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# MAJOR ELEMENTS ABUNDANCE IN THE KALAM LAVAS

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## ABSTRACT

*Andesite and salic eruptives of calc–alkaline affinity in the Kalam volcanic zone constitute the upper part of the 'Kohistan sequence' (Tahirkheli et al., 1979) developed in the western branch of the Himalayan syntaxis between 71°E and 75 E. The sequence is interpreted as a complete cross section of a mature island arc formed by subduction during Mesozoic in the southern part of the Neotethys and obducted onto the Indian plate in Upper Cretaceous time (Bard et al., 1980). The Kohistan sequence includes a thick complex of amphibolites, hypersthene gabbros, pyroxene diorites, hornblende diorites, granodiorites, metasediments and volcanic rocks.*

*The potential usefulness of the geochemical parameters of the extrusive rocks from the Kalam area, Swat as tectonic fingerprints and gentic indicators is discussed in this paper. There is a close correspondence between the available petrochemical indices of genetic significance of the studied suite to the calc-alkaline volcanics in western and southwestern Pacific regions, which substantiates earlier workers' designation of an Island arc environment in the Kohistan Himalaya during Mesozoic time.*

## INTRODUCTION

Calc-alkaline volcanism is widespread in a northeast-southwest elongated volcanic belt stretching from Kalam through Dir and Bajaur to the northern part of Mohmand Agency. This is one of the volcanic province in the Kohistan Himalaya and has been described as the 'Kalam volcanic zone'. Further north there is another volcanic province within which lavas are exposed in an arcuate fashion more or less following the trend of the Main Karakoram Thrust right from Lowari top in Chitral through Yasin up to east of Shigar river in the Gilgit Agency as shown in Fig 1. (the Rakaposhi volcanic complex, Tahirkheli, 1981).

Within the Kalam volcanic zone the most extensive and spectacular activity is observed in the north and northwest of Kalam in the northern Swat. Excellent accounts of petrology of lavas from this area are given by Jan and Mian (1971), Majid and Paracha (1980). In a preliminary geological map of Kohistan and adjoining areas Tahirkheli and Jan (1979) have shown lavas for most of the

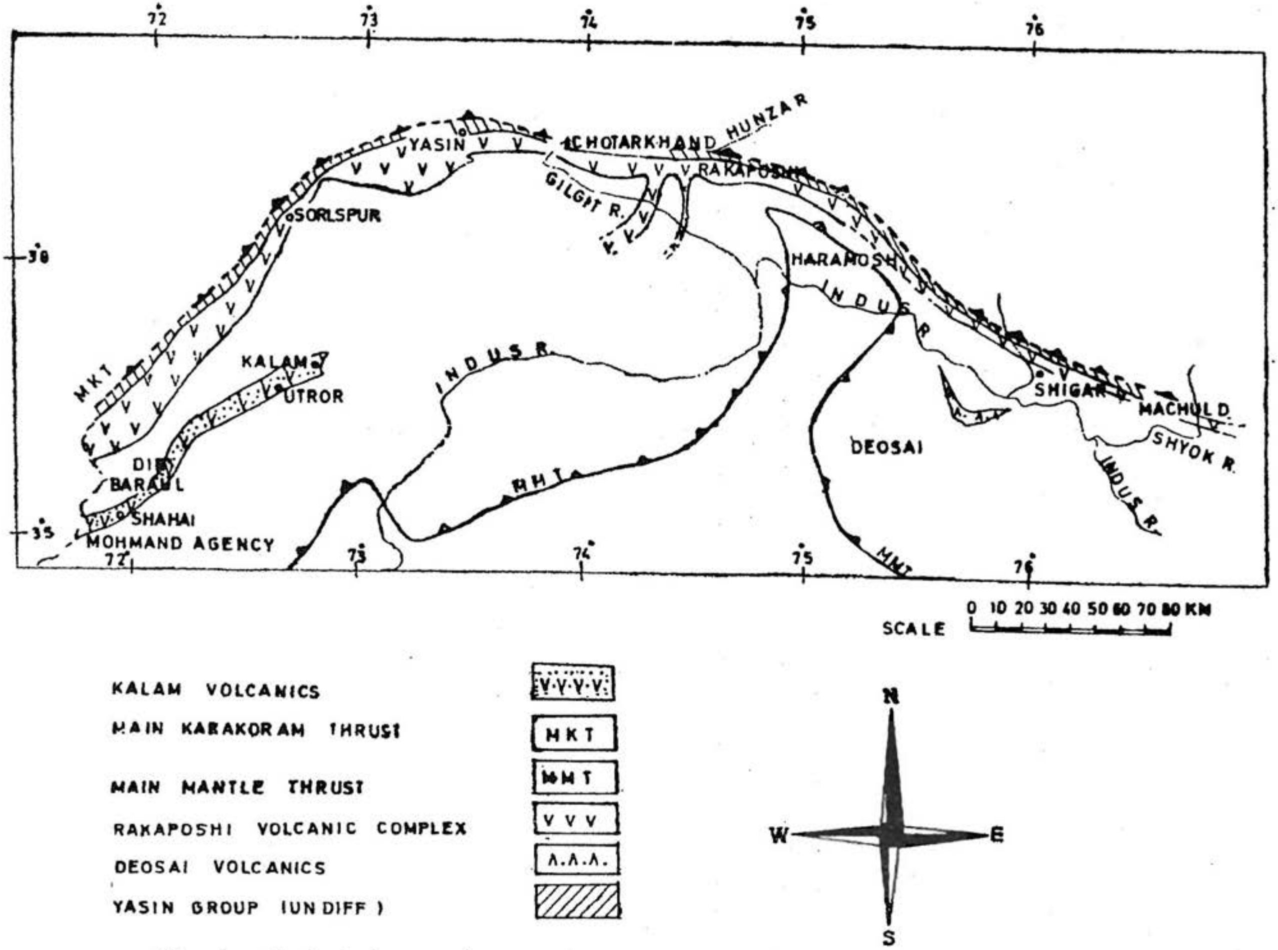


Fig. 1. Geological map showing distribution of volcanics in Kohistan, Northern Pakistan. (After R.A. Tahirkheli 1981)

length of the Kalam volcanic zone bordered by Deshai diorites in the north and metasediments in the south. Khan (1979) described lavas of the Kalam volcanic zone developed in the Barual Valley of Dir, west of Kalam. Further west the volcanic extend through the Mamun Salarzai area of Bajaur to the northern Jandul (Kakar *et al.,* 1971). In the northern part of Mohmand Agency and in the Mamun area of Bajaur, lavas are concentrated around a group of small volcanic necks (Badshah, **1979**).

The generalized sequence of volcanic rocks within the Kalam zone indicates that salic eruptives are the most voluminous rock types between Bahan Khwar and Utror in the eastern extremely of the volcanic belt. These are associated with andesites in Utror, Dir and Bajaur. Color variations and widespread alterations of the nature of chloritization and epidotization are the most significant features of almost all volcanics.

Sultan (1970) correlated the volcanics of the Kalam zone on the basis of a very restricted study of lavas in the vicinity of Utror with the Panjal eruptive rocks of Upper Carboniferous age (Davies, 1956), Wadia, 1966) in Kashmir Valley. In a recent description of geological zonation of Karakoram and southern Hindukush in Pakistan, Tahirkheli (1981) assigned a comparatively younger age to lavas of the Kalam volcanic zone by considering them equivalent to the Deosai volcanics of late Upper Eocene age exposed near Skardu in Gilgit Agency.

Lavas of the Kalam volcanic zone are recently interpreted as part of the 'Kohistan sequence' (Tahirkheli *et al.,* 1979) which is considered as a cross section of the crust of an island arc developed during the suturing of Indo-Pakistan and Eurasia. This study attempts to document and clarify the petrologic and geochemical relationships of the lavas within the Kalam volcanic zone, which at least in the field appear to be genetically related. The particular attraction of the volcanic sequence in the vicinity of Kalam lies in the association of several chemically distinct rhyolite types, dacite and andesite flows.

In view of the tectonic setting of Kohistan, the petrochemical indices of these rocks are compared with published geochemical data for the equivalent volcanic suites of various geographic and/or tectonic regions where subduction is interpretted to play a key role in magma genesis.

## PETROGRAPHY

Petrologic sampling has been virtually limited to stream sections and road cuts. Almost all the volcanic rocks from the studied suite are porphyretic with phenocrysts of plagioclase and ferromagnesian minerals commonly replaced by chlorite in the basic volcanics, and plagioclase, quartz in the salic eruptives. The salic volcanics are by far most plentiful rocks in the studied area. In most of the studied samples the modal mineral contents can not be accurately determined because of the microcrystalline or even glassy texture of the groundmass. Their nomenclature, therefore, necessitates the recalculation of the chemistry in to the necessary normative mineralogy to determine their position in the QAPF diagram of IUGS classification and nomenclature of volcanic rocks (Streckeisen, 1979). The data points are confined to the fields of andesite, dacite and rhyolite. Few samples plot close to the boundary line of field No. 4 and 3b and are described as rhyodacites.

