GEOCHEMISTRY OF THE WARSAK IGNEOUS COMPLEX,

NWFP, N. PAKISTAN.

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by

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ABSTRACT

The Warsak Igneous Complex (WIC) is a bimodal suite of granites and basic rocks, with no or little intermediate compositions. The field relations are ambiguous because of shearing and metamorphism, however, there are indications that the basic rocks are older than the granites. The granites, occurring in three petrographic varieties are closely similar in geochemical composition, in particular, in terms of incompatible trace elements. They have all the characteristics of A-type within-plate granites. The basic rocks are typical tholeiitic, formed in intracontinental settings, probably in the initial stages of a rifting event. The close similarity of the Warsak granites with the Carboniferous granites of Ambela and Koga, suggests a Palaeozoic age of the WIC. The magmatism in the Warsak area (including both basic and alkaline acidic) was probably related with the Palaeozoic fragmentation of the Gondwanaland and the separation of India.

CHAPTER 1.

INTRODUCTION

The Warsak Igneous Complex

The Warsak Igneous Complex (WIC), comprising a bimodal suite of granites and basic plutonic and hypobassal rocks, is exposed about 30 km WNW of Peshawar, at the site of the Warsak dam. The two diverse igneous lithologies occur as alternating sheeted masses, intrusive, apparently concordantly, into a sequence of metasediments of Palaeozoic age. The Kabul river enters into the Peshawar plain at Warsak, where the hard granite bedrock has been used for the foundation of the Warsak dam. The ENE flowing Kabul river bisects WIC across the strike, yielding excellent exposures now observable on the road leading to the dam.

The metasediments in the Warsak area and in the Khyber Agency, west of Peshawar, include slates, phyllites, schists, marbles, and limestones, probably deposited in shelf-type environments. Several thrust faults occur in the Khyber Agency (Azhar Khan, personal communication), which have tectonically repeated the metasedimentary sequence. In the Warsak proper, there is a large synclinal fold plunging towards north (Ahmed et al., 1969). The WIC is involved in this folding phase, and has locally developed lineations parallel to the synclinal fold axis.

Regional Geological Setting

The Peshawar plain in N. Pakistan is an intramontane basin in the Himalayan foreland thrust-fold belt (Burbank and Tahirkheli, 1985). The hill ranges immediately to the south and north of the Peshawar plain are part of the internal zone according to the recent classification of the Himalayan foreland thrust-fold belt by Coward et al. (1989) (Figure 1.1). The internal zone, the southern limits of which are marked by the Cherat-Nathiagali fault, differs from a southern or external zone in which the Precambrian to recent strata are distinctly unmetamorphosed.

Another difference between the internal and external zones of the N. Pakistan thrust-fold belt is the occurrence of magmatic rocks; the internal zone is commonly intruded by dykes, sills and bodies of batholithic dimensions mainly of granitic and less commonly of basic composition, whereas the external zone is typically devoid of igneous rocks (except for, of course, the Khewra trap in the Salt Ranges).

A characteristic feature of the magmatism in the internal zone of the Himalayan thrust-fold belt is the occurrence of alkaline rocks of both granitic and basic composition. For instance, alkaline rocks ranging from carbonatites/ijolites/melteigites, through syenites/nepheline syenites to alkaline/peralkaline granites are exposed at several places in the hill ranges bordering the Peshawar plain on its west and north, including Loe Shilman, Warsak, Salai Patti, Shewa Shahbazgarhi, Ambela, Koga, and Tarbela (Figure 1.2). Kempe and Jan (1970), Kempe (1973), Kempe and Jan (1980), Butt et al. (1980), and Kempe (1983) considered these isolated occurrences of alkaline rocks to be genetically related and constituting an alkaline province of Eocene age. Recent age data by Le Bas et al. (1986) have, however, suggested that whereas the Salai Patti and Loe Shilman carbonatites are of Oligocene (~30 Ma. K-Ar data on biotite) age, the Koga carbonatites/syenites and the Ambela granites are Carboniferous in age (Rb-Sr whole-rock isochron). Maluski and Matte (1984), on the basis of Ar^{40}/Ar^{39} age data on separated minerals like amphibole, biotite, and muscovite, suggested that the Malakand granite is Tertiary in age, but the Tertiary age data from the Warsak granites was interpreted to be representing a tectonometamorphic event rather than emplacement. Zeitler, (1989) has dated separated zircons from the Malakand and Ambela granites obtaining Carboniferous ages, close to that of Le Bas et al. (1986). It is interesting to point out that all the ages suggesting Tertiary alkaline magmatism in the Peshawar plain are mineral ages using systems K-Ar and Ar^{40}/Ar^{39}, which are characterised by low blocking temperatures and thus are most suitable for dating tectonometamorphic events rather primary ages of emplacement. It is suggested that all the alkaline magmatism in the Peshawar plain may be genetically related, and the original suggestion of Kempe and Jan (1970) about the existence of one alkaline province may still be valid, despite objections by Le Bas et al. (1986). However, this magmatism took place sometime in late to middle Palaeozoic rather than during Tertiary (Le Bas et al., 1986; Mian, 1987 and Personal communication, 1990).

The basic-ultrabasic rocks in the internal zone of the Himalayan thrust-fold belt (south of the Main Mantle Thrust: MMT) are 1) related with the Kohistan arc and the MMT; such as those of Dargai, emplaced in the vicinity of the Peshawar plain as a result of thin-skinned tectonics 2) related with the alkaline basic rocks (e.g., ijolites at Koga: Mian, 1987; and melteigites at Tarbela: Siddiqui, 1973; ultrabasic to basic rocks derived from alkali olivine basalt at Tarbela: Jan et al., 1981) and 3) tholeiitic dykes and sills of flood/plateau basalt type. The basic rocks at Warsak, a partial subject of this study are associated in space with peralkaline granites, but were suggested to be similar to the basic calc-alkaline rocks occurring in the Chilas Complex in the Kohistan arc (Kempe, 1978); a conclusion which is re-evaluated in this study.

Previous Work

The alkaline complexes around Peshawar, and in particular, the WIC has previously been subject of several publications. The credit of discovery of alkaline rocks goes to Sir Lewis Fermor of the Geological Survey of India, who collected a granite specimen from the Warsak area, and a porphyry specimen from the Shahbazgarhi area (near Mardan) in 1935. Coulson (1936), following Fermor's lead collected further samples from the same localities, and published first ever account of alkaline igneous rocks from this part of then united India. His account included three major-element chemical analyses, one from the Warsak granite, and other two from the Shahbazgarhi porphyries. He concluded that the alkaline rocks from these distant areas were similar in chemical composition and thus were probably petrogenetically related.

The first detailed mapping of the WIC was carried out by Ahmed et al. (1969), which included a detailed petrographic account of all the rock types occurring in the complex. Jan and Kempe (1970) suggested a correlation between the porphyritic granites from Warsak and the porphyries from the Shewa-Shahbazgarhi, and equated the Warsak main alkaline granite with the syenites and related granites at Ambela and Koga. Kempe (1973) published several chemical analyses (including both major elements and trace elements) and a limited K/Ar age data from the Warsak area. In another paper Kempe (1978) described petrography and a limited geochemistry of the basic rocks occurring in association with the Warsak granites. Kempe and Jan (1980), Butt et al. (1980) and Kempe (1983) made brief mentions of the Warsak granites while describing the Peshawar-plain alkaline province. Maluski and Matte (1984) determined a number of Ar^{40}/Ar^{39} mineral dates from the Warsak granites and concluded that they suffered a major tectonometamorphic event in middle Tertiary. Recently, the Peshawar-plain alkaline province has been a subject of detailed investigation by Ihsan Mian (Le Bas et al., 1986; Mian, 1987) and M. Rafiq (see Rafiq, 1987). Le Bas et al. (1986) presented first ever Rb/Sr whole-rock isochron data from the Peshawar plain alkaline province, suggesting a Carboniferous age for the part of province (Koga carbonatites, nepheline syenites, and Ambela granites), which was previously considered to be Tertiary in age.

Aims and Objectives of this Work

The WIC has previously been mapped in considerable details and a sound petrographic data is available (Ahmed et al., 1969; Kempe, 1973, 1978). A limited geochemistry was presented by Coulson (1936), Kempe (1973, 1978), but was clearly insufficient to properly characterise the WIC in terms of petrogenesis and tectonic setting of magma generation. For instance, Kempe (1978) concluded that the basic rocks in the WIC are calc-alkaline in composition and are related with the basic rocks of the Kohistan arc; a proposition which warranted a re-evaluation in the light of modern geochemistry. In this work I have used both major and to a greater extent, trace element data to evaluate the petrogenesis and tectonic setting of magma generation in the Warsak igneous complex. The thesis is divided into two parts; the first part describes petrography, geochemistry, petrogenesis, and tectonic setting of magma generation of the granites, whilst, in the second part basic rocks have been treated in a similar fashion. In the final chapter a synthesis of the thesis is presented with a brief discussion about the implications of this work.

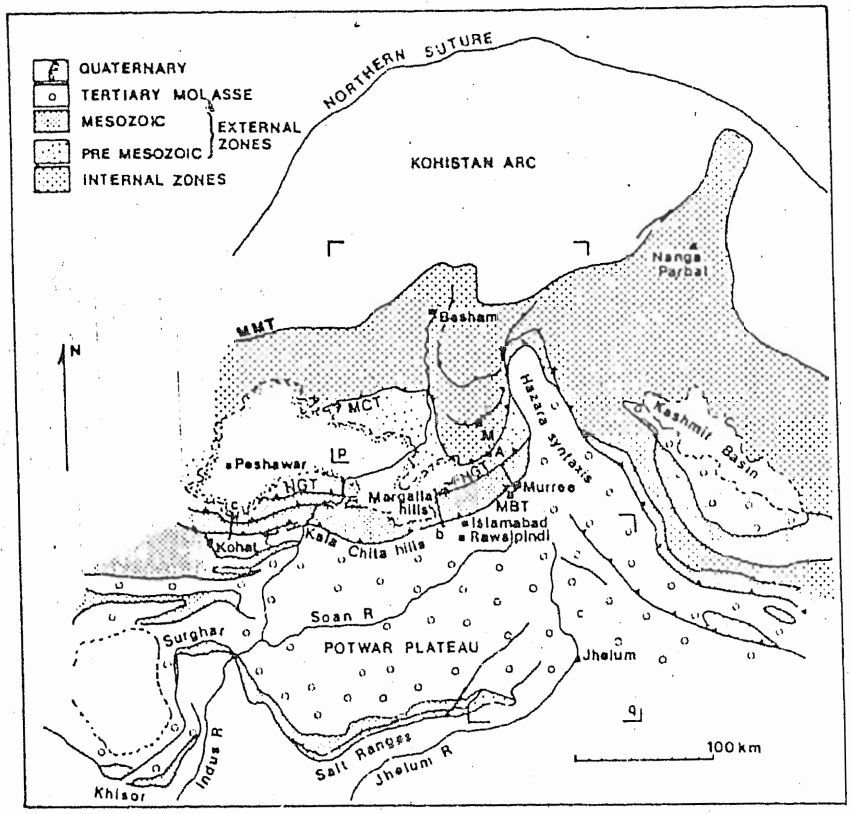


Figure (1.1). Classification of the thrust-fold belt in the northern margin of the Indain plate into an internal (or metamorphosed) zone and an external (or unmetamorphosed) zone (After Coward et al., 1989).

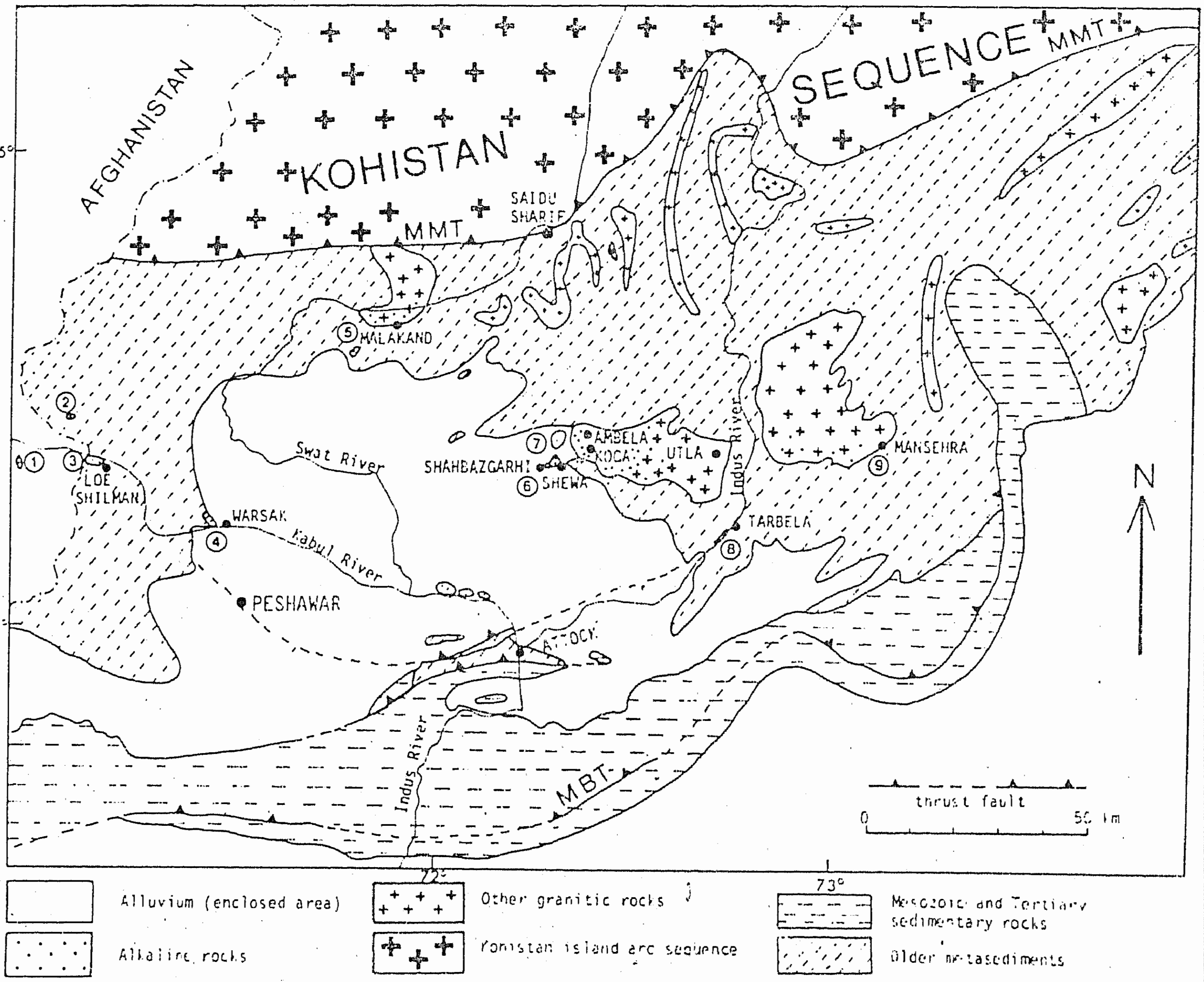


Figure (1.2). A regional map of the Peshawar plain and surrounding hill ranges showing the position of various alkaline complexes.

P A R T 1.

T H E W A R S A K G R A N I T E S

CHAPTER 2

FIELD RELATIONS AND PETROGRAPHY

Introduction

The Warsak Igneous Complex (WIC) contains three major varieties of granites distinguished from each other on the basis of texture, mineralogy, and geochemistry.

1) There are granites which are medium to coarse grained, range in texture from equi-granular and non-porphyritic to inequi-granular and slightly porphyritic, and characteristically contain type alkaline minerals such as aegirine and riebeckite. These granites have been previously termed as Warsak Alkaline Granites (Ahmed et al., 1969, Kempe, 1973; Kempe, 1983), and in this work are referred to as Warsak Aegirine Reibeckite Granites (WMARG).

2) The second variety of granites is fine to medium grained and is characteristically porphyritic. It ranges from being fresh to slightly sheared and is mineralogically similar to the MARG in that it contains sodic pyriboles such as aegirine and riebeckite. In this work this variety of granite is referred to as Warsak Porphyritic Aegirine Reibeckite Granite (WPARG).

3) The third variety of granite, noted in the WIC, is texturally similar to the WPARG in that it is fine-grained and porphyritic, but is relatively much more deformed (sheared). The distinguishing feature of this variety, however, is the mineral assemblage lacking sodic pyriboles, and containing aluminous minerals such as biotite, muscovite and garnet. This granite type will be referred to as the Warsak Porphyritic Biotite Muscovite Granite (WPBMG).

The age relationship amongst the three granitic varieties is not clear in the field. Following Ahmed et al. (1969), the relatively deformed and garnetiferrous (and metamorphosed) WPBMG is considered older than the other two varieties, which are assumed to be contemporaneous on the basis of common mineral assemblage.

All the three varieties of granites are intimately associated with a suite of basic rocks, occurring as sheeted masses alternating with those of the granites (Figure 2.1). Again there is little field evidence to deduce the relative age relationship between the granites and the basic rocks. Ahmed et al. (1969) noted, in addition to rare xenoliths of basic rocks in the granites, some granitic veins cutting across the basic rocks. On a limited scale similar field relations have been observed by this author. It is, however, remarkable that despite a considerable volume of the two varieties of rocks and their occurrence in innumerable discrete bodies (normally in the form of alternating tabular, masses), evidence of cross-cutting field relations is only rarely found. It has to be noted that Ahmed, M. (1951) considered the basic rocks to be younger than the granites.

The detailed mapping of the warsak igneous complex is available since the work of Ahmed et al. (1969). The following description is based mostly on their work, and that of Kempe (1973, 1983), supplemented with observations during this work.

Warsak Main Aegirine Reibeckite Granite (WMARG)

Field Distribution

The principal occurrence of the Warsak Main Aegirine Reibeckite Granite (WMARG) is at and around the Warsak Damsite (Figure 2.1). The granite body at this place is a massive sheet which is about 1 km. in width, and over 5 km in length. The sheet is apparently intruded into Palaeozoic metasediments. Ahmed et al. (1969) have shown it to be concordantly separating the phyllites and marbles of Upper Palaeozoic age in the north and north-east, from a unit of pebbly quartz-biotite schists of Siluro-Devonian age in the south and south-west. The host metasediments and the enclosed WMARG sheet are folded together in the form of a synform.

Whereas the above described main sheeted mass of WMARG is emplaced at the contact of Lower and Upper Palaeozoic, a ~1.5 km long sill occurs entirely within the Upper Palaeozoic phyllites at the northern slopes of the Spera Ghar. This is in addition to several small stock like bodies which occur within this metasedimentary unit.

Field Features

Both massive and foliated varieties are observed in the WMARG. In the former, the constituent medium to coarse grains of feldspathic minerals (alkali and plagioclase feldspars and quartz) are equi-granular, and the dark minerals are either tabular or prismatic but rather randomly oriented. The massive variety of WMARG is more common at the Warsak damsite. Foliated WMARG is principally found in the south in the vicinity of the Mula Gori road. Majority of the foliated rocks contain a single planar structure, which is apparently concordant with the strike of the adjacent country rocks. The foliation is mostly defined by tabular crystals of dark minerals such as riebeckite amphibole and aegirine clinopyroxene, but tabular and prismatic crystals of feldspars also have a concordant orientation. This foliation has been interpreted to be a primary flow structure formed at the time of emplacement (Ahmed et al., 1969). Data recorded during the present work confirms this interpretation, as the foliation is found to be parallel to the strike of the sheets and the limbs of the major synform fold structure rather than the axial plane of the fold. At places, the WMARG is marked by a strong linear fabric, defined by lenticular crystals of dark sodic minerals. This liner fabric plunges towards north, apparently parallel to the orientation of the fold axis. It is suggested that this linear fabric developed in response to metamorphism accompanying the deformation which produced the major fold structure in this area.

Commonly the WMARG is homogeneous, both in terms of composition and texture . There is little grain size variation, and dark minerals to feldspathic minerals ratio remains grossly same throughout the observed outcrops. Rarely there are linear bands which are relatively coarser grained, some reaching a grain size appropriate to pegmatites. Compositionally these coarser grained rocks, however, are similar to the main mass of the WMARG.

Petrography

The Warsak Main Aegirine Riebeckite Granite (WMARG) is fine- to mediaum grained, even-granied to subporphyritic rock. Commonly the dark minerals (aegirine, and riebeckite) are oriented parallel to each other defining a flow fabric. Feldspar is mostly microcline with a well developed cross-hatched twinning. It is present both in the porphyritic parts, (where it occurs both as phenocrysts and in groundmass), as well as even-grained portions of the granite. It makes < 10% of the overall volume of the rock. Perthite is relatively more abundant (making about one third of the volume), occurring more commonly in the porphyritic portions of the rock, but occurring also in the even grained portions. Albite makes about 10 to 15% of the rock, concentrated mostly in the fine-grained portions of the rock. Aegirine (making about 10% of the rock occurs in large tabular grains or in irregular aggregates. Riebeckite occurs as small prismatic crystals disseminated in the rock with a weak allignment. Astrophylite, biotite, sphene, zircon, epidote, and opaque minerals occur in minor to trace amounts.

Warsak Porphyritic Biotite Muscovite Granite (WPBMG)

Field Distribution and features

The Warsak porphyritic non-alkaline granite (WPBMG) occurs in the form of sheeted masses or sills conformable to the attitude of the WMARG and that of the sheets of the basic rocks with which they alternate at regular intervals. The size of the sills is highly variable ranging from a few metres to 200 metres. More than three sheeted bodies of the WPBMG are mapped (Figure 2.1). It is to be noted that the WPBMG occupies an intervening position between the main body of the WMARG at the damsite and the bodies of the Warsak Porphyritic Aegirine Riebeckite Granite (WPARG) near the Ali-Baba Ziart. The western most WPBMG body is a 200 m thick sheet occurring just to the west of the Warsak bridge. This body is flanked by conformable sheets of basic rocks. To the east of the bridge, there are several meter-scale thin sheeted bodies alternating with the sheets of basic rocks (Figure 1). A common feature of the WPBMG is a state of high deformation. There is a strong foliation defined by lenticular streaks of groundmass alternating with highly stretched phenocrysts of feldspars and ribbons of recrystallised quartz presumably derived from what were originally phenocrysts of quartz. Biotite. which is at places accompanied by muscovite, displays a shape fabric parallel to the foliation. The strongly foliated WPBMG gives a schistose appearance in the field and in the hand-specimen.

Petrography

In thin sections the WPBMG shows a texture comprising phenocrysts of microperthite floating in a fine-grained, polymineralic groundmass. The microperthite phenocrysts are generally euhedral to subhedral, without showing much affect of ductile deformation. Several of the phenocrysts, however, have an assymetrical lenticular shape with pointed ends merging with the foliation. A marked feature of the WPBMG is a scarcity of quartz phenocrysts, although there are aggregates of ploygonal grains of quartz generally in the form of lenticular ribbon-like structures. The groundmass of the WPBMG is typically fine-grained equi-granular, and consists of grains with polygonal outlines. The textures in the WPBMG can best be explained considering a superimposition of ductile deformation on a porphyritic igneous texture. Deformation at temperatures appropriate to epidote-amphibolite and greenschist facies is capable of causing a ductile flow and recrystallisation in quartz, but may not ductily deform feldspar (see Brodie and Rutter, 1985 for relative strength of common rock-forming minerals in response to deformation at various temperature-pressure conditions). In the WPBMG, deformation under greenschist or epidote amphibolite conditions resulted in obliteration of all the quartz phenocrysts which were turned into ribbon like aggregates of polygonal grains. Since the groundmass was rich in quartz, most of the shearing was accommodated in there. The perthite phenocrysts retained their igneous shape because they floated in ductily flowing quartz-rich groundmass and thus suffered only a bodily rotation.

Compositionally the WPBMG shows a variation in mineral assemblage from one place to the another. The main sheet just to the west of the Warsak bridge, is composed of perthite, microcline, quartz, muscovite, biotite and garnet. The sheeted bodies of the WPBMG, to the east of the bridge, lack muscovite and garnet and the only ferromagnesian mineral is biotite. None of the WPBMG is observed containing sodic ferromagnesian minerals.

Warsak Porphyritic Aegirine Riebeckite Granite (WPARG)

Field distribution and features

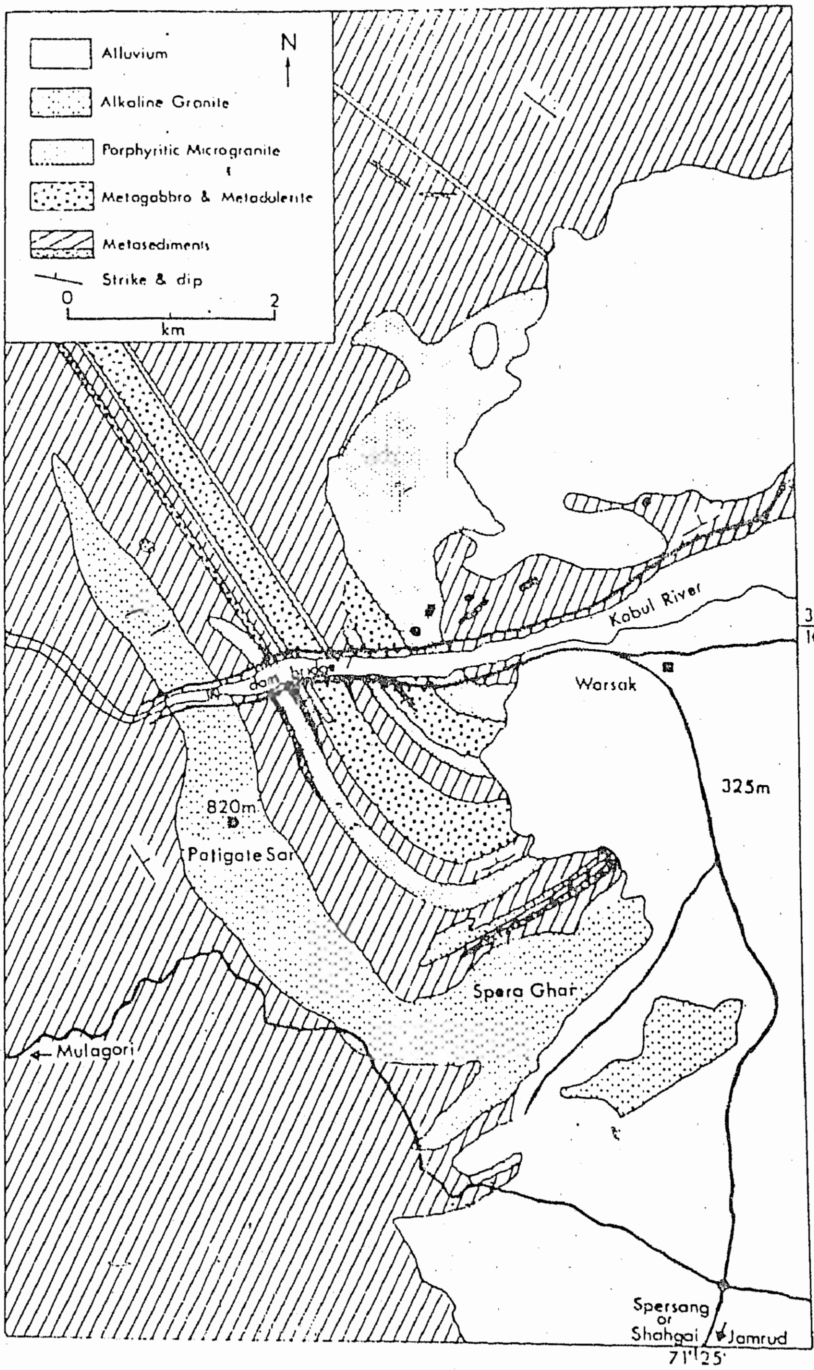
The Warsak Porphyritic Aegirine Riebeckite Granite (WPARG) has a mode of occurrence in the form of sill-like intrusions common to the rest of the rock types of the Warsak igneous complex. The principal occurrence is near the Ali-Baba Ziarat where a 100 m thick sill is well exposed on the road leading to the Warsak damsite. The continuation of this sill, north of the river is more voluminous, attaining a thickness of more than 1 km. Several thinner sills occur to the west of this main body alternating with the sheet-like intrusions of basic rocks and the WPBMG.

In hand-specimen, the WPARG has a general appearance similar to the WPBMG, particularly in terms of a flow structure in the groundmass which furnishes a well defined foliation to the rocks. Unlike the WPBMG, however, there are distinct euhedral phenocrysts of perthite, microcline and quartz, which can be readily observed with naked eye.

Petrography

Under the microscope, the thin sections of the WPARG show a typical porphyritic igneous texture, with little evidence of mylonitisation so common in the WPBMG. There are eu- to subhedral phenocrysts of perthite, microcline, and quartz set in a granular groundmass of fine grained quartz, microcline, and perthite. Albite may also be locally present in the groundmass. There is an abundance of magnetite and ilmenite oxide-mineral phases, reaching 12% (by volume) in some specimen. Both perfect euhedral and anhedral grains of oxide minerals are found. Ferromagnesian silicates include riebeckite, aegirine, and biotite. The aegirine is usually subordinate to riebeckite, and occurs either in stocky prismatic to stubby crystals, or in aggregates of lenticular shape. The riebeckite is typically in needle like prismatic crystals, generally oriented parallel to the foliation. Biotite is either in individual prismatic grains oriented parallel to the foliation or in aggregates associated with the oxide minerals. The accessory minerals include sphene, zircon, alanite, and astrophyllite.

Figure (2.1.). Geological map of the Warsak Igneous Complex, simplified after Ahmed et al. (1969).


Alluvium
N
Alkaline Granite
Porphyritic Microgranite
Metagabbro & Metadolerite
Metasediments
Strike & dip
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km
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820m
Patigate Sar
Spera Ghar
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Spersang
or
Shahgai
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CHAPTER 3.

