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ISLAND ARC SIGNATURES FROM THE WAZIRISTAN IGNEOUS COMPLEX, N.W.F.P., PAKISTAN

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ABSTRACT

The Waziristan igneous complex consists of peridotite, gabbro, diorite, diabase and a variety of volcanic rocks. Petrographic studies and mineral chemistry of the rocks contradict their oceanic crust origin and evince an island arc parentage. The high Mg# (89–95) of the olivine and pyroxenes, and absence of plagiocalse in the cumulus peridotite suggest crystallization at high pressures — not typical of oceanic crust. The calcic-plagioclase (An_{90-97}) and clinopyroxene ($Wo_{44-46}En_{44-50}Fs_{5-12}$) association in the gabbroic rocks of the Waziristan igneous complex is akin to other island arc-related gabbros. A variety of diagrams used for discrimination of clinopyroxenes from different tectonic environments, also indicate the island arc affinity of this complex.

INTRODUCTION

The suture zone that dissociates the Indo-Pakistan plate from the Eurasian block and the Gondwanic microcontinents (*e.g.,* the Afghanistan and Iran blocks; *cf.* Shah, 1984), is marked by a number of mafic and ultramafic complexes. Some of these have been considered as fragments of oceanic crust/ophiolites (*e.g.* Gansser, 1979), while others have been associated with Island arc(s) (*e.g.* Jan *et al.,* 1984). Among these mafic-ultramafic complexes no less than six occur in Pakistan. With an area of 500 sq. km., the Waziristan igneous complex stands as the third largest of these complexes, after Bela and Zhob (*cf.* Bakr and Jackson, 1964; Kazmi and Rana, 1982). The Waziristan igneous complex is located in the North and South Waziristan agencies of the tribal belt of Pakistan. Some preliminary investigations of the area have been conducted in the past (Khan *et al.,* 1982; Badshah, 1985; Jan *et al.,* 1983, 1985). The complex is associated with Jurassic-Cretaceous and Early Tertiary stratigraphic sequences and is locally covered by Quaternary deposits. It occurs in thrust slices overiding the Mesozoic sequence of the Indo-Pakistan plate, and is unconformably overlain by the Eocene strata. Thus it can be inferred that the Waziristan igneous complex was allochthonously emplaced in the Paleocene to early Eocene. This time of emplacement is similar to that of Bela (Ahmed and Abbas, 1979; Allemann, 1979) and Zhob (DeJong and Subhani, 1979) ultramafic complexes, thus coinciding with the event of the closure of the Neo-Tethys (also see Hamidullah and Onstat, in press).

Complexity of structure in the area depicts intense tectonic activity (Fig. 1). No stratigraphic sequence is discernible in the igneous complex and its configuration is mostly chaotic, due to imbricate thrusting and folding. Nevertheless, the different rock types that have been recognised by the previous workers are : ultramafic masses, mafic to intermediate intrusives and basic to acidic extrusives. The ultramafic rocks consist of serpentinized peridotites, dunites, and pyroxenites. The intrusives comprise gabbros, diabase and diorites, whereas the volcanics consist of pillow basalts, andesites, dacites, rhyodacites, tuffs and agglomerates. Abundant copper mineralization has also been reported from the complex (Badshah, 1985).

So far, the entire Waziristan igneous complex has been labelled as an ophiolite complex (Asrarullah *et al.,* 1979; Khan *et al.,* 1982; Shah, 1984; Badshah, 1985; Jan *et al.,* 1985), neglecting the significance of dacites, andesites and associated tuffs, agglomerates and copper deposits. Such an association is, however, not very typical of oceanic crustal environments. Rather, it is indicative of supra-Benioff zone igneous activity (Hughes, 1982).

The main object of our present work was to study primary mineral chemistry of Waziristan igneous complex, leading ultimately to petrogenetic interpretation. Samples from peridotite, gabbro, diabase and some volcanics were collected for this purpose. Mineral compositions were determined with computer automated 2–spectrometer JCXA–733 electron microprobe, using wavelength dispersive system. Data were reduced on-line using ZAF quantitative analysis program and reference to natural and synthetic standards.

GENERAL GEOLOGY AND PETROGRAPHY

The general geological setting of the area has been described by Khan *et al.* (1982), Jan *et al.* (1983, 1985) and Badshah (1985). According to these studies major lithologies of the area are (a) Mesozoic sedimentary sequence, containing fossiliferous limestone, shale and sandstone, representing a continental margin sequence of Jurassic to Cretaceous age, (b) an Eocene sedimentary sequence, containing limestone and shale, which disconformably overlies the volcanics of the Waziristan igneous complex, (c) a pelagic sequence having a tectonic contact with the volcanics of the complex, suggesting a Paleocene emplacement age, and (d) the rocks of the Waziristan igneous complex. The Waziristan igneous complex is the subject of present studies, the details of which are described as follows.