### *Rhyolite*

A generalized stratigraphic sequence of volcanics in a section along the Gabral River between Bahan Khwar and Utror Village, lavas specified as rhyolite constitute upper parts of the volcanic sequence. These are hard and compact rocks brownish in Color and porphyretic in texture and are of one feldspar type, having plagioclase ($An_{11-28}\%$) as the only feldspar phenocryst. Interbedding of light colored flows with the brownish lavas is conspicuous.

Post to the main rhyolite extrusive phase there are rhyolite dikes of greyish-white color with fragments of basic volcanics and maroon-coloured glassy rocks. Samples of the dike rocks are obtained from stream section northeast of Batander Banda. These are porphyretic rocks with phenocrysts of plagioclase, and quartz. The phenocryst content is more than 50%, no glass is present in the groundmass. The brown-colored lavas form the main rhyolite flows are characterized by having a more or less glassy groundmass riddled with dust like brown iron oxide grains.

### *Dacite*

Banded dacite underlain the maroon – colored rhyolites. In hand specimens these are greenish-grey to dark green in color with abundant white phenocrysts. Inclusion of small fragments are common. Important phenocryst minerals include plagioclase ($An_{33-46}\%$) and quartz. Fresh phenocrysts of ferromagnesian minerals are rare. Groundmass is rich in feldspar, quartz and devetrified brownish glass. Some of the studied samples on the basis of normative QAP, plot close to the boundary line of dacite and rhyolite field on the QAP triangle (Fig 2) and are described as rhyodacite. Distinction of such lavas from dacite in the field or in thin section is however difficult.

### *Andesite*

Andesite is developed in the Kalam volcanic zone at Utror (Majid and Paracha, 1980; Jan and Mian, 1971) Baraul in Dir (Khan, 1979) and in Bajaur and northern part of Mohmand Agency (Badshah, 1979).

The phenocrysts of ferromagnesian minerals are almost invariably chloritized though fresh brownish-green hornblende in the andesite of Baraul and

Utror is exception. Plagioclase with anorthite contents ranging from 32 to 59 per cent is generally sericitized. Groundmass minerals include plagioclase, epidote, chlorite, carbonate, opaque minerals and rarely quartz. Sericite, chlorite and carbonate locally occur as patches.

## MAJOR ELEMENT CHEMISTRY

Major element chemical analyses of dacite and rhyolite alongwith andesite are presented in Table 1. It includes 14 new analyses of salic eruptives ($SiO_2 > 60\%$) as well as analyses originally published by Majid and Paracha (1980). $SiO_2$ has been determined by gravimetric method, $Al_2O_3$ and CaO by volumetric, and the remaining elements by atomic absorption spectrophotogetry. The data is presented diagrammatically in a series of plots to test in a qualitative sence the degree to which their distribution described a chemical trend and to demonstrate the degree of coincidence elements of the studied suite with the similar rock populations developed in various geographic and/or tectonic regions (e.g. the salic volcanic suite of the western U.S.A., excluding Casacades, the Andean province of western South America, Japan, Taiwan, Kuriles, Kamchatka, Saipan and S.W. Pacific regions including Papua, New Guinea, Fiji, New Zealand etc.).

Analyses of the salic eruptives with $SiO_2 > 60\%$ are tabulated into five chemical groups using the $SiO_2$ intervals (60–63, 63–66, 66–69, 69–73,

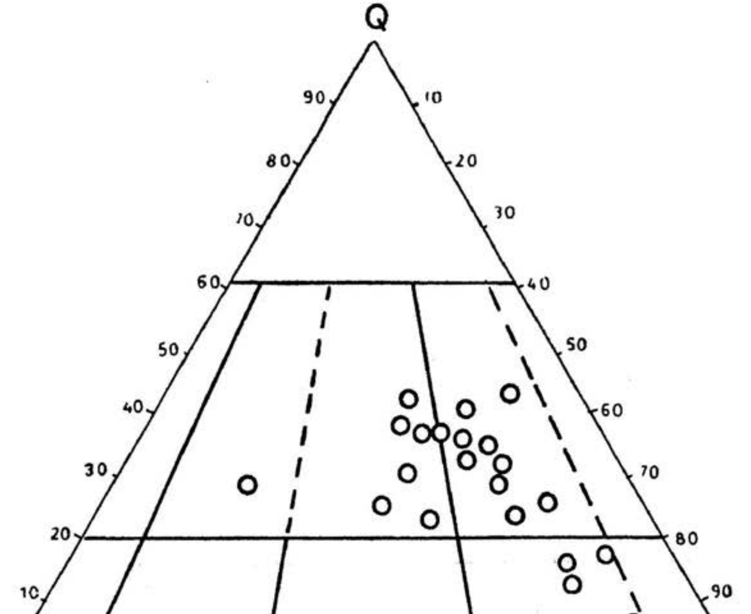


Fig. 2. Ternary plot of normative Q–A–P of the lavas of Kalam volcanic zone after Streckeisen (1979).

> 73% $SiO_2$) suggested for silicic lavas of subduction tectonic environments (Ewart, 1979). Some of the specimens which are described as dacite and rhyodacite on the basis of their normative mineral compositions, however, fall within the range of rhyolite in the chemical classification scheme of salic eruptive rocks of orogenic zones. According to the definition of Taylor (1969) basic members of volcanics are mostly normal andesites. Recalculated to 100 on anhydrous basis the data is presented in Table 2 alongwith the analyses of andesites. Except the siliceous andesite, most of the samples typically contain on the average 2.4 per cent normative corundum where as two compositions (Ba–18 and BB–10) having $SiO_2$ within the range of 72–73% are wollastonite normative (0.08–0.14%). Sample No. Ba–15 is unique in composition by having 1.6% acmite and 3% sodium metasilicate (NS) in the CIPW norms. Composition No. Ba–18 on the other hand has only 4% sodium metasilicate.

From a first glance at the analyses in Table 2 it is apparent that with an increase in the contents of $SiO_2$ the rocks are enriched in $K_2O$ relative to $Na_2O$. This results in a K–rich rather than Na–rich variation trend on the $CaO - Na_2O - K_2O$ plot, (Fig. 3). The chemistry is also reflected in the nor-

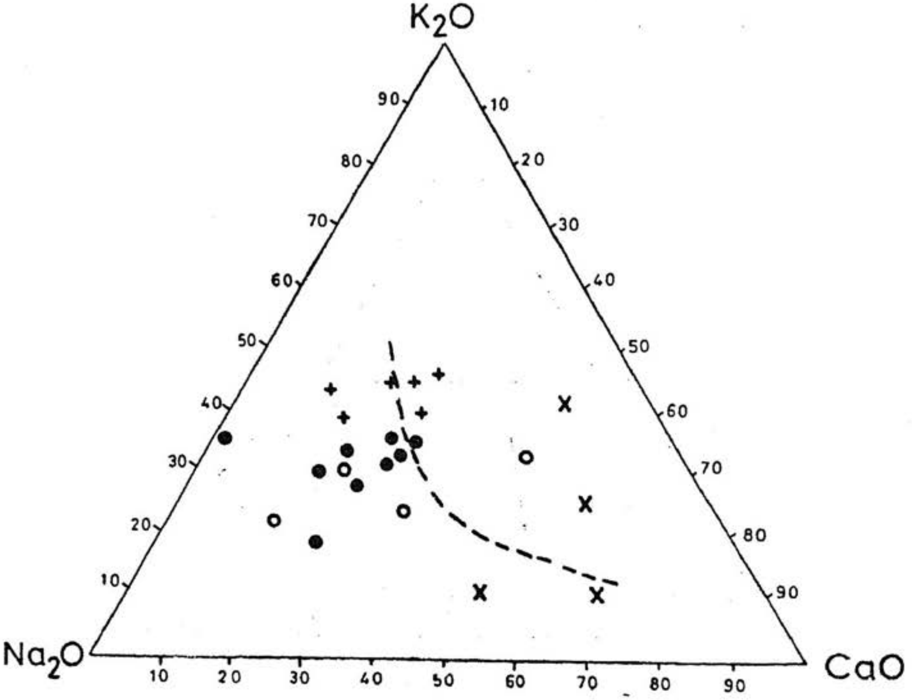


Fig. 3. $CaO–Na_2O–K_2O$ plot for the andesitic and salic lavas of Kalam volcanic zone.
The symbols used are:
X = andesite
● = rhyolite
o = dacite
+ = high-K rhyolite.

