Calc-alkaline Magmatism at Destructive Plate Margin in Kohistan, Northern Pakistan

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Abstract: Four episodes of calc-alkaline igneous activity have been identified in the crust of a fossil island arc, 'the Kohistan Sequence', in the Kalam area, Swat. The sequence which includes a thick complex of pyroxene granulite, amphibolite, various types of diorites along with metasediments and associated volcanics is 10-15 kilometers thick and is presumed to have developed, as a result of subduction of the primary Tethyan oceanic crust beneath an arc during the suturing of Indo-Pakistan and Eurasia.

The calc-alkaline rocks within the sequence are divisible into two distinct associations. One of these, characterised by iron- and alkali-rich differentiation on variation diagrams, is volcanic, (the Utror volcanics), consisting of andesite, dacite, rhyodacite and rhyolite. The second association includes rocks varying from hornblende biotite diorite to pyroxene-biotite diorite. Analyses of these rocks, unlike the volcanics, display an iron- and alkali-poor and Mg-rich variation trend. Chemically these rocks have been distinguished into low-silica diorite, normal diorite, high-K diorite and granodiorite (Majid, 1979). The former two types contain lesser K_2O than the later two.

Field evidences suggest that the volcanic phase follows plutonic activity within the province. Most of the first-order features of the studied suite are identical with the calc-alkaline rocks of the circum Pacific type. The petrochemical indices, which identify the Kohistan calc-alkaline rocks, reflect a pronounced episodicity in their evolution. The macro episode of major significance defined in the proposed genetic scheme is synchronous with first major tectonic event which is referred to as the subduction of the Tethyan ocean crust in the plate tectonic model of Kohistan.

INTRODUCTION

In Northern Pakistan, the India-Eurasia suture zone is marked by the Kohistan sequence. It is bordered to the south by the Lower Swat-Buner schistose group with which it has a thrusted contact (the Main Mantle Thrust) and to the north by the sialic metamorphosed rocks of the Hindukush and Karakorum ranges. Rocks of the sequence cover most of Swat Kohistan, Dir and substantial part of the Gilgit agency. The Swat Kohistan succession, especially the Kalam, Pattan and Jijal sections have played an important part in the history of research on the Kohistan Himalayas. Their systematic description by Jan and Mian (1971), Jan and Kempe (1973) and Jan (1977) led Tahirkheli *et al.* (1979) to suggest that the sequence represents a rather complete and perhaps typical cross-section of the crust of a calc-alkaline arc, associated with the subduction of the former Tethyan ocean crust.

Major and trace element abundances within the studied suite favour the possibility of their derivation as a result of active consumption of a downgoing oceanic lithosphere along a northward dipping benioff zone in the area.

Diorites and related rocks within the Kohistan calc-alkaline province were studied previously by one of us (Majid, 1979). In this paper the whole calc-alkaline suite has been reviewed in the framework of the Himalayan tectonics.

THE KOHISTAN CALC-ALKALINE SERIES

I. Calc-alkaline volcanic series

The extensive lavas of the Kohistan calc-alkaline suite have been shown on a preliminary geologic map of Kohistan and adjoining areas (Tahirkheli and Jan, 1979) in the form of a linear belt, trending northeast-southwest between Kalam in the Upper Swat in the east, and in Suraighat mountains and Jabazai near Shai in the west, in the western part of Dir, near Afghanistan border.

Lavas from the vicinity of Utror were studied in the field and in thin sections by Jan and Mian (1971) and Sultan, (1970). These authors allocate the Kalam lavas to three major rock types, i.e. andesite, dacite and rhyolite but the chemistry of lavas never received a detailed attention.

The present study includes a petrographic and chemical account of all the major groups of Kalam lavas. Each flow in the type section of Utror has been resampled and carefully selected specimens have been cut into thin sections and analysed for important major and trace elements. The results are compared with the

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adjacent calc-alkaline plutonics and with world-wide occurrences of calc-alkaline lavas.

Petrography

In the following description the terms basalt, low-silica andesite, normal andesite, high-K andesite and rhyodacite will be used in accordance with the definition of Taylor (1969) proposed for andesitic rocks of orogenic belts. Although Taylor used only the chemical criteria while defining these rocks, in the present study both the chemical as well as petrographic characteristics are employed in differentiating various lava flows.

Andesite

Rocks classified as andesite have 53-62% SiO_2 and 0.7 to 2.5% K_2O. Only one sample having SiO_2 42.27% and K_2O 0.84% is classified as high-Al basalt according to the Taylor's definition. These are dark-green to light greyish-green rocks with a very restricted occurrence. The principal phenocryst phase is plagioclase, accompanied by sparse alkali feldspar and rarely a ferromagnesian mineral which is altered to chlorite. The groundmass always shows appreciable conversion of feldspar into carbonate and epidote minerals.

