

## GEOCHEMISTRY AND PETROGENESIS OF THE AMBELA GRANITIC COMPLEX, NW PAKISTAN

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### ABSTRACT

*The Ambela granitic complex comprises three groups of rocks. Group I, the product of the first magmatic episode, consists of granites and alkali granites which occupy ~70% of the 900 km<sup>2</sup> area of the batholith. Group II, following the granites sequentially, comprises quartz syenites, syenites, feldspathoidal syenites and related rocks. Following these, the area was invaded by delerite dykes which occupy ~5% of the complex. These (Group III rocks) are not discussed in this paper. The granitic rocks range from dominantly peraluminous to metaluminous to mildly alkaline. These were derived from melts produced by crustal anatexis due to crustal thinning and rifting. Different degrees of partial melting and fractional crystallization led to variation in the composition of these Group I rocks. With deepening of the zone of magma generation in the crust, the underlying mantle was activated, resulting in the influx of volatiles and alkalis. This led to the generation of magma batches which were successively more SiO<sub>2</sub>-undersaturated and alkaline, resulting in the production of Group II rocks. The Ambela batholith appears to have developed during a major phase of crustal thinning and rifting towards the end of Palaeozoic.*

### INTRODUCTION

The northwestern part of the Indian plate in Pakistan contains several igneous complexes of mildly to strongly alkaline character. These extend for more than 200 km from the Loe Shilman carbonatite complex in the west, through the Warsak alkaline granites, the Sillai Patti carbonatite complex, the Malakand granite, the Shewa-Shahbaz Garhi porphyries, the Ambela granitic complex, to the Tarbela 'alkaline complex' in the east. With a total outcrop area of more than 1000 km<sup>2</sup>, these complexes were considered to define the Peshawar Plain alkaline igneous province (Kempe and Jan, 1970, 1980; Ahmad and Ahmed, 1974). The magmatism in this province was attributed to rebound relief tension or rifting (Kempe and Jan, 1980; Chaudhry et al., 1981; Kempe, 1983; Rafiq et al., 1984). Shams (1983) described the rocks of this province as the product of reconstituted and remobilized basement belonging to the northern margin of the Indo-Pak craton.

The Ambela granitic complex (AGC) is the principal member of the alkaline igneous province and covers over 900 km<sup>2</sup> area. It has a variety of lithologies ranging from granite to nepheline syenite and carbonatite. Prior to the detailed data of Rafiq (1987), geological investi-

gations were limited to the central part of the AGC around Koga (Siddiqui, 1965, 1967; Siddiqui et al., 1968; Chaudhry et al., 1981). This paper presents details of chemical characteristics and petrogenesis of the complex, and is based on the major element analyses of 166 samples (from a collection of more than 1000), half of which were also analyzed for trace elements. The alkaline rocks of Koga, however, were not studied in detail. The present work also does not concern the dolerite dykes in the AGC.

## GENERAL GEOLOGY AND PETEROGRAPHY

The country rocks hosting the AGC belong to the Lower Swat-Buner Schistose- and Swabi-Chamla groups of Martin et al. (1962). These rocks, with deformed sheets of granitic gneisses of Cambrian age, probably constitute the Precambrian basement and Paleozoic cover of the Indian plate (see Ashraf et al., 1980; Coward et al., 1982, 1986; Baig et al., 1988, for further details).

The AGC is a composite batholith. Based on field data and petrography (Rafiq, 1987; Rafiq and Jan, 1988), it can be classified into the following groups of lithologies:

Group I, earliest, consisting of granites (some of which fall on the border of granodiorite), alkali granites and microporphyrics.

Group II consists of younger saturated rocks (quartz syenites, alkali-quartz syenites, alkali syenites, syenites) and undersaturated rocks (feldspathoidal syenites, fenites, carbonatites, ijolite and related rocks). Considerable metasomatic changes were associated with the successive alkali-enriched intrusive phases of this group.

Group III consists of youngest, minor basic dykes succeeding the batholith-forming magmatism of Groups I and II. Petrography and geochemistry of this group will be presented in a separate paper.

## GEOCHEMISTRY

### Analytical Techniques

Following detailed petrography, 43 samples were selected for wet chemistry.  $\text{SiO}_2$  was determined gravimetrically, and FeO by titration, following Wilson (1960).  $\text{Al}_2\text{O}_3$ ,  $\text{TiO}_2$  and  $\text{P}_2\text{O}_5$  were measured colorimetrically through the use of a UV/visible spectrometer, and MgO,  $\text{Fe}_2\text{O}_3$  (total), MnO, CaO,  $\text{Na}_2\text{O}$  and  $\text{K}_2\text{O}$  by atomic absorption spectrophotometer.  $\text{H}_2\text{O}^-$  was estimated by drying the rock powder at  $120^\circ\text{C}$ , and ignition loss was measured at  $1000^\circ\text{C}$ . Duplicating these 43 analyses, a total of 166 samples were analysed for major and minor elements, together with trace elements in half of them, by XRF method. Calibration curves were determined using a set of standards including G-2, BCR-1, PCC-1, BHVO-1, and DNC-1. Representative analyses are given in Appendices 1-3.

### Chemical Characteristics of the Complex

Detailed petrography of the AGC, based on 800 thin sections, has been presented by Rafiq (1987) and Rafiq and Jan (1988). The modal plots of the AGC rocks in QAPF diagram (Fig. 1, following Streckeisen, 1976) suggest that the Group I rocks cover a broad area in the fields of granite (some close to granodiorite and quartz monzonite) and alkali granite, while those of Group II fall in the fields of quartz syenite, alkali-quartz syenite, syenite, alkali syenite and feldspathoidal syenite.

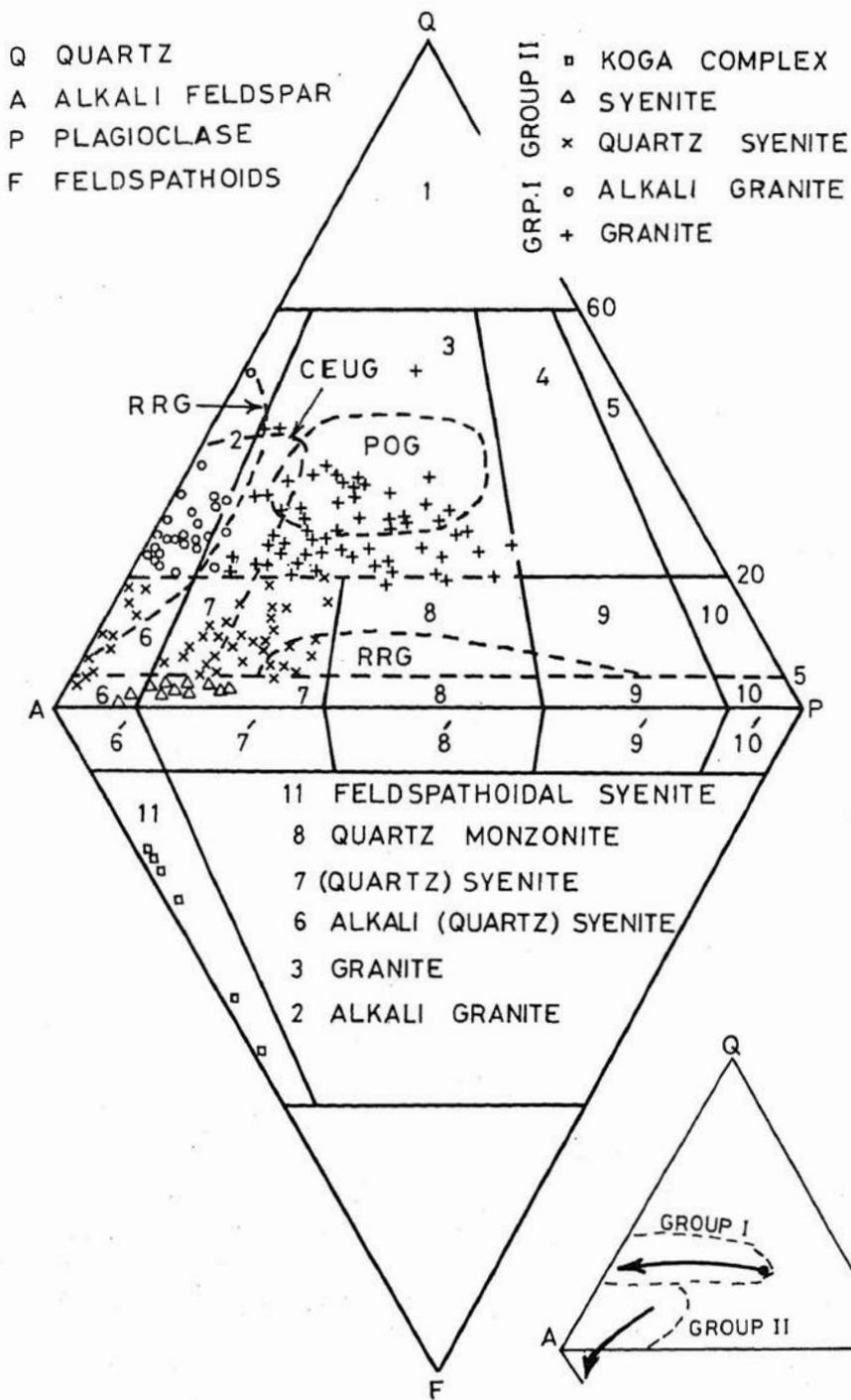


Fig. 1. Modal classification of the Ambela rocks on Streckeisen (1976) diagram. Fields of post-orogenic, rift-related (PRG) and continental epierogenic uplift (CEUG) granites after Maniar and Piccoli (1989). QAP triangle on the right bottom shows the fields and evolutionary trends (arrowed) of the Groups I and II rocks.

