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# Mineral chemistry and origin of ophiolitic rocks from the Waziristan ophiolite complex, NW Pakistan

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ABSTRACT: *The Waziristan Ophiolite Complex demarcates the spatial disposition of the suture zone between the Indian plate and the Afghan block in the Waziristan area. The complex is located along the western margin of the Indian plate and consists of a chaotically arranged stack of thrust slices. Section(s) showing a complete sequence is not preserved but all members of a typical ophiolite are separately present in the area. Dominant rocks include basic lavas, ultramafics, and gabbros, with subordinate amounts of dikes, granites, and pelagic sediments.*

*Major minerals (pyroxene, spinel, and plagioclase) within the rocks were analyzed using Jeol Superprobe Microanalyser. Pyroxenes from basalts, apparently crystallized at temperatures above 1000 °C, plot in the fields of volcanic arc basalts and ocean floor basalts. Pyroxene and chromite data have been further interpreted to reveal the tectonic environment at the time of generation and emplacement of the ophiolite sequence. The pyroxene data show a transitional character from tholeiitic to calc-alkaline, and from ocean floor to island arc type environment. Chromite data, with moderate to high cr#, also exhibit oceanic (abyssal) to arc affinities. The chemical data on pyroxene and chromite suggest an oceanic and/or arc related origin for the Waziristan ophiolite complex.*

## INTRODUCTION

Among the six major ophiolites of Pakistan, the Waziristan Ophiolite Complex (WOC) constitutes the third most extensive occurrence of ophiolitic rocks after those of Bela and Muslim Bagh (Asrarullah et al., 1979; Kazmi & Rana, 1982). The WOC occupies about 5000 $km^2$ area in a north-south elongated belt in the Boya-Razmak region of north and south Waziristan agencies. It extends westwards into Afghanistan (Treloar & Izzat, 1993). The WOC demarcates the suture zone that separates the Indian plate from the Asiatic rocks and the Gondwanic microcontinents such as the Afghanistan and Iran blocks (Shah, 1984).

The study area lies 20 km west of Miranshah (the Agency headquarter). Igneous rocks of the WOC occupy a major portion of the study area (Fig. 1) and occur as thrust slices overriding Jurassic to Cretaceous sediments (calcareous) of the Tethyan shelf sequence (Jan et al., 1985). According to Beck et al. (1995; 1996) the ophiolite bodies can be regarded as allochthonous fragments of the Neo-Tethys basin that probably closed in the Cretaceous and Early Tertiary time (see also Treloar & Izzat, 1993; Robinson et al., 2000).

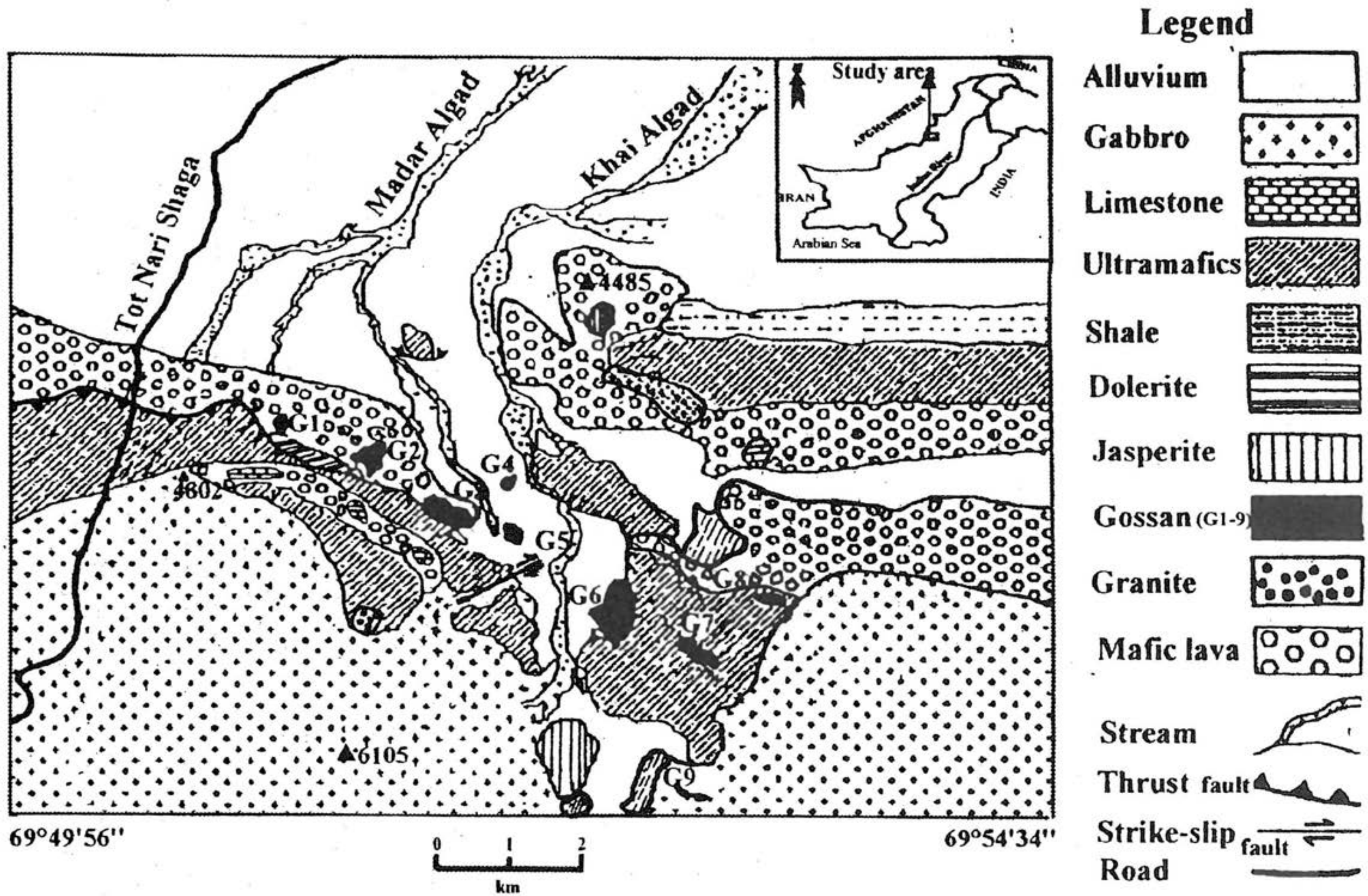


Fig. 1. Geological map of Shinkai area, north Waziristan, Pakistan. Inset: Index map of Pakistan showing the location of WOC.