Specimen for thin section and chemical study were obtained from the Gabral valley section near Utror. Some of the andesites contain flattened dark-green fragments which in thin sections are consisting of tiny plagioclase laths set in a light-green completely glassy groundmass.

Dacite-rhyodacite

These are light-green to dark-green rocks with abundant white phenocrysts and rarely enclose angular fragments of strongly porphyritic dark weathered rocks. These constitute the most voluminous flows in the Gabrel valley, Bahan Khwar and Ushu valley. 17 samples of these rocks have been studied petrographically and three samples, (B-2, B-4, B-5) have been selected for chemical analyses. Important phenocryst minerals are plagioclase, alkali feldspar and quartz. In rhyodacites the plagioclase and alkali feldspar are approximately equal in abundance and can be distinguished from dacite because of having more alkali feldspar and also because of the sodic nature of their plagioclase. In dacites the plagioclase phenocrysts range in composition from labradorite or even bytownite to oligoclase but most of them consist of basic andesine and acidic labradorite.

The groundmass is rich in feldspar, quartz and devitrified brownish glass. The texture of these rocks varies from porphyritic to intersertal and hylopilitic. The alteration of the phenocryst as well as groundmass minerals into secondary minerals like epidote, chlorite and calcite is a common feature.

Rhyolite

These are maroon-coloured compact rocks followed by dacite-rhyodacite flows between Bahan Khwar and Utror bridge in the Gabral valley. The flows are very brecciated at the base in a section at the junction of Bahan Khwar and Gabral river.

The rocks are composed of plagioclase, rounded and embayed quartz and alkali feldspar (both orthoclase and sanidine) phenocrysts in a dirty devitrified glassy matrix. Plagioclase shows alteration to calcite and epidote. Occasionally, patches of fine grained sericitic material are developed in the glassy groundmass. Among the phenocryst minerals alkali feldspar predominates over the plagioclase.

II. Calc-alkaline Plutonic Series

Petrography

Two petrographic varieties have been described from the plutonic calc-alkaline suite.

Hornblende-biotite diorite

These diorites have a coarse grained texture with a spotted appearance. These are extensively developed to the south-east of Dewanghar and at Deshai and are also sparsely distributed at Gabral and Kedam. Beside plagioclase (An 34 to 60%), green hornblende and biotite are important minerals, hence named as hornblende-biotite diorite (Majid, 1979).

Pyroxene-biotite diorite

These are dark-grey medium grained rocks with high concentrations of clinopyroxene, orthopyroxene and biotite and are described as pyroxene-biotite diorite. Plagioclase (An 47%) is highly clouded. Clinopyroxene predominates over orthopyroxene in most of the pyroxene-biotite diorites but specimens having equal proportion of clino- and orthopyroxenes are not uncommon.

CHEMISTRY

A total of 17 samples of the Kohistan lava flows showing minimum post consolidation alteration were analysed by atomic absorption spectrophotometer for major and selective trace elements. Some of the previously described analyses of the calc-alkaline plutonics (Majid, 1979) are reported here in the accompanying tables for comparison and discussion. These specimens were analysed by X-ray flouresence spectrometry. A few of them were employed as standards while analysing the volcanic samples by atomic absorption spectrophotometer.

According to the scheme of classification proposed by Taylor (1969) for andesites of orogenic belts and latter applied to diorites by Gulson *et al.* (1972), rocks having SiO_2 53-68% and K_2O more than 0.7% from the Kohistan calc-alkaline province are distinguished as follow:

Volcanic Series	Plutonic Series	SiO_2	K_2O
Low-silica andesite	Low-silica diorite	53-56%	0.7-2-.5%
Normal andesite	Normal diorite	56-62%	0.7-2.5%
High-K andesite	High-K diorite	53-62%	>2.5%
Rhyodacite	Granodiorite	62-68%	>2.5%

In the volcanic suite the SiO_2 variation trend extends both way beyond the defined limit for andesite (53-62%) so that it includes rocks having silica less than 53% as well as rocks having silica more than 62%. The former are designated as high-Al basalt and the latter as dacite, rhyodacite and rhyolite.

In plutonic series the SiO_2 variation is restricted to the diorite range. Only rarely it increases 62% among the studied samples (e.g. sp. No. 4). The sample then has been described as granodiorite. Low-K varieties (i.e. K_2O<0.7%) are typically absent from volcanic as well as from the plutonic series.

