	5.6	64.3	10.3	44.4	0.9	3.0	159.5	2.0
Rb/Ba	0.2	0.3	11.6	0.5	0.2	0.2	0.1	13.8	0.2	9.1	0.2	0.8	22.8	0.1
Ga/Al	3.49	2.47	3.24	2.77	3.25	4.25	3.95	4.92	3.95	4.77	3.02	3.76	6.18	5.10
A.I.	0.89	0.89	0.96	0.89	0.92	0.94	0.98	1.07	1.00	1.04	0.92	0.90	1.15	1.14

A-type suites. For example, the Topsails igneous suite varies in Rb/Sr and Rb/Ba from 0.45 to 70 and 0.07 to 13.8, respectively. Such variations suggest feldspar fractionation, which is supported by the marked negative Eu anomalies of these granites. A plot of Rb/Ba versus Zr+Ce+Y (Fig. 6) for the Ackley, Sandy Cape and Topsails suites depicts these differences in trace element characteristics between fractionated other types and A-type granites. A strong negative trend is exhibited by the fractionated granites, whereas in the Topsails suite there is no apparent relationship between Rb/Ba and Zr+Ce+Y. Probably as the result of the fractionation of accessory phases, plots of Zr+Nb+Ce+Y versus major element ratios (Fig. 5) appear to be capable of discriminating between unfractionated M-, I- and S-type granites, fractionated granites and A-type granites.

Discrimination of fractionated granites from A-type granites may be facilitated by recognizing the relative volumes of different granite types with which these granites are associated. In the case of the Ackley granite, the more evolved granite forms less than 30% of the outcrop area of a large (5,400 km²), composite, felsic pluton. The other phases are K-feldspar megacrystic biotite granites which clearly are not A-type. Field and geochemical evidence suggests that the evolved phase may have formed by crystal fractionation near the roof of this I-type pluton (Whalen 1983). By contrast, in the Topsails suite, the largest proportion of the suite is alkaline to peralkaline with the less alkaline phases (see Fig. 3b) forming less than 20% of the suite. The correct classification of felsic granites, such as the Ackley granite, is particularly important, for such granites are often the hosts or progenitors to significant Mo and Sn