Previous studies regarding the geology of the area include Khan et al. (1982), Badshah (1983; 1985), Jan et al. (1985), Ahmad and Hamidullah (1987), Hamidullah (1994), Beck et al. (1995; 1996), Gnos (1998), and Shah and Khan (1999). The present study is based on the chemistry of major minerals in the context of tectonic setting of the Waziristan ophiolite.

## GEOLOGICAL SETTING

Mafic volcanics, gabbros and ultramafic rocks besides small proportions of pelagic sediments, limestones, shales, dolerite dikes and granitic plugs (Fig. 1) occupy much of the study area. Most of the southern portion is occupied by gabbros which also occur in a few isolated patches in the northern portion of the area. The volcanics consist of basalts and andesites with subordinate breccia and minor dacites, tuffs and agglomerates. Basalts and andesites occur either as massive beds or have developed characteristic pillow structures. They occupy the central portion of the area and have a sharp contact with the gabbros. Pyroxenites, peridotites, dunites and serpentinites represent the ultramafic rocks. They occupy not only the western and central portions but also occur to the eastern limit of the study area.

The northern portion of the study area is covered by alluvium. To the east of the area there is a 300m thick, thinly interbedded limestone, shale and siltstone. Eocene limestone and shale formations are also encountered. These rocks are intensely folded and thrust eastward on younger Molasse sediments (Kakar, 1975). Limestone occurs as isolated patches on the massive lavas and jasperites have an isolated occurrence in the southern portion of the area along one of the main stream (Khai Algad). The area is marked by a number of thrust faults and strike slip displacements.

## MINERAL CHEMISTRY

The major primary minerals within the ultramafics, basalts and gabbros of the WOC are pyroxene, serpentine, plagioclase, and spinel. A total of eight polished thin sections were selected for analyzing the minerals by JEOL 733 Electron Superprobe Microanalyser using wavelength despersive system and 20 KV accelerating potential with $400x10^{-7}$ ampere probe current. Suitable laboratory standards were used and mineral formulae in chromite were determined by stoichiometry.

**Pyroxene**

Pyroxene occurs in gabbros, basalts, and ultramafic rocks. Clinopyroxene was analyzed in basalt and gabbro, together with orthopyroxene in peridotite-dunite. Table 1 lists representative analyses along with number of ions per six oxygen atoms. The data is plotted on the compositional diagram of Morimoto (1988) in Figure 2. In addition to a restricted overall compositional variation displayed by pyroxene in the three types of rocks, there are small-scale chemical variations within the domain of a single thin section. As there is no zoning within the analyzed pyroxene grains, within grain variation is generally insignificant.

Basaltic pyroxenes plot in the field of augite. Pyroxenes from gabbros are more scattered on the pyroxene quadrilateral and plot in the fields of diopside and augite. Compared with the analyses of basaltic pyroxenes, these are relatively poor in $SiO_2$ and enriched in $Al_2O_3$ and CaO. Pyroxenes from ultramafic rocks plot in the fields shown for diopside, augite and enstatite. Clinopyroxenes from the ultramafic rocks contain lower $Al_2O_3$ (<2.46 wt. %) MnO (<0.35 %), and $Na_2O$ (<0.17 %). CaO ranges from 17.86 to 23.71 %, $FeO_t$ from 2.65 to 4.04 % and MgO from 17.28 to