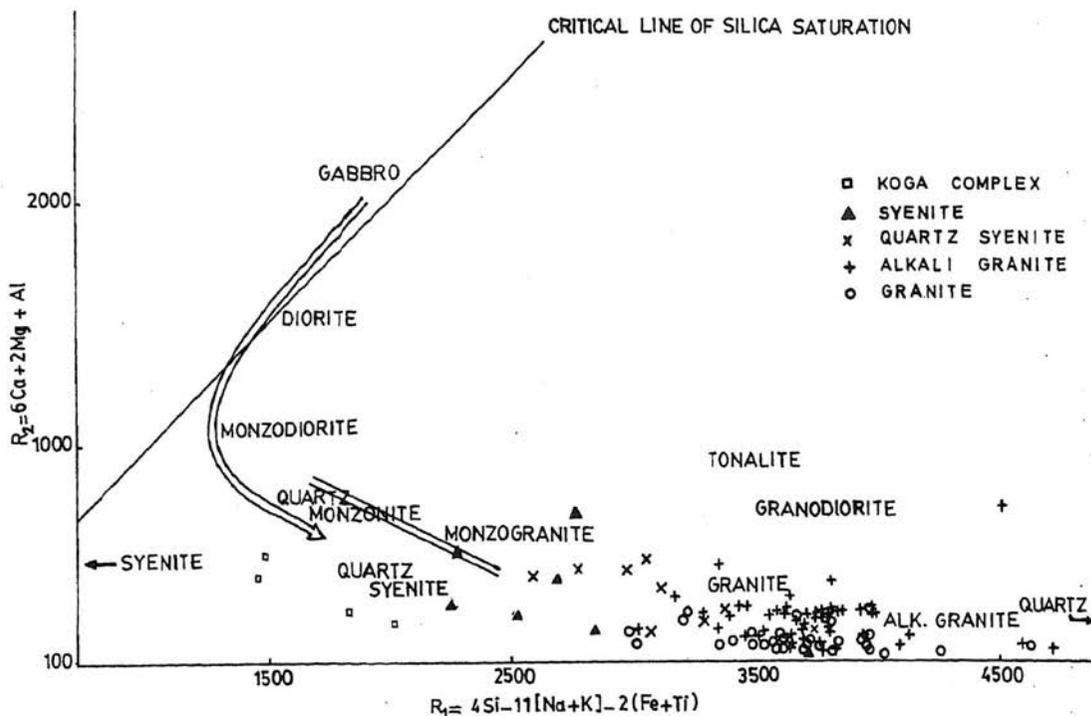


Fig. 2.  $R_1$ - $R_2$  chemical classification of the Ambela rocks (after La Roche and Leterrier, 1973).

Such a sub-division is also supported when the analyses are plotted on the  $R_1$ ,  $R_2$  chemical parameters (Fig. 2, following La Roche and Leterrier, 1973; La Roche, 1976, 1980). Here the rocks classify as granite, alkali granite, monzogranite, and quartz syenite. Using  $Q = Si/3 - (K + Na + 2Ca/3)$  and  $P = (K - (Na + Ca))$  as coordinates (after Debon and Le Fort, 1983), plots of 102 analyses are displayed in Fig. 3. There is a wide range from quartzose granitoids to monzonite and syenite but 81 of the analyses occupy the fields of granite and adamellite.

In order to examine the aluminous character of the rocks in chemico-mineralogical terms, the A ( $=Al - (K + Na + 2Ca)$ ) and B ( $=Fe + Mg + Ti$ ) parameters of La Roche (1978) were used (Fig. 4). The plots here indicate that while some rocks are metaluminous, a vast majority have peraluminous affinities as defined by Debon and Le Fort (1983). The majority of the analyses define a rough trend subparallel to that of the Kosciusko batholith (compare Fig. 4 of Debon and Le Fort, 1983), which is an S-type pluton (Hine et al., 1978).

On the basis of alkali ratio ( $K/(K+Na)$ ), the Group I rocks are soda-potassic and Group II rocks soda-potassic to sodic. With decrease in the alkali ratio, quartz content increases in Group I rocks but it shows a steady decrease in Group II Rocks. The available data (Siddiqui et al., 1968; Ahmad and Ahmed, 1974; Kempe, 1983; Chaudhry et al., 1981; Rafiq et al., 1984; Rafiq, 1987) suggest a subalkaline to alkaline affinity for the rocks of the AGC. On the  $SiO_2$  vs alkalinity ratio diagram of Wright (1969), the majority of the analyses fall in alkaline field (Fig. 5). On the basis of alkalinity ratio (2.0 to 9.5; average 4.0), relative volumes of acid and basic rocks, and tectonic settings (Rafiq, 1987), the AGC can be compared with the younger alkaline to peralkaline granites of Nigeria (i.e. Group 3 of Wright, 1969).

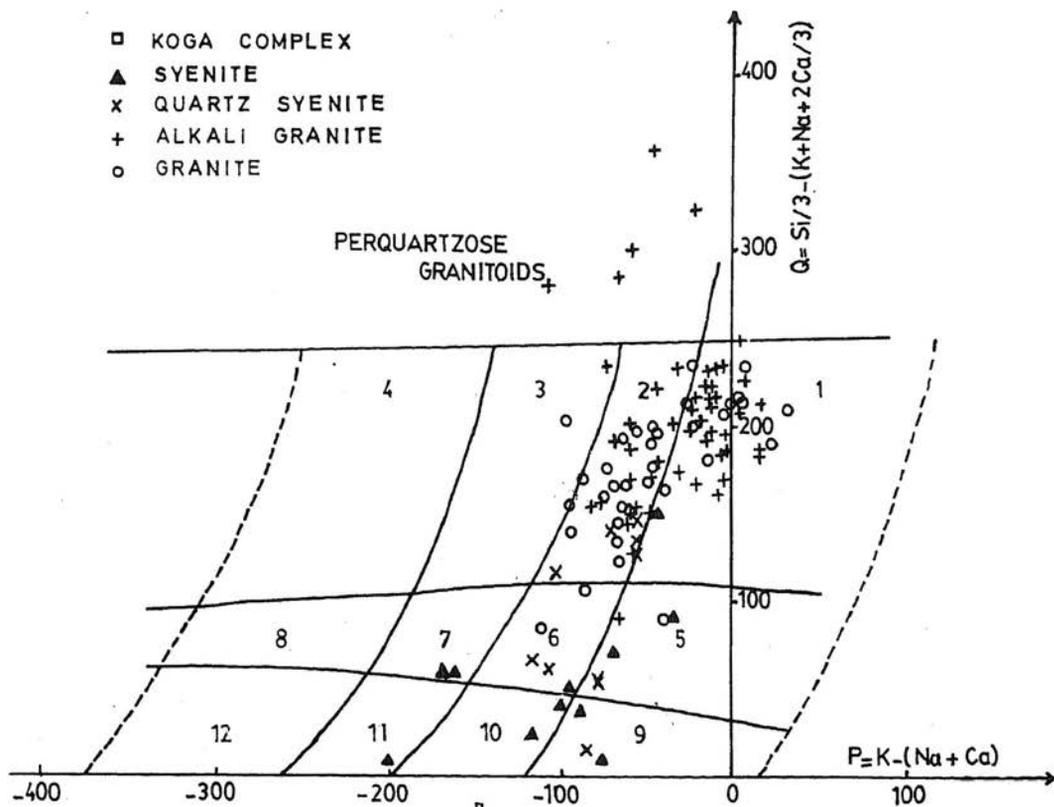


Fig. 3. Nomenclature of the Ambela rocks following Debon and Le Fort, 1983. 1 granite, 2 adamellite, 3 granodiorite, 4 tonalite, 5 quartz syenite, 6 quartz monzonite, 7 quartz monzodiorite, 8 quartz diorite, 9 syenite, 10 monzonite, 11 monzogabro, 12 gabbro.