Instead of having an almost patternless chemical variations as in fig. 1, the lavas and diorites are forming two distinct 'high-alkali' and 'low-alkali' trends on the alkali vs. silica diagram. At a given per cent silica a lava on the andesite-dacite-rhyolite trend shows higher total alkalies than the one on the diorite trend. The

Table 1. Chemical analyses of the Low-Silica Andesites and Diorites from the Kohistan Calc-Alkaline Series

Constituents	B 36	B 12	1	2	8	9	11	13	14
SiO_2	54.54	54.00	55.42	53.00	55.07	55.55	55.27	55.64	54.25
Al_2O_3	16.59	15.09	15.74	16.14	17.10	17.22	15.76	16.00	16.89
FeO	11.23*	*7.98	6.56	6.73	5.24	5.36	6.05	6.31	6.25
Fe_2O_3	—	—	2.45	3.30	3.38	3.34	3.19	2.67	2.61
MnO	0.19	0.19	0.18	0.22	0.17	0.15	0.17	0.17	0.16
MgO	4.15	4.44	4.88	5.75	5.01	4.81	6.13	4.56	5.50
CaO	4.76	5.80	8.35	9.85	8.75	8.90	8.76	8.75	9.13
Na_2O	3.85	4.61	2.77	2.17	2.63	2.40	2.18	2.17	2.87
K_2O	2.21	1.16	1.15	0.82	1.32	0.93	0.78	0.81	0.81
				Parts per million					
Ni	—	—	8	14	8	6	24	22	35
Co	63.08	40	—	—	—	—	—	—	—
Cr	—	—	20	23	12	12	30	18	30
V	—	—	204	199	197	204	218	229	271
Rb	—	—	29	33	58	27	25	32	31
Sr	—	—	325	369	444	411	353	350	351
V/Ni	—	—	25.5	14.2	24.6	34	7.8	10.4	7.7
Rb/Sr	—	—	0.08	0.08	0.13	0.06	0.07	0.09	0.08

* Total iron expressed as FeO

B–36 and B–12. Low-silica andesites

1, 2, 8, 9, 11, 13 & 14. Low silica diorites (Majid, 1979).

Table 2. Chemical Analyses of normal Andesite and normal Diorites from the Kohistan Calc-Alkaline Series and their comparison with the Average Normal Andesite of Taylor (1968a)

Constituents	1	P 7	3	5	6	7	10	15	16	19	20	22	5 A
SiO_2	59.50	56.11	58.52	58.81	58.90	57.74	59.37	58.18	58.52	59.02	59.30	58.76	59.70
Al_2O_3	17.20	16.98	16.00	16.09	15.78	16.75	15.88	14.92	15.85	15.46	15.50	14.89	15.38
FeO	6.10*	*9.50	4.71	4.54	4.53	4.81	4.10	5.24	1.64	4.32	3.44	5.10	4.41
Fe_2O_3	—	—	2.68	2.64	3.11	2.59	2.84	3.33	5.15	2.32	3.41	1.62	2.42
MnO	—	0.16	0.15	0.14	0.14	0.15	0.13	0.20	0.12	0.12	0.12	0.12	0.14
MgO	3.40	2.05	4.00	4.09	4.23	4.89	4.15	4.08	5.65	4.79	4.54	5.89	4.24
CaO	7.00	4.04	7.41	7.11	7.26	7.99	7.18	6.38	8.05	6.46	6.92	6.75	6.67
Na_2O	3.70	3.55	2.80	2.42	2.65	2.43	3.11	4.19	2.45	3.49	3.06	2.81	2.94
K_2O	1.60	1.09	1.09	2.40	1.67	1.15	1.56	0.95	1.16	1.98	1.68	1.97	2.15
Parts per million													
Ni	18	—	7	8	10	7	13	5	38	31	38	92	13
Co	24	90	—	—	—	—	—	—	—	—	—	—	—
Cr	56	—	20	18	15	10	30	13	44	38	40	165	13
V	175	—	141	160	175	170	149	148	140	158	170	163	156
Rb	—	—	75	76	71	44	47	32	75	98	71	95	108
Sr	—	—	546	352	405	429	428	296	669	373	309	362	369
Ni/Co	0.75	—	—	—	—	—	—	—	—	—	—	—	—
V/Ni	9.70	—	20.14	20	17.5	24.3	11.4	29.6	3.68	5.09	4.47	1.77	12
Rb/Sr	—	—	0.13	0.21	0.17	0.10	0.10	0.10	0.11	0.25	0.22	0.26	0.29

* Total iron expressed as Feo

1 Normal andesite (Taylor, 1968a)

P 7 Normal andesite.

3, 5, 6, 7, 10, 15, 16, 19, 20, 22 & 5A. Normal diorites (Majid, 1979).

Table 3. Chemical Analyses of the High-K Andesite and Diorite from the Kohistan Calc-Alkaline Series and their comparison with High-K Diorites from Yeoval Complex, Australia; with Taylor's High-K Andesite and with similar Caledonian Igneous Rocks.