5 B SH14	5 C SH124	5 D SH130	6 A E29	6 B E49	6 C E61	6 D E224	6 E E42	6 F E4963	6 G E4966	7 A JW156	7 B AC'D98	8 A LFB1753	8 B LFB1757	9 Aav
69.10	71.50	75.60	74.50	76.30	76.90	60.40	76.06	76.36	75.23	73.58	77.65	72.17	73.72	73.39
0.46	0.31	0.08	0.16	0.10	0.06	0.55	0.07	0.11	0.11	0.30	0.05	0.31	0.05	0.30
12.80	12.50	9.60	12.60	12.10	12.80	17.50	11.89	11.50	10.40	12.98	12.14	14.57	14.79	12.88
2.30	3.40	2.60	0.60	0.50	0.40	1.30	0.45	1.50	3.03	0.84	0.23	0.31	0.17	0.90
3.50	0.60	1.60	1.10	0.50	0.50	4.40	0.91	0.34	0.92	0.79	0.20	1.43	0.52	1.66
0.14	0.09	0.06	0.04	0.02	0.06	0.18	0.03	0.03	0.04	0.07	0.02	0.04	0.05	0.06
0.23	ND	ND	0.09	0.07	0.06	0.33	0.02	ND	0.03	0.25	ND	0.58	0.07	0.30
0.95	0.48	0.56	0.81	0.37	0.72	2.34	0.26	0.30	0.12	0.64	0.34	0.82	0.40	1.07
6.00	5.50	4.80	4.10	3.60	3.60	5.50	4.15	4.22	4.52	3.64	3.70	3.17	4.00	3.49
4.78	4.88	4.42	5.09	4.44	4.89	6.49	4.69	4.51	4.29	4.88	4.93	4.74	4.11	4.61
0.07	0.03	0.04	0.03	0.02	0.03	0.12	ND	ND	ND	0.07	0.01	0.27	0.42	0.08
0.01	0.01	0.02	0.01	0.02	0.02	0.03	0.02	ND	ND	ND	0.05	ND	ND	ND
0.01	0.05	ND	0.01	0.01	0.02	0.01	0.01	NA	NA	NA	NA	NA	NA	NA
0.05	0.10	0.06	0.14	0.03	0.04	0.01	0.06	NA	NA	NA	NA	NA	NA	NA
0.40	0.40	0.40	0.60	1.00	0.60	0.70	0.60	0.14	0.03	1.52	0.57	1.16	0.93	0.82
ND	ND	0.10	0.10	0.70	0.10	0.10	ND	NA	NA	ND	0.18	0.13	0.41	0.17
0.29	0.16	0.17	0.12	0.10	0.08	0.45	0.09	0.14	0.26	0.15	0.10	0.13	0.13	0.16
101.09	100.01	100.11	100.10	99.88	100.88	100.41	99.31	99.15	98.98	99.71	100.17	99.83	99.77	99.89
375	68	38	125	82	44	1530	4	12	6	365	30	150	2	546
145	126	155	211	246	317	71	162	257	475	215	312	478	945	188
43.5	6.5	4.0	24.5	18.0	15.0	83	0.5	2.5	10.0	78	11.5	57	14.5	97
36	20	12	24	26	30	15	13	32	55	20	41	28	18	27
25.0	12.0	8.0	23.5	48.0	35.0	9.5	17.0	27.0	73.0	27.2	66.0	24.5	3.4	24
3.5	2.5	1.5	6.5	9.5	10.5	2.0	4.5	9.4	15.6	5.0	18.4	6.8	21.0	5
865	555	710	293	154	82	1420	207	441	1751	200	138	112	27	325
154	77	54	23	26	13	29	19	44	84	23	25	27.5	47.0	26
107	48	42	59	48	34	45	73	94	174	42	31	20	12	71
297	131	121	96	52	37	295	69	106	194	100	35	62	10	131
3	ND	ND	2	ND	2	16	ND	ND	ND	5	2	NA	NA	12
3	ND	ND	4	3	ND	2	ND	ND	ND	11	ND	14	ND	9
1040	680	4090	345	120	470	1370	240	230	330	580	170	320	395	430
ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	1	ND	ND	2	2
2	3	3	ND	19	ND	2	ND	3	ND	2	9	ND	ND	5
240	168	158	80	55	22	127	117	138	291	55	83	56	53	95
38.5	39.0	48.0	20.5	20.0	14.0	19.5	22.5	27.0	35.0	16.2	16.6	21.8	26.4	22
274	322	237	200	150	128	759	240	146	75	188	131	82	36	204
3.3	19.4	38.8	8.6	13.7	21.1	0.9	324.0	102.8	47.5	2.8	27.1	8.4	65.2	1.9
0.4	1.9	4.1	1.7	3.0	7.2	0.1	40.5	21.4						