TABLE 1. COMPILIATION OF TOTAL MAJOR ELEMENT DATA AND CIPW NORMS FOR ANDESITES AND SALIC ROCKS FROM KALAM VOLCANIC ZONE.

| Rocks | Andesite | | | | Dacite | | | | Rhyolite | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Samples No. | B–12 | Low-silica andesite | P–7 | Normal andesite | B–18 | P–6 | B–2 | B–19 | B–4 | Ba–21 | Ba–15 | Ba–1 | Ba–18 | Ba–23 | Ba–19 | Ba–2 | Ba–9 | Ba–6 | BB–10 | BB–1 | BB–11 | B–21 |
| $SiO_2$ | 54.00 | 54.75 | 56.11 | 58.85 | 62.17 | 64.40 | 66.33 | 67.42 | 63.64 | 68.85 | 69.10 | 70.49 | 70.51 | 70.69 | 70.71 | 71.20 | 71.50 | 71.70 | 72.95 | 73.58 | 73.64 | 75.10 |
| $TiO_2$ | 0.74 | 0.60 | 0.60 | 0.65 | — | 0.28 | 0.45 | 0.61 | 0.40 | 0.32 | 0.48 | 0.62 | 0.59 | 0.47 | 0.52 | 0.43 | 0.49 | 0.51 | 0.61 | 0.51 | 0.46 | 0.10 |
| $Al_2O_3$ | 15.09 | 16.41 | 16.98 | 15.69 | 15.03 | 16.90 | 16.05 | 15.35 | 15.03 | 15.79 | 12.60 | 13.73 | 11.99 | 12.96 | 12.80 | 12.85 | 12.89 | 12.93 | 12.66 | 12.91 | 12.00 | 13.50 |
| $Fe_2O_3$ | — | — | — | — | — | — | — | — | — | 1.53 | 0.58 | 0.91 | — | 0.71 | 1.28 | 0.16 | 0.07 | 0.07 | 1.27 | 0.60 | 1.31 | — |
| FeO | 7.98* | 8.76* | 9.50* | 6.99* | 3.72* | 5.60* | 3.24* | 3.98* | 2.08* | 0.04 | 0.77 | 0.81 | 0.94 | 1.33 | 1.01 | 1.02 | 1.45 | 1.30 | 0.83 | 1.37 | 0.77 | 2.86 |
| MnO | 0.19 | — | 0.16 | — | 0.11 | 0.10 | 0.12 | 0.10 | 0.08 | 0.06 | 0.04 | 0.04 | 0.04 | 0.05 | 0.05 | 0.06 | 0.07 | 0.07 | 0.05 | 0.09 | 0.05 | 0.07 |
| MgO | 4.44 | 5.01 | 2.05 | 4.30 | 0.97 | 1.04 | 0.93 | 1.01 | 0.16 | 2.76 | 0.49 | 0.34 | 0.41 | 0.51 | 0.40 | 0.56 | 0.62 | 0.42 | 0.49 | 0.39 | 0.48 | 0.50 |
| CaO | 5.80 | 8.12 | 4.09 | 6.79 | 2.70 | 4.60 | 1.60 | 1.88 | 2.16 | 3.48 | 2.20 | 2.00 | 1.85 | 2.78 | 1.75 | 2.78 | 2.49 | 2.40 | 1.79 | 1.69 | 1.69 | 0.10 |
| $Na_2O$ | 4.61 | 2.85 | 3.55 | 2.79 | 3.68 | 3.23 | 6.35 | 4.44 | 3.30 | 2.99 | 5.67 | 4.22 | 5.28 | 3.55 | 2.82 | 3.31 | 2.53 | 3.02 | 4.89 | 4.28 | 3.72 | 5.46 |
| $K_2O$ | 1.16 | 1.11 | 1.09 | 1.80 | 1.99 | 2.06 | 2.30 | 2.70 | 2.36 | 0.59 | 4.75 | 2.62 | 5.27 | 3.10 | 3.53 | 4.61 | 4.03 | 3.71 | 2.74 | 1.36 | 2.56 | 3.00 |
| ZnO | — | — | — | — | — | — | — | — | — | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.02 | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | — |
| $P_2O_5$ | 0.35 | 0.20 | 0.27 | — | 0.30 | 0.11 | 0.38 | 0.37 | 0.35 | 0.59 | 0.70 | 0.53 | 0.49 | 0.49 | 0.60 | 0.68 | 0.61 | 0.59 | 0.48 | 0.59 | 0.61 | 0.15 |
| $H_2O+$ | — | — | — | — | — | — | — | — | — | 2.37 | 1.57 | 2.91 | 1.97 | 2.61 | 2.53 | 1.87 | 2.74 | 1.97 | 1.53 | 2.10 | 2.13 | — |
| Total | 94.36 | 97.81 | 94.35 | 97.81 | 90.63 | 98.32 | 97.75 | 97.86 | 89.56 | 99.54 | 98.95 | 99.23 | 99.35 | 99.27 | 98.02 | 99.54 | 99.51 | 98.69 | 100.3 | 99.48 | 99.43 | 100.84 |

CIPW NORMS OF KALAM VOLCANICS

| | B–12 | Low-silica andesite | P–7 | Normal andesite | B–18 | P–6 | B–2 | B–19 | B–4 | Ba–21 | Ba–15 | Ba–1 | Ba–18 | Ba–23 | Ba–19 | Ba–2 | Ba–9 | Ba–6 | BB–10 | BB–1 | BB–11 | B–21 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Qz | 3.7 | 4.74 | 12.72 | 10.81 | 24.36 | 21.76 | 14.20 | 22.76 | 31.42 | 30.52 | 19.34 | 31.67 | 23.76 | 31.36 | 40.22 | 28.57 | 33.18 | 34.59 | 29.68 | 37.65 | 37.89 | 20.02 |
| Or | 7.45 | 6.74 | 6.92 | 10.95 | 12.93 | 13.10 | 13.70 | 16.38 | 15.75 | 18.35 | 28.55 | 16.20 | 31.97 | 19.22 | 21.30 | 28.20 | 25.05 | 23.05 | 16.59 | 8.41 | 15.82 | 16.70 |
| Ab | 44.95 | 26.24 | 34.15 | 25.72 | 36.42 | 29.35 | 57.40 | 40.83 | 33.35 | 33.42 | 41.25 | 39.59 | 35.11 | 33.35 | 26.75 | 30.70 | 23.90 | 28.45 | 44.89 | 39.97 | 34.85 | 46.15 |
| An | 18.54 | 29.43 | 19.65 | 25.48 | 12.71 | 22.60 | 5.50 | 7.10 | 9.55 | 10.43 | — | 6.75 | — | 10.74 | 4.35 | 6.77 | 12.50 | 8.50 | 3.19 | 8.62 | 4.61 | 2.60 |
| Ns | — | — | — | — | — | — | — | — | — | — | 2.52 | — | 3.85 | — | — | — | — | — | — | — | — | — |
| Ac | — | — | — | — | — | — | — | — | — | — | 1.64 | — | — | — | — | — | — | — | — | — | — | — |
| C | — | — | 3.80 | — | 3.23 | 1.13 | 1.22 | 2.89 | 4.84 | 3.67 | — | 1.80 | — | — | 3.26 | — | — | 1.09 | — | 1.59 | 1.69 | — |
| Wo | — | — | — | — | — | — | — | — | — | — | 0.52 | — | 1.62 | — | — | — | — | — | — | — | — | 3.26 |
| Di | 10.1 | 8.49 | — | 7.33 | — | — | — | — | — | — | 0.52 | — | 1.67 | 0.30 | — | 2.80 | 0.40 | — | 2.17 | — | — | 10.56 |
| En | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | 0.31 | — | — | — |
| Hy | 8.56 | 23.10 | 21.22 | 18.80 | 9.56 | 11.40 | 7.23 | 5.69 | 3.64 | 2.44 | — | 1.18 | — | 2.38 | 1.18 | 0.71 | 2.44 | 1.07 | — | 2.32 | 1.99 | — |
| Mt | — | — | — | — | — | — | — | — | — | 0.65 | — | 0.75 | — | 0.78 | 0.20 | 0.37 | 0.46 | 0.39 | 0.77 | 0.65 | — | — |
| Ap | 0.06 | 0.48 | 0.68 | — | 0.78 | — | 0.90 | 0.89 | 0.90 | 1.44 | 1.71 | 1.16 | 1.18 | 1.21 | 1.55 | 1.27 | 1.34 | 1.30 | 1.15 | 0.05 | 1.50 | 0.33 |
| Il | 6.35 | 0.86 | 0.92 | 0.92 | — | — | 0.63 | 0.87 | 0.62 | 0.46 | 0.68 | 0.90 | 0.84 | 0.68 | 0.77 | 0.61 | 0.73 | 0.74 | 0.87 | 0.74 | 0.67 | 0.14 |
| Hm | — | — | — | — | — | — | — | — | — | — | — | — | — | — | 0.44 | — | — | — | 0.39 | — | — | — |

* = Total iron expressed as FeO

Ba–1. Calc-alkali rhyolite. Collected from a road section approx: 1/4 mile northeast of Batandar Banda.
Ba–2, 6, 9. High–K rhyolite (dike rock) along Utror road and striking N70°E, approx: 2 miles west of Bahan Banda.
Ba–15, 18, 19. High–K rhyolite. Rhyolite dike exposed near Batandar Banda.
Ba–21. Calc-alkali rhyolite, Batandar Banda.

