

PETROLOGY OF DIORITES FROM THE "KOHISTAN SEQUENCE", SWAT, NORTHERN PAKISTAN. A GENETIC INTERPRETATION AT PLATE SCALE

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ABSTRACT

Diorites and related rocks of the calc-alkaline nature include by far the most dominant rocks of various composite plutons extensively distributed within the suture zone in the Kohistan Himalayas in northern Pakistan. The main Himalayan suture zone has been recently traced across Kohistan through the Districts of Hazara, Swat, Dir and Mohmand by Tahirkheli *et. al.* (1979).

The development of the thick complex of various types of diorite, granodiorite, hypersthene gabbro and calc-alkaline volcanics (andesite-dacite-rhyolite) within the suture zone in Kohistan is unique in nature because along the Tsang Po and Indus valley in the east, the suture zone is characterized by a belt of flysch and volcanics with some ophiolites and "melanges" (Gansser, 1964, 1977) and to the west in Afghanistan it is marked by large "nappes" of typical ophiolitic rocks.

In a tectonic discussion of the Kohistan area it has been pointed out that igneous rocks within the "Kohistan Sequence" represent products of calc-alkaline activity, associated with the subduction of the floor of the former Tethyne ocean under a marginal basin. The mineralogical and chemical constraints of the diorites and related rocks described in this paper from the Kalam area (between latitude 35° 15' to 35° 52' N and longitude 72° 20' to 72° 27' E) favour the possibility of their derivation as a result of the active consumption of the oceanic crust dragged beneath the marginal basin while the concentra-

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means an intrusive. The M.M.T. is clearly observable in areas south of Patan and can be traced to the west through Shangla Pass across the Swat valley near Khwazakhela and the Dir valley at Zullum.

THE KALAM DIORITES

Petrography

Out of 22 samples obtained from various diorite occurrences within the suture zone, 14 were selected for thin section study. The diorites are medium to coarse grained rocks characteristically rich in plagioclase. The plagioclase content varies from 73% (Sp. No. 7) up to 85% (Sp. No. 6) with only minor amounts of alkali feldspar and quartz. Colour index ranges from 8 to 22. The data points of these rocks plot in field 10 on the double triangle—quartz-alkali feldspar-foids-plagioclase of the I. U. G. S. classification (1973). The average composition of the plagioclase is in the andesine range except in samples 2, 6 and 5A where the anorthite content of the plagioclase is slightly more than An 50%. Almost all the samples studied in thin sections are fairly fresh.

On the basis of the dark coloured constituents, diorites are distinguished into (a) hornblende-biotite diorites and (b) pyroxene-biotite diorites. Hornblende-biotite diorites are the extensively developed rocks in the studied area while the pyroxene-rich varieties are reported only from a limited area north of Diwargar, in the vicinity of Asrit and in a stream section west of Kedam. Biotite is invariably present in thin sections of both types of diorite but the former group contains a green hornblende while the later variety is characterized by having abundant pyroxene (clino and/or orthopyroxene), with only traces of amphibole in certain cases. Rocks containing approximately equal proportions of pyroxene and hornblende are, however, not uncommon (e. g. Sp. No. 11, table I).

Hornblende-biotite diorites. These are mostly coarse-grained rocks with a spotted appearance and are extensively developed east of Dewangar and at Deshai. Few samples of these rocks were also obtained for thin section and chemical study from Gabral and Kedam areas. Modal compositions are given in table I.

Major portion of each section consists of mineral grains ranging in size from 1.3×0.9 mm up to 2.25×1.5 mm across. Rounded crystals of apatite in thin section are approximately 0.3 mm in diameter. Plagioclase is fresh, occasionally slightly zoned and the anorthite contents range from 34% (Sp. No. 21) up to 60% (Sp. No. 2).

TABLE 1. MINERAL COMPOSITION OF THE KALAM DIORITES.

Sample No.	1	2	3	4	5	6	7	10	11	12	20	21	22	5 A
Plagioclase.	73	80	81	79	75	85	73	83	82.5	82	77	77	77.5	82
K-feldspar.	2	traces	3	5	3	...	2	1	1	...	1	...	1	traces
Quartz.	3	5	5	8	6	4	5	6	3	3	6	4	3.5	6
Clinopyroxene.	15	...	...	...	...	...	...	...	4.5	...	9	...	8	...
Orthopyroxene.	...	...	...	...	...	...	...	...	...	...	4	...	6	...
Biotite.	4	5	4	5	4	2.5	6	3	3	7	3	12	2	5
Hornblende.	1.5	8	7	3	12	6	12	6	5	8	...	6	...	5
Apatite.	0.5	1	traces	...	...	0.5	...	traces	...	...	...	...	...	...
Epidote.	...	...	...	...	...	0.5	...	...	...	...	...	traces	...	...
Sphene.	...	...	...	...	...	...	traces	...	...	...	...	...	...	...
Opaque.	1	2	...	...	traces	1.5	2	1	1	...	...	2	1	traces
An % Plagioclase.	48%	60%	42%	38%	40%	56%	40%	36%	42%	44%	56%	34%	44%	53%
Mafic index.	21.5	15	11	8	16	10.5	20	10	9	15	16	20	16	10

Biotite and green hornblende are important dark-coloured constituents. Hornblende is usually more abundant than biotite except in specimens 4, 12 and 21 which contain proportionally more biotite than hornblende. Section 4 also exhibits maximum amount of quartz and K-feldspar among the studied samples. Hornblende-biotite diorite from the Gabral area (smoky diorites of Khalil and Afridi, 1973) are comparatively poor in both quartz and alkali feldspar. Alkali feldspar in these rocks is present only in trace amounts. Section 11 which was collected near Gabral Village contains upto about 4% clinopyroxene in addition to hornblende.