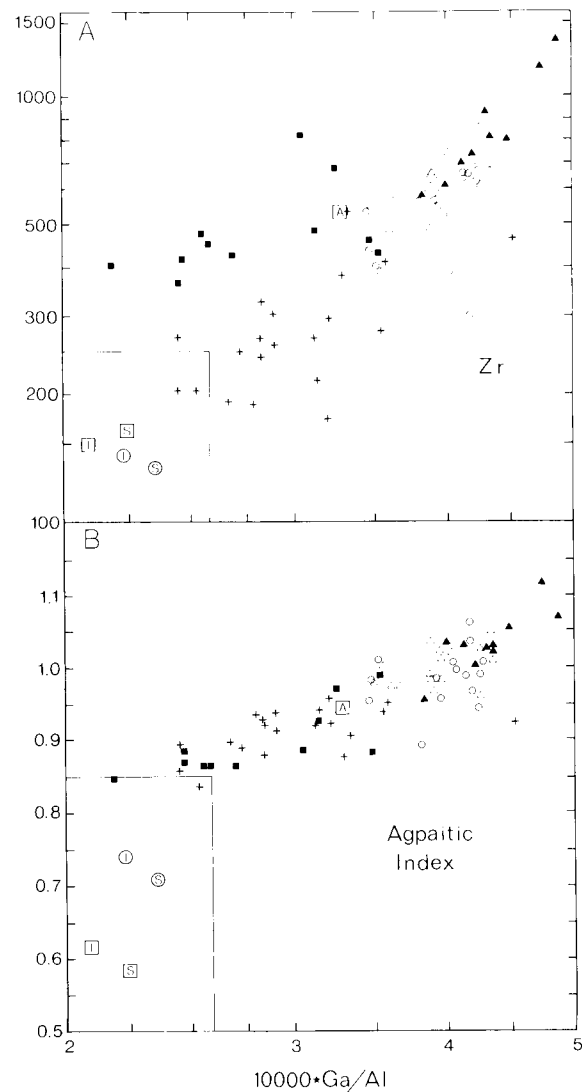


Fig. 3. $10000 \cdot \text{Ga}/\text{Al}$ versus Zr and agpaitic index plots for various phases of the Topsails suite. Fields and symbols for various granites averages as in Fig. 1, other symbols used are: \blacktriangle quartz-K-feldspar porphyry; \triangle coarse-grained amphibole granite. Marginal phases of the cg. amphibole granite; \circ hypersolvus fg-mg amphibole granite; $+$ hypersolvus fg-mg amphibole-biotite and subsolvus biotite \pm amphibole granite; \blacksquare quartz syenite to granite

Rb-(Y+Nb) and Y-Nb diagrams (Fig. 7) show that most of our samples are clearly classified as within-plate type granites. Some of the strongly peralkaline granites of the Nigerian Shira complex plot within the volcanic-arc type granite field because of low Y and Nb contents (see Fig. 2). As for the fractionated non-A-type granites, the Sandy Cape granite plots mainly in the syn-collision granite field and the Ackley granite plots mainly in the within-plate granite field. The average M-, I- and S-type granites plot in the volcanic-arc type granites field. We believe that plots of Ga/Al against major element ratios and Zr, Nb, Ce and Y (Figs. 1 and 2) or Zr+Nb+Ce+Y versus major element ratios (Fig. 5) more clearly differentiate A-type granites. Rb, a trace element mainly partitioned into the major rock forming minerals of granites (McCarthy and Hasty 1976), has been documented in many studies to be readily susceptible to alteration processes and is probably not an appro-