BB–10, 11. Calc-alkali rhyolite, exposed in stream section in Batandar Banda.
BB–1. Low–K rhyolite. Main rhyolite flow, Utror road, Batandar Banda.
B–4. Calc-alkali rhyolite flow. North of Utror road at Batandar Banda.
B–21. Maroon-colored Calc-alkali rhyolite. Collected from a section north of Gabral River.
P–6. Dacite. Ushu Valley, 2 miles south of Paloga Village.

B–2, 18, 19. Dacite. Near Utror village from a section north of Gabral River.
P–7. Normal andesite. Ushu Valley, 2½ miles south of Paloga village.
B–12. Andesite. Near Utror village.
Low-silica andesite. North of Gabral River near Utror village.
Siliceous and normal andesite. Near Utror village.

TABLE 2. COMPILATION OF TOTAL MAJOR ELEMENT DATA AND CIPW NORMS FOR ANDESITES AND SALIC ROCKS FROM KALAM VOLCANIC ZONE. THE DATA ARE GROUPED INTO SIX $SiO_2$ INTERVALS. ANALYSES ARE RECALCULATED TO 100% ON AN ANHYDROUS BASIS.

| $SiO_2$ interval Rocks | 60% Andesite | | | 60-63% Siliceous Andesite | 63–66% Dacite | 66–69% Dacite | | | 69–73% Rhyolite | | | | | | 73% Rhyolite | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Samples No. | Low-silica Andesite | B–12 | P–7 | Normal Andesite | P–6 | B–2 | B–18 | B–19 | B–4 | Ba–15 | Ba–21 | Ba–18 | Ba–2 | Ba–23 | Ba–1 | BB–10 | Ba–9 | Ba–19 | Ba–6 | B–21 | BB–1 | BB–11 |
| $SiO_2$ | 55.98 | 57.23 | 59.46 | 60.17 | 65.50 | 67.86 | 68.60 | 68.89 | 71.10 | 70.97 | 70.99 | 72.41 | 72.90 | 73.14 | 73.19 | 73.86 | 73.89 | 74.07 | 74.14 | 74.47 | 75.55 | 75.68 |
| $TiO_2$ | 0.61 | 0.78 | 0.66 | 0.67 | 0.27 | 0.46 | — | 0.62 | 0.45 | 0.49 | 0.33 | 0.60 | 0.65 | 0.48 | 0.64 | 0.62 | 0.51 | 0.54 | 0.52 | 0.09 | 0.52 | 0.47 |
| $Al_2O_3$ | 16.77 | 15.99 | 17.99 | 15.99 | 17.20 | 16.42 | 16.58 | 15.68 | 16.78 | 12.94 | 16.28 | 12.31 | 13.15 | 13.40 | 14.25 | 12.81 | 13.32 | 13.40 | 13.36 | 13.38 | 13.26 | 12.33 |
| $Fe_2O_3$ | — | — | — | — | — | — | — | — | — | 0.59 | 0.62 | — | 0.17 | 0.73 | 0.94 | 1.28 | 0.07 | 1.34 | 0.07 | — | 0.61 | 1.35 |
| FeO | 8.96* | 8.96* | 10.10* | 7.15* | 5.70* | 3.32* | 4.11 | 4.07* | 2.32* | 0.79 | 0.96 | 0.97 | 1.04 | 1.37 | 0.84 | 0.84 | 1.49 | 1.05 | 1.34 | 2.83 | 1.40 | 0.79 |
| MnO | — | 0.20 | 0.17 | — | 0.10 | 0.12 | 0.12 | 0.10 | 0.09 | 0.04 | 0.04 | 0.04 | 0.06 | 0.05 | 0.04 | 0.05 | 0.07 | 0.05 | 0.07 | 0.06 | 0.09 | 0.05 |
| MgO | 5.12 | 4.71 | 2.17 | 4.40 | 1.06 | 0.95 | 1.07 | 1.03 | 0.18 | 0.50 | 0.64 | 0.42 | 0.57 | 0.52 | 0.35 | 0.50 | 0.64 | 0.41 | 0.43 | 0.49 | 0.40 | 0.49 |
| CaO | 8.30 | 6.15 | 4.28 | 6.94 | 4.68 | 1.64 | 2.98 | 1.92 | 2.41 | 2.26 | 2.84 | 1.89 | 2.84 | 2.87 | 2.08 | 1.81 | 2.57 | 1.84 | 2.48 | 0.09 | 1.73 | 1.74 |
| $Na_2O$ | 2.91 | 4.88 | 3.76 | 2.85 | 3.29 | 6.49 | 4.04 | 4.54 | 3.87 | 5.82 | 3.59 | 5.42 | 3.39 | 3.67 | 4.38 | 4.95 | 2.61 | 2.95 | 3.15 | 5.41 | 4.40 | 3.82 |
| $K_2O$ | 1.14 | 1.23 | 1.15 | 1.84 | 2.10 | 2.35 | 2.17 | 2.76 | 2.64 | 4.88 | 3.08 | 5.40 | 4.72 | 3.20 | 2.72 | 2.77 | 4.16 | 3.70 | 3.83 | 2.97 | 1.39 | 2.63 |
| ZnO | — | — | — | — | — | — | — | — | — | 0.01 | 0.02 | 0.01 | 0.01 | 0.02 | 0.01 | 0.02 | 0.02 | 0.02 | 0.02 | — | 0.01 | 0.01 |
| $P_2O_5$ | 0.21 | 0.37 | 0.29 | — | 0.11 | 0.39 | 0.33 | 0.38 | 0.39 | 0.71 | 0.61 | 0.50 | 0.69 | 0.51 | 0.55 | 0.49 | 0.63 | 0.62 | 0.61 | 0.14 | 0.60 | 0.62 |
| CIPW NORMS OF KALAM VOLCANICS | | | | | | | | | | | | | | | | | | | | | | |
| Qz | 4.67 | 0.49 | 12.62 | 10.73 | 27.07 | 13.42 | 24.34 | 20.88 | 31.36 | 20.25 | 30.94 | 23.36 | 28.66 | 31.80 | 30.20 | 29.55 | 35.61 | 38.28 | 24.40 | 26.54 | 39.41 | 37.89 |
| Or | 6.75 | 7.20 | 6.90 | 10.95 | 12.55 | 13.70 | 12.95 | 16.50 | 15.75 | 28.50 | 18.35 | 31.70 | 28.10 | 19.15 | 16.20 | 16.45 | 25.03 | 22.30 | 22.95 | 17.55 | 8.30 | 15.80 |
| Ab | 26.25 | 43.30 | 34.15 | 25.70 | 29.90 | 57.35 | 36.45 | 41.00 | 33.35 | 41.20 | 32.40 | 34.85 | 30.60 | 33.30 | 39.50 | 43.10 | 23.81 | 26.95 | 28.40 | 48.50 | 39.90 | 34.80 |
| An | 29.40 | 17.97 | 19.65 | 25.50 | 22.70 | 5.56 | 12.74 | 7.15 | 9.50 | — | 8.95 | — | 6.72 | 10.00 | 10.35 | 4.55 | 7.50 | 3.85 | 7.93 | — | 3.45 | 5.70 |
| Ns | — | — | — | — | — | — | — | — | — | 3.12 | — | 4.00 | — | — | — | — | — | — | — | — | — | — |
| Ac | — | — | — | — | — | — | — | — | — | 1.64 | — | — | — | — | — | — | — | — | — | — | — | — |
| C | — | — | 3.80 | — | 1.42 | 1.22 | 3.21 | 2.80 | 4.85 | — | 4.10 | — | — | 0.20 | 0.35 | — | 1.99 | 3.50 | 1.60 | 1.27 | 3.61 | 1.25 |
| Wo | — | — | — | — | — | — | — | — | — | — | — | 0.14 | — | — | — | 0.08 | — | — | — | — | — | — |
| Di | 8.48 | 8.12 | — | 7.68 | — | — | — | — | -- | — | — | 3.76 | 1.24 | — | — | — | — | — | — | — | — | — |
| En | — | — | — | — | — | — | — | — | -- | — | — | — | — | — | 0.98 | 1.40 | — | — | — | — | — | 1.38 |
| Fs | — | — | — | — | — | — | — | — | -- | — | — | — | — | — | — | — | — | — | — | — | — | — |
| Hy | 23.10 | 21.10 | 21.27 | 18.62 | 5.66 | 7.21 | 9.54 | 9.94 | 3.62 | 2.18 | 2.48 | — | 1.66 | 2.48 | — | — | 3.50 | 1.20 | 2.65 | 5.68 | 2.26 | — |
| Mt | — | — | — | — | — | — | — | — | — | — | 0.65 | — | 0.18 | 0.77 | 0.70 | 0.78 | 0.07 | 0.74 | 0.07 | — | 0.65 | 0.99 |
| Ap | 0.50 | 0.86 | 0.69 | — | 0.30 | 0.90 | 0.78 | 0.87 | 0.93 | 2.16 | 1.89 | 1.53 | 2.14 | 1.59 | 1.71 | 1.53 | 1.98 | 1.95 | 1.84 | 0.30 | 1.89 | 1.95 |
| Il | 0.86 | 1.10 | 0.92 | 0.82 | 0.40 | 0.64 | — | 0.86 | 0.64 | 0.67 | 0.46 | 0.82 | 0.90 | 0.68 | 0.92 | 0.86 | 0.72 | 0.76 | 0.73 | 0.12 | 0.74 | 0.66 |
| Hm | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | 0.37 | — | — | — | — | — | 0.29 |
| T.T. index | 37.67 | 50.99 | 53.61 | 47.38 | 69.52 | 84.47 | 73.74 | 78.38 | 80.40 | 89.95 | 81.69 | 89 91 | 87.36 | 84.25 | 85.90 | 89.10 | 84.45 | 87.53 | 85.81 | 92.59 | 87.61 | 88.49 |

* = Total iron expressed as FeO.

