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The Waziristan complex: some more chemical data and their interpretation

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ABSTRACT: *Tholeiitic and calcalkline affinities are reflected by two different sets of rocks from the Waziristan island arc in 22 major element rock analyses. Previously published clinopyroxene anlyses are used for comparison. The data confirms the existance of a fossil island arc in Waziristan.*

INTRODUCTION

The Waziristan igneous complex of possible early to late Cretaceous age is located in western Waziristan (Fig. 1; Ahmed & Hamidullah, 1987; Beck et al., 1992). It covers an area of >500 km^2. Preliminary studies of the complex were carried out in past by Khan et al., (1982), Badshah (1985) and Jan et al. (1983, 1985). Rock types identified are ultramafic masses (dunite, pyroxenite, serpentinized peridotite), mafic to intermediate intrusives (gabbro, dolerite, diorite) and basic to acidic extrusives (pillow basalt, andesite, dacite, rhyolite, agglomerate and tuff). Copper mineralization is associated with volcanic rocks. Jurrasic (?) to Cretacious and Early Tertiary sequences are associated with, and Quaternary deposits partialy cover, the complex (see Ahmed & Hamidullah, 1987). Earlier, due to the presence of ultramafic and mafic cumulate rocks, the complex was labelled as an ophiolite complex (Asrarullah et al., 1979; Khan et al., 1982; Shah, 1984; Badshah, 1985; Jan et al., 1985). On the bases of local field observations some workers considered it to be a product of simple obduction and crustal shortening with little or no subduction related magmatism (M.I.Afridi, FATA D.C., personal commun.). Realizing the significance of andesites, dacites, rhyolites, tuffs and agglomerates and associated copper mineralization and using clinopyroxene chemistry for affinity descremination, Ahmed and Hamidullah (1987) registered it as an island arc sequence. Latter, investigating the detail stratigraphy, Beck et al. (1992) confirmed its status as an intra-oceanic arc with eruptions through fragments of continental crust with in this arc. The present study represents whole rock chemistry of various rock types from the Shinkai and Degan areas of the complex (Fig.2) in oder to varify their magmatic characters. Clinopyroxene data of Ahmed and Hamidullah (1987) have also been reprocessed and used for comparison.

ROCK CHEMISTRY

Twenty two whole rock analyses of major elements (Table 1) show SiO_2 variation from 37.25 wt.% in ultramafic rocks (D27) to 69.88 wt.% in the rhyolite (D20). Alkali vs SiO_2 plot reflects two distinct groups of rocks (Fig.3a): (i) A high-alkali (Na) group containing only certain volcanics confined to the field of calcalkaline rocks and one altered volcanic that fall in the field mildly alkaline rocks. According to classification of Cox et al. (1979), these rocks are basalts, andesites, dacits and rhyolites. (ii) A low alkali (Na) group that includes