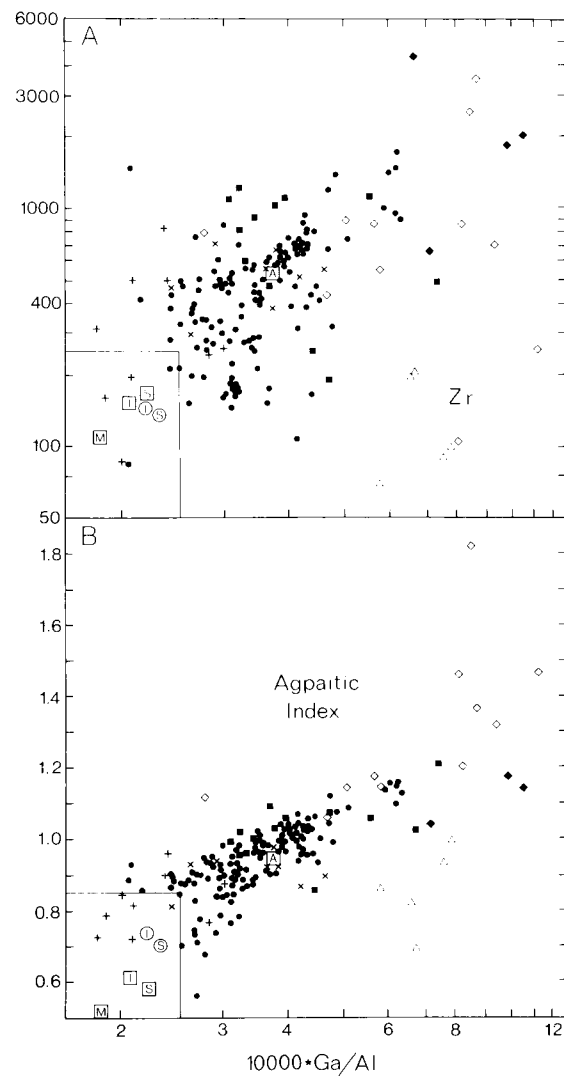


Fig. 4A, B. $10000 \cdot \text{Ga}/\text{Al}$ versus Zr and agpaitic index plots comparing A-type granite data of this study with other published data. Fields and symbols for various granite averages as in Fig. 1, other symbols used are: \bullet all A-type granite data of this study except for Nigerian granites; \diamond Shira complex, Nigeria of this study. Representative Younger Nigerian granites of Imokparia (1985); \triangle subalkaline granites; \blacklozenge peralkaline granites. Anorogenic granites of the Davis Inlet-Flowers Bay area (Collerson 1982); $+$ subsolvus granites; \times hypersolvus non-alkaline granites; \blacksquare peralkaline granites

priate parameter for discrimination diagrams. Although our diagrams are particularly designed for the study of A-type granites, we believe that they could also be helpful in subdividing granites of other types. Data from M-type granites in New Britain (Whalen 1985) exhibit distinctively low contents of Rb, Zr, Nb, Y and REE which suggest a means of discriminating between oceanic island arc sources and evolved island arc to orogenic continental sources. A reconnaissance survey of intrusive rocks in the Papua New Guinea - Solomon Islands area by Mason and McDonald (1978) clearly indicated variations in large lithophile element content which probably reflect the proportion of continental crust in the source rocks. Also, the classifications of Pearce et al. (1984) and Brown et al. (1984) indicate that the content of such trace elements in granites is indicative

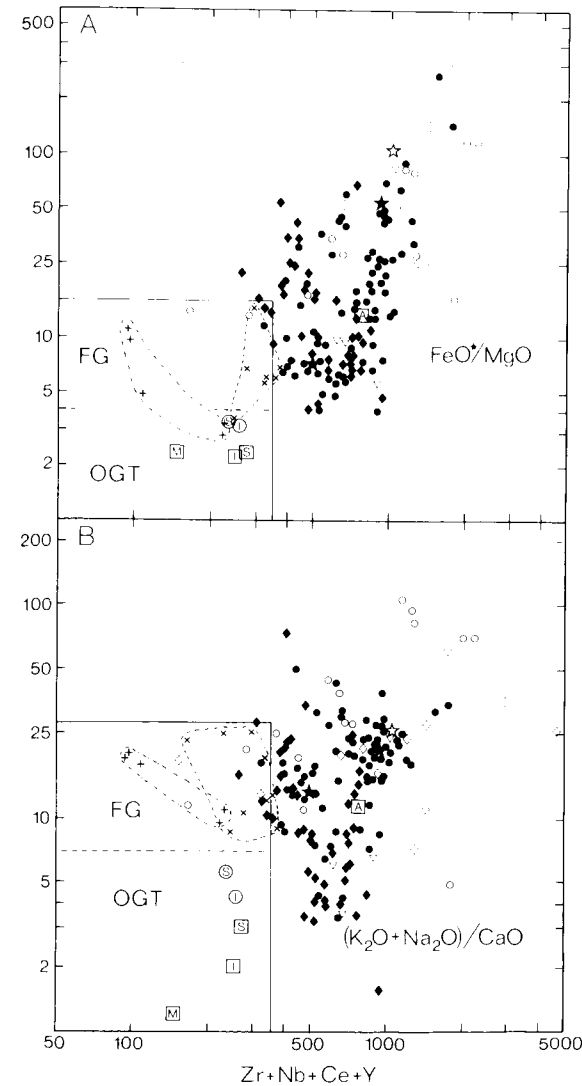


Fig. 5A, B. Zr+Nb+Ce+Y versus FeO^*/MgO and $(\text{K}_2\text{O} + \text{Na}_2\text{O})/\text{CaO}$ plots of A-type granites and also fields for fractionated felsic granites (FG) and unfractionated M-, I- and S-type granites (OGT). Coordinates of these fields are X=350, Y=4 and 16 (A) and 7 and 28 (B). Symbols as in Fig. 1

of tectonic setting of formation. More Ga data from a variety of granitic rocks in different tectonic settings is required to further evaluate the utility of Ga/Al against large lithophile element plots, but we believe that these plots are promising tools. In combination with the plots of Pearce et al. (1984), they should help to clarify the tectonic setting and classification of granitic rocks in the same way that similar plots have expedited the study of mafic volcanic rocks.