Oxides percentages are plotted against the differentiation index of Thornton and Tuttle (1960) in Fig. 6. There is an increase in alkalis and decrease in the remaining oxides plots with increase in the index. Such a variation is also displayed by Harker diagram. But in both the diagrams, there is a considerable scatter. This could possibly be the result of 1) source rock heterogeneity, 2) different degrees of melting, 3) contamination, 4) continuous fractionation of feldspar, 5) mixing of magma batches, and 6) influx of mantle derived alkalis, volatiles, etc. As in the AGC, decrease in  $\text{TiO}_2$  and  $\text{Al}_2\text{O}_3$  with differentiation has been reported in the salic rocks of the alkaline igneous province of Mongol Tuva, USSR (Pavlenko, 1974) and Madian granites of Saudi Arabia (Harris and Marriner, 1980).

In the projection of normatic quartz, albite and orthoclase (Fig. 7), the majority of Group I rocks tend to plot near the minimum temperature composition at  $\text{PH}_2\text{O}=500 \text{ kg/cm}^2$ , with some into the low temperature trough of the petrogeny residua system. These plots and the abundance of perthite suggest that the granitic rocks are hypersolvus.

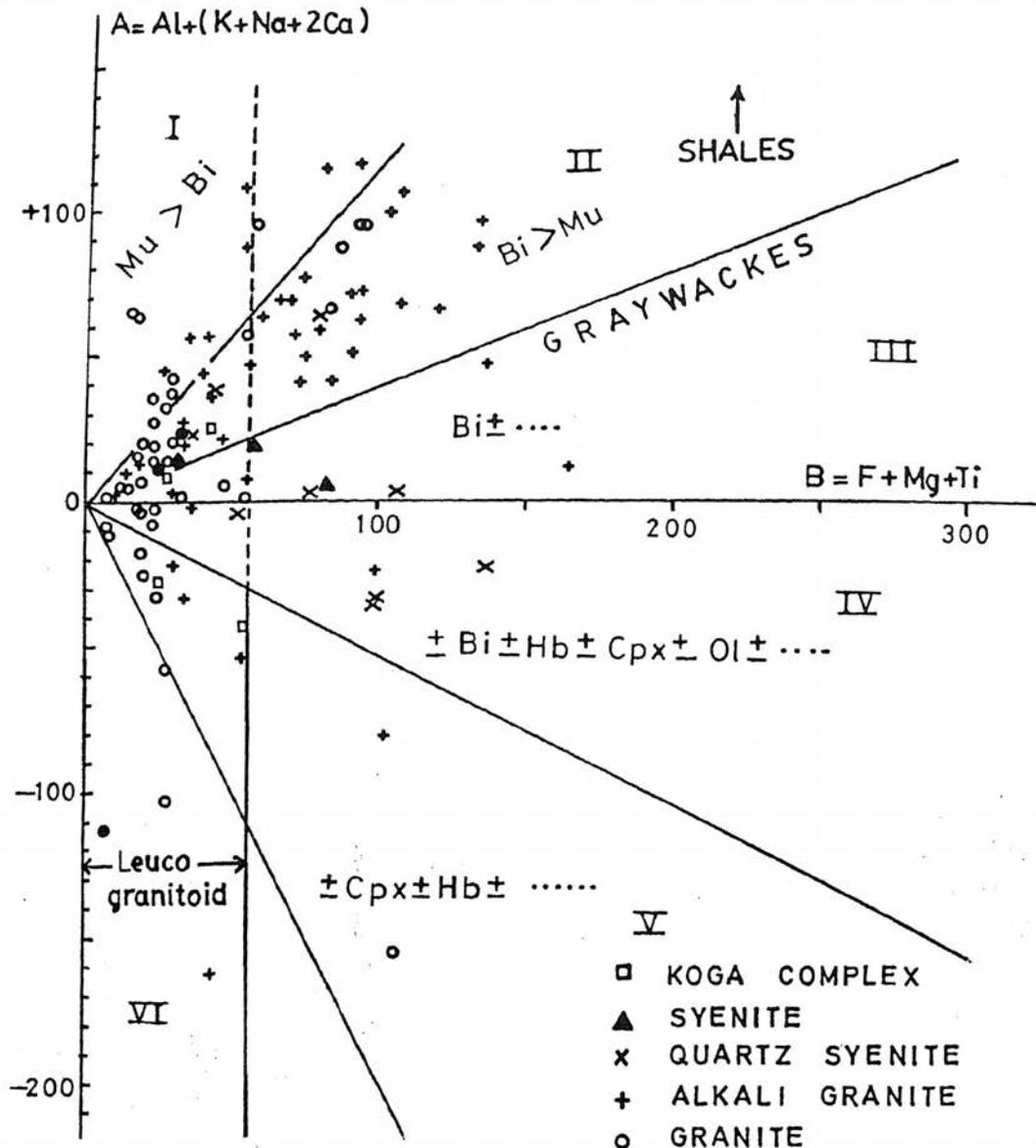


Fig. 4. Chemico-mineralogical diagram showing the plots of the Ambela rocks (after Debon and Le Fort, 1983).

Variations in silica content are demonstrated by the use of  $SiO_2-Al_2O_3$ -alkalis ternary plots in Fig. 8. The Group I rocks display a close clustering. This is because crystallization differentiation was limited and the final products of the process were alkali granites which are not different significantly from the initial melts that produced the granites. Group II rocks, however, define a progressive desilicification trend. This relation is similar to that displayed by the Arabian and Nile alkaline provinces (Harris, 1981).

### Tectonic Setting

When fields of silicic rocks from various tectonic settings (after Maniar and Piccoli, 1989) are superimposed on the QAPF diagram (see Fig. 1). The alkali granites are confined to the field of rift-related granitoids. The granites and quartz syenites, on the other hand, fall within as well as outside the fields of post-orogenic granitoids and continental epeirogenic

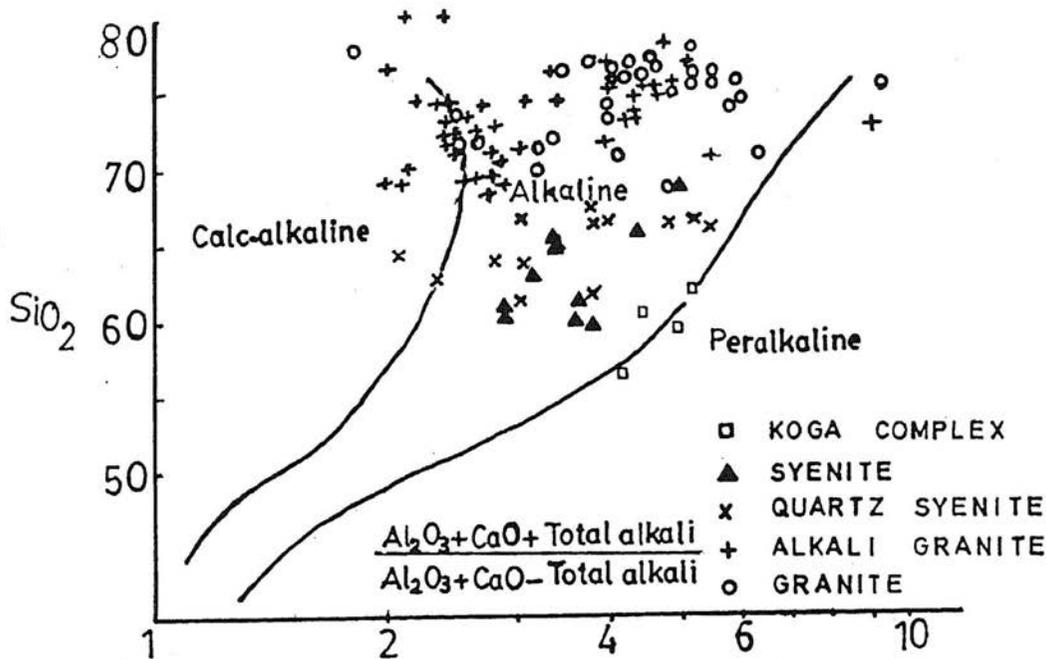


Fig. 5 Positions of the Ambela analyzed samples on  $\text{SiO}_2$  vs. alkalinity ratio diagram of Wright (1969).

uplift granitoids. Petro et al. (1979) noted differences in the D.I., CaO, total alkali contents, and  $\text{CaO}/(\text{Na}_2\text{O}+\text{K}_2\text{O})$  ratios of organic and anorogenic rocks. The mean values of these variables for the  $\text{SiO}_2$  interval of 70–75% in the Ambela rocks are compared with those of four other areas (Table 1). A close similarity between the rocks of AGC and those of the British Isles and Iceland (nonorogenic) is obvious.