GEOCHEMISTRY, TECTONIC SETTING AND PETROGENESIS

Introduction

Petrographic studies (Ahmed et al., 1969; Kempe, 1973, 1983; Chapter 1 of this study) have shown that the two of the three varieties of granites in the Warsak Igneous Complex contain sodic minerals (aegirine and riebeckite) and are thus peralkaline in composition. The third granite variety contains an assemblage comprising aluminous minerals like biotite, muscovite and garnet. Whereas peralkaline granites are commonly considered to be anorogenic and derived from an igneous protolith (and are thus I-type according to classification scheme of Chappel and white, 1974), granites with aluminous mineral assemblage are generally derived from partial melting of supracrustal sedimentary rocks (S-type granites). This partial melting may be induced by influx of heat and anhydrous volatiles (e.g., halogens, CO2) from mantle or from mantle-derived basic magmas on their way to shallow crustal levels, a condition envisaged to be peculiar to intra-cratonic anorogenic setting with extensional environments. Alternatively, heat for the partial melting in crustal regimes may be provided by thickening of the crust during orogenesis (e.g., continent-continent collision). Granite magmatism at Warsak has previously been related to India-Eurasian collision (Himalayan orogeny) on the basis of radiometric ages of ~40-50 Ma (Kempe, 1973). If so, the granites from the WIC, in particular the metaluminous granites, should have trace-element characteristics resembling those of type collisional granites such as those summarised by Harris et al. (1984). Alternatively, if the Warsak granites are within-plate type, their relationship with the Himalayan orogeny is to be reconsidered assessing the validity of K/Ar mineral ages of Kempe (1973), as pointed out by the later data of Malusky and Matte (1984) and Le Bas et al. (1986), as primary ages of granite emplacement.

This chapter is based on whole-rock analyses of selected samples from all the three varieties of granites from the WIC. The data used in this work are obtained using a Philips X-Ray Fluorescence Spectrometer at the Leicester University, using pressed-powder pellets. The details of the technique are described by Petterson (1984). Several of the samples are analysed only for trace elements since their greater applicapablity in petrogenesis and determination of tectonic setting of magma generation. Previously reported analyses (Coulson, 1936 and Kempe, 1973) are also included in the dataset, though trace-element data in Kempe (1973) shows severe limitations when compared with XRF data from this work.

Classification

The granites from the Warsak area have all the major-element characteristics typical of alkali granites., such as high SiO_2, and Alkalies, and low CaO, and MgO. On the La Roche et al. (1980) classification diagram (Figure 3.1), the Warsak main aegirine riebeckite granites (WMARG) and the porphyritic aegirine riebeckite granites (WPARG) plot as a coherent group in the field of alkali granites (except for one sample which is hybridised with associated basic rocks and plots in the field of granodiorite). The Warsak porphyritic biotite muscovite granites (WPBMG), devoid of sodic pyriboles, plot as a separate group in the field of granite proper.

When classified on the basis of Shand's indices ($Al_2O_3/CaO+Na_2O+K_2O$; Al_2O_3/Na_2O+K_2O), the Warsak main granites (WMARG) are typically peralkaline having the both A/CNK and A/NK ratios typically < 1 (except for one sample which is hybridised with the basic rocks and plots in the field of metaluminous granites away from the rest of samples of this group) (Figure 3.2). Both the porphyritic varieties of granite, on the other hand, irrespective of their mineral assemblage plot in the field of metaluminous and peraluminous granites. Majority of the porphyritic granites devoid of sodic pyriboles pare peraluminous, whereas the porphyritic granites containing sodic minerals, are metaluminous according to this criterion.

In summary, the various classification schemes using major elements as basis, suggest that the Warsak granites range from peralkaline, through metaluminous to peraluminous in their chemistry. Despite this they make a coherent group plotting in the fields of rift-related granites (RRG) and continental epeirogenic uplift granites (CEUG) defined by Maniar and Piccoli (1989). A peculiar feature of the Warsak granites, apparent from the classification schemes used here, is their restricted composition; i.e., unlike common granitic suites having compositions ranging from diorite or granodiorite through granite to alkali granite, the Warsak granites do not have any associated intermediate or more felsic rocks.

Major and Trace Element Variations

Compositional variations in the Warsak granites are exhibited by plots of major- and trace-element contents against Zr (Figure 3.3). Amongst major elements, SiO_2, Fe_2O_3(total), and MnO show steady increase, with increasing content of Zr, whereas Al_2O_3, TiO_2, MgO, and CaO decrease. Amongst alkalies, K_2O is marked by an earlier depletion, but a later steady trend. Na_2O shows a similar initial trend of negative slope, but shows enrichment in most evolved rocks.

Amongst the large-ion lithophile trace elements, Ba and Sr decrease with increasing Zr, whereas the rest of the LIL elements such as U and Th show a steady increase. A truly incompatible relation is also shown by high-field strength elements (HFSE) such as Nb, and Y. Rare-earth elements (REE) are generally incompatible in most magma systems. In the Warsak granites, however, the light REE (La and Ce) show a negative slope between Zr contents of 500-1500 ppm, inflicting to a positive slope for Zr content > 1500 ppm. Nd differs from the La and Ce in its variation relative to Zr. Unlike La and Ce, Nd does not deplete but remain constant in the Zr range 500-1500 ppm, showing an enrichment with increasing Zr in the rocks with Zr > 1500 ppm. Light REEs are known for their incompatible behaviour during fractionation in basalts. In granitic systems, where k-feldspar, plagioclase, and anorthoclase are the early crystallising minerals, the light REEs are expected to be depleted in the melt as long as these minerals keep crystallising. This is because of higher Kds of LREEs for the feldspar minerals. The depletion of La, and Ce, and a constant level of Nd in the early crystallising granites is attributed to crystallisation of feldspar minerals. The cessation of these minerals around Zr content of 1500 ppm could account for subsequent increase in the contents of these light REEs.

Compositional variations such as those shown in the Figure (3.3) can either be a result of partial melting or fractional crystallisation. The simultaneous depletion of alkalies and Al_2O_3 points to fractionation of feldspar. Depleting Ba, and Sr, both having high Kds for feldspars (6.12 and 3.87 respectively; see Hanson, 1978) supports the fractional crystallisation involving feldspars. Enrichment in SiO_2 points to a lack of crystallisation of minerals like pyroxenes and quartz, which crystallised only in late stages of crystallisation. An interesting relation is shown by iron, TiO_2, and MnO. Whereas the former two show a trend of enrichment with increasing Zr, TiO_2 shows progressive depletion. This points to an early crystallisation of a mineral which contains TiO_2 but not iron, such as rutile or sphene.

In summary, the limited major- and trace-element variations in the Warsak granites suggest a role of fractional crystallisation. Early crystallising feldspar and a TiO_2-rich mineral depleted Al_2O_3, TiO_2, alkalies, Sr, and Ba. Quartz, pyroxene, amphibole, and magnetite all crystallised in the late stages of crystallisation.

Tectonic Setting of Magma Generation

Granites are found in almost all the major tectonic settings, including mid-oceanic ridges, island arcs, continental margins, and within plates (see Pearce et al., 1984 for an exhaustive review). The granite magmatism in the Peshawar plain, on the basis of its geological position as the northern margin of the Indian plate, can be of several different origins. Some possibilities are 1) magmatism in Andean-type continental margin: The Thethys ocean subducted southward below the Indian plate, producing calc-alkaline granitic plutons of granitic composition similar to those formed in the Kohistan and Asian plates due to northward subduction of the Thethys (see Petterson and Windley, 1985; Le Fort et al., 1983); 2) collision granites, formed by thickening of the crust of the Indian plate after its collision with Kohistan. Such granites are reported from the northern margin of the Indian plate such as the famous Mansulu granite of Nepal (Le Fort ???). 3) Within-plate A-type granitic magmatism, related with an episode of rifting, which could be simultaneous with the India-Kohistan collision (Kempe and Jan, 1980; Butt et al., 1980), or earlier (Le Bas et al., 1986; Mian, 1987). Obviously, for a precise determination of tectonic setting of magma generation for the Warsak and other granites in the Peshawar plain (Such as Ambela, Malakand, Shewa Shahbazgarhi and Tarbela; see Kempe and Jan, 1980 for the basis of correlation) a two-fold approach is required: firstly the chemistry of granites, in particular in terms of incompatible trace elements, needs evaluation in order to constrain the type of magma. Secondly, radiometric age data are required in order to determine relationship between various varieties of granites in the context of plate tectonics. The radiometric age dating is out of scope of this study, but in the following pages a re-evaluation of existing age data will be carried out. However, incompatible trace elements will be used extensively to determine the petrogenetic type of the Warsak granites and their possible tectonic setting of origin.

The three petrographic varieties of the Warsak granites are compared in terms of mantle-normalised incompatible trace elements in Figure (3.4). The most striking feature apparent from this plot is the close similarity in the trace element patterns of all the three granite varieties. Interestingly even the porphyritic granites devoid of sodic minerals and some major-element differences are not substantially different in terms of incompatible trace-elements from the other two granite varieties. This is suggestive of close petrogenetic relationship between the granite varieties of Warsak irrespective of their current mineralogical and major-element composition.

Once established that all the granites at Warsak are petrogenetically related, it is desired to establish their petrogenetic type. The major and trace element contents of the Warsak granites unambiguously classify the Warsak granites as within-plate A-type (defined by Loiselle and Wones , 1979; further characterised by Collins et al., 1982; and Whalen et al., 1987). In Figure (3.5), the Warsak granites are compared with granites from various tectonic settings such as island arcs, mid-oceanic ridges, granites from collision zones, and within-plate granite. There is a close match in the trace element pattern of the Warsak granites and in the patterns of granites from within-plate setting. Pearce et al. (1984) have further classified the within-plate granites in terms of dominance of mantle or crustal components reflected in differences in enrichment in elements such as K, Rb, Th, Ce, and Nd relative to high field strength elements (HFSEs) such as Zr and Nb. The Sabalokha, Mull and Skaergaard granites in Figure (3.5) are type example of trace element pattern with a dominantly crustal component, whereas the granites from the Oslo Rift and Ascention Island represent within-plate granites with a dominantly mantle component in the parent magma. When compared, the Warsak granites are closely similar in trace element pattern to that of the Ascension Island characterised by mantle-normalised Nb/Rb and Nb/Th ratios close to 1 or higher, suggesting a dominance of mantle over crustal component.

The major and trace element characteristics which suggest A-type nature of the Warsak granites include high SiO_2, Na_2O+K_2O, Fe/Mg, Zr, Nb, Ga, Y, and REE contents and low CaO, Ba, and Sr contents. The A-type nature of the Warsak granites is clearly exhibited in Figure (3.6), which is specially devised for the discrimination of A-type granites from the granites of other types such as M-, I-, and S-type (Whalen et al., 1987).

In summary, the incompatible trace element contents suggest that the Warsak granites 1) are closely related despite differences in mineral assemblages, and major-element contents, 2) are A-type in nature, and 3) were derived in within-plate settings with a considerable contribution from the mantle in their petrogenesis.

Petrogenesis

Several models have been suggested for the origin of A-type within-plate granites including metasomatism, crystal fractionation, and partial melting (see Whalen et al., 1987 for a detailed review). Any model accounting for the petrogenesis of the Warsak granites should take into consideration the following characteristics. 1) There are peralkaline and subalkaline (metaluminous) granites in close association 2) the Warsak granites are closely associated with basic rocks, which have complex field relations with the granites i.e., at places basic rocks appear to be enclosed in the granite sheets whereas sometime veins and dykes of granites cut across the basic rocks. 3) The Warsak granites irrespective of their petrographic varieties are closely similar in incompatible trace-element contents suggesting a close petrogenetic relation; 4) The Warsak granites are closely similar to A-type granites of within-plate origin. In particular, they resemble granites from the Ascension Island and Solo Rift.

A generally uniform composition of the Warsak granites negates any major role of processes such as metasomatism and crystal fractionation in their petrogenesis. This leaves partial melting as the most important process in the origin of the Warsak granites. A high SiO_2 content (67 to 74 wt%) necessarily implies that direct melting of upper mantle (of a dominantly mafic composition) was not involved in the origin of the parent melt for Warsak granites. The partial melting of lower continental crust, capable of yielding felsic melts such as those of Warsak, however, needs a mechanism to induce melting.

1) Harris and Marriner (1980) invoked a high flux of mantle-derived halogen-rich volatiles to induce melting and to provide the high concentration of alkalies and high-field strength elements in A-type granites.

2) Baker et al. (1975) proposed a reaction-melting model in which mantle-derived mafic magma was considered causing partial melting of granulite-facies lower continental crust followed by various stages of contamination and differentiation.

3) Collins et al. (1982) postulated the formation of A-type granites by partial melting at elevated temperatures of an anhydrous source which was previously depleted in water by extraction of a minimum-melt

I-type magma. The granulite source they proposed is expected to be high in F- and/or Cl due to enhanced thermal stability of micas and amphiboles rich in these elements. This origin has been supported by Clemens et al. (1986) in the light of their experimental work.

4) Anderson and Thomas (1985) suggested that muscovite bearing A-type granites may be derived from a dehydrated S-type source in the lower continental crust.

Assuming that the the Warsak basic rocks are not substantially different in age from the granites, the heat for the partial melting might have been provided by their passage through the lower continental crust. Alternatively a release of pressure in rifting extensional environments might have caused partial melting in a granulite source in the lower continental crust. The high content of HFS elements in the Warsak granites is acquired from the break down of accessory minerals in the source, further enhanced by crystallisation under high F- and Cl content (see Whalen et al., 1987 for the role of halogens in enrichment of HFS elements in magmas).

The presence of peralkaline and metaluminous granites in Warsak suggests derivation from a source with mainly I-type but locally S-type protolith, a lithological feature expected in lower continental crust. The important feature, however, is the comparable contents of the HFS elements in two types of granites suggestive of a similar dehydrated nature of the two source types. Coexisting peraluminous and peralkaline A-type granites in N. America were considered to be derived from a similar dehydrated interlayered I- and S-type source (Anderson, 1983; Anderson and Thomson, 1985).

File name A:WSKGNT.ROC

Sample	W1	W2	W3	W4	W7	W8	W9	W11	W13	W44	W46	W47	W49	Kempe7	Kempe8
Group #	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
Qual	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Key	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Ref	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
SiO_2	72.80	72.90	73.20	73.00	75.00	73.74	72.00	73.00	73.00	71.00	72.00	73.00	73.00	67.99	73.19
TiO_2	0.29	0.32	0.36	0.32	0.18	0.33	0.29	0.24	0.24	0.34	0.30	0.32	0.37	0.51	0.23
Al_2O_3	10.65	10.60	10.10	13.00	11.00	10.50	12.00	12.00	11.00	12.00	12.00	12.00	12.00	15.20	10.85
Fe_2O_3	4.75	4.80	5.80	3.00	4.00	4.70	3.36	3.30	4.00	4.00	3.00	4.00	4.00	4.97	4.10
FeO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.00
MnO	0.14	0.14	0.15	0.10	0.07	0.15	0.13	0.05	0.20	0.20	0.10	0.20	0.20	0.09	0.25
MgO	0.10	0.10	0.00	0.10	0.00	0.00	0.10	0.10	0.00	0.10	0.10	0.10	0.20	0.65	0.49
CaO	0.26	0.25	0.10	0.30	0.07	0.17	0.29	0.14	0.20	0.20	0.20	0.10	0.10	2.79	0.23
Na_2O	4.70	4.70	4.30	5.34	4.40	4.37	5.00	5.00	4.00	5.00	5.00	5.00	5.00	3.25	5.12
K_2O	4.60	4.55	4.60	4.05	4.48	4.86	4.54	4.40	4.80	4.00	4.47	4.00	5.00	4.49	4.32
P_2O_5	0.02	0.02	0.02	0.03	0.01	0.02	0.02	0.02	0.01	0.02	0.01	0.02	0.02	0.04	0.00
Total	98.31	98.38	98.63	99.24	99.21	98.84	97.73	98.25	97.45	96.86	97.18	98.74	99.89	100.07	98.78
Trace Elements (ppm)															
Nb	134.4	143.4	294.7	119.0	184.5	518.3	124.2	142.9	190.7	160.0	151.3	138.0	123.9	200.0	100.0
Zr	989.0	975.8	2487.0	929.3	1768.0	3099.5	1159.7	1413.6	1872.8	1125.9	1311.4	2042.7	1064.0	1500.0	3000.0
Y	126.1	126.4	279.3	87.5	131.3	373.4	94.8	94.8	129.4	109.0	122.8	103.8	62.9	50.0	150.0
Sr	5.7	5.7	3.6	24.7	7.7	8.3	10.5	27.5	10.3	5.2	7.1	3.9	3.8	317.0	0.0
U	3.0	1.0	8.0	1.0	4.0	15.0	0.5	2.0	4.0	2.0	4.0	4.0	1.0	0.0	0.0
Rb	150.4	150.9	198.7	102.1	122.2	181.3	153.0	141.0	223.9	137.1	134.5	141.2	123.4	105.0	180.0
Th	26.0	29.0	156.0	17.0	23.0	71.5	20.5	22.0	35.0	24.0	24.5	25.0	19.0	0.0	0.0
Pb	9.0	12.0	21.0	13.0	24.5	23.0	14.0	25.0	28.0	30.5	5.0	22.0	16.5	0.0	0.0
Ga	33.7	33.6	29.9	31.6	33.6	29.6	30.6	32.5	30.7	29.9	29.9	30.1	29.7	0.0	0.0
Zn	215.9	247.4	174.5	166.2	149.2	159.0	192.0	128.8	239.6	201.5	174.5	203.4	169.5	114.0	322.0
Ni	2.4	2.3	5.8	0.1	2.0	7.2	2.4	3.0	2.9	3.9	1.6	1.9	2.4	10.0	50.0
Cr	3.0	1.0	4.0	3.0	4.0	3.0	3.0	3.0	4.0	3.0	5.0	2.0	3.0	10.0	0.0
V	4.0	3.0	1.0	5.0	11.0	1.0	2.0	16.0	2.0	2.0	2.0	1.0	3.0	20.0	0.0
La	124.4	124.6	173.5	93.6	84.5	211.9	112.8	89.8	114.9	133.1	124.1	123.8	143.5	0.0	0.0
Ce	236.4	242.2	388.2	204.2	209.7	526.5	240.2	205.5	269.4	284.6	265.9	272.0	303.2	0.0	0.0
Nd	132.2	129.3	181.0	95.6	107.9	276.6	110.3	95.7	142.5	133.3	124.2	124.8	120.3	0.0	0.0
Ba	203.0	204.0	165.0	541.0	171.0	243.0	578.0	365.0	175.0	511.0	460.0	501.0	342.0	1595.0	405.0
Ga/Al	6.0	6.0	6.0	4.6	5.8	5.3	4.8	5.1	5.6	4.7	4.7	4.7	4.7	0.0	0.0
Zr+Nb+Ce+Y	1485.9	1487.8	%34492.0	1340.2	2293.5	4517.2	1618.9	1856.8	2462.3	1683.6	1842.2	2556.5	1554.0	1750.0	3250.0
(Alk/CaO)	35.8	37.0	89.0	31.0	126.8	54.3	32.9	67.1	44.0	45.0	47.4	90.0	100.0	2.8	4104.0
FeOt/MgO	43.2	43.7	0.0	27.3	0.0	0.0	30.6	30.0	0.0	36.4	27.3	36.4	18.2	7.0	7.6
Zr+Y+Ce	1351.3	1351.0	3154.5	1221.0	2109.0	3998.9	1494.7	1713.9	2271.6	1519.5	1700.1	2417.8	1430.1	1550.0	3150.0
Rb/Ba	0.7	0.7	1.2	0.7	0.8	0.7	0.3	0.4	1.3	0.3	0.3	0.3	0.4	0.0	0.0
Zr+Nb+Ce+Y	1486.0	1487.0	3450.0	1340.0	2293.0	4517.0	1619.0	1856.0	2462.0	1680.0	1851.0	2556.0	1554.0	1750.0	3250.0
Al_2O_3/CNK	0.8	0.8	0.8	0.9	0.9	0.8	0.9	0.9	0.9	0.9	0.9	0.9	0.9	1.0	0.8
Al_2O_3/Alk	0.8	0.8	0.8	1.0	0.9	0.8	0.9	1.0	0.9	1.0	0.9	1.0	0.9	1.5	0.8
FeOt	4.28	4.32	5.22	2.70	3.60	4.23	3.02	2.97	3.60	3.60	2.70	3.60	3.60	4.56	3.69
Mg#	0.026	0.026	0.000	0.040	0.000	0.000	0.036	0.037	0.000	0.031	0.040	0.031	0.059	0.139	0.131
Zr/Nb	7.4	6.8	8.4	7.8	9.6	6.0	9.3	9.9	9.8	7.0	8.7	14.8	8.6	7.5	30.0
Rb/Sr	26.386	26.474	55.194	4.134	15.974	21.843	14.567	5.127	21.844	26.612	19.078	36.675	32.907	0.331	0.000
K/Rb	254	250	192	329	304	222	246	259	178	242	276	235	336	355	199
K/Ba	188.1	185.1	231.4	62.1	217.5	166.0	65:2	100.1	227.7	65.0	80.7	66.3	121.3	23.4	88.5
den	2.32	2.32	2.32	2.32	2.31	2.32	2.32	2.31	2.31	2.32	2.31	2.32	2.32	2.37	2.32

File name A:WSKGNT.ROC

Sample	Kempe9	Kempe1	T28	T29	T45	T46	W21	W23	Kempe5	T32	T33	T37	T40	T41	T42
Group #	3.00	3.00	3.00	3.00	3.00	3.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Qual	3	3	3	3	3	3	2	2	2	2	2	2	2	2	2
Key	3	3	3	3	3	3	2	2	2	2	2	2	2	2	2
Ref	3	3	3	3	3	3	2	2	2	2	2	2	2	2	2
SiO_2	74.16	75.88	0.00	0.00	0.00	0.00	66.00	67.00	73.03	0.00	0.00	0.00	0.00	0.00	0.00
TiO_2	0.42	0.18	0.00	0.00	0.00	0.00	0.55	0.48	0.48	0.00	0.00	0.00	0.00	0.00	0.00
Al_2O_3	11.86	10.14	0.00	0.00	0.00	0.00	14.00	15.00	11.58	0.00	0.00	0.00	0.00	0.00	0.00
Fe_2O_3	3.98	3.89	0.00	0.00	0.00	0.00	3.00	2.00	3.75	0.00	0.00	0.00	0.00	0.00	0.00
MnO	0.19	0.14	0.00	0.00	0.00	0.00	0.14	0.08	0.19	0.00	0.00	0.00	0.00	0.00	0.00
MgO	0.14	0.38	0.00	0.00	0.00	0.00	0.30	0.90	0.69	0.00	0.00	0.00	0.00	0.00	0.00
CaO	0.38	0.06	0.00	0.00	0.00	0.00	0.80	0.80	0.94	0.00	0.00	0.00	0.00	0.00	0.00
Na_2O	4.74	4.73	0.00	0.00	0.00	0.00	5.60	1.30	4.11	0.00	0.00	0.00	0.00	0.00	0.00
K_2O	4.32	4.20	0.00	0.00	0.00	0.00	4.30	6.80	3.71	0.00	0.00	0.00	0.00	0.00	0.00
P_2O_5	0.02	0.00	0.00	0.00	0.00	0.00	0.11	0.11	0.04	0.00	0.00	0.00	0.00	0.00	0.00
Total	100.21	99.60	0.00	0.00	0.00	0.00	94.80	94.47	98.52	0.00	0.00	0.00	0.00	0.00	0.00
Nb	0.0	400.0	101.0	158.7	124.6	115.4	103.6	119.8	250.0	107.6	117.1	130.3	122.5	139.2	144.0
Zr	0.0	3000.0	951.7	1505.2	2100.1	979.6	801.5	769.9	1800.0	847.8	815.5	826.9	948.0	911.5	1013.0
Y	0.0	50.0	69.1	91.7	119.1	80.5	72.4	80.5	100.0	69.1	76.8	74.1	73.6	75.7	82.6
Sr	0.0	0.0	19.6	8.7	12.0	8.3	106.9	164.3	72.0	110.6	119.9	111.0	45.6	17.1	277.9
U	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Rb	0.0	205.0	143.0	212.1	177.4	167.5	106.5	137.6	56.0	108.9	116.3	117.3	110.1	98.1	104.6
Th	0.0	0.0	16.7	21.1	24.1	15.0	17.5	18.0	0.0	16.9	16.1	17.5	17.6	19.0	14.9
Pb	0.0	0.0	0.0	0.0	0.0	0.0	10.5	27.0	0.0	30.6	0.0	0.0	0.0	0.0	0.0
Ga	0.0	0.0	32.9	36.5	34.0	33.8	27.8	30.0	0.0	30.6	28.6	31.4	27.3	32.5	36.0
Zn	0.0	199.0	61.2	84.8	259.1	157.3	136.7	74.8	200.0	93.5	92.4	51.9	82.6	87.8	117.7
Ni	0.0	25.0	2.9	2.5	2.5	1.4	1.9	1.8	10.0	0.5	1.9	1.8	1.6	0.2	2.9
Cr	0.0	0.0	0.0	0.5	3.7	0.0	4.0	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
V	0.0	0.0	0.7	27.4	0.0	0.0	12.0	15.0	20.0	2.3	3.9	2.4	3.2	0.6	18.0
La	0.0	0.0	68.8	67.4	63.6	57.1	151.2	146.7	0.0	120.2	108.4	85.1	105.8	96.0	89.8
Ce	0.0	0.0	160.8	169.8	153.4	139.0	309.9	285.5	0.0	270.9	240.3	200.1	217.8	212.5	210.3
Nd	0.0	0.0	81.7	101.7	81.0	73.2	134.2	129.3	0.0	128.3	115.8	100.9	109.5	99.2	106.1
Ba	0.0	245.0	483.5	181.1	381.8	234.8	947.0	1618.0	425.0	887.0	876.4	636.5	556.6	425.8	1031.1
Ga/Al	0.0	0.0	0.0	0.0	0.0	0.0	3.8	3.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Zr+Nb+Ce+Y	0.0	3450.0	0.0	0.0	0.0	0.0	1286.3	1255.7	2150.0	0.0	0.0	0.0	0.0	0.0	0.0
(Alk/CaO)	23.8	148.8	0.0	0.0	0.0	0.0	12.4	10.1	8.5	0.0	0.0	0.0	0.0	0.0	0.0
FeOt/MgO	25.9	0.0	0.0	0.0	0.0	0.0	9.1	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Zr+Y+Ce	0.0	3050.0	1181.6	1750.3	2372.6	1068.4	1984.8	1135.6	1900.0	1187.8	1132.3	1101.1	1241.4	1199.7	1305.9
Rb/Ba	0.0	0.0	0.3	1.2	0.5	0.7	0.1	0.1	0.0	0.1	0.1	0.2	0.2	0.2	0.1
Zr+Nb+Ce+Y	0.0	3450.0	1283.0	1909.0	2532.0	1315.0	2089.0	1256.0	2150.0	1295.4	1249.0	1231.0	1363.0	1339.0	1450.0
Al_2O_3/CNK	0.9	0.8	0.0	0.0	0.0	0.0	0.9	1.4	0.9	0.0	0.0	0.0	0.0	0.0	0.0
Al_2O_3/Alk	1.0	0.8	0.0	0.0	0.0	0.0	1.0	1.6	1.1	0.0	0.0	0.0	0.0	0.0	0.0
FeOt	3.58	3.50	0.00	0.00	0.00	0.00	2.70	1.80	3.38	0.00	0.00	0.00	0.00	0.00	0.00
Mg#															
Zr/Nb	0.0	7.5	9.4	9.5	16.9	8.5	7.7	6.4	7.2	7.9	7.0	6.3	7.7	6.5	7.0
Rb/Sr	0.000	0.000	7.296	24.379	14.783	20.181	0.996	0.837	0.778	0.985	0.970	1.057	2.414	5.737	0.377
K/Rb	0	170	0	0	0	0	335	410	550	0	0	0	0	0	0
K/Ba	0.0	142.3	0.0	0.0	0.0	0.0	37.7	34.9	72.5	0.0	0.0	0.0	0.0	0.0	0.0
den															

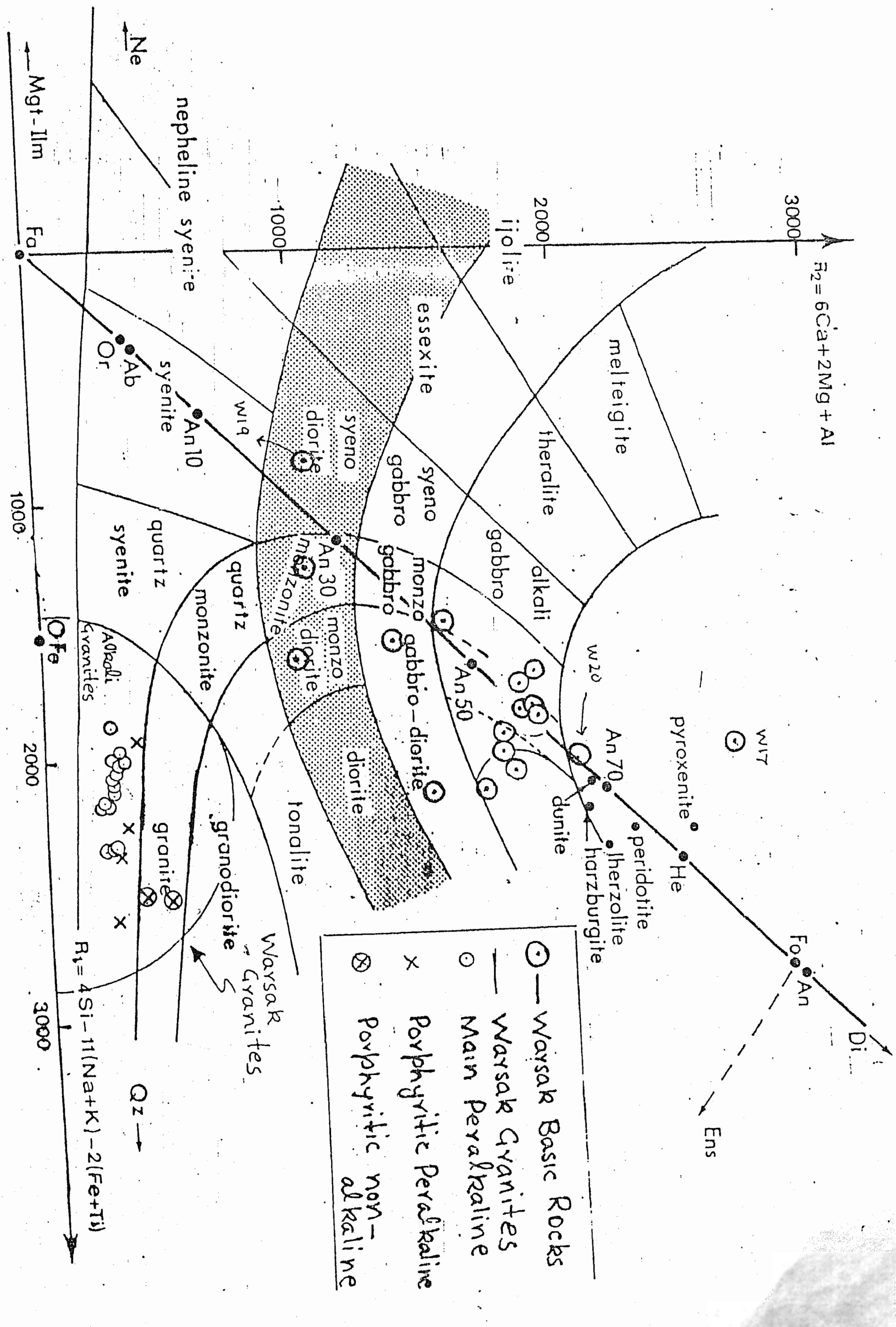
T28 T29 T45 T46 T32 T33 T37 T40 T41 T42 Major elements not analysed.