TABLE 1. REPRESENTATIVE PYROXENE SPOT ANALYSES FROM MAFIC AND ULTRAMAFIC ROCKS OF WAZIRISTAN

| | Cpx from Basalt (WSH10) | | | | | Cpx from Gabbro (WSH41A, 19A) | | | Cpx from pyroxenite (WSH36) | | | Opx from peridotite (WSH38) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5* | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| $SiO_2$ | 53.27 | 52.86 | 53.04 | 52.12 | 52.29 | 51.76 | 51.38 | 50.24 | 54.41 | 53.49 | 53.91 | 55.68 | 55.62 | 52.65 | 55.09 |
| $TiO_2$ | 0.00 | 0.07 | 0.11 | 0.11 | 0.36 | 0.41 | 0.15 | 0.83 | 0.08 | 0.08 | 0.05 | 0.03 | 0.00 | 0.08 | 0.06 |
| $Al_2O_3$ | 1.07 | 1.92 | 1.43 | 2.46 | 1.55 | 3.20 | 2.01 | 4.99 | 1.33 | 1.28 | 1.44 | 2.04 | 2.22 | 2.07 | 2.13 |
| FeO** | 5.89 | 6.12 | 8.12 | 8.63 | 10.27 | 6.44 | 4.49 | 6.53 | 4.04 | 2.81 | 2.65 | 6.08 | 6.19 | 6.34 | 6.23 |
| MnO | 0.03 | 0.19 | 0.18 | 0.26 | 0.16 | 0.25 | 0.05 | 0.22 | 0.08 | 0.03 | 0.05 | 0.11 | 0.06 | 0.19 | 0.09 |
| MgO | 20.19 | 18.24 | 21.36 | 15.57 | 16.15 | 15.49 | 15.18 | 14.86 | 22.40 | 17.89 | 17.28 | 32.46 | 31.44 | 33.73 | 31.61 |
| CaO | 18.26 | 20.63 | 15.71 | 19.97 | 19.23 | 23.59 | 24.85 | 20.30 | 18.31 | 23.58 | 23.71 | 1.56 | 1.89 | 1.98 | 1.43 |
| $Na_2O$ | 0.06 | 0.06 | 0.08 | 0.12 | 0.23 | 0.13 | 0.11 | 0.05 | 0.11 | 0.14 | 0.17 | 0.05 | 0.07 | 0.04 | 0.06 |
| $Cr_2O_3$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.90 | 0.79 | 1.31 |
| Total | 98.77 | 100.09 | 100.03 | 99.24 | 100.24 | 101.27 | 98.22 | 98.02 | 100.76 | 99.30 | 99.26 | 98.01 | 98.39 | 97.87 | 98.01 |
| Number of ions calculated on 6 Oygen basis | | | | | | | | | | | | | | | |
| Si | 1.960 | 1.936 | 1.935 | 1.943 | 1.927 | 1.895 | 1.930 | 1.882 | 1.945 | 1.959 | 1.972 | 1.962 | 1.958 | 1.881 | 1.949 |
| Aliv | 0.040 | 0.062 | 0.062 | 0.054 | 0.067 | 0.094 | 0.066 | 0.095 | 0.053 | 0.039 | 0.027 | 0.037 | 0.042 | 0.087 | 0.049 |
| Ti | 0.000 | 0.002 | 0.003 | 0.003 | 0.010 | 0.011 | 0.004 | 0.023 | 0.002 | 0.002 | 0.001 | 0.001 | 0.000 | 0.002 | 0.002 |
| Alvi | 0.006 | 0.021 | 0.000 | 0.055 | 0.000 | 0.044 | 0.023 | 0.126 | 0.003 | 0.017 | 0.035 | 0.048 | 0.050 | 0.000 | 0.040 |
| $Fe^{2+}$ | 0.181 | 0.187 | 0.248 | 0.269 | 0.327 | 0.197 | 0.141 | 0.205 | 0.121 | 0.086 | 0.081 | 0.179 | 0.182 | 0.189 | 0.184 |
| Mn | 0.001 | 0.006 | 0.006 | 0.008 | 0.005 | 0.008 | 0.002 | 0.007 | 0.002 | 0.001 | 0.002 | 0.003 | 0.002 | 0.006 | 0.003 |
| Mg | 1.107 | 0.995 | 1.161 | 0.865 | 0.887 | 0.845 | 0.850 | 0.830 | 1.193 | 0.977 | 0.942 | 1.705 | 1.650 | 1.796 | 1.667 |
| Ca | 0.720 | 0.809 | 0.614 | 0.798 | 0.759 | 0.925 | 1.000 | 0.815 | 0.701 | 0.925 | 0.929 | 0.059 | 0.071 | 0.076 | 0.054 |
| Na | 0.002 | 0.002 | 0.003 | 0.004 | 0.016 | 0.005 | 0.004 | 0.002 | 0.004 | 0.005 | 0.006 | 0.002 | 0.002 | 0.001 | 0.002 |
| Cr | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.025 | 0.022 | 0.037 |
| Mg# | 85.93 | 84.15 | 82.42 | 76.28 | 73.06 | 81.08 | 85.76 | 80.22 | 90.81 | 91.90 | 92.08 | 90.49 | 90.05 | 90.46 | 90.04 |
| Wo | 35.85 | 40.63 | 30.35 | 41.29 | 38.47 | 47.03 | 50.23 | 44.07 | 34.80 | 46.55 | 47.60 | 3.03 | 3.75 | 3.68 | 2.85 |
| En | 55.13 | 49.96 | 57.40 | 44.78 | 44.96 | 42.95 | 42.68 | 44.87 | 59.21 | 49.12 | 48.25 | 87.75 | 86.68 | 87.13 | 87.48 |
| Fs | 9.02 | 9.41 | 12.25 | 13.93 | 16.57 | 10.02 | 7.08 | 11.06 | 5.99 | 4.33 | 4.15 | 9.22 | 9.58 | 9.19 | 9.68 |

5* Cpx phenocryst from volcanics taken from Hamidullah (1994).

** Total iron expressed as FeO

Magnesium No. (Mg#) = 100xMg/(Mg + $Fe^{2+}$); Wollastonite (Wo) = 100xCa/(Mg + $Fe^{2+}$ + Ca); Enstatite (En) = 100xMg/(Mg + $Fe^{2+}$ + Ca); Ferrosilite (Fs) = 100x$Fe^{2+}$/(Mg + $Fe^{2+}$ + Ca)

22.40 wt. %. Compositional variation in the analyzed grains of orthopyroxenes in the ultramafic rock (peridotite-dunite) is very limited ($En_{86}$ to $En_{87}$). Pyroxene data from Ahmad and Hamidullah (1987) and Hamidullah (1994) closely correspond to the present data except for the basaltic pyroxene analysed currently indicating high values for $TiO_2$ (0.36-0.71wt.%) and $FeO_t$ (9.41-11.75%).

**Pressure and temperature estimation**

Due to the non-availability of adequate data, precise estimation of pressure for the ultramafic rocks of WOC is not possible. The absence of garnet and plagioclase and the occurrence of spinel may point to the final equilibration of the ultramafic rocks in a pressure range of ~8 to 12kb assuming a temperature of 1000 °C (Obata, 1976). These data when utilized in the graphical thermometer of Lindsley (1983), calibrated for 10kb pressure, temperature ranges of 1020-1330°C, 600-900°C, and 900-1300°C were obtained for basalts, gabbros and ultramafic rocks, respectively (Fig. 3).

**Plagioclase**

Plagioclase is an important component of basalt, basaltic-andesite, andesite, gabbro and granite in the study area. Three grains, each from basalt (WSH10), basaltic andesite (WSH15A), gabbro (WSH19) and ten spots in granite sample WSH27A were analyzed for major elements. Representative analyses, recalculated on the basis of eight oxygens, are listed in Table 2. All the analyses in the basalt sample are albite due to spilitized nature of the rock. This is also the case in basaltic andesite where altered compositions are as sodic as ($An_{10}$), however, some grains that have survived spilitization are labradoritic (analysis 3, Table 2).

**Spinel**

Two thin sections were selected for the spinel analyses (WSH38 and WSH15A). The spinel grains were analyzed for $SiO_2$, $TiO_2$, $Al_2O_3$, $FeO_t$, MnO, MgO, and $Cr_2O_3$. The analyses range from chromian spinel (24.25 to 25.93 wt. % $Al_2O_3$ and 35.42 to 41.51% $Cr_2O_3$) to magnetite (49.25 to 62.66% $Fe_2O_3$). Representative analyses, recalculated on the basis of 32 oxygens are given in Table 3. The $TiO_2$ content of the chromian spinel (analyses No 1-5) is low (< 0.21 wt. %). $Cr_2O_3$ ranges from 35.42 to 41.51 wt. %, however, Jan et al., (1985) have reported distinctly different chromites from chromitites and peridotites of the complex containing much higher $Cr_2O_3$, and lower $Al_2O_3$ than the current data shown in Table 3.

