

The geochemistry and metamorphism of calc-silicate rocks, marbles and amphibolites in a portion of the Zambezi belt, Southern Zambia.

By

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A dissertation submitted to the University of Zambia in fulfillment of the requirement of the Degree of Master of Mineral Sciences (Geology) of the School of Mines.

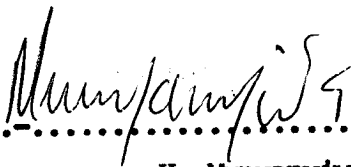
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September, 1985



DECLARATION

I declare that this thesis was written in accordance with the rules and regulations governing the award of Master of Mineral Sciences Degree of the University of Zambia. I further declare that the thesis has neither in part nor in whole been presented as substance for award of any degree, either to this or to any other University. Where other peoples work has been drawn upon, acknowledgement has been made.

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To my Teachers, a source of my inspirations.

ABSTRACT

Calc-silicate rocks and marbles of Katangan age underlie a significant segment of the Zambezi belt in Southern Province. The calc-silicate rocks are represented by spectacularly banded calc-silicate gneisses, calc-silicate schists, massive calc-silicate rocks and a few mottled varieties. The marbles are uniformly calcite - and dolomite-marbles. In the Mapanza area, minor amphibolites are sporadically distributed as lenticular bodies, bands and boudins within the marbles and calc-silicate rocks.

The rocks were deformed and metamorphosed to amphibolite facies and later partly retrogressed to greenschist facies during Pan-African tectonothermal events. Amphibolite facies assemblages in the calc-silicate rocks include biotite + scapolite + quartz + calcite, quartz + actinolite + diopside + grossularite + sphene and quartz + plagioclase + diopside + calcite + sphene. Those in the marbles include dolomite + tremolite, calcite + biotite + scapolite, dolomite and dolomite + diopside.

The amphibolites are of basic igneous origin with a possible minor sedimentary component for the amphibolite boudins and bands. Their mineralogy is largely influenced by the bulk composition, with garnet occurring only in amphibolites with $Fe/(Fe + Mg) > 0.5$.

Geochemical data, Niggli parameters and plots of inter-element correlations for the calc-silicate rocks and marbles are presented. These support the conclusion that during metamorphism the major and trace elements were not significantly mobilized. Instead the variation in bulk chemical composition of the rocks and the resulting variations

in equilibrium metamorphic mineral assemblages, are best explained in terms of original variations in the proportions of clays and other detrital phases intermixed with carbonate during deposition.

Geothermobarometry is applied for the first time in this part of the Zambezi belt. Compositions of coexisting biotite and garnet in the amphibolite yield temperatures of $630-660^{\circ}\text{C}$ and compositions of coexisting plagioclase and hornblende in the amphibolites yield temperatures of $560-630^{\circ}\text{C}$ and pressures of 5-6 Kbars for the peak of metamorphism. These values are in accord with intermediate pressure (Barrovian type) amphibolite facies metamorphism, and are consistent with the phase assemblages in the calc-silicate rocks, marbles and amphibolites based on published experimental data. Compositions of calcite coexisting with dolomite in the marbles yield maximum temperatures of $490-500^{\circ}\text{C}$, apparently reflecting re-equilibration following the peak of metamorphism.

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CHAPTER ONE

INTRODUCTION

1.1. Statement of the Problem

The geochemistry and metamorphic petrology of the Katangan succession underlying a significant portion of the Zambezi belt in Southern Zambia has recieved relatively little attention. Prior to the present study, no detailed geochemical studies or precise estimates of metamorphic conditions have been attempted.

The thesis concerns the geochemistry and metamorphic petrology of the carbonate and calc-silicate rocks and amphibolites in the Zambezi belt south of Kafue. It presents detailed petrographical, geochemical and petrological studies of the rocks.

Petrographical and geochemical data for these rocks sheds light on processes of metamorphism, nature of banding in the rocks and causes of variations in the metamorphic mineral assemblages. Knowledge of the metamorphic petrology of the rocks is necessary because it gives information on pressure and temperature conditions as well as the nature of mineral-forming reactions occurring during Pan-African metamorphism.

1.2 Location and accessibility

The investigated area is located within Southern Province. It falls within the region covered by Quarter Degree sheets 1527SE,

1528SW, 1627NE and 1628NW and lies between the Munal Hills to the north and Magoye to the south. Rocks further to the southwest within Quarter Degree Sheet 1626NE of the Mapanza Mission Area have also been studied.

Accessibility through the study area is by the Great North Road (GNR) from which there is a network of tracks to commercial farms which are motorable throughout the year. All weather roads branching off the GNR in Choma and Pemba and leaving to Namwala pass through Mapanza Mission. Accessibility into the surrounding areas from the Mission is by dirt roads, some of which are not motorable during the rainy season.

1.3 Geologic Setting

1.3.1 Regional Setting of the Zambezi belt

The study area is located structurally within the Zambezi belt. The belt is a major linear fold belt of Pan-African age (C. 500-950 Ma, (1)) which forms a large part of central and southern Zambia (Fig. 1.1). It is also part of the broad region of metamorphic rocks recently defined as the Luangwa-Kariba region and covering the eastern and southern parts of Zambia (3).

The Zambezi belt is one of the Southern African Precambrian mobile belts and has an arcuate form (4). In Zambia, the belt has northwest - southeast regional trends in most parts of central and southern Zambia, which change to west-northwest further to the southwest in the Mapanza Mission area.

The northern boundary of the Zambezi belt in Zambia has been defined as the Mwembeshi dislocation, a major crustal discontinuity which separates the belt from the Pan-African Lufilian Arc of the Copperbelt to the North^(5,6). To the Southwest in the Mapanza area, the belt becomes covered by recent alluvial sediments of the Kafue flats. Further to the Southwest in Namibia, a correlation of the Zambezi belt with the southern segment of the Damaran mobile belt has been advanced based on broad lithological similarity⁽⁶⁾.

The Zambezi belt truncates the northeast trending structures of the older Irumide belt (C. 1100-1350 Ma, (1)) at almost right angles in central and southern Zambia, and terminates to the Southeast against the Post-Karoo faults in the mid-Zambezi valley. It reappears in Zimbabwe where it forms a narrow strip of country between the northern margin of the Zimbabwe craton and the Karroo rocks of the mid-Zambezi valley. Its eastern prolongation is poorly defined but it is believed to merge structurally into the north-south trending Mozambique belt, also of Pan-African age⁽⁷⁾.

1.3.2 Lithological and stratigraphic make-up

Reconnaissance regional geological mapping by the geological survey, Zambia, has revealed a thick supracrustal sequence of various pre-Karoo lithologies in the Zambezi belt. This consists of metapelites, semipelites, psammites, calc-silicate and carbonate rocks, and minor volcanic rocks deposited during the late Proterozoic Pan-African cycle (8,9,10,11,12,13,14). In addition, there are two large units of orthogneiss interleaved with the metasedimentary

rocks. These were previously interpreted to represent earlier, refo-
liated basement rocks.⁽⁵⁾ Recent field and geochronological data for
these rocks, however, suggest that they represent syntectonic granites
intruded during Pan-African deformation⁽¹⁵⁾. Less abundant metabasic
rocks, mainly amphibolites, are also sporadically distributed within
the Zambezi belt.

Lithostratigraphic correlation within the belt is hampered by the
intense Pan-African deformation and regional metamorphism. The meta-
sedimentary rocks were recently assigned to the Monze Group by the
stratigraphic committee of the Geological Survey (Ray et al., in
Prep.) A generalized correlation of metasedimentary rocks within the
Zambezi belt is set out in Table 1.1.

The metasedimentary rocks of the Zambezi belt are separated from
those of the Lufilian Arc in the Copperbelt to the north by a marked
difference in structural vergence and metamorphic grade across the
Mwembeshi dislocation^(5,16). The rocks of Zambezi belt are generally
higher in metamorphic grade and show a south and southwest vergence
whereas the lower grade Katangan succession of the Copperbelt shows a
northerly vergence. Despite these differences, the Zambezi belt meta-
sedimentary rocks have been correlated with the Katangan Supergroup of
the Copperbelt⁽⁵⁾. This correlation is suggested by the general simi-
larity of the lithological succession of the Copperbelt with that to
the South, and by the available geochronological evidence^(17,1,15).

Table 1.1 Suggested correlation of the Katanga Supergroup Metasedimentary rocks in Central and Southern Province (partly after de Swardt et al (4)),

Mapanza Mission area (Tavener-Smith (8))	Magoye-Gwembe area (Newton (7))	Mazabuka area (Brown (12))	Mazabuka area (Smith (10))	Kafue area (Smith (10))	Lusaka area (Simpson et al (9))
not represented	not represented	not represented	not represented	Lusaka Dolomite (dolomite and calcite marbles)	Lusaka dolomite (dolomite and calcite marbles)
Mapanza Carbonate Formation (marbles and calc-silicate rocks.)	Kaleya Lime- stone? (Mar- bles) Muzuma calc-silicate Formation	Marble hori- zon within orthogneiss Muzuma calc- silicate	Kaleya Lime- stone (Mar- bles) Muzuma Calc-silicate Formation and Chifumpu Lime- stone	Cheta Form- ation (impure marbles quartzite metasilt- stone	Cheta Formation (impure marbles Psammites)
Chilumbwe Schist Formation (biotite- muscovite schist, quartz-biotite schist and micace- ous quartzite)	Chivuna Form- ation quart- zite and quartz-biotite schist 'beds' within so- called Nadongo Group.	Nega Forma- ation (quart- biotite schist) Sachenga For- mation (quart- z-biotite schist) Nteme Formation (quartz-biotite schist)	Nega Formation (quartzite and quartz-musco- vite schist, minor marbles.	Chipongwe Formation (pelite or semipelite) Fuswe Pelite (biotite- Kyanite schist) Mulola Formation (schists, quartzites)	Chunga Formation (biotite-muscovite schists).

In the area between Lusaka and Rufunsa, Katangan supracrustal rocks are in general absent, but east-west Pan-African structures are strongly developed and overprint earlier structures in the basement rocks. Barr⁽¹⁸⁾ maintains that this area represents portion of the Zambezi belt where the original Katangan supracrustal sequence has been stripped off.

1.3.3. Structural framework

Several phases of deformation related to the Pan-African cycle have been recognized in the Zambezi belt (10,11,19,14). In most parts of the belt, an earlier, main-phase deformation was intense and gave rise a regional penetrative northwest and west-north-west trending foliation.

This penetrative foliation is related to tight to isoclinal recumbent folds with northwest trending axes around the Lusaka area and Central Province. A similar style of folding is present further south in southern Province, but there the folds have more steeply dipping axial surfaces. In the Kafue area, however, this style of folding is complicated by the rise of the Mpande dome (11). This distorted the regional structural trends to produce concentric structures around the dome (11,20).

In some parts of the belt, the main-phase deformation was followed by relatively less intense open folding coaxial with the tight to isoclinal F_1 folds, and by still later open folds with northeast trending axes (10,14,13).

In addition, recent structural data has been accumulated in Southern Province along the boundary between the Irumide and Zambezi belts, which show that the main-phase deformation in the Zambezi belt was accompanied by shearing resulting in transposition of earlier north-east trending Irumide structures into the north-west Zambezi trends. Furthermore, sheath fold development and down - dip mineral extension lineation in some Katangan lithologies within the Zambezi belt suggests southwards thrusting of the metasedimentary rocks during the main phase of deformation ⁽¹⁵⁾. This is consistent with the general south and southwest vergence of the Katanga succession south of the Mwembeshi dislocation Zone ^(5,21).

1.3.4 Metamorphic framework

The metamorphic petrology of the pre-Karoo sequence in the Zambezi belt has mainly been documented on a cursory basis, and information regarding the metamorphic state of the rocks is mainly derived from the Geological Survey reports.

In the Lusaka area, metamorphic grade in the sequence apparently depends on stratigraphic position. At the base of the succession, the pelites contain kyanite and staurolite, characteristic of amphibolite facies. These pass upwards into low grade, greenschist facies schists and phyllites containing muscovite and chlorite. The situation, however, is complicated by the presence of small bodies of eclogite of presumed Katangan age contained within the metasedimentary rocks ⁽²²⁾. These were initially regarded as having been tectonically emplaced.

Vrana et al⁽²³⁾, however, concluded from petrological studies that the eclogite bodies were formed by deformation and metamorphism of gabbros which intruded the Katangan sequence prior to regional metamorphism.

In the Zambezi belt in the Rufunsa area and in some parts of the Lufilian Arc, Vrana and Barr⁽²⁴⁾ and Barr⁽¹⁸⁾ have documented talc-kyanite assemblages, characteristic of high pressure metamorphism. They have deduced pressures in the order of at least 10 Kbars for the formation of the assemblages during the Pan-African metamorphism, based on comparisons with experimental data.

Around and south of Kafue, kyanite and staurolite - bearing assemblages diagnostic of amphibolite facies are abundant in the metapelites (8,9,11,12,13). A comprehensive investigation of the metamorphism of pelites, semipelites, carbonate rocks and volcanic rocks in relation to phases of deformation was conducted in the Kafue area around the Mpande dome⁽²⁵⁾. There, it was shown that the maximum grade reached was of the Kyanite Zone.