File name A:WSKGNT.ROC

Sample	W42	W51	W53	Kempe6	T47	T48	T49
Group #	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Qual	1	1	1	1	1	1	1
Key	1	1	1	1	1	1	1
Ref	1	1	1	1	1	1	1
SiO_2	73.00	75.00	68.00	76.77	0.00	0.00	0.00
TiO_2	0.42	0.50	0.61	0.41	0.00	0.00	0.00
Al_2O_3	13.00	12.00	13.00	11.79	0.00	0.00	0.00
Fe_2O_3	3.00	3.00	4.10	1.56	0.00	0.00	0.00
MnO	0.10	0.08	0.12	0.09	0.00	0.00	0.00
MgO	0.30	0.40	0.65	0.38	0.00	0.00	0.00
CaO	0.20	0.03	0.50	0.03	0.00	0.00	0.00
Na_2O	4.00	4.00	5.50	4.24	0.00	0.00	0.00
K_2O	5.00	5.00	2.90	4.33	0.00	0.00	0.00
P_2O_5	0.04	0.04	0.08	0.01	0.00	0.00	0.00
Total	99.06	100.05	95.46	99.61	0.00	0.00	0.00
Nb	123.2	120.6	109.7	200.0	128.0	113.8	122.9
Zr	990.1	1098.2	813.2	1500.0	988.2	1051.4	1096.1
Y	80.2	86.3	68.9	80.0	77.3	72.5	79.7
Sr	10.1	11.7	36.3	0.0	101.5	4.2	15.9
U	1.5	2.5	1.0	0.0	0.0	0.0	0.0
Rb	120.9	122.2	69.0	110.0	179.0	107.1	106.2
Th	19.5	35.0	16.0	0.0	17.8	18.2	18.5
Pb	19.0	10.5	19.5	0.0	0.0	0.0	0.0
Ga	31.7	27.5	28.8	0.0	33.1	33.4	33.4
Zn	164.3	110.2	140.8	62.0	62.0	149.6	124.7
Ni	1.7	3.2	4.3	25.0	3.8	1.5	1.8
Cr	3.0	8.0	9.0	0.0	1.7	0.0	0.0
V	6.0	10.0	17.0	0.0	8.2	0.0	0.0
La	99.5	0.0	96.5	0.0	71.2	80.3	82.6
Ce	215.1	383.9	207.4	0.0	175.8	179.4	194.8
Nd	96.9	189.1	93.4	0.0	87.3	88.0	97.6
Ba	454.0	491.0	728.0	555.0	1110.0	404.4	256.5
Ga/Al	4.6	4.3	4.2	0.0	0.0	0.0	0.0
Zr+Nb+Ce+Y	1408.6	1689.0	1199.2	0.0	0.0	0.0	0.0
(Alk/CaO)	45.0	300.0	16.8	0.0	0.0	0.0	0.0
FeO*/MgO	9.1	6.8	5.7	3.7	0.0	0.0	0.0
Zr+Y+Ce	1984.8	1568.4	882.1	1580.0	1241.3	1303.3	1370.6
Rb/Ba	0.1	0.3	0.1	0.0	0.2	0.3	0.4
Zr+Nb+Ce+Y	1408.0	1688.0	992.0	1780.0	1369.0	1417.0	1494.0
Al_2O_3/CNK	1.1	1.0	1.0	1.0	0.0	0.0	0.0
Al_2O_3/Alk	1.1	1.0	1.1	1.0	0.0	0.0	0.0
FeO*	2.70	2.70	3.69	1.40	0.00	0.00	0.00
Mg#							
Zr/Nb	8.0	9.1	7.4	7.5	7.7	9.2	8.9
Rb/Sr	11.911	10.489	1.899	0.000	1.764	25.500	6.679
K/Rb	343	340	349	327	0	0	0
K/Ba	91.4	84.5	33.1	64.8	0.0	0.0	0.0
den							

T47 T48 T49 Major elements not analysed.

Figure (3.1). Classification and nomenclature of the Warsak granites using scheme of La Roche et al. (1980).



$R_2 = 6Ca + 2Mg + Al$
3000
2000
1000
$R_1 = 4Si - 11(Na+K) - 2(Fe+Ti)$
Mgt-Ilm
Ne
Qz
Di
Ens
Fo
An
He
An70
An50
An30
An10
Ab
Or
Fa
Fe
melteigite
ijolite
theralite
essexite
alkali gabbro
gabbro
pyroxenite
peridotite
lherzolite
harzburgite
dunite
nepheline syenite
syenite
syeno gabbro
syeno diorite
monzo gabbro
monzo diorite
monzonite
gabbro-diorite
diorite
tonalite
quartz syenite
quartz monzonite
granodiorite
granite
Alkali Granites
Warsak Granites
W17
W19
W20
Warsak Basic Rocks
Warsak Granites
Main Peralkaline
Porphyritic Peralkaline
Porphyritic non-alkaline

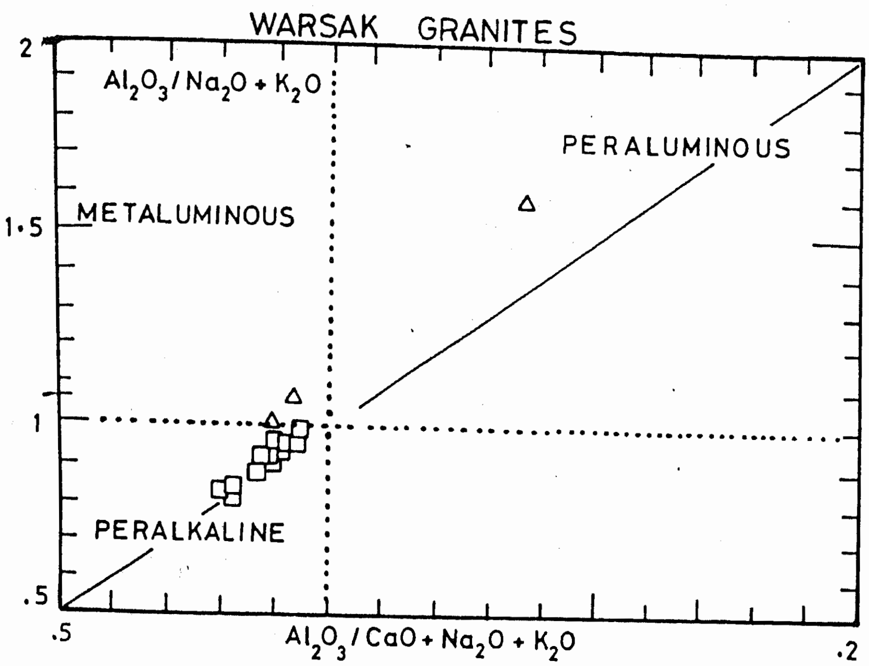
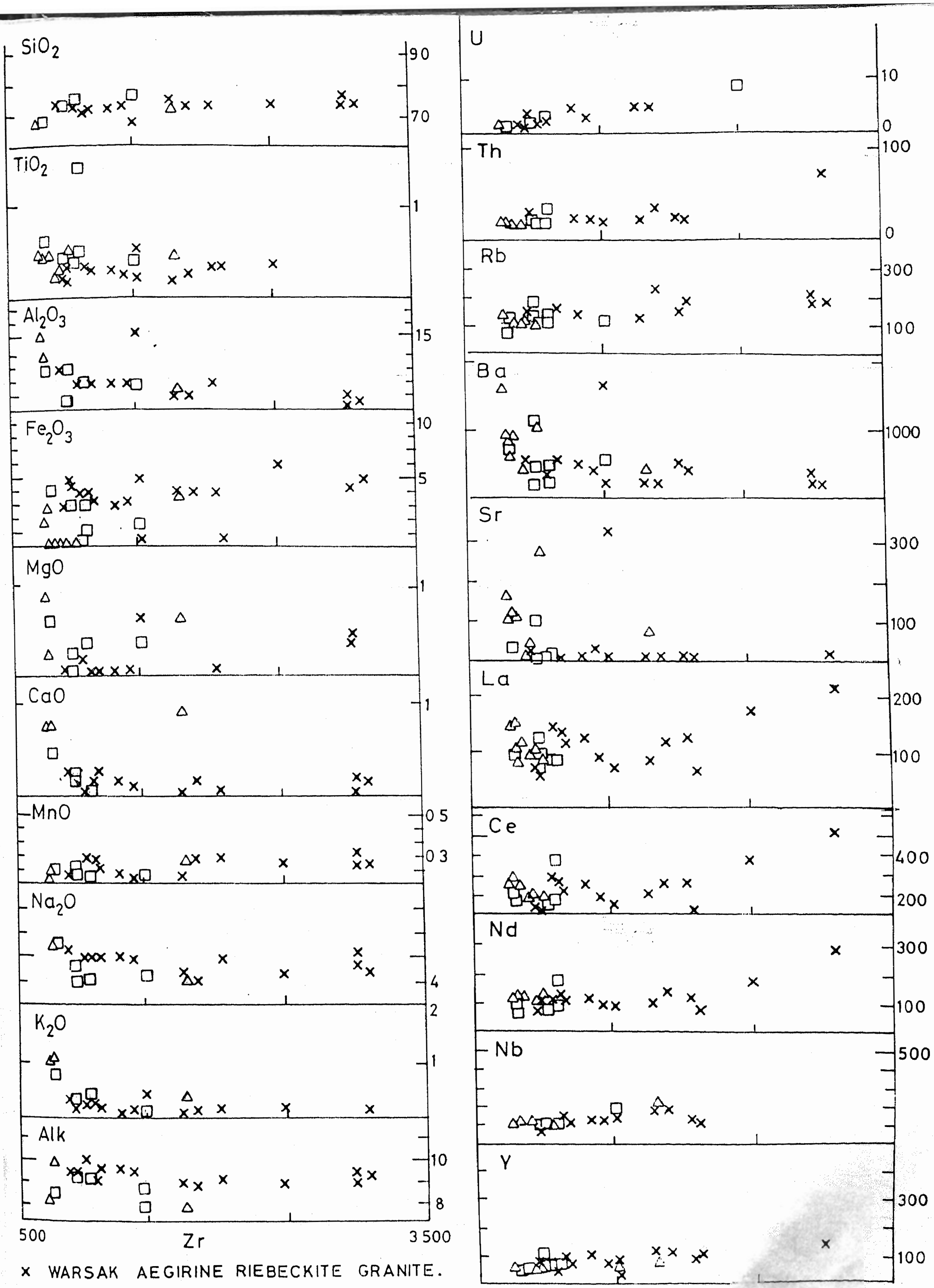


Figure (3.2). Classification of the Warsak granites on the basis of Shand's Indices (After Maniar and Piccoli, 1989).

Figure (3.3). Variation in major and trace elements in the Warsak granites with increasing degree of fractionation.



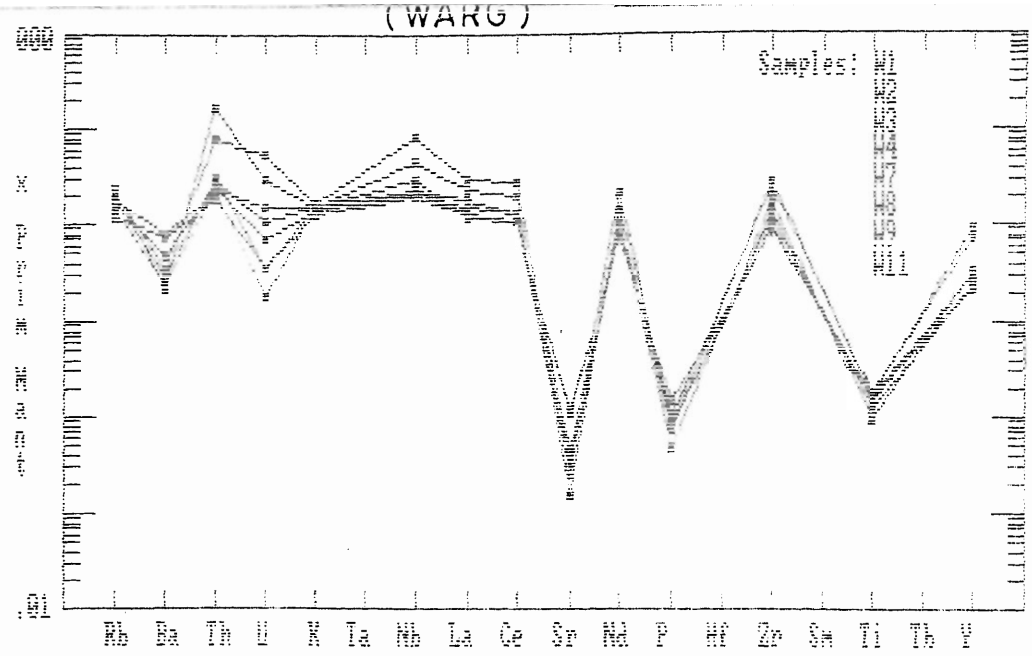
× WARSAK AEGIRINE RIEBECKITE GRANITE.

△ WARSAK PORPHRITIC AEGIRINE RIEBECKITE GRANITE.

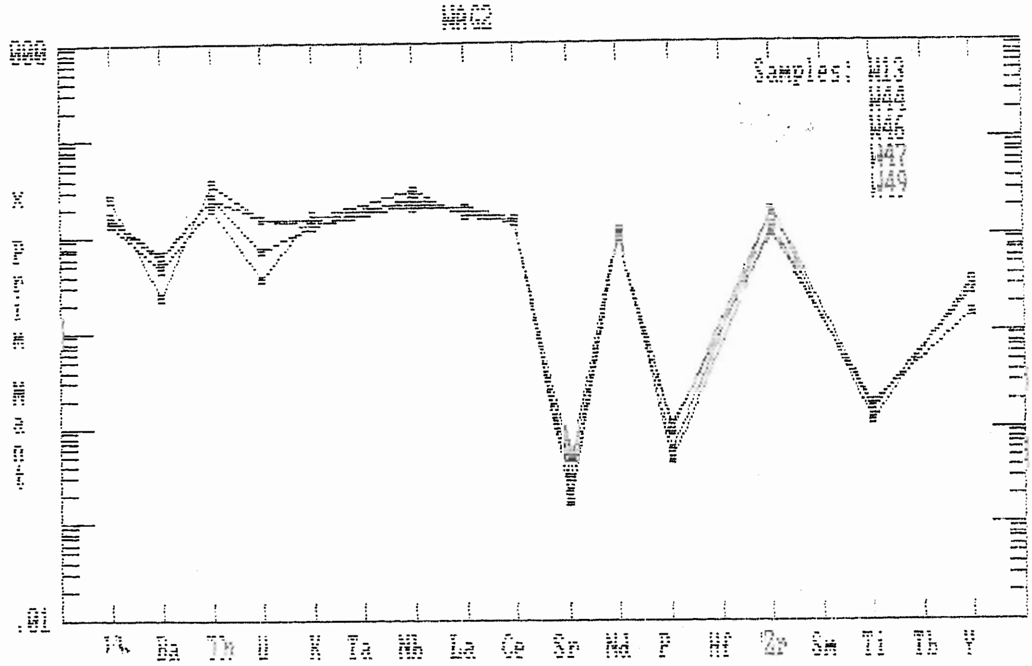
□ WARSAK BIOTITE MUSCOVITE GRANITE.

igure (3.4). Mantle-normalised trace element patterns of the three arieties of granites from Warsak for a mutual comparison.

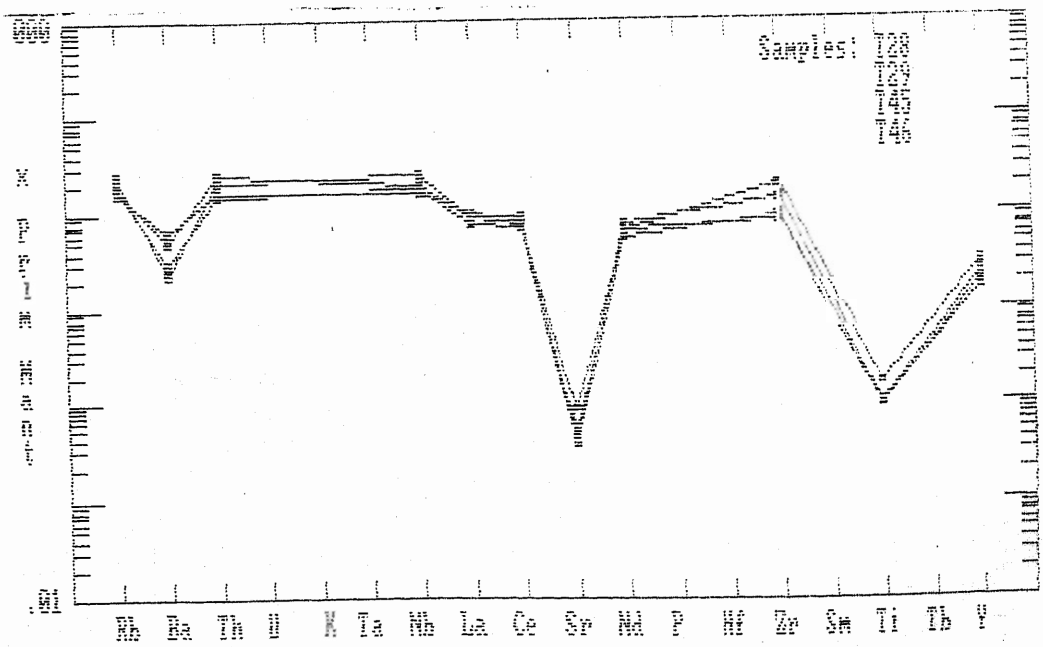
MARG	A_1, A_2, A_3
PARG	B_1, B_2
PBMG	C_1, C_2


(WARG)
Samples: W1
W2
W3
W4
W7
W8
W9
W11
Rb
Ba
Th
U
K
Ta
Nb
La
Ce
Sr
Nd
P
Hf
Zr
Sm
Ti
Tb
Y
.01

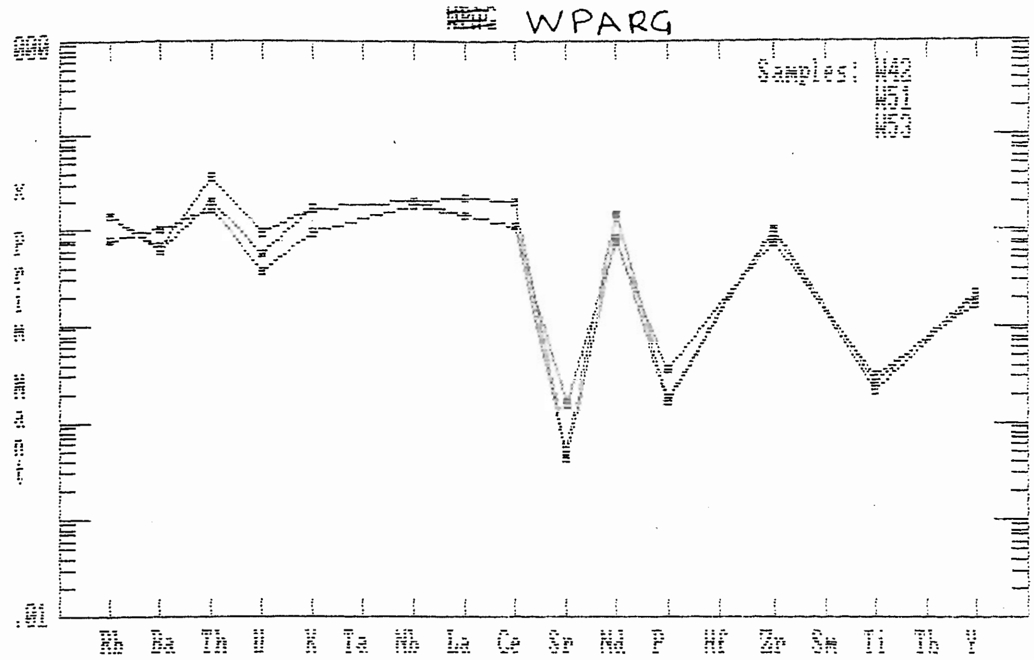
A-1


WAG2
Samples: W13
W44
W46
W47
W49
Ba
Th
U
K
Ta
Nb
La
Ce
Sr
Nd
P
Hf
Zr
Sm
Ti
Tb
Y
.01

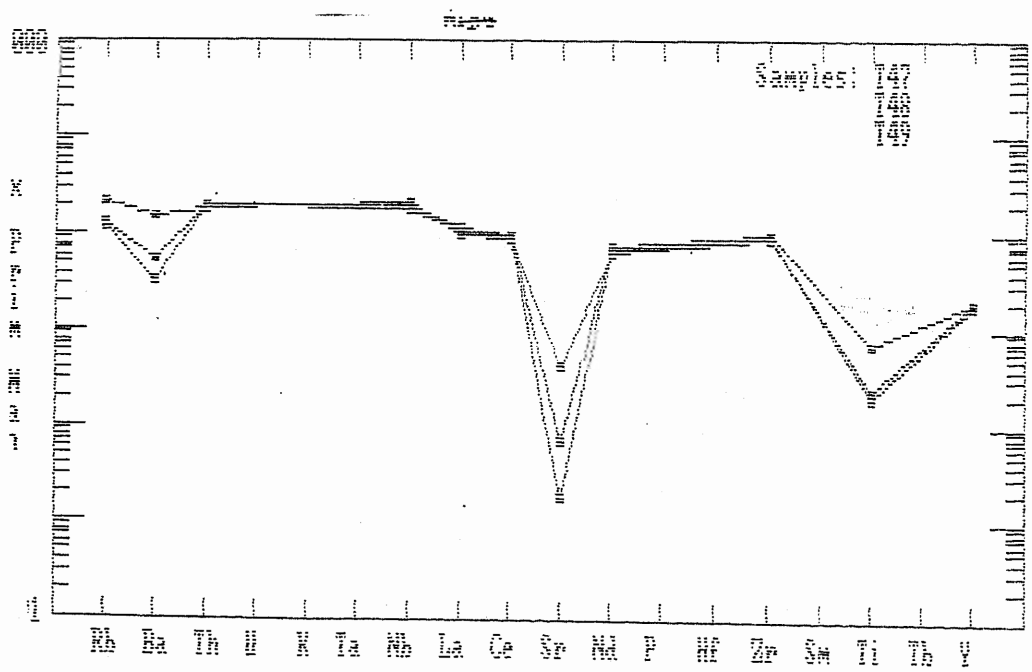
A-2


Samples: T28
T29
T45
T46
Rb
Ba
Th
U
K
Ta
Nb
La
Ce
Sr
Nd
P
Hf
Zr
Sm
Ti
Tb
Y
.01

A-3

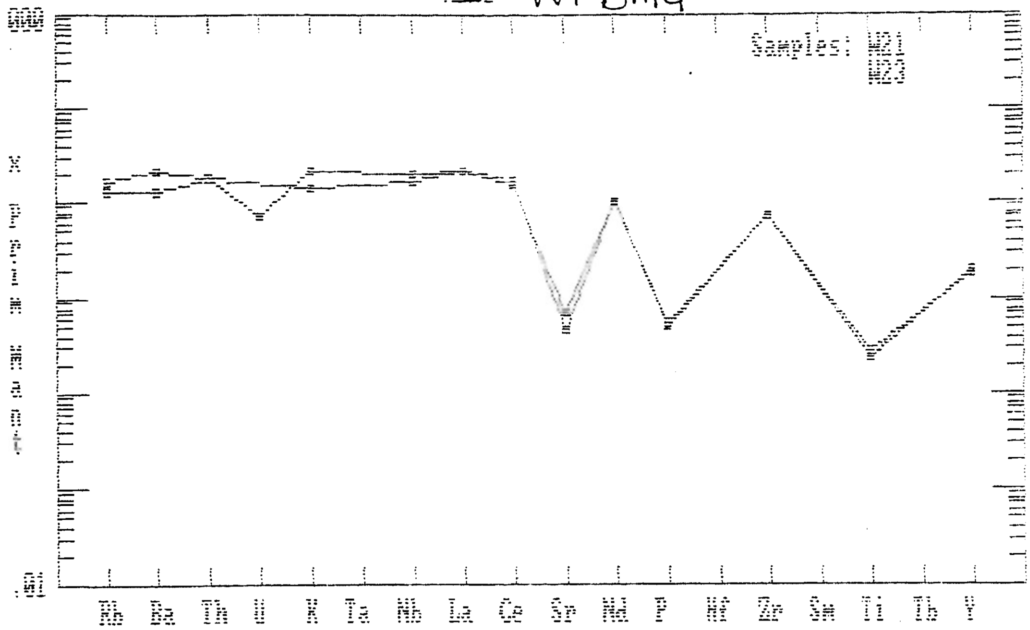

WPARG
Samples: W42
W51
W53
x Prim Mant
.01
Rb Ba Th U K Ta Nb La Ce Sr Nd P Hf Zr Sm Ti Tb Y

B-1

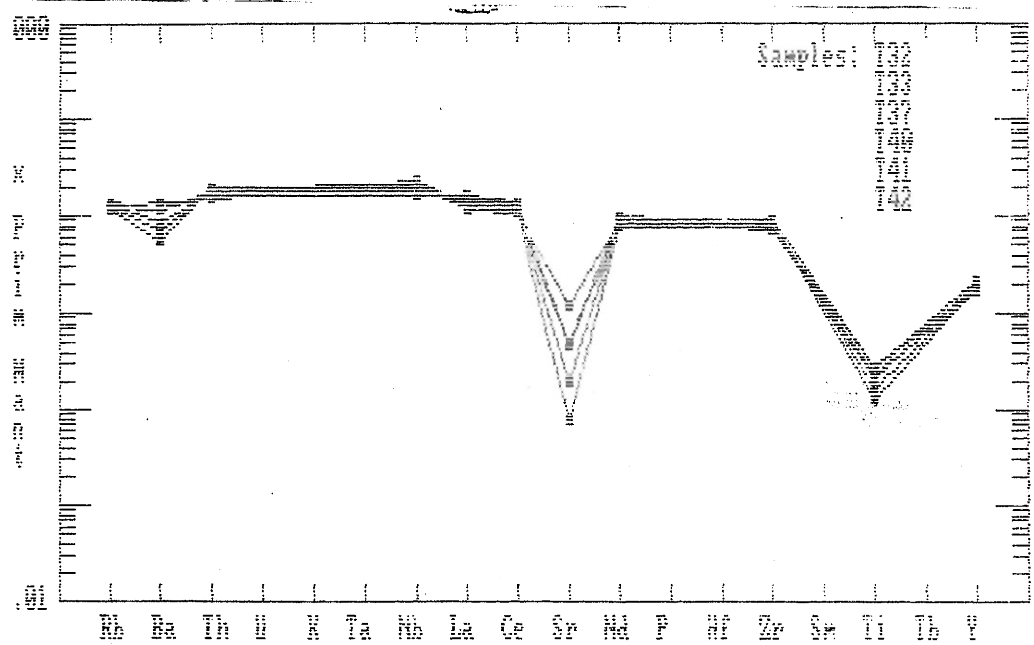

Samples: T47
T48
T49
x Prim Mant
Rb Ba Th U K Ta Nb La Ce Sr Nd P Hf Zr Sm Ti Tb Y

B-2

WPBMG


1000
x Primitive Mantle
.01
Samples: W21
W23
Rb Ba Th U K Ta Nb La Ce Sr Nd P Hf Zr Sm Ti Tb Y

C-1

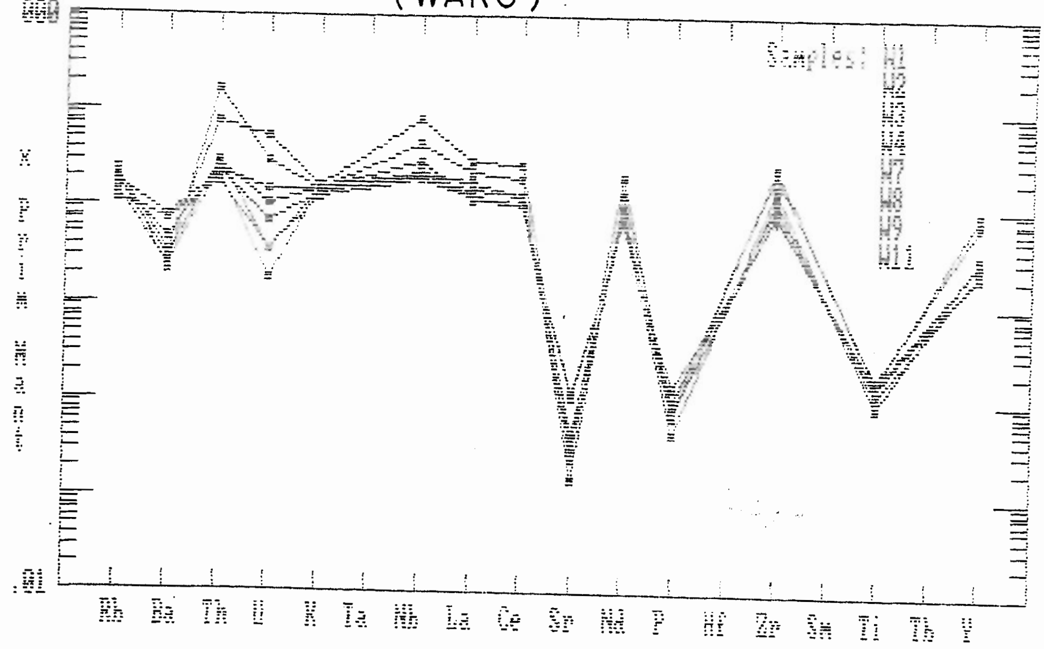

1000
x Primitive Mantle
.01
Samples: T32
T33
T37
T40
T41
T42
Rb Ba Th U K Ta Nb La Ce Sr Nd P Hf Zr Sm Ti Tb Y

C-2

Figure (3.5). Mantle-normalised trace element patterns of the Warsak granites compared with type granites from within-plate settings, including continental granites (Skaergaard, Mull, and Sabalokha) and rift-related granites (Oslo rift, and Ascension island). The Warsak granites are particularly similar to the granites from the Ascension islnad. Data are from Pearce et al. (1984).