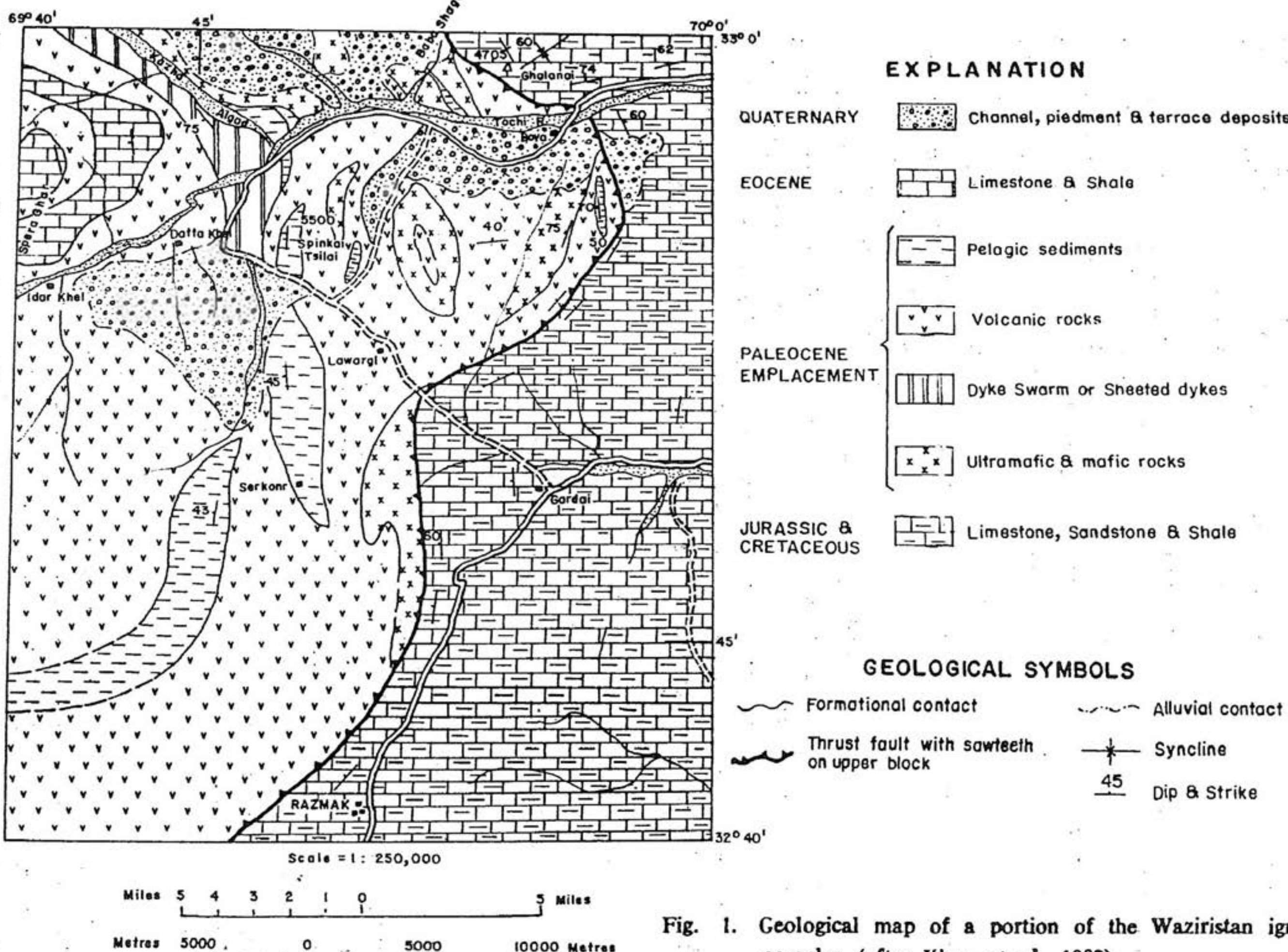

Fig. 1. Geological map of a portion of the Waziristan igneous complex (after Khan *et al.*, 1982).

Ultramafic rocks

Altered peridotites, dunites and pyroxenites constitute the ultramafic rocks of the complex *(cf.* Jan *et al.,* 1985; Badshah, 1985). Most of these ultramafic rocks have been thoroughly and extensively serpentinized.

The peridotite studied during the present work, has antigorite as the major alteration product (confirmed through XRD, data available from authors on request) containing cleavage traces of pyroxenes and pseudomorphs of olivine. The less altered peridotite contains subhedral to anhedral grains of olivine (Fo_{89-91}), enstatite ($Wo_{0.6-2}En_{88-91}Fs_{8-10}$) and diopside ($Wo_{48-50}En_{45-47}Fs_{2-5}$), commonly ranging in size from 2mm to 5mm (Fig. 2). The pyroxenes are unzoned and make up approximately 30–40% (visual estimate, including the serpentinized pyroxenes as well) of the rock. Chromite occurs as disseminated subhedral grains and segregated stringers and lenses in the peridotite. The Cr# [Cr/(Cr+Al)] of these chromites ranges from 0.68 to 0.82 (Jan *et al.,* 1985). Magnetite grains also occur as minute dusty particles and small euhedral to subhedral grains filling fractures in the serpentinite matrix. The peridotite does not show any signs of strong deformation or recrystallization, although some minor deformation features, such as minute kink bands are variably present in some olivine grains. The large grain-size, unzoned character of pyroxenes and absence of deformation or recrystallization features suggest a cumulate origin for the studied peridotite.

Basic to intermediate plutonics

These plutonics mostly comprise gabbros with some subordinate diorites. As in the rest of the complex, alteration has been pervasive in these rocks too. Secondary minerals like chlorite and amphibole occur abundantly.

Plagioclase (An_{95-97}) and Ca-rich pyroxene ($Wo_{44-46}En_{44-50}Fs_{5-12}$) are the dominant unaltered igneous phases in the studied gabbros. Most of the pyroxene grains, ranging in size from 0.5 to 5 mm, have been altered to talc/serpentine, chlorite and uralite, but the original subhedral shape of the grains is preserved. The plagioclase is subhedral and commonly seen enclosing the pyroxene grains poikilitically. It commonly shows albite twining, while some grains show both albite and pericline twining. The plagioclase is not much altered but is commonly fractured, with chlorite from the adjacent altering pyroxenes growing into these fractures.

In the diorites, the constituent plagioclase is subhedral and ranges in composition from oligoclase to andesine. Quartz occurs as anhedral grains. All the ferromagnesian phases have been invariably altered to fibrous amphibole/chlorite. Fine grains of a subhedral opaque oxide, probably magnetite, are disseminated throughout the rock. Epidotization and calcitization have quite obviously affected the rock.

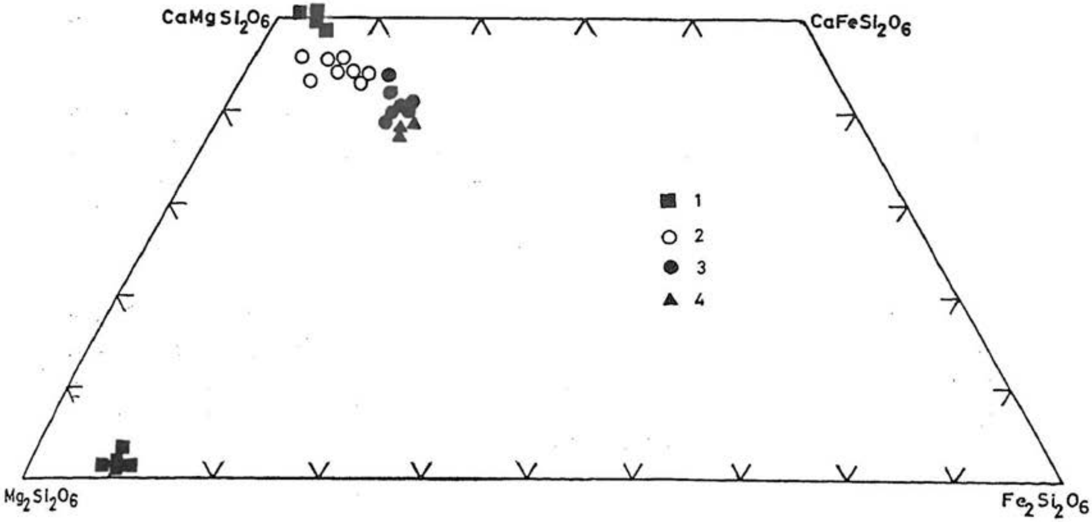

Fig. 2. Pyroxene compositions from the Waziristan igneous complex. 1: peridotite; 2: gabbro; 3: volcanics; 4: diabase.

Diabase

The diabase is also affected by post emplacement alteration and the ferromagnesian phases have been dominantly replaced by chlorite, tremolite and actinolite. The phenocryst phases comprise of plagioclase (An_{89-95}) and clinopyroxenes ($Wo_{37-39}En_{32-34}Fs_{18}$). Like in the gabbros, the plagioclase phenocrysts are mostly unzoned and some of them have enclosed clinopyroxene grains. The matrix is comprised of plagioclase (An_{88-92}) microlites, chlorite and fibres of secondary amphibole.