Pseudomorphs possibly after andalusite have been recorded in the Munali Hills area in the Nega Formation⁽¹¹⁾. To the south and south-east in the same formation, however, kyanite is abundant⁽¹³⁾. When mapping the area between Magoye and Gwembe (sheet 1627NE), Newton⁽⁸⁾ concluded that the grade of metamorphism increased slightly to the South. This was based on the fact that 'staurolite and kyanite are found only in the South accompanied by large garnets, but in the north, rocks of comparable composition show only very small garnets.'

In the Mapanza Mission area near the Southwestern extremity of the Zambezi belt in Zambia, Tavener-Smith⁽⁹⁾ has documented kyanite, staurolite and almandine - bearing assemblage in the metapelites, again diagnostic of amphibolite facies.

The metamorphic petrology of the calc-silicate rocks and marbles in the Zambezi belt south of Kafue was briefly described by Newton⁽⁸⁾, Tavener - Smith⁽⁹⁾ and Brown⁽¹³⁾, who showed that these rocks contain diopside, hornblende, plagioclase and scapolite, suggesting that they are isofacial with the adjacent Katangan metapelites.

Another petrological study of a regional nature is that of Ramsay and Ridgway⁽³⁾. Based on the identification of diagnostic phases in thin sections, these workers have concluded that the broad Luangwa-Kariba region within which the Zambezi belt forms a part, was largely subjected to intermediate pressure, upper amphibolite facies metamorphism during the Pan-African Orogenic events. Their work, however, has been strongly criticized by Vrana⁽²⁶⁾ who argue that the method adopted by Ramsay and Ridgway⁽³⁾ cannot be applied in a structurally complex region such as the Luangwa-Kariba area, which has been subjected to repeated episodes of deformation and metamorphism.

CHAPTER TWO

FIELD RELATIONS AND PETROGRAPHY

2.1 Introduction

The field relations and petrography of the calc-silicate rocks, marbles and amphibolites are discussed. Representative modal analyses obtained from point-counting at least 600 points per thin section are given in Tables 2.2, 2.3 and 2.4. The calc-silicate gneisses and a few mottled calc-silicate rocks were not point counted due to their banded and porphyroblastic nature. Representative mineralogical compositions of the individual layers of the calc-silicate gneisses and the mottled calc-silicate rocks, however, are listed in Table 2.1.

Numbers of samples referred to in the discussion of petrography designate thin sections which exhibit the particular features being discussed. These samples are not in all cases listed in Tables 2.1-2.4. Samples with the same number but different letters added on refer to different discrete samples collected from the same outcrop

In some cases, textural evidence has enabled the classification of the individual minerals into primary (P) and secondary (S) depending on whether or not the mineral formed during retrograde replacement of earlier, primary minerals. This is the procedure adopted by Kretz⁽²⁷⁾ and has an important bearing on the discussion of metamorphism to follow.

In the marbles, calcite was distinguished from dolomite by staining with alizarin red S solution as outlined by Warne⁽²⁸⁾. Staining of

slabs of the calc-silicate rocks revealed all carbonate grains to be calcite.

The distribution and sample locations of the calc-silicate rocks and associated marbles and amphibolites are indicated on Figure 2.1. Sampling was conducted along and across the regional northwest trend and covered most calc-silicate rock types and marbles. In some cases, this was hindered by poor exposure and the presence of large commercial farms within the calc-silicate terrane. Sampling of amphibolites was restricted to the Mapanza Mission area.

2.2 FIELD RELATIONS

2.2.1 Calc-silicate rocks

The calc-silicate rocks are well-developed in Southern Province, south of Kafue. They are located within a strip of country starting south of the Munali Hills and extending about 30 Km southwards to Magoye.

The rocks form a thick sequence, the Muzuma Calc-silicate Formation, which is part of the northwest plunging Mazabuka synclinorium⁽¹³⁾. They extend along strike for about 80 Km, and to the southeast terminate against the Post-Karroo faults of the mid-Zambezi valley (Fig. 2.1). Locally in the pelitic Nega Formation⁽¹³⁾, which flanks the Muzuma Calc-silicate Formation to the north, the calc-silicate rocks crop out as bands 5 to 10m thick and extend along strike for about 1 Km.

26°05'E
05°S

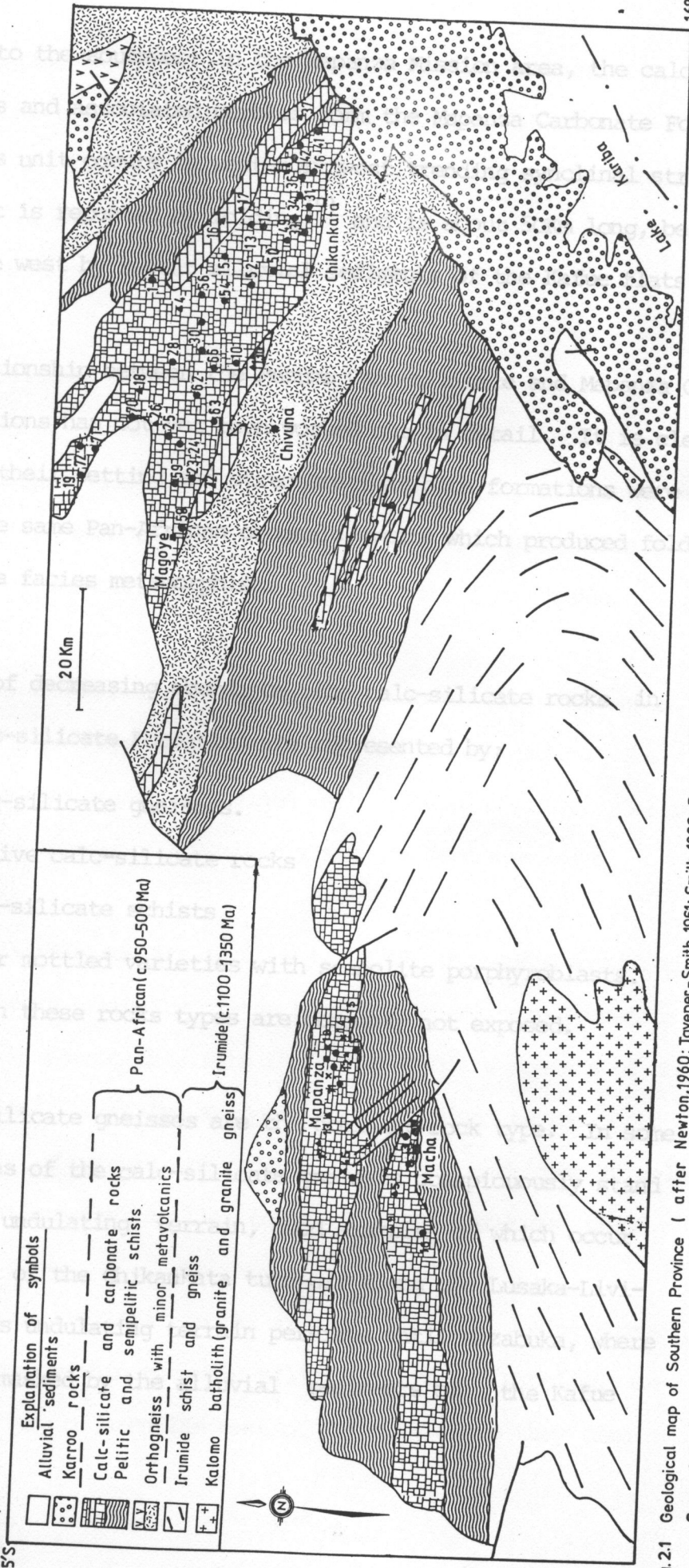


Fig.2.1 Geological map of Southern Province (after Newton,1960; Brown,1966,1967) showing sample localities. ● represents calc-silicate rocks, ▲ marbles, × minor amphibolites. Some of the samples spatially too close have not been plotted and their locations are indicated in Appendix IV.

16°40'S
28°28'E

Further to the southwest in the Mapanza Mission area, the calc-silicate rocks and associated marbles form the Mapanza Carbonate Formation⁽⁹⁾. This unit occurs in west-northwest trending synclinal structures where it is repeated by folding⁽⁹⁾ and is about 50Km long, being covered to the west by recent alluvial sediments of the Kafue flats.

The relationship between the Muzuma Calc-silicate and Mapanza Carbonate Formations has not yet been worked out in detail. It is clear, however, from their setting and structure that both formations were affected by the same Pan-African orogenic events which produced folding and amphibolite facies metamorphism.

In order of decreasing abundance, the calc-silicate rocks in the Muzuma Calc-silicate Formation are represented by:

- (1) Calc-silicate gneisses.
- (2) Massive calc-silicate rocks
- (3) Calc-silicate schists
- (4) Minor mottled varieties with scapolite porphyroblasts.

Contacts between these rocks types are commonly not exposed.

The calc-silicate gneisses are the dominant rock type. In some places, exposures of the calc-silicate gneisses conspicuously stand out in a gently undulating terrain, good examples of which occur about 5 Km north of the Chikankata turn-off along the Lusaka-Livinstone road. This undulating terrain persists until Mazabuka, where it starts to be masked by the alluvial sediments of the Kafue flats.



Plate 1a. Folded calc-silicate layers of the calc-silicate gneisses with a well-developed lineation. Coin is approximately 3cm in diameter.



Plate 1b. Folded calc-silicate layers in calc-silicate gneisses.

interbands up to 3-4m thick within the calc-silicate gneisses. The latter show the mottled texture only in the fine-grained dark bands.

The mottled calc-silicate rocks are massive, dark grey and speckled with whitish grey ovoid scapolite porphyroblasts 0.5 to 1cm in diameter set in a fine - to medium-grained weakly foliated matrix. On some outcrops, these porphyroblasts stand out on weathered surfaces.

In the Mapanza Carbonate Formation to the Southwest, the calc-silicate rocks are generally poorly exposed, but excellent outcrops are located along the Munyeke River. The rocks are similar to those of the Muzuma Calc-silicate Formation in most respects except for the lack of mottled calc-silicate rocks. The calc-silicate rocks are also closely associated with marbles similar to those of the Muzumba Calc-silicate Formation. The calc-silicate rocks are abundant in the lower part of the Mapanza Carbonate Formation where they are associated with thin bands of impure quartzite and pass upwards into the marbles⁽⁹⁾.

2.2.2 Marbles

The marbles are extensively distributed on both the northern and southern margins of the Muzuma Calc-silicate Formation, forming units that extend along strike for up to 20 Km. In addition, lenses and bands of marbles some 5 Km long and up to 200m thick occur sporadically within the calc-silicate terrane. Excellent exposures of these crop out along the Munyameshi River, northeast and east of the Chikankata

Mission area. There, the bands are in sharp contact with the adjacent calc-silicate gneisses. Isolated bands of marbles about 200m thick are located within the psammitic and pelitic Chivuma Formation⁽⁸⁾, about 500m south of the Chivuma Mission. Distinctive horizons of the marbles are also extensively developed within the Nadongo Group, further to the South of the Chivuma Mission⁽⁷⁾. These are up to one km in width and extend up to 50km along strike. These horizons, however, were not studied in the present work.

In the Mapanza Carbonate Formation, the marbles are poorly exposed. Exposure of these rocks are largely confined to the Munyeke River, with excellent examples being found beneath the bridge along the Choma-Namwala road. In this area, the relationship between the marbles and calc-silicate rocks is gradational, with the former confined to the top of the Mapanza Carbonate Formation where they form a thick unit⁽⁹⁾.

In general, the marbles in both formations occur either as calcite marbles or dolomite marbles. The former are predominantly medium grained, massive and generally greyish in color. The dolomite marbles are fine to medium grained and vary in color from pinkish-white and white to grey. Dolomite marble cropping out some 500m South of the Chivuma Mission shows excellent streaks of white fibrous tremolite. A few specimens of the calcite marbles show color banding defined by calcite crystals alternating with biotite-rich layers about 2mm in thickness.

2.2.3 Amphibolites

Amphibolites are widely scattered within the Zambezi belt (8,9,10,11,13). Those that have been studied in the present work are located within the Mapanza Mission area, within the Mapanza Carbonate Formation. In this formation, the amphibolites crop out in two forms: as boudins, lenses and bands about one metre thick concordant with the foliation in the host carbonate and calc-silicate rocks, and as larger linear to lenticular bodies forming ridges parallel to the regional west-northwest trend.

Excellent examples of the boudins, lenses and bands of amphibolite crop out beneath the bridge along the Choma-Namwala Road, across the Munyeke River (plates 2a and b). Here, disrupted boudins and contorted lenses and bands of amphibolite have sharp contacts against the enclosing calc-silicate gneisses and marbles. Banding in the host carbonate and calc-silicate rocks flows around the amphibolites, indicating that during deformation the host rocks were less competent than the amphibolites. The amphibolites have a weak foliation which is parallel to the foliation in the country rocks and is defined by orientated hornblende. The rocks are medium grained with a dark green color. In addition to hornblende and plagioclase, pink garnet may be seen in hand specimens.

Numerous larger linear to lenticular bodies of amphibolite occurring as ridges are sporadically developed within the Mapanza Carbonate Formation. These bodies are mainly 500 to 150m in length,

20 to 50m wide, and rise 10 to 20m above the flat-lying carbonate terrain. Contacts with the country rocks are not exposed, but the bodies apparently thin out before they disappear into the flat-lying country. To the Southeast from the Mapanza Mission hospital, along the road to Pemba, an amphibolite body exhibit a possible intertonguing relation with the country rocks.

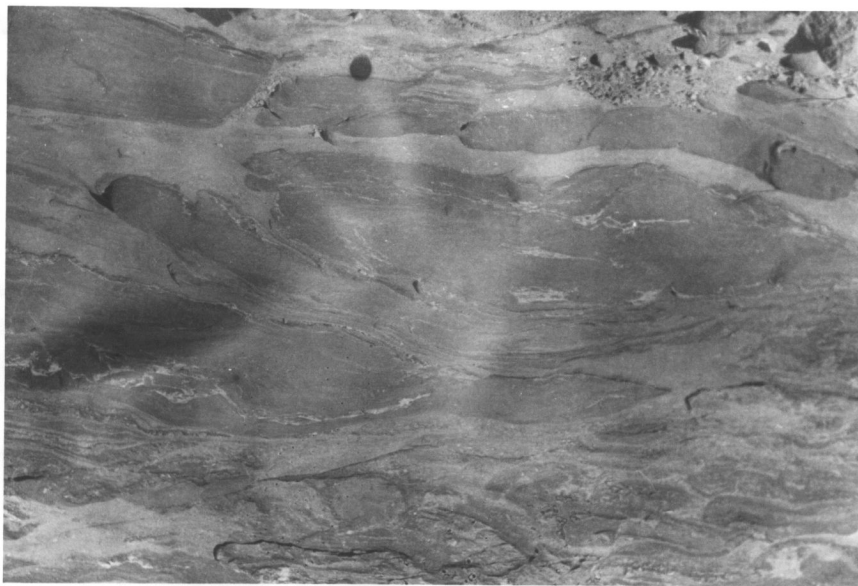


Plate 2b. Contorted amphibolite boudins and lenses in the Mapanza Carbonate Formation beneath Road bridge over Munyeke River.

This foliation is parallel to the west-northwest trending foliation of the country rocks, as in the amphibolite bands and boudins. A few are also strongly lineated, the lineation being defined by hornblende plunging to the west - northwest parallel to the fold axes of minor folds in the calc-silicate rocks. Hornblende, plagioclase and epidote are the only minerals that may be seen in hand specimens.

20 to 50m wide, and rise 10 to 20m above the flat-lying carbonate terrain. Contacts with the country rocks are not exposed, but the bodies apparently thin out before they disappear into the flat-lying country. To the Southeast from the Mapanza Mission hospital, along the road to Pemba, an amphibolite body exhibit a possible intertonguing relationship with adjacent calcite marble. Exposure is poor but the amphibolite forms two large bodies separated by about 10m of marble, suggesting that the marble forms a tongue within the amphibolite. An amphibolite body cropping out north of the Kabanze school contains small xenoliths of randomly oriented calcite marble some 20cm in length. These relationships suggest that the larger, ridge-forming amphibolites were derived from parent mafic rocks which intruded the country rocks. This is in accordance with Tavenner-Smith⁽⁹⁾, who regarded the amphibolites as minor basic intrusions.

These larger amphibolite bodies are homogeneous, showing no internal variation, and are coarse grained and dark green in color. They are commonly massive but a few have a weak foliation defined by orientated hornblende. This foliation is parallel to the west-northwest trending foliation of the country rocks, as in the amphibolite bands and boudins. A few are also strongly lineated, the lineation being defined by hornblende plunging to the west - northwest parallel to the fold axes of minor folds in the calc-silicate rocks. Hornblende, plagioclase and epidote are the only minerals that may be seen in hand specimens.

2.3 Petrography

2.3.1 Calc-silicate rocks

In thin section, the calc-silicate rocks show various textures. These include granoblastic-polygonal, poikiloblastic and schistose textures in the calc-silicate gneisses and a well-defined compositional layering. Additionally, disequilibrium features as defined by replacement textures are also widespread in all calc-silicate rock types. The majority of the latter textures are secondary being imposed during retrograde metamorphism.

The rocks show a fairly consistent mineralogy (Table 2.1 and 2.2). In some of the calc-silicate rocks, the primary or secondary nature of some of the quartz could not be ascertained. It is possible based on the textural evidence in most of the calc-silicate rocks that the quartz is largely or entirely primary, although some of the retrograde reactions discussed later could also produce some secondary quartz.

2.3.1.1 Calc-silicate gneisses

Representative mineralogical compositions for the calc-silicate gneisses are shown in Table 2.1. The compositional layering in these rocks shows an interesting mineralogical variation.

The coarse-grained bands consist mainly of calcite, scapolite, plagioclase, quartz, diopside and secondary actinolite. Biotite is present in minor amounts or is absent. Sphene, tourmaline, apatite,

Table 2.1 Representative mineralogical compositions of the calc-silicate gneisses and mottled calc-silicate rocks.**

sample number	quartz	calcite	plagioclase	scapolite	actinolite	hornblende	diopside	sphene	biotite	muscovite	chlorite	tourmaline	apatite	magnetite	hematite	ilmenite
OSI (CG)	++	+	Tr	++	++(S)		++	+	Tr	-	-	-	-	-	-	-
OSI (FG)	++		+	-	-	+	++	+	+	-	-	+	-	-	+(S)	-
FO17 (CG)	++	-	+	+	+(S)	-	++	+	-	-	-	-	-	+	+(S)	-
FO17 (FG)	++	+	-	++	-	-	++	+	++	-	-	+	+	-	-	-
FO34 (CG)	++	-	-	++	+(S)	-	++	+	Tr	-	-	-	Tr	-	+(S)	-
FO34 (FG)	++	++	-	++	-	-	++	+	++	-	-	+	Tr	-	-	-
FO37 (CG)	++	++	++	-	+(S)	-	++	+	Tr	-	-	-	-	-	-	-
FO37 (FG)	++	Tr	++	-	-	+	++	-	++	+(S)	+(S)	+	-	-	-	-
FO51 (CG)	+	++	-	++	-	-	++	+	-	-	+(S)	+	+	-	-	+
FO51 (FG)	++	-	+	-	-	+	++	-	++	-	-	+	-	-	+(S)	-
FO33 (CG)	++	++	+	++	-	-	++	+	Tr	-	-	-	+	-	-	+
FO33 (FG)	++	+	+	++	-	-	++	+	++	-	-	+	+	-	-	-
FO15 (CG)	++	+	++	++(S)	-	+	+	-	Tr	-	-	+	-	-	-	+
FO15 (FG)	+	+(S)	++	-	-	-	++	-	++	-	-	+	+	-	+(S)	+
CH3 (CG)	++	+	-	++	+(S)	-	++	+	-	-	-	+	+	-	-	-
CH3 (FG)	++	+	-	++	-	-	++	+	++	+(S)	+(S)	+	-	-	-	-
MA10	+	++	+	++	-	-	++	+	++	+(S)	+(S)	+	-	-	-	-

** OSI through CH3 are calc-silicate gneisses

MA10 representative mottled calc-silicate rock.

CG = coarse-grained layer, FG = fine-grained layer

++ = abundant

+

Tr = present in trace amount

S = secondary; other minerals primary

ilmenite and rarely magnetite are present as accessory minerals.

The fine-grained layers consist of biotite, quartz, scapolite and plagioclase as the main mineral constituents. Calcite and hornblende are also present, generally in subordinate amounts. Tourmaline is the most common accessory mineral in these layers whereas sphene apatite and ilmenite are rare. Hematite is found as a secondary mineral replacing biotite. One unusual section has mineral proportions in the fine-grained layers which differ markedly from the fine-grained layers in most of the calc-silicate gneisses. The fine-grained layers in this sample (FO2A) consist mainly of small anhedral quartz crystals. Other less abundant minerals present are plagioclase, biotite and sphene.

In addition to replacement textures described in some detail below, the coarse-grained layers of the calc-silicate gneisses have a well-developed granoblastic-polygonal texture consisting mainly of a mosaic of scapolite, calcite, quartz and diopside (e.g, OS1). The fine-grained layers show a crude to well-developed schistosity, which is defined by orientated biotite flakes and which is parallel to the compositional layering, except on the hinges of folds, where the schistosity can be seen to be axial planar to the folds.

On the fold hinges, the coarser grained layers show a weak foliation which is outlined by minor biotite crystals which have grown axial planar to the folds of the banding. Calcite shows a granoblastic elongate texture which is also axial planar to the folds.

Diopside is mainly present as ragged columnar and anhedral crystals commonly containing rod-shaped quartz, calcite and occasionally scapolite inclusions. It is mostly colorless but crystals with a pale green pleochroism are present in a few specimens (e.g., FO 23A). A large number of grains are marginally replaced by colorless to pale green pleochroic actinolite. Where this replacement is almost complete (e.g., OS1), a poikiloblastic texture is developed in which inclusions of diopside are present in the cores of the actinolite crystals.

Primary hornblende occurs commonly as subhedral crystals with a pale green to green pleochroism and $Z \wedge \gamma = 20-25^{\circ}$. It is mostly found in the fine-grained layers where it forms sieve-textured crystals 1-3mm long containing quartz and biotite inclusions. The crystals are either parallel to the schistosity or are aligned at a high angle to it (e.g., FO32, plate 3a). This suggests that growth of the hornblende poikiloblasts occurred both during and after deformation.

Biotite is abundant in the fine-grained layers where it occurs mainly as small brown flakes about 0.1 to 0.5mm long orientated along the foliation. Minute crystals occurring as inclusions are contained in the hornblende poikiloblasts and occasionally in scapolite crystals. Biotite flakes partially replaced by pale green chlorite and muscovite are also present in some of the rocks (e.g., FO37).

Scapolite is generally anhedral. Locally it occurs as aggregates or clots about 2mm in diameter more prominent in the fine-grained layers (e.g., FO33). These clots impart a knotted texture to the rocks and appear as whitish-grey porphyroblasts in hand specimens. Most of these

clots contain biotite and quartz inclusions and are similar to those present in the mottled calc-silicate rocks discussed below. Locally, a few clots contain irregularly shaped cores of plagioclase and suggest a replacement of the latter by scapolite. In one sample (FO33) scapolite form rims around plagioclase. In all the calc-silicate gneisses scapolite has second order interference color. The maximum birefringence is about 0.025 in the specimens, indicating that the mineral is an intermediate member of the scapolite series and corresponds to mizzonite (Me_6O , where Me is meionite).

Plagioclase occurs as anhedral crystals in a granoblastic mosaic with other minerals. The mineral is not as widespread in these rocks as is scapolite. Its composition as determined by the statistical Michel Levy method in uniformly andesine (An_{32-35}). In some specimens, (e.g., FO34, OS1,) the mineral appears to be more abundant in the fine-grained layers than scapolite which in turn is more abundant in the coarse-grained layers. In one sample (FO32) plagioclase forms sieve-textured crystals about 1mm in diameter in the fine-grained layers and contains biotite inclusions. Plagioclase in contact with scapolite has the same composition as that isolated from scapolite. Some crystals are partly altered to sericite.

Sphene is present in various forms but most crystals have anhedral or subhedral shapes; rarely, euhedral crystals showing the characteristic wedge-shaped habit are present. The mineral varies in size from 0.1 to 0.5mm and has a pale brown to deep brown pleochroism. It tends to be more abundant in the coarse-grained bands than in the fine-grained layers

where most of the Ti is probably in the biotite.

Quartz occurs commonly as anhedral crystals in a granoblastic-polygonal mosaic in contact with other minerals. It is also present as inclusions in diopside, scapolite and hornblende. In the calc-silicate gneisses and other calc-silicate rock types, the mineral is most likely largely primary on the basis of its straight, even contact relationships with other mineral grains. Some of the quartz, however, may be secondary as discussed above.

Tourmaline is present commonly as small anhedral to subhedral elongate crystals parallel to schistosity in the fine-grained layers. In some coarse-grained layers (e.g., CH3), however, anhedral grains about 2mm in size are present. Most crystals show a well-pronounced color zoning from pale yellowish-green rims to dark greenish-blue core, suggesting that they are a solid solution of mainly dravite and schorlite.

Apatite occurs as tiny anhedral crystals less than 0.02mm in size in both the fine-grained and coarse-grained layers. In the former, it occurs as interstitial crystals between biotite, plagioclase and quartz. In the coarse-grained layers, it is generally randomly distributed but a few crystals are interstitially located between scapolite crystals (e.g., F034b).

Opaque minerals in the calc-silicate gneisses are ilmenite, magnetite and secondary hematite after biotite. The minerals are present in minor amounts without any special paragenesis.

Calcite is mainly present as anhedral and subhedral crystals. The mineral is largely concentrated in the coarse-grained layers where it varies in size from 1 to 2mm and is mostly twinned. It is present in minor amounts in the fine-grained layers. In one sample FO15, it forms rims around plagioclase crystals in the fine-grained layers indicating that it is partly secondary.

2.3.1.2 Calc-silicate schists

The mineralogical composition of the calc-silicate schists is similar to that of the fine-grained layers of the calc-silicate gneisses (Table 2.2). The rocks consist of biotite, plagioclase, and quartz as the main mineral constituents. Calcite, sphene, tourmaline and pyrite are present in minor amounts whereas zircon, apatite, hornblende and epidote are rare. In some calc-silicate schists (e.g. FO9A), scapolite occurs instead of plagioclase and diopside is locally abundant (e.g. FO48). Pale green chlorite and muscovite are present as secondary minerals replacing biotite.

The rocks show a well-developed schistosity defined by almost all minerals but most conspicuously by orientated brown biotite flakes (plate 3b). This schistosity everywhere parallels the compositional layering in the calc-silicate gneisses, except on the hinges of folds.

Table 2.2 Representative modal analyses of the massive calc-silicate rocks and calc-silicate schists*.

sample number	quartz	calcite	plagioclase	scapolite	microcline	actinolite	hornblende	diopside	grossularite	biotite	muscovite	chlorite	sphene	tourmalines	rutile	zircon	pyrite	apatite	epidote
FO1A	40P	1P	-	19P	2P	29S	-	3P	-	-	-	-	5P	-	-	-	1P	-	-
FO11	11P	4S	10P	8P	3P	13S	-	36P	TrP	-	-	-	3P	-	-	-	-	-	5S
FO12A	23P	2P	45P	-	-	23S	-	4P	-	-	-	-	2S	-	1P	TrP	1P	-	-
FO12	30P	1P	32P	-	1P	20S	-	12P	-	-	-	-	2S	-	2P	TrP	-	-	-
FO23A	23P	33P	3P	18P	-	6S	-	17P	-	1P	-	-	2P	-	-	-	-	1P	15
FO50	15P	-	-	31P	5P	10S	-	32P	TrP	TrP	-	-	5P	-	-	-	-	TrP	55
FO25	18P	2P	16P	12P	7P	15S	-	23P	TrP	1P	-	-	3P	1P	-	-	TrP	TrP	2S
FO66	24P	-	40P	-	2P	4S	-	26P	-	-	-	-	4P	-	-	TrP	-	TrP	Tr(S)
FO12A	19P	28P	14P	-	-	22S	-	8P	-	3P	-	-	4P	1P	-	-	1P	-	-
CH17	50P	3P	-	5P	-	4S	-	34P	TrP	-	-	-	1P	-	-	-	-	TrP	3P
FO27A	30P	5P	36P	-	-	24S	-	3P	-	-	-	-	2S	1P	1P	TrP	1P	-	-
LU1	27P	6P	6P	-	TrP	13P	-	9P	10P	-	-	-	9P	-	-	-	1P	TrP	12P
MA16	21P	14P	24P	-	-	22P	-	4P	-	-	-	-	2P	-	-	-	-	TrP	13P
FO9A	29P	1P	1P	25P	-	-	1P	4P	-	35P	-	-	1P	Trp	-	-	-	-	-
FO42	15P	2P	23P	-	-	-	-	-	-	50P	5S	5S	TrP	2P	-	-	TrP	TrP	Tr(P)
FO8	26P	13P	29P	-	-	-	1P	-	-	12P	13S	4S	-	1P	-	1P	2P	-	-
FO48	25P	-	-	13P	-	4S	-	27P	-	26P	-	-	-	1P	-	-	3P	-	-

** FO1A, FO11, FO12A, FO12, FO23A, FO50, FO25, FO66, FO72A, CH17, FO27A,

LU1 and MA16 are massive calc-silicate rocks. FO9A, FO42, FO48, and

FO8 are calc-silicate schists. P = primary, S = secondary,

Tr = present in trace amount

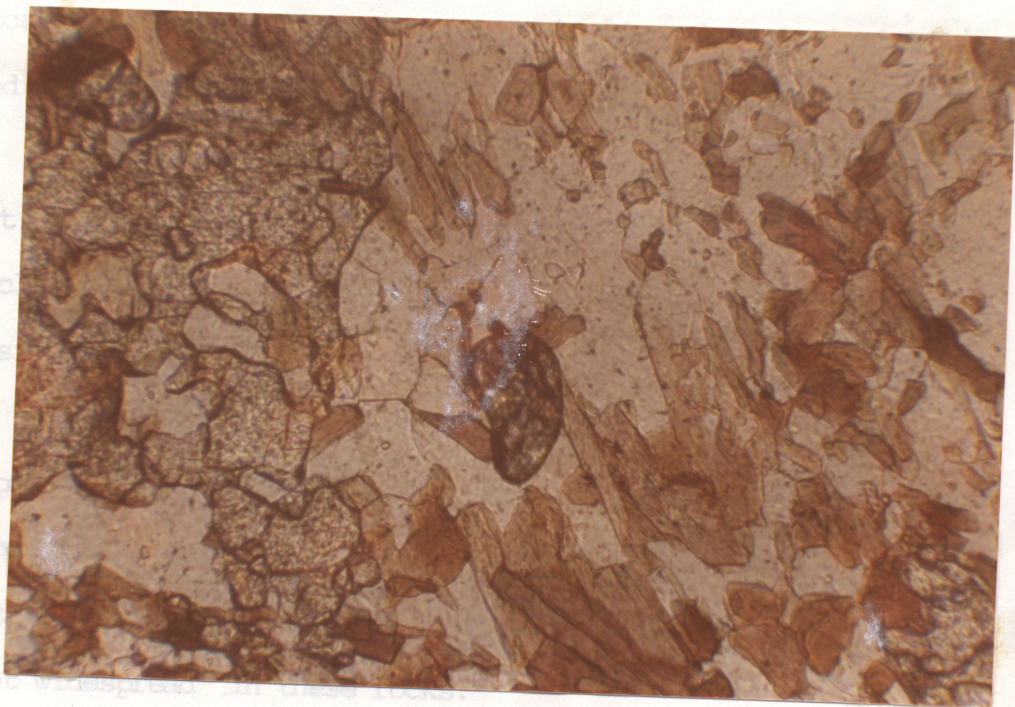


Plate 3a. Hornblende poikiloblast sieved with inclusions of quartz in the calc-silicate gneisses. (X10, under plane polarized light).

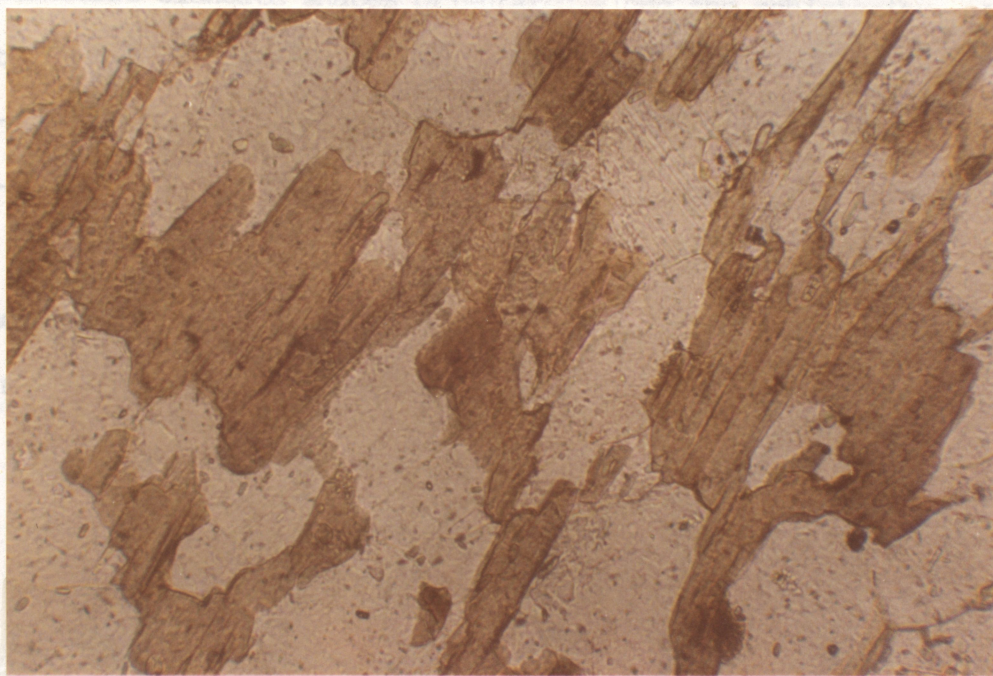


Plate 3b. Calc-silicate schist (F042) showing a well-developed schistosity defined by orientated biotite crystals. (X10, under plane polarized light).

In the scapolite-bearing varieties, granoblastic -elongate texture is exhibited by a mosaic of quartz and scapolite.

Most plagioclase crystals are commonly anhedral and show albite and pericline twinning. The crystals are generally andesine (An_{36-40}) in composition, similar to plagioclase in the calc-silicate gneisses.

Scapolite has interference colors of second-order and is mizzonite in composition, like the scapolite in the calc-silicate gneisses. The mineral occurs as anhedral elongate crystals about 0.5mm in size, but is not widespread in these rocks.

Crystals of tourmaline are commonly associated with biotite and exhibit subhedral elongate shapes orientated along the schistosity. A few crystals show the same color zoning as the tourmaline crystals in the calc-silicate rocks discussed above, but many crystals have a common brownish-green color.

In addition to being present mostly as a secondary mineral replacing biotite, muscovite locally occurs as porphyroblasts about 5 to 10mm long (FO 19A). These porphyroblasts have in some cases grown mimetically along the schistosity but commonly transect it at a high angle suggesting that they are post-tectonic.

Primary green hornblende present in one sample (FO8) also occur in a similar manner to muscovite, being present as poikiloblasts orientated along and at an angle to the foliation. It is most likely that

crystallization of hornblende was post-tectonic and partly syn-tectonic to deformation that produced the schistosity.

Calcite is present as a minor constituent in most calc-silicate schists, being significant only in FO8 where it forms up to 13 per-cent of the rock. It occurs as anhedral elongate crystals with long axes parallel to the schistosity.

Quartz and apatite crystals occur in a similar manner to that described above in the fine-grained layers of the calc-silicate gneisses, whereas sphene is rare or absent in these rocks.

Zircon is found as minute crystals occasionally enclosed by biotite crystals giving rise to pleochroic haloes. A few crystals of zircon are present as cracked grains and are most likely of detrital origin.

2.3.1.3 Massive calc-silicate rocks

The massive calc-silicate rocks contain quartz, scapolite, plagioclase, diopside and actinolite as the main mineral constituents (Table 2.2). Calcite, microcline, epidote, biotite and sphene are present in minor and varying proportions. Rutile, zircon, tourmaline, pyrite and apatite are present as accessory minerals. Garnet is rare in the massive calc-silicate rocks of the Muzuma Calc-silicate Formation and was identified in only a few samples, but it appears to be abundant

in the massive calc-silicate rocks which form bands in the pelitic Nega Formation to the north, represented by sample LUL (Table 2.2).

Under the microscope, the massive calc-silicate rocks commonly have a well-developed granoblastic-polygonal texture formed of an interlocking mosaic of quartz, plagioclase, scapolite and diopside crystals. Most other textural features that are present reflect disequilibrium effects and are described below. One sample (MA16) has a weak foliation discernible only in thin section and is defined by orientated prisms of primary actinolite.

Diopside is colorless and mainly occurs as anhedral to subhedral crystals and as ragged poikiloblasts about 2-4mm in length containing quartz and occasionally randomly oriented biotite inclusions (e.g., CH17). In sample LUL, the crystals show excellent multiple twinning. Many crystals are mantled by pale green to green actinolite, indicating replacement of diopside by actinolite (e.g., CH17, CH18, FO66).

In addition to occurring as a replacement mineral after diopside, actinolite occurs as a primary mineral in a few samples (e.g., LUL, MA 16). In these rocks, the mineral occurs as euhedral prisms 2mm long showing a preferred orientation. Where these crystals are in contact with diopside, the boundary is sharp and straight, which suggests that the two minerals are in textural equilibrium.

Epidote-group minerals commonly present in these rocks are zoisite and clinozoisite, but a few samples (e.g., LUL, FO11) also contain a pistacite-rich variety. Epidote-group minerals interpreted as primary phases commonly form discrete anhedral crystals with zoisite and clinozoisite

displaying yellow-green to green blue anomalous interference colors. Pistacite-rich epidote tends to be zoned, showing interference colors of second-order which increase towards the rims. In places where zoisite and clinozoisite come in contact with scapolite (e.g, FO50), the crystals contain inclusions of scapolite and also occur partly as rims around scapolite, indicating that clinozoisite and zoisite have formed partly by replacement of scapolite. In three sample (FO11, FO25, and FO50), zoisite completely mantles garnet, also indicating that zoisite has replaced the garnet. In the other two garnet-bearing samples (B- 18 and LUL), however, zoisite and clinozoisite are in a apparent textural equilibrium with the other minerals.

Scapolite is present largely as anhedral grains commonly forming equigranular, granoblastic and polygonal aggregates with diopside and quartz. The mineral has second-order interference colors and is mizzonite (Me65) in composition, as in the other calc-silicate rock types.

Plagioclase crystals form anhedral grains and are andesine (An 33-36) in composition. Most crystals are twinned, but untwinned crystals also occur. The crystals do not commonly coexist with scapolite in the same rock.

Microcline with tartan twinning is not widespread but forms up to 7 per cent of some samples (e.g, FO25, FO66). The minerals occurs as anhedral grains about 0.2 to 0.5mm in size forming part of the granoblastic-polygonal texture.

Rutile occurs in a few samples as rounded to elongate crystals with a strong yellow to yellow-brown color. The crystals range in size from 0.1 to 0.3mm and are commonly irregularly mantled by sphene (e.g, F012). The significance of this texture is discussed in chapter 6.

In rocks lacking rutile, sphene is present as small discrete subhedral to anhedral grains and is a common minor constituent in all the massive calc-silicate rocks.

Colorless grains of zircon are present in most specimens and are commonly found as small crystals ranging up to about 0.2mm in size. The grains are cracked and have elongate forms with rounded corners. A few much smaller rounded grains less than 0.05mm in diameter are located in interstices between quartz and scapolite crystals in CH18.

Tourmaline crystals are mostly anhedral and have the same yellowish-green rims surrounding bluish-green cores as present in the calc-silicate gneisses and schists.

Garnet is brown in color and is most probably grossularite-rich. It is mostly present as tiny crystals mantled by zoisite. In the one sample (LUL) taken from a band of massive calc-silicate rock in the Nega Formation, garnet is abundant and is present mainly as anhedral and subhedral grains with a few euhedral crystals ranging in size up to 0.5mm and containing blebs of quartz.

Apatite occurs commonly as tiny anhedral crystals about 0.05mm in diameter occasionally enclosed in scapolite crystals and also located in interstices between calcite crystals.

Quartz is abundant in the massive calc-silicate rocks and its paragenesis is similar to that described in other calc-silicate rock types above.

Calcite is present as a minor constituent up to 3mm in size. The mineral occur as anhedral, subhedral with a few euhedral crystals showing characteristic rhombic cleavage. Both twinned and untwinned crystals are present.

2.3.1.4 Mottled calc-silicate rocks

The mottled calc-silicate rocks (e.g. MA10, Table 2.1) shows a well-developed poikiloblastic texture displayed by aggregates of anhedral scapolite crystals 5 to 10mm in diameter, seen in hand specimens as whitish-grey porphyro blasts. These are set within a matrix composed mainly of biotite, quartz and calcite and contain numerous inclusions of these minerals. The scapolite is mizzonite in composition and forms well over 50 per cent of the rock.

Brown biotite flakes display a moderate schistosity that partly wraps around the poikiloblasts, but inclusions of biotite in a preferred orientation parallel to this schistosity are also contained in these

sieve-textured scapolite crystals. Some biotite flakes have been partly replaced by muscovite and colorless to pale green fibrous and radiating sprays of chlorite.

Calcite is mainly found as inclusions within the scapolite poikiloblasts and also as discrete grains within the matrix. Uncommonly, it forms aggregates about 1mm in diameter with an excellent granoblastic-polygonal texture.

Plagioclase is found in minor amounts as anhedral crystals within the biotite-quartz matrix. Twinned and untwinned crystals occur and are andesine (An36-38) in composition.

Small euhedral tourmaline crystals about 0.03mm in length are present. Most crystals are contained in the scapolite poikiloblasts but a good number are also present in the biotite-rich matrix. Well-developed color zoning with pale green rims surrounding dark-green-bluish cores is prominently shown by euhedral hexagonal cross-sections.

Sphene occurs as small subhedral to euhedral grains with the characteristic wedge-shaped habit. Most crystals occur as inclusions in the scapolite.

Quartz occurs mainly as small inclusions contained within the scapolite poikiloblasts. Other anhedral quartz crystals about 0.5mm in diameter are randomly oriented within the rocks and form granoblastic-polygonal mosaic texture with calcite crystals.

2.3.2 Marbles

Cut surfaces of the carbonate rocks and uncovered thin sections were stained with alizarin red S Solution as described by Warne⁽²⁸⁾. In this technique, calcite changes to a red color whereas dolomite is not affected. This facilitated the subdivision of the marble into calcite marbles and dolomite marbles.

2.3.2.1 Calcite Marbles

Under the microscope, the calcite marbles are generally massive with a well-developed equigranular granoblastic-polygonal textures defined by a mosaic of interlocking twinned and untwinned calcite crystals.

Other mineral constituents besides calcite are present in small and varying proportions (Table 2.3) and include scapolite, quartz, biotite, tremolite, plagioclase, pyrite, apatite and sphene. Tourmaline, magnetite, ilmenite and rutile are rare, and chlorite and muscovite occur as secondary minerals replacing biotite.

Plagioclase occurs commonly as anhedral, twinned crystals and is uniformly andesine (An₃₆₋₄₀) in composition. A few grains in MA6 show oscillatory zoning with diffuse and irregular zones. Crystals replaced by sericite are not uncommon in these rocks (e.g. MA6, MA17).

Table 2.3 Representative modal analyses of the marbles*

	calcite	dolomite	scapolite	plagioclase	diopside	quartz	tremolite	biotite	phlogopite	chlorite	sphene	muscovite	apatite	rutile	magnetite	tourmaline	pyrite	ilmenite
MA2	58P	-	-	13P	-	9P	-	11P	-	4S	4P	2S	Tr (P)	-	-	-	-	Tr (P)
MA5	71P	-	1P	3P	-	16P	-	2P	-	-	2P	2S	1P	1P	-	-	-	-
MA9	72P	-	4P	Tr (P)	-	9P	-	14P	-	-	-	-	Tr (P)	-	-	-	-	-
MA13M	70P	-	-	11P	-	6P	2P	5P	-	2S	-	3S	-	-	1P	-	-	-
MA17	69P	-	-	6P	-	14P	-	6P	-	2S	1P	2S	-	Tr (P)	-	-	-	-
FO4A	73P	-	6P	-	-	15P	-	3P	-	-	Tr (S)	-	-	-	-	-	2P	-
FO6A	70P	-	-	-	-	9P	-	10P	-	2S	-	5S	-	-	-	-	-	-
FO18B	50P	-	-	-	-	18P	-	8P	-	8S	-	4S	-	-	-	2P	-	-
FO26B	70P	-	11P	-	-	12P	-	4P	-	-	-	-	Tr (P)	-	-	-	3P	-
FO20	-	100P	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
FO13B	12P	80P	-	-	-	-	8P	-	-	-	-	-	-	-	-	-	-	-
FO15A	-	93P	-	-	-	-	5P	-	2P	-	-	-	-	-	Tr (P)	-	-	-
FO16	-	98P	-	-	2P	-	-	-	-	-	-	-	-	-	-	-	-	-
FO21B	18P	80P	-	-	-	-	Tr (P)	-	Tr (P)	-	-	-	-	-	-	-	-	-
FO22	4P	95P	-	-	-	-	-	-	Tr (P)	-	-	-	-	-	-	-	-	-

*MA2 through FO26B are calcite marbles :

FO20 through FO22 are dolomite marbles

P = Primary, S = secondary

Tr. = present in trace amount

Unlike most of the calc-silicate rocks where scapolite is present as anhedral grains, in the calcite marbles scapolite is found as subhedral elongate columnar poikiloblasts about 3mm long containing quartz, calcite and biotite inclusions (e.g., FO4, FO4A, FO26). Anhedral crystals also occur (e.g. MA5, MA9). Both textural types are mizzonite (Me 60) in composition, as shown by their birefringence. This composition was confirmed by X-ray diffraction analysis on scapolite from sample FO4A at Delft University (Dr. Kuhnel 1985, Pers. Commun).

In a few specimens where brown biotite is present in significant amounts (e.g., FO8B), a weak compositional layering is defined by calcite-rich layers alternating with biotite-rich layers about 2 to 4mm thick. The biotite-rich bands show a schistosity discernible only under the microscope. Within these biotite-rich layers, pale green, radiating, fibrous chlorite occurs as veinlets as well as a replacement of biotite.

Sphene is a minor mineral constituent that is present mainly as very small subhedral grains. It is randomly distributed within the calcite marbles.

Tiny anhedral crystals of tourmaline about 0.3mm in diameter are also present and have a greenish-brown pleochroism. A color zoning is defined by a dark-green core surrounded by a pale-green rim, suggesting similarity with the tourmaline crystals in the calc-silicate rocks.

Rutile is rare and was only found in samples MA5 and MA6 of the calcite marbles. Most crystals are anhedral, occurring as small, discrete grains with a reddish brown color, but euhedral rutile occurs in MA6 and shows twinning and an excellent (110) cleavage.

Quartz is found in varying proportions in the calcite marbles as equant, anhedral crystals about 0.5mm in size and also as inclusions in scapolite.

Opaque minerals present in the calcite marbles are mainly pyrite but hematite of secondary origin is also present and imparts a brownish stain to the minerals in thin section. The hematite is interpreted to reflect surficial weathering processes. Minor amounts of magnetite are also present in a few samples and ilmenite occurs in MA2.

Small equant apatite crystals about 0.05mm in diameter are present in some calcite marbles (e.g., MA2, MA5, MA9). The crystals are commonly present as interstitial grains between calcite crystals.

Tremolite present in one sample is identical to that in the dolomite marbles described below.

2.3.2.2 Dolomite Marbles

The dolomite marbles are almost pure dolomites, with a few containing no other phase (e.g., FO20 Table 2.3). Other minerals occurring in minor amounts in most of the dolomite marbles are

phlogopite, calcite, tremolite and rare magnetite (Table 2.3. Diopside was identified in only one sample (F016)).

In thin section, the rocks display a well-developed granoblastic-polygonal texture which is defined mainly by interlocking crystals of dolomite.

Calcite where present in the dolomite marbles (e.g., F013A) is generally anhedral against dolomite and exhibits a granoblastic-polygonal texture with the latter. The crystals are devoid of the exsolution lamellae of dolomite commonly observed in marbles described in other areas (27). In one specimen (F021B), calcite is marginally replaced by turbid dolomite. The latter is poorly crystalline and differs markedly from primary dolomite which is coarse, twinned, subhedral, and has a perfect cleavage. The replacement of calcite post-dates twinning in both calcite and dolomite and is most likely post-metamorphic.

Tremolite crystals up to 0.5mm in size are present as colorless euhedral prismatic crystals and are randomly distributed without any preferred orientation. It forms streaks in sample F015A seen in hand specimen as white, fibrous and radiating stringers imbedded within the carbonate matrix.

Phlogopite flakes form subhedral crystals and are colorless to pale brown with a small 2V ($5-15^{\circ}$). They occur as small, randomly oriented flakes 0.2 to 0.5mm long mostly in interstices between

dolomite crystals and also as inclusions within the dolomite (e.g., FO21B, FO22).

Diopside occurs in minor amounts in FO16 as colorless anhedral crystals much smaller in size than the dolomite crystals.

2.3.3 Amphibolites

Two varieties of amphibolite may be distinguished in thin section: garnet amphibolite and garnet-free amphibolite. The former occurs as concordant bands, lenses and boudins within the carbonate and calc-silicate rocks and the latter as discrete larger bodies.

Hornblende and plagioclase are the main mineral constituents in these rocks (Table 2.4). Other minerals generally present in varying proportions are quartz and epidote. Magnetite, sphene, ilmenite, calcite and apatite are commonly present as accessory minerals whereas biotite, rutile and secondary chlorite occur in some samples. Zircon is rare. Garnet when present occurs in small amounts (e.g., MA 19, MA 19A). Diopside was identified in only two of the garnet-free samples (MA 7 and MA 14).

Under the microscope, the rocks are generally isotropic but some samples of both garnet amphibolite and garnet-free amphibolite show a weak to moderate foliation defined by orientated hornblende.

Table 2.4 Representative modal analyses of the amphibolites*.

Sample number	hornblende	plagioclase	quartz	epidote	calcite	sphene	apatite	biotite	diopside	rutile	almandine	ilmenite	magnetite	chlorite	zircon	cummingtonite
MA 7	45P	25P	5P	15P	-	1P	1P	-	7P	-	-	Tr(P)	-	-	-	-
MA 8	47P	32P	3P	-	45	5P	2P	5P	-	-	-	2P	-	-	-	-
MA11	51P	20P	8P	3P	35	6P	Tr(P)	-	-	-	-	-	4P	5(s)	-	-
MA13	53P	25P	10P	2P	-	5S	2P	-	-	-	-	1P	1P	-	-	-
MA13A	49P	30P	10P	1P	-	5S	2P	-	-	-	-	-	1P	-	-	-
MA14	60P	20P	5P	5P	28	4S	-	-	-	2P	-	2P	-	-	-	-
MA15	50P	28P	5P	5P	3P	-	-	-	-	2P	-	-	5P	-	-	-
MA19	47P	24P	10P	1P	3P	3P	1P	3P	-	-	2P	-	5P	1(s)	Tr	-
MA19 (A)	45P	26P	9P	1P	5P	5P	Tr(P)	3P	-	-	3P	-	2P	Tr(s)	-	-
MA45	58P	18P	6P	3P	45	2S	-	-	Tr(P)	4P	-	2S	-	3S	-	Tr

*P = Primary mineral, S = secondary mineral

Tr = present in trace amount

Hornblende crystals are present mostly as subhedral prisms about 1-3mm in length. They are pleochroic with pale green to green colors along Z and an olive green color along Y, with $Z \wedge Y = 12-31^\circ$. The crystals are occasionally sieved with quartz and epidote inclusions (e.g., MA 13). In a number of specimens (e.g., MA 45), hornblende is marginally rimmed by pale green secondary chlorite. Locally in sample MA8, MA14 and MA45, hornblende is replaced marginally by granules of secondary sphene.

In one sample (MA45), colorless, fibrous and radiating cumingtonite occurs in a veinlet about 2mm thick transecting the minerals in the thin section.

Epidote-group minerals mainly occur as zoisite and clinozoisite but a pistacite-rich variety is also present in a few specimens (e.g., MA45). The minerals occur as randomly scattered discrete anhedral granules about 0.3 to 0.5mm in diameter. Abundant inclusions of zoisite prisms and granules about 0.05mm in size are also contained in plagioclase crystals (e.g., MA 13).

Biotite occurs commonly as small, randomly oriented brown flakes and is mainly confined to the garnet amphibolites, but was also identified in one of the garnet-free amphibolites (MA8). Some crystals are partly replaced by green chlorite which show blue anomalous interference colors. The biotite crystals commonly occur in small proportions and are randomly oriented.

Almandine-rich garnet is present as cracked anhedral grains with a neutral to pale brown color. The grains vary in width from 0.5 to

2mm and are devoid of inclusions. Although in some cases the adjacent biotite is partly chloritized, garnet appears fresh, which suggests that it was little affected by retrograde effects.

Apatite occurs as lath-like elongate crystals about 0.1mm long. Many crystals occur interstitially between larger plagioclase crystals (e.g., MA 19). In sample MA8, however, surprisingly large euhedral apatite crystals over 3mm long are present.

Diopside was found in two samples of the garnet-free amphibolites (Table 2.4). In these rocks, it occurs as colorless to pale green crystals. It is present in minor amounts in one sample as anhedral crystals about 2mm in size in textural equilibrium with the other primary minerals. In MA14, it is present in the cores of hornblende, where it is apparently being replaced by the latter. In this case it may be a relict igneous mineral.

Quartz is a minor phase in all the amphibolites where it occurs as small anhedral crystals and rarely as inclusions in hornblende.

Calcite is present as a primary as well as a secondary mineral. The latter clearly replaces plagioclase marginally (e.g., MA11) and is distinguished from primary calcite which has well-defined and straight grain boundaries with other minerals (e.g., MA14).

Sphene occurs as small anhedral discrete grains with brownish pleochroic color and also as larger granules mantling hornblende

(e.g., MA 13). In the latter textural type, it is probable that the mineral is of secondary origin after hornblende.

Opaque minerals in the amphibolites are magnetite and ilmenite which are present as discrete grains. In samples MA14 and MA45, ilmenite forms rims around rutile and possibly has replaced the latter.

Anhedral crystals of rutile with an excellent golden yellowish color are present in minor amounts in MA14 and MA45 up to 1mm in size and are commonly rimmed by ilmenite.

Plagioclase is medium grained, anhedral and is uniformly andesine (An33-45) in composition as determined by the Michel Levy method and confirmed by electron microprobe analyses (Table 5.3). The plagioclase crystals generally show albite twin lamellae but grains with pericline twinning are also present, untwinned crystals are also not uncommon. In MA19, plagioclase crystals contain inclusions of zircon and anhedral garnet crystals. Some plagioclase crystals have been partly replaced by calcite and sericitic material. A few crystals from both garnet amphibolites and garnet-free amphibolites (MA8, MA19) show oscillatory zoning with 3 to 4 indistinct and diffuse zones.

Oscillatory zoning in plagioclase in amphibolites has been interpreted by some workers⁽²⁹⁾ to indicate an igneous protolith.

Cannon⁽³⁰⁾, however, has pointed out that such oscillatory zoning may also be caused by metamorphism and metasomatism involving varying concentrations of Na and Ca in the pore fluids. The presence of oscillatory zoning in a few plagioclase crystals in one of the calcite marbles described above suggests that the similar zoning of plagioclase in the amphibolites described here could have originated during metamorphism as suggested by Cannon⁽³⁰⁾.

CHAPTER THREE

GEOCHEMISTRY AND ORIGIN OF THE CALC-SILICATE ROCKS AND MARBLES

3.1 Introduction

The geochemistry of the calc-silicate rocks and marbles is presented in this chapter. Major and trace element analyses of the rocks by X-ray fluorescence analysis are given. Details of the analytical technique and precision and accuracy of the analyses are outlined in Appendix II.

The geochemical data is relevant because it may shed some light on processes occurring during sedimentation and metamorphism.

3.2. Calc-silicate rocks

Chemical analyses of the calc-silicate gneisses, massive calc-silicate rocks and calc-silicate schists are given in Tables 3.1, 3.2 and 3.3. Where possible, in the calc-silicate gneisses in which banding was notably distinct and continuous, the layers were split apart as accurately as possible by saw and analysed separately. In other calc-silicate gneisses, layers were not split apart and these will be referred to as undifferentiated gneisses throughout the discussion.

The mean compositions and ranges of the individual calc-silicate rock types are given in Table 3.4. The different layers of the calc-silicate gneisses show some interesting chemical trends in both major and trace element concentrations. The fine-grained layers have higher SiO_2 , Al_2O_3 , FeO total, K_2O and Na_2O and lower CaO than the coarse-grained layers. This trend is accompanied by higher Ba, Cr, Rb, Zr, Nb, Ni, Y, Zn and lower Sr.

Table 3.1 Chemical analyses of the calc-silicate gneisses

Major Elements (wt.%)

	Fine - grained layers						Coarse - grained layers			
	BA-N2	FO34	FO65B	FO10A	FO33	FO35A	FO71A	FO34	FO23	FO58
SiO ₂	60.10	49.79	61.47	59.64	60.20	57.03	22.34	30.42	39.21	30.72
Al ₂ O ₃	0.79	0.58	0.76	0.63	0.61	0.63	0.25	0.30	0.43	0.35
FeO	16.07	11.57	15.14	10.23	11.36	8.46	5.48	6.10	7.73	6.92
MnO	3.00	4.85	5.10	3.81	5.19	3.00	2.44	2.64	3.14	2.86
MgO	0.02	0.04	0.02	0.08	0.08	0.06	0.04	0.07	0.06	0.06
CaO	3.21	4.91	4.27	3.89	4.72	3.18	1.94	2.72	3.34	4.41
Na ₂ O	3.18	16.09	4.24	13.72	10.32	16.03	35.75	31.59	26.83	30.74
K ₂ O	2.74	1.34	2.41	1.21	1.27	1.73	0.83	0.74	1.06	1.00
Sum	5.35	3.56	3.83	1.79	3.45	1.65	1.44	1.63	1.90	1.40
SiO ₂	0.01	0.07	0.01	0.05	0.03	n.d	0.04	n.d	0.03	0.01
SiO ₂	0.19	n.d	0.19	n.d	n.d	n.d	n.d	n.d	n.d	n.d

Trace Elements (ppm)

610	583	518	415	564	207	195	251	389	271
71	57	76	36	45	34	14	14	22	23
179	198	237	292	257	467	102	134	144	107
446	1756	943	324	684	762	2512	1922	1395	892
237	121	179	78	148	62	66	58	78	22
30	24	26	53	41	60	20	31	31	31
12	9	10	8	10	4	n.d	4	5	6
72	95	137	64	36	48	30	78	45	51
4	16	15	7	13	4	4	3	4	5

* Total Fe As FeO

n.d..... not detected

Table 3.2 Chemical analyses of undifferentiated calc-silicate gneisses and the massive calc-silicate rocks.

Major elements (wt.%)

	Undifferentiated gneisses					Massive calc-silicate rocks				
	FO30B	FO24	FO60	FO57	CH5	CH17	FO27	MA16	FO56	FO12D
SiO ₂	51.11	34.40	58.58	61.54	61.94	75.36	72.31	70.85	57.05	70.09
TiO ₂	0.50	0.53	0.69	0.38	0.38	0.47	0.41	0.43	0.63	0.47
Al ₂ O ₃	9.25	9.67	8.52	8.40	9.35	6.27	9.69	7.88	7.78	9.30
*FeO	3.25	5.11	3.48	2.51	3.25	3.37	1.30	2.79	7.96	1.68
MnO	0.06	0.10	0.10	0.05	0.11	0.11	0.03	0.10	0.10	0.04
MgO	3.29	4.48	4.16	2.56	4.40	2.75	4.70	2.54	3.32	6.19
CaO	14.54	15.55	15.55	11.45	14.55	8.57	4.23	10.26	15.63	5.56
Na ₂ O	1.50	1.62	1.11	1.44	1.26	0.93	5.66	1.13	1.75	5.56
K ₂ O	2.08	2.42	2.45	3.14	1.21	1.41	0.11	0.06	1.74	0.12
S	0.03	0.03	0.05	0.01	0.01	0.01	0.01	n.d	n.d	n.d
P ₂ O ₅	n.d	n.d	n.d	n.d	0.03	n.d	n.d	n.d	n.d	0.01

Trace elements (ppm)

Ba	350	492	464	343	452	313	11	37	273	50
Cr	30	50	35	23	30	29	46	21	28	59
Zr	182	134	459	231	193	142	179	198	528	187
Sr	960	256	672	544	370	57	18	703	625	23
Rb	80	61	81	109	27	35	n.d	n.d	54	n.d
Y	33	39	58	30	45	26	34	41	63	48
Nb	4	8	7	4	5	3	8	4	5	5
Zn	50	67	54	65	54	30	5	82	30	10
Ni	4	144	5	3	5	4	11	6	3	n.d

*Total Fe as FeO

n.d.....not detected

Table 3.3 Chemical analyses of the calc-silicate schists.

Major elements (wt.%)				
	FO19A	FO42	FO43	FO49
SiO ₂	59.28	58.04	60.05	61.17
TiO ₂	0.67	0.81	0.80	0.71
Al ₂ O ₃	13.06	17.56	17.06	14.22
* FeO	5.37	7.83	7.68	5.46
MnO	0.03	0.09	0.09	0.05
MgO	4.29	4.12	4.00	4.05
CaO	6.29	4.13	4.46	5.84
Na ₂ O	1.96	2.04	2.15	1.99
K ₂ O	3.59	4.35	3.46	4.31
S	n.d	0.01	0.01	0.01
P ₂ O ₅	0.11	0.14	0.17	0.09

Trace elements (ppm)				
Ba	456	599	429	482
Cr	59	98	92	68
Zr	205	171	174	191
Sr	747	152	149	361
Rb	164	183	194	215
Y	35	36	47	32
Nb	8	12	9	8
Zn	133	146	143	127
Ni	15	43	39	19

* Total Fe as FeO.

n.d not detected

Table 3.4 Mean compositions and ranges of the calc-silicate rocks compared to Dalradian calc-silicate rocks and unmetamorphosed sedimentary rocks

	Major elements (wt.%)					
	Calc-silicate schists (n=4)		Fine-grained layers of the calc-silicate gneisses (n=6)		Coarse-grained layers of the calc-silicate gneisses (n=4)	
	Mean	range	Mean	range	mean	range
SiO ₂	59.64	58.04-61.17	58.04	49.79-61.47	30.67	22.34-39.21
TiO ₂	0.75	0.67-0.81	0.67	0.58-0.76	0.33	0.25-0.43
Al ₂ O ₃	15.48	13.06-17.56	12.14	8.46-16.07	6.56	5.48-7.73
* FeO	6.58	5.37-7.83	4.14	3.00-5.01	2.77	2.44-3.14
MnO	0.06	0.03-0.09	0.05	0.02-0.08	0.06	0.04-0.07
MgO	4.12	4.00-4.29	4.03	3.18-4.91	3.10	1.94-4.41
CaO	5.18	3.46-4.35	10.70	3.81-16.09	31.23	26.83-35.75
Na ₂ O	2.04	1.96-2.15	1.78	1.21-2.74	0.91	0.74-1.06
K ₂ O	3.93	3.59-4.35	3.27	1.79-5.35	1.59	1.40-1.90
Trace elements (ppm)						
Ba	492	429-599	483	207-610	277	195-389
Cr	79	59-98	53	36-76	18	14-23
Zr	185	171-205	258	179-467	122	102-134
Sr	352	152-747	819	324-1756	1680	892-2512
Rb	189	164-215	138	62-237	56	22-58
Y	38	32-47	39	24-60	28	20-31
Nb	9	8-12	9	4-12	4	0-6
Zn	137	127-146	78	36-137	51	30-78
Ni	29	15-43	10	4-16	4	3-5

* Total Fe as FeO

Table 3.4 cont'd

Major elements (wt.%)						
	Massive calc-silicate rocks (n=5)		Undifferentiated gneisses (n=5)		Dalradian calc- silicates (38) rocks (n=14)	
	Mean	Range	Mean	Range	Mean	Range
SiO ₂	69.13	57.05-73.36	53.51	34.40-61.93	59.38	28.08-73.77
TiO ₂	0.48	0.41-0.63	0.51	0.38-0.69	0.61	0.28-1.13
Al ₂ O ₃	8.18	6.27-9.69	9.04	8.40-9.67	13.66	4.98-22.82
*FeO	2.42	1.30-3.37	3.52	2.51-5.11	6.44	2.40-7.77
MnO	0.08	0.03-0.11	0.08	0.05-0.11	0.29	0.04-0.94
MgO	3.90	2.75-6.19	3.28	2.56-4.48	3.60	1.36-9.84
CaO	8.85	4.23-15.63	14.33	11.45-15.55	8.22	3.14-30.95
Na ₂ O	3.01	0.93-5.56	1.39	1.11-1.62	2.16	0.36-4.79
K ₂ O	0.69	0.06-1.74	2.26	1.21-3.14	2.37	0.22-7.22
Trace elements (ppm)						
Ba	137	11-313	420	343-492	539	0-910
Cr	37	21-59	34	23-50	74	29-142
Zr	245	142-528	240	134-459	89	0-264
Sr	285	18-703	560	370-960	740	61-1971
Rb	18	0-54	72	27-109	92	2-356
Y	42	26-63	41	33-58	29	12-47
Nb	5	3-8	6	4-8	7	0-18
Zn	27	5-82	59	50-67	79	47-107
Ni	5	0-11	6	3-14	49	17-100

* Total Fe as FeO

Table 3.4 cont'd

	Calcareous argillite (33)	Shales (32)	
	<u>(single analysis)</u>	<u>(n=85)</u>	
			mean range
SiO ₂	48.12	59.93	53.60-66.26
TiO ₂	0.78	0.85	0.28-1.42
Al ₂ O ₃	12.80	16.62	13.29-19.95
* FeO	4.69	3.18	1.34- 5.02
MnO	0.09	-	-
MgO	2.55	2.63	0.65- 4.61
CaO	10.77	2.18	0.00- 4.72
Na ₂ O	0.60	1.73	0.46- 3.00
K ₂ O	3.60	3.54	2.21- 4.87

* Total Fe as FeO

These compositional variations are reflected by mineralogical variations between the fine-grained and coarse-grained layers. The chemical composition of the fine-grained layers reflects high modal biotite in these bands, whereas the coarse-grained layers have much higher calcite scapolite, diopside and plagioclase, but are relatively poor in biotite (See Table 2.1).

Most undifferentiated gneisses show chemical features which are roughly intermediate between those of the fine-grained layers and coarse-grained layers as would be expected. In some specimens, however, total alkalies ($\text{Na}_2\text{O} + \text{K}_2\text{O}$), SiO_2 , TiO_2 , Ba, Zr, Rb, Ni and Y are fairly high. In these specimens, a large proportion of the analyzed rock consisted of the fine-grained layers, which are rich in these elements.

The calc-silicate schists are similar in composition to the fine-grained layers of the calc-silicate gneisses (Table 3.4). This reflects the similar mineralogical composition of these rocks (Table 2.2).

The massive calc-silicate rocks show high SiO_2 contents. These rocks generally also have relatively low values of Ba, Sr, Rb and Zr. The high SiO_2 contents are reflected by relatively high modal quartz.

3.3 Marbles

Chemical analyses of the marbles are listed in Table 3.5 and mean compositions and ranges are given in Table 3.6. In comparison to the dolomite marbles, the calcite marbles have lower MgO , as expected,

Table 3.5 Chemical analyses of the marbles

	Major elements (wt.%)								
	Dolomite marbles				calcite marbles				
	FO13B	FO16	FO22	FO21B	FO11A	FO26	MA5	MA17	MA13M
SiO ₂	4.66	0.33	2.22	0.73	6.38	12.45	13.55	23.47	3.74
TiO ₂	n.d	0.01	0.02	n.d	0.08	0.12	0.16	0.24	0.05
Al ₂ O ₃	0.05	0.08	0.35	0.04	1.58	2.67	3.37	3.48	0.87
* FeO	0.31	0.37	0.54	0.24	0.81	1.10	1.57	1.28	0.46
MnO	0.02	0.04	0.03	0.03	0.02	0.04	0.03	0.03	0.01
MgO	20.41	21.54	20.93	20.50	0.55	0.01	1.25	1.22	0.33
CaO	30.07	30.65	31.65	31.79	49.22	44.66	42.25	37.17	51.64
Na ₂ O	n.d	n.d	n.d	n.d	0.11	0.43	0.41	0.82	0.17
K ₂ O	n.d	0.04	0.23	0.01	0.55	1.00	0.84	0.85	0.25
S	0.02	0.01	n.d	0.01	0.12	n.d	0.16	0.02	0.02
P ₂ O ₅	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d
Trace elements (ppm)									
Ba	37	19	99	53	81	197	158	204	93
Cr	n.d	n.d	4	n.d	5	3	11	6	n.d
Zr	2	10	2	8	73	89	189	111	105
Sr	139	463	108	370	2810	2672	2198	3151	4320
Rb	n.d	n.d	6	n.d	14	20	34	28	13
Y	9	11	5	7	9	15	20	13	6
Nb	n.d	n.d	n.d	n.d	3	4	1	n.d	n.d
Zn	3	5	10	22	n.d	1	22	19	n.d
Ni	n.d	n.d	1	n.d	n.d	n.d	n.d	n.d	n.d

* Total Fe as FeO

n.d not detected.

Table 3.6 Mean compositions and ranges of the marbles compared to unmetamorphosed dolostones and limestones.

	Calcite marbles (n=5)		Limestones (30) (n=4)		Impure limestones (31) (n=2)	
	Mean	range	mean	range	mean	range
SiO ₂	11.92	3.74-23.47	1.08	0.11-2.05	10.29	6.21-14.37
TiO ₂	0.13	0.05-0.25	-	-	0.08	0.00-0.17
Al ₂ O ₃	2.39	0.87-3.48	0.70	0.08-1.32	4.28	0.43-8.13
*FeO	1.04	0.46-1.28	0.27	0.00-0.63	0.95	0.65-1.30
MnO	0.03	0.01-0.04	-	-	0.22	0.12-0.32
MgO	0.87	0.33-1.22	0.52	0.40-0.64	2.01	1.03-2.90
CaO	44.99	37.17-49.22	54.05	52.82-55.28	41.90	36.89-46.91
Na ₂ O	0.39	0.11-0.82	0.09	0.15-0.03	1.38	0.00-3.12
K ₂ O	0.70	0.25-1.00	0.03	0.00-0.06	0.56	0.13-0.90

Trace elements (ppm)

Ba	145	81-204
Cr	5	0-11
Zr	113	73-189
Sr	3030	2672-4320
Rb	22	13-34
Y	13	6-20
Nb	2	0-4
Zn	8	0.22
Ni	-	-

*Total Fe as FeO

Table 3.6 (Cont'd)

	Dolomite marbles (n = 4)		Major elements (wt.%) dolomites (31) (n = 3)		Connemara Calcite marbles (3) (n = 10)	
	Mean	Range	Mean	Range	Mean	Range
SiO ₂	1.98	0.33-4.66	2.17	0.87-3.47	13.92	5.86-21.9
TiO ₂	0.01	0.00-0.02	0.01	0.00-0.02	0.16	0.06-0.26
Al ₂ O ₃	0.13	0.04-0.35	0.20	0.00-0.023	4.13	2.16-6.10
*FeO	0.36	0.24-0.54	0.47	0.00-1.08	1.11	0.49-1.67
MnO	0.03	0.02-0.04	0.01	0.00-0.03	0.04	0.02-0.06
MgO	20.84	20.50-21.54	20.66	20.41-20.91	1.96	0.55-3.37
CaO	30.04	30.07-31.65	30.28	29.30-31-26	43.41	36.86-49.96
Na ₂ O	-	-	0.01	0.00-0.03	0.70	0.45-0.95
K ₂ O	0.07	0.00-0.23	0.02	0.00-0.04	0.88	0.24-1.52

Trace elements (ppm)

Ba	52	19-99
Cr	1	0-4
Zr	6	2-10
Sr	220	108-463
Rb	2	0-6
Y	8	5-11
Nb	-	-
Zn	10	5-22
Ni	-	-

Total Fe as Feo

but are generally enriched in the other major elements and in most of the trace elements.

The chemical trends shown by the rocks are consistent with their mineralogical compositions. The calcite marbles are more abundant in biotite and other calc-silicate phases than the dolomite marbles (Table 2.3).

Average analyses of unmetamorphosed ~~dolomite~~ and limestone are also given in Table 3.6. The dolomite marbles of the present study are stoichiometrically close to pure dolomite, whereas the composition of the calcite marbles compares closely with impure limestone and differs markedly from relatively pure limestone.

3.4 Niggli Parameters

Niggli parameters are chemical numbers that are commonly used in the discussion of igneous and metamorphic rocks (34,35,36). Computation of these parameters is outlined in Appendix III.

Niggli parameters for the calc-silicate rocks and marbles are tabulated in Table 3.7. Striking differences in the parameters fm , al , $al-alk$ and si within the individual calc-silicate rocks and marbles are clearly evident and follow the trends of the major elements outlined above. The parameters mg and k are general similar in all rock types, with an average of $mg = 0.66$ and $k = 0.44$ for

Table 3.7 Niggli parameters for the calc-silicate rocks and marbles

	<u>Fine-grained layers</u>						<u>coarse-grained layers</u>			
	BA-N2	FO34	FO65B	FO10A	FO35A	FO33	FO71A	FO34	FO23	FO58
al	13	17	31	19	15.5	20.5	7	8	11	8
alk	23	9	16	7	8.5	10.5	4	4	5	4
fm	27	29	37	28	23	35	10	14	18	19
c	15	44	16	46	53	34	79	74	66	69
mg	0.65	0.64	0.60	0.65	0.65	0.61	0.58	0.64	0.65	0.73
k	0.56	0.63	0.51	0.39	0.64	0.64	0.53	0.59	0.54	0.48
si	222	124	213	188	177	184	48	68	70	60
al-alk	12	8	15	12	7	10	3	4	6	4

	<u>Undifferentiated gneisses</u>					<u>Massive calc-silicate rocks</u>				
	FO30B	FO24	FO60	FO57	CH5	CH17	FO27	MA16	FO56	FORD
al	17	16	15	19	17	17	24	20	14	20
alk	9	8	8	13	6	8	23	5	9	19
fm	24	30	27	22	29	32	34	27	24	39
c	50	46	50	46	48	42	19	48	51	22
mg	0.65	0.60	0.67	0.64	0.70	0.58	0.86	0.61	0.66	0.86
k	0.48	0.50	0.59	0.59	0.39	0.50	0.01	0.03	0.04	0.01
si	159	97	175	236	191	347	304	305	187	256
al-alk	8	8	7	6	11	9	1	15	5	1

Table 3.7 Cont'd.

	Dolomite marbles				calcite marbles				
	FO13B	FO16	FO22	FO21B	FO4A	FO26	MA17	MA5	MA13M
al	-	-	-	-	2	3	4	4	1
alk	-	-	-	-	1	1	3	2	1
fm	49	50	48	47	3	5	6	6	1
c	51	50	52	53	95	91	86	88	97
mg	0.99	0.99	0.98	0.99	0.55	0.61	0.62	0.58	0.56
k	-	0.1	1.0	-	0.76	0.94	0.40	0.57	0.49
si	8	0.5	3	1	14	24	46	27	7
al-alk	-	-	-	-	1	2	1	2	-

calc-silicate schists

	FO19A	FO42	FO43	FO49
al	26	32	32	28
alk	14	15	14	16
fm	38	39	39	35
c	22	14	15	21
mg	0.56	0.48	0.48	0.57
k	0.55	0.58	0.52	0.59
si	200	179	191	204
al-alk	12	17	18	12

the calc-silicate rocks. These values compare reasonably well with those computed by Senior and Leake⁽³⁸⁾ for the Dalradian calc-silicate rocks.

3.5 Inter-element Correlations

Leake et al⁽³⁷⁾ and Senior and Leake⁽³⁸⁾ have shown that marbles and calc-silicate rocks may show strong correlations between certain major and trace elements. Such correlations have petrogenetic significance and may lead to an understanding of the form in which the elements were incorporated into the original protolith.

Details of the distribution of some of the minor and trace elements in the calc-silicate rocks and marbles of the present study are outlined below. Elements which possess similar variations are discussed together. Other inter-element correlations are discussed later, in the section on element immobility.

3.5.1 Rb, Ba, K_2O , Na_2O and Al_2O_3

Figure 3.1a shows that Rb is remarkably well correlated with K_2O in all calc-silicate rock types and marbles. The highest K_2O and Rb values are present in the calc-silicate schists and fine-grained layers of the gneisses, whereas these elements are much lower in the marbles and coarse-grained layers of the calc-silicate gneisses. Also, a strong correlation of Rb with Al_2O_3 is indicated on Figure 3.1b. Again, the calc-silicate schists and the fine-grained layers in the gneisses are higher in these elements than the coarse-grained layers and the marbles.

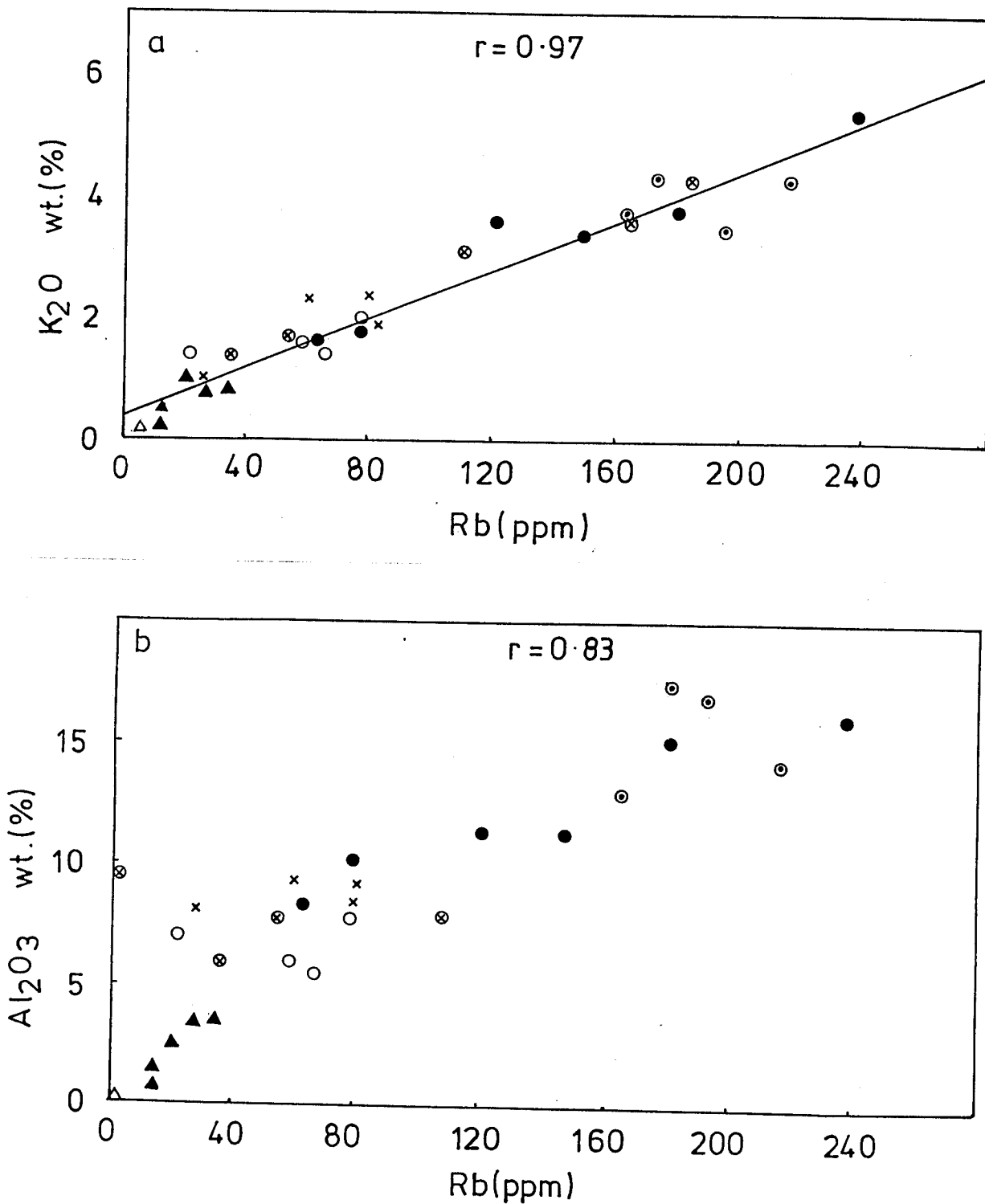


Figure 3.1. Plots of (a) K₂O and Al₂O₃ weight per cent against Rb(ppm) for the calc-silicate rocks and marbles. Δ represents dolomite marbles; $\blacktriangle$, calcite marbles; $\otimes$, massive calc-silicate rocks; $\times$, undifferentiated calc-silicate gneisses; $\bullet$, fine-grained layers; $\circ$, coarse-grained layers of the calc-silicate gneisses; $\odot$, calc-silicate schists. r is correlation coefficient.

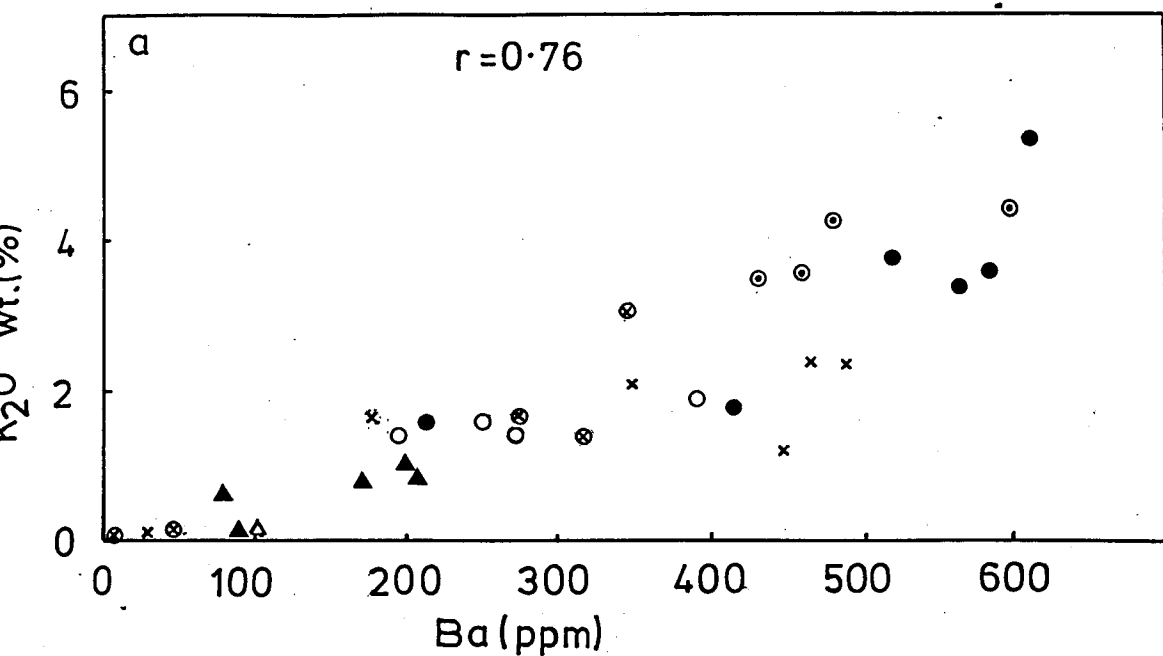
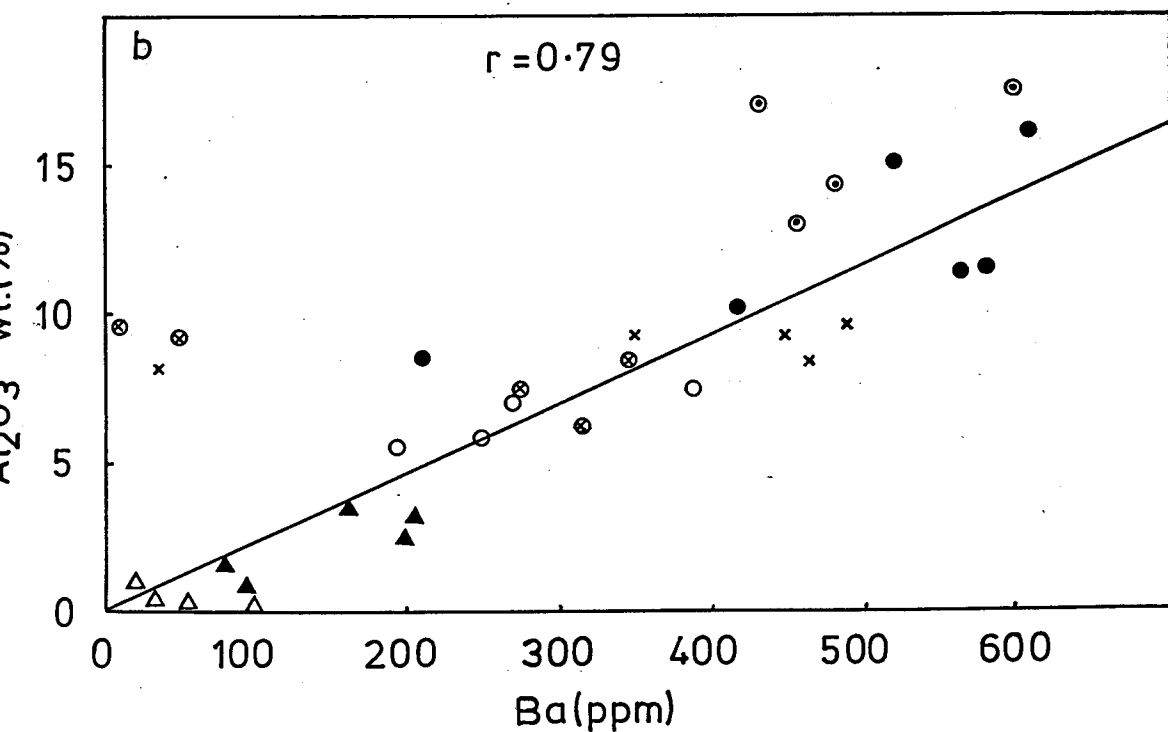


Figure 3.2. Plots of (a) K₂O and (b) Al₂O₃ weight per cent against Ba (ppm) for the calc-silicate rocks and marbles. Symbols as for Figure 3.1.

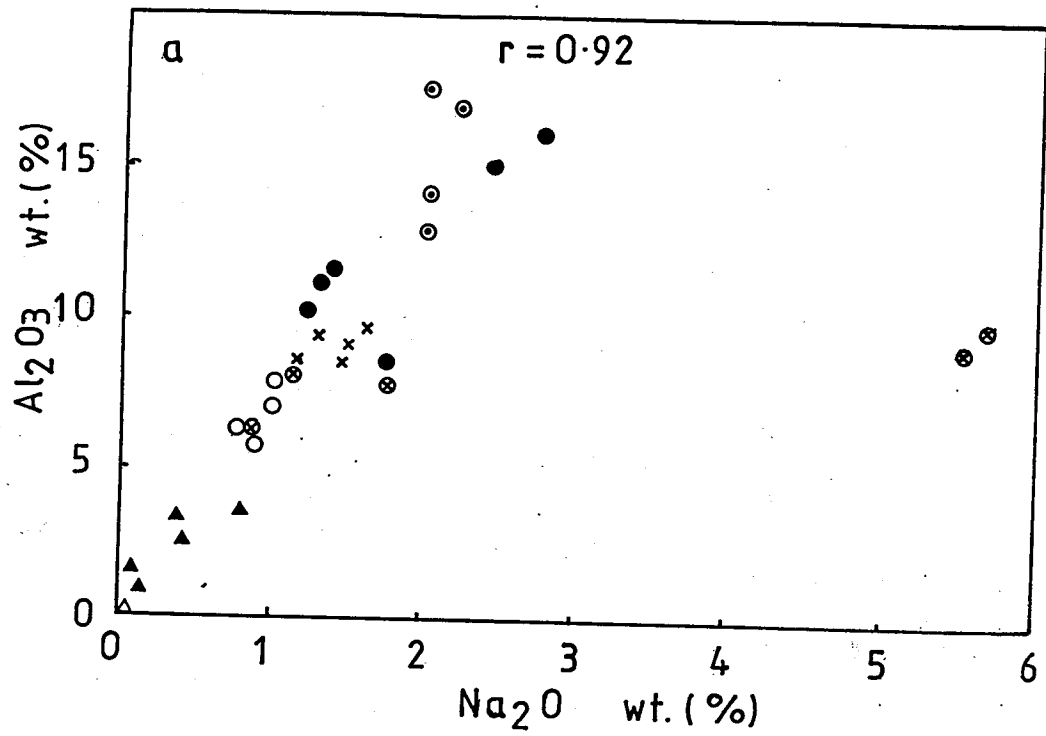