Constituents	G 5	1	2	3	4	5	6	7	8
SiO_2	62.18	56.11	59.40	56.17	57.93	60.25	60.10	53.46	60.80
Al_2O_3	N.D.	16.56	16.30	16.80	15.87	17.35	16.29	18.40	16.80
FeO	N.D.	6.99	6.03	6.63	6.21	4.83	5.27	7.09	5.10
MgO	N.D.	7.51	2.86	5.06	4.95	2.95	2.83	3.54	2.20
CaO	N.D.	6.91	5.68	6.40	5.69	3.71	4.85	8.26	5.60
Na_2O	3.98	2.22	3.83	3.87	3.20	4.56	3.92	4.00	4.10
K_2O	4.17	3.04	2.87	2.92	3.45	3.59	3.41	2.64	3.30
				parts per million					
Ni	—	4	—	—	—	—	—	—	3
Co	6.3	7	—	—	—	—	—	—	13
Cr	—	38	—	—	—	—	—	—	3
V	—	236	—	—	—	—	—	—	160
Ni/Co	—	0.6	—	—	—	—	—	—	0.23
V/Ni	—	59	—	—	—	—	—	—	53

N.D. Not determined.

G 5. High-K andesite.

1. High-K diorite (Majid, 1979).
2. Average high-K diorite. Yeoval complex. Australia (Gulson *et al.,* 1972).
3. Average two-pyroxene biotite diorite (High-K). Comrie diorite complex, Scotland (Majid, 1974).
4. Average hypersthene biotite diorite (High-K). Comrie diorite complex, Scotland (Majid, 1974).
5. Average of 8 analyses of high-K diorite (Porphyritic hornblende biotite granodiorite) Foyers granitic complex (Marston, 1971, analysis 8, 9, 10, 11, 12, 13, 14 and 15).
6. High-K diorite (Tonalite) Cairnsmore of Carsphairn complex (Deer, 1935, analysis-5).
7. Augite biotite diorite (High-K). Comrie diorite complex, Scotland (Majid, 1974).
8. **High-K andesite (Taylor, 1969,** table 1).

TABLE 4. CHEMICAL ANALYSES OF A DACITE FROM THE KOHISTAN CALC-ALKALINE SERIES AND AVERAGE DACITE OF NOCKOLDS (1954).

Constituents	P 6	2
SiO_2	64.40	63.40
Al_2O_3	16.90	16.70
FeO	5.60*	3.00
Fe_2O_3	—	2.00
MnO	0.10	0.10
MgO	1.04	2.10
CaO	4.60	5.50
Na_2O	3.23	4.00
K_2O	2.06	1.40

* Total iron expressed as FeO.

P.6. Dacite.

2. Average dacite (Nockolds, 1954).

Table 5. Chemical Analyses of Rhyodacites and a Granodiorite from the Kohistan Calc-Alkaline Series and their Comparison with Average Rhyodacite of Nockolds (1954).

Constitution	1	B 2	B $4_{(i)}$	B 18	B 19	4
SiO_2	66.30	66.33	63.64	62.17	67.42	62.07
Al_2O_3	15.24	16.05	15.03	15.03	15.35	15.16
FeO	2.20	3.24*	*2.08	*3.72	*3.90	3.85
Fe_2O_3	2.10	—	—	—	—	1.92
MnO	0.10	0.12	0.08	0.11	0.10	0.42
MgO	1.60	0.93	0.16	0.97	1.01	3.32
CaO	3.70	1.60	2.16	2.70	1.88	5.90
Na_2O	4.10	4.35	3.30	3.66	4.44	2.74
K_2O	2.30	2.30	2.36	1.97	2.70	2.96

* Total iron expressed as FeO

1. Average rhyodacite (Nockolds, 1954)

B 2, B $4_{(i)}$, B 18 & 19 Rhyodacites.

4. Granodiorite (Majid, 1979).

TABLE 6. CHEMICAL ANALYSES OF A RHYOLITE FROM THE KOHISTAN CAL-ALKALINE SERIES AND ITS COMPARISON WITH AVERAGE RHYOLITE OF NOCKOLDS (1954).

Constituents	B 21	1
SiO_2	75.10	73.60
Al_2O_3	13.50	18.40
FeO	*2.86	0.80
Fe_2O_3	—	1.20
MnO	0.07	0.30
MgO	0.50	0.30
CaO	0.10	1.10
Na_2O	5.46	3.00
K_2O	3.00	5.40

* Total iron expressed as FeO.

B 21. Rhyolite.