## TABLE 3.

### COMPARISON OF THE AVERAGED MAJOR ELEMENT DATA OF THE SALIC ERUPTIVES FROM THE KALAM VOLCANIC ZONE WITH EQUIVALENT ROCKS FROM JAPAN, TAIWAN, KURILES, KAMCHATKA, SAIPAN AND S.W. PACIFIC (INCLUDING PAPUA, NEW GUINEA, SOLOMAN ISLAND, NEW HEBRIDES, FIJI AND NEW ZEALAND).

| | Kalam volcanics | Japan | S. W. Pacific | Kalam volcanics | Taiwan | S. W. Pacific | Kalam volcanics | Kuriles | S. W. Pacific | Kalam volcanics | Kamcha-tka | S. W. Pacific | Kalam volcanics | Saipan | S. W. Pacific |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ interval | 60—63% | | | 63—66% | | | 66—69% | | | 69—73% | | | 73% | | |
| $SiO_2$ | 60.17 | 61.58 | 61.24 | 65.50 | 64.34 | 64.50 | 68.45 | 67.46 | 67.27 | 71.67 | 70.88 | 71.28 | 74.22 | 75.37 | 75.15 |
| $TiO_2$ | 0.67 | 0.71 | 0.69 | 0.29 | 0.68 | 0.67 | 0.36 | 0.60 | 0.57 | 0.50 | 0.48 | 0.42 | 0.48 | 0.26 | 0.25 |
| $Al_2O_3$ | 15.99 | 16.86 | 16.47 | 17.20 | 16.27 | 15.57 | 16.23 | 15.70 | 15.45 | 14.29 | 14.96 | 14.49 | 13.27 | 13.33 | 13.28 |
| $Fe_2O_3$ | — | 2.74 | 2.59 | — | 2.57 | 2.13 | — | 2.03 | 1.94 | 0.46 | 1.51 | 1.43 | 0.79 | 0.98 | 0.88 |
| FeO | 7.15* | 3.83 | 3.75 | 5.70* | 3.25 | 3.73 | 3.83* | 2.61 | 2.76 | 1.21 | 1.67 | 1.75 | 1.32 | 1.12 | 1.01 |
| MnO | — | 0.13 | 0.12 | 0.10 | 0.14 | 0.13 | 0.11 | 0.12 | 0.11 | 0.05 | 0.09 | 0.08 | 0.05 | 0.06 | 0.06 |
| MgO | 4.40 | 2.87 | 3.23 | 1.06 | 2.16 | 2.31 | 1.02 | 1.42 | 1.40 | 0.46 | 0.83 | 0.65 | 0.47 | 0.45 | 0.31 |
| CaO | 6.94 | 6.20 | 6.22 | 4.68 | 5.17 | 5.24 | 2.18 | 4.22 | 4.26 | 2.44 | 3.02 | 2.44 | 1.91 | 1.83 | 1.52 |
| $Na_2O$ | 2.85 | 3.39 | 3.55 | 3.29 | 3.61 | 3.73 | 5.02 | 3.98 | 4.06 | 4.38 | 3.98 | 4.57 | 3.92 | 3.86 | 4.23 |
| $K_2O$ | 1.84 | 1.52 | 1.92 | 2.10 | 1.64 | 1.78 | 2.43 | 1.69 | 1.99 | 4.14 | 2.44 | 2.81 | 3.04 | 2.62 | 3.27 |
| $P_2O_5$ | — | 0.19 | 0.23 | 0.11 | 0.18 | 0.20 | 0.36 | 0.17 | 0.18 | 0.58 | 0.13 | 0.09 | 0.53 | 0.12 | 0.05 |

* = Total iron expressed as FeO.

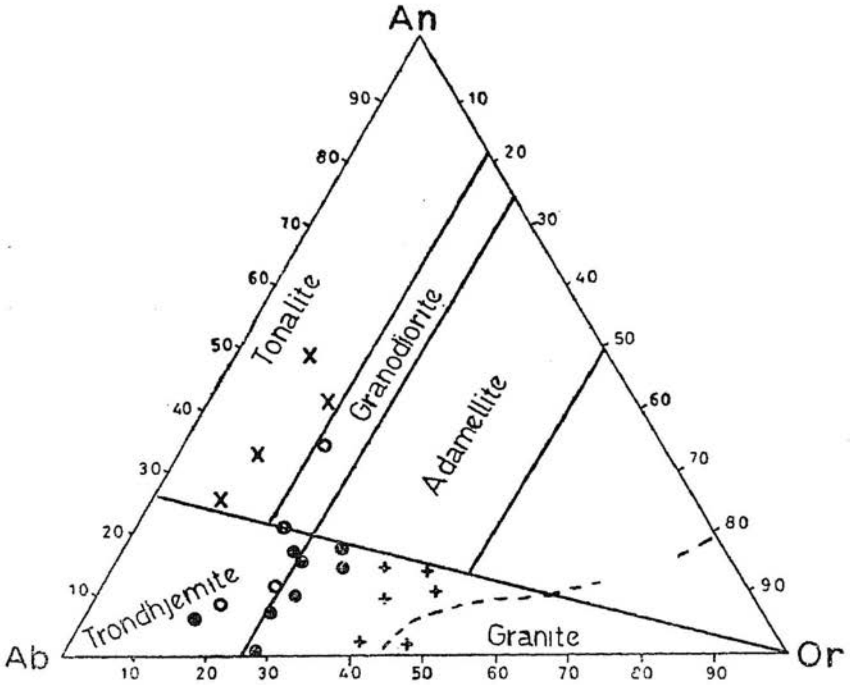


Fig. 4. Ternary plot of normative An–Ab–Or–for the lavas of Kalam volcanic zone. The classification boundries are from O'Connor (1965). Symbols as for Fig. 3.

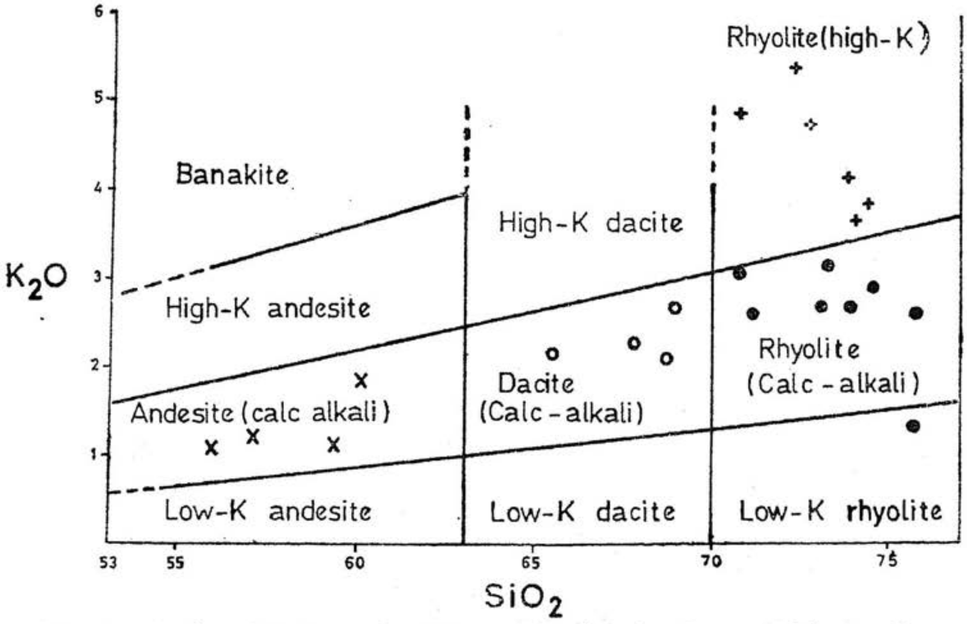


Fig. 5. A plot of K₂O versus SiO₂(wt %) for the data (Table 2) for andesitic and salic rocks of Kalam volcanic zone. Symbols as for Fig. 3.

mative feldspar plot (Fig. 4) where strong orthoclase enrichment is evident and all the salic eruptives fall in the granite field and andesite within the tonolite/dacite field of O'Connar (1965). Mackenzie and Chappell (1972), Peccerillo and Taylor (1976) and Ewart (1979) have employed the magnitude of $K_2O$ variation within the salic volcanics of the subduction tectonic environments as a mean of distinguishing these rocks into three series i.e. low–K series, calc-alkali series, and high–K series. In the $SiO_2$ versus $K_2O$ diagram, the frequency occurrence of the siliceous andesite, dacite and rhyolite is restricted to the calc-alkali field, while dike rock rhyolites plot in high–K field. Cluster analyses of the averaged data for each of the compositional grouping of the studied suite in Fig. 6 suggest their close correlation with the silicic lavas of the island arc systems of western and south-western Pacific regions. The clustering characterized by calc-alkaline lava suite tends to separate these rocks from the high–K salic series of the western U.S.A. (excluding Casacades), and the Andean province of western South America.