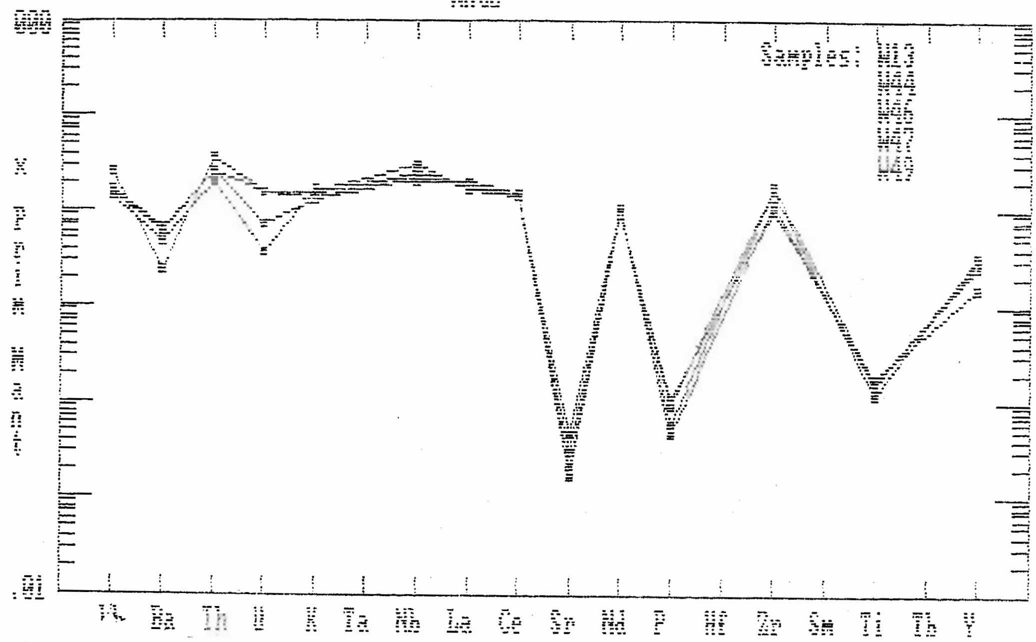
WG	A_1, A_2, A_3
WPG	E_1, E_2, E_3
ORG	B
VOLG	C
CALLG	D

(WARG)

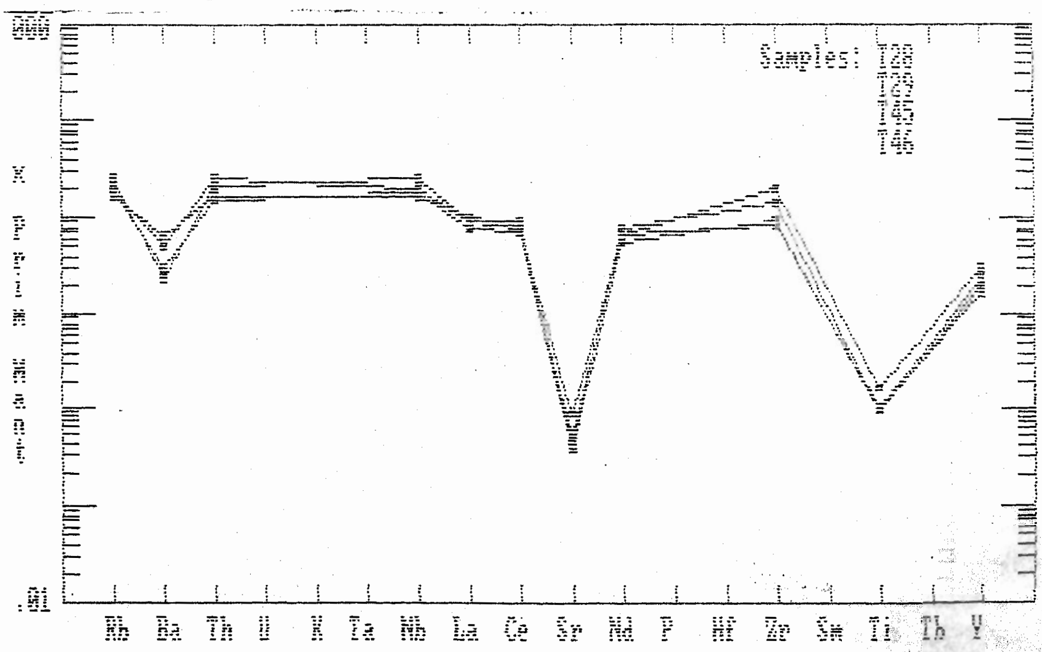


A-1

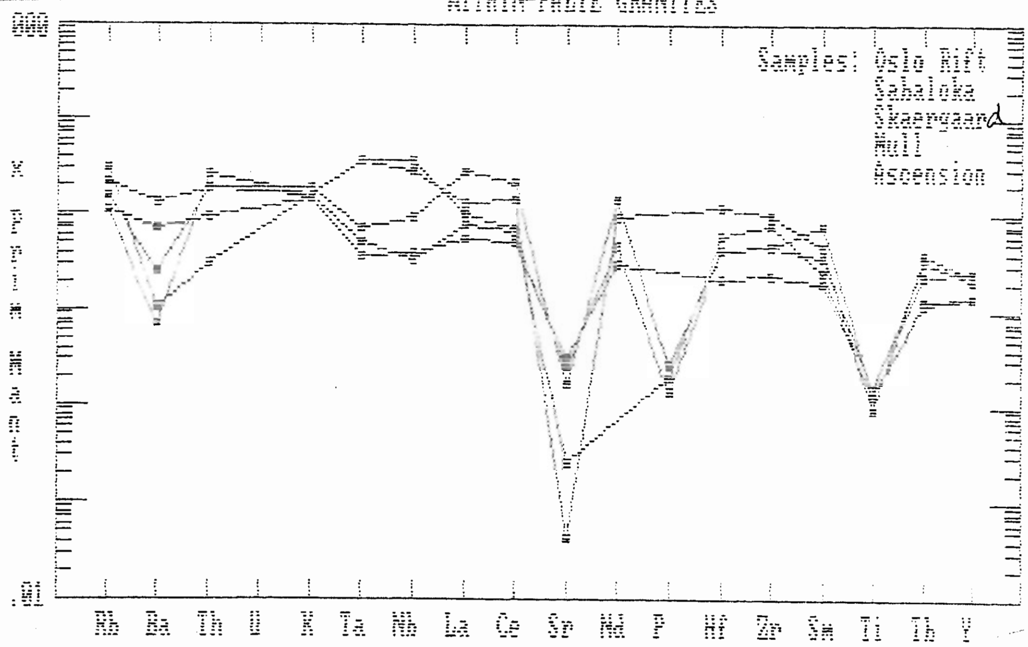
WAG2



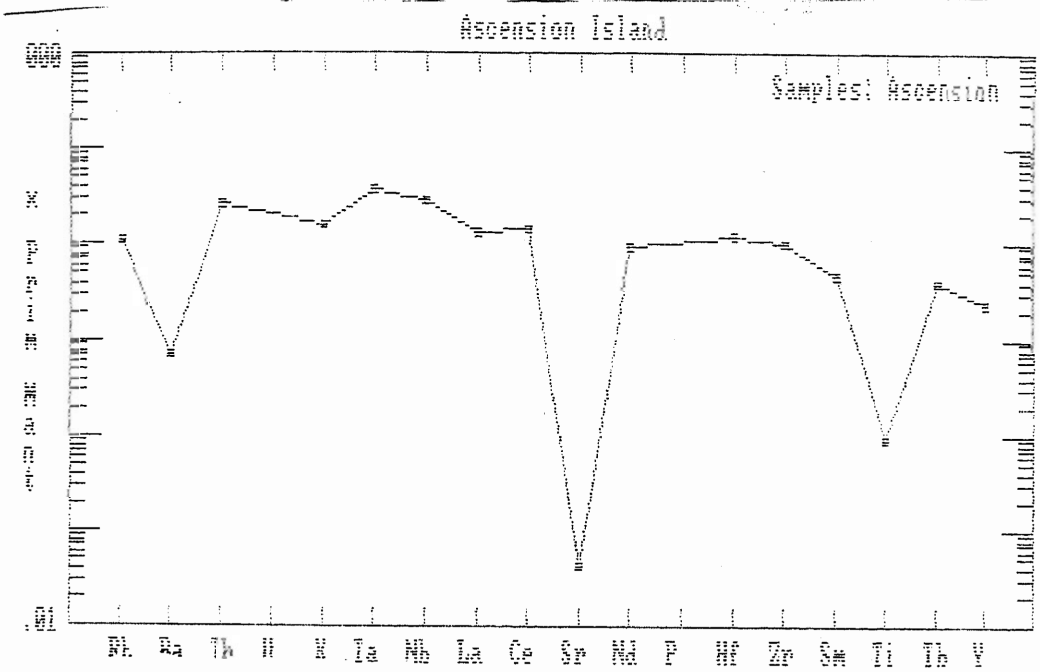
A-2



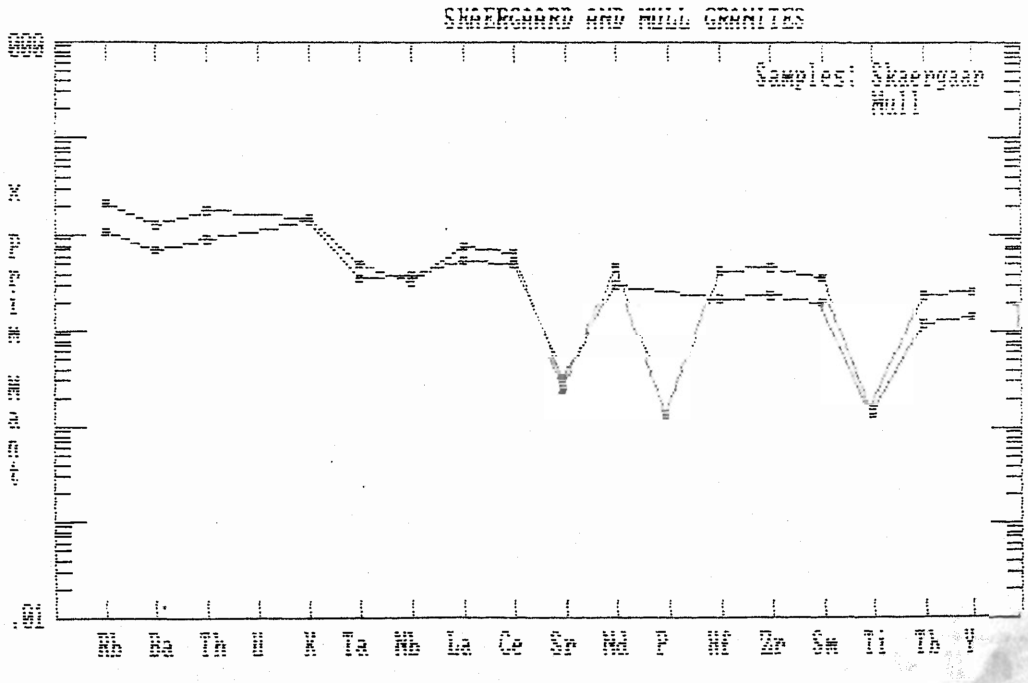
A-3


Samples: Oslo Rift
Sabaloka
Skaergaard
Mull
Ascension
000
x Prim Mant
.01
Rb Ba Th U K Ta Nb La Ce Sr Nd P Hf Zr Sm Ti Tb Y

E-1

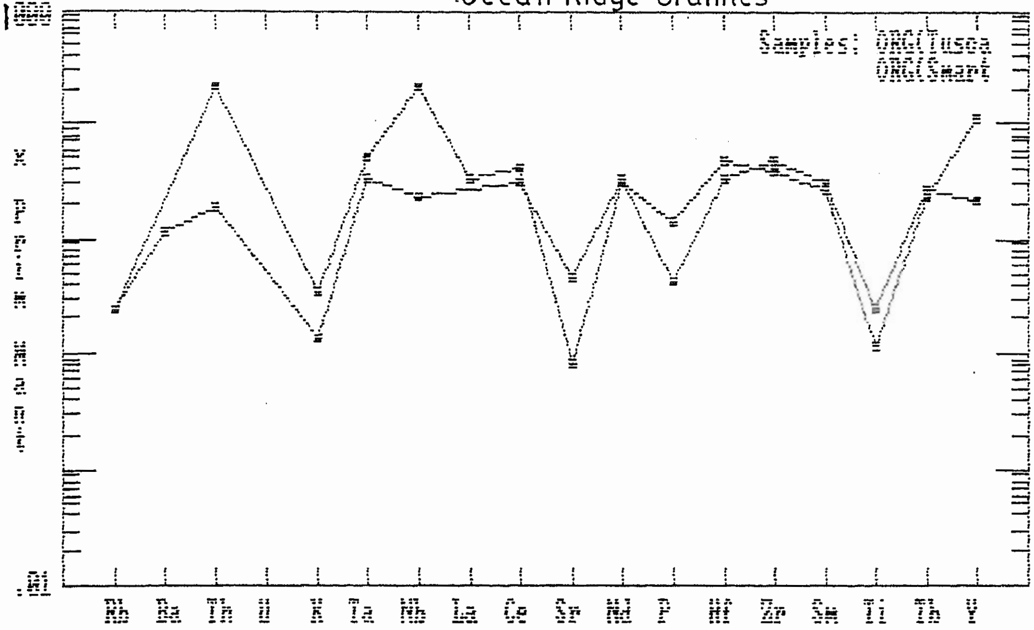

Ascension Island
Samples: Ascension
000
x Prim Mant
.01
Rb Ba Th U K Ta Nb La Ce Sr Nd P Hf Zr Sm Ti Tb Y

E-2


SKAERGAARD AND MULL GRANITES
Samples: Skaergaar
Mull
000
x Prim Mant
.01
Rb Ba Th U K Ta Nb La Ce Sr Nd P Hf Zr Sm Ti Tb Y

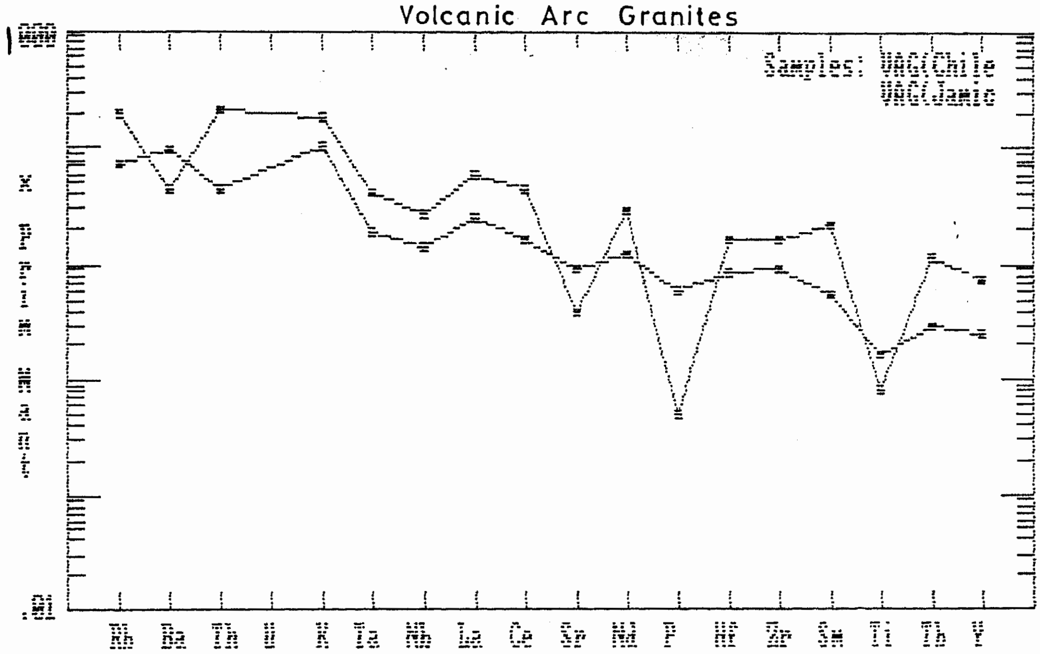
E-3

Ocean Ridge Granites



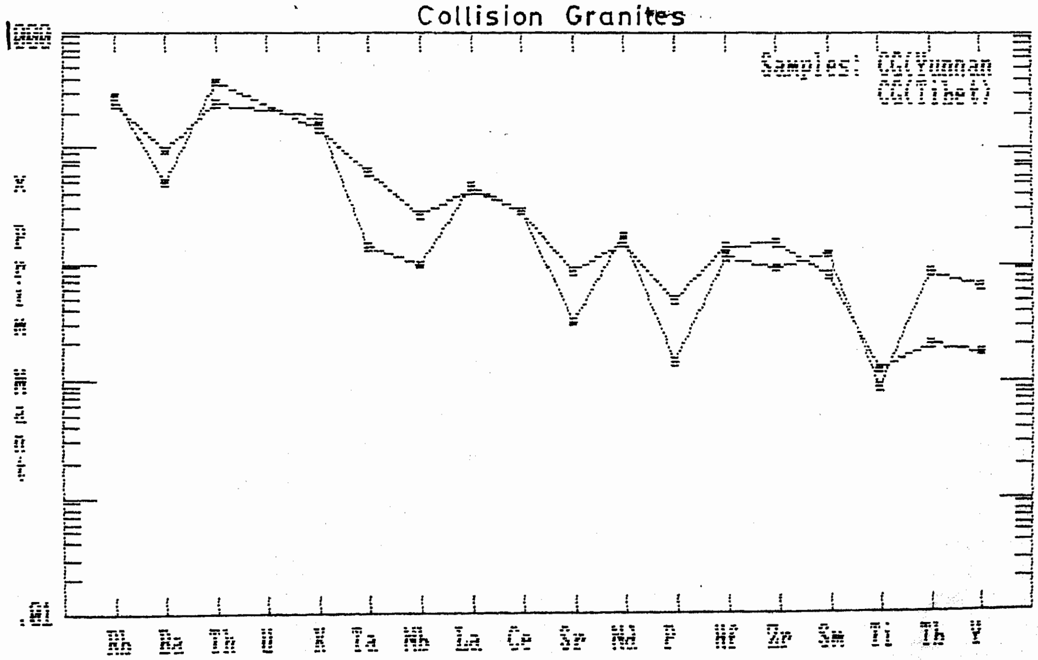
B

Volcanic Arc Granites



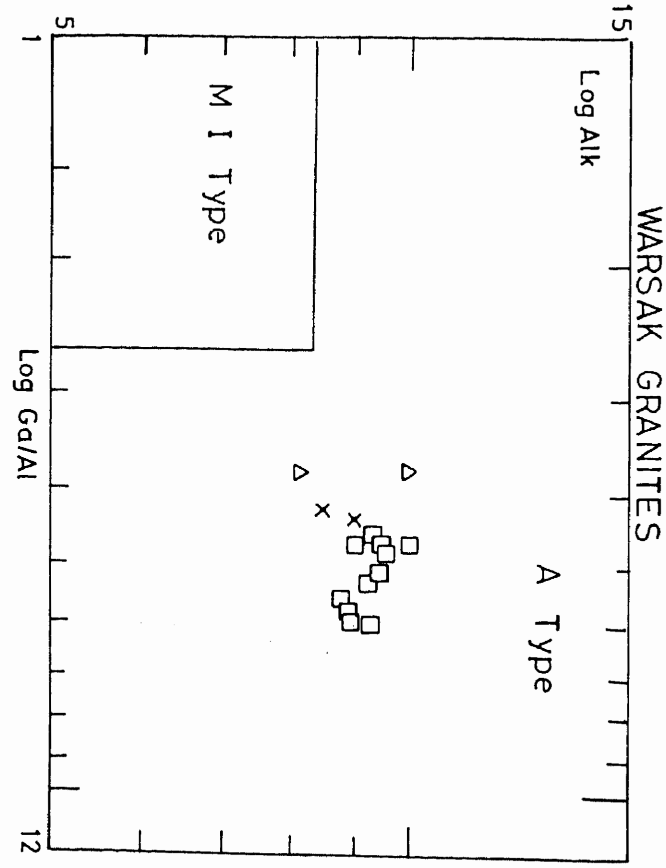
C

Collision Granites

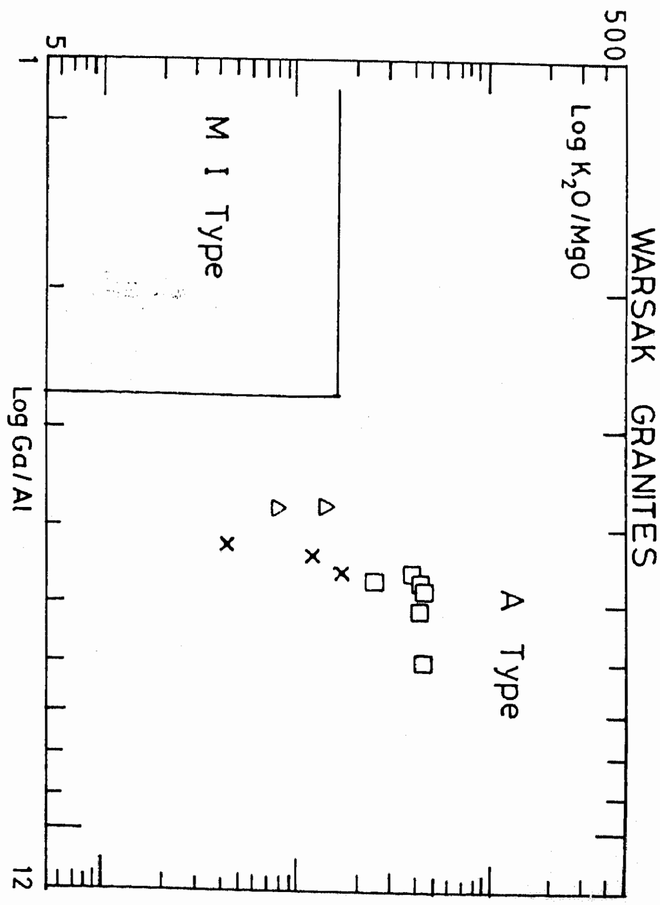


D

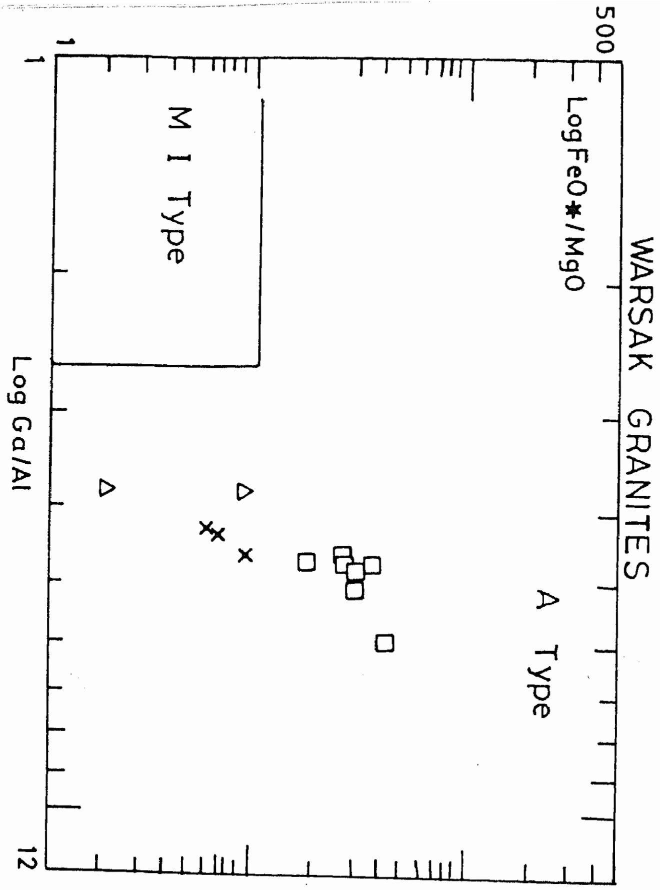
Figure (3.6). Various diagrams based on trace elements (devised by Whalen et al., 1987) showing that the Warsak granites are A-type. The box at bottom left in each diagram encloses the position of M-, I-, and S-type granites.