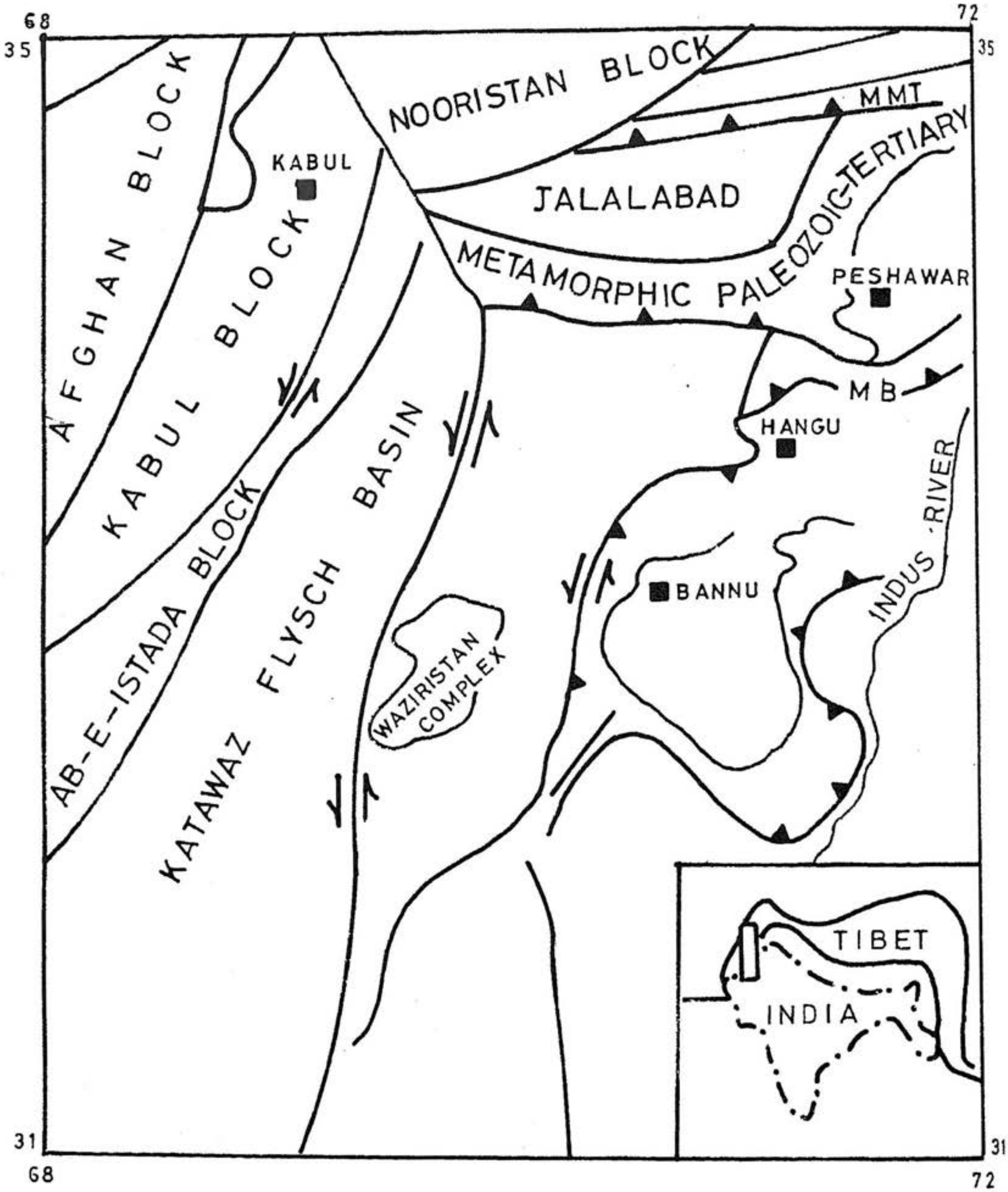

Fig. 1. The Waziristan complex shown in the speculative tectonic map of NW Pakistan and eastern Afghanistan (after Beck et al., 1992).

ultramafics, gabbros, quartzo-feldspathic dykes and the remaining volcanic rocks with the latter three types falling in the field of tholeiitic rocks. On the classification criteria of Cox et al. (1979), the low-alkali volcanics can be classified as basalts, andesites and dacites.

All the high-alkali volcanics follow the non-iron enrichment trend characteristic of