## TECTONIC AFFINITY

Pyroxene analyses from gabbro and basalt plot in the filed of orogenic environment (Fig. 4). On the $SiO_2$ vs $Al_2O_3$ diagram pyroxene analyzed from basalts and ultramafic rocks suggest a non-alkaline character for the host rock (Fig. 5). The analyses are further confined to the combined field of calc-alkaline and tholeiitic basalts on the Ti vs Ca+Na diagram and to the field of calc-alkaline basalt on the Ti vs $Al_{(tot)}$ diagram of Leterrier et al. (1982; Figs. 6,7). The same conclusions have been derived from the whole rock geochemical data by Asim et al., (2000). On all the above three diagrams, however, the clinopyroxene from the gabbros, exhibit a variable character, as has been displayed by the whole rock data from these rocks (Asim et al., 2000; Hamidullah, 1994).

On the F2 vs F1 plot of Nisbet and Pearce (1977), four analyses of pyroxene from basalts fall in the field of volcanic arc basalts (VAB) while the remaining pyroxene analyses from the same rocks are confined to the combined field of VAB and ocean floor basalts (OFB) (Fig. 8). As the data is mainly

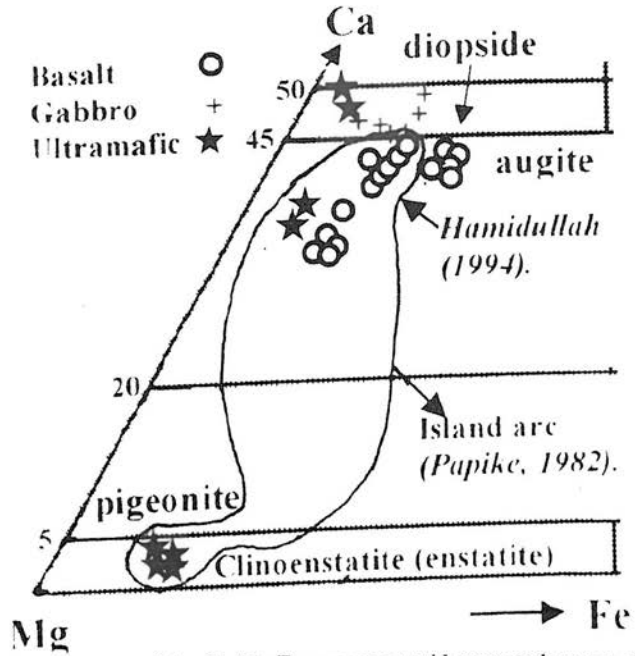


Fig. 2. Compositional ranges of the Ca-Mg-Fe pyroxenes with accepted names after Morimoto (1988).

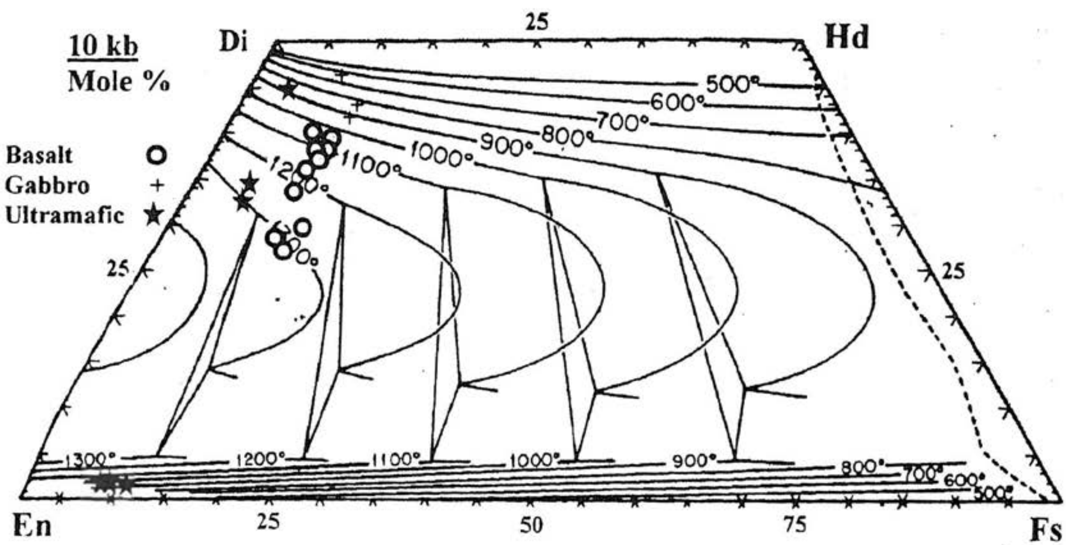


Fig. 3. Graphical pyroxene thermometer (after Lindsley, 1983).

confined to the fields of calc-alkaline basalts on most of the affinity diagrams (Figs. 5-7), therefore, their occurrence in the combined field of VAB and OFB is because of their origin in the former type of environment. A similar overlap can also be observed on the $SiO_2$ vs $TiO_2$ and $Na_2O$-$TiO_2$-MnO plots (Figs. 9, 10) of Nisbet and Pearce (1977) and Table 1 can be interpreted similarly. The above interpretation is strongly supported by the occurrence of these data in the field defined by Papike (1982) for the island arc basalts on the quadrilateral of Morimoto (1988; Fig. 2). It is interesting to note that pyroxene data from the ultramafic rocks of the WOC also occupy the field of island arc basalts of Papike (1982) in Figure 2. This correlation indicates that the ultramafic and basaltic rocks of the WOC have possibly the same or similar origin.