The Y, Nb and Ta against  $\text{SiO}_2$  plots of the AGC rocks fall in the field of WPG (within plate granites) and ORG (oceanic ridge granites), as defined in Pearce et al. (1984). The Rb vs.  $\text{SiO}_2$  relations, however, characterize them as WPG rather than ORG (Fig. 9).

TABLE 1. COMPARISON OF MEANS OF VARIABLES FOR  $\text{SiO}_2$  INTERVAL 70-75%.

	Ambela	BIT	ISL	ARA	SCB
DI*	90.00	88.87	91.97	83.10	83.34
CaO	1.00	1.24	0.86	2.40	2.22
Alkalies	8.75	8.57	8.40	6.68	6.91
CaO	0.11	0.15	0.10	0.38	0.34
$\frac{\text{Na}_2\text{O}+\text{K}_2\text{O}}{\text{SiO}_2}$					

\* Differentiation index of Thornton and Tuttle, 1960.

BIT = British Isles Tertiary granites; ISL = Iceland granites; ARA = Aleutian-Alaska Batholith; SCB = South California Batholith (from Petro et al., 1979).

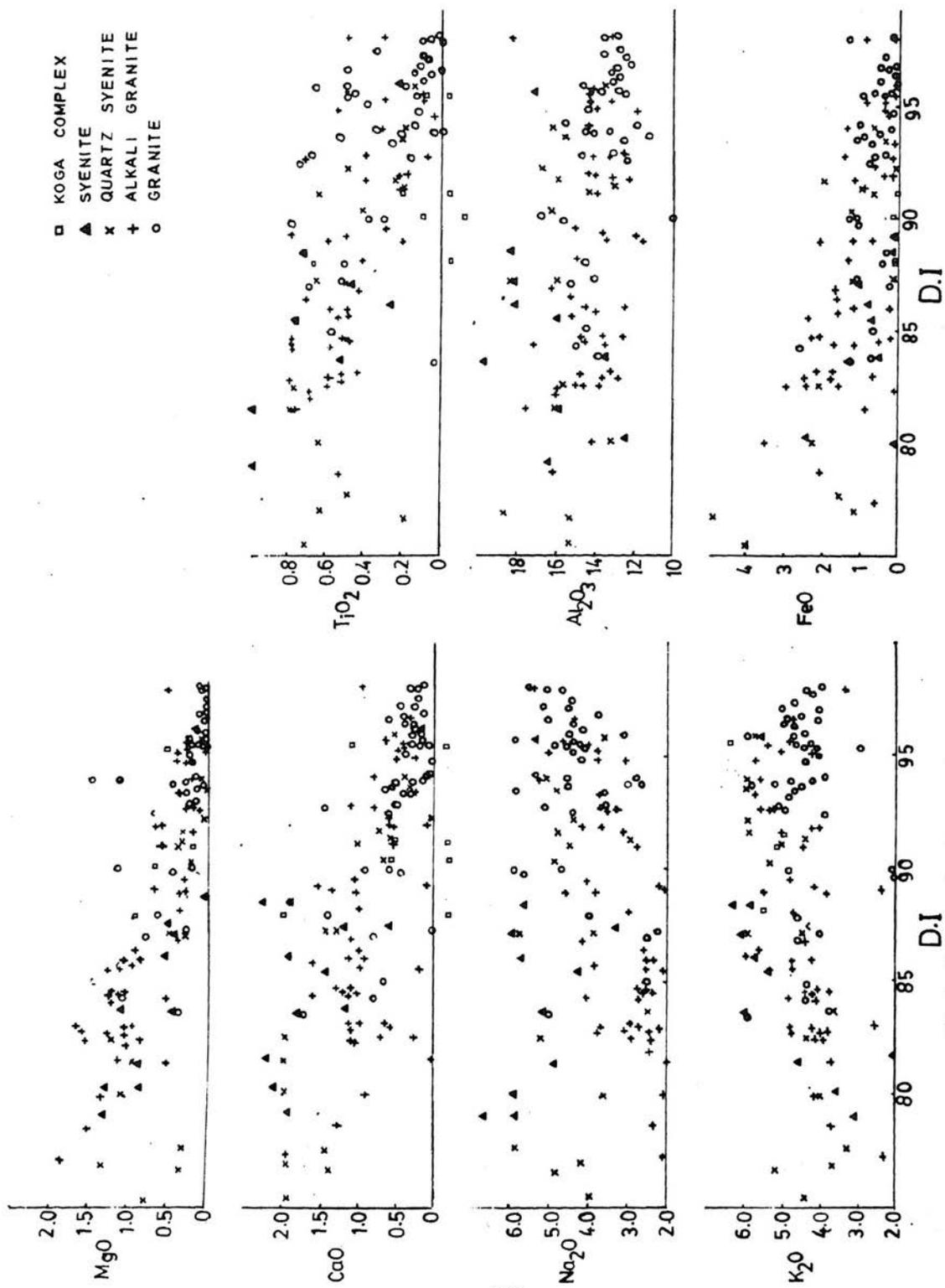


Fig. 6. Variations in oxide percentages with differentiation index (D.I) of Thornton and Tuttle (1960).

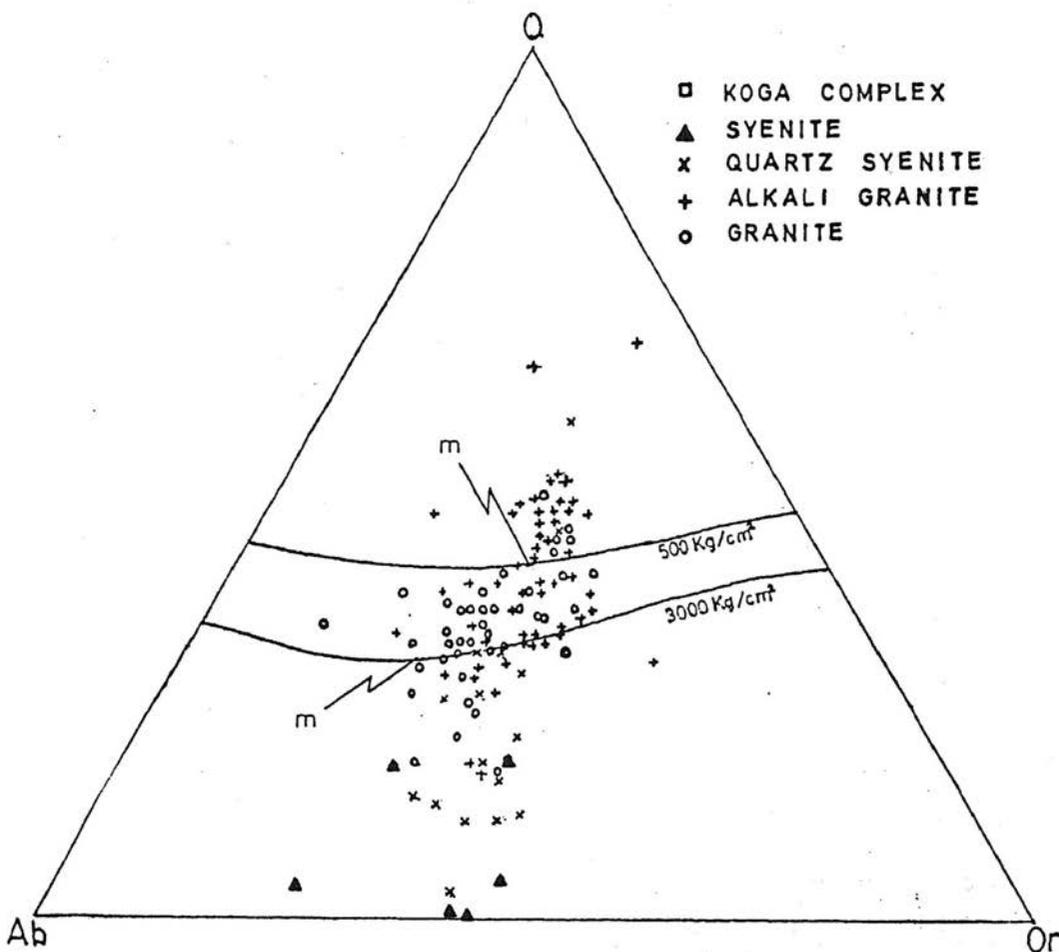


Fig. 7. Normative quartz-albite-orthoclase plots for the AGC rocks. Also shown are the low temperature troughs and minima (m) for  $P_{H_2O}=550$  and  $3000 \text{ kg/cm}^2$  (after Tuttle and Bowen, 1958).