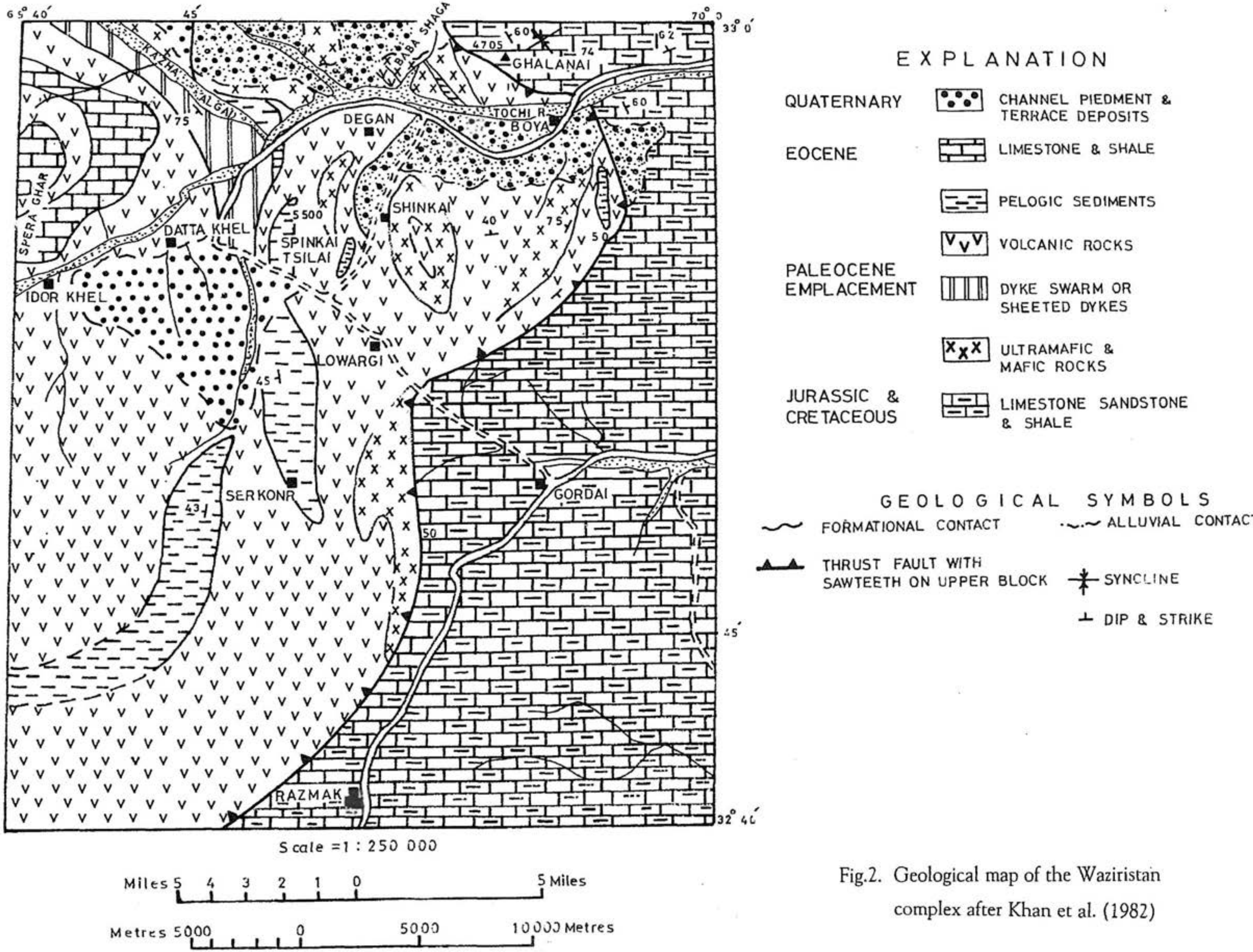

Fig.2. Geological map of the Waziristan complex after Khan et al. (1982)

TABLE 1. MAJOR ELEMENT DATA OF ROCKS FROM THE WAZIRISTAN COMPLEX.

	1 M10	2 D21	3 D27	4 D33	5 D2	6 D30	7 D11	8 D12	9 D16	10 D17	11 D18
SiO_2	39.32	40.64	37.25	38.00	53.17	43.50	62.87	61.64	66.54	67.37	61.00
TiO_2	0.04	0.23	0.33	0.26	0.17	0.40	0.10	0.23	0.88	0.70	0.66
Al_2O_3	0.00	6.94	17.60	12.59	8.60	13.50	13.96	15.30	13.10	14.50	18.96
Fe_2O_3	0.00	1.96	5.46	10.91	5.94	8.21	5.65	6.93	4.84	4.03	5.42
FeO	10.35	5.40	4.13	0.55	4.32	7.53	2.55	1.65	1.74	0.93	1.11
MnO	0.18	0.21	0.18	0.09	0.15	0.18	0.11	0.10	0.14	0.16	0.09
MgO	49.83	31.84	13.72	14.99	14.84	17.70	2.03	2.11	1.66	1.16	1.37
CaO	0.24	5.81	15.14	0.12	8.88	3.86	4.89	7.55	1.64	1.73	1.54
Na_2O	0.35	0.40	0.94	0.61	1.13	0.49	4.42	3.02	6.96	7.26	4.38
K_2O	0.00	0.01	0.19	0.10	0.12	0.06	0.18	0.07	0.12	0.11	1.93
P_2O_5	0.01	0.01	0.00	0.00	0.04	0.00	0.13	0.18	0.16	0.17	0.00
H_2O+	0.00	6.57	5.60	22.20	2.30	4.70	2.10	0.45	2.12	1.57	2.50
Total	100.32	100.02	100.54	100.42	99.66	100.13	98.99	99.23	99.9	99.69	98.96