On the cr# vs mg# plot (Fig. 11), the chromites from the ultramafic rocks plot in the combined field of Alpine and abyssal peridotites. However, chromite data from chromitites of the WOC by Jan et al. (1985) plot in the field where Alpine, abyssal and stratiform peridotites overlap indicating a

TABLE 2. REPRESENTATIVE PLAGIOCLASE SPOT ANALYSES FROM VARIOUS ROCK TYPES

| | Basalt and Bas. Andesite | | | Gabbro | | | Granite | | |
|---|---|---|---|---|---|---|---|---|---|
| | (WSH 10) | | (WSH 15A) | (WSH 41A) | | (WSH 19) | (WSH 29) | (WSH 27A) | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| $SiO_2$ | 65.99 | 66.85 | 54.83 | 42.90 | 43.73 | 67.50 | 64.29 | 68.58 | 66.98 |
| $TiO_2$ | 0.00 | 0.00 | 0.27 | 0.00 | 0.06 | 0.00 | 0.00 | 0.04 | 0.00 |
| $Al_2O_3$ | 19.92 | 19.10 | 27.88 | 33.73 | 35.07 | 18.91 | 24.13 | 19.58 | 21.00 |
| $Fe_2O_3$* | 0.00 | 0.23 | 0.00 | 0.31 | 0.11 | 0.00 | 0.02 | 0.02 | 0.00 |
| MnO | 0.00 | 0.07 | 0.00 | 0.00 | 0.00 | 0.15 | 0.00 | 0.01 | 0.00 |
| MgO | 0.05 | 0.03 | 0.05 | 0.03 | 0.00 | 0.04 | 0.00 | 0.01 | 0.00 |
| CaO | 0.46 | 0.14 | 10.98 | 19.71 | 19.45 | 0.84 | 5.34 | 0.34 | 1.26 |
| $Na_2O$ | 12.09 | 12.24 | 4.99 | 0.79 | 0.64 | 9.22 | 6.16 | 12.08 | 9.89 |
| $K_2O$ | 0.02 | 0.09 | 0.19 | 0.02 | 0.00 | 0.00 | 0.14 | 0.06 | 0.04 |
| Total | 98.53 | 98.75 | 99.19 | 97.49 | 99.06 | 96.66 | 100.08 | 100.72 | 99.17 |
| Number of ions calculated on 8(O) basis | | | | | | | | | |
| Si | 2.941 | 2.974 | 2.490 | 2.047 | 2.044 | 3.026 | 2.810 | 2.982 | 2.943 |
| Ti | 0.000 | 0.000 | 0.009 | 0.000 | 0.002 | 0.000 | 0.000 | 0.001 | 0.000 |
| Al | 1.047 | 1.002 | 1.493 | 1.898 | 1.933 | 0.999 | 1.243 | 1.004 | 1.088 |
| $Fe^{3+}$ | 0.000 | 0.009 | 0.000 | 0.012 | 0.004 | 0.000 | 0.001 | 0.001 | 0.000 |
| Mn | 0.000 | 0.003 | 0.000 | 0.000 | 0.000 | 0.006 | 0.000 | 0.000 | 0.000 |
| Mg | 0.003 | 0.002 | 0.003 | 0.002 | 0.000 | 0.003 | 0.000 | 0.001 | 0.000 |
| Ca | 0.022 | 0.007 | 0.534 | 1.008 | 0.974 | 0.040 | 0.250 | 0.016 | 0.059 |
| Na | 1.045 | 1.056 | 0.439 | 0.073 | 0.058 | 0.801 | 0.522 | 1.018 | 0.843 |
| K | 0.001 | 0.005 | 0.011 | 0.001 | 0.000 | 0.000 | 0.008 | 0.003 | 0.002 |
| Ab | 97.84 | 98.90 | 44.62 | 6.75 | 5.62 | 95.21 | 66.93 | 98.15 | 93.19 |
| Or | 0.11 | 0.48 | 1.12 | 0.11 | 0.00 | 0.00 | 1.00 | 0.32 | 0.25 |
| An | 2.06 | 0.63 | 54.26 | 93.13 | 94.38 | 4.79 | 32.07 | 1.53 | 6.56 |

*Total iron expressed as $Fe_2O_3$.
Ab=100xNa/(Na+K+Ca); Or=100xK(Na+K+Ca); An=100xCa/(Na+K+Ca)

TABLE 3. REPRESENTATIVE SPINEL SPOT ANALYSES FROM ULTRAMAFIC ROCKS

| | Peridotite (WSH 38) | | | | | | Bas. Andesite (WSH 15A) | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| $SiO_2$ | 0.18 | 0.14 | 0.14 | 0.11 | 0.10 | 0.29 | 3.05 | 0.24 |
| $TiO_2$ | 0.17 | 0.09 | 0.09 | 0.15 | 0.21 | 0.18 | 2.12 | 6.18 |
| $Cr_2O_3$ | 41.37 | 40.85 | 40.64 | 41.51 | 35.42 | 59.02 | 0.00 | 0.00 |
| $Al_2O_3$ | 24.25 | 25.17 | 25.69 | 25.54 | 25.93 | 10.59 | 0.59 | 0.18 |
| $Fe_2O_3$ | 3.30 | 3.35 | 3.72 | 2.52 | 7.15 | 3.14 | 61.73 | 62.66 |
| FeO | 15.50 | 15.69 | 14.75 | 16.00 | 13.82 | 11.70 | 29.80 | 29.27 |
| MnO | 0.17 | 0.43 | 0.21 | 0.01 | 0.21 | 0.39 | 0.26 | 0.38 |
| MgO | 12.71 | 12.65 | 13.56 | 12.85 | 13.65 | 14.01 | 0.16 | 0.08 |
| Total | 97.65 | 98.37 | 98.80 | 98.69 | 96.49 | 99.32 | 97.71 | 98.99 |
| Number of ions calculated on 32(O) basis | | | | | | | | |
| Si | 0.045 | 0.035 | 0.034 | 0.027 | 0.025 | 0.075 | 0.926 | 0.073 |
| Ti | 0.032 | 0.017 | 0.017 | 0.028 | 0.039 | 0.035 | 0.484 | 1.404 |
| Cr | 8.155 | 7.981 | 7.851 | 8.064 | 6.972 | 12.049 | 0.000 | 0.000 |
| Al | 7.129 | 7.333 | 7.401 | 7.399 | 7.611 | 3.225 | 0.211 | 0.064 |
| $Fe^{3+}$ | 0.619 | 0.623 | 0.684 | 0.468 | 1.340 | 0.610 | 14.104 | 14.292 |
| Z | 15.98 | 15.99 | 15.99 | 15.99 | 15.99 | 15.99 | 15.73 | 15.83 |
| $Fe^{2+}$ | 3.232 | 3.243 | 3.014 | 3.286 | 2.878 | 2.526 | 7.567 | 7.378 |
| Mn | 0.036 | 0.090 | 0.043 | 0.002 | 0.044 | 0.085 | 0.067 | 0.097 |
| Mg | 4.723 | 4.659 | 4.938 | 4.706 | 5.065 | 5.393 | 0.072 | 0.036 |
| Y | 7.99 | 7.99 | 8.00 | 7.99 | 7.99 | 8.00 | 7.71 | 7.51 |
| Aliv | 1.955 | 1.965 | 1.966 | 1.973 | 1.975 | 1.925 | 0.211 | 0.064 |
| Alvi | 5.174 | 5.368 | 5.435 | 5.426 | 5.636 | 1.300 | 0.000 | 0.000 |
| Cr# | 53.36 | 52.11 | 51.48 | 52.15 | 47.81 | 78.89 | 0.00 | 0.00 |
| Mg# | 59.37 | 58.96 | 62.10 | 58.88 | 63.77 | 68.10 | 0.95 | 0.49 |
| $Fe^{3+}$# | 3.89 | 3.91 | 4.29 | 2.94 | 8.41 | 3.84 | 98.52 | 99.55 |