Petrogenesis

The petrogenesis of alkaline to peralkaline granites has generated a large and polemic literature, recently reviewed by Collins et al. (1982) and Anderson (1983). By contrast, the tectonic setting of these rocks is commonly assumed to be well-established, namely anorogenic rifting. Our chemical data, and the geological data underlying the sampling, cast

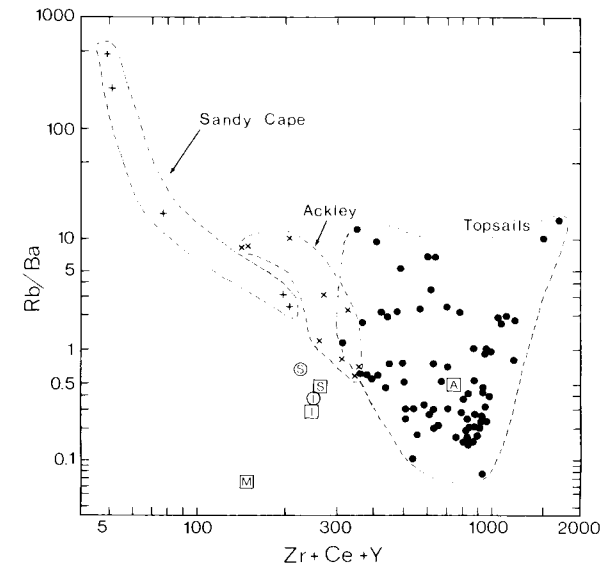


Fig. 6. Zr+Ce+Y versus Rb/Ba plot for the Ackley, Sandy Cape and Topsails granite suites. Symbols as in Fig. 1

new light on these subjects. We consider first the problem of petrogenesis.

Any theory on petrogenesis for A-type granites needs to explain:

1. The generation of peralkaline melts and the common association between contemporaneous peralkaline and non-alkaline and hypersolvus and subsolvus granite phases.
2. Petrographic evidence that these granites crystallized from relatively dry, high-temperature, completely molten (i.e., restite free), Cl- and F-rich magmas.
3. Their enrichment in highly charged cations such as REE, Nb, Zr and Y and also Ga and Zn.

In broad terms, theories on the petrogenesis of alkaline granites fall into three (not necessarily mutually exclusive) categories. (1) Alkalinity developed by metasomatism of a more normal magma, either early (e.g., Bailey 1978; Currie et al. 1986) or late (e.g., Taylor et al. 1980) in its development. (2) Alkalinity developed as a consequence of fractionation (e.g., Currie 1976), usually assumed to involve either plagioclase or an aluminous amphibole. (3) The initial melt was alkaline due to peculiarities of the source (e.g., Collins et al. 1982). According to our data, igneous complexes containing peralkaline granites can show a continuous range of compositions toward normal I- and S-type granites. This observation has important consequences for all three petrogenetic theories, which we discuss below in order.