Pyroxene-biotite diorites. These are dark grey-coloured medium-grained rocks with comparatively high concentrations of ferromagnesian minerals. Clinopyroxene, orthopyroxene and biotite are important dark-coloured phases present. The proportion of clinopyroxene to orthopyroxene is somewhat variable. Specimen No. 1 contains clinopyroxene as the only pyroxene with traces of hornblende and shows the highest colour index (22) for this type of diorites. There are samples, however, which contain roughly equal amount of ortho and clinopyroxene.

Plagioclase in these rocks is highly clouded due to the presence of minute dark particles. Its composition is An 47% on the average. Specimens 20 and 22 contain 4 and 6% hypersthene respectively. The hypersthene is pleochroic from light pinkish to faint green.

Chemistry

The chemical composition of the collected samples were determined by X. R. F. analyser. The total iron as Fe_2O_3 from the X. R. F. analyses was further distinguished for each sample into FeO and Fe_2O_3 by the ammonium metavanadate method (Wilson, 1955, 1960). The C. I. P. W. norms were calculated using a computer program. The major and trace element concentrations are listed in tables 2 to 7.

The K_2O contents of the analysed samples are constantly less than 2.5% except in case of the specimens 17 and 4 which fall in the high-K diorite and granodiorite fields respectively. (Fig. 1)

TABLE 2. CHEMICAL ANALYSES AND C. I. P. W. NORMS OF THE NORMAL DIORITES,
GRANODIORITE AND SPECIMENS 12 AND 21.

Sample No.	3	4	5	6	7	10	12	15	16	19	20	21	22	5A
SiO ₂	58.52	62.07	58.87	58.90	57.74	59.37	64.30	58.18	58.52	59.02	59.30	63.14	58.76	59.70
Al ₂ O ₃	16.00	15.16	16.09	15.78	16.75	15.88	13.62	14.92	15.85	15.46	15.50	15.10	14.89	15.38
Fe ₂ O ₃	2.68	1.92	2.64	3.11	2.59	2.84	2.18	3.33	5.15	2.32	3.41	2.34	1.62	2.42
FeO	4.71	3.85	4.54	4.53	4.81	4.10	4.04	5.24	1.64	4.32	3.44	3.12	5.10	4.48
MgO	4.00	3.32	4.09	4.23	4.89	4.15	3.04	4.08	5.65	4.79	4.54	3.33	5.89	4.24
CaO	7.41	5.90	7.11	7.26	7.99	7.18	5.27	6.38	8.05	6.46	6.92	5.91	6.75	6.67
Na ₂ O	2.80	2.74	2.42	2.65	2.43	3.11	2.42	4.19	2.45	3.49	3.06	3.57	2.81	2.94
K ₂ O	1.90	2.96	2.40	1.67	1.15	1.56	2.39	0.95	1.16	1.98	1.68	1.30	1.97	2.15
TiO ₂	0.72	0.54	0.66	0.68	0.68	0.64	0.76	1.02	0.76	0.80	0.91	0.61	0.80	0.67
MnO	0.15	0.42	0.14	0.14	0.15	0.13	0.12	0.20	0.12	0.12	0.12	0.10	0.12	0.14
P ₂ O ₅	0.21	0.12	0.16	0.14	0.21	0.12	0.17	0.30	0.20	0.24	0.22	0.16	0.21	0.22
Total :	99.10	99.00	99.12	99.09	99.39	99.08	98.31	98.79	99.55	99.00	99.10	98.68	98.92	99.01

Continued Table 2.

C. I. P. W. NORMS.

Sample No.	3	4	5	6	7	10	12	15	16	19	20	21	22	5A
Qtz.	13.34	17.13	14.09	15.32	14.21	14.26	24.09	11.02	16.84	10.69	15.10	20.37	11.21	13.78
Or.	11.23	17.49	14.18	9.87	6.80	9.22	14.12	5.61	6.86	11.70	9.93	7.69	11.64	12.71
Ab.	23.70	23.19	20.48	22.42	20.56	26.32	20.48	35.46	20.73	29.53	25.89	30.21	23.78	24.88
An.	25.48	20.32	25.95	26.23	31.40	24.76	19.24	19.10	28.83	20.67	23.60	21.34	22.20	22.42
Di.	8.05	6.64	6.71	7.17	5.55	8.12	4.72	8.60	7.63	8.01	7.38	5.57	8.02	8.01
Hy.	11.58	9.84	12.26	11.96	15.34	10.79	9.86	11.54	10.53	12.99	10.04	8.60	17.72	12.06
Mt.	3.89	2.78	3.83	4.51	3.78	4.12	3.16	4.83	3.48	3.37	4.95	3.39	2.35	3.51
Il.	1.37	1.03	1.25	1.29	1.29	1.22	1.44	1.94	1.44	1.52	1.73	1.16	1.52	1.27
Ap.	0.45	0.28	0.37	0.33	0.49	0.28	0.40	4.83	0.46	0.51	0.51	0.37	0.49	0.28
T. T. Index.	48.27	57.81	48.75	47.61	41.57	49.80	58.69	52.09	44.43	51.92	50.92	58.27	46.63	51.37

*Sp. No. 4 Granodiorite.

TABLE 3. TRACE ELEMENT CONTENTS OF THE NORMAL DIORITES, GRANODIORITE*
AND SPECIMENS 12 AND 21. (IN PARTS PER MILLION.)