	12 D20	13 D22	14 D23	15 D24	16 D13	17 D14	18 D15	19 D19	20 D25	21 M1	22 M2
SiO_2	69.88	50.00	47.80	53.12	55.32	47.50	62.87	65.70	52.25	52.25	50.00
TiO_2	0.32	1.78	1.54	2.16	0.72	0.42	0.40	0.28	0.28	0.59	0.37
Al_2O_3	13.51	14.87	15.04	16.00	15.04	16.75	13.87	15.00	13.67	18.58	16.06
Fe_2O_3	2.28	9.22	8.66	5.99	6.36	8.42	0.08	2.92	6.23	7.55	6.33
FeO	1.14	1.58	3.85	4.76	2.00	5.36	4.12	0.66	4.89	4.42	5.08
MnO	0.10	0.15	0.17	0.18	0.11	0.32	0.19	0.10	0.18	0.08	0.13
MgO	1.72	2.84	4.21	3.96	2.51	10.87	1.33	0.83	12.40	11.28	9.55
CaO	1.42	9.97	7.44	5.26	9.57	1.88	2.27	5.12	9.48	1.63	6.23
Na_2O	5.70	4.66	5.36	5.12	3.06	0.40	1.04	0.74	0.71	1.71	0.34
K_2O	0.73	0.01	0.04	0.66	0.09	0.07	1.86	1.68	0.40	0.30	0.99
P_2O_5	0.07	0.20	0.22	0.20	0.09	0.00	0.13	0.07	0.04	0.31	0.03
H_2O+	2.10	3.98	3.89	2.66	4.39	7.90	10.61	6.55	0.00	2.20	4.90
Total	98.97	99.26	98.22	100.07	99.26	99.89	98.77	99.65	100.53	100.9	100.01

1-4 ultramafics; 5-6 gabbros; 7-8 dykes; 9-15 high alkali volcanics; 16-22 low alkali volcanics.

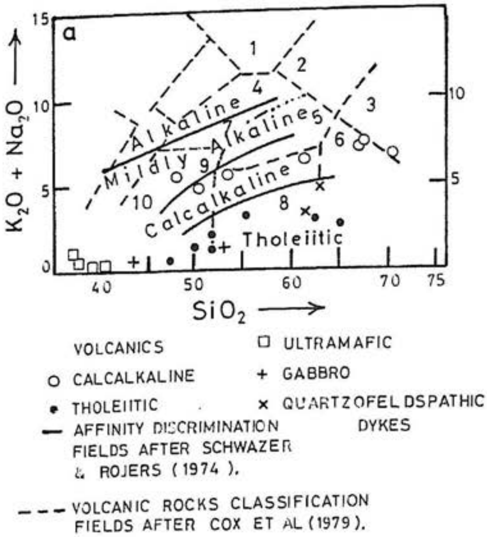

Fig. 3a. Alkali-SiO_2 diagram of the Waziristan complex rocks.

calcalkaline rocks on the AFM plot (Fig. 3b). Four of the low-alkali volcanics lie close to the F-M boundary within the field of island arc

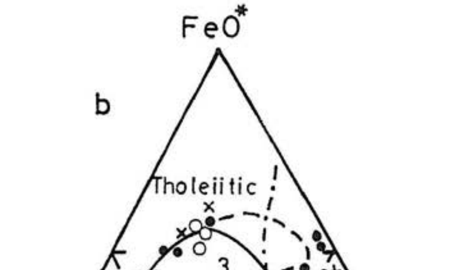

Fig. 3b. AFM plot of the Waziristan complex rocks. Fields shown after Beard (1986) are of ophiolitic cumulates (1), island arc cumulates (2) and island arc non-cumulates (3). The solid lines represent the general partitions between calcalkaline and tholeiitic rocks after after Irvine and Barager (1971).