Metasomatic model

Taylor et al. (1980) suggested that the peralkaline character of anorogenic granites, in particular the northern Topsails granites, results from metasomatism by a CO_2 and halogen-rich volatile phase during and after emplacement. We believe the strikingly anhydrous and CO_2 -free mineralogy and chemistry of the peralkaline phases analysed by us refute this suggestion. Peralkaline, homogeneous coarse-grained amphibole granite (see analysis TB129 in Table 1), crops out over about 1700 km^2 of the Topsails complex in many separate, distinct plutons. Such large scale homogeneity in a peralkaline magma witnesses against local and structur-

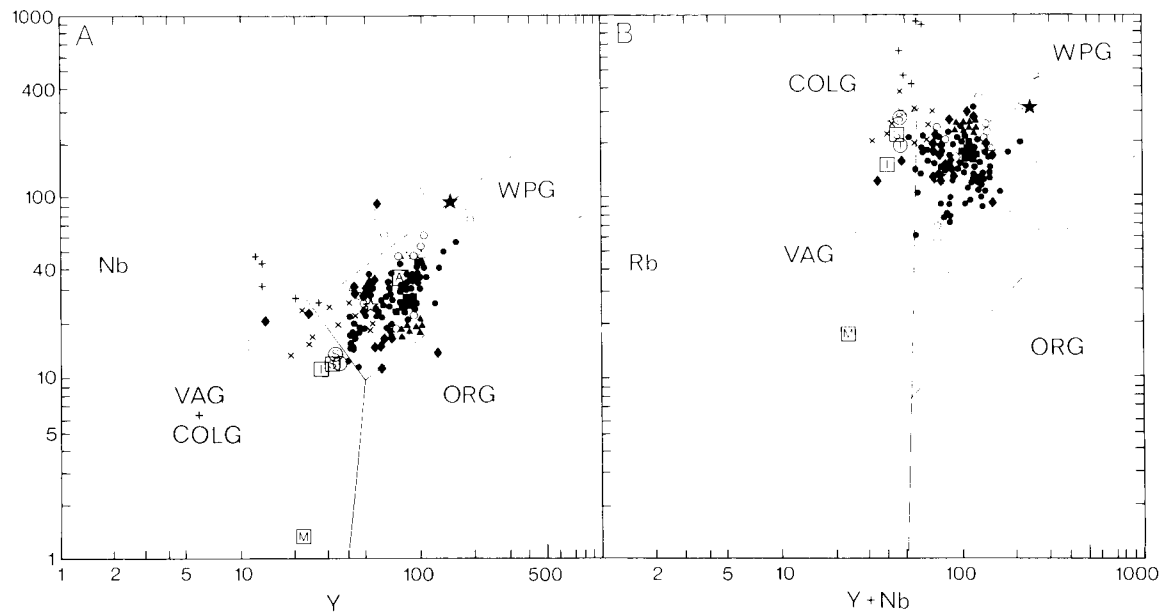


Fig. 7A, B. Distribution of granite data of this paper on the Nb–Y and Rb–(Nb+Y) discrimination diagrams of Pearce et al. (1984). Fields for syn-collision (COLG), volcanic arc (VAG), within plate (WPG) and ocean ridge (ORG) granites are indicated; symbols as in Figure 1

ally controlled processes like metasomatism. Field relationships in the Topsails terrane suggest derivation of subordinate alkaline to metaluminous granitic phases from a primary peralkaline magma rather than vice versa.

The aberrant chemical character (decreasing SiO_2 and high-charge density elements with increasing Na_2O and K_2O) of peralkaline rocks formed by interaction with genetically unrelated saline brines, as documented by Currie et al. (1986), suggests that this cannot be a major cause of peralkalinity in granites. Metasomatism of the protolith of alkaline granites prior to generation has also been invoked (Bailey 1978). While we cannot refute such a suggestion from our data, we see no necessity for such metasomatism.

There is a close association in many alkaline granite complexes between hypersolvus, alkaline to peralkaline, anhydrous phases and subsolvus, subalkaline phases which contain evidence for a separate fluid phase (pegmatites, miarolitic cavities, granophyres, degassing breccias, vein mineralization). Martin and Bonin (1976), based on the effect of water pressure on feldspar crystallization, suggested that the association of hypersolvus and subsolvus granites results from late, high level uptake of water by hot crystalline granite, inducing local fusion and remobilization of the early granite. This wet granitic magma would then crystallize as a subsolvus granite. This model does not explain either the chemical differences between the two types, or the homogeneous character of many subalkaline A-type plutons. The chemical differences may reflect variations in the protolith, both in initial water content and in trace element content. This could explain both the gradation from strongly alkaline compositions to more normal granite compositions, and the restriction of Sn–W–Mo mineralization to subalkaline phases.