Sample No.	3	4	5	6	7	10	12	15	16	19	20	21	22	5A
Ce	47	32	34	45	45	67	46	40	37	54	44	42	63	43
Nd	21	7	13	14	11	21	15	22	16	14	17	11	18	10
Ba	597	676	666	497	360	604	560	381	350	263	491	389	461	630
Cr	20	12	18	15	10	20	27	13	44	38	40	20	165	13
Ti	4003	3031	3900	4065	3835	3572	4341	5957	4268	4748	5324	3585	5115	4110
V	141	130	160	175	170	149	132	148	140	158	170	136	163	156
Sr	546	407	352	405	429	428	218	296	669	373	309	471	362	369
Zr	208	219	238	241	220	212	271	220	217	230	259	273	251	243
Ni	7	9	8	10	7	13	12	5	38	31	38	19	92	13
Rb	75	80	76	71	44	47	69	32	75	98	71	59	95	108
y.	22	21	24	21	22	24	24	26	20	20	21	19	21	18
Zn	69	62	70	74	75	70	57	86	71	68	71	63	72	74
K/Rb	210	307	263	195	219	275	286	247	128	168	198	183	172	165
Ba/Rb	7.96	8.45	8.76	7.0	8.18	12.85	8.11	11.90	4.66	2.68	6.91	6.59	4.85	5.83
Ba/Sr	1.09	1.66	1.89	1.22	0.83	1.41	2.56	1.28	0.52	0.70	1.58	0.82	1.27	1.70
Rb/Sr	0.13	0.19	0.21	0.17	0.10	0.10	0.31	0.10	0.11	0.26	0.22	0.12	0.26	0.29

*Sp. No. 4 Granodiorite.

TABLE 4. CHEMICAL ANALYSES AND C. I. P. W. NORMS OF THE
LOW SILICA DIORITES.

Sample No.	1	2	8	9	11	13	14
SiO ₂	55.42	53.00	55.07	55.55	55.27	55.64	54.25
Al ₂ O ₃	15.74	16.14	17.10	17.22	15.76	16.00	16.89
Fe ₂ O ₃	2.45	3.30	3.38	3.34	3.19	2.67	2.61
FeO	6.56	6.73	5.24	5.36	6.05	6.31	6.25
MgO	4.88	5.75	5.01	4.81	6.13	4.56	5.50
CaO	8.35	9.85	8.75	8.90	8.76	8.75	9.13
Na ₂ O	2.77	2.17	2.63	2.40	2.18	2.17	2.87
K ₂ O	1.15	0.82	1.32	0.93	0.78	0.81	0.81
TiO ₂	1.26	1.41	0.76	0.82	0.92	0.95	0.92
MnO	0.18	0.22	0.17	0.15	0.17	0.17	0.16
P ₂ O ₅	0.43	0.32	0.21	0.21	0.19	0.20	0.19
Total :	99.19	99.71	99.64	99.63	99.40	99.23	99.58

Continued Table 4.

C. I. P. W. NORMS.

Sample No.	1	2	8	9	11	13	14
Qtz.	9.67	8.04	8.81	11.71	11.36	8.67	6.40
Or.	6.80	4.85	7.80	5.50	4.61	7.79	4.79
Ab.	23.44	18.36	22.25	20.31	18.45	26.83	24.29
An.	27.12	31.88	31.00	33.47	30.91	27.04	30.81
Di.	9.40	12.09	8.96	7.54	9.14	12.33	10.77
Hy.	15.84	16.17	14.04	14.23	18.12	13.45	16.55
Mt.	3.55	4.79	4.90	4.84	4.63	3.87	3.79
Il.	2.39	2.68	1.44	1.56	1.75	1.81	1.75
Ap.	1.00	0.74	0.49	0.49	0.44	0.46	0.44
T. T. Index.	39.90	31.25	38.86	37.51	34.42	40.28	35.47

TABLE 5. TRACE ELEMENT CONTENTS OF THE LOW SILICA DIORITES
(IN PARTS PER MILLION)

	1	2	8	9	11	13	14
Ce	53	61	49	92	45	40	37
Nd	22	16	18	18	18	14	18
Ba	384	349	423	3.65	3.19	422	437
Cr	20	23	12	12	30	18	30
Ti	7132	7817	4408	5027	5366	5424	5543
V	204	199	197	204	218	229	271
Sr	325	369	444	411	353	350	351
Zr	224	205	212	215	223	225	223
Ni	8	14	8	6	24	22	35
Rb	29	33	58	27	25	32	31
Y	29	24	22	24	25	24	23
Zn	92	96	82	84	78	88	96
K/Rb	332	205	190	287	264	211	218
Ba/Rb	13.24	10.57	7.29	13.51	12.76	13.18	14.09
Ba/Sr	1.18	0.94	0.97	0.88	0.90	1.20	1.24
Rb/Sr	0.08	0.08	0.13	0.06	0.07	0.09	0.08

TABLE 6. CHEMICAL COMPARISON OF THE HIGH-K DIORITES FROM THE STUDY AREA WITH HIGH-K DIORITES FROM YEOVAL COMPLEX, AUSTRALIA; WITH TAYLOR'S HIGH-K ANDESITE AND WITH SIMILAR CALEDONIAN IGNEOUS ROCKS.