Volcanics

The volcanics of the complex range from basalts to andesites, dacites and rhyodacites, with associated tuffs and agglomerates. These volcanics are also extensively altered showing secondary phases like chlorite, fibrous amphibole and epidote.

Relict subophitic texture can still be observed in the basaltic rocks, inspite of their altered nature. The phenocryst phases in the basalts comprise of clinopyroxene, plagioclase and some olivine. The clinopyroxenes ($Wo_{38-43}En_{40-44}Fs_{14-18}$) mostly occur as small (.05mm–1mm) subhedral microphenocrysts (10–15 modal%), although larger grains are also present but are mostly pseudomorphed by fibrous amphibole and chlorite. The plagioclase phenocrysts (1mm to 3mm) are euhedral to subhedral and zoning is observable in some. They are variably affected by corrosion and incipient saussuritization. The olivine phenocrysts (2–5 modal%)

are invariably pseudomorphed by talc/serpentine. The groundmass is dominantly constituted by chlorite, minute amphibole fibres, albite (Ab_{92-94}) microlites and devitrified glass and shows small scale spherulitic texture. Minute magnetite octahedras are distributed quite regularly throughout the matrix.

In the andesites and dacites the presence of quartz is noticeable (5–10 modal%) as a microphenocryst phase and in the matrix as well. Besides intermediate plagioclase, albite laths are also present. Epidotization is quite evident throughout these rocks. Along with chlorite, fibrous amphibole forms most of the groundmass, enclosing pseudopmorphed pyroxene phenocrysts.

The tuffs and agglomerates consist of chloritized glassy matrix and show a very obvious flow texture. Plagioclase, occuring as crystal fragments and also as whole crystal laths clouded by saussuritization, dominates the phases enclosed by the matrix. Some altered pyroxenes are also present. Magnetite grains and hematitic dust is distributed throughout the tuffs.

DISCUSSION: TECTONIC SETTING

The mineral compositions of the ultramafic and mafic rocks of the Waziristan igneous complex indicate that they are not in complete semblance with the rocks of oceanic crust or the typical ophiolite suites. Rather, more than to any other affinity, they point towards an island arc origin.

In the ultramafic cumulates, the olivine consistently shows a high Fo content of 89 to 91. Similarly, the clino- and orthopyroxenes of these cumulates are also highly magnesian (100 Mg/(Mg+Fe) = 89–95) (Fig. 3). The absence or near absence of plagioclase and the presence of highly magnesian olivine and pyroxene in these ultramafic cumulates indicates that they were formed by high-pressure ($\gtrsim$ 10 kbar) crystal fractionation (Elthon *et al.*, 1982). In case of primary magmas proposed for oceanic basalts, it has been shown by Elthon *et al.* (1982) that for low to moderate pressures ($<$ 10 kbar) olivine is the liquidus phase and is followed by plagioclase and clinopyroxene, whereas under higher pressures ($\gtrsim$ 10 kbar), clinopyroxene crystallizes before plagioclase. The high Mg# of the analyzed pyroxenes and olivines (Table 1) is in agreement with the values predicted by Elthon *et al.* (1982) for such high pressure cumulus phases. Normally in the oceanic crust, orthopyroxene is not a dominant cumulus phase, rather it occurs as a late intercumulus mineral (*cf.* Burns, 1985). In the studied peridotite from the Waziristan igneous complex, orthopyroxene is an obvious cumulus phase, indicating the same paragenesis (*i.e.*, high degree of Si saturation in the melt than MORB magmas, or crystallization at moderate pressures), as the Border Ranges ultramafic complex, which represents the root of an island arc (Burns, 1985). These features show a prominent contrast with the rocks of the oceanic crust which generally crystallize in a low pressure environment

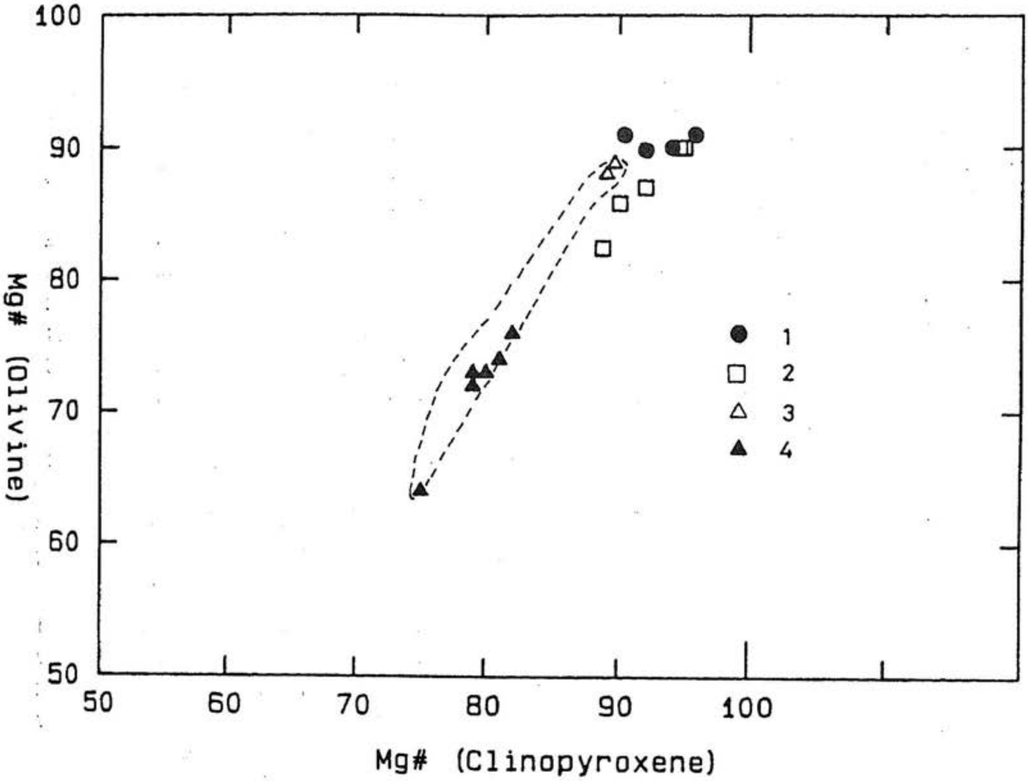

Fig. 3. The Mg number [100 Mg/(Mg+Fe)] of coexisting olivine and clinopyroxene. 1: peridotite from Waziristan igneous complex; 2: ultramafic cumulates from Border Ranges ultramafic complex (Burns, 1985); 3: oceanic ultramafic cumulates (Hodges and Papike, 1976); 4: oceanic gabbroic rocks (Tiezzi and Scott, 1980). The field shown is for oceanic ultramafic and gabbroic rocks, after Eithon *et al.* (1982).