Within plate granites are effectively distinguished from those of several other tectonic environments by the use of Y vs. Nb and Rb vs. Y+Nb relations. The plots of the Ambela rocks are clearly restricted to the field of within plate granites (Fig. 10).

### PETROGENESIS AND CONCLUSIONS

Field, petrographic and geochemical data suggest that three episodes of magmatism may be involved in the formation of the batholithic Ambela granitic complex. The first episode produced widespread granites and alkali granites of Group I. These dominantly peraluminous to metaluminous to mildly alkaline rocks cover about 70% of the outcrop area of the AGC. Quartz syenites, syenite, feldspathoidal syenite, carbonatite and ijolite, constituting the Group II rocks, are intrusive into the granites and were produced during the second magmatic episode. The last magmatism was responsible for the dolerites (Group III), which intruded the rest of the rocks. These make ~ 5% of the complex and are not discussed any further.

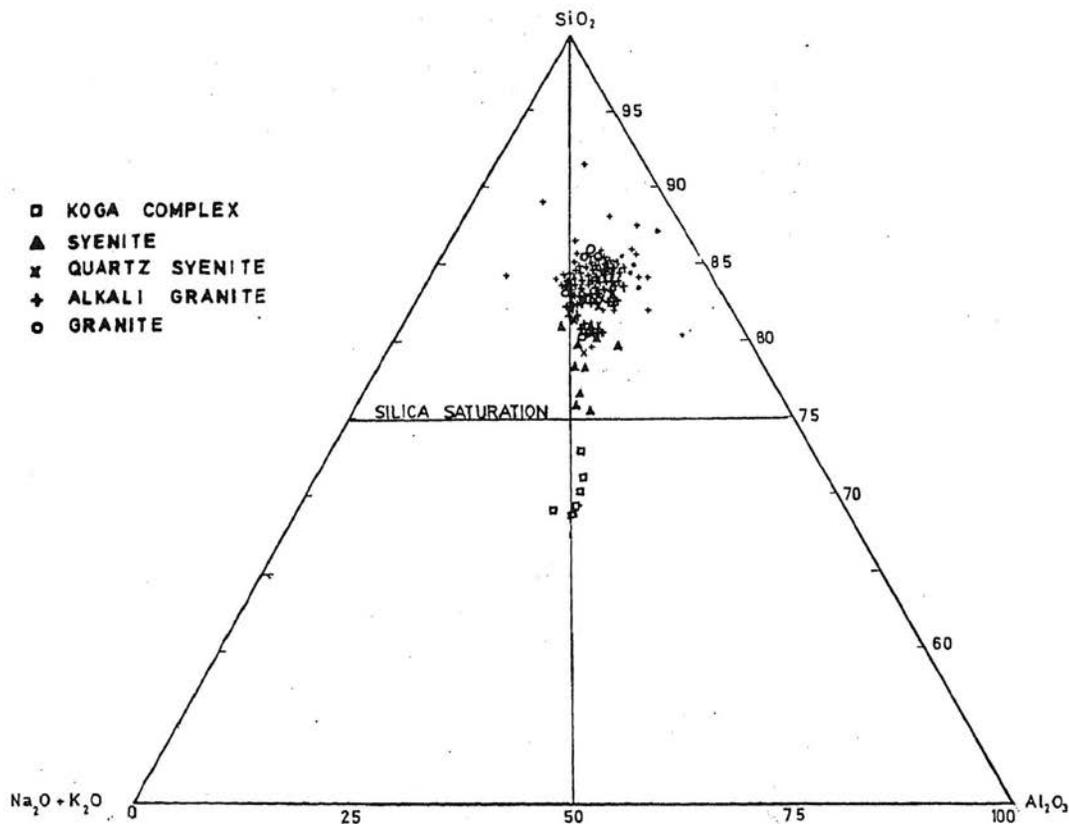


Fig. 8. SiO<sub>2</sub>-Al<sub>2</sub>O<sub>3</sub> — alkalis mole per cent plots of the analyses from Ambela granitic complex (after Harris, 1981).

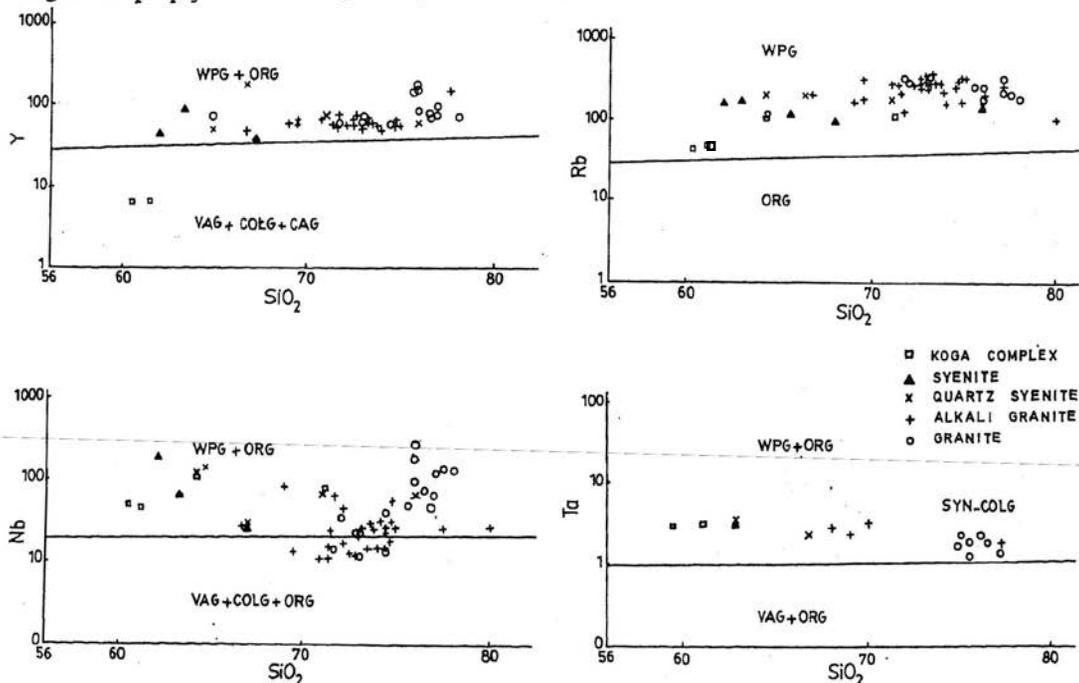


Fig. 9. Y, Nb, Rb, and Ta plots against SiO<sub>2</sub> for the Ambela rocks. The various fields are after Pearce et al., 1984.

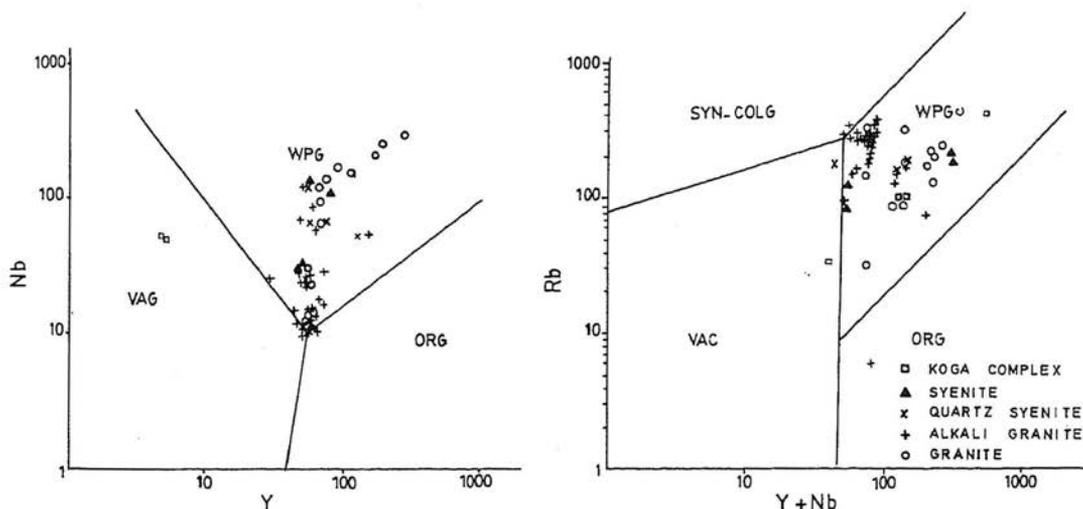


Fig. 10. Nb-Y and Rb-(Y+Nb) discriminant plots for the Ambela rocks. Fields distinguished are after Pearce et al., 1984.