	1	2	3	4	5	6	7	8
SiO ₂	56.11	59.40	60.80	56.17	57.93	60.25	60.10	53.46
Al ₂ O ₃	16.56	16.30	16.80	16.80	15.87	17.35	16.29	18.40
FeO	6.99	6.03	5.13	6.63	6.21	4.83	5.27	7.09
MgO	7.51	2.86	2.15	5.06	4.95	2.95	2.82	3.54
CaO	6.91	5.68	5.60	6.40	5.69	3.71	4.85	8.26
Na ₂ O	2.22	3.83	4.10	3.87	3.20	4.56	3.92	4.00
K ₂ O	3.04	2.87	3.25	2.92	3.45	3.59	3.41	2.64
TiO ₂	0.88	0.59	0.77	1.08	1.14	0.93	1.17	1.51

1. High-k diorite. Kalam area.
2. Average high-k diorite. Yeoval complex. Australia (Gulson *et. al.* 1972, table 2).
3. High-k andesite. (Taylor, 1969, table 1).
4. Average two-pyroxene biotite diorite (High-k). Comrie diorite complex, Scotland. (Majid, 1974).
5. Average hypersthene biotite diorite. (High-k). Comrie diorite complex, Scotland. (Majid, 1974).
6. 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, 15).
7. High-k diorite. (Tonalite) Cairnsmore of Carsphairn complex. (Deer, 1935, Analysis. 5).
8. Augite biotite diorite (high-k). Comrie diorite complex, Scotland. (Majid, 1974).

TABLE 7. TRACE ELEMENT CONTENTS OF THE HIGH-K DIORITES
(IN PARTS PER MILLION)

Sample No. 17

Ce	41
Nd	16
Ba	287
Cr	38
Ti	4612
V	236
Sr	242
Zr	231
Ni	45
Rb	150
Y	18
Zn	77
K/Rb	168
Ba/Rb	1.91
Ba/Sr	1.18
Rb/Sr	0.61

The boundary lines between the four distinct chemical varieties of diorite and granodiorite (Gulson, Lovering, Taylor, and White, 1972) on the K_2O vs. SiO_2 diagram have been drawn according to the intervals suggested by Taylor (1969). The data points of 6 samples plot in the low-silica diorite area while majority of the specimens are normal diorites. Samples 21 and 12 contain 1.3 and 2.39 % K_2O respectively with SiO_2 concentrations much more than what is expected for diorites with such K_2O in the studied area. They fall, therefore, outside the area of diorites defined in fig. 1. The grouping of the analysed specimens into low-silica diorite, normal diorite, high-K diorite and granodiorite has, however, no petrographic significance.

The analyses of specimens 21, 12, and 4 (granodiorite) however, constitute a continuous series with the diorites when the variation trends on the silica variation diagram for major oxides are projected into the high silica portion. There is, however, a wide compositional gap (SiO_2 53.64 to 57.74 %) between the low-silica and normal diorite types in figure 2. The high-K diorite characteristically shows slightly high Al_2O_3 , MgO and $Na_2O + K_2O$, and low CaO and Fe_2O_3 .

The distinction between various types of diorite is not apparently evident on the T. T. index variation diagram (Fig. 3) where the data points form a single scattered trend. The position of the high-K diorite is much displaced for MgO , ($Na_2O + K_2O$) and CaO from the general variation trend in fig. 3.

The plot of K_2O vs. CaO for the analysed samples exhibits that the rather single scattered trend in diorites on the silica and T. T. index variation diagram may be actually consist of 3 separate curved lineages with low-silica diorite—normal diorite—granodiorite series as the major series in the area. Analyses of samples 12 and 21 fall on smooth curves in figures 2 and 3 but on K_2O vs. CaO figure these constitute a distinct trend at the lowest potassium level.

Fig. 5 is an F. M. A. plot of the analysed samples. A non-iron enrichment trend is illustrative of their calc-alkaline nature. The three series illustrated in fig. 4 are, however, not marked on the triangular plot of $(FeO + Fe_2O_3) - MgO - (Na_2O + K_2O)$.