cumulates (these rocks are not cumulates) but close to the boundary of arc-related non cumulates. The other three low alkali volcanics follow the trend of calcalkaline rocks. On the other hand two of the ultramafic rocks occupy the exclusive field of ophiolitic cumulates, two ultramafics and two gabbros plot in the area of overlap by the fields of ophiolitic and arc cumulates. On the Al_2O_3 vs %An plot of Irvine and Barager (1971) all the high-alkali volcanics fall in the calcalkaline field whereas, except one low-alkali volcanic rock (M1) showing negative %An, all other low alkalic rocks (ultramafics, gabbros, quartzo-feldspathic dykes and volcanics) indicate tholeiitic affinities (Fig. 4a). On the Fe_2O_3 vs MgO plot (Fig. 4b) the high-alkali volcanics togather with quartzo-feldspathic dykes and one low-alkali volcanic sample occupy the field of calcalkaline rocks. Two of the ultramafic rocks, gabbros and two low alkali volcanic rocks plot either in or close to the boundary of tholeiitic rocks. The other two ultramafic rocks can not be seen in this plot because of their very high MgO contents. The two low-alkali volcanics following calcalkaline trend on the AFM plot (Fig. 3b) also show similar characters on the Fe_2O_3 vs MgO plot (Fig. 4b). A more or less corresponding affinity subdivision is also reflected by the data on the TiO_2 vs MgO plot (Fig. 4c).

CLINOPYROXENE

As mentioned earlier, Ahmed and Hamidullah (1987) described island arc signatures on the basis of the chemistry of clinopyroxene from gabbros, dolerites and volcanic rocks at Shinkai and Degan areas of the "Waziristan igneous complex". These data have been replotted on various discrimination diagrams after recalculating mineral formulae and ferrous-ferric irons on the bases of four cations and six oxygens, using the relatively recent methods of Droop

TABLE 2. CLINOPYROXENE ANALYSES FROM VARIOUS ROCKS OF THE WAZIRISTAN COMPLEX.

	1 GABCPX1	2 GABCPX2	3 GABCPX4	4 GABCPX5	5 GABCPX6	6 DYKCPX1	7 DYKCPX2	8 VOLCPX1
SiO_2	52.650	52.550	53.020	53.330	54.140	51.570	51.490	52.290
TiO_2	0.060	0.060	0.280	0.160	0.090	0.110	0.110	0.360
Al_2O_3	1.560	1.690	2.320	2.040	1.670	1.480	2.460	1.550
Fe_2O_3	1.190	1.170	0.190	0.280	0.220	2.960	2.340	2.060
FeO	6.020	5.560	5.100	5.250	4.460	8.330	9.170	8.210
MnO	0.000	0.090	0.090	0.110	0.090	0.150	0.130	0.160
MgO	16.270	16.180	16.180	16.500	16.890	15.900	15.220	16.150
CaO	21.790	21.960	22.440	21.820	22.610	19.260	19.420	19.230
Na_2O	0.020	0.060	0.190	0.260	0.260	0.060	0.080	0.230
Total	99.56	99.32	99.81	99.75	100.43	99.82	100.42	100.24
				Formulae on the bases of 4 cations and 6 oxygens				
Si	1.945	1.943	1.940	1.953	1.964	1.906	1.903	1.927
Ti	0.002	0.002	0.008	0.004	0.002	0.003	0.003	0.010
Al	0.068	0.074	0.100	0.088	0.071	0.064	0.107	0.067
Fe^{3+}	0.040	0.040	0.005	0.008	0.006	0.121	0.085	0.074
Fe^2	0.186	0.172	0.156	0.161	0.135	0.258	0.283	0.253
Mn	0.000	0.003	0.003	0.003	0.003	0.005	0.004	0.005
Mg	0.895	0.891	0.882	0.900	0.913	0.876	0.838	0.887
Ca	0.862	0.870	0.879	0.856	0.879	0.763	0.769	0.759
Na	0.001	0.004	0.013	0.018	0.018	0.004	0.006	0.016
^{iv}Al	0.055	0.057	0.060	0.047	0.036	0.064	0.097	0.067
^{vi}Al	0.013	0.016	0.040	0.041	0.036	0.000	0.010	0.000

(Continued Table 2)