Differentiation model

The role of fractional crystallization in producing alkaline to peralkaline compositions has been debated for decades

(see Currie (1976) for brief review). The phases most often cited are plagioclase and aluminous amphiboles. Most A-type granite complexes are comprised of large volumes of felsic rocks lacking associated intermediate rocks and plutons seem to lack significant internal differentiation according to standard indices (K/Rb, K/Ba, Rb/Sr, Rb/Ba) (Anderson 1983; Collins et al. 1982; Jackson et al. 1984). In felsic granites where differentiation has been documented, the trace element changes are marked (Ludington 1981; Whalen 1983). In the Ackley granite, the concentration of Zr and REE decreased and U, Th, Nb, Zn and Ga increased in the magma near the roof of the pluton, probably due to the removal of feldspars plus accessory mineral phases (Whalen 1983) (compare samples JW156 and ACD98 in Table 2). Similar trace element behavior is exhibited by the Sandy Cape suite. Differentiation has produced minor volumes of granite with a partial A-type signature. However, even in these cases, A-type granites can be distinguished from non-A-type magmas. Crystal fractionation within some individual A-type granite suites is evidenced by variation in Rb/Sr and Rb/Ba (see Table 2). However, we are aware of no evidence that differentiation alone could produce the distinctive chemistry of A-type granites.

Partial melting model

Much recent work (e.g., Barker et al. 1975; Collins et al. 1982; Anderson 1983; Jackson et al. 1984) suggests that anorogenic granites form from primary magmas produced by partial melting of relatively anhydrous lower crustal source rocks. Harris and Marriner (1980) invoke a high flux of mantle-derived halogen-rich volatiles to induce melting and to provide the high concentration of alkalis and high field strength elements in anorogenic granites. Barker et al. (1975) proposed a reaction-melting model in which emplacement and fractionation of a mantle-derived mafic magma caused partial melting of granulite facies lower crust with various stages of contamination and differentiation

of the magma producing both the hypersolvus peralkaline and non-alkaline granites of the Pikes Peak Batholith. Collins et al. (1982) and recent experimental work (Clemens et al. 1986) favour the formation of A-type granites by partial melting at elevated temperatures ($>830^\circ\text{C}$) of an essentially anhydrous source which has been depleted in water by extraction of a minimum-melt I-type magma. This granulitic source is thought to be enriched in F- and/or Cl due to the enhanced thermal stability of micas and amphiboles rich in these elements. Anderson (1983) has suggested that a tonalitic to granodioritic meta-igneous source is a viable alternative to the granulite source of Collins et al. (1982). Also, Anderson and Thomas (1985) have described muscovite-bearing peraluminous A-type granites which they consider to be derived by melting of previously dehydrated metasedimentary source rocks. Vapour-absent breakdown of hydrous minerals provides the volatile component necessary for partial melting, while accessory phases provide the large content of highly charged cations. F and Cl in the magma distort the aluminosilicate framework providing sites for the highly charged cations and stabilize complexes of large highly charged metal ions (e.g., Ta, Nb, Mo, W, REE, U). An excess of alkalis over alumina and high F in the melt inhibits zircon formation and promotes the formation of zircono-fluoride melt complexes. Zinc also complexes with F and a high Zn content in some A-type granites is promoted by the presence of excess alkalis in the melt. Ga is enriched relative to Al because the latter is preferentially trapped in residual plagioclase, while Ga is stabilized in the melt in GaF_6^{-3} structures. We believe this picture to be reasonable and probably correct in its general outlines. However, our data show that additional factors must be involved. In contrast to the data of Collins et al. (1982), our data demonstrate that individual A-type granite suites exhibit considerable variation in chemical composition, and grade towards I- and S-type granite compositions. If partial melting of mixed source regions is the cause of such variations, small A-type suites, such as those studied by Collins et al. (1982), reflect quite homogeneous protoliths, whereas large A-type suites such as the Topsails tapped extensive heterogeneous source regions. Causes of heterogeneity can easily be suggested, for example primary diversity in source rocks, varying amounts of extraction of an earlier melt phase, or tectonic juxtaposition or even interleaving of diverse terranes. Other processes, such as different degrees of partial melting or removal of successive batches of magma from a suitable source, might also produce ranges of subalkaline to peralkaline magmas. Fractionation and solidification, involving metasomatism or not, is certainly responsible for some chemical dispersion in A-type granite suites, but we believe this factor to be relatively minor.