6*. Ferrit-Chromit analysis from a chromitite taken from Jan et al., (1985).
Cr#=100xCr/(Cr+al)  Mg#=100xMg/(Mg+$Fe^{2+}$)  $Fe^{3+}$#=100x$Fe^{3+}$/(Cr+Al+$Fe^{3+}$)

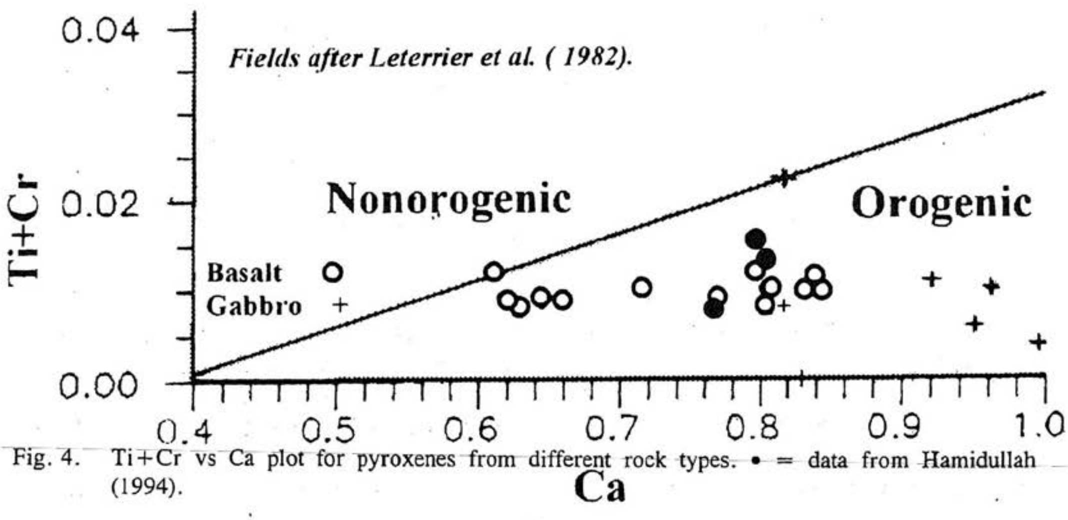


Fig. 4. Ti+Cr vs Ca plot for pyroxenes from different rock types. • = data from Hamidullah (1994).

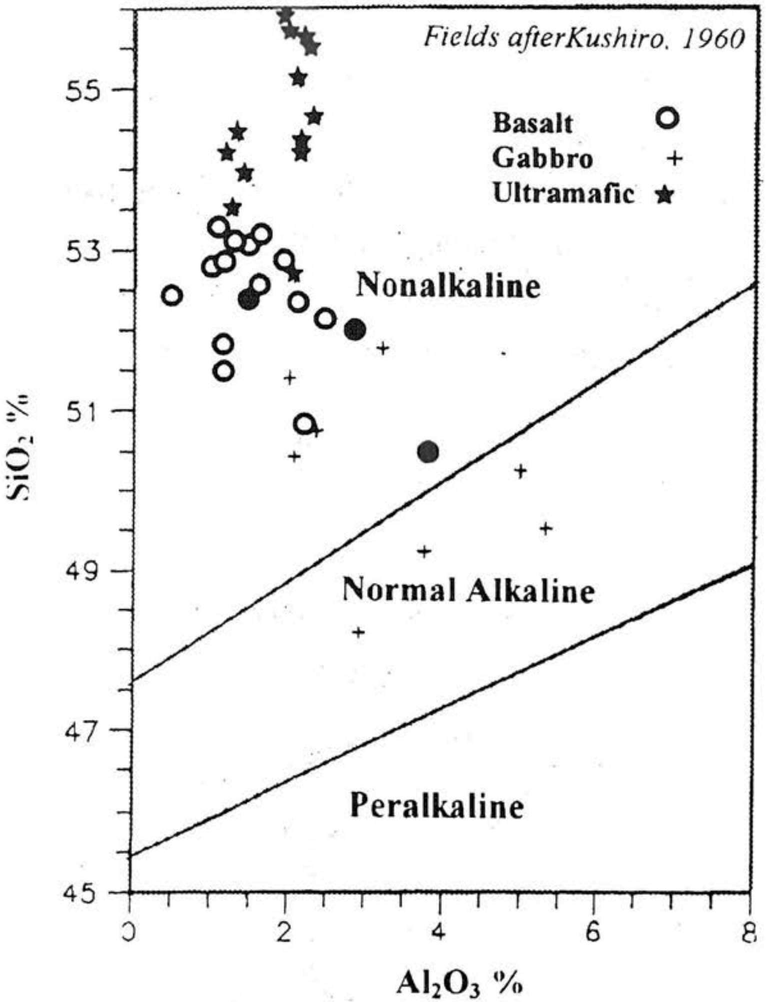


Fig. 5. $SiO_2$ vs $Al_2O_3$ plot for pyroxenes from different rock types. • = data from Hamidullah (1994).