	9 VOLCPX2	10 VOLCPX3	11 VOLCPX4	12 VOLCPX5	13 VOLCPX6	14 VOLCPX7	15 VOLCPX8
SiO_2	52.010	51.530	49.720	49.540	49.800	50.840	49.800
TiO_2	0.590	0.710	0.640	0.640	0.650	0.540	0.680
Al_2O_3	2.790	3.060	3.820	3.130	2.960	2.180	2.910
Fe_2O_3	2.130	1.710	2.400	2.750	3.250	2.950	3.050
FeO	8.490	7.470	7.900	7.400	6.310	6.010	6.350
MnO	0.170	0.200	0.130	0.130	0.210	0.210	0.130
MgO	15.190	15.150	13.940	14.450	15.200	15.810	14.790
CaO	19.880	20.520	19.750	19.630	19.770	20.050	20.320
Na_2O	0.330	0.280	0.400	0.300	0.260	0.260	0.280
Total	101.58	100.63	98.7	97.97	98.41	98.85	98.31
			Formulae on the bases of 4 cations and 6 oxygens				
Si	1.898	1.894	1.866	1.865	1.842	1.873	1.852
Ti	0.016	0.020	0.018	0.018	0.018	0.015	0.019
Al	0.120	0.133	0.169	0.139	0.129	0.095	0.128
Fe^{3+}	0.076	0.059	0.093	0.117	0.168	0.146	0.151
Fe^{2+}	0.259	0.230	0.248	0.233	0.195	0.185	0.197
Mn	0.005	0.006	0.004	0.004	0.007	0.007	0.004
Mg	0.826	0.830	0.779	0.810	0.838	0.868	0.820
Ca	0.777	0.808	0.794	0.792	0.784	0.792	0.810
Na	0.023	0.020	0.029	0.022	0.019	0.019	0.020
^{iv}Al	0.102	0.106	0.134	0.135	0.129	0.095	0.128
^{vi}Al	0.018	0.027	0.034	0.004	0.000	0.000	0.000

"Clinopyroxene from gabbros (1-5), dykes (6-7) and high-alkali volcanics (8-15)."

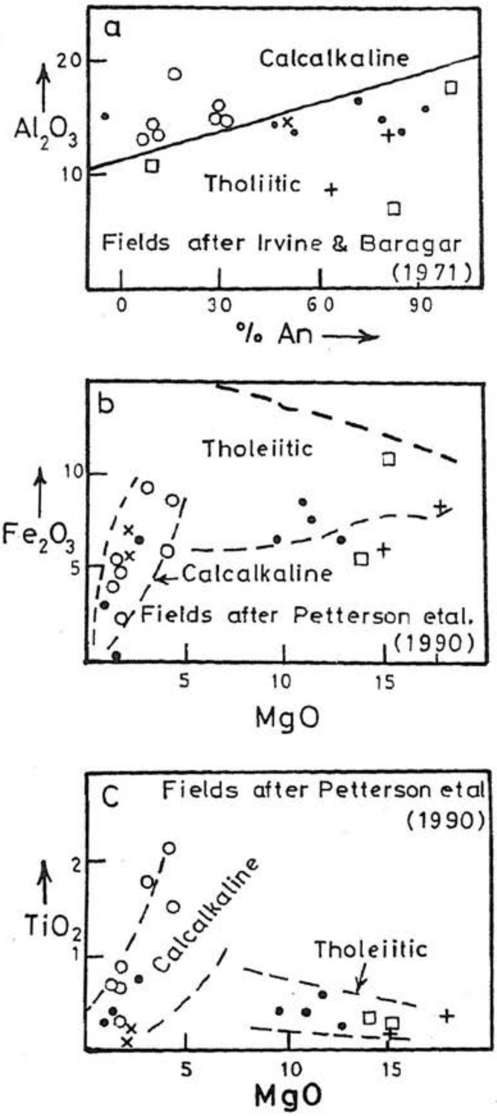

Fig. 4. (a) Al_2O_3 vs %An (normative), (b) Fe_2O_3 vs MgO and (c) TiO_2 vs MgO plot of the rocks from Waziristan complex. Symbols as in Figure 3a.

(1987) and Schumacher (1991). "Less than perfect analyses" have been discarded and the data are shown in Table 2. The gabbroic clinopyroxene straddle across the junction of diopside and augite fields whereas the data from volcanic rocks and dolerite dykes exclusively occur in the augite field on the clinpyroxene quadrilateral of Poldervaart and Hess (1951) (Fig.5a). On the ^{vi}Al vs ^{iv}Al plot of Aoki and Kushiro (1968) three of the gabbroic clinopyroxene analyses show metamorphic origin where as two gabbroic clinopyroxene spots reflect igneous characters. All other clinopyroxene data (8 from high alkaline volcanics and two from dolerites) show igneous characters (Fig.5b). On the F2 vs F1 plot of Nisbet and Pearce (1977) most of the clinopyroxene data fall in the exclusive field of volcanic arc basalts (above subduction zones) with a few occurring in the combined field of volcanic arc basalts and oceon floor basalts (Fig.5c). Similarly, on the Na vs $Fe^{2+}/Fe^{2+}+Mg$ plot of Papike (1982) majority of the clinopyroxene analyses from the volcanic rocks and three gabbroic clinopyroxene spots are confined to the island arc field (Fig.5d). Most of the clinopyroxene data show non-alkaline characters with only two volcanic compositions falling in the normal-alkaline field, but close to the boundary of non-alkaline ones on the SiO_2 vs Al_2O_3 plot of LeBas (1962) (Fig.6a). In addition all the clinopyroxenes indicates non-alkaline characters and orogenic environment on the Ti vs Ca+Na and Ti+Cr vs Ca plots (Figs. 6b,c) of Leterrier et al. (1982). Interestingly, as suggested by their corresponding rock chemistries, clinopyroxene from volanic rocks show calcalkaline affinities while those from gabbros and dolerites reflect crystallisation from tholeiitic magama on the Ti vs ^{t}Al plot (Fig .6d) of Leterrier et al.(1982).