Tectonic implications

The "conventional wisdom" linking A-type granites to rifting of "anorogenic" cratons appears to need revision. The genetic model of Collins et al. (1982), which we believe to be correct in its main lines, indicates no obvious reason for such a restriction. Indeed, we would presume that the depleted protoliths assumed by them should be most common in reactivated orogenic belts. There is no obvious reason why such sources should necessarily be of I-type, since protoliths depleted by removal of S-type melts should also be common (e.g. Anderson and Thomas 1985). However,

attainment of the high melting temperatures ($>830^\circ\text{C}$) (Clemens et al. 1986) required to generate A-type granite magmas, probably by the emplacement of mantle derived mafic magmas into the lower crust, may constrain the tectonic conditions under which they are formed.

Active peralkaline volcanoes occur on the flanks of a major rift (Fantale, Ethiopia: Gibson 1974), over an active subduction zone (Mayer Island, New Zealand: Ewart et al. 1968), on a transversely faulted subduction zone (D'Entrecasteaux Island: Smith 1976), and in a doubtful, probably post-tectonic setting (Pantellaria: di Girolamo 1984). Particularly instructive examples of diverse tectonic settings for A-type granites occur in the Appalachian-Caledonide orogen. Within the Topsails igneous terrane of western Newfoundland, there is a transition from orogenic M-type granite magmatism in Late Ordovician time to voluminous A-type magmatism in the Early Silurian. Current tectonic models (Whalen et al. in press; Van Staal, in press; Kirkham, in press) suggest that following Middle Ordovician collision of a magmatic arc, which includes the Topsails terrane, with North America, a marginal basin closed during the Late Ordovician by westward directed subduction beneath the Topsails terrane. Underthrust North American Grenville basement rocks could have been partially melted during crustal upwarping and transcurrent faulting to produce the Topsails suite. The Late Silurian Welsford complex is closely associated with a major dextral transcurrent fault, while the Devonian St. Lawrence granite may be associated with a major sinistral fault. We believe that the common features linking these diverse tectonic settings are a) a source of dehydrated, reasonably salic crust, and b) a source of heat sufficient to partially melt this crust, and c) a conduit to lead the magma to high level. These conditions are by no means restricted to within plate rifting, and can occur associated with transcurrent faulting, or even during subduction.

Acknowledgements. We wish to thank Dr. B. Bonin for providing samples from the Evisa complex, Corsica, Dr. P. Bowden for providing samples from the Shira complex, Nigeria and Dr. R.F. Martin for providing samples from the Welsford complex, New Brunswick. Also, we wish to thank Dr. R.E. Emslie, Dr. J.D. Hill, Dr. O.D. Hermes, and Dr. A. Ewart for critical reading of the manuscript.

Appendix

Major element analyses were determined in the labs of the Geological Survey of Canada, Ottawa by X-ray fluorescence on duplicate glass buttons, except for duplicate analyses for Na_2O (atomic absorption spectrometry), FeO (titration against $\text{K}_2\text{Cr}_2\text{O}_7$), and volatiles (infra-red). F and Cl were determined in duplicate by fusion with lithium tetraborate followed by selective ion electrode analyses and colorimetric (thiocyanate) analysis, respectively. Trace elements were determined in duplicate in the Department of Geology, The Australian National University by B.W. Chappell by the X-ray fluorescence methods of Norrish and Chappell (1977). Relative percent standard deviation ($\text{SD} \times 100/\text{Mean}$) on BCR-1 was 5 to 10 percent for Th, U and Ni; 1 to 5 percent for Pb, Sc, Nb, Ce and Cu; less than 1 percent for the other trace elements.

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