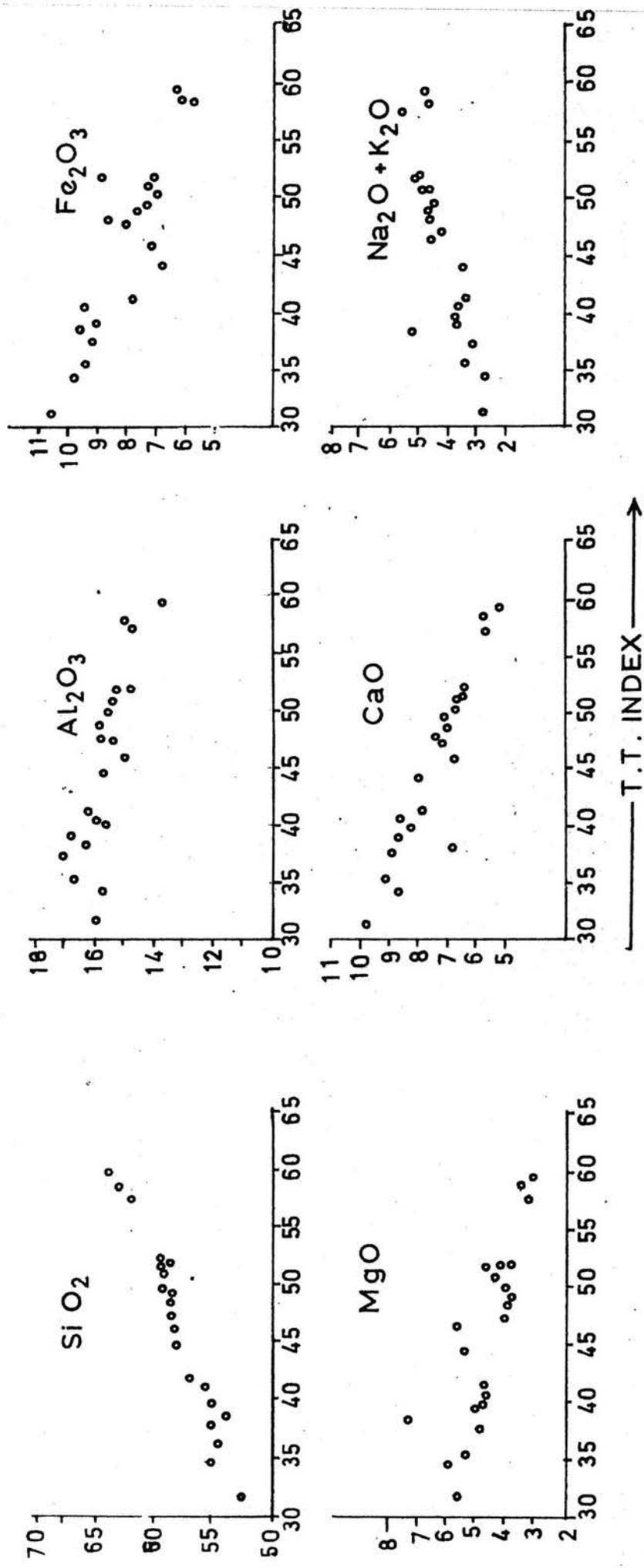


FIG. 3. T.T. INDEX VARIATION DIAGRAM FOR THE STUDIED SAMPLES.

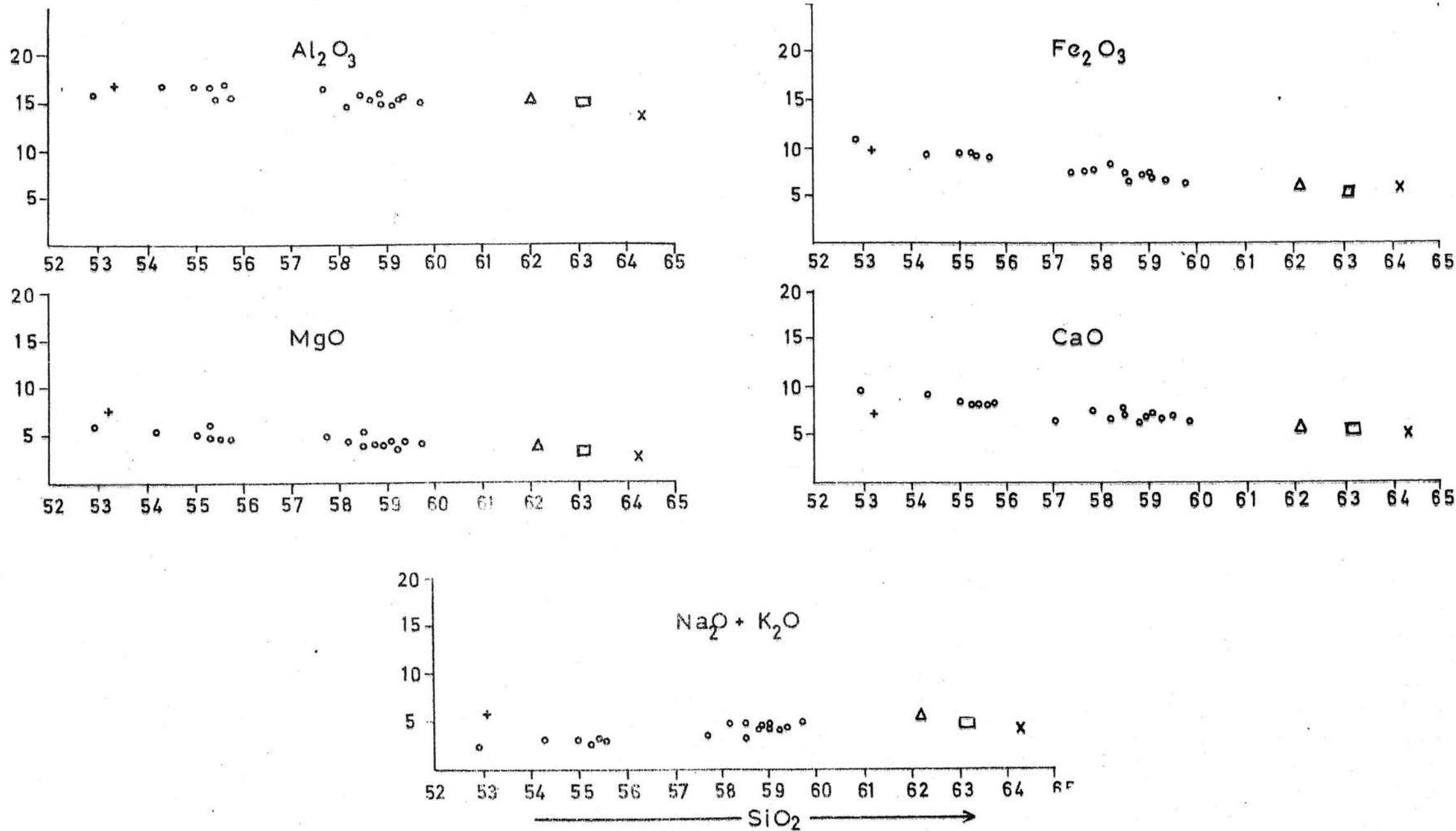


FIG. 2. MAJOR OXIDES PLOTTED AGAINST SiO₂ FOR THE KALAM DIORITES.
 Δ GRANODIORITE, □ SP. No. 21, x SP. No. 12 + HIGH-K DIORITE, ○ LOW-SILICA AND NORMAL DIORITES.