### The origin of Group I rocks

The AGC is characterized by an abundance of silicic rocks. The area does not contain earlier mafic rocks to suggest that the complex is a product of differentiation of a basaltic magma. The low Sr content (<100 ppm in vast majority) of the granites also suggests that they are formed from melts of palingenic rather than residual origin. Indeed the most "primitive" rocks in the AGC are probably the porphyritic granites (with magmatic phenocrysts of feldspar) some of which have granodioritic composition. These, occupying the central part (core) of the complex, seem earliest in the intrusive sequence, contain abundant biotite  $\pm$  hornblende and are peraluminous in character. Like similar alkaline complexes in Africa, Arabia, and Greenland, we regard that the AGC granites are also related to crustal anatexis (cf. Harris, 1974; Harris et al., 1983; Debon and Le Fort, 1983), followed by fractional crystallization that produced the alkali granites.

Rb increases in amount relative to Ba and Sr during progressive differentiation (Ahrens et al., 1952; Taylor et al., 1956). The average values for Rb in the AGC granites and alkali granites are 210 and 247 respectively. These values are close to those of "normal" and strongly differentiated granites (190 and 260 ppm, according to Bouseily and Elsokkary, 1975). Low K/Rb ratios are also characteristic of highly fractionated granites. The average K/Rb ratio of the continental crust has been estimated as 230 to 250 ppm (Taylor, 1968; Shaw, 1968). The K/Rb ratios of the AGC granites (90–300, average 175 ppm) and alkali granites (69–247, average 158 ppm) support their derivation from the crustal melts, followed possibly by differentiation.

It is proposed that the area under discussion was probably a part of a broad continental Swell (cf. Bailey, 1964) or a lithospheric scar of asthenospheric hot spot (as proposed for African alkaline provinces, Rhodes 1971; Duncan, 1981). Partial melting may be related either to release of pressure or to a rise in temperature by radioactivity, heat transfer from the hotspot, or release of mechanical / frictional energy during convective or gravitational movement

(cf. Oxburgh and Turcotte, 1968). Whatever the mechanism for partial melting, many workers (e.g., Harris, 1974; Bailey, 1964, 1974) are of the view that initial arching/warping is all that is needed, because it is a self-perpetuating action leading to magmatism along zones of rifting.

It is concluded that the early phases of the granite magmatism in the AGC are a product of crustal anatexis. The later phases, on the other hand, may have been produced by fractional crystallization, but other factors, such as contamination, volatile transfer, source rock heterogeneity, may also have added to the overall process. These conclusions are supported by field, petrographic and geochemical data.

### The origin of Group II rocks

Whilst the Group I rocks display a limited variation from granite-granodiorite boundary to alkali granite, the Group II rocks are more variable and show a progressive desilicification and enrichment of alkalis, volatiles, and HFSE (High Field Strength Elements) such as Zr, Nb, Ta, Y in the successive intrusive phase. Enrichment of the HFS elements is a characteristic of alkaline and peralkaline rocks (Tauson, 1967; Buma et al., 1971). It is the ability of non-hydrous volatiles (F, Cl, CO<sub>2</sub>) to form stable complexes that leads to the concentration of Zr, Nb, Ta and Y (Bailey and Macdonald, 1975; Mineyev, 1963). Experimental data show that F actively delays the withdrawal of Zr from magma (Dictrich, 1986; Aoki et al., 1981). Siddiqui et al., (1968) and Chaudhry et al., (1981) reported traces to 4% fluorite in Group II rocks of the Koga area. Our analyses of the Group II rocks contain 127 to 486 ppm F. Occurrence of fluorite has been reported in other post-orogenic alkaline rocks, e.g. alkaline granites of Arabia (Stoesser and Elliott, 1979). Enrichment of CO<sub>2</sub> in the successive phases of Group II rocks is suggested by the presence of carbonatite veins and plugs (Siddiqui et al., 1968; Rafiq, 1987).

The Nb content of Group II rocks has a considerable range from 75 to 210 ppm. Pearce and Gale (1977) and Harris (1981) reported low values of Nb (0–15 ppm) above subduction zones under the condition of high P<sub>H<sub>2</sub>O</sub>. Since the mantle wedge above subduction zone is modified by aqueous fluid derived from the dehydration of subducting lithosphere, this leads to the concentration of alkalis but not Zr, Nb and Y in the residual melt. In contrast, within plate magmatism has no equivalent H<sub>2</sub>O reservoir, consequently the volatile phase becomes enriched in non-hydrous components, leading to enrichment of Zr, Nb, Y, Ta. Plots of these HFS elements versus SiO<sub>2</sub> for the AGC rocks clearly discriminate them as the product of within plate magmatism (Fig. 9).

Over the past decade initial <sup>87</sup>Sr/<sup>86</sup>Sr ratios have been widely used to constrain petrogenetic models. Low initial ratios (0.701–0.706), according to Faure and Powell (1972), suggest mantle source and high ratios (> 0.720) indicate that the magma source lies in the crust. Intermediate to high ratios have been interpreted as indicating crustal contamination or hybridization of magmas of contrasting composition and source (Halliday et al., 1980).

Le Bas et al. (1986) have presented <sup>87</sup>Sr/<sup>86</sup>Sr data for eight samples mainly from the Group II rocks of AGC. These define a low initial <sup>87</sup>Sr/<sup>86</sup>Sr ratio of about 0.704, suggesting the involvement of mantle processes in their evolution. Rb decreases with desilicification from an average of 145 in quartz syenite and syenite to 23 ppm in the feldspathoidal syenite of Group II. Sr also increases from quartz syenite to feldspathoidal syenite (Appendix 3).

Keeping all these observations in view, the origin of Group II may in some way be connected to the upper mantle. This is because the asthenosphere represents a regional source of  $\text{CO}_2$  (Wyllie, 1977) and because undersaturated to strongly undersaturated magmas may not be derived from partial melting of common crustal rocks. But the close association in space and time of the two groups of rocks in AGC suggests that their origin cannot be totally divorced from each other. Of the several mechanisms proposed for the origin of alkaline rocks, the following two appear to be more relevant for the origin of the AGC.

1. Derivation from a quartz-trachytic magma through crystal differentiation, which in turn was derived from an alkaline-olivine basalt (Bailey and Schairer, 1964).
2. Partial melting in the deep crust (leading to the formation of Group I rocks), followed by successive addition of influx from the underlying mantle to the down-sagging magma chamber, leading to Group II rocks.

Keeping in view the small volume of Group II rocks as compared to the granites of Group I, a simple crystal differentiation from a common trachytic magma cannot be invoked. According to Bailey and Schairer (1964), differentiation of such a magma would lead either to oversaturated (rhyolitic endpoint, as Kungnat complex, South Greenland; Upton, 1960) or to undersaturated rocks as in the Gardar province of South Greenland; Upton, 1960). Unambiguous intrusive contacts and fenitization associated with successive desilicified phases of Group II suggest that these were the late magmatic phases, rather than representing the initial parent magma. Therefore, we prefer the second hypothesis.

Crustal thinning, thermal perturbation in the asthenosphere, progressive deepening of the source region and/or presence of a hot spot may have activated the upper mantle. Influx of appropriate components including non-hydrous volatiles and alkalis from the activated mantle caused the desilicification of the overlying residual crustal melt. This led to a variety of "hybrid" rocks, i.e. quartz syenite, syenite, feldspathoidal syenite, etc. of Group II. The progressive desilicification can also be explained in terms of progressive deepening of the source (Wyllie and Huang, 1976), and increase of  $\text{CO}_2$  (Eggler, 1978) or F (Manning et al., 1980) or combination of these (Harris, 1981).

Successive phases forming rocks of Group II became enriched in carbonate resulting in carbonatite plugs, veins and attendant fenites (Chaudry et al., 1981; Rafiq, 1987; Rafiq and Jan, 1988) in the presence of non-hydrous phases (F,  $\text{CO}_2$ , Cl) derived from the upper mantle. However, carbonate rich magma may exist in the asthenosphere (Wyllie, 1977) and the possibility of liquid immiscibility cannot be totally ruled out for the carbonatites and ijolites (I. Mian, pers. comm.).