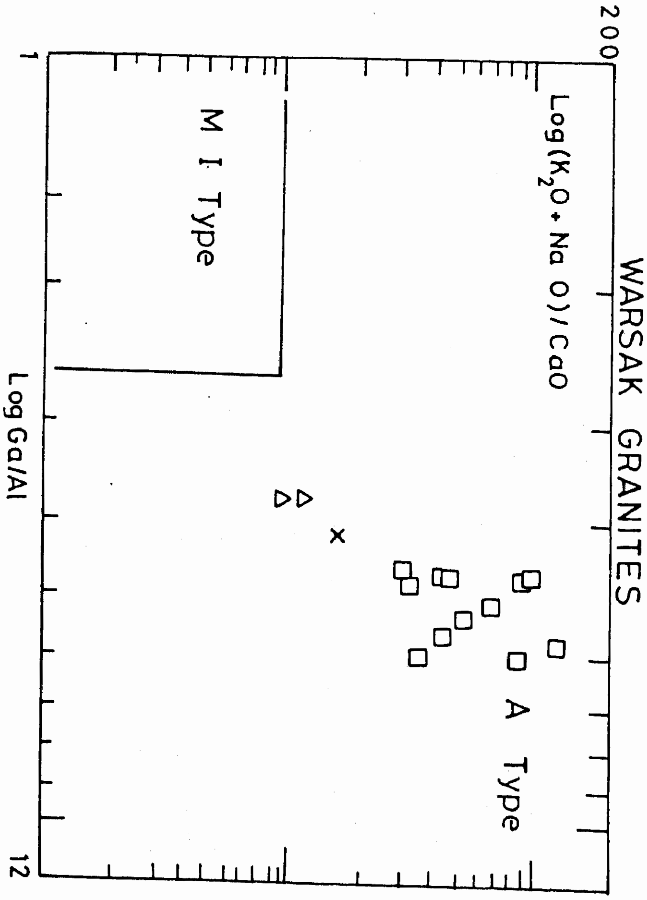
WARSAK GRANITES
Log Alk
15
5
1
12
Log Ga/Al
M I Type
A Type



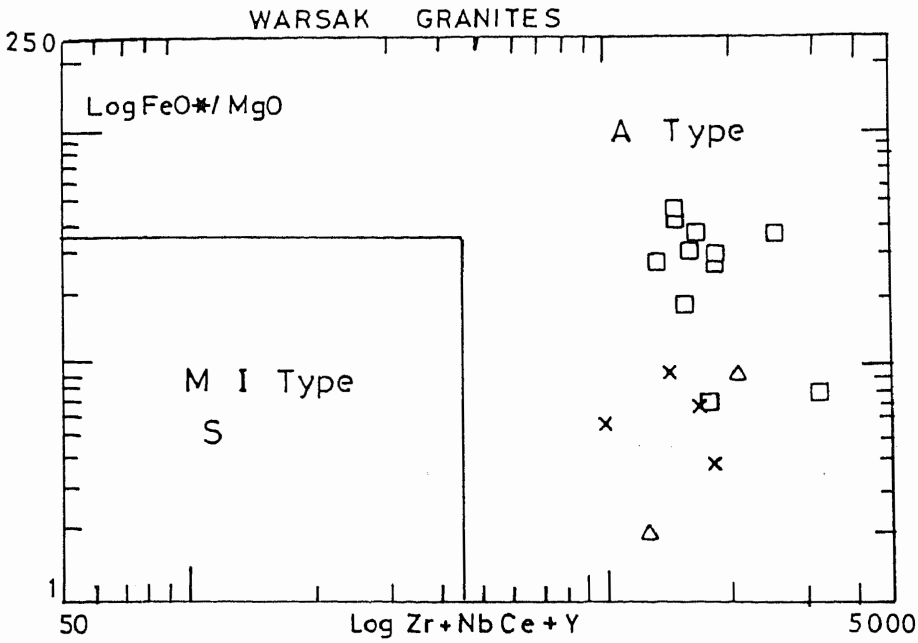
WARSAK GRANITES
Log K_2O/MgO
500
5
1
12
Log Ga/Al
M I Type
A Type

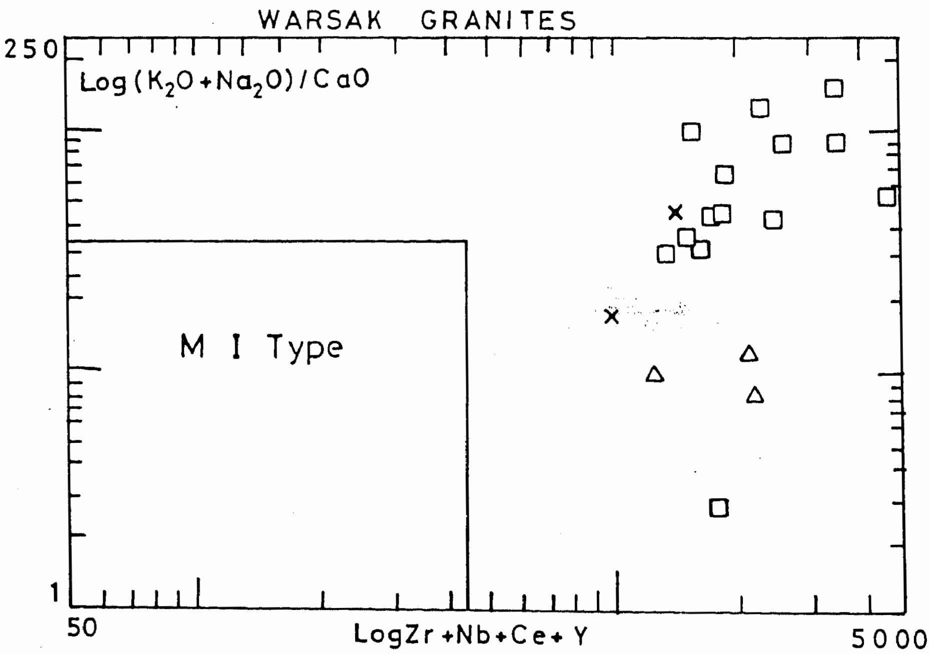


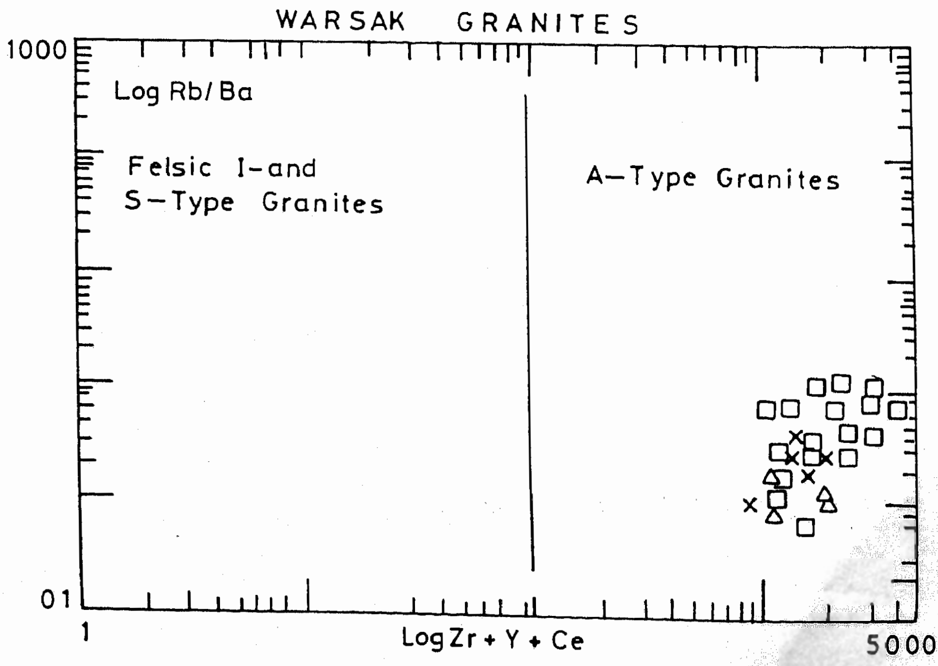
WARSAK GRANITES
Log FeO*/MgO
500
1
1
12
Log Ga/Al
M I Type
A Type

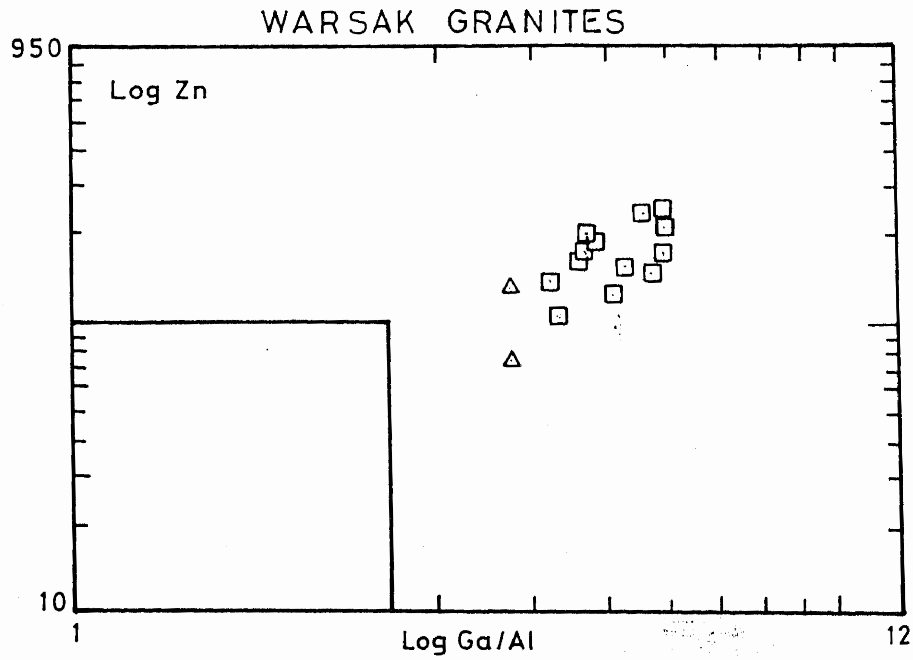


WARSAK GRANITES
Log (K_2O + Na O)/ CaO
200
1
12
Log Ga/Al
M I Type
A Type


WARSAK GRANITES
250
1
Log FeO*/ MgO
A Type
M I Type
S
50
Log Zr + Nb Ce + Y
5000


WARSAK GRANITES
250
1
Log (K2O + Na2O) / CaO
M I Type
50
LogZr + Nb + Ce + Y
5000


WARSAK GRANITES
1000
01
Log Rb/ Ba
Felsic I-and
S-Type Granites
A-Type Granites
1
LogZr + Y + Ce
5000



11

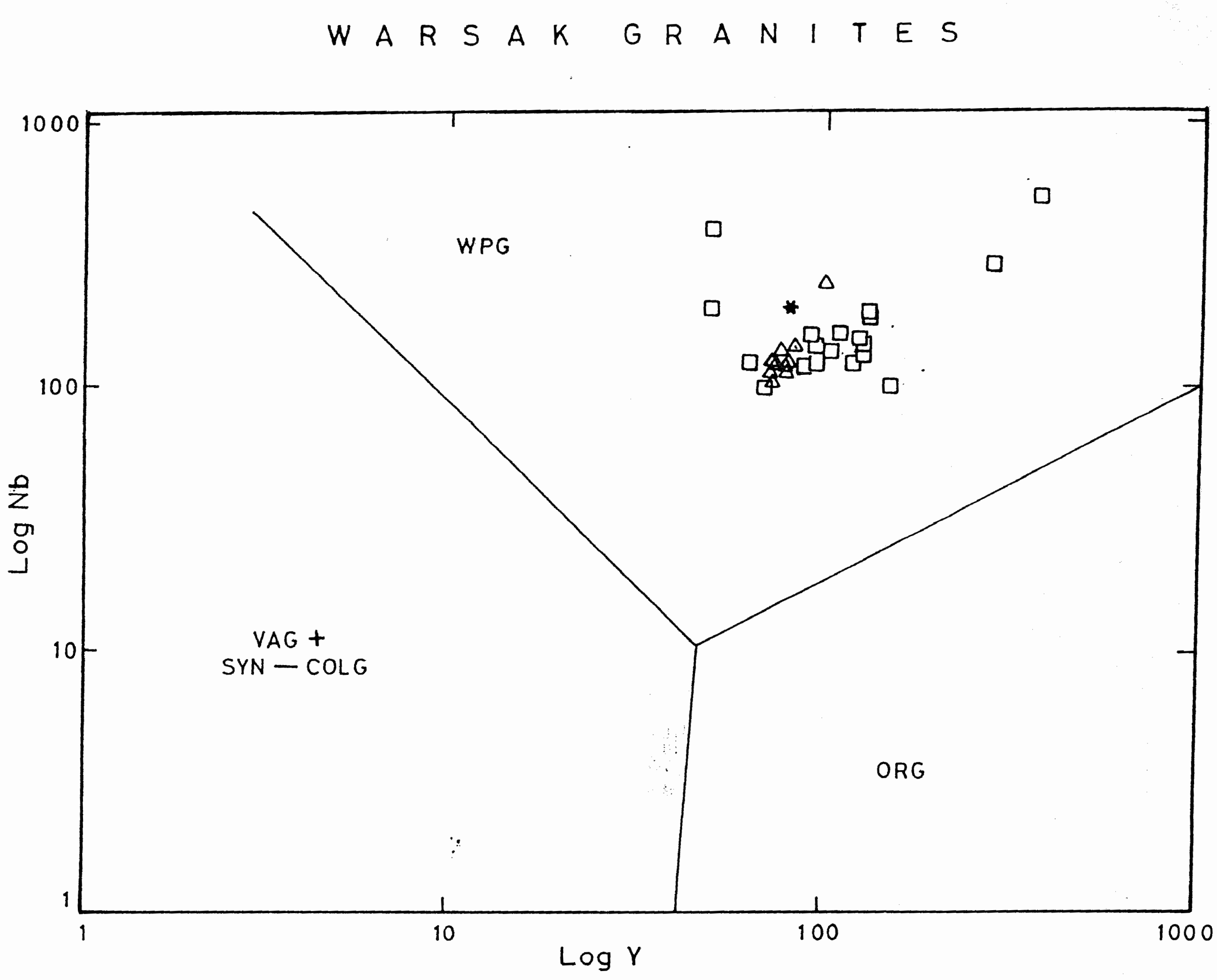


Figure (3.7). The Y Vs Nb Plot of Warsak granites showing that the warsak granites are WPG.

P A R T 2.

T H E W A R S A K B A S I C R O C K S

CHAPTER 4.

FIELD RELATIONS AND PETROGRAPHY

Introduction

The Warsak area has been traditionally famous for its two rock types: the granites and the marble (Coulson, 1939), both of which have been exploited for commercial gains. The Marble quarry near the Mullagouri village in the Warsak area is one of the oldest mine of high quality white marble. Whereas the granite at the Warsak has successfully been used as the site for the foundation for the Warsak dam. An equally voluminous rock type in the Warsak area, although of a little economic significance, is a microgabbro or dolerite. Ahmed et al. (1969) mapped these basic rocks in detail together with the granites and described their field features and petrography. Kempe (1978) described the Warsak basic rocks both in terms of petrography and geochemistry. This work re-evaluates the geochemistry of the Warsak basic rocks with particular emphasis on their tectonic significance. Prior to that, however, it is felt necessary to give a brief account of the field distribution, field features and petrography of these basic rocks. This account is mainly based on the work of Ahmed et al. (1969) and Kempe (1978), however, considerable observations are recorded during this work.

Field Distribution

Sheeted bodies of basic rocks concordant to the foliation in granites and bedding in the metasediments are common in the Warsak area, making about 50% by volume of the igneous complex. On the road leading to the Dam, the first outcrops near the village Ismail Kili are those of fine-grained dolerite. Alternating with the sheets of granites of porphyritic texture, there are two major sheets of basic rocks, 600 and 400 m wide respectively (Figure 4.1). Further to the west there are dozens of sheeted masses ranging in width from few metres to several tens of metres. The Warsak main granite at the damsite contains several basic sheets each few metres in width, apparently enclosed in the granite mass. Ahmed et al. (1969) have reported minor stock-like intrusions of basic rocks in the Warsak porphyritic granites to the north of the river.

In addition to the basic rocks of an unambiguous igneous origin, there are sheets of basic composition which are apparently volcaniclastic in origin. These rocks which have been interpreted to be metamorphosed tuffs by Kempe (1978) and mapped as accicular hornblende schists by Ahmed et al. (1969) make about 10% of the basic rocks. The sheets of these rocks are generally less than 10 m in width. occurring in alternation with sheets of granites and metasediments in a fashion similar to the main basic sheets of dolerite/microgabbro composition.

Field Features

The Warsak basic rocks are mainly fine grained and homogeneous. In one outcrop pillow-lava like structures are observed which are obliterated by shearing. At several places the fine-grained basic rocks grade into medium grained gabbros, apparently without any break. The larger bodies are commonly cut across by shear zones, whereas the smaller sheets are commonly wholly sheared, furnishing a distinct planar fabric to the rocks.

The basic rocks generally lack any xenoliths. Their contact relations with the adjacent granite sheets are also not clear, either being knife-edge sharp or sheared. Apophyses of the basic rocks extending into the granites or vice versa are rare. As mentioned earlier, at the damsite, sheets of basic rocks are seen enclosed in the granites. Reverse relations have been mapped by Ahmed et al. (1969), whereby basic bodies of circular shape are seen intrusive into the micrograníte (Figure 2.1). Thus it is generally not clear that whether the basic rocks are older than the granites or younger on the basis of field relations.

Petrography

The Warsak microgabbros, now metamorphosed to amphibolites are generally black to dark green in colour and black to greyish yellow on the weathered surface. As mentioned earlier some are highly sheared and thus are schistose in appearance. Others range from foliated to massive depending upon the degree of shearing. Amphibolitization is also controlled by degree of deformation; the sheared rocks are generally more metamorphosed than the homogeneous rocks.

The Warsak basic rocks are composed essentially of amphibole, plagioclase, epidote, quartz, biotite, sphene, ilmenite and rarely garnet. This mineralogy is typically found in the basic rocks now metamorphosed to amphibolites. Amphibole in these rocks occur as short prismatic grains, with a matrix comprising of plagioclases commonly altered to epidote either partly or wholly. In the sheared rocks all the amphibole prismatic grains are aligned together defining shear fabric. In such rocks quartz epidote and relict plagioclase are concentrated into bands alternating with amphibole rich bands. In some rocks two textural varieties of amphibole are observed; one short prismatic to tabular and other in thin prismatic grains of substantial lengths (up to 6 mm) running parallel to the foliation. Plagioclase, when relict occurs as untwined grains containing abundant tiny epidote grains as alteration product. In the sheared rocks plagioclase is generally recrystallised to smaller grains accompanied by abundant alteration to epidote. Quartz typically occur in small ameoboidal grains with undulatory extinction.

At several places the gabbroic rocks have escaped shearing and metamorphism yielding original igneous textures. There are certain rocks which are typical cumulates approaching ultramafic composition. In them there are large (4 x 4 mm in diameter) randomly oriented tabular crystals of clinopyroxene forming mosaics in which the interstices between the pyroxene crystals are occupied by post-cumulus plagioclase. In relatively unmetamorphosed gabbros both clinopyroxene and plagioclase are cumulus minerals, and it is only the magnetite and ilmenite and minor quartz which form post cumulus minerals. Unfortunately the proportions of the unmetamorphosed basic rocks are with original igneous mineralogy and textures intact are very small in the

Warsak Igneous Complex to determine the sequence of crystallisation of the constituent minerals. On the basis of limited number of fresh samples, it has been concluded that the earliest crystallising mineral in the Warsak basic rocks was clinopyroxene, followed or accompanied by orthopyroxene, followed by plagioclase, iron-titanium oxides, and quartz. This sequence of crystallisation of minerals is typical of tholeiitic basic suites.

Summary

The Warsak basic rocks, on the basis of present textures and mineralogy, can be classified as amphibolites. These amphibolite rocks are both homogeneous (static metamorphism) and sheared with a well-developed schistosity and comprise of prismatic amphibole and variably saussuritized plagioclase. Escaping the metamorphism and shearing, there are local relict of original igneous basic lithology, ranging in composition from pyroxenites to gabbros. Cumulate textures suggest that clinopyroxene was the first mineral crystallising in the Warsak igneous complex, followed by orthopyroxene, plagioclase, iron-titanium oxides and quartz; a crystallising sequence commonly observed in the basic suites of tholeiitic composition.

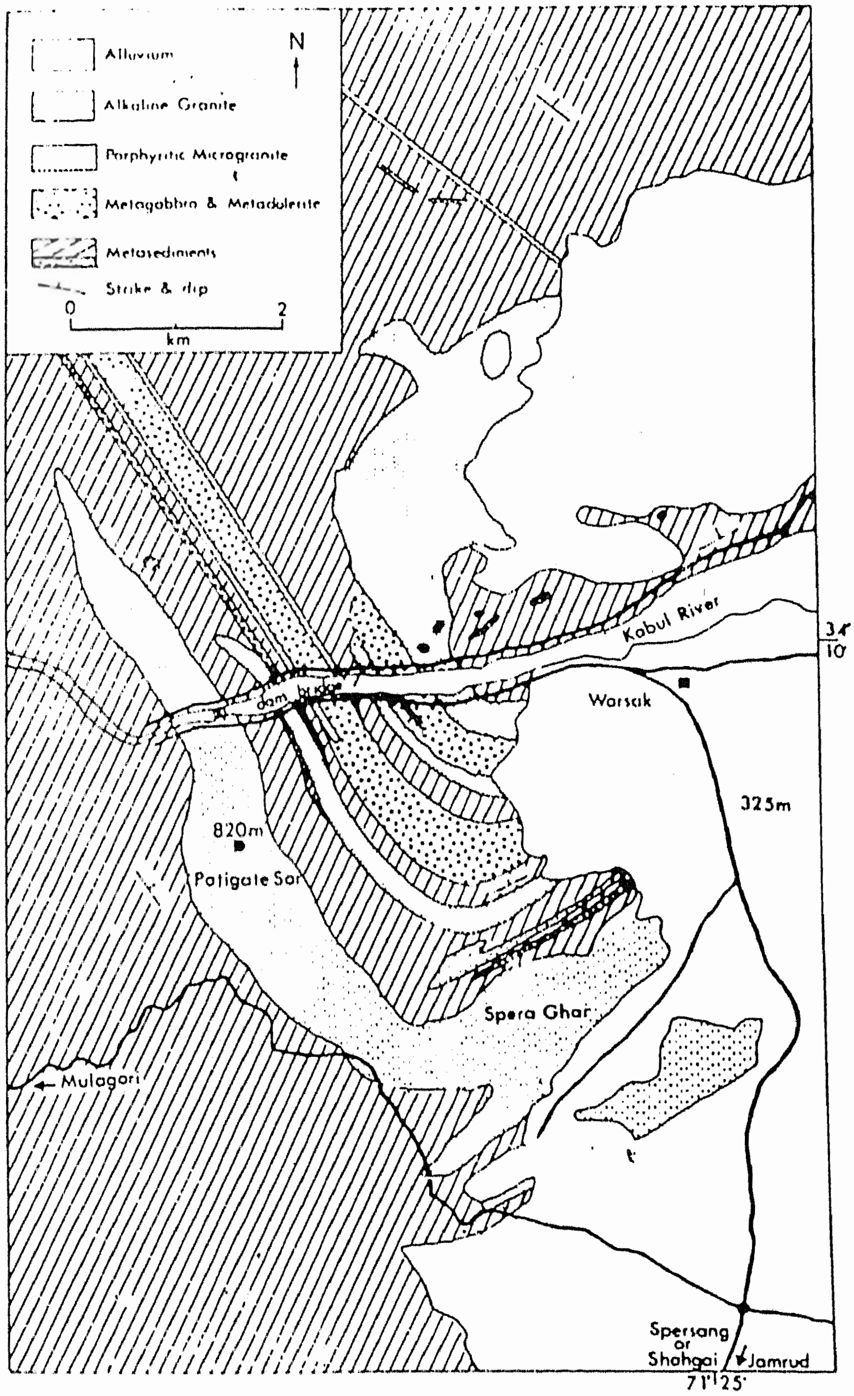


Figure (2.1.). Geological map of the Warsak Igneous Complex, simplified after Ahmed et al. (1969).

CHAPTER 5.

GEOCHEMISTRY, TECTONIC SETTING, AND PETROGENESIS

Introduction

Geochemistry, based on a limited number of samples have previously been carried out by Kempe (1978). His work concluded that the Warsak basic rocks belong to a calc-alkaline series, closely comparable and possibly related to the calc-alkaline basic rocks of Kohistan such as the pyroxene granulites (Kempe and Jan, 1973b, Jan, 1977) later termed as the Chilas Complex (Jan et al., 1984; Khan et al., 1989). This is, however, at variance with the position of the Warsak area as the northern margin of the Indian plate. So far three types of basic rocks have been reported in the northern margin of the Indian plate in the areas around Peshawar. Alkaline basic rocks such as those exposed at Tarbela are example of the one type. Tholeiitic dolerite dykes and sills intruding the Precambrian to Palaeozoic metasedimentary sequence in the hill ranges of N. Pakistan make the second variety of the basic rocks exposed around Peshawar. The basic rocks of the third type are ophiolitic in nature and are found in tectonic Killippes such as that of Dargai. In this chapter whole-rock geochemistry is used to precisely define the nature of the Warsak basic rocks, particularly in terms of their tectonic setting of origin and relationship with the varieties of basic rocks found around Peshawar.

In Table (5.1) twenty seven samples are listed of which 17 are analysed for both major and trace elements, whereas 10 are analysed only for the trace elements. All the analyses were carried out on a Philips spectrometer using pressed powder pellets. Five analyses previously published by Kempe (1978) are listed in Table (5.1) and are used in subsequent plots.

Classification

Since the Warsak basic rocks are generally metamorphosed, their modal mineralogy classifying them as amphibolites does not yield much information about their original igneous nomenclature. La Roche et al. (1980) and Cox et al. (1979) have proposed classification schemes which are based on major elements and are thus particularly useful for rocks which are either fine grained or altered to that extent that original mineralogy is no more intact. Most of the Warsak basic rocks plot as a coherent group in the fields of various types of gabbros (including olivine gabbro, gabbronorite, and gabbrodiorite) in the classification diagram of La Roche et al. (1980) (Figure 5.1). There are two samples which plot in the field of ultramafic rocks; W20 near the position of dunite and W17, in the field of pyroxenites. Three samples are relatively feldspathic and plot in the field of syenodiorite, monzonite and monzodiorite. These latter three are suspected to have been hybridised by reaction with closely associated granitic fluids. In the classification scheme of Cox et al. (1979) (Figure 5.2) the majority of the Warsak basic rocks plot in the field of basalts, whereas samples WS17 and WS20 plot in the field of picrites.

Major Element Geochemistry and C.I.P.W Norms

Analytical data including major- and trace elements and C.I.P.W norms are listed in Table (5.1a,b). The Warsak basic rocks are characterised by a vast variation in the degree of silica saturation. Most of the rocks are quartz normative accompanied by hypersthene in the norms. Others are hypersthene and olivine normative, whereas one sample contains nepheline in the norms. These variations are reflected in the spread of data on Figure (5.1).

Variations in major element contents in the Warsak basic rocks are shown in Figure (5.3). Apparently, TiO_2, Fe_2O_3, CaO and MgO decrease with increasing SiO_2, whereas Al_2O_3 and alkalies increase. These variations suggest a relatively greater role of crystallisation of ferromagnesian minerals (mainly clinopyroxene) than plagioclase during differentiation.

Figure (5.4) representing relative proportions of major elements MgO, FeO, and alkalies has important implications for the determination of petrogenetic type of rock suites. In this figure the Warsak basic rocks are typically enriched in iron relative to alkalies; a character found in tholeiitic basalts rather than calc alkaline. It is interesting that same figure was used by Kempe (1978) to show that the Warsak basic rocks are calc alkaline in chemistry, comparable to the type calc-alkaline basic rocks of Kohistan (although even on his figure, the Warsak basic rocks plot distinctly away from the Kohistan rocks, towards the FeO corner). The greater number of samples used in this study unambiguously classify the Warsak basic rocks as tholeiites (Figure 5.4, 5.5). Since the basic rocks of possible alkaline nature are previously reported from the Peshawar plain from Tarbela (Siddiqui, 1973; Jan et al., 1981) and Koga (Siddiqui et al., 1968; Mian, 1987), it was felt important to explore the alkaline character of the Warsak basic rocks. In Figure (5.6) total alkalies are plotted against SiO2. Except for one sample, all the basic rocks from the Warsak area plot in the field of subalkaline rather than alkaline rocks, omitting the possibility of a similarity with alkaline basic complexes of the Peshawar plain.

Trace-Element Geochemistry

The Warsak basic rocks have been analysed for a large number of trace elements, and their variation is shown by plotting them against Zr (Figure 5.7). Interestingly most of the elements show good positive correlation with Zr suggesting a truly incompatible behaviour. These include K, Nb, Y, Th, Ga, Zn, La, Ce, and Nd. Some of the elements show an earlier positive correlation with Zr, inflicting to a negative slope at a Zr content of ~250 ppm. Rb and Ba are two such elements suggesting entry of k-feldspar or biotite in the crystallisation sequence late in the history of crystallisation. Scatter and a lack of enrichment in the case of Sr is partly due to crystallisation of plagioclase and partly due to alteration. A negative correlation of Ni, Cr, and V against Zr suggests a role of crystallisation of olivine and/or cr spinel and clinopyroxene early in the history of crystallisation.

Tectonic Setting of Magma Generation

A stated earlier, determination of tectonic setting of magma generation for the basic rocks of the Warsak area is important in the context of changing palaeo-environments in the northern margin of the Indian plate. Alkaline ultrabasic and basic rocks are already reported from the surroundings of the Peshawar plain (e.g., Tarbela: Jan et al., 1981; Koga; Siddiqui et al., 1968; Mian, 1987), which together with the peralkaline granites (such as those of Warsak and Shewa Shahbazgarhi) and nepheline syenite of Koga area (Rafiq, 1987; Le Bas et al., 1986) suggest extensional environments (rifting) in the Indian plate sometime in Carboniferous (Le Bas et al., 1986). The tholeiitic nature of the Warsak basic rocks demonstrated above negates any direct comparison with the alkaline basic magmatism, but the question arises that cannot the Warsak tholeiites be precursor to the alkaline basic magmatism in early rift stages?. An alternative possibility is that the Warsak tholeiites are ophiolitic (ocean-floor tholeiites) in nature. Ophiolites are not foreign to the surroundings of the Peshawar plain; the Dargai ophiolite is a large tectonic clippen tectonically emplaced in the Peshawar plain sometime at the time of closure of the Tetheys at the Main Mantle Thrust (Tahirkheli et al., 1979).

Detailed treatment of trace element data in terms of discrimination diagrams show that the Warsak basic rocks represent within-plate continental tholeiites with a strong component of initial-rift regimes.

Within-plate position of the Warsak Basic Magmatism

In the last two decades several discriminatory diagrams have been proposed to determine tectonic setting of magmatism. High-field strength elements such as Zr, Y, Ti, and Nb, which are least susceptible to alteration are found to be particularly useful in determining the tectonic setting of magma generation. Figure (5.8) shows incompatible trace element composition of tholeiite basalts from the three main settings of magma generation; island arc, mid-ocean ridge, and within plate (including within ocean island and within continent). The within-plate tholeiites are clearly enriched in all the incompatible trace elements (except for Sr) relative to the tholeiites of other two tectonic settings. Although, the lower or higher concentrations of incompatible trace elements may be due the composition of the source material, their concentration is also influenced by the degree of fractional crystallisation. Inter-element ratios of incompatible trace elements are, however, indices which are not changed by processes such as fractional crystallisation, but reflect composition of the source material. There are several discriminatory diagrams which are based on concentrations of the trace elements, in particular, HFS elements and their inter-element ratios.

1) Pearce and Norry (1979) showed that the basalts from island arcs, mid-oceanic ridges and within-plate environments contain different levels of Zr contents, being lowest in the arc basalts and highest in the within-plate basalts. In the Warsak basic rocks there is a variable content of Zr with a minimum at 60 ppm, which is distinctly higher than what is commonly found in basic rocks of island arcs and oceanic ridges (Figure 5.9).

2) Pearce and Norry (1979) showed that although the Zr content is generally high in the within-plate basalts, it is the ratio of Zr/Y which is of a greater diagonostic value. They emphasised that whereas the content of Zr (or for that matter any incompatible element) may vary depending upon the degree of fractional crystallisation, ratios such as Zr/Y reflect the differences in the source mantle regions or degree of partial melting. They showed that the arc basalts have least, MORBs intermediate and within-plate basalts highest Zr/Y ratios (Figure 5.9). The differences in the Zr/Y ratio between MORB and within-plate basalts is attributed to differences in the source mantle; being depleted (N-type) in the case of MORB and enriched (E-type) in the case of the within-plate basalts. In the case of arc basalts the lowest Zr/Y ratio was attributed to relatively greater degree of partial melting from a depleted mantle source. Most of the basic rocks from Warsak have high contents of Zr and high Zr/Y ratios comparable with within-plate basalts (Figure 5.9).

3) Pearce and Gale (1977) demonstrated that Nb is typically high in

within-plate basalts compared to the arc volcanics and mid-oceanic ridge basalts. The Warsak tholeiites contain Nb in the range of 3-50 which is distinctly higher than arc and mid-oceanic ridge basalts, comparable with basalts from the within plate settings (Figure 5.10).

4) A discriminatory plot involving Zr, Nb, and Y was suggested to be most powerful in distinguishing various types of tholeiitic basalts by Meschede (1986). The Warsak basic rocks do not plot a coherent group in this plot, some of the samples plot in the field of volcanic arc basalts, a couple in the field of P-type MORB, and one in the field of within-plate alkali basalts. Most of the samples from Warsak however plot in the field of within-plate tholeiitic basalts (Figure 5.11).

4) High Ti content is another diagonostic characteristic of within-plate basalts. The Warsak basic rocks plot clearly in the field of within plate tholeiites in diagrams involving Ti as dicriminatory element (Figure 5.12a,b,c).

5) Higher Zr and Ti contents relative to Y in within plate basalts have been used to discriminate them from basalts of other tectonic setting (Pearce and Cann, 1973). Some of the Warsak basic rocks have abnormally higher Ti and thus cluster near the Ti end in this diagram, however, rest of the samples plot in the field of within-plate basalts (5.13).