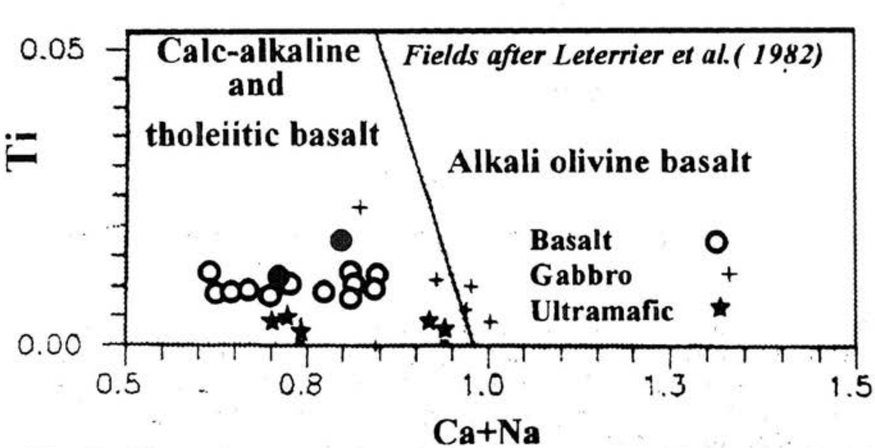


Fig. 6. Ti vs Ca+Na plot for pyroxenes from different rock types. • = data from Hamidullah (1994).

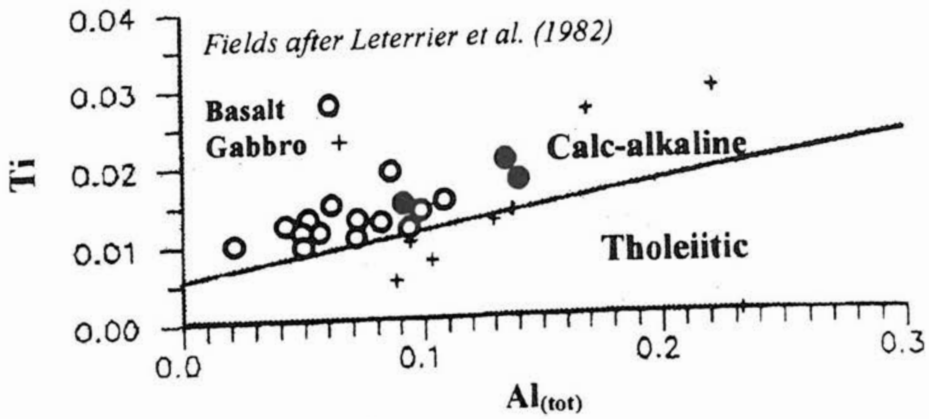


Fig. 7. Ti vs Al $_{(tot)}$ plot for pyroxenes from different tectonic settings • = data from Hamidullah (1994).

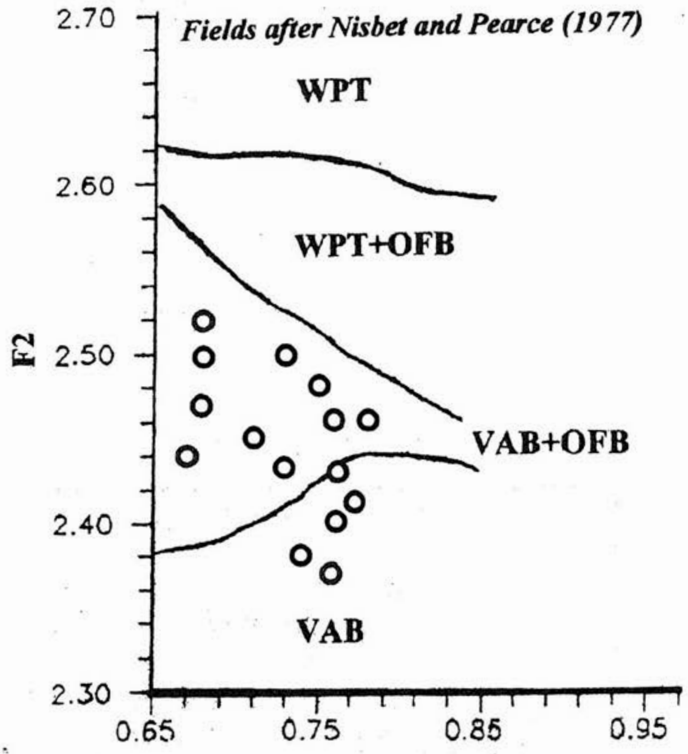


Fig. 8. Plot of discriminant functions F1 and F2 for basaltic pyroxenes. Ocean-floor basalts (OFB), volcanic arc basalts (VAB), within plate tholeiitic basalts (WPT), F1 = $-0.012xSiO_2$-$0.087xTiO_2+0.0026xAl_2O_3$-$0.0012xFeO^*$-$0.0026xMnO+0.0087xMgO$-$0.0128xCaO$-$0.0419xNa_2O$.F2=-$0.0469xSiO_2$-$0.0818xTiO_2+0.00212xAl_2O_3$-.$0041xFeO^*$-$0.1435xMnO+0.0029xMgO+0.0085xCaO+0.0160xNa_2O$.

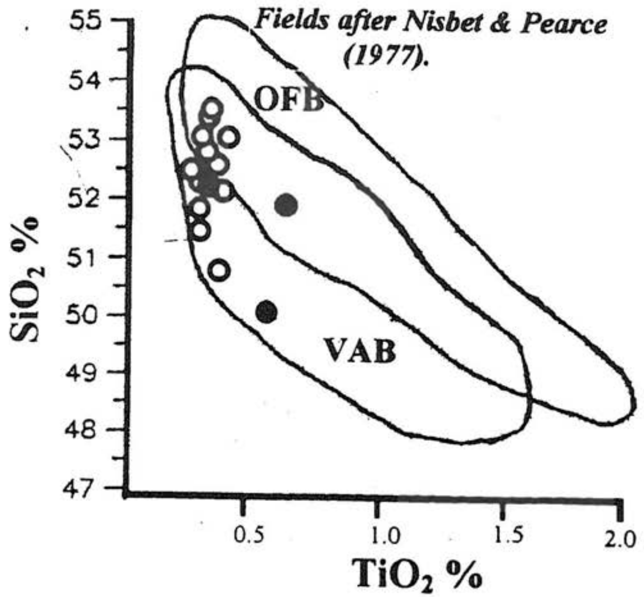


Fig. 9. $SiO_2$ vs $TiO_2$ variation in basaltic pyroxenes from different tectonic settings. Ocean-floor basalts (OFB), volcanic arc basalts (VAB).