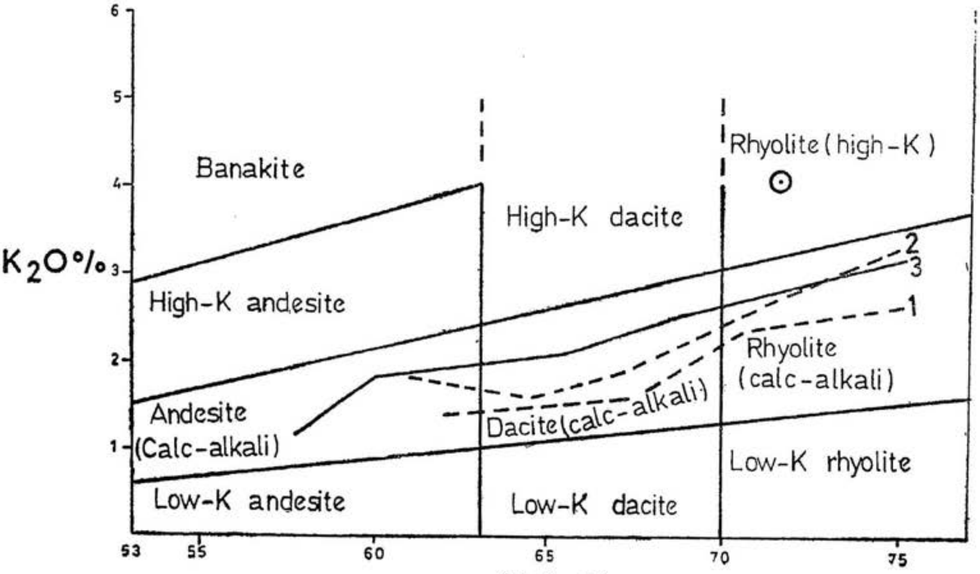


Fig. 6. A plot of $K_2O$ versus $SiO_2$(wt %) for the total averaged data (Table 2) for andesitic and salic rocks of Kalam volcanic zone and two salic volcanic series from the Japan, Taiwan etc. and S.W. Pacific regions. The trends are based on the averaged compositions from each of the five $SiO_2$ compositional groupings (60–63, 63–66, 66–69, 69–73, 73%).

Symbols as for Fig. 3.

1. Trend of variation of calc-alkali volcanic from Japan, Taiwan, Kuriles, Kamchatka and Saipan.
2. S.W. Pacific trend (after Ewart, 1979).
3. Trend of variation of Kalam volcanic zone.

The averaged major element data of each of the five $SiO_2$ compositional grouping of the Kalam eruptives are compared with equivalent data (Table–3) from those geographic and/or tectonic regions having close correlation with the studied suite in Fig. 6. Similarities in the abundances of major elements simply confirm the general picture arising from the composite plots of Fig. 6.

The calc-alkaline chemical affinities of the lavas from the Kalam volcanic zone are distinct on the other conventional variation diagrams. On the AFM plot, the lava exhibit a well defined trend showing no iron enrichment. The trend having a small degree of scatter at the basic end is comparable with some of the characteristic (or perhaps the better known) calc-alkali trend (e.g. Taupo volcanic zone, Newzealand; Steiner, 1958, Lewis, 1968, and Ewart 1969). The distinction between rhyolite from the main flows and high–K rhyolite from the dike rocks is no longer obvious in Fig. 7.

## DISCUSSION

The whole – rock major – element data on the T.T. index and $SiO_2$ variation diagrams show smooth transition from andesite to rhyolite compatible with differentiation modal for the origin of the andesite – dacite – rhyolite suite. The gap in $SiO_2$ of about 5% that separate the siliceous andesite from the dacite may be merely an artifact of incomplete sampling. The decrease of $Al_2O_3$, CaO,

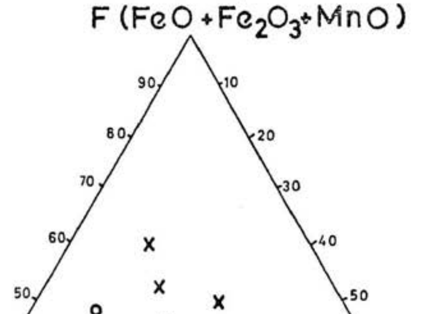
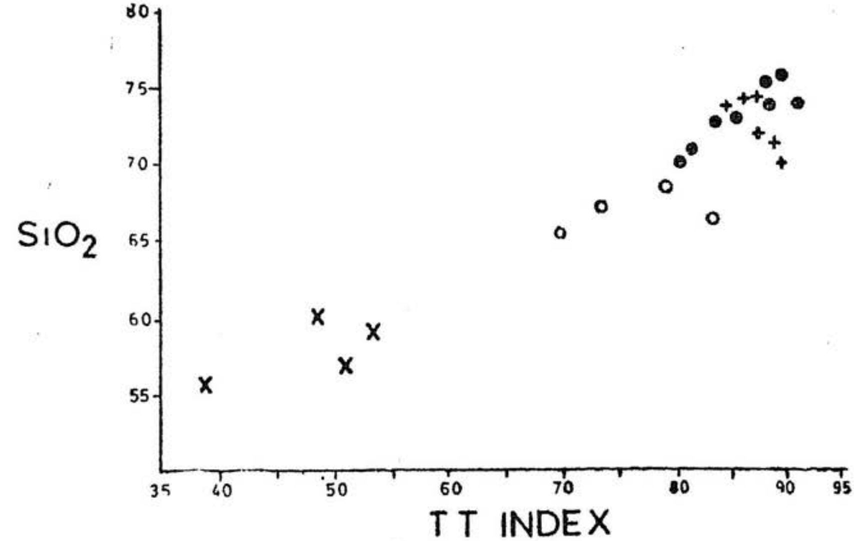
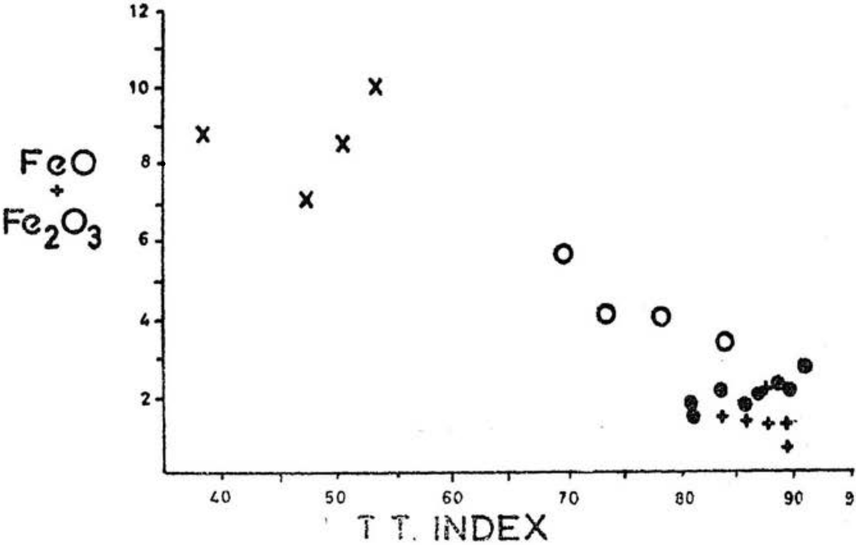


Fig. 7. A.F.M. triangular plot for lavas of Kalam volcanic zone.
Symbols as for Fig. 3.

$FeO + Fe_2O_3$ and MgO with increasing $SiO_2$ and the presence of hornblende (mostly chloritized) as the major mafic phenocryst phase in all the andesites suggest that differentiation was probably controlled by hornblende and plagioclase fractionation. The cluster analyses of data from Table–2 on the MgO versus $FeO+Fe_2O_3$ variation diagram demonstrate that fractionation controlled by the subtraction of hornblende can account for much of the variation in FeO/MgO ratios of the volcanics from the studied suite.