(≤ 2.5 kbar) (Flower *et al.*, 1977; Sleep, 1975; Dewey and Kidd, 1977). Though some high pressure crystal fractionation does occur at greater depths (> 30 km) in the mantle beneath the oceanic ridges, but these have been reported as anomalous features in the oceanic crust (e.g., Elthon *et al.,* 1982). Such high pressure environments would be more likely at the base of island arcs *(e.g.* Burns, 1985).

The spinels can provide useful clues for discriminating the tectonic settings. According to Dick and Bullen (1984), spinels with Cr# [Cr/(Cr+Al)] < 0.6 are typical of oceanic crust. Whereas spinels with Cr# > 0.6 are found in volcanic arcs, stratiform complexes, zoned Alaskan complexes and oceanic plateau basalts. The spinels from the peridotite of the Waziristan igneous complex contain Cr# greater than 0.6 and thus show a definite contrast with

TABLE 1. REPRESENTATIVE ANALYSES OF OLIVINE AND PYROXENES FROM THE PERIDOTITE.

	01	01	01	Opx	Opx	Cpx	Cpx
SiO_2	40.42	40.67	40.21	54.86	54.57	53.18	51.31
Al_2O_3	0.01	0.00	0.01	3.82	3.44	2.37	2.95
TiO_2	0.00	0.00	0.01	0 02	0.01	0.06	0.02
Cr_2O_3	0.01	0.00	0.00	0.85	0.77	0.73	0.92
FeO*	9.26	8.83	10.44	6.68	6.59	1.32	2.53
MgO	50.14	50.03	49.85	34.00	33.23	17.00	16.48
MnO	0.09	0.07	0.09	0.11	0.09	0.06	0.04
CaO	0.01	0.01	0.00	0.51	0.60	25.26	24.85
Na_2O	0.06	0.09	0.13	0.09	0.07	0.19	0.14
TOTAL	99.99	99.71	100.74	100.95	99.37	100.18	99.24
IONS BASED ON 4 OXYGENS FOR OLIVINE AND 6 OXYGENS FOR PYROXENES							
Si	0.989	0.995	0.983	1.886	1.904	1.931	1.895
Al	0.00	0.00	0.00	0.155	0.141	0.101	0.128
Ti	0.00	0.00	0.00	0.001	0 00	0.002	0.0 1
Cr	0.00	0.00	0.00	0.023	0.021	0.021	0.027
Fe	0.189	0.181	0.213	0.192	0.192	0.040	0.078
Mg	1.829	1.825	1.816	1.742	1.728	0.920	0.907
Mn	0.002	0.001	0.002	0.003	0.003	0.002	0.001
Ca	0.00	0.00	0.00	0.019	0.022	0.983	0.984
Na	0.003	0.004	0.006	0.006	0.005	0.013	0.010
Wo(%)	—	—	—	0.97	1.16	50.59	49.96
En(%)	—	—	—	89.20	88.94	47.35	46.07
Fs(%)	—	—	—	9.84	9.90	2.06	3.97
100xMg/(Mg+Fe)	90.60	90.97	89.48	90.07	90.00	95.83	92.08

* Total iron expressed in ferrous state.
Abbreviations : 01 = olivine; Opx = orthopyroxene; Cpx = clinopyroxene.

abyssal peridotites. Although these spinels plot in the "alpine peridotite" field on the Cr-Al-Fe^{3+}+Ti diagram (Jan *et al.*, 1985), it is interesting to note that the spinels from the Border Ranges ultramafic complex (Burns, 1985), also plot in the same field. Thus it is suggested that these rocks cannot be unequivocally called upper mantle tectonites on the basis of this diagram. Other characteristics of these peridotites from Waziristan, such as their cumulate texture and absence of strong tectonite fabric also support their island arc origin, along with the additional evidences from the related rocks as discussed below.

A prominent feature of the gabbros from the Waziristan igneous complex is that they invariably contain unzoned Ca-rich plagioclase (An_{90-97}), which is comparable with the Ca-rich plagioclase commonly associated with island arc magmatism. An (90–100) is a prominent and essential constituent of basic volcanic rocks of calc-alkaline suites of present-day circum-oceanic island arcs where it occurs as phenocrysts in basalt flows (Byers, 1955; Lewis, 1973). It also occurs in plutonic ejecta from these volcanoes, as in the plutonic blocks from Soufriere volcano, West Indies (Lewis, 1973) and islands in the Lesser Antilles (Arculus and Wills, 1980). Besides, such a highly Ca-rich plagioclase is also found in basic plutonic rocks of calc-alkaline suites like the Batholith of Southern California (Miller, 1937), Border Ranges mafic-ultramafic complex (Burns, 1985) and the Chilas complex (Jan *et al.,* 1984; Khan *et al.,* in press).

In the studied gabbros of the Waziristan igneous complex, the clinopyroxene is commonly enclosed poikilitically in plagioclase. This feature also suggest crystallization of clinopyroxene prior to plagioclase, indicating high pressure ($\gtrsim$ 10 kbar) crystallization. The pyroxenes of the studied gabbros generally shows Al^{vi}/Al^{iv} ratios, ranging from 1.29 to 0.28 (with a few values < 0.2), which indicate higher pressures of crystallization uncommon of shallow crystal igneous rocks (Aoki and Kushiro, 1968). Such Al^{vi}/Al^{iv} ratios of these pyroxenes and their crystallization prior to plagioclase further contradict oceanic crust affinity and favours an island arc origin for Waziristan igneous complex. This interpretation is also supported by the An mole% of plagioclase vs. Mg# [100Mg/(Mg+Fe)] of the coexisting clinopyroxenes plot (Fig. 4; *cf*. Burns, 1985).

The chemical composition of primary clinopyroxenes reflects the chemistry of host rocks (Kushiro, 1960; LeBas, 1962; Verhoogen, 1962; Deer *et al.,* 1978; Hamidullah and Bowes, in press). In view of this, the clinopyroxenes have been previously used for discrimination of different paleo-tectonic settings (Nishet and Pearce, 1977; Leterrier *et al.,* 1982; Capedri and Venturelli, 1979). The clinopyroxenes from the gabbro, diabase and volcanics of the Waziristan igneous complex were similarly employed for the purpose of working out the magmatic affinity of the complex.

The clinopyroxenes from the studied area differ from the alkaline rocks by virtue of their lower Ti and Al contents (Tables 2 and 3). Their non-alkaline nature is further indicated by Figures 5 and 6. The trend shown by these pyroxenes on the Alz vs. TiO_2 diagram (Fig. 5) of LeBas (1962) and Kushiro (1960), probably indicates increasing P_{H_2O} with crystallization (see Hamidullah, 1983; Hamidullah and Bowes, in press).