DISCUSSION

Both the mineral and rock chemistries of the high-alkali volcanics, representing a basalt-andesite-dacite-rhyolite association, are characteristics of calkalkaline rocks and thus refelect evolution in subduction-related island-arc type of environment. This interpretation is in ac-

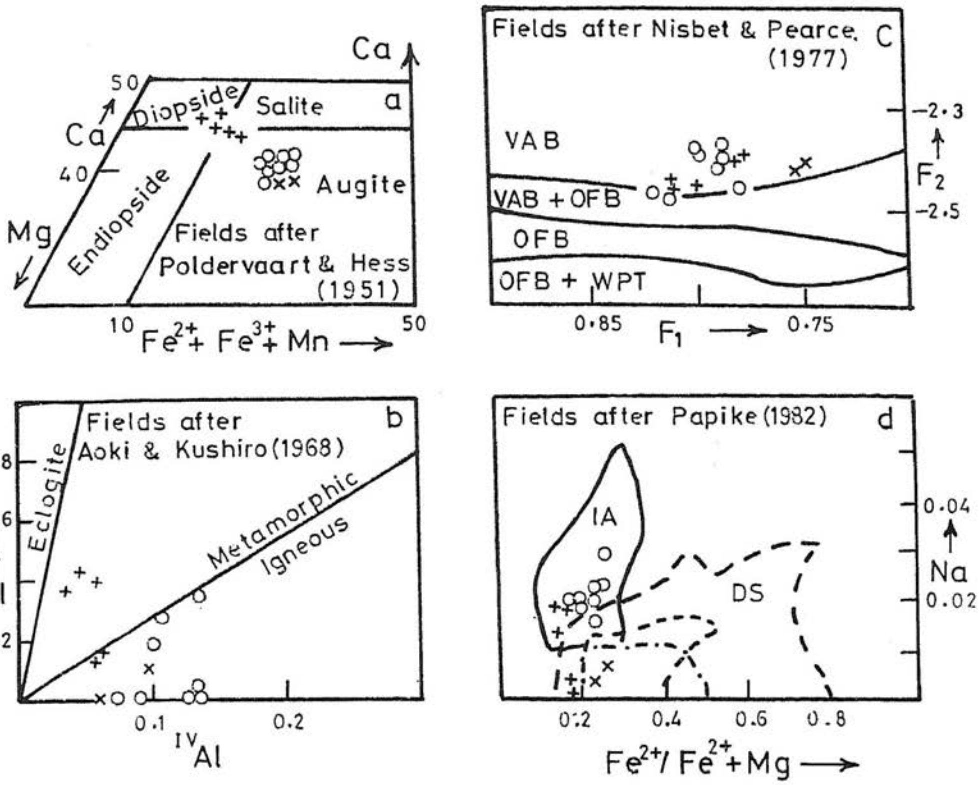

Fig. 5. Clinopyroxene compositions from the Waziristan complex (a) in the pyroxene quadrilateral of Pldervaart and Hess (1951), on (b) ^{iv}Al vs ^{vi}Al plot, (c) F_2 vs F_1 plot and (d) on Fe^{2+}/Fe^{2+}+Mg plot. plus = gabbroic, cross = doleritic, circle = volcanic.