To summarise this discussion, we suggest that the Ambela granitic complex has a two-fold origin. Crustal arching and swelling may have led to partial melting of the crust and generation of silicic magma that produced the granitic rocks of Group I. During succeeding phases, the crustal melts were progressively modified (mainly desilicified) in composition due to an influx of material (mainly alkalis and volatiles) from the underlying upper mantle that was activated. This resulted in a range of strongly alkaline rocks that characterise the Group II association. A hypothetical model for the evolution of the complex is shown in Fig. 11.

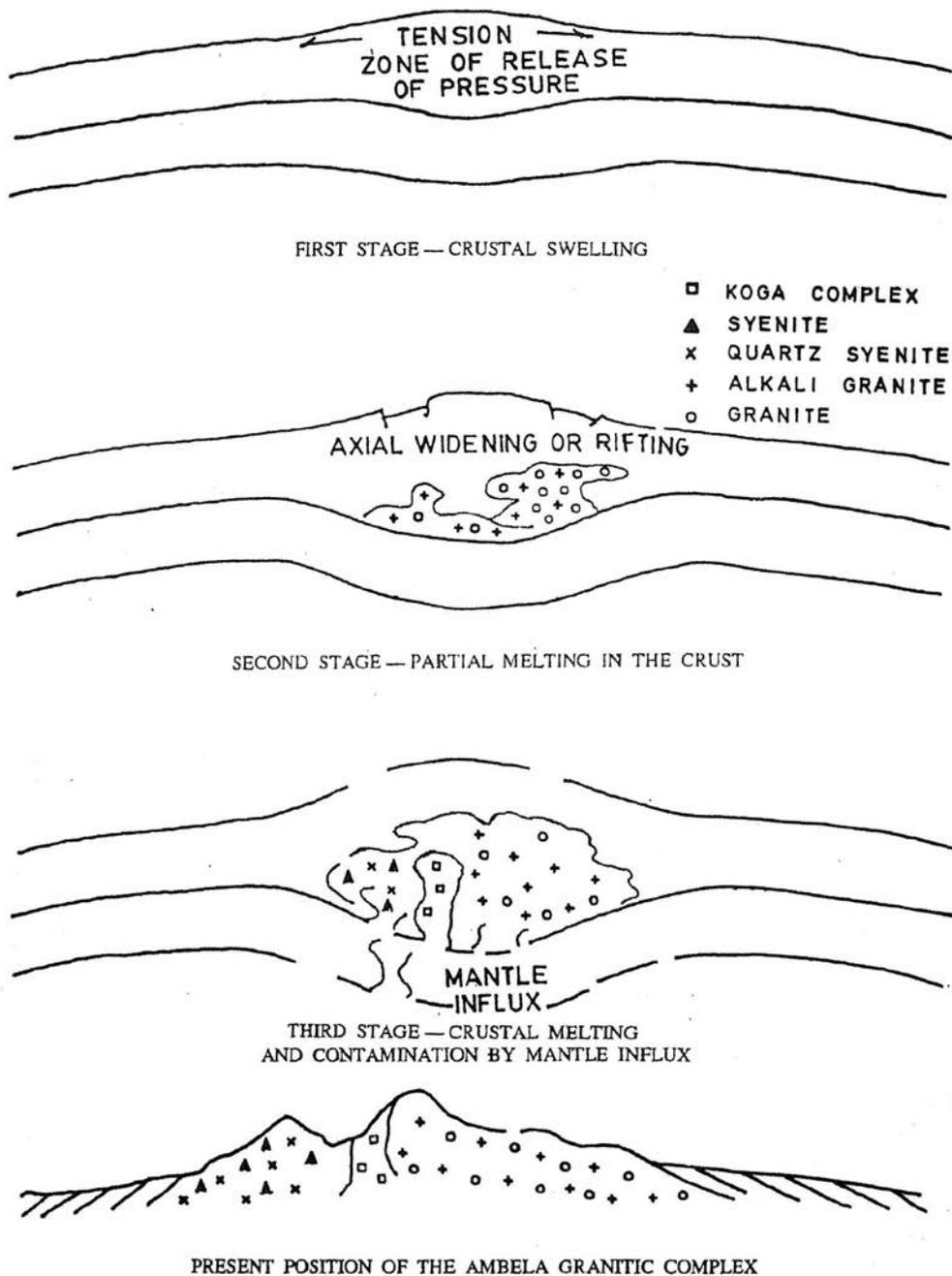


Fig. 11. Hypothetical cartoon showing the evolution of the Ambela granitic complex.

The alkaline rocks of Koga area in the AGC have Rb-Sr isochron ages of  $297 \pm 4$  and  $315 \pm 15$  m.y. (Le Bas et al., 1986). Carboniferous U-Pb Zr ages have also been reported for these rocks and the Malakand alkali granite (Zietler, 1988). Kempe (1986) has reported a K/Ar hornblende age from the nearby Tarbela 'alkaline complex' (Jan et al., 1981). These ages are in agreement with the late Carboniferous and Permian fossil ages for the voluminous rift-related Panjal volcanics of Kashmir (Honegger et al., 1982). It is possible that the entire region witnessed crustal thinning and rifting towards the end of the Palaeozoic.

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## APPENDIX I. REPRESENTATIVE ANALYSES (WT. %) AND CIPW NORMS OF THE GRANITIC ROCKS (GROUP 1) FROM THE AMBELA GRANITIC COMPLEX

S. No.	731	649	680	725	394	692	716	728	395	13	355	375	510	170	327	391
SiO <sub>2</sub>	64.62	74.60	74.55	72.06	77.64	72.80	71.38	70.88	76.00	75.03	75.51	76.06	75.84	77.53	77.20	76.50
TiO <sub>2</sub>	0.62	0.79	0.58	0.42	0.55	0.55	0.73	0.53	0.20	0.21	0.07	0.16	0.04	0.12	0.49	0.04
Al <sub>2</sub> O <sub>3</sub>	18.65	13.40	12.59	14.20	11.70	14.64	15.29	13.78	13.11	14.32	13.25	12.80	13.13	12.31	12.97	13.17
Fe <sub>2</sub> O <sub>3</sub>	1.90	2.60	2.75	2.40	0.84	2.90	0.30	0.60	1.20	0.80	1.66	1.40	0.31	0.82	0.95	0.17
FeO	1.17	0.34	0.23	2.39	0.30	0.00	1.64	2.40	1.00	0.40	0.10	0.00	0.11	0.10	0.70	0.32
MnO	0.07	0.07	0.07	0.07	0.03	0.07	0.05	0.70	0.03	0.04	0.04	0.01	0.01	0.02	0.06	0.03
MgO	1.31	1.60	1.14	0.99	0.34	1.32	0.96	1.12	0.38	0.45	0.06	0.05	0.12	0.12	0.22	0.08
CaO	2.59	0.71	1.13	0.86	0.50	1.07	0.92	1.08	0.58	0.28	0.30	0.42	0.15	0.14	0.16	0.60
Na <sub>2</sub> O	4.15	2.18	2.34	2.97	3.02	2.74	2.66	2.50	3.02	3.76	4.42	4.33	5.53	3.71	4.40	5.00
K <sub>2</sub> O	3.63	4.01	4.22	4.15	4.32	4.00	5.54	4.74	4.97	5.72	5.06	4.71	4.03	4.47	4.24	4.00
H <sub>2</sub> O <sup>-</sup>	0.01	0.02	0.00	0.00	.02	0.02	0.00	0.00	0.10	n.d.	0.06	0.15	0.20	0.03	0.05	0.10
H <sub>2</sub> O <sup>+</sup>	1.50	0.50	0.80	0.20	0.35	1.10	0.20	0.80	0.54	n.d.	0.10	0.18	0.80	0.85	0.20	0.47
P <sub>2</sub> O <sub>5</sub>	0.14	0.14	0.16	0.22	0.05	0.11	0.15	0.15	0.11	0.11	0.02	0.02	0.05	0.02	0.00	0.03
Total	100.36	100.96	100.56	100.93	99.66	101.32	99.82	99.28	101.24	101.12	100.65	100.29	100.32	100.24	101.64	100.51