1. Average rhyolite (Nockolds, 1954).

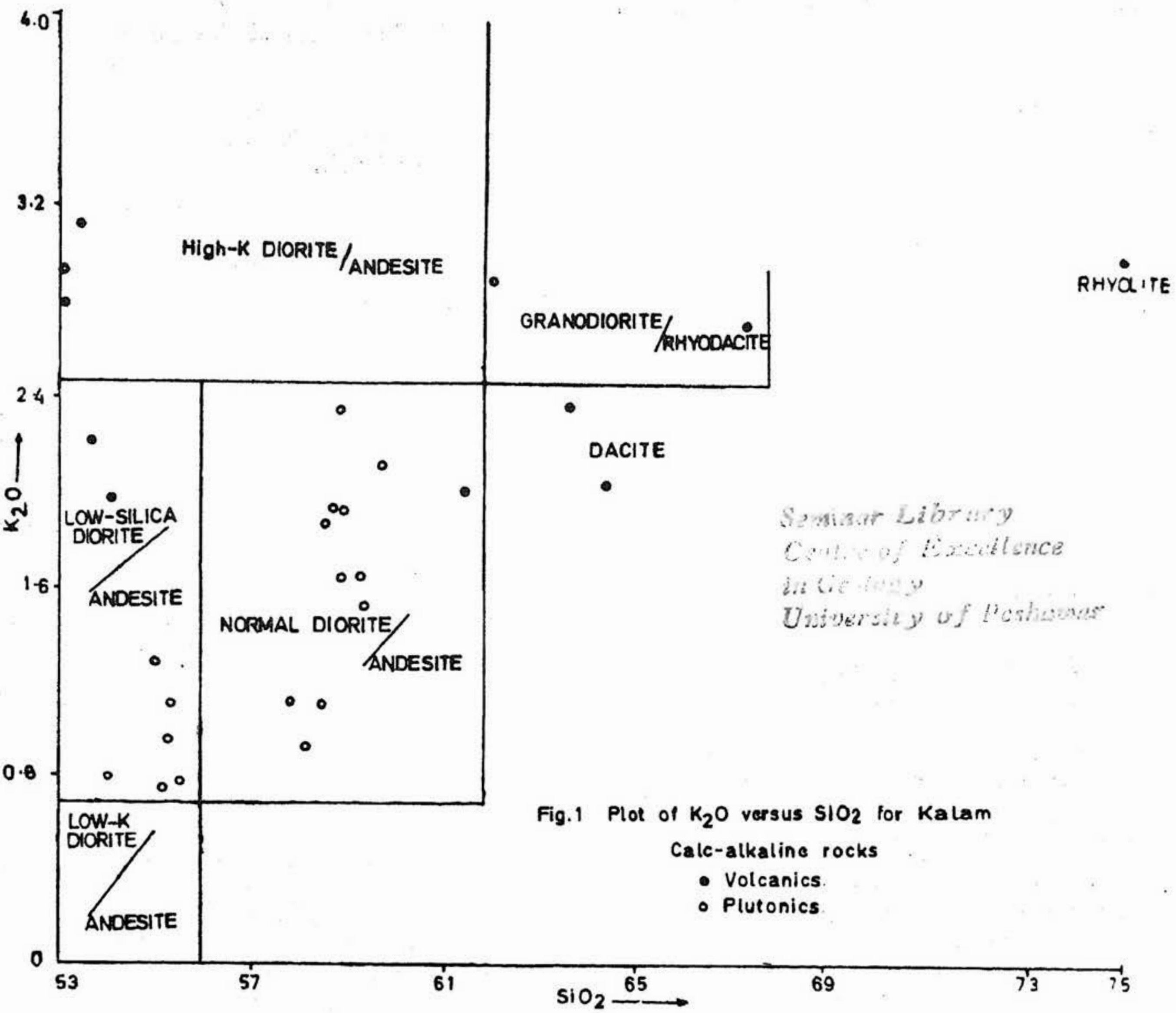

Fig.1 Plot of K_2O versus SiO_2 for Kalam

Calc-alkaline rocks

● Volcanics

○ Plutonics

compositions of the analysed diorites lie within the field of the Japanese tholeiites (Kuno, 1969) while the volcanic series plot in the high-Al basalt area.

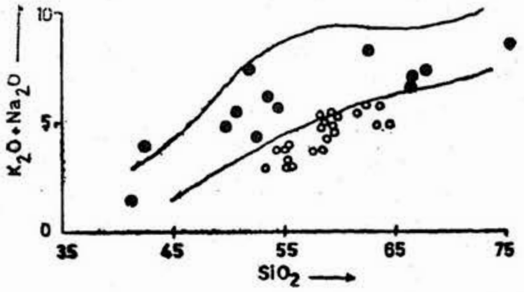

Fig. 2. Alkali-Silica diagram for the Kalam calc-alkaline rocks. Samples represented by symbols as in fig. 1.

In fig. 3 K_2O of the analysed samples is plotted against CaO. It is clear that below a CaO content of 9-8% in the analyses, K_2O is increasing with decrease of CaO at a much higher rate in the plutonic than in the volcanic series.

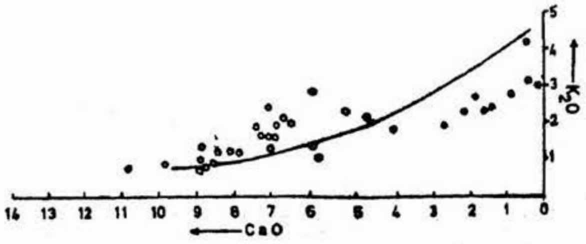

Fig. 3. Plot of K_2O versus CaO for the Kalam calc-alkaline rocks. Samples represented by symbols as in Fig. 1.

Fig. 4 is a plot of total iron ($FeO + Fe_2O_3$) against MgO. The high-iron linear trend formed by the volcanics mostly along the iron/magnesium ratio line of 0.9 contrasts strongly with the rather scattered trend of variation of the diorite granodiorite series. The analyses of diorites fall closely on slope of variation curve exhibited by the typical island arc calc-alkaline series on this diagram, (Yoder, 1969). If varying amounts of MgO are added to the volcanics, it appears that both types of the Kohistan calc-alkaline rocks would form a slightly scattered continuum of variation covering the entire length of island arc calc-alkaline trend upto the base of the olivine control line on this diagram. Fig. 2-4 emphasize the tendency for this continuum to separate into two groups. Fig. 5 is the alkali, iron and magnesian variation diagram of the studied samples. The data points exhibit a non-iron enrichment trend which is indicative of the calc-alkaline nature of the included specimens.

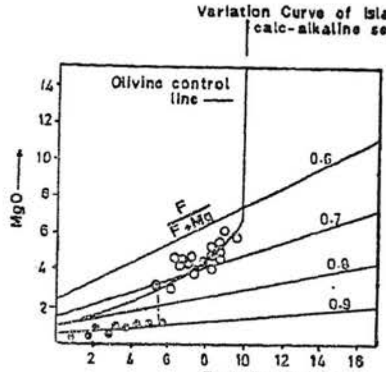

Fig. 4. MgO Versus $Feo+Fe_2O_3$ plot of the Kalam calc-alkaline rocks. Samples represented by symbols as in Fig 1.

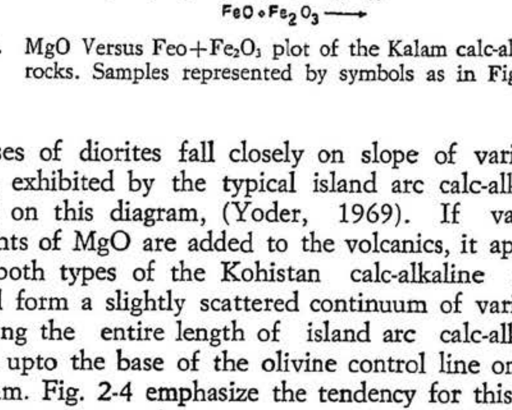

Fig. 5. AFM diagram of the Kalam Calc-alkaline rocks, Samples represented by symbols as in fig. 1.

The division in the Kohistan calc-alkaline differentiation trend can be traced back to distinctive mineralogical differences among the studied samples. All the analysed specimens which are characterized by the K- and Mg-rich variation trend contain abundant pyroxene, hornblende and biotite—minerals, all rich in MgO. The lava samples on the other hand exhibit a Mg-poor variation trend simply because of the scarcity of Mg-bearing minerals.

It is, therefore, assumed that variation in chemistry of diorite-granodiorite series and lavas can be explained simply in terms of addition of varying amount of Mg-rich minerals to a single homogeneous andesitic liquid.

DISCUSSION

The Kohistan calc-alkaline province embraces major portion of the Kohistan zone which constitutes a distinct tectonic unit of about 36,000 square kilometers area in Indo-Pakistan-Eurasia suture zone. The zone is bounded by two megashears, the Hini-chalt-Yasin-Drosh fault to the north and M.M.T. to the south (Tahirkheli *et al.,* 1979).

The plutonic calc-alkaline series is the most extensively developed series in the province while volcanic rocks are restricted to two elongated belts. Besides these, there are abundant granulite, amphibolite and minor ultramafics. (The Kohistan complex) and metasediments (the Kalam group). The thickness of the whole sequence varies from 10 to 15 kilometers and perhaps locally more than 20 kilometers.

The composition of the major rock types (calc-alkaline) and the thickness of the sequence impart a distinct character to the Kohistan suture zone in contrast to area north of eastern and central Himalayas and in Afghanistan where the India-Eurasia suture zone is marked by ophiolitic rocks. Both because of its average composition and its great thickness it is difficult to consider the Kohistan suture zone sequence as a segment of oceanic or continental crust. Thus, Tahirkheli and others (1979) and Tahirkheli (1979) described the said sequence as a complete cross-section of calc-alkaline island arc associated with the subduction of the former Tethyan ocean crust.

The present study also favours the possibility of occurrence of an island arc system beneath which the oceanic crust actively consumed for the growth of the Kohistan calc-alkaline suite before the final closure of the Tethyan ocean. This point has been explained further in the following genetic interpretation.

The genetic scheme formulated for the Kohistan calc-alkaline series is based on convincing evidences supplied by:

Table 7. Major and ferromagnesiam trace element composition (average) of the Kalam diorite/andesites and Calc-alkaline andesites of the circum-Pacific type with data for high-Al basalt and for alkali- and tholeiitic basalts. Data for calc-alkaline andesites, from Taylor (1968b).

Constituent	Alkali & tholeiitic Basalt	High-Al Basalt	High-Al Basalt (Kalam)	Low-Si Andesite*	Low-Si And/ Diorite (Kalam)	Normal Andesite*	Normal And/ Diorite (Kalam)	High-K* Andesite	High-K And/ Diorite (Kalam)
SiO_2	49.2	51.7	42.27	54.9	54.75	59.5	58.85	60.8	58.16
Al_2O_3	15.7	16.9	15.3	17.5	16.41	17.2	15.64	16.8	16.80
**FeO	11.2	10.4	12.43	8.2	8.76	6.1	6.99	5.1	5.88
MgO	8.7	6.5	5.32	4.7	5.01	3.4	4.30	2.2	3.98
CaO	10.8	11.0	10.78	8.5	8.12	7.0	6.79	5.6	5.89
Na O	2.3	3.1	3.12	3.4	2.85	3.7	2.97	4.1	4.21
K O	1.0	0.4	0.84	1.1	1.11	1.6	1.80	3.3	3.26
TiO_2	1.8	—	—	0.8	0.6	0.7	0.65	0.8	0.79
				Parts per million					
Ni	120	25	—	28	17	18	23	3	4
Co	50	40	43.36	28	40	24	30	13	7
Cr	130	40	—	85	21	56	34	3	38
V	200	250	—	200	217	175	155	160	236
Ni/Co	2.4	0.63	—	1.0	0.43	0.75	0.77	0.23	0.6
V/Ni	1.7	10	—	7.1	12.7	9.7	13.69	53	59

* andesites of circum-Pacific type
** total iron expressed as FeO.

i) Major and trace element abundances within the studied suite. This discussion attempts to integrate the chemical information of the Kohistan rocks with the available data on calc-alkaline rocks, to mark the common petrochemical indices and to suggest, among the conflicting conceptions regarding the origin of the calc-alkaline rocks, a scheme to which many of the first-order features of andesite/diorite can be related.

ii) Understanding of petrogenetic aspects of calc-alkaline magmatism in terms of the interpretations from purely structural pattern of development of the Kohistan part of the Himalayan suture zone.

Table 7 shows average composition of major and selective trace elements of representative samples of andesite/diorite and high-Al basalt from the project area compared with the average compositions of calc-alkaline andesites of the circum-Pacific type.

Analyses of the calc-alkaline rocks from the studied suite are consistent with corresponding compositions reported by Taylor, (1968a, 1969), but are collectively different from the composition of alkali and tholeiitic basalts. Most of the ferro-magnesian trace elements, specifically, display much lower concentrations in andesitic/dioritic rock and high-Al basalt than in alkali and tholeiitic basalt. Beside this, pronounced difference exists in certain element ratios. Ni/Co ratio, for example, is characteristically less than 1 in andesitic rocks but is slightly more than 2 in alkali and tholeiitic rocks. The V/Ni ratio exhibits the reverse relationship.

Conclusively it can be stated with reference to table 7 that andesitic/dioritic rocks of Kohistan are characterized by low contents of Ni (13 ppm average), low Cr, low Ni/Co ratio (< 1) and high V/Ni ratio (8-59) like the calc-alkaline rocks in the orogenic zones along the western margin of the Pacific Ocean.

Major element chemistry of the andesitic rocks has been the subject of such interest and discussion in most of petrogenetic models for these rocks that studies of the trace element concentrations have received only limited attention. With the increasing interest in the genesis of andesitic calc-alkaline suite it has become apparent that their trace element contents specially Ni, Cr, Co and V concentrations offer a special challenge to petrologists.

The hypothesis of parent-daughter relationship of high-Al basalt and andesite is greatly hindered by the similarities in Ni/Co and V/Ni ratios and the absolute abundances of the ferro-magnesian trace elements in calc-alkaline rocks and high-Al basalt. Fractional crystallization processes which involve separation of olivine, orthopyroxene or clinopyroxene for derivation of andesite from high-Al basalt cannot account for the similarities in Ni in these rocks. There are abundant octahedral co-ordination sites in these minerals where Ni will preferentially enter. The derivative liquid will, therefore, be poor in Ni in comparison with high-Al basalts.

Osborn's mechanism (1962) of fractional crystallization which involve early crystallization and removal of magnetite from a basic parent to produce andesitic liquids is critically reviewed by Taylor *et al.* (1969). This scheme although emphasizes the most fundamental character of the calc-alkaline association on the A.F.M. diagram is inadequate, however, because it cannot explain the more or less same distribution of V in the supposed basic parent and rocks of the calc-alkaline series.

If the existing differences in the content of iron in high-Al basalt and andesite/diorite are expressed in terms of early crystallization and removal of magnetite (at least 4%) it will result in a strong depletion of V in the andesite/diorite as V is readily accommodated (upto 6.60%, Duncan and Taylor, 1968) in the magnetite structure. Similarities in the contents of V (± 200 ppm) in basalts and calc-alkaline series are strictly against such a process.

Low Ni and high V contents also present special problems to hypotheses involving sialic material in the generation of calc-alkaline series. Large scale dilution of basalts with sialic material could account for the major element chemistry except K but is greatly opposed by the Ni and V contents of andesite/diorite and basalts. Andesite/diorite produced by such mixing would be expected to show Ni and V much lower than the values listed in table 7. This is because the reported values of both these elements in acid material are typically low (< 10 ppm, Taylor, 1968a).

The idea of partial melting of homogeneous crustal material (Brown and Fyfe, 1970; Brown, 1973) for the generation of Kohistan calc-alkaline suite is very unlikely because of the observed Rb/Sr ratio. The average Rb/Sr ratio of nearly 20 analysed samples is 0.13 which is well below the normal average (0.25 Turekian and Kulp, 1956) for crustal rocks.

The Kohistan calc-alkaline series cannot be directly related to the upper mantle as the chemical feature of these rocks are not consistent with information about the major and trace element abundances gained through the pyrolite model of Ringwood (1962).

In fact, most of the petrochemical indices which identify the studied suite reflects a profound episodicity in the evolution of Kohistan calc-alkaline series.

This is what has been described as a multistage process for the development of the calc-alkaline suite in general by Taylor and White (1966), Green and Ringwood (1966, 1968a), Taylor (1968a) and Taylor, Kay, White, Duncen and Ewart (1969).

At least two macro-episodes of major significance are defined in the development scheme of the calc-alkaline suite in Kohistan. These are (i) prior depletion of the parent material in certain components relative to the normal mantle composition and (ii) active consumption of the then basic parent to produce calc-alkaline rocks, according to scheme shown by Green and Ringwood (1966, 1968a). Experimental work carried out by these authors on compositions varying from quartz tholeiite to rhyodacite has produced satisfactory evidences to conclude that fractional crystallizations of basalt through the removal of garnet and clinopyroxene or partial melting of quartz tholeiite at pressure greater than 23 kilobars corresponding to a depth of 100-140 kilometers, could produce andesite leaving behind the residuum of clinopyroxene and garnet. If the first major stage as referred to above is omitted then there are, however, objections to this practice mostly on the basis of trace element abundances in the calc-alkaline rocks. Analytical data of garnet and clinopyroxene from high temperature eclogite (Lovering and White, 1969, Nixon *et. al.*, 1963) suggest that non-equilibrium partial melting of quartz eclogite would produce liquid having high Ni/Co ratio in contrast to the low values listed in table 7, since clinopyroxene rich in Ni will melt first. During equilibrium melting where Ni, Cr and V are partitioned between residual phases and melt, the derivative liquids will be strongly depleted in these elements because for crystal-chemical reasons the above mentioned elements should favour the residual phases. This process can explain the low Ni content of andesite but not the high values of V in these rocks.

Supported by the petrochemical data, the multistage derivative aspect of the proposed scheme can be understood best within the framework of the plate tectonic model of Kohistan.

In view of the evolving concept of the global tectonics, the Kohistan zone has been considered to have originated as an island arc in the shrinking Tethyan ocean between the India-Pakistan and Eurasia platforms. The first major tectonic event after the basin and arc formation was the continued subduction of the Tethyan ocean crust under the arc.

Within the island arc region, the downgoing oceanic slab (pillow lavas of layer 2 and rocks of layer 3—dyke swarms and layered gabbros; Hill, 1957; Nafe and Drake, 1957; Raitt, 1963; Cann and Vine, 1966; Melson, Thomson and Van Andel, 1968; Dewey and Bird, 1970; Oxburg, 1967) along a northward dipping benioff zone should have been subjected to varied pressure and thermal gradients. Under such conditions, basic rocks, because of pronounced phase instabilities, might have been converted into eclogite and garnet amphibolitic mineral assemblages. The enormous volume of the calc-alkaline rocks of the 'hanging wall' to the sinking Tethyan ocean plate indicate partial melting of eclogite and amphibolite deep into the upper mantle at depth of 100-140 kilometers.

The micro-episode of major significance defined in the petrogenetic scheme on the basis of element abundances, can be considered synchronous with the first main tectonic event, i.e. the subduction of the oceanic crust beneath the arc during upper Cretaceous-Eocene.

The deep sea clays and oceanic sediments which intermix with basaltic volcanics in the upper part of the oceanic crust might have contributed some material to partial melting but their low V/Ni ratio (0.5, Turekian and Wedepohl, 1961) neglect any such involvement in such a process.

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