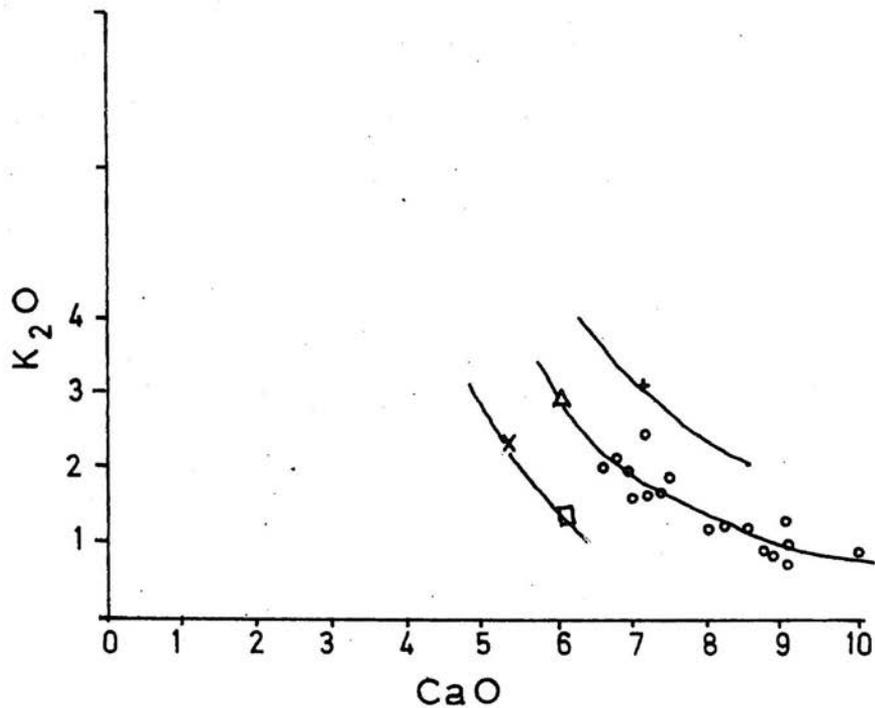


FIG. 4. K_2O VERSUS CaO FOR THE DIORITES SAMPLES MARKED BY SYMBOLS AS IN FIG. 2.

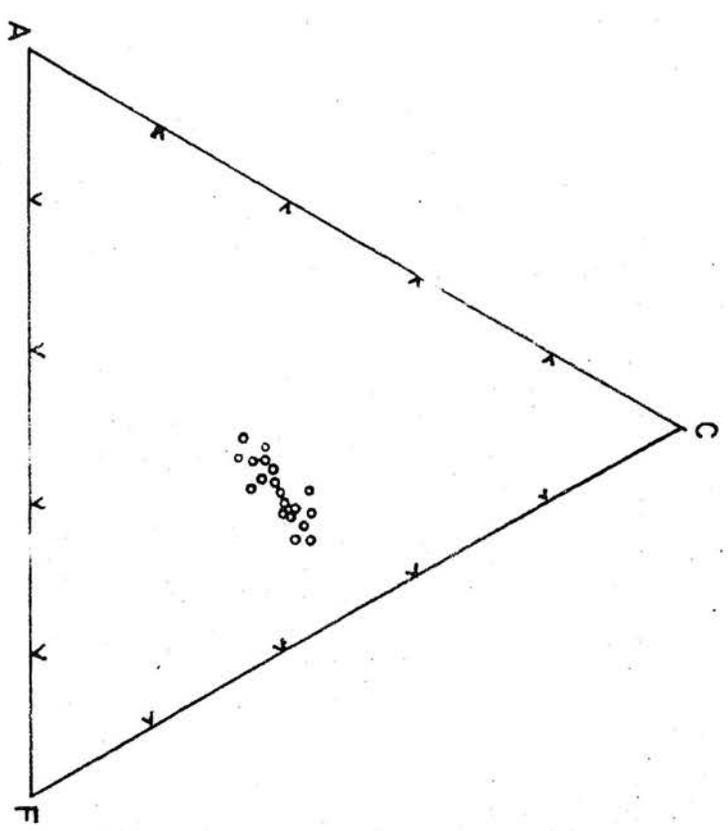
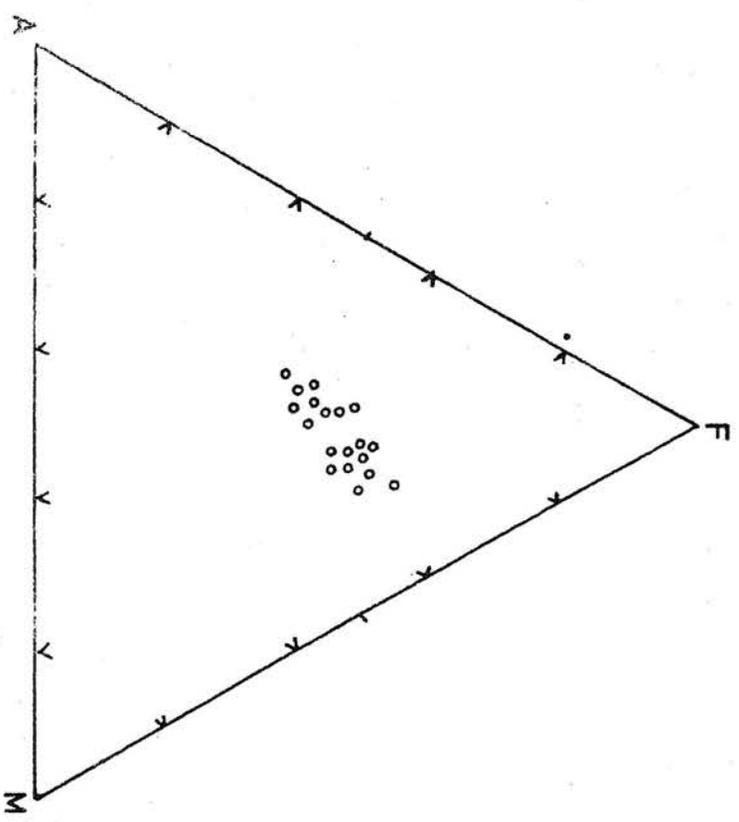


FIG. 5. FMA AND FCA DIAGRAMS FOR THE DIORITES.