It is clear from the incompatible trace element data of the Warsak basic rocks that they belong to a within-plate setting of magma generation. Within plate tholeiites however can be either oceanic or continental.

The Warsak Basic Rocks as continental tholeiites

It is generally difficult to distinguish continental basalts from the basalts erupted in oceanic islands from within-plate oceanic settings. Rocks from both these settings are considered to have derived from mantle sources enriched in incompatible trace elements. Moreover the degree of partial melting is considered to be low, so that melting of major constituent mineral phases does not dilute the concentrations of the incompatible trace elements. Lo (1981) have devised diagrams involving ratios of Rb/Sr, Ca/Sr, K/Rb, and K/Sr distinguishing continental tholeiites from the oceanic and island arc tholeiites. The Warsak basic rocks have high Rb contents, and low K/Rb and Ca/Sr ratios which clearly assign them a setting similar to that of the continental tholeiites (Figure 5.1 4 a,b,c).

Initial-Rift component in the Genesis of the Warsak Basic Rocks

Myers and Breitkopf (1989) have rightly pointed out that the tectonic settings of magma generation are not static but evolve continuously. The implication is that basalt compositions are as transitional as the tectonic processes. Although it has been demonstrated that the Warsak basic rocks are within-plate continental tholeiites, there are certain trace-element characteristics which suggest their transitional composition between plateau-type continental flood basalts and basalts erupted in initial rifting of a continental plate.

1) Pearce et al. (1975) devised a diagram based on incompatible elements K, Ti, and P to separate basalts of oceanic and continental tholeiites (Figure 5.15). Holm (1985) has introduced a diagram based on elements Nb, Ti, and Th, with a similar objective (Figure 5.16). Whereas the Warsak basic rocks have yielded signatures of truly within-plate, continental tholeiites on several diagrams, their plots in Figures (5.16 & 5.17) yield scatters between the continental and oceanic tholeiites. As reviewed by both Holm (1985) and Myers and Breitkopf (1980), there are several basaltic suites from apparently within-plate continental settings (including e.g., Tertiary basalts of Scoresby Sund area of East Greenland; basalts of west Greenland and Baffin Island; basalts of the Deccan plateau) which, like the Warsak basic rocks, straddle the fields of oceanic and continental tholeiites in Pearce et al. (1975) and Holm (1985) discriminatory diagrams. Although it can be argued that factors like alteration, contamination and fractional crystallisation may be responsible for the scatter of the data in these diagrams, more likely it is the transitional nature of the basalts from these suites which accounts for their combined conti-

nental and oceanic characters. In theory, a thinned continental crust with eruption of plateau basalts is likely to ultimately develop into a actinic basin with MORB like basalts, if extensional environments prevail for a considerable geological time. Pearce et al. (1975) interpreted the transitional nature of the basalts from East Greenland, West Greenland and Baffin island, and Deccan plateau as indicating "initial rifting of the continent and generation of sea floor" of the Atlantic ocean, Labrador Sea, and Indian ocean, respectively. The transitional characteristics of the Warsak basic rocks can similarly be interpreted as related to tholeiites erupted in the initial stages of a rift. The initial rifting component in the Warsak basic rocks is also indicated in Figure (5.17), based on TiO2 vs K2O/Alkalies devised by Chandrasekharam and Parthasarty (1978) for distinguishing plateau basalts from rift volcanics.

2) Affiliation of the Warsak basic rocks to initial rifting is also indicated by mantle-normalised multi-element patterns such as those shown in Figure (5.18). According to Holm (1985), the mantle-normalised trace element patterns of continental flood/plateau basalts by a general negative slope (sloping towards left), with a negative Nb anomaly. The initial-rifting tholeiites, in comparison are characterised by an asymmetrical inverted U, positive Nb anomaly, and a high Ti/Y ratio, reflected in a negative slope for the segment Ti-Y (Figure 5.18a). Representative samples from the basic rocks from Warsak are shown in Figure (5.18b). It is noticeable that except for some differences in the segment Rb-K, which comprises relatively mobile trace elements, the pattern of Warsak basic rocks is comparable with initial-rifting tholeiites particularly in terms of a positive Nb anomaly and a high Ti/Y ratio.

Conclusions

The evaluation of the major, minor, and trace element data has resulted in characterisation of the Warsak basic rocks in terms of classification, basaltic type (i.e., whether tholeiitic, calc-alkaline or alkaline), and tectonic setting of magma generation. Some of the main conclusions of this study include:

1) The Warsak basic rocks range from ultramafic to diorite in composition, though a majority of the samples are gabbroic (basaltic) in composition.

2) They are characterised by a distinct iron-enrichment suggesting a tholeiitic nature rather than calc-alkaline as suggested by Kempe (1978).

3) The variations in major and trace elements are probably a consequence of fractional crystallisation involving olivine, clinopyroxene, plagioclase and k-feldspar or biotite at a later stage.

4) The high contents of trace elements such as Ti, Zr, Y, and Nb and high ratios such as Zr/Y and Nb/Y classify the Warsak basic rocks as within-plate tholeiites of continental origin.

5) Further evaluation of the trace element data in terms of relative proportions of trace elements such as K, Ti, and P and Ti, Nb, and Th, has shown that the Warsak basic rocks have transitional characteristics between truly continental flood/plateau basalts and basalts from oceanic setting, suggesting an origin in initial rifting environments.

File name A:WSKBAS.ROC

Sample	W5	W14	W17	W18	W19	W20	W26	W29	W30	W34	W36	W54	T30	T31	T34
Group #	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
Qual	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Key	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Ref	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
SiO_2	49.00	49.00	46.00	44.00	48.00	47.00	48.00	49.00	48.00	48.00	48.00	50.00	0.00	0.00	0.00
TiO_2	1.91	1.54	2.02	5.22	3.56	1.46	3.32	2.83	3.66	1.59	1.51	2.89	0.00	0.00	0.00
Al_2O_3	11.00	13.00	9.00	10.00	16.00	11.10	10.00	13.00	11.00	12.00	12.00	11.90	0.00	0.00	0.00
Fe_2O_3	16.00	14.00	11.00	17.00	13.00	14.00	15.00	12.00	15.00	12.00	12.00	14.46	0.00	0.00	0.00
MnO	0.24	0.24	0.10	0.20	0.08	0.22	0.20	0.20	0.20	0.20	0.20	0.17	0.00	0.00	0.00
MgO	6.00	7.00	6.00	7.00	6.00	6.50	8.00	7.00	5.00	7.00	7.00	5.10	0.00	0.00	0.00
CaO	11.00	11.00	19.00	12.00	4.00	12.80	10.00	9.00	8.00	11.00	10.00	8.15	0.00	0.00	0.00
Na_2O	2.40	3.00	2.00	1.40	5.00	2.20	2.00	2.00	2.00	3.00	2.00	2.47	0.00	0.00	0.00
K_2O	0.47	0.51	0.45	1.13	0.92	0.20	0.42	0.52	1.00	0.30	1.00	1.48	0.00	0.00	0.00
P_2O_5	0.21	0.17	0.24	0.66	0.21	0.18	0.21	0.21	0.61	0.19	0.17	0.42	0.00	0.00	0.00
Total	98.23	99.46	95.81	98.61	96.77	95.66	97.14	95.76	94.47	95.28	93.88	97.04	0.00	0.00	0.00
Nb	6.9	7.0	23.6	46.5	37.0	4.1	14.3	10.4	25.6	10.6	8.9	28.5	6.3	5.3	18.0
Zr	127.7	98.4	220.6	236.7	405.8	93.9	143.7	121.6	308.5	133.4	116.8	339.4	69.9	99.4	203.2
Y	37.5	24.0	36.3	33.2	65.5	27.8	27.2	17.3	40.0	26.5	25.9	51.9	21.5	32.8	25.3
Sr	186.2	261.3	829.3	822.6	587.5	687.8	330.7	374.8	338.8	300.3	274.9	320.4	453.0	703.3	363.0
Rb	10.7	12.2	13.7	36.3	29.7	2.1	12.5	17.0	45.8	5.4	25.4	44.6	14.8	2.0	31.8
Th	4.0	3.5	11.5	5.0	12.5	1.0	4.5	4.0	5.5	4.5	3.5	8.5	1.0	0.0	2.1
Pb	6.0	4.0	12.5	10.0	9.5	11.0	6.5	4.0	9.5	8.5	5.5	4.0	0.0	0.0	0.0
Ga	21.3	19.1	25.4	25.1	34.3	19.0	20.8	23.0	24.4	22.0	19.8	23.4	19.8	19.2	24.1
Zn	108.2	86.2	69.6	140.1	83.8	83.1	119.7	90.7	146.5	82.5	82.4	125.2	88.8	81.7	101.8
Ni	52.5	56.9	76.7	43.9	135.0	56.3	96.3	26.4	16.9	99.1	97.8	49.5	61.9	57.3	26.6
Cr	53.0	70.0	381.0	20.0	366.0	46.0	121.0	42.0	17.0	248.0	245.0	51.0	38.3	49.1	32.7
V	439.0	350.0	216.0	474.0	355.0	363.0	587.0	344.0	418.0	313.0	306.0	367.0	473.8	373.6	397.8
La	6.7	6.9	32.3	34.3	52.6	5.9	13.2	8.9	24.1	9.7	8.2	28.2	0.0	10.0	13.5
Ce	19.6	18.4	75.8	77.2	113.0	16.7	30.1	20.2	54.5	25.3	18.8	68.3	23.1	26.9	32.3
Nd	14.1	10.5	37.4	44.5	63.2	11.5	17.1	12.6	31.0	14.5	13.1	38.1	11.0	16.2	19.4
Ba	128.0	131.0	242.0	399.0	197.0	54.0	323.0	214.0	345.0	72.0	179.0	381.0	231.9	66.8	341.0
Ca/Sr	432.0	300.0	163.0	104.0	48.0	125.0	216.0	172.0	169.0	262.0	260.0	182.0	0.0	0.0	0.0
FeO*	14.40	12.60	9.90	15.30	11.70	12.60	13.50	10.80	13.50	10.80	10.80	13.01	0.00	0.00	0.00
Mg#															
Zr/Nb	18.5	14.1	9.4	5.1	11.0	23.2	10.1	11.7	12.1	12.6	13.2	11.9	11.1	18.8	11.3
Rb/Sr	0.057	0.047	0.017	0.044	0.051	0.003	0.038	0.045	0.135	0.018	0.092	0.139	0.033	0.003	0.088
K/Rb	365	347	273	260	257	810	279	253	181	465	327	276	0	0	0
K/Ba	30.5	32.2	15.4	23.6	38.7	30.7	10.8	20.2	24.1	34.6	46.4	32.2	0.0	0.0	0.0
den															

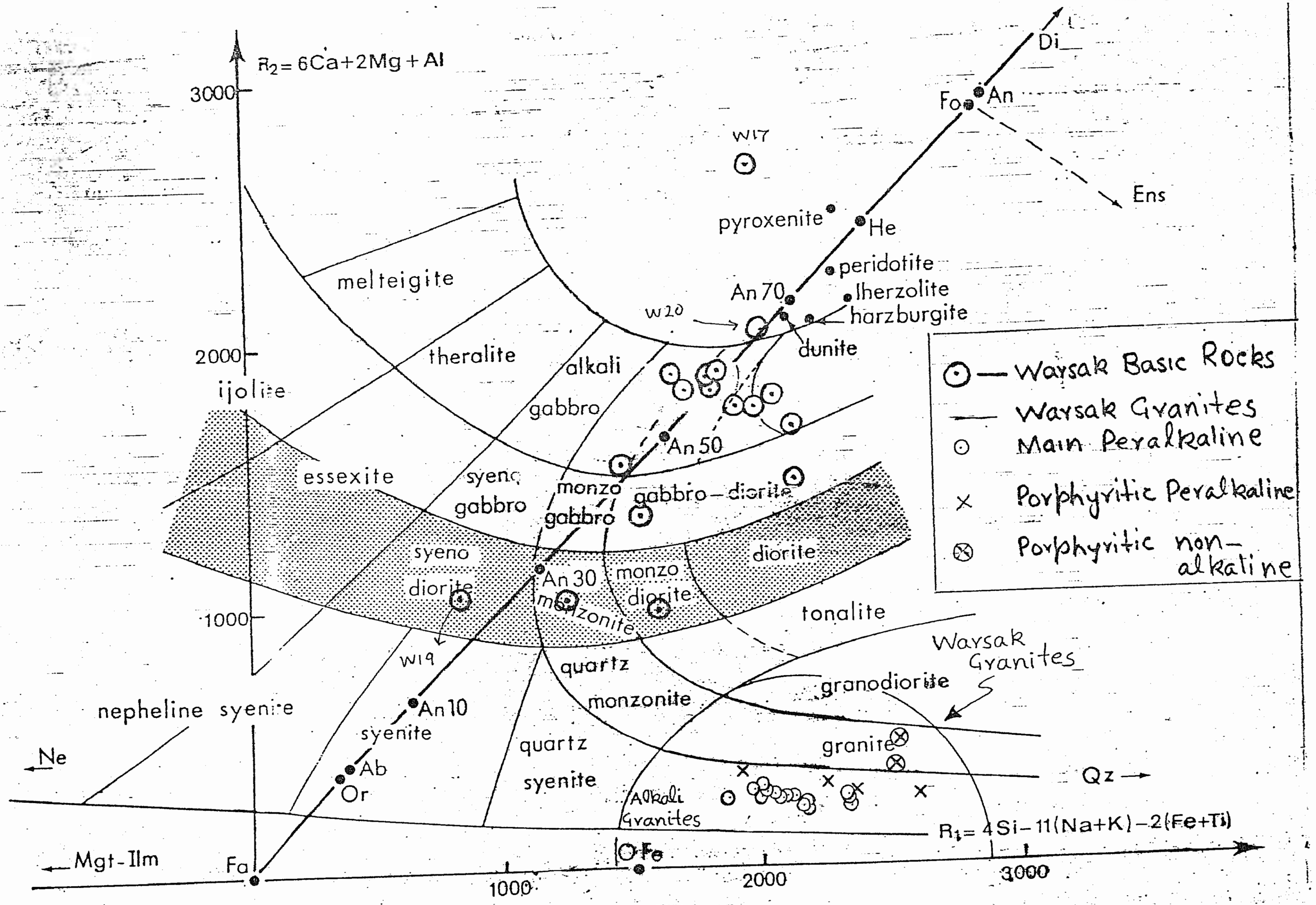
T30 T31 T34 Major elements not analysed

File name A:WSKBAS.ROC

Sample	T35	T38	T39	T43	T44	T50	T52	P94	P59	P62	P68	P61
Group #	3.00	3.00	3.00	3.00	3.00	3.00	3.00	4.00	2.00	2.00	2.00	2.00
Qual	3	3	3	3	3	3	3	4	2	2	2	2
Key	3	3	3	3	3	3	3	4	2	2	2	2
Ref	3	3	3	3	3	3	3	4	2	2	2	2
SiO_2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	48.20	48.70	46.90	56.50	53.20
TiO_2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.66	1.60	4.78	2.32	3.14
Al_2O_3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	15.20	15.00	12.30	13.20	13.30
Fe_2O_3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	9.02	10.94	14.51	11.58	12.99
MnO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.18	0.23	0.23	0.28
MgO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.65	6.86	5.09	2.39	2.58
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	11.60	10.38	9.02	5.61	5.72
Na_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.24	2.93	2.94	4.23	4.31
K_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.59	0.94	1.59	1.71
P_2O_5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.21	0.13	0.27	0.56	0.69
H_2O+	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.60	1.80	1.56	1.23	1.46
H_2O-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.12	0.10	0.15	0.08	0.14
Total	0.00	0.00	0.00	0.00	0.00	0.00	0.00	95.92	99.21	98.69	99.52	99.52
Nb	6.8	8.6	27.7	9.6	10.7	24.0	22.1	0.0	0.0	0.0	0.0	0.0
Zr	115.4	134.1	386.4	130.0	129.4	198.8	263.0	0.0	0.0	0.0	0.0	0.0
Y	33.7	20.2	46.0	27.9	26.6	39.1	41.5	0.0	0.0	0.0	0.0	0.0
Sr	307.5	406.3	367.5	251.4	237.3	316.9	407.4	0.0	293.0	310.0	280.0	240.0
Rb	1.7	14.0	49.9	21.5	11.2	10.4	65.8	0.0	4.0	20.0	40.0	50.0
Th	0.9	0.8	4.1	2.4	1.6	1.7	5.1	0.0	0.0	0.0	0.0	0.0
Ga	19.4	23.3	26.2	16.7	19.3	24.5	25.5	0.0	0.0	0.0	0.0	0.0
Zn	111.6	91.7	145.5	80.2	79.9	111.0	120.9	0.0	0.0	0.0	0.0	0.0
Ni	53.2	28.7	20.6	93.3	107.1	26.3	10.7	0.0	150.0	65.0	60.0	55.0
Cr	37.7	39.5	17.2	254.2	260.0	11.7	13.8	0.0	236.0	0.0	0.0	0.0
V	375.6	327.9	389.5	314.2	316.4	520.0	358.6	0.0	0.0	0.0	0.0	0.0
La	0.0	12.3	27.1	9.2	10.0	18.7	23.4	0.0	0.0	0.0	0.0	0.0
Ce	18.0	27.8	67.8	20.9	22.2	51.7	62.9	0.0	0.0	0.0	0.0	0.0
Nd	13.0	16.5	40.1	13.8	14.3	30.0	34.4	0.0	0.0	0.0	0.0	0.0
Ba	61.2	109.0	271.4	219.1	80.1	84.0	296.7	0.0	0.0	0.0	0.0	0.0
Ca/Sr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	253.0	208.0	143.0	170.0
FeO*	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.12	9.85	13.06	10.42	11.69
Mg#												
Zr/Nb	17.0	15.6	13.9	13.5	12.1	8.3	11.9	0.0	0.0	0.0	0.0	0.0
Rb/Sr	0.006	0.034	0.136	0.086	0.047	0.033	0.162	0.000	0.014	0.065	0.143	0.208
K/Rb	0	0	0	0	0	0	0	0	1224	390	330	284
den												

T35 T38 T39 T43 T44 T50 T52 Major elements not analysed.

Figure (5.1). Classification of the Warsak basic rocks using scheme of La Roche et al. (1980).


R2 = 6Ca+2Mg+Al
3000
2000
1000
R1 = 4Si−11(Na+K)−2(Fe+Ti)
1000
2000
3000
Di
Fo
An
Ens
W17
pyroxenite
He
peridotite
lherzolite
harzburgite
An 70
W20
dunite
melteigite
theralite
alkali
gabbro
ijolite
An 50
essexite
syeno
gabbro
monzo
gabbro
gabbro—diorite
diorite
syeno
diorite
An 30
monzonite
monzo
diorite
tonalite
W19
quartz
monzonite
granodiorite
Warsak
Granites
An10
syenite
Ab
Or
quartz
syenite
granite
Qz
nepheline syenite
Ne
Alkali
Granites
Mgt-Ilm
Fa
Fe
Warsak Basic Rocks
Warsak Granites
Main Peralkaline
Porphyritic Peralkaline
Porphyritic non-alkaline

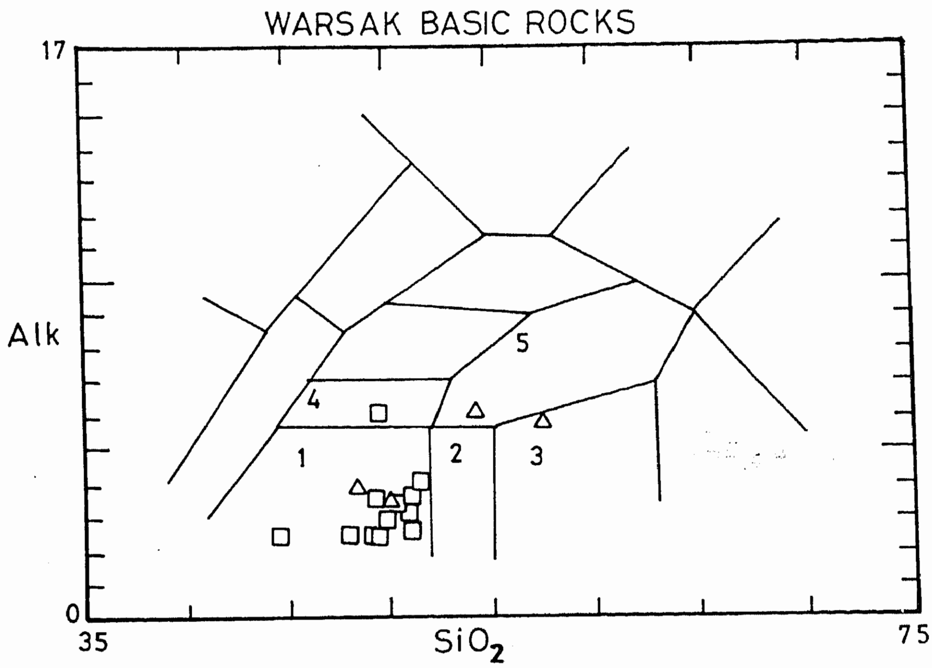


Figure (5.2). Classification of the Warsak basic rocks using scheme of Cox et al. (1979).

1 = Basalt.   2 = Basalt andisite   3 = Andisite

4 = Hawiites   5 = Dacite.

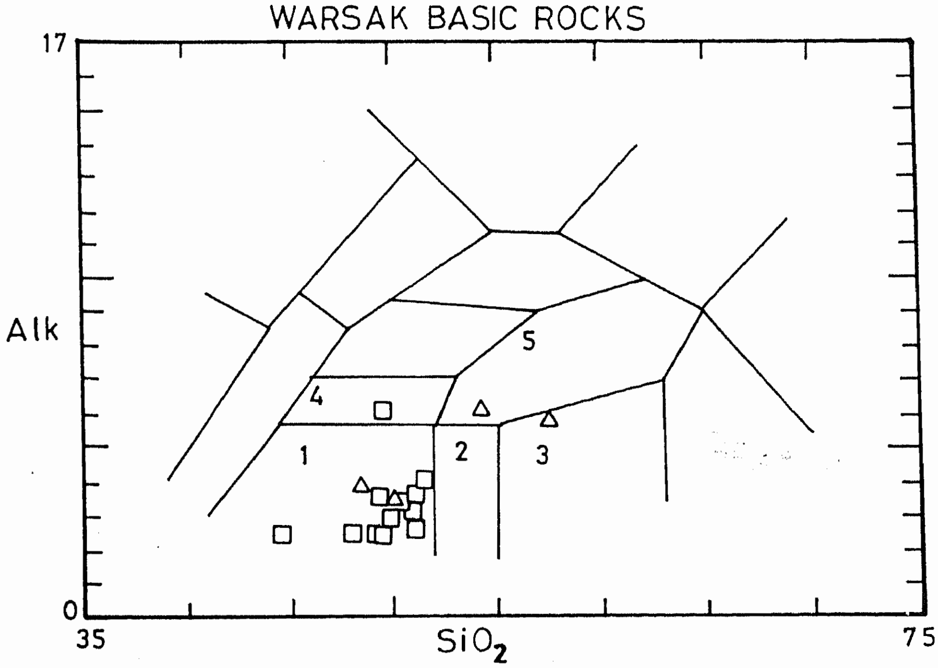


Figure (5.2). Classification of the Warsak basic rocks using scheme of Cox et al. (1979).

1 = Basalt. 2 = Basalt andisite 3 = Andisite

4 = Hawiites 5 = Dacite.

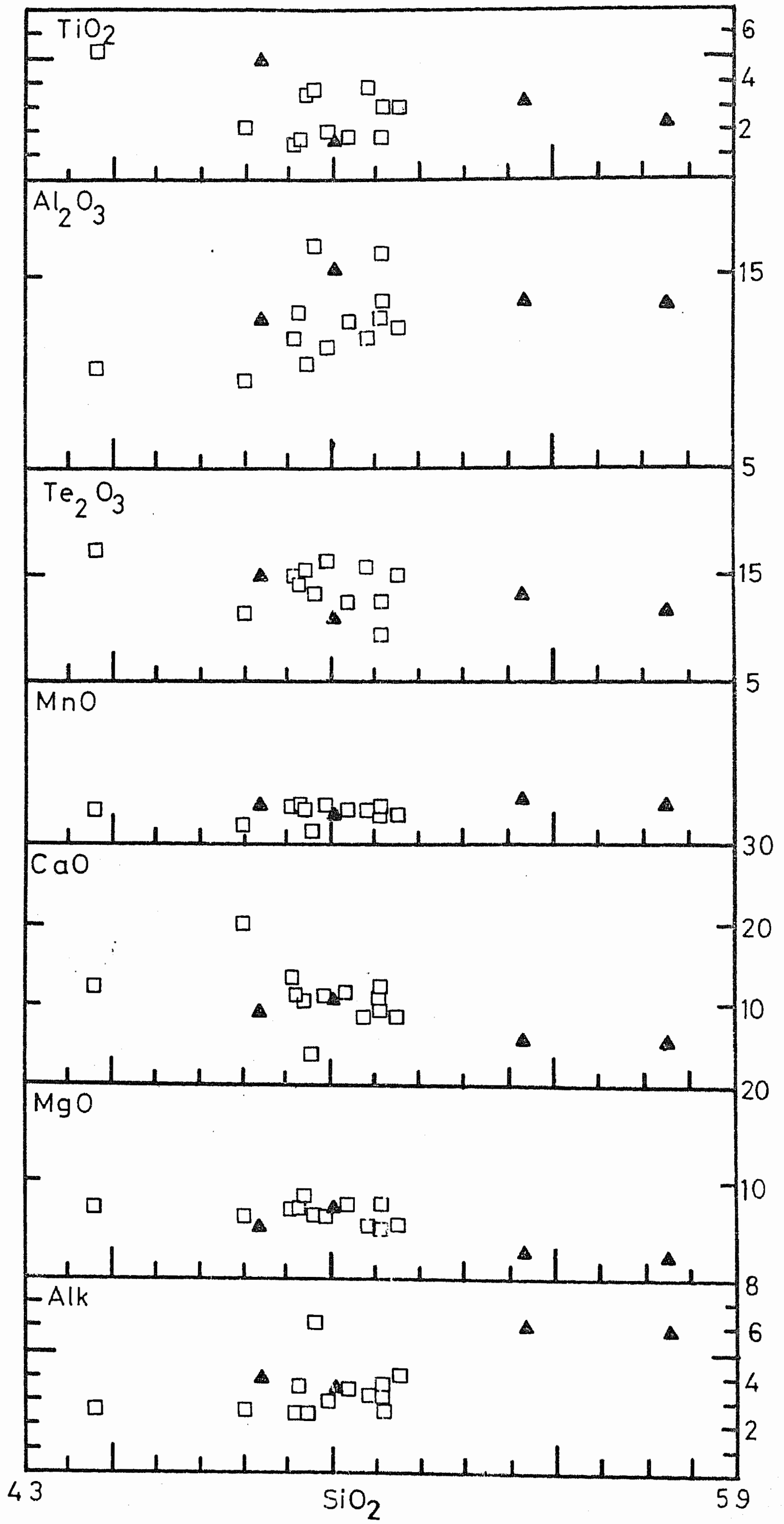


Figure (5.3). Major-element variations in the Warsak basic rocks, using Harker-type variation diagrams. Squares (data from this study), Triangles (data from Kempe, 1978).

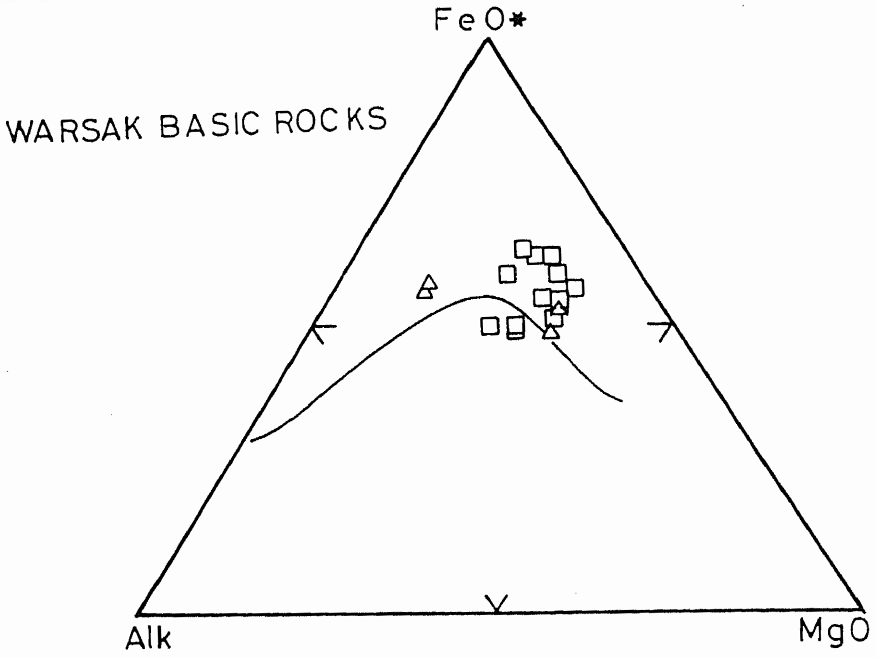


Figure (5.4). A (Alkalies)-F(FeO total)-M(MgO) plot of the Warsak basic rocks. The line demarcating the division between calc-alkaline and tholeiite basalts after Irvine and Baragar (1971).