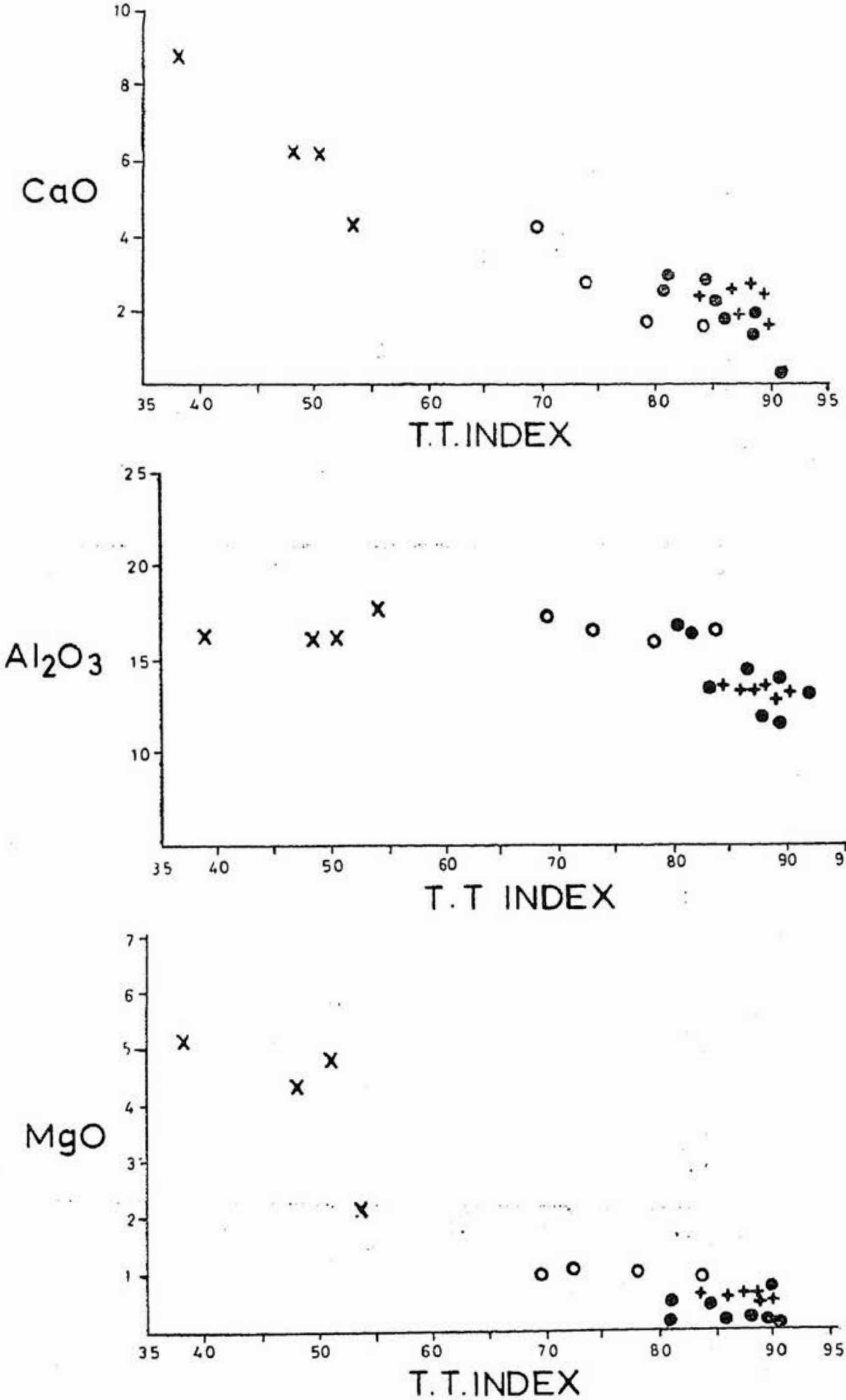
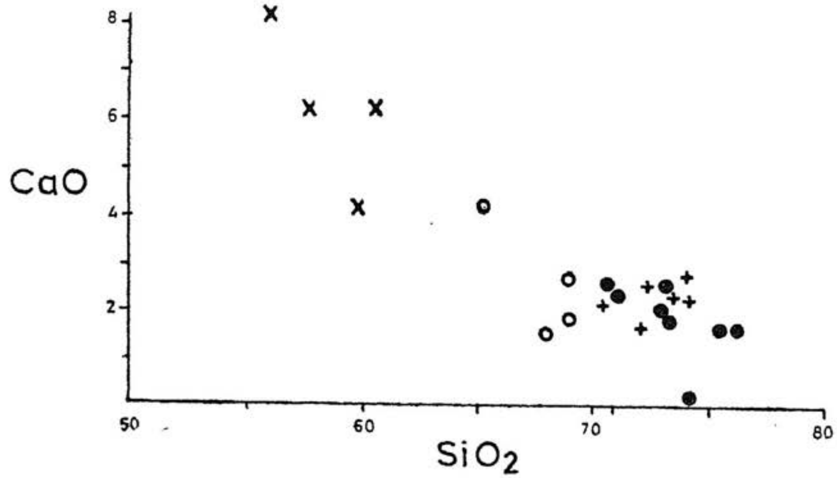
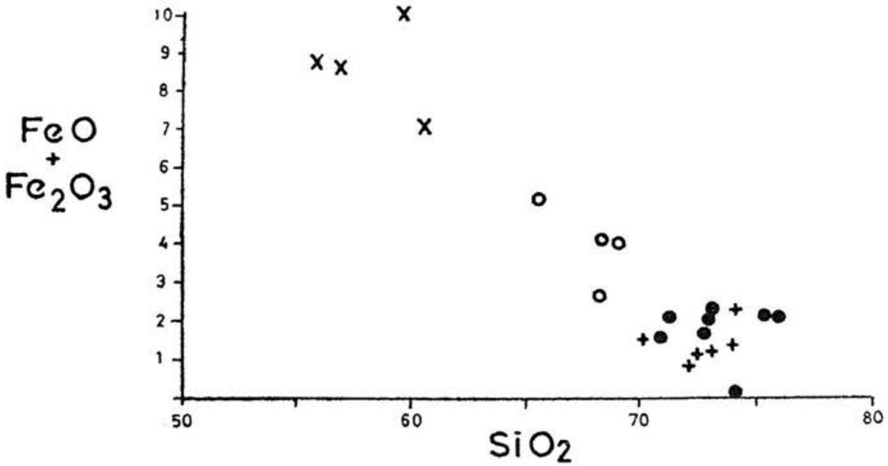


Fig. 8 Various oxides of lavas from Kalam volcanic zone plotted against their Thornton–Tuttle (T.T.) index. Symbols as for Fig. 3.


CaO
8
6
4
2
50
60
70
80
SiO2


FeO + Fe2O3
10
9
8
7
6
5
4
3
2
1
50
60
70
80
SiO2

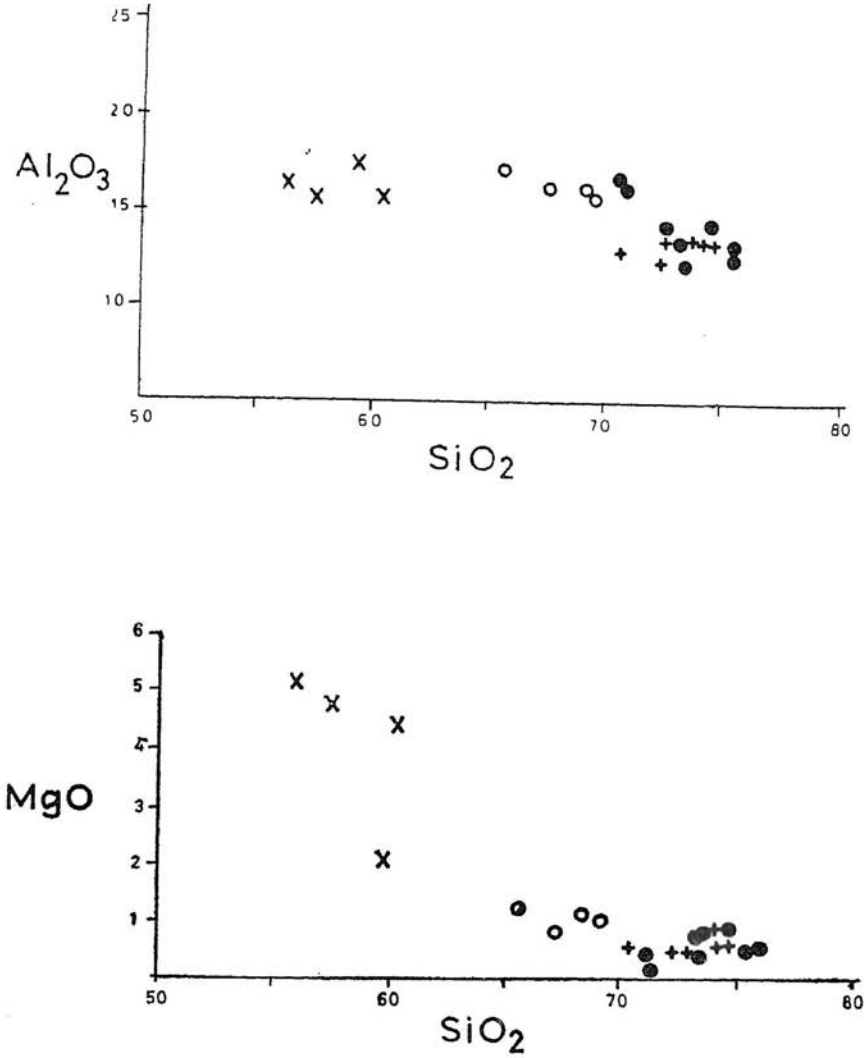


Fig. 9. Major oxides percentage plotted against $SiO_2$ for the lavas of Kalam volcanic zone. Symbols as for Fig. 3.