The low Ti and Cr values of these pyroxenes evince their similarity with rocks from supra-Benioff zone (including island arc tholeiites and calc-alkaline basalts), and contradict their oceanic crust affinity (Fig. 7). Figure 8 shows that the

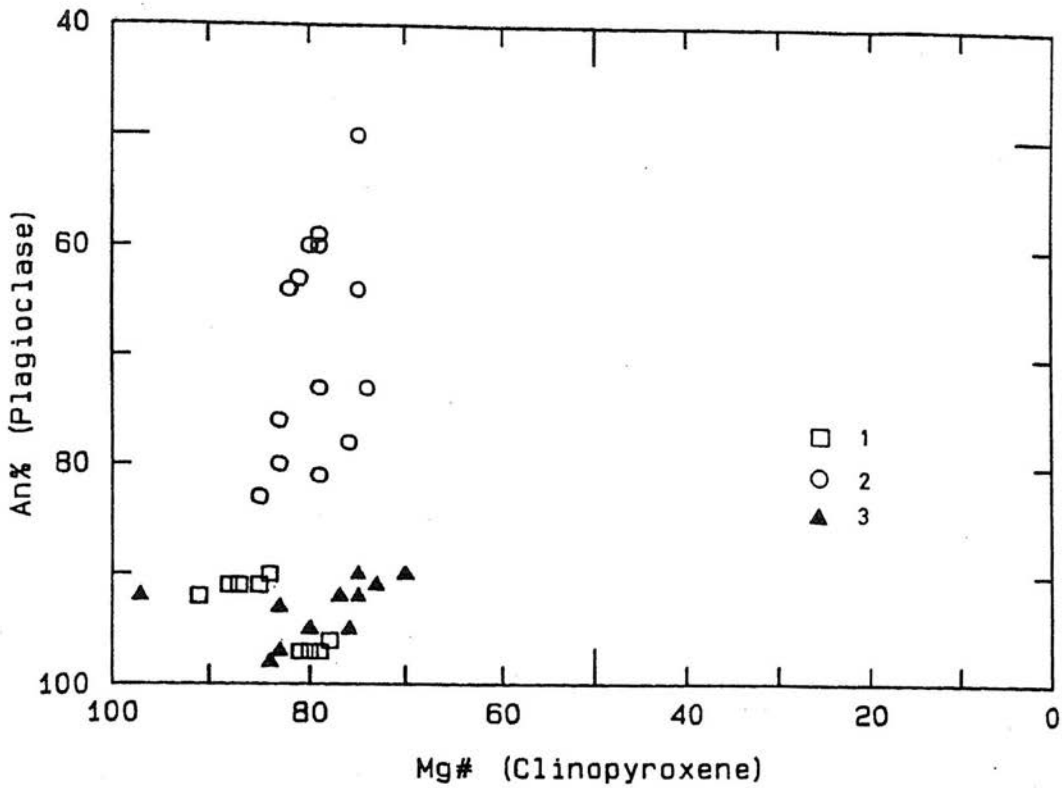

Fig. 4. Compositions of plagioclase and coexisting clinopyroxene from the gabbroic rocks of Waziristan igneous complex (1) compared with gabbros of the oceanic crust (2) and other island arc-related gabbroic rocks (3). Oceanic data are from Hodges and Papike (1976), Tiezzi and Scott (1980), Pallister and Hopson (1981). Island arc data are from Burns (1985) and Arcuius and Wills (1980).

pyroxenes from the volcanics of the Waziristan complex are of calc-alkaline type, whereas those from the diabase and the gabbros are of island arc tholeiitic nature. The TiO_2–MnO–Na_2O discrimination diagram of Nisbet and Pearce (1977) also supports the volcanic-arc affinity of these rocks (Fig. 9). The clinopyroxenes from the volcanics plot in the mixed field of this diagram, whereas most of clinopyroxenes from the diabase and the gabbros dominantly plot in field for volcanic-arc basalts, with some occupying the common field for volcanic-arc basalts and within-plate alkalic basalts. As the alkalic nature of these pyroxenes has been ruled out above, the volcanic arc-affinity remains the only alternate origin suggested by this diagram too. The copper mineralization associated with the rocks of the complex is probably the result of this island arc volcanism also (*cf*. Mitchell and Bell, 1973).

TABLE 2. REPRESENTATIVE ANALYSIS OF CLINOPYROXENES FROM GABBRO AND DIABASE.

	Gabbro						Diabase	
	1	2	3	4	5	6	7	8
SiO_2	52.65	52.55	53.66	53.02	53.33	54.14	51.57	51.49
Al_2O_3	1.56	1.69	2.15	2.32	2.04	1.67	1.48	2.46
TiO_2	0.06	0.06	0.13	0.28	0.16	0.09	0.11	0.11
Cr_2O_3	0.02	0.06	0.26	0.47	0.27	0.25	0.00	0.04
FeO*	7.32	6.86	2.98	5.28	5.51	4.67	12.24	11.91
MgO	16.27	16.18	17.58	16.18	16.50	16.89	15.90	15.22
MnO	0.00	0.09	0.08	0.09	0.11	0.09	0.15	0.13
CaO	21.79	21.96	22.49	22.44	21.82	22.61	19.26	19.42
Na_2O	0.02	0.06	0.19	0.30	0.26	0.26	0.06	0.08
TOTAL	99.69	99.51	99.51	100.39	100.01	100.98	100.77	100.88
NUMBER OF IONS ON THE BASIS OF 6 OXYGENS								
Si	1.951	1.949	1.955	1.939	1.954	1.969	1.926	1.916
Al	0.068	0.074	0.092	0.10	0.088	0.071	0.065	0.108
Ti	0.002	0.002	0.003	0.008	0.004	0.003	0.003	0.003
Cr	0.001	0.002	0.008	0.014	0.008	0.007	0.00	0.001
Fe	0.227	0.213	0.091	0.161	0.169	0.141	0.382	0.371
Mg	0.899	0.894	0.955	0.882	0.901	0.910	0.885	0.844
Mn	0.00	0.003	0.002	0.003	0.003	0.003	0.005	0.004
Ca	0.865	0.873	0.878	0.879	0.857	0.876	0.771	0.775
Na	0.001	0.005	0.013	0.021	0.018	0.018	0.004	0.006
Wo(%)	43.46	44.07	45.65	45.74	44.46	45.44	37.82	38.93
En(%)	45.14	45.18	46.63	45.85	46.77	47.23	43.42	42.43
Fs(%)	11.40	10.75	4.72	8.40	8.77	7.33	18.76	18.64
100xMg/(Mg+Fe)	79.84	80.78	91.30	84.56	84.21	86.58	69.85	69.47

* Total iron expressed in ferrous state.

TABLE 3. REPRESENTATIVE ANALYSES OF CLINOPYROXENE PHENOCRYSTS FROM THE VOLCANICS.