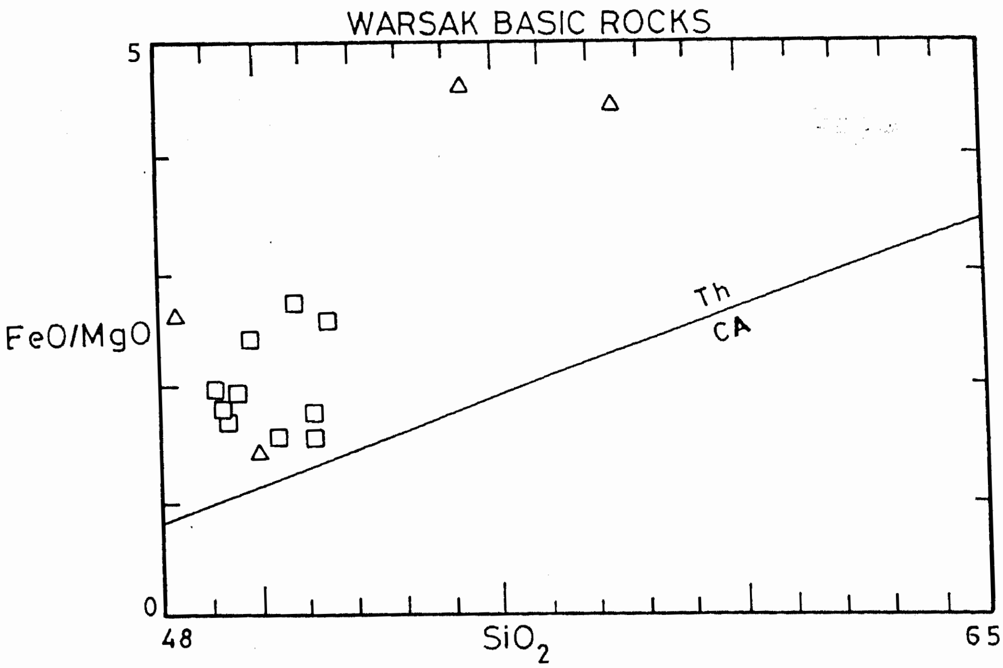


Figure (5.5). The FeO(total)/MgO vs SiO2 plot of the Warsak basic rocks for the characterisation of their tholeiitic nature (after Miyashiro, 1974).

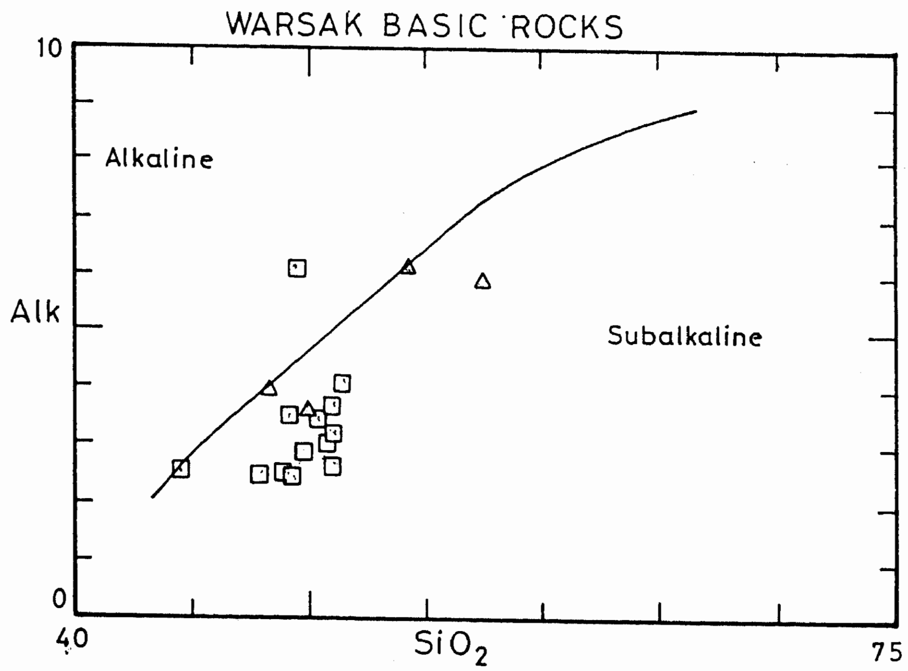
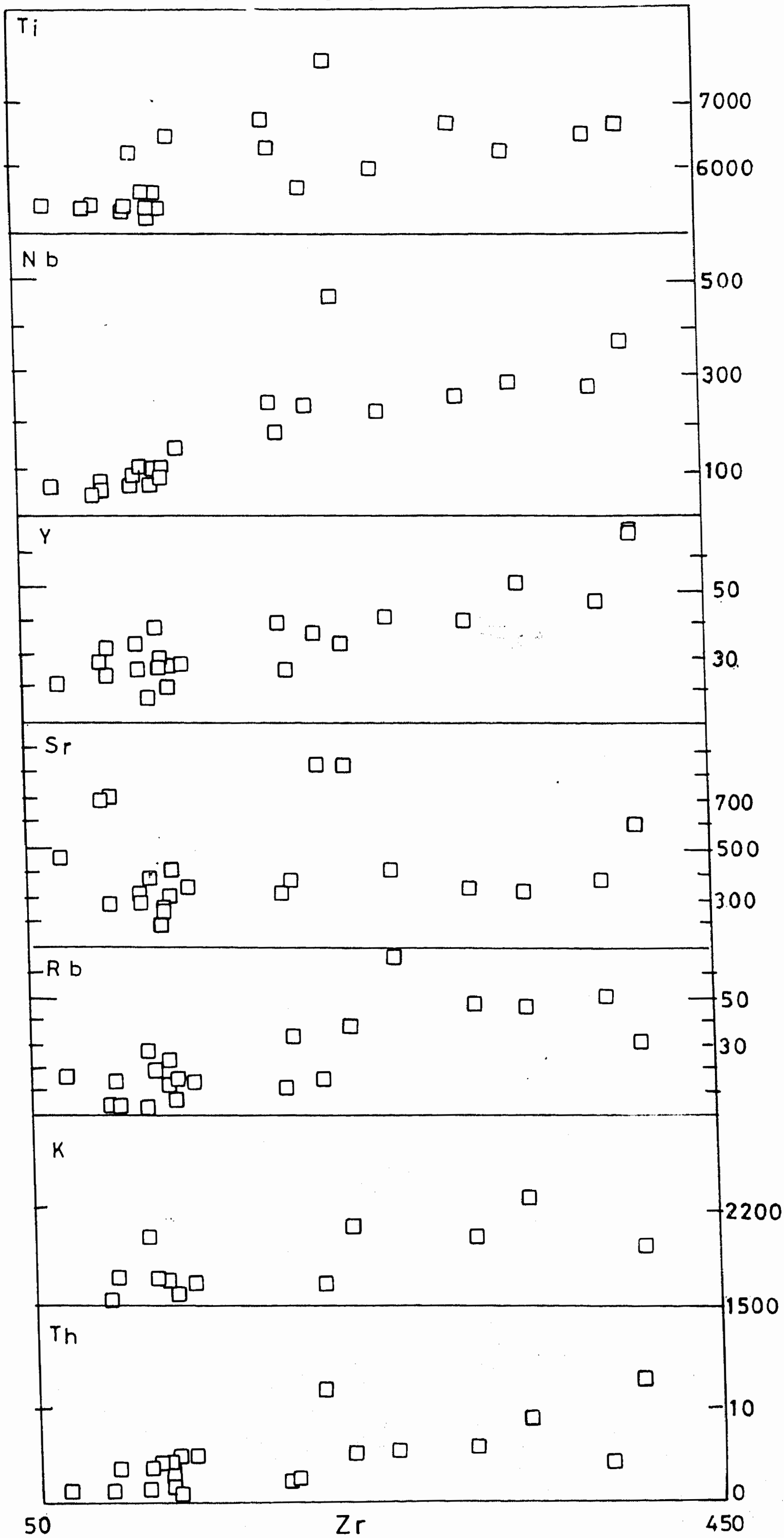
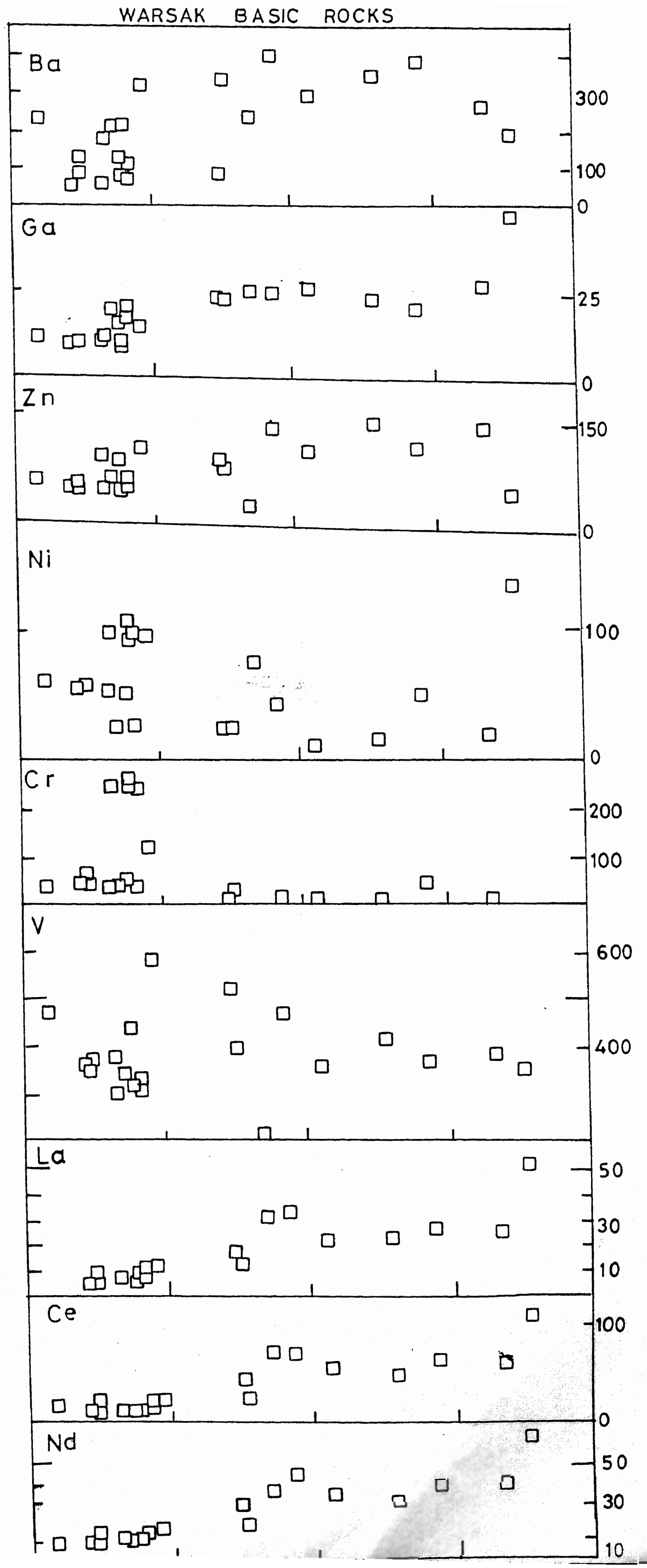


Figure (5.6). The characterisation of tholeiitic vs alkaline character of the Warsak basic rocks (after Irvine and Baragar, 1971).

Figure (5.7). Trace element variations in the Warsak basic rocks.

WARSAK BASIC ROCKS




WARSAK BASIC ROCKS
Ba
300
100
0
Ga
25
0
Zn
150
0
Ni
100
0
Cr
200
100
V
600
400
La
50
30
10
Ce
100
0
Nd
50
30
10

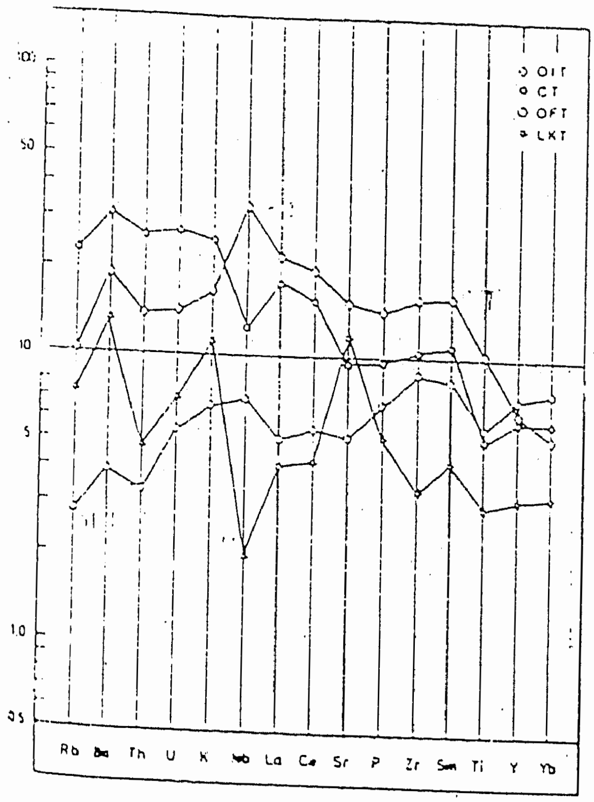


Figure (5.8). Mantle-normalised patterns of incompatible trace elements of tholeiitic basalts from various tectonic settings including mid-oceanic ridge, oceanic island, island arc and within-plate continental (after Holm, 1985).

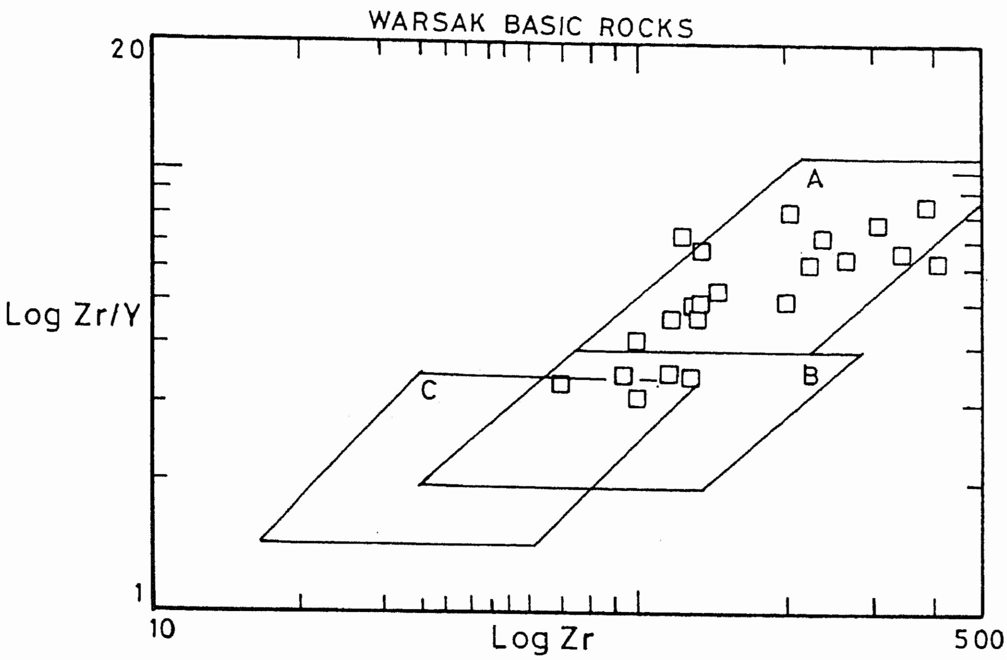


Figure (5.9). Characterisation of the tectonic setting of origin of the Warsak basic rocks using Zr content and Zr/Y ratios (after Pearce et al., 1979). A = Within plate basalts, B = Mid-ocean ridge basalts, C = Island arc basalts.

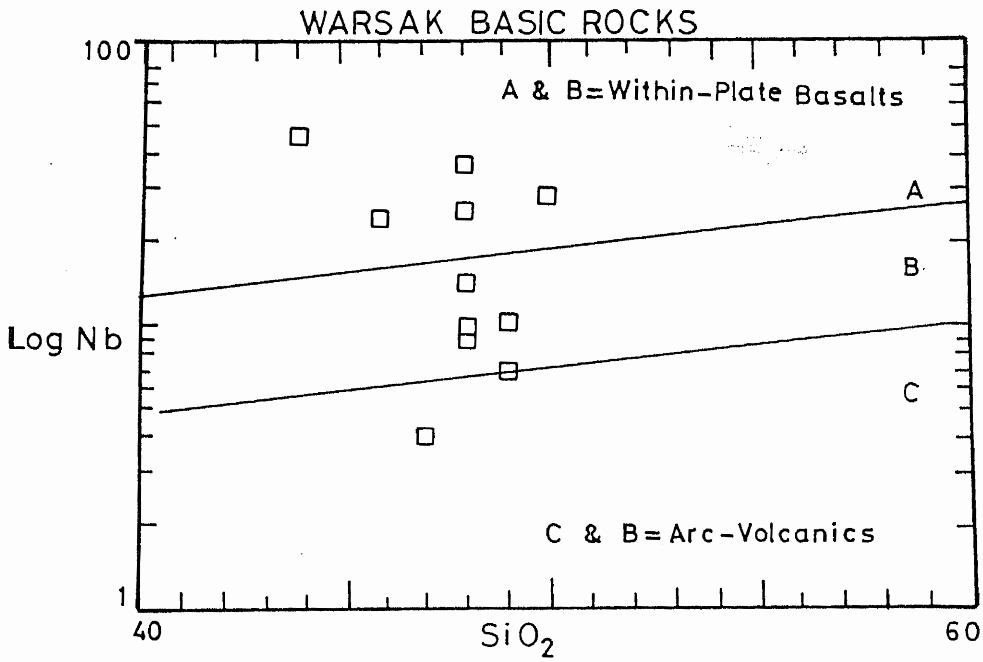


Figure (5.10). The Nb content used to distinguish the tectonic setting of the Warsak basic rocks (after Pearce and Gale, 1977).

Figure (5.11). Distinction of the tectonic setting of magma generation for the basic rocks of Warsak using Nb, Zr and Y based triangular plot suggested by Meschede (1986).

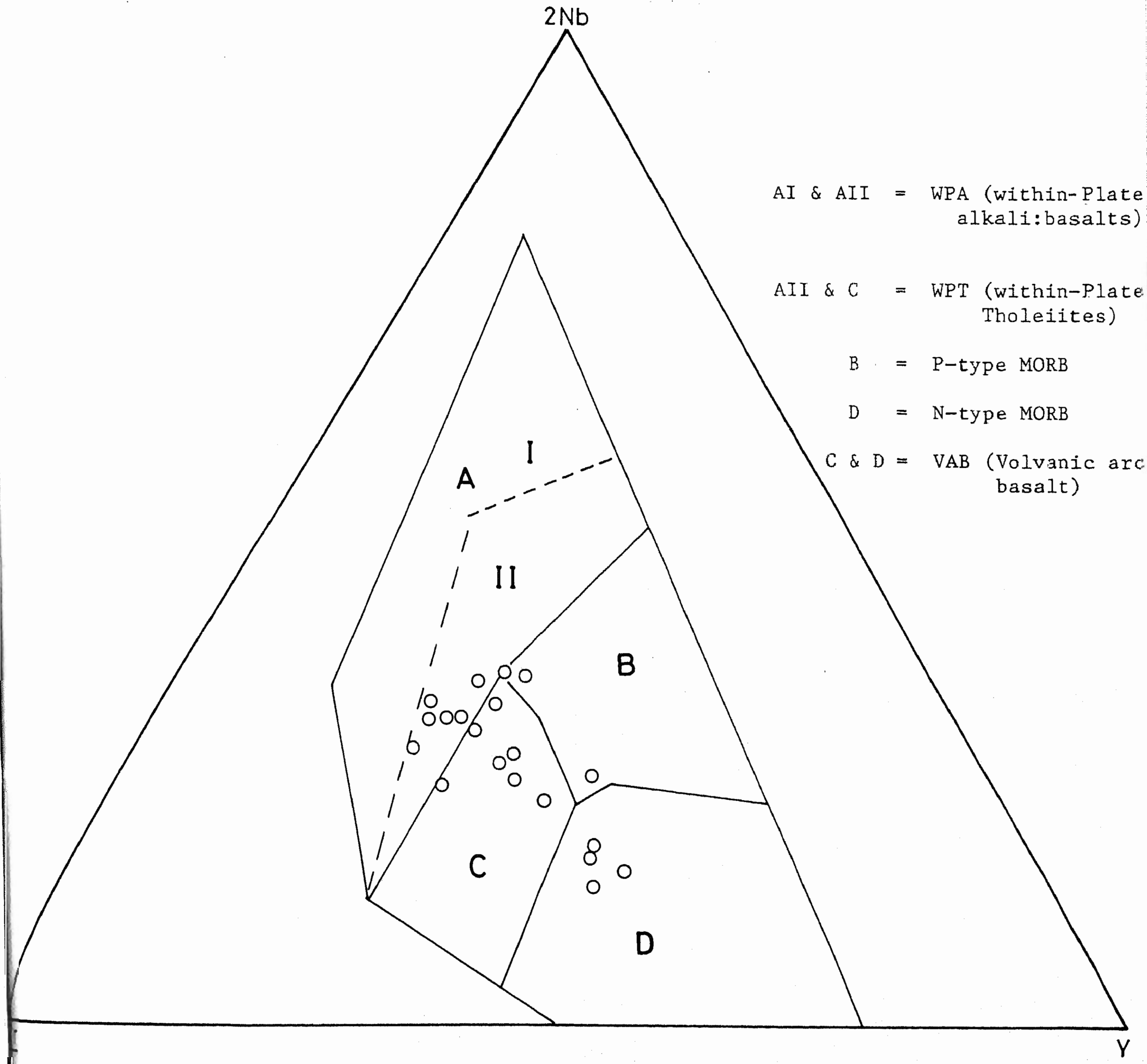
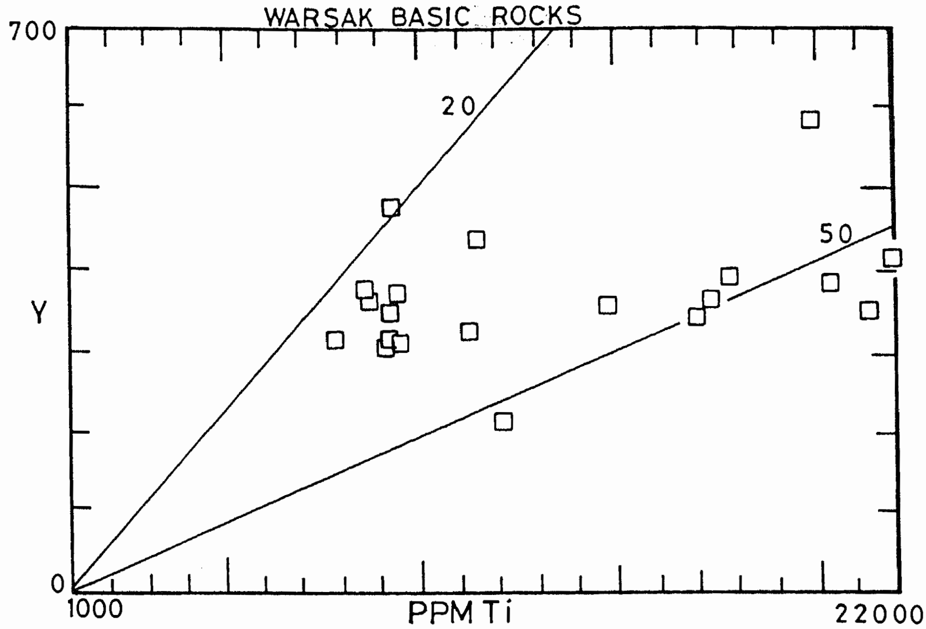

2Nb
Y
A
I
II
B
C
D
AI & AII = WPA (within-Plate alkali:basalts)
AII & C = WPT (within-Plate Tholeiites)
B = P-type MORB
D = N-type MORB
C & D = VAB (Volvanic arc basalt)

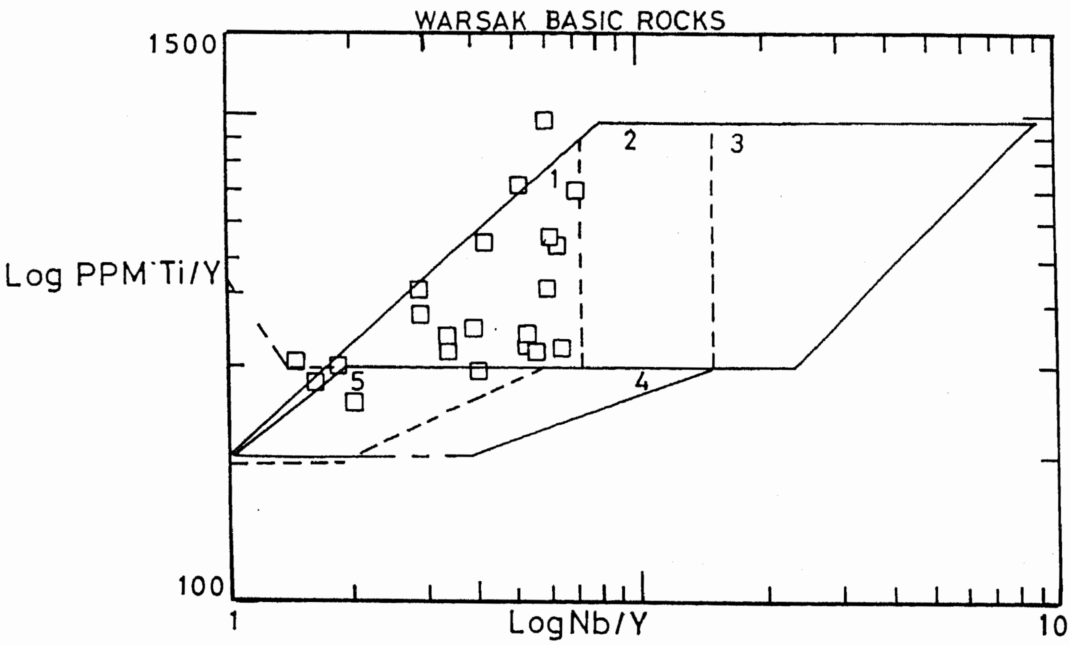
Figure (5.12). Various discrimination diagrams involving Ti, for the characterisation of tectonic setting of magma generation for the Warsak basic rocks:

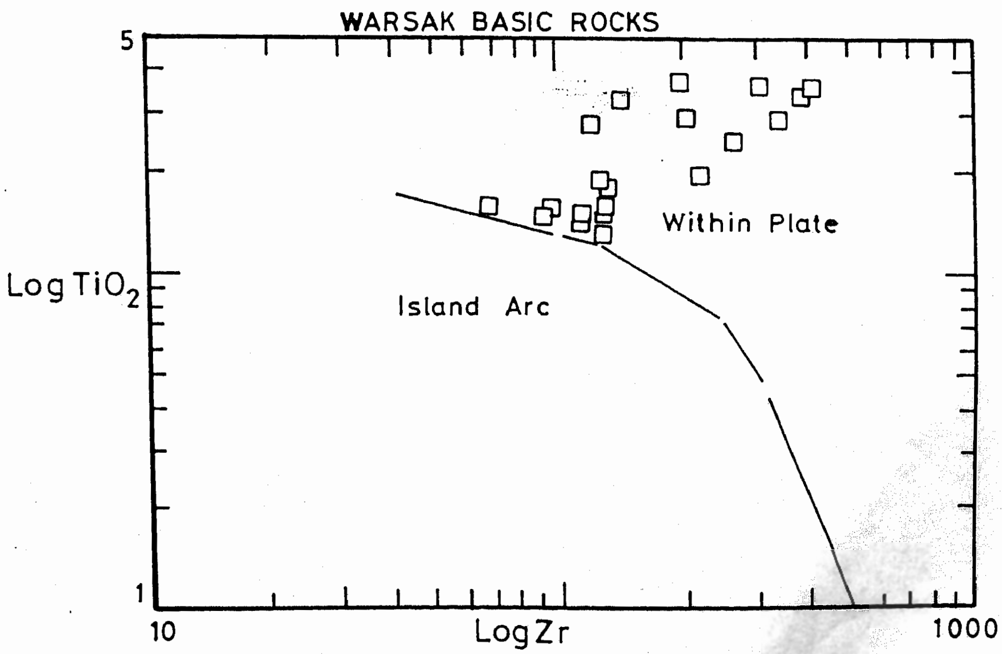
a) Ti vs V plot (after Shervais, 1982). Flood basalts of within plate origin (e.g., Columbia river) plot between the lines defining V/Ti ratios 20 and 50.

c) Ti vs Zr (After Gas, 1982). 1 = Intraplate tholeiites, 2 = transitional tholeiites, 3 = intraplate alkalic, 4 = ocean floor tholeiites, 5 = arc tholeiites.

b) Ti/Y vs Nb/Y (After Hughes, 1972).


WARSAK BASIC ROCKS
700
20
50
Y
0
1000
PPM Ti
22000


WARSAK BASIC ROCKS
1500
Log PPM Ti/Y
1
2
3
4
5
100
1
Log Nb/Y
10


WARSAK BASIC ROCKS
5
Log TiO2
Within Plate
Island Arc
1
10
Log Zr
1000

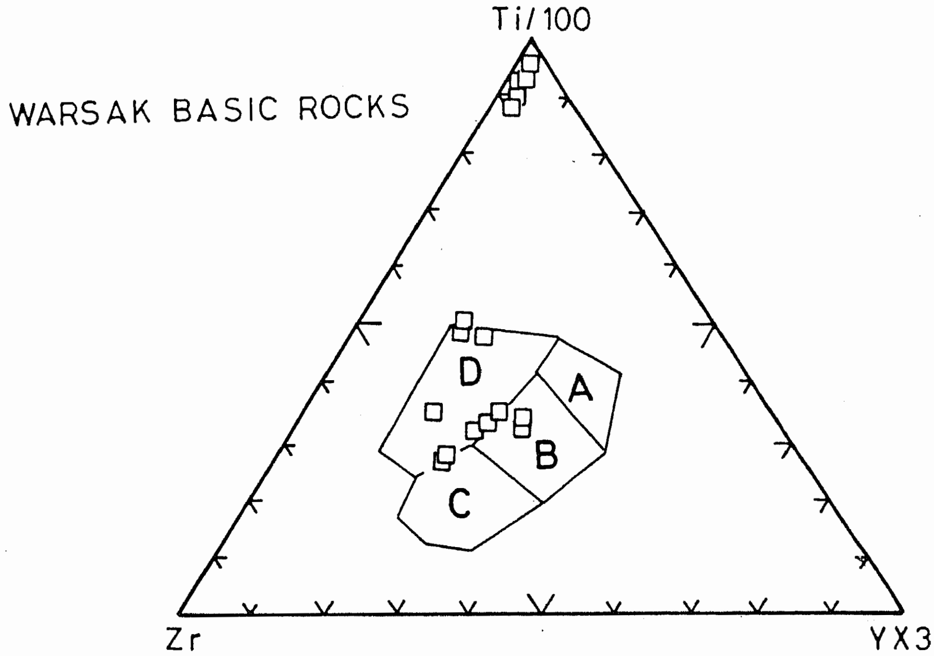


Figure (5.13). Zr Ti Y diagram (after Pearce and Cann, 1973) used for the determination of the tectonic setting for the Warsak basic rocks. A = Arc basalts, B = Ocean-floor basalts, B & C = Calc-alkali basalts and D = Within-plate basalts.