## CIPW NORMS

Q	19.71	41.77	41.22	35.20	42.84	37.61	31.10	33.93	39.53	29.98	29.62	32.01	28.65	36.67	34.43	30.83
Or	21.70	22.93	25.00	23.94	25.97	23.60	32.86	28.62	26.39	33.43	29.75	27.84	23.98	26.58	24.64	23.65
Ab	35.52	17.85	19.85	24.53	26.00	23.14	22.59	21.62	25.53	31.46	37.22	36.65	45.54	31.59	36.61	42.33
An	12.07	2.52	4.57	3.25	2.19	4.43	3.60	4.47	2.16	0.66	1.35	1.65	0.00	0.57	0.78	1.75
C	3.60	5.66	2.53	4.23	0.29	4.20	3.65	3.02	2.54	1.71	0.03	0.00	0.00	1.19	0.86	0.00
Ac	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.90	0.00	0.00	0.00
Cpx	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.34	0.00	0.00	0.88
Hy	3.30	3.86	2.85	4.21	0.86	3.28	4.06	3.09	1.52	1.11	0.15	0.12	0.29	0.30	0.54	0.19
Mt	2.23	2.56	0.00	3.40	0.00	0.00	0.44	0.89	1.74	0.80	0.25	0.00	0.00	0.04	0.01	0.25
Hm	0.39	0.75	2.76	0.00	0.85	2.90	0.00	0.00	0.00	0.24	1.48	1.90	0.00	0.80	0.23	0.00
Il	1.19	1.82	0.64	0.78	0.71	0.15	1.39	1.03	0.38	0.39	0.13	0.02	0.08	0.23	0.92	0.08
Py	0.31	0.30	0.35	0.47	0.11	0.24	0.33	0.33	0.24	0.24	0.04	0.04	0.11	0.04	0.00	0.07

731-13 granites; 335-391 alkali granites; n.d. = not done.

APPENDIX 2. TRACE ELEMENT (IN PPM) CONTENT OF REPRESENTATIVE GRANITIC ROCKS FROM THE AMBELA GRANITIC COMPLEX.

S. No.	731	649	680	725	394	692	716	728	395	13	355	327	375	510	170	391
Ni	62	64	66	66	—	63	58	61	18	79	—	58	—	71	35	82
Cr	70	61	95	148	—	71	67	80	3	28	—	81	—	70	59	11
Sr	150	65	94	67	239	96	133	86	338	62	43	36	23	98	88	118
Nb	12	17	11	19	41	12	11	11	67	17	121	95	133	639	25	152
Co	52	90	125	54	—	—	58	92	111	116	—	144	—	90	96	188
Rb	223	298	250	396	160	273	257	267	165	290	177	186	177	335	209	206
Y	57	73	60	69	102	59	54	64	58	59	141	71	143	92	68	109
Ba	351	372	392	234	1173	49	997	463	1410	337	569	143	454	69	189	69
Cs	—	—	—	—	—	—	—	—	3	—	—	—	—	7	4	6
Ce	103	129	133	101	783	117	115	121	375	94	586	196	570	297	344	299
V	24	41	25	7	—	14	—	17	1	—	—	—	—	1	—	1
Zr	187	193	174	130	288	164	127	167	3	88	72	315	591	7	3	2
Cl	—	—	—	—	—	—	—	—	—	—	—	—	—	81	57	—
Gd	—	—	—	—	—	—	—	—	19	—	—	—	—	16	15	25
Er	—	—	—	—	—	—	—	—	870	—	—	—	—	970	961	901
Nd	—	—	—	—	—	—	—	—	178	—	—	—	—	122	123	164
F	—	—	—	—	—	—	—	—	1846	—	—	651	—	—	540	—
Sn	—	—	—	—	—	—	—	—	41	—	—	—	—	53	69	50
Zn	64	13	75	71	—	66	48	67	161	60	—	44	—	217	330	143
S	—	—	—	—	—	—	—	—	—	—	—	—	—	341	145	77
Th	—	—	—	—	30	—	—	—	—	24	25	—	28	—	—	—
U	—	—	—	—	4	—	—	—	—	4	5	—	4	—	—	—
Ta	—	—	—	—	2	—	—	—	—	2	2	—	2	—	—	—
K/Rb	135	111	140	95	223	121	178	147	225	163	236	183	220	99	177	161
K/Ba	85	89	89	153	30	67	46	84	26	140	73	91	85	483	195	478
K/Sr	200	477	373	511	149	345	344	454	109	768	983	750	1697	341	423	281

713-13 granites; 355-391 alkali granites.

APPENDIX 3. SELECTED ANALYSES (Wt. %) AND CIPW NORMS OF THE SYENITIC ROCKS (GROUP II).

S. No.	12'	234	377	220	214	9'	100	261
SiO <sub>2</sub>	66.72	64.19	63.58	61.75	62.79	65.47	61.08	59.52
TiO <sub>2</sub>	0.43	0.80	0.72	0.52	1.10	0.68	0.10	0.22
Al <sub>2</sub> O <sub>3</sub>	16.39	15.72	15.25	18.45	16.15	18.08	19.90	21.93
Fe <sub>2</sub> O <sub>3</sub>	2.80	2.32	1.93	3.27	4.95	1.00	2.60	2.89
FeO	1.28	2.10	4.80	1.20	0.00	1.20	0.07	0.00
MnO	0.03	0.10	0.07	0.10	0.10	0.11	0.00	0.08
MgO	0.24	1.27	0.85	0.53	1.00	0.59	0.80	0.36
CaO	0.65	2.26	2.72	1.25	2.50	0.41	0.60	0.50
Na <sub>2</sub> O	4.90	5.25	4.19	5.81	5.00	6.70	8.73	8.84
K <sub>2</sub> O	5.40	4.59	4.44	5.92	4.72	5.26	5.14	4.86
H <sub>2</sub> O <sup>-</sup>	0.03	0.10	0.21	0.25	0.22	0.20	n.d.	n.d.
H <sub>2</sub> O <sup>+</sup>	0.51	0.50	0.30	0.64	0.45	0.60	n.d.	n.d.
P <sub>2</sub> O <sub>5</sub>	0.05	0.03	0.49	0.11	0.24	0.22	0.00	0.00
Total	99.43	99.23	99.55	99.80	99.22	100.52	99.02	99.20

CIPW NORMS

Q	16.13	11.59	20.76	2.17	10.29	6.81	0.00	0.00
Or	32.27	25.88	26.98	35.37	28.30	31.26	30.37	28.72
Ab	41.92	45.04	27.76	49.70	42.93	54.47	54.37	48.98
An	2.93	6.75	10.59	5.54	7.88	0.60	2.98	2.48
Ne	0.00	0.00	0.00	0.00	0.00	0.00	5.98	13.99
C	1.47	0.00	1.49	0.52	0.00	1.68	0.53	1.22
Cpx	0.00	2.10	0.00	0.00	0.00	0.00	0.00	0.00
Hy	0.60	3.02	7.00	1.33	2.53	1.94	0.00	0.00
Ol	0.00	0.00	0.00	0.00	0.00	0.00	0.52	0.63
Mt	3.01	3.41	2.88	2.72	0.00	1.46	0.00	0.00
Hm	0.76	0.00	0.00	1.43	5.02	0.00	2.60	2.89
Il	0.83	1.54	1.41	1.00	0.22	1.30	0.15	0.17
Py	0.11	0.66	1.10	0.24	0.53	0.48	0.00	0.00

12-377 quartz syenites; 220-9' syenites; 100-261 feldspathoidal syenites.

TRACE ELEMENT CONTENT (IN PPM) OF THE SYENITIC ROCKS.

S. No.	12'	234	220	214	9'	230	100	261
Ni	—	226	218	—	43	—	220	209
Cr	—	141	130	—	25	50	844	575
Sr	81	529	168	600	40	113	1036	527
Nb	28	121	144	87	29	111	40	42
Co	—	71	43	—	13	64	533	972
Rb	194	197	145	158	102	102	22	25
Y	113	55	53	90	29	47	4	5
Ba	621	639	405	843	1107	1081	58	57
Cs	—	3	3	—	—	2	3	3
Ce	472	290	217	496	138	234	406	481
V	—	1	1	—	—	1	—	—
Zr	11	5	7	682	113	5	—	—
Cl	—	—	—	—	—	430	—	—
Gd	—	—	—	—	—	23	—	—
Er	—	—	821	—	—	648	—	—
Nd	—	805	153	—	—	165	—	—
F	—	140	—	—	—	12	—	—
Sn	—	4	25	—	—	27	—	—
Zn	—	222	248	—	76	—	—	—
S	—	222	200	—	—	—	—	—
Th	28	—	—	17	—	—	—	—
U	5	—	—	3	—	—	—	—
T	2	—	—	4	—	—	—	—
K/Rb	191	182	338	247	425	277	193	192
K/Ba	59	55	121	46	39	26	41	76
K/Sr	456	67	291	65	1094	251	50	70

n.d. = not determined.