	1	2	3	4	5	6	7	8
SiO_2	52.29	52.01	51.53	49.72	49.54	49.80	50.84	49.80
Al_2O_3	1.55	2.79	3.06	3.82	3.13	2.96	2.18	2.91
TiO_2	0.36	0.59	0.71	0.64	0.64	0.65	0.54	0.68
Cr_2O_3	0.04	0.00	0.00	0.00	0.02	0.01	0.03	0.00
FeO*	10.60	10.97	9.41	10.87	11.11	11.75	10.75	11.19
MgO	16.15	15.19	15.15	13.94	14.45	15.20	15.81	14.79
MnO	0.16	0.17	0.20	0.13	0.13	0.21	0.21	0.13
CaO	19.23	19.88	20.52	19.75	19.63	19.77	20.05	20.32
Na_2O	0.23	0.33	0.28	0.40	0.30	0.26	0.26	0.28
TOTAL	100.61	101.93	100.86	99.28	99.01	100.59	100.67	100.11
NUMBER OF IONS ON THE BASIS OF 6 OXYGENS								
Si	1.939	1.910	1.904	1.880	1.882	1.869	1.896	1.875
Al	0.068	0.121	0.133	0.170	0.140	0.131	0.096	0.126
Ti	0.010	0.016	0.020	0.018	0.018	0.018	0.015	0.019
Cr	0.001	0.00	0.00	0.00	0.001	0.00	0.001	0.00
Fe	0.329	0.357	0.291	0.344	0.355	0.369	0.335	0.352
Mg	0.893	0.831	0.834	0.786	0.818	0.850	0.879	0.830
Mn	0.005	0.005	0.006	0.004	0.004	0.007	0.007	0.004
Ca	0.764	0.782	0.8.2	0.80	0.799	0.795	0.801	0.820
Na	0.016	0.023	0.02	0.029	0.022	0.019	0.019	0.02
Wo(%)	38.49	40.10	41.94	41.48	40.51	39.47	39.75	40.94
En(%)	44.96	42.63	43.05	40.71	41.49	42.22	43.61	41.46
Fs(%)	16.56	17.27	15.01	17.81	18.00	18.31	16.64	17.60
100xMg/(Mg+Fe)	73.07	71.15	74.13	69.56	69.74	69.73	72.41	70.22

* Total iron expressed in ferrous state.

TABLE 4. REPRESENTATIVE ANALYSES OF PLAGIOCLASE FROM GABBRO AND DIABASE.

	Gabbro						Diabase	
	1	2	3	4	5	6	7	8
SiO_2	44.15	43.88	42.91	44.92	44.92	45.27	44.22	46.57
Al_2O_3	35.69	35.34	35.20	34.29	34.59	34.32	34.64	32.88
FeO*	0.87	0.48	1.05	0.41	0.77	0.00	0.36	1.03
MgO	0.06	0.06	0.08	0.04	0.04	0.00	0.08	0.13
CaO	19.84	20.29	19.89	19.28	19.55	19.17	19.76	18.04
Na_2O	0.29	0.45	0.39	1.02	0.96	1.06	0.55	1.82
K_2O	0.02	0.03	0.00	0.00	0.00	0.01	0.02	0.06
TOTAL	100.93	100.53	99.51	99.96	100.83	99.82	99.63	100.57
			NUMBER OF IONS ON THE BASIS OF 8 OXYGENS					
Si	2.032	2.030	2.009	2.083	2.070	2.096	2.059	2.147
Al	1.936	1.927	1.943	1.874	1.879	1.873	1.901	1.787
Fe	0.034	0.018	0.041	0.016	0.030	0.00	0.014	0.042
Mg	0.004	0.004	0.005	0.003	0.003	0.00	0.005	0.009
Ca	0.979	1.005	0.998	0.958	0.965	0.951	0.986	0.891
Na	0.026	0.04	0.035	0.092	0.086	0.095	0.049	0.163
K	0.001	0.002	0.00	0.00	0.00	0.001	0.001	0.003
An (%)	97.33	96.00	96.59	91.26	91.83	90.89	95.13	84.29

* Total iron expressed in ferrous state.

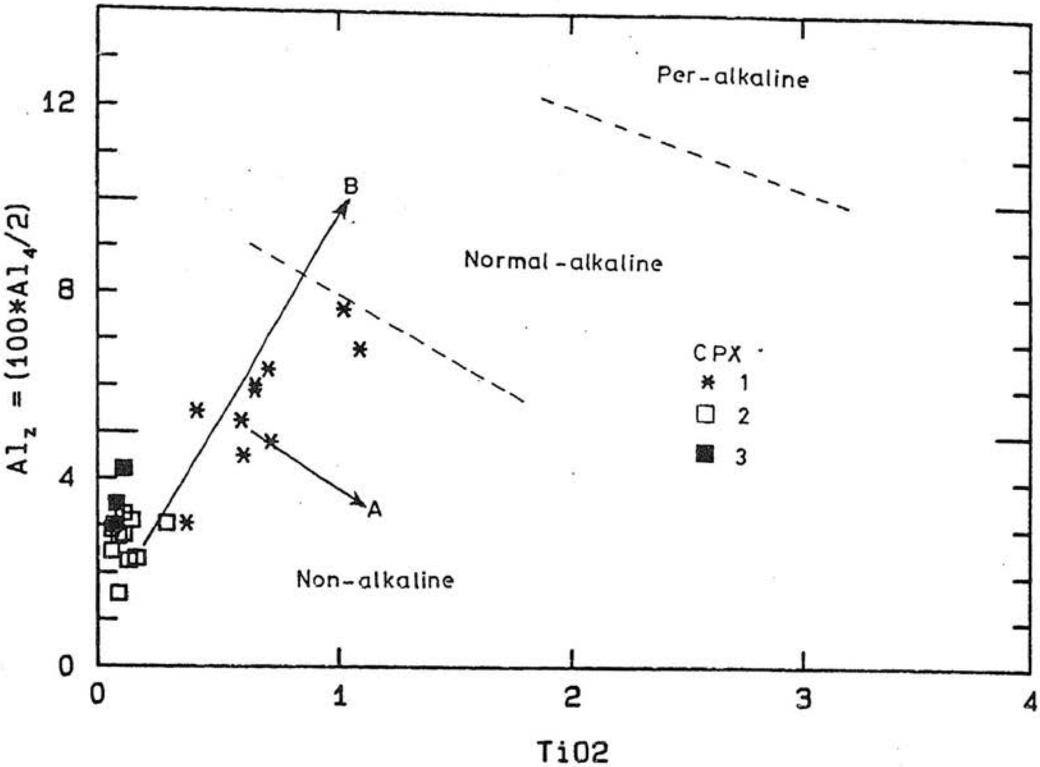

Fig. 5. Discrimination diagram on the basis of Alz vs. TiO_2 for clinopyroxenes from Waziristan igneous complex. 1: volcanics, 2: gabbros, and 3: diabase. Rays A and B indicate the differentiation trends of non-alkaline rocks (LeBas 1962) and appinite suite of western Scotland (Hamidullah, 1983), respectively. Fields are after Kushiro (1960) and LeBas (1962).