cordance with conclusions drawn by previous workers (Ahmed & Hamidullah, 1987; Beck et al., 1992). Calcalkaline and tholeiitic chemistries have been previously described in the Waziristan igneous complex by Ahmed and Hamidullah (1987) but they did not envisage the presence of tholeiitic components amoung the extrusives members revealed in the present study, on the basis of whole rock chemistry. These tholeiitic volcanics and the associated plutonics may be representing fragments of the ophiolitic melange (see Jan et al., 1983, 1985; Beck et al., 1992) or may be the product of island arc-related subduction process. The clinopyroxne chemistry from gabbros and dolerites support the latter interpretation (see Figs.5c,d). Effort were made to varify the tectonic environment of the tholeiitic members of the complex on the basis of major element chemistry. Unfortunately none of the discrimination diagrams was found to be conclusive. This feature may be a reflection of the type of tectonic environment mentioned by Beck et al. (1991), i.e. oceonic island arc+continental fragments; thus carrying signatures of a mixed protolitic material. Trace element/rare earth and isotopic studies may be able to further discriminate such parantages. It is worth mentioning however that, in general, subduction-related island arc type of environments existed and are supported by both mineral and rock chemistries of at least one

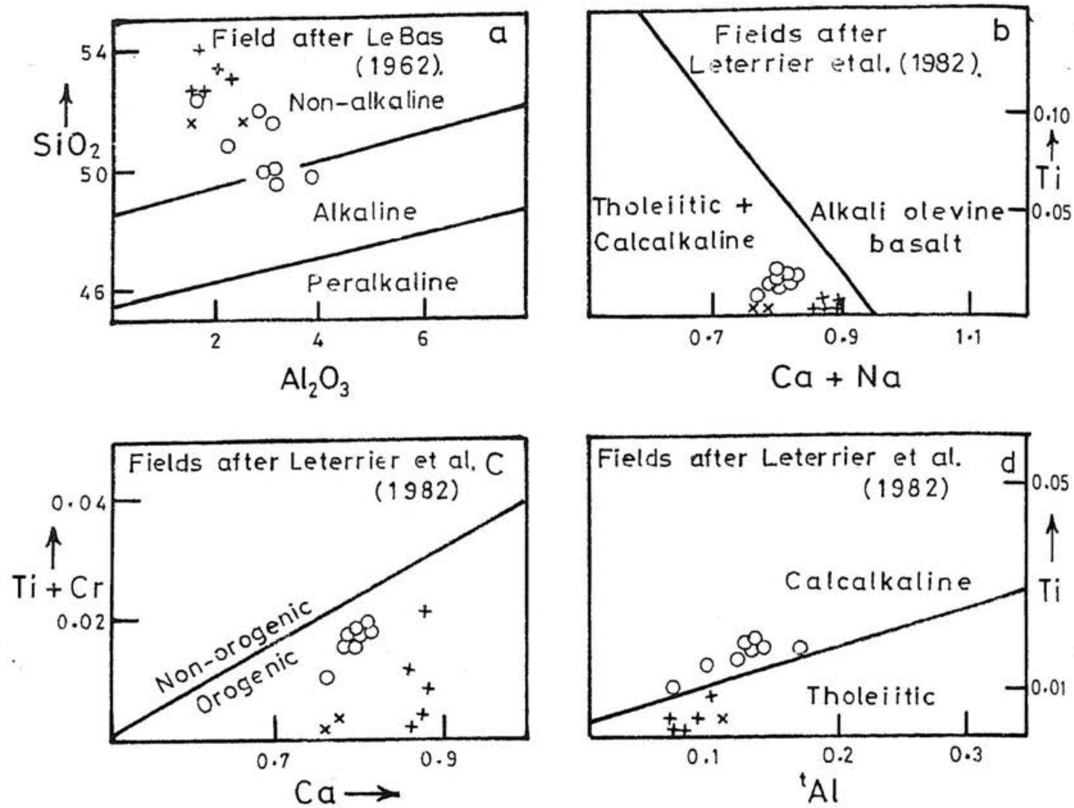

Fig. 6a-d. Clinopyroxene compositions from the Waziristan complex shown on various affinity and tectinic setting discrimination diagrams. Symbols as in Figure 5a.

well specified group of rocks, i.e. the high-alkali volcanics. As Beck et al., (1992) have described the association of metasedimentary and ophiolitic melange rocks with the island arc ones, the whole sequence at Waziristan may be better referred to as "Waziristan complex" rather than "Wazirisatn igneous complex" of Ahmed and Hamidullah (1987).

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