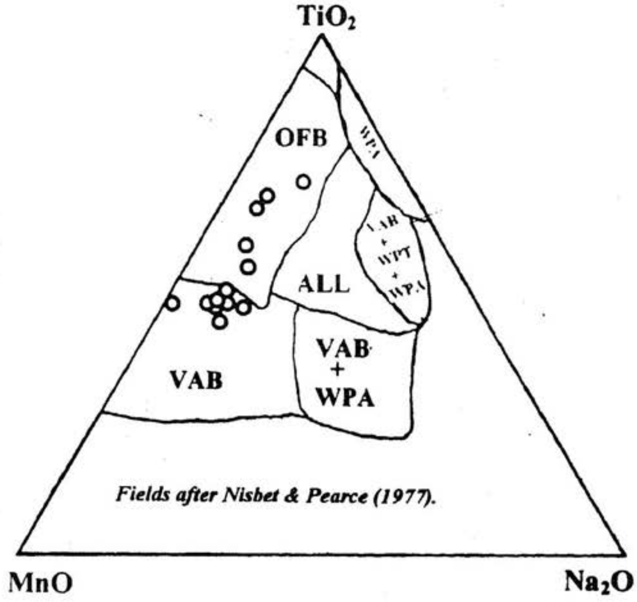


Fig. 10. $Na_2O$-$TiO_2$-MnO plot for discriminating pyroxenes from different tectonic settings. Volcanic arc basalts (VAB), ocean-floor basalts (OFB), within-plate tholeiitic basalts (WPT), within-plate alkalic basalts (WPA).

bonninitic affinity. The Alpine peridotite nature of these chromites is, however, supported by the occurrence in the combined field of alpine peridotite and stratifom complexes on the $Fe^{3+}$# vs mg# plot and the field features indicating an ophiolitic origin (Beck et al., 1995).

The above studies indicate two major types of chemistries for the WOC i.e., a) island arc chemistry reflected by the pyroxene composition and b) Alpine peridotite chemistry reflected in the chromite composition. Such a combination of lithologies indicates that the geology of the area under investigation represent a collage of rocks typical of a mélange zone. Lithologies of various evolutionary histories (oceanic and arc related) have juxtaposed together producing the Waziristan Ophiolite Complex.

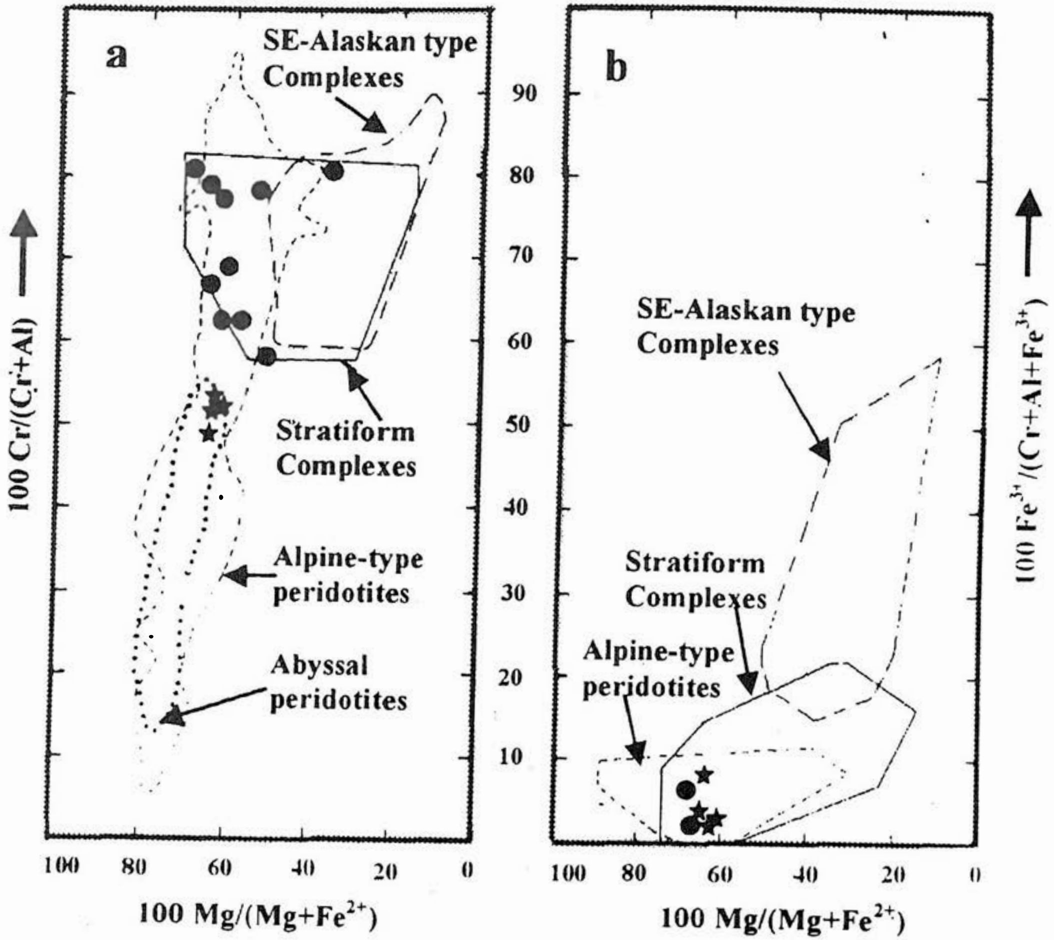


Fig. 11. 100Cr/(Cr+Al) and 100 $Fe^{3+}/R^{3+}$ variation against 100Mg/(Mg+$Fe^{2+}$) in the chromites. •= data from Jan et al., (1985). * = current data. Fields after Jan & Windley (1990).

## CONCLUSIONS

- Pyroxene data from basalts and ultramafic rocks suggest a non-alkaline character. The data is further confined to the field of calc-alkaline and tholeiitic rocks and plot in the area outlined for island arcs.
- The basaltic pyroxenes show a calc-alkaline nature for the host rocks and plot in the combined fields of volcanic arc & ocean floor basalts suggesting a transitional character.
- The moderately low cr-*number* of the present analyses (<60) is akin to abyssal peridotites. Chromites with higher cr-*number* are present elsewhere in the WOC which constitute a rather wide range of cr-*number*, suggesting Alpine peridotite nature.
- The chemical data on pyroxene and chromite suggest a) island arc chemistry shown by the pyroxene composition and b) Alpine peridotite chemistry reflected by the chromite composition.
- In summary, the ophiolite may contain component lithologies belonging to a spreading ridge or island arc or it may have grown in a back-arc basin type of environment.

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