Fig. 6. Discrimination diagram for clinopyroxenes from alkali basalts (field A) and other basalts (field T), after Leterrier *et al.* (1982). Level of confidence for each group is given on either side of the dividing line. Same symbols as in Fig. 5

(see opposite page)
⟶

Fig. 7. Discrimination diagram for clinopyroxenes from non-orogenic tholeiites (field D) and orogenic basalts (field O), after Leterrier *et al.* (1982). 1—3: same as in Fig. 5; 4: abyssal tholeiites. Oceanic data are from Ridley *et al.* (1974), Frey *et al.* (1974) and Schweitzer *et al.* (1979).

(see opposite page)
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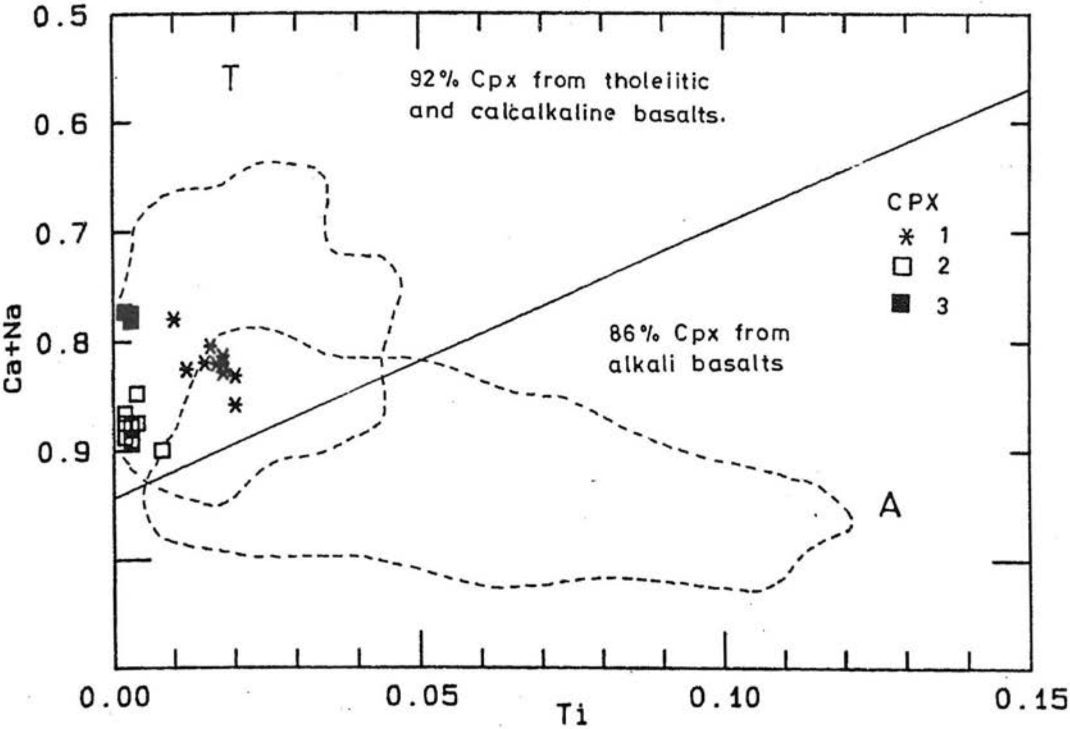
0.5
0.6
0.7
0.8
0.9
Ca+Na
T
92% Cpx from tholeiitic and calcalkaline basalts.
CPX
1
2
3
86% Cpx from alkali basalts
A
0.00
0.05
0.10
0.15
Ti

Fig. 6.

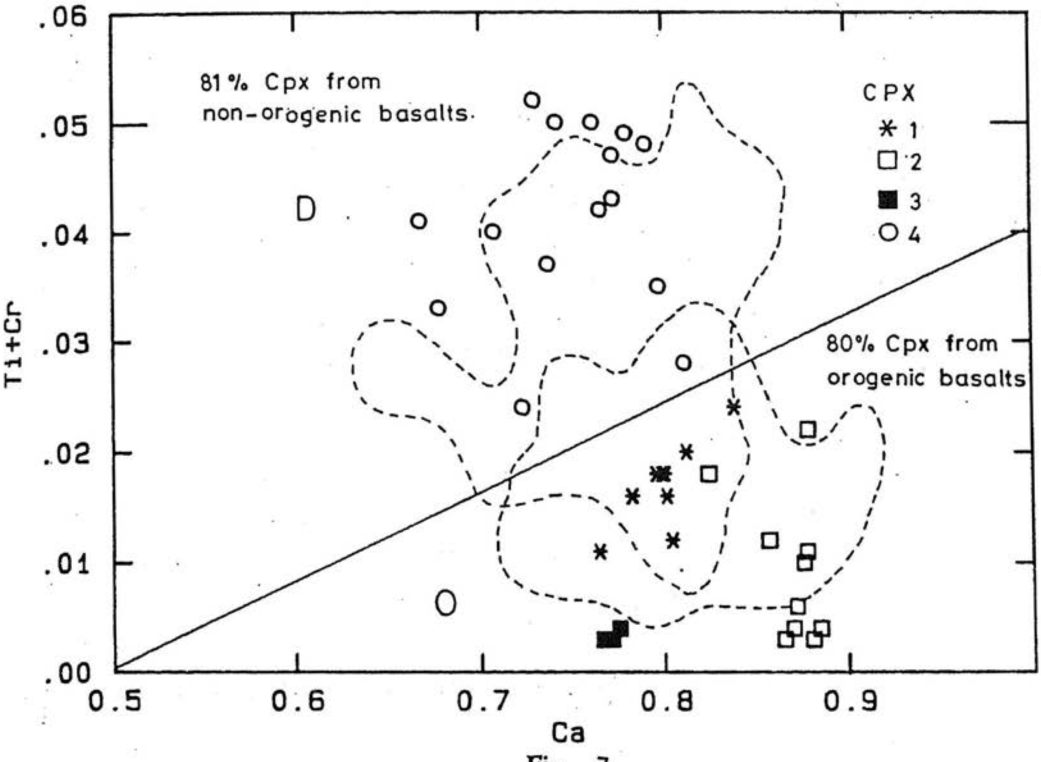
.06
.05
.04
.03
.02
.01
.00
Ti+Cr
81% Cpx from non-orogenic basalts.
D
CPX
1
2
3
4
80% Cpx from orogenic basalts
O
0.5
0.6
0.7
0.8
0.9
Ca

Fig. 7.

Fig. 8. Discrimination diagram for clinopyroxenes from calc-alkaline basalts (field C) and island arc tholeiites (field I), after Leterrier *et al.* (1982) Some symbols as in Fig. 5.