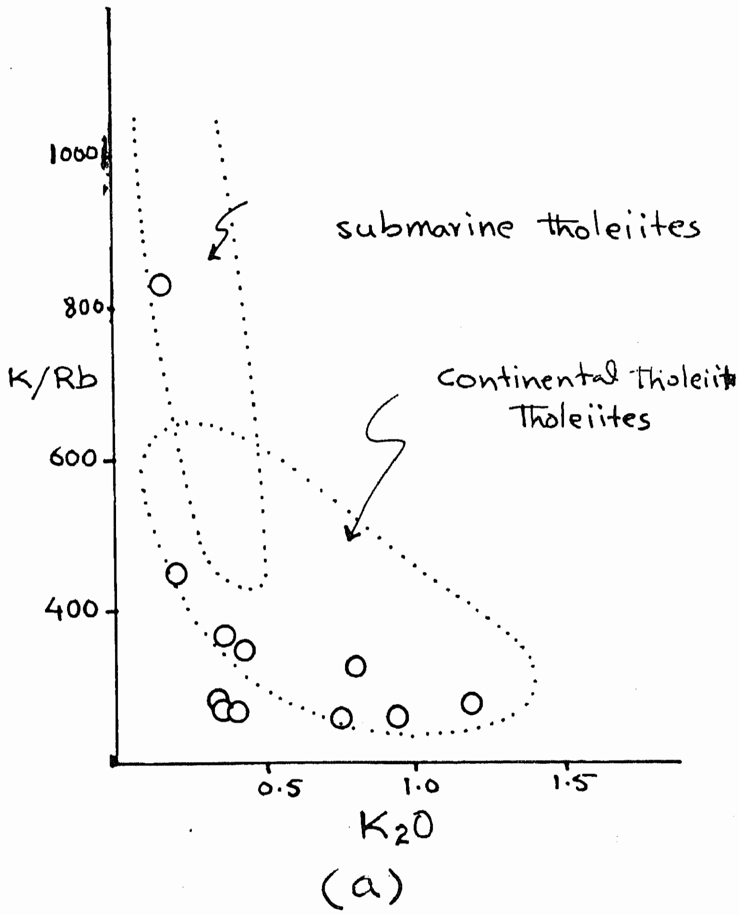
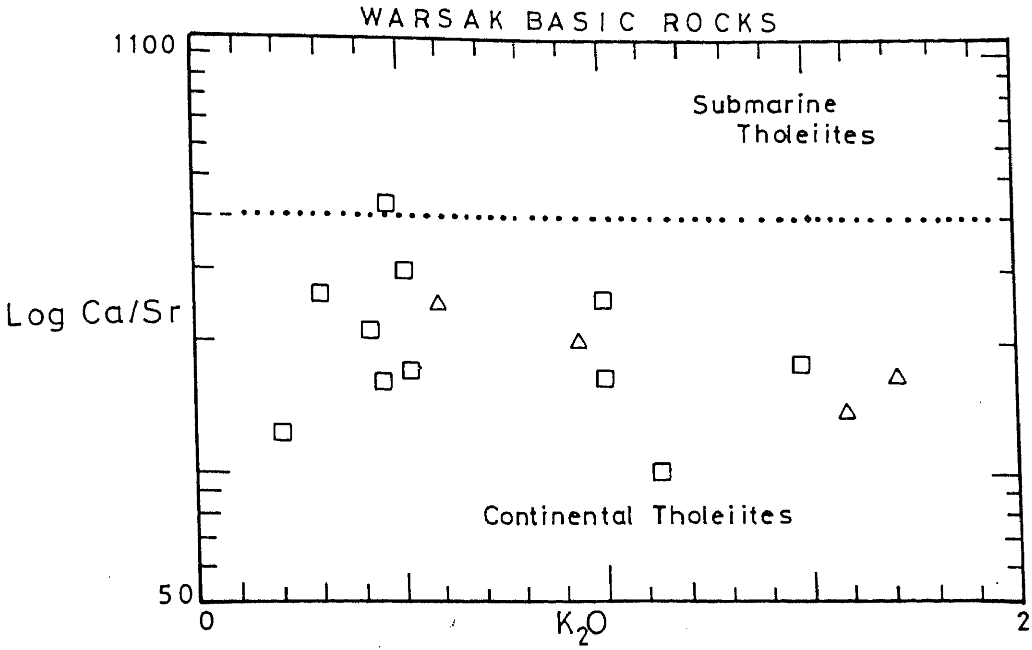
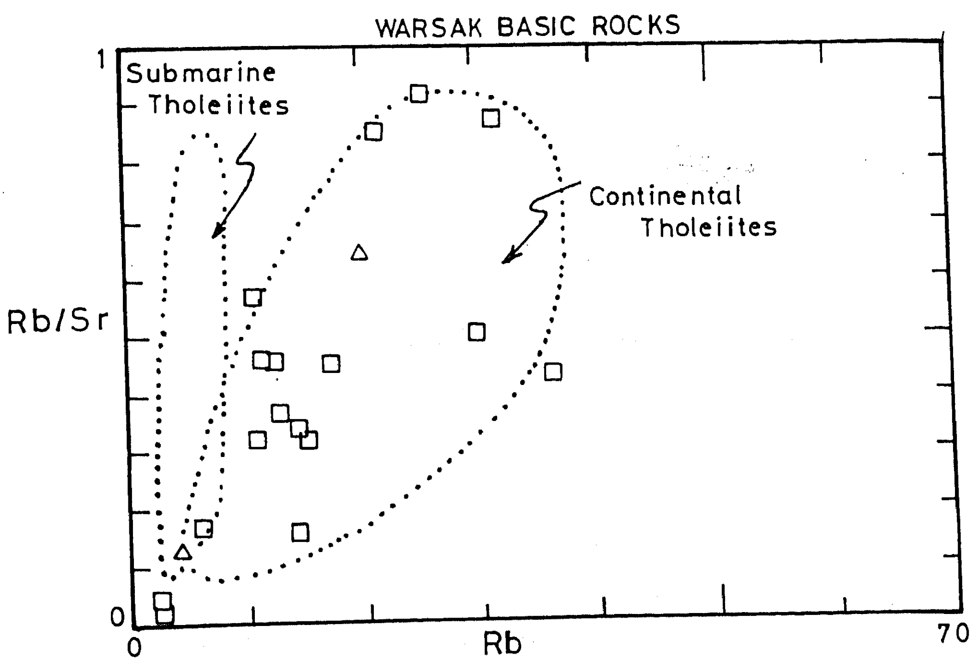


Figure (5.14). Distinction of continental and oceanic tholeiites (after Lo, 1981).


WARSAK BASIC ROCKS
1100
50
Submarine Tholeiites
Log Ca/Sr
Continental Tholeiites
0
K2O
2

(b)


WARSAK BASIC ROCKS
1
0
Submarine Tholeiites
Continental Tholeiites
Rb/Sr
0
Rb
70

(C)

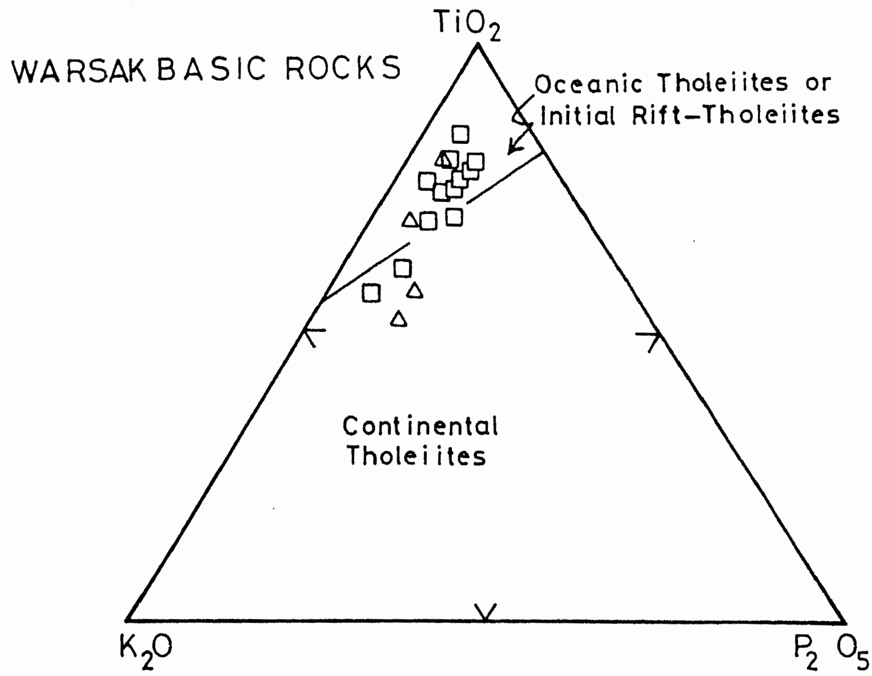


Figure (5.15). The TiO2-P2O5-K2O diagram of the Warsak basic rocks for the determination of initial rift component (After Pearce et al., 1975).

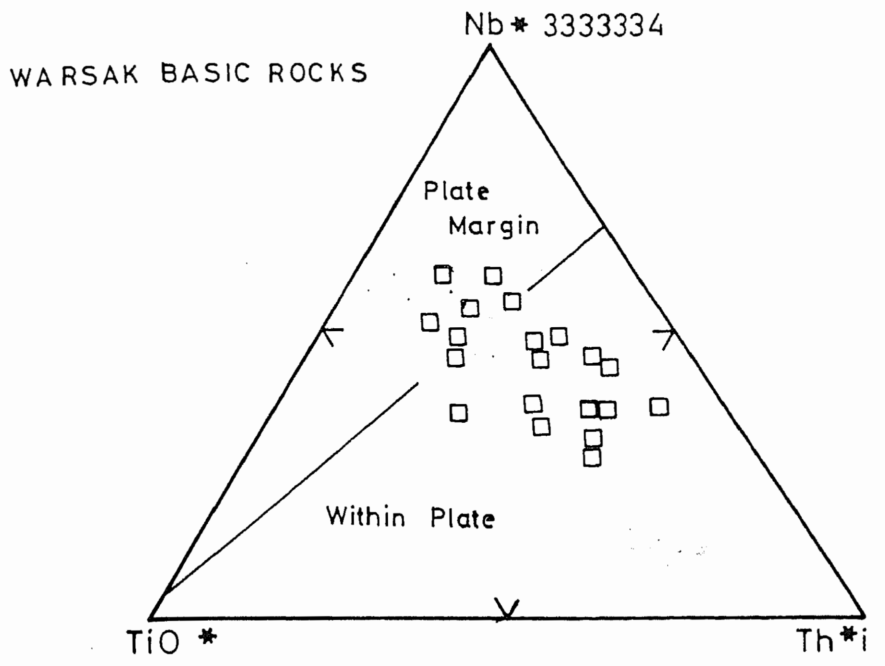


Figure (5.16). The TiO2-Nb/3-Th diagram (after Holm, 1985) used for determination of initial-rifting component in the Warsak basic rocks.

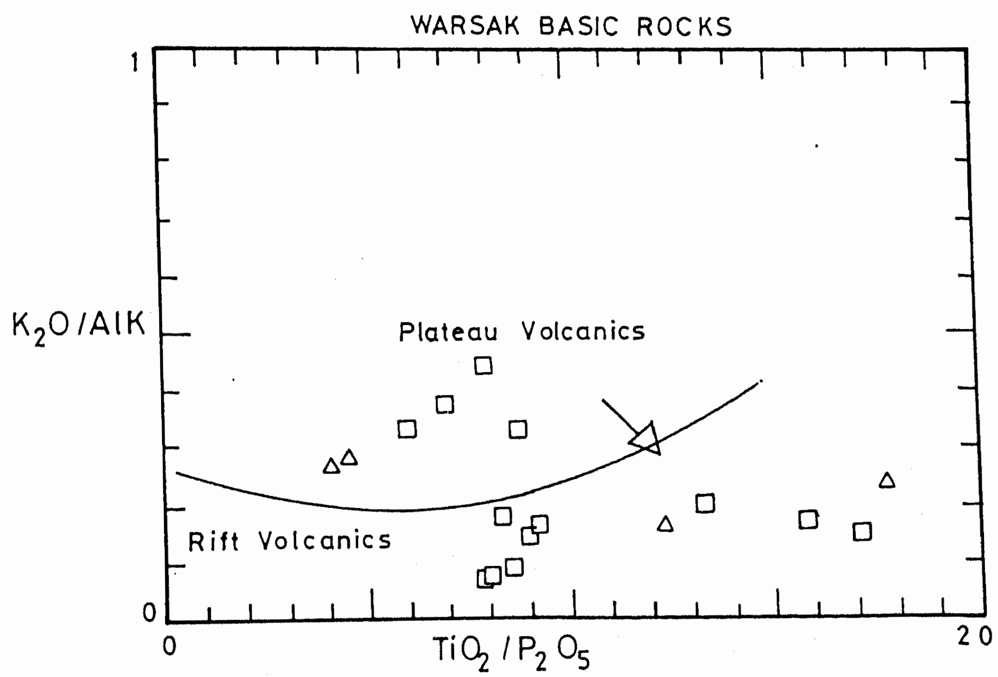
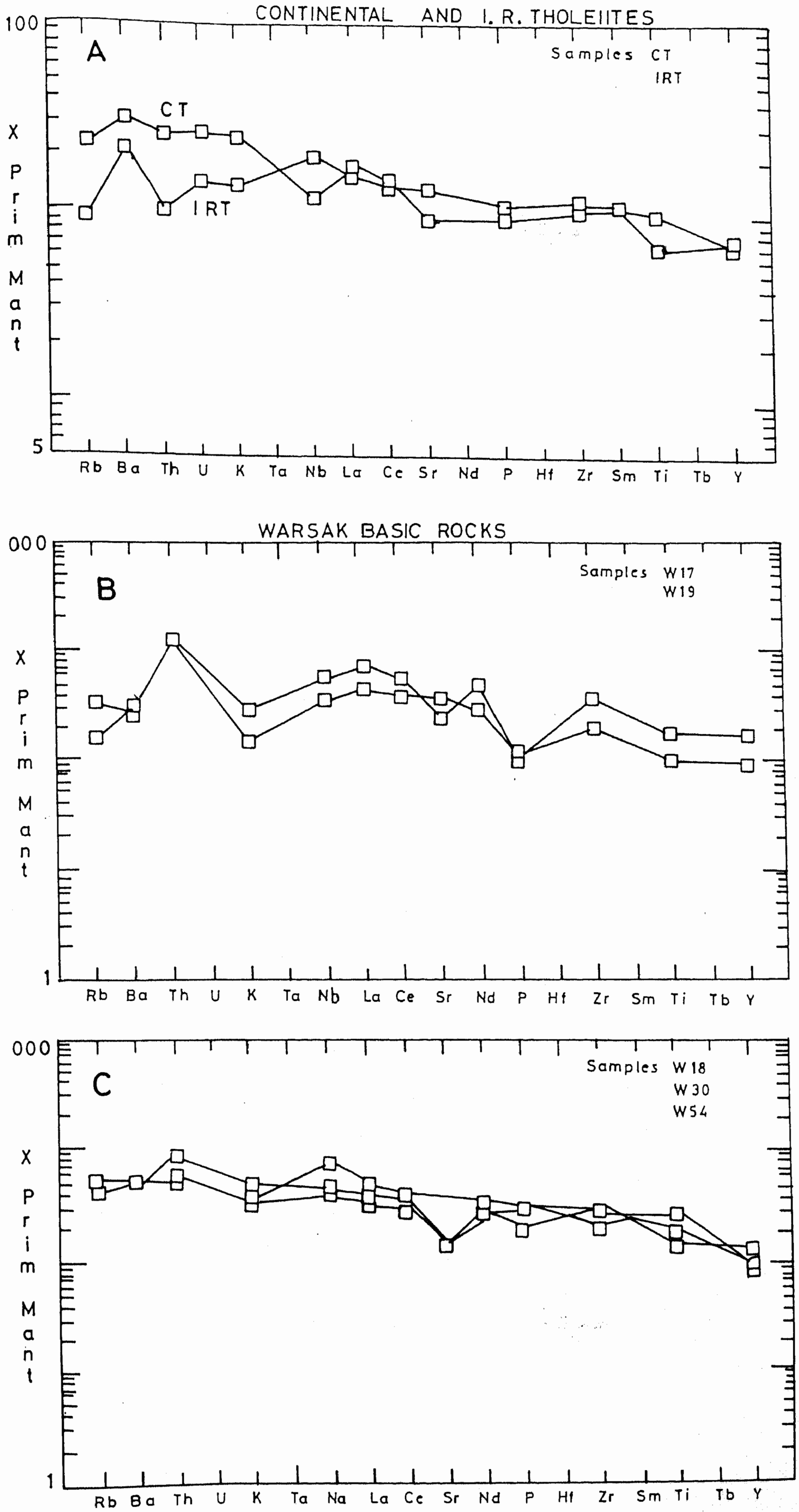


Figure (5.17). Determination of rifting component in the Warsak basic rocks using K2O/Alkalies vs TiO diagram of Chandrasekharam and Parthasarty (1978).

Figure (5.18). A) Mantle normalised trace element patterns of the continental tholeiitic basalts compared with tholeiites with components of initial rifting (after Holm, 1985), B, C) Mantle normalised patterns of the Warsak basic rocks showing an initial rifting component reflected in a positive Nb anomaly and a high Ti/Y ratio. Data for continental tholeiites (CT) and Initial Rift Tholeiite (IRT) from Holm (1985).


CONTINENTAL AND I. R. THOLEIITES
A
Samples CT
IRT
CT
IRT
100
5
X Prim Mant
Rb Ba Th U K Ta Nb La Ce Sr Nd P Hf Zr Sm Ti Tb Y
WARSAK BASIC ROCKS
B
Samples W17
W19
000
1
X Prim Mant
Rb Ba Th U K Ta Nb La Ce Sr Nd P Hf Zr Sm Ti Tb Y
C
Samples W18
W30
W54
000
1
X Prim Mant
Rb Ba Th U K Ta Na La Ce Sr Nd P Hf Zr Sm Ti Tb Y

CHAPTER 6.

SYNTHESIS & DISCUSSIONS

The WIC is a biomdodal suite of igneous rocks comprising peralkaline to peraluminous granites on the one hand and basic rocks of gabbroic composition on the other. These diverse igneous lithologies are in a closed field association, in the form of alternating sheeted masses which are concordant both mutually and with the metasedimentary country rocks. The field relations do not yield unambiguous relative age relations between the two rock types; Ahmed (1951) considered the granites to be older than the basic rocks, whereas Ahmed et al (1969) suggested the basic rocks to be older. During this work the large-scale field relations such as occurrences of the basic rocks as large xenoliths in the granites were used to show that the basic rocks are probably older than the granites, though on outcrop scales thin basic dykes were seen intruding the granites, whereas in the nearby outcrops basic rocks were seen cut across by granite veins. Rocks of intermediate composition between the gabbros and granites are rare, restricted to the marginal portions of the sheets which are probably a consequence of mutual contamination of the diverse lithologies.

The Warsak Granite

The granites in the Warsak area occur in three petrographic varieties; main aegirine-riebeckite granite (WMARG), porphyritic aegirine-riebeckite granite (WPARG), and porphyritic biotite-muscovite granite (WPBMG). The WMARG and WPARG classify as "alkali granites" and the WPBMG as "granite" according to the scheme of La Roche (1980). When evaluated using Shand's indices (using relative proportions of $Al2O3$, CaO, and alkalies), it is only the WMARG which is peralkaline, the WPARG is mainly metaluminous and the WPBMG is both metaluminous and peraluminous. Whereas the WMARG and WPARG, with a similar mineral assemblage are apparently derived from a same parental magma, the WPBMG may or may not be a product of the same parent magma. The differences between these granites of contrasting mineral assemblages may be due 1) differences in the source composition during derivation of the parent melts; the parent magmas of WMARG and WPARG were derived from an igneous protolith whereas that of the WPBMG was derived from a sedimentary protolith (S-type), or 2) contamination of a I-type parent melt with sediments; the WMARG and WPARG were crystallised from the pure I-type melt, whereas the fraction of the I-type melt contaminated with sediments crystallised WPBMG. Interestingly, the Warsak granites, irrespective of their textural, mineralogical and major element composition differences, are remarkably similar in terms of ratios involving incompatible trace elements reflected in mantle-normalised trace element patterns presented in the form of spidergrams. This suggest that all the granite varieties in the Warsak area were probably derived from a same parental melt, the earlier fractions involved a greater degree of contamination by S-type components and crystallised as WPBMG, whereas the subsequent fractions following the established channels and thus an easy unrestricted passage, reached the surface as relatively uncontaminated melts crystallising into WMARG and WPARG granites.

The Warsak granites are type A-type granites (Loiselle and Wones, 1979; Whalen et al., 1987), with compositional characteristics such as high SiO_2, Na_2O+K_2O, Fe/Mg, Zr, Nb, Ga, Y, and REE contents, and low CaO, Ba, and Sr. In this respect they resemble closely with granites from Lachlan Fold Belt of Australia (White and Chappel, 1983), Topsails igneous terrane, Western Newfoundland (Whalen et al., 1987), Midian mountain peralkaline granites, Saudi Arabia (Harris and Marriner, 1980). Although previously, the A-type granites were considered to be related with rifting of anorogenic cratons (Loiselle and Wones, 1979,; Collins et al., 1982), Whalen et al. (1987) have sited examples of A-type granites in diverse tectonic environments (including active rifts, trascurrently faulted subduction zone, in Applalachian-Caledonide orogen and post orogenic settings). The A-type granites from the Warsak area are however, typically generated in intra-plate continental environments, with a strong component of rifting, as shown by their close resemblance in trace elements with the granites from the known rifting environments such as Oslo, and Ascention island.

The Basic Rocks

The WIC contains sheeted masses of basic rocks which are equally abundant and have a mode of occurrence closely similar to the closely associated granites. Although the mineralogy is greatly obscured by an amphibolite-facies metamorphism, a few rocks retain relict cumulate pyroxene crystals. The major elements (e.g., relative proportions of alkalies, MgO, and total FeO) suggest a type tholeiitic composition contrary to the calc-alkaline composition suggested by Kempe (1978). The major and trace element variations suggest a role of olivine, clinopyroxene and plagioclase during fractional crystallisation. The low mg no (?) supports this conclusion that the Warsak basic rocks are derivative rather than being close to primary magmas. Occurrence of cumulate and derivative rocks in same sheeted suggest that that fractional crystallisation took place in the current position of the intrusions. However, it cannot be ruled that the magma which was emplaced to form sill-like bodies at Warsak was itself derivative from a fractionation event at lower crustal levels, a feature common to most tholeiitic flood basalts (Cox, 1980).

The tectonic setting of magma generation for the Warsak basic rocks has been characterised by using trace elements and their mutual ratios. The Warsak basic rocks are typically rich in Zr, Y, NB, and TiO, which is a characteristic compositional trait of within-plate tholeiitic flood basalts of continental origin. Some of the trace element characteristics of the Warsak basic rocks are however transitional between continental flood basalts and oceanic tholeiitic basalts, suggesting that the Warsak basic rocks may have a component of initial rifting environments, similar to that suggested for continental flood basalts from Scoresby Sund area, Eastern Greenland, Baffin islands, Western Greenland, and basalts from the Deccan Plateau (Pearce et al., 1975; Rickwood, 1989).

DISCUSSION

The within-plate (alkaline) magmatism around the Peshawar plain is known since 1936, when Coulson (1936) first reported occurrence of alkaline granites from Warsak and Shahbazgarhi areas. By 1970, alkaline granites and carbonatites were reported from several other places from Loe Shilman, Sillai Patti. Ambela, Koga, Malakand, and Tarbela, which led to suggestion by Kempe and Jan 1970; repeated by Kempe and Jan, 1980; Kempe, 1983; Butt et al., 1980) that there was an alkaline province in the vicinity of Peshawar plain, formed around mid Tertiary (based on K/Ar age data by Kempe, 1973). In the recent years various occurrences of carbonatites and other alkaline rocks have been studied in considerable details (Jan et al., 1981; Rafiq, 1987; Mian, 1987). Le Bas et al. (1986) has produced new age data based on Rb/Sr whole-rock isochron for the alkaline rocks from the Koga-Ambela area, suggesting a Carboniferous age for the Peshawar plain alkaline province. The Warsak granites were considered by Kempe (173) to be Tertiary in age on the basis of K/Ar data on separated minerals. Maluski and Matt (1984) obtained similar ages from the Warsak granites which they interpreted as age of a tectonometamorphic event and not the age of primary emplacement. The age of the Warsak granites is probably same as that of the Ambela-Koga alkaline rocks; i.e., Carboniferous rather than Tertiary, but this has to be confirmed by dating of the Warsak granites with a dating system with higher blocking temperatures than the Ar^{40}/Ar^{39}.

The basic rocks are not that abundant, but are commonly found in association with alkaline rocks in the Peshawar plain alkaline province, including Tarbela, Shewa-Shahbazgarhi, Ambela, Koga, and Sillai Patti (Kempe and Jan, 1980). At places the basic rocks are older than the associated alkaline granites and other alkaline rocks, such as Warsak, Tarbela, and Sillai Patti, whereas in Ambela and Shewa Shahbazgarhi, the basic rocks are relatively younger than the alkaline granites. The composition of the basic rocks is also not consistent; in the Warsak area they are tholeiitic, in Tarbela they are alkali olivine basalts, whereas in Koga, they are strongly alkaline with ijolitic compositions (Mian, 1988). Interestingly, the whole spectrum of the basic rocks in the Peshawar-plain alkaline province ranging from tholeiites to ijolites indicate a tectonic setting in which an episode of intra-cratonic rifting is ongoing; a setting which is indicated also by the alkaline granites. It is suggested that the rift-related magmatism in the Peshawar plain initiated with tholeiitic plateau-type basalts, now represented by the Warsak basic rocks and common tholeiite dykes found intruding the Precambrian slates and Palaeozoic strata in N. Pakistan (Karim and Sufian, 1989). The rift-related magmatism in the Peshawar plain probably continued for a considerable time during the late Palaeozoic while India was in the process of separating from the Gondwana, the supercontinent. The various compositions of basic rocks were intruded during this rifting event ranging from tholeiitic, through alkali olivine basaltic to strongly alkaline basic rocks. The thinning of the continental crust and the emplacement and passage of these basic rocks resulted in the partial melting of lower continental crust, resulting in the A-type granite magmatism ranging from peralkaline to peraluminous compositions.

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Appendex

Warsak Main Aegirine Reibeckite Granite.

W1.2,3, 44,46.	About 6Km SE of Warsak dame site, near Zagai Sar.
W47,49	About 4. 50 Km SE of dame site near Adam-Khan Killi.
W4,7,8	Right at the dame-site.
W9,11,13	3.25Km SE of dame-site at the northern slope of Spera Ghar.
T28	Right at the dame site.
T29	Warsak Main Aegirine Reibeckite Granite 100 M below the dame-site.
T45	Warsak Main Aegirine Reibeckite Granit
T46	Fine grained granite intrusive into coarse grained T45.
Kemp7,9	Mulagori Road south of Warsak
Kemp 8	Spera Ghar, South of Warsak.
Comp	Quartz , Perthite , Albite , Aegirine , Riebeckite , Astrophylite , Biotite , Sphene , Zircon , Epidote , Ore.

Warsak Porphyritic Biotite Muscovite Granite

W21,23	About 50m East of damesite near the bridge in the road cut.
T32,33	100 feet east of dame-site first out crop of this type coming from dame site.
T40	Right at the bridge.
T41,42	Exect 100M east of dame site in the road cut.

Kemp5	North-East of dame-site.
Comp	Quartz , Microperthite , Perthite , Muscovite , Biotite , Epidote Garnet.
	Warsak Porphyritic Aegirine Reibeckite Granite
W42,51,53.	2Km east of dame-site near Ali-baba Ziarat at road leading to Dame-site.
W47. 51,53	From sills west of main body near Ali-baba Ziarat.
Kemp6	Road to Warsak dam.
Comp	Perthite , Microcline , Quartz , Aibite ,riebeckite , Aegirine , Ilminite , Magnitite , Biotite.

Fine grained basic rock

W5	Right at dame-site dyke in the main aegirine-reibeckite granite.
W14	Few meter east of dame-site in the road cut.
W17,18	About 1Km east of damesite on the northern side of river.
W19,20	1.50Km east of dame site near bridge.
W34,36	South of the river about 1.25Km east of dame-site.
T30,31	200m east of dame, a sheared basic dyke near aluminum gate.
T34	Near the bridge on the north side of the river.
T35	From the south side of river at the mouth of bridge near the check-post.
T38,39	100M from the bridge. 100m below the bridge.
T44	2Km east of dame on the nort of river.
T52	Near check-Post.
Kemp94	Right at the dame-site from the basic dyke in main alkaline granites.

P61,62	North side of rivrer near the bridge.
P59	Near the Check-Post.
Comp	Amphibole . Plagioclase , Epidote , Quartz , Biotite , Sphene , Ilmenite and rarely garnet.,

Coarse grained basic rocks

W26,29,30	2Km east of dame-site on the north side of river.
W54	2Km east of dame-site close to WPBMG body near Ali-baba Ziarat.
T43	2Km east of dame on the north side of river.
T50	Near Check-Post.
Comp	CPX,OpX,Plg,sphene,rutile,Qtz,Bio.