Origin of the Kohistan calc-alkaline association.

Based on the results of their experimental work Brown and Fyfe (1970) and Brown (1973) suggested the possibility of derivation of diorite-granodiorite-granite by the partial fusion of various quartzo-felspathic mineral mixes. Experiments were carried out at pressure and temperature ranges which were considered appropriate for melting within the crust. The results are shown in fig 7. From the diagram it is clear that if the homogeneous crustal material is subjected to increase temperature and pressure during metamorphism, partial melting would produce a series of liquid varying in composition from granite to granodiorite and diorite.

According to these authors true granitic rocks represent the products of partial melting at the lowest temperature and shallowest level where as granodiorite and diorite are generated at progressively deeper crustal levels.

The Kohistan sequence, with the exception of post tectonic granitic intrusion, does not include typical sialic rocks. Moreover, the observed Rb/Sr ratios in the Kalam diorites indicate a source region surely not of the sialic character because these values (tables 2 to 7) are distinctly different from the normal average for crustal rocks (about 0.25, Turekian and Kulp, 1956).

The idea of contamination of any type of basalt, with the granitic material to produce calc-alkaline igneous rock series (Daly, 1933; Tilley, 1950; Kuno, 1950; Water, 1955; and Wilcox, 1954) is greatly hindered by very similar trace element contents especially of V in the three types of basalt and in the analysis of the more basic diorite in the area. (Table 8). If the hypothesis of contamination is accepted then simple bulk mixing of granite and basalt in the proportion (1 : 1) which approximate to diorite major element composition would dilute the V content in basalt by a great factor because granites contain typically very low concentration of V. (10 P. P. M. Taylor, 1968). The diorites will then show V P.P.M. much lower than basalt.

There remain for consideration the assumption of a parental calc-alkaline liquid whose evolution within the segment of the Himalayan orogen between Afghanistan border and Nanga Parbat can be explained as a consequence of a descending oceanic plate during the process of collision of the Indian and Asian continents.

TABLE 8. MAJOR ELEMENT AND FERROMAGNESIAN TRACE
ELEMENT COMPOSITION OF BASALT* AND BASIC DIORITE
(KALAM DIORITE-GRANODIORITE SERIES).

	1	2	3
SiO ₂	49.2	51.7	53.00
Al ₂ O ₃	15.7	16.9	16.14
FeO	11.2	10.4	
MgO	8.7	6.5	5.75
CaO	10.8	11.0	9.85
Na ₂ O	2.3	3.1	2.17
K ₂ O	1.0	0.4	0.82
TiO ₂	1.8	...	1.41
P.P.M.			
Ni	120	25	14
Cr	130	40	23
V	200	250	199
V/Ni	1.7	10.00	14

1. Alkali and tholeiitic basalt.
2. High-Al basalt.
3. Basic diorite (Kalam diorite-granodiorite Series).

*Major and trace element data of basalt taken from Taylor (1969).

Table 9. Approximate chemical composition of parent liquid of the Kohistan calc-alkaline suite and its comparison with parent magmas of calc-alkaline series of the High Cascades and Oregon plateaus, Scottish Caledonian, Crater lake, Paricutin, and Southern California Batholith.

	1	2	3	4	5	6	7
SiO ₂	55.07	55.3	54.4	56.3	54.9	54.0	49.56
Al ₂ O ₃	17.10	17.0	16.5	17.4	18.1	17.6	17.88
Fe ₂ O ₃	3.38	3.1	1.6	1.9	3.9	1.7	2.78
FeO	5.24	4.0	6.4	6.3	3.8	6.0	7.26
MgO	5.01	6.1	6.6	4.7	5.4	7.0	6.97
CaO	8.75	7.5	7.8	7.9	8.6	8.1	9.99
Na ₂ O	2.63	3.3	3.5	3.1	3.4	3.6	2.90
K ₂ O	1.32	2.1	1.7	1.2	0.8	0.7	0.73
TiO ₂	0.76	1.3	1.0	1.1	0.8	1.0	1.53
MnO	0.17	0.1	0.2	0.1	0.1	0.1	0.14
P ₂ O ₅	0.21	0.4	0.3	0.1	0.2	0.2	0.26

1. Kohistan Sequence.
2. Comrie diorite complex.
3. Scottish Caledonian.
4. Southern California batholith.
5. Crater lake.
6. Paricutin, Mexico.
7. High Cascades and Oregon plateaus.

(Analysis 2. Majid, 1974; analyses 3 to 6 from Nockolds and Allen, 1953. table 8. analysis 7. from Water, 1962. table 9, also quoted by Best 1969, table 1.)

During the initial stages of closer of Tethys, the oceanic floor was dragged along a northward dipping benioff zone under an arc (Tahirkheli *et. al.* 1979). With the descent of the plate, rocks within the slice of the oceanic crust must have been subjected to phase transformations due to the instability of the crustal silicates at high pressure. The plagioclase, olivene and pyroxene within the basic rocks of the descending oceanic crust (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) must have been replaced by eclogitic assemblages (Green, 1967; Yoder and Tilley, 1962) with increased depth.