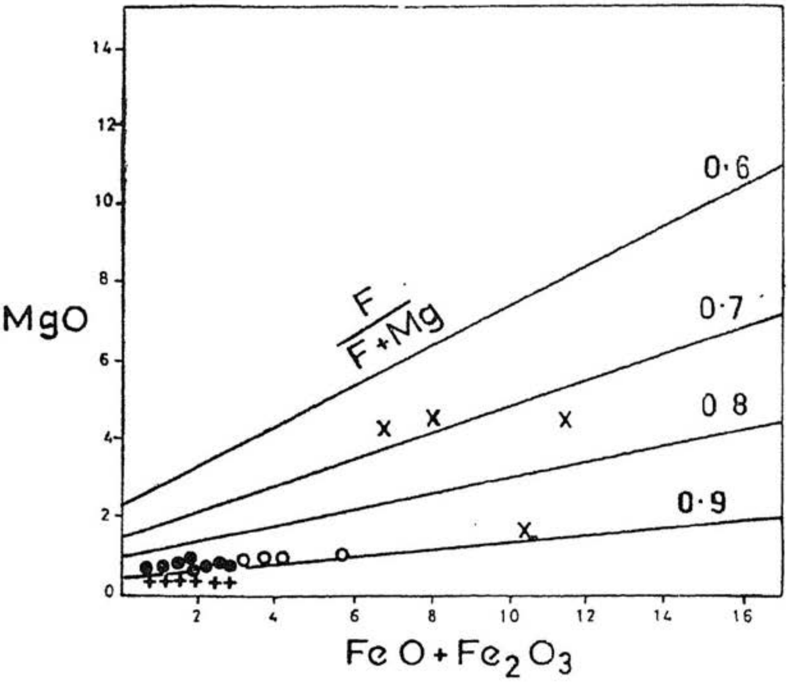


Fig. 10. MgO versus FeO + $Fe_2O_3$ (total iron) for andesitic and salic lavas of Kalam volcanic zone. Symbols as for Fig. 3.

However the plot of the normative CIPW compositions in the feldspar – silica and in the ternary feldspar system exhibit much less convincing chemical evidences for the control of their compositions by fractional crystallization. The set of data for the analysed specimens project away (even the highest $SiO_2$ compositions) from the lower pressure 'ternary minima' composition in the quartz-feldspar system and terminate before reaching the quartz – saturated two feldspar curve in the ternary feldspar system. This is the typical trend exhibited by the calc-alkali liquids, specially of the island arc regions, and is believed to represent increasing advanced stages of partial fusion (Ewart, 1979). Compilation of both isotopic and extensive trace element data (e.g. REE) is needed to give support to this interpretation.

The high–K rhyolites, however, plot in the close proximity of $An_3$ piercing point ( 1 Kb $H_2O$ ) in Figure 11 and fall on or close to the two feldspar boundary curve in the ternary feldspar system (Fig. 4). This is certainly explicable in terms of crystal fractionation controlling their composition.

The field relationship of the high–K rhyolite certainly provide evidence to their derivative nature. These are present only as dike rock and represent liquids remain after the consolidation of the andesite – dacite – rhyolite suite.

Calc-alkaline volcanic rocks are predominant in the island arcs and orogenic (mobile) continental marginal zones, both being regions in which subduction is interpreted to play a major role in the generation of magmas. Within the volcanic rocks developed in these regions well-defined chemical variations of different magnitude in each region are often recognized even within a given compositional type. McBirney (1969), Forbes *et al.* (1969) and Yoder (1969) identified differences in the petrochemical indices of the calc-alkaline rocks in island arc and continental marginal zones but Jake and White (1972) pointed out that the contrast in the petrochemical indices advocated by these workers is not necessarily real. Instead they introduced a new scheme of generalized differences between calc-alkaline volcanic rocks developed in each of subduction tectonic environments.

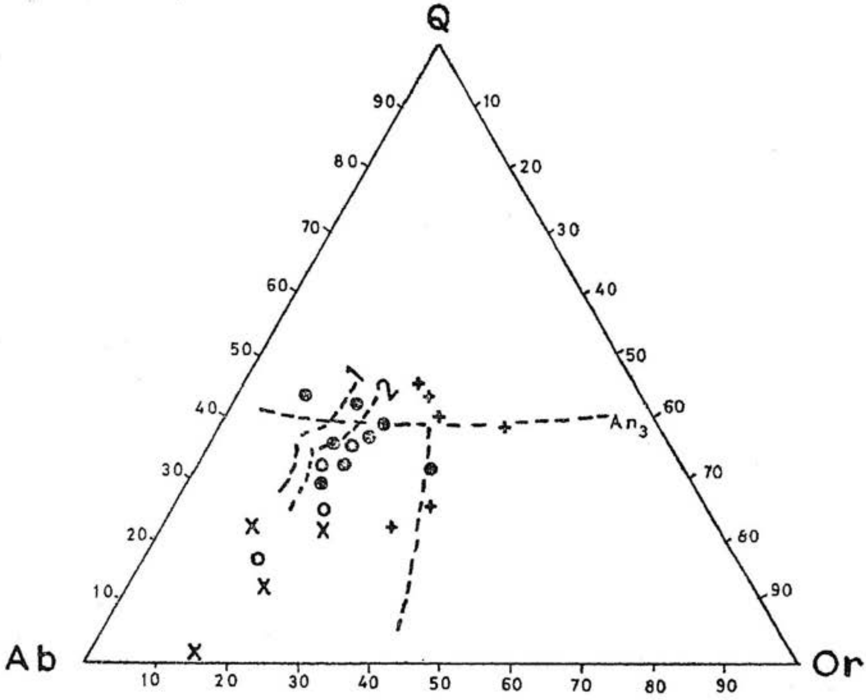


Fig. 11. Normative (CIPW) Q–Ab–Or components of chemical analyses from Table 2. Symbols as for Fig. 3.

1. Trend of variation of the calc-alkali volcanic from Japan, Taiwan, Kuriles, Kamchatka and Saipan.
2. S.W. Pacific trend, after Ewart (1979).

TABLE 4. COMPARISON OF CHEMICAL INDICES OF THE CALC-ALKALINE LAVAS FROM THE KALAM VOLCANIC ZONE WITH THE DATA FOR CALC-ALKALI ISLAND ARC AND THAT OF THE CONTINENTAL MARGIN (ANDEAN) AFTER JAKE AND WHITE (1972).

| | Continental margin (Andean) | Island Arc | Kalam volcanic zone (average) |
|---|---|---|---|
| Range of $SiO_2$ | 56 to 75% | 50 to 60% | 56 to 75.6% |
| $FeO+Fe_2O_3/MgO$ | higher than 2.0% | lower than 2.0% | 3.74% |
| $K_2O/Na_2O$ | 0.60 to 1.1% | less than 0.8% | 0.75% |

In the studied suite the chemical parameters which have been selected for such a distinction, varies within the limits defined for the continental margin calc-alkaline rocks (Andean type).

Andesite and salic eruptives from the Kalam volcanic zone would have been doubtlessly regarded as developed in the continental marginal environments if the previous 2 diagrams (i.e. Fig. 4 and 11) and Table 3 had not been considered.

Complete range of major element average data comparison of the studied suite with equivalent compositions of Andean versus island arc type, however, indicate similarities of the Kalam volcanic series with the latter type. In addition, the chemical trends established in figures 4 and 11 are identical to the calc-alkaline trends of island arc systems of the western and southwestern Pacific regions (Ewart, 1979).

Our data are not sufficient to be employed in fingerprinting the palaeotectonic setting of terrain in which the calc-alkaline rocks were developed but the potential usefulness of some of the determined major element ratios can not, however, be overlooked. The available data of the andesite and salic eruptives from the Kalam volcanic zone suggest that these rocks are mostly of island arc affinity rather than of Andean or normal calc-alkaline types. The element abundances of the studied suite and the well defined trend line, non-directional towards lower pressure 'ternary minima' composition in the silica – feldspar system corresponds to the Ewart (1979) characterization of the island arc salic volcanics.

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