(see opposite page) →

Fig. 9. TiO_2–MnO–Na_2O plot for clinopyroxenes from the volcanics (1), gabbros (2) and diabase (3) of the Waziristan igneous complex, compared with cpx from oceanic (4) and other island arc-related (5) rocks. Oceanic data are from Ridley *et al.* (1974) and Schweitzer *et al.* (1979). The island arc data are from Arculus and Wills (1980). Fields defined by Nisbet and Pearce (1977) are: a = volcanic arc basalts; b = oceanic floor basalts; c = within-plate alkali basalts; d = all; e = volcanic arc basalts + within-plate tholeiites + within-plate alkali basalts; f = volcanic arc basalts + within-plate alkali basalts; g = within-plate alkali basalts.

(see opposite page) →

In view of these mineralogical characters of the rocks from Waziristan igneous complex, it is suggested that these rocks represent a tectonically dismembered and fragmented island arc suite. The tectono-stratigraphical position of the complex indicates its temporal relation with other island arc-related rocks along the suture zone between Indo-Pakistan plate and the northern continental blocks.

CONCLUSIONS

Present study of the Waziristan igneous complex provides evidences for the supra-Benioff zone parentage of this complex. The ultramafic and mafic plutonic rocks of the complex indicate crystallization under high pressures ($\gtrsim$ 10 kbar). Such high pressures are more likely at the base of an island arc than oceanic crust. The mineral chemistry of the plutonics as well as the volcanics of the complex also contradicts their relation to oceanic crust and shows a greater similarity with island-arc related rocks. The Waziristan igneous complex is thus related to the volcanic-arc activity which took place as a consequence of the northward drift of the Indo-Pakistan plate. The complex was emplaced tectonically in its present position in Paleocene to early Eccene, due to the final collision of the Indo-Pakistan plate with the northern continental masses.

Further investigations, including detailed sampling for trace elements and REE studies, are needed to elaborate the extent and geochemistry of the complex.

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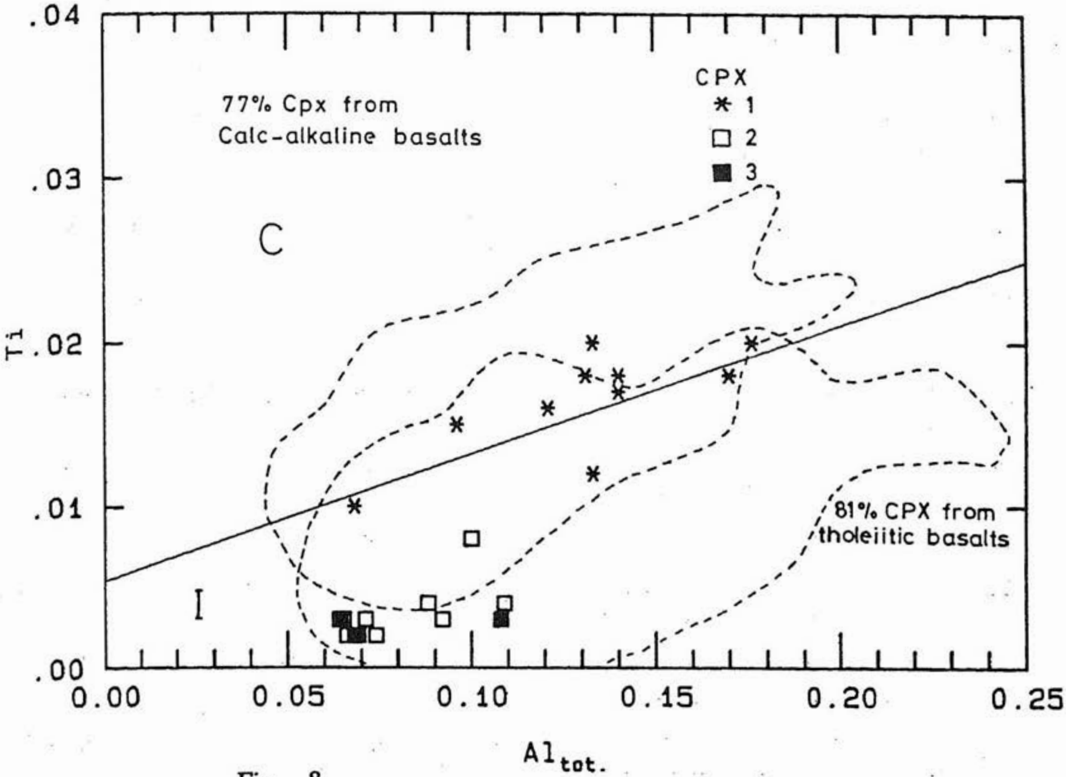
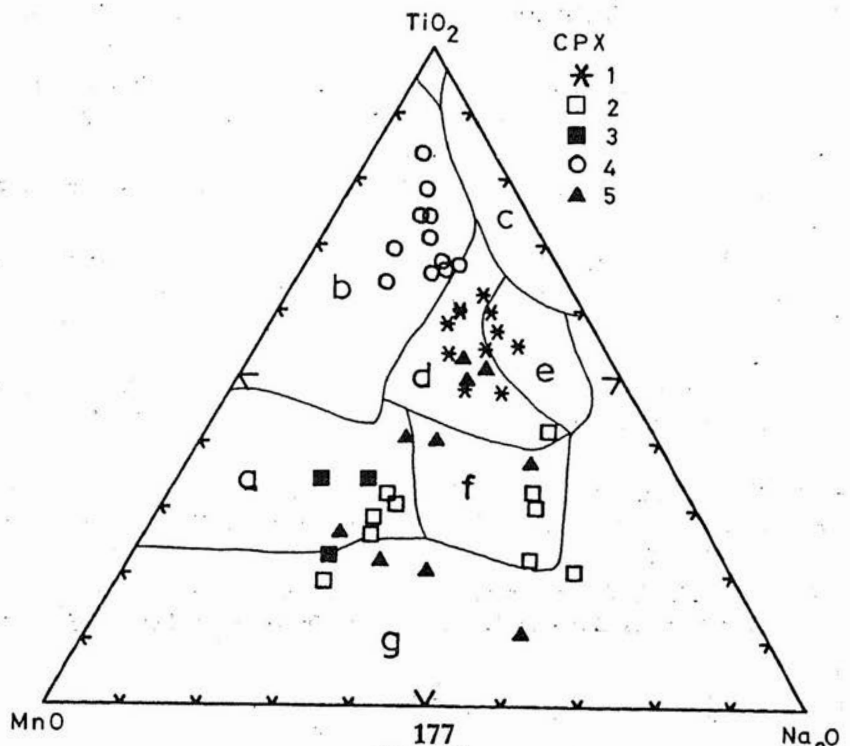


.04
.03
.02
.01
.00
Ti
0.00
0.05
0.10
0.15
0.20
0.25
$Al_{tot.}$
77% Cpx from
Calc-alkaline basalts
CPX
1
2
3
C
I
81% CPX from
tholeiitic basalts

Fig. 8.



TiO_2
CPX
1
2
3
4
5
a
b
c
d
e
f
g
MnO
Na_2O

Fig. 9

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