Green and Ringwood (1968 a) have demonstrated that at 25-40 Kbars pressure and in the absence of water, andesite is the low melting fraction of quartz eclogite with a composition similar to basalt found in association with the calc-alkaline series. Partial melting at about 100 Km. depth of the basic material of the oceanic crust along the benioff zone, after undergoing phase transformation, must have provided liquids for the calc-alkaline plutons intruded into the arc before the suturing and collision of the arc with the indian continent.

The ultramafic rocks with mantle densities, exposed in the lower portion of the Kohistan sequence can not be related to the calc-alkaline series in the proposed scheme. In fact these can best be explained in terms of tectonic rise of the upper mantle slices as suggested by Tahirkheli *et. al.* (1979). According to these authors the Kohistan sequence represents an ideal cross section of the crust of a calc-alkaline arc having tectonically emplaced slabs of the upper mantle material in the lower portion and lavas and sediments (comparable to the volcanics of presently active arcs) in the upper most part.

Nature of the Liquid

On the silica variation plot (fig. 2) most of the oxides in the analyses of the studied samples exhibit a smooth variation trend from 55% SiO₂ onwards. Data points of few samples, having less than approximately 55% SiO₂ in the analysis, lie within a region of scattering. Such rocks can be linked with the diorite-granodiorite series by a process of selective crystal accumulation.

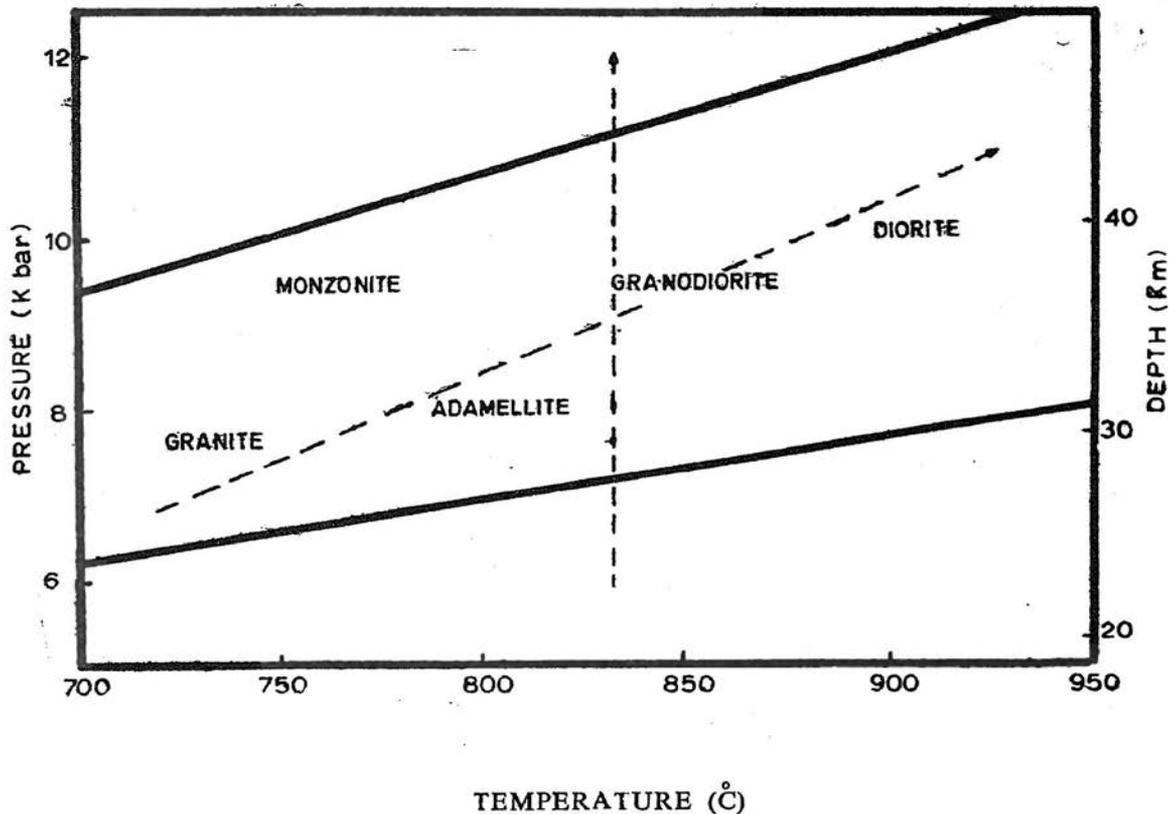


FIGURE 7. Summary of the compositional affinities of the granite family for various pressure-temperature-depth regimes as deduced from experimental results. The two arrows show decreasing normative quartz and increasing albite/orthoclase ratios. (after Brown, 1973).

Nöckolds (1941) while studying the igneous rocks from the Garabal Hill-Glen Fyne complex, Scotland, related the associated gabbro and minor ultrabasics to the calc-alkaline series of the complex by the same process rather than giving them a parental status in the series. In the region of continuous variation analysis no. 8 (table 4) is the most basic composition and it has been considered closely approximating to the original liquid. It has been compared with the compositions of the original liquids of some important calc-alkaline series reported by Nöckolds and Allen (1953, table 8) and Best (1969, table 1) in table 9. The assumed original liquid composition of the Kohistan calc-alkaline suite resemble very closely to the listed compositions.

The diorites and related rocks from the studied area, however, differ from the Caledonian calc-alkaline series in respect of the alkali-silica relations. The compositions of the analysed samples from the Kohistan zone lie within the field of the Japanese tholeiites (Kuno, 1969) on the alkali vs. silica diagram while diorites from the Scottish Caledonian calc-alkalic series (e. g. from the Comrie-diorite complex, Majid, 1974) plot in the high-Al. basalt area (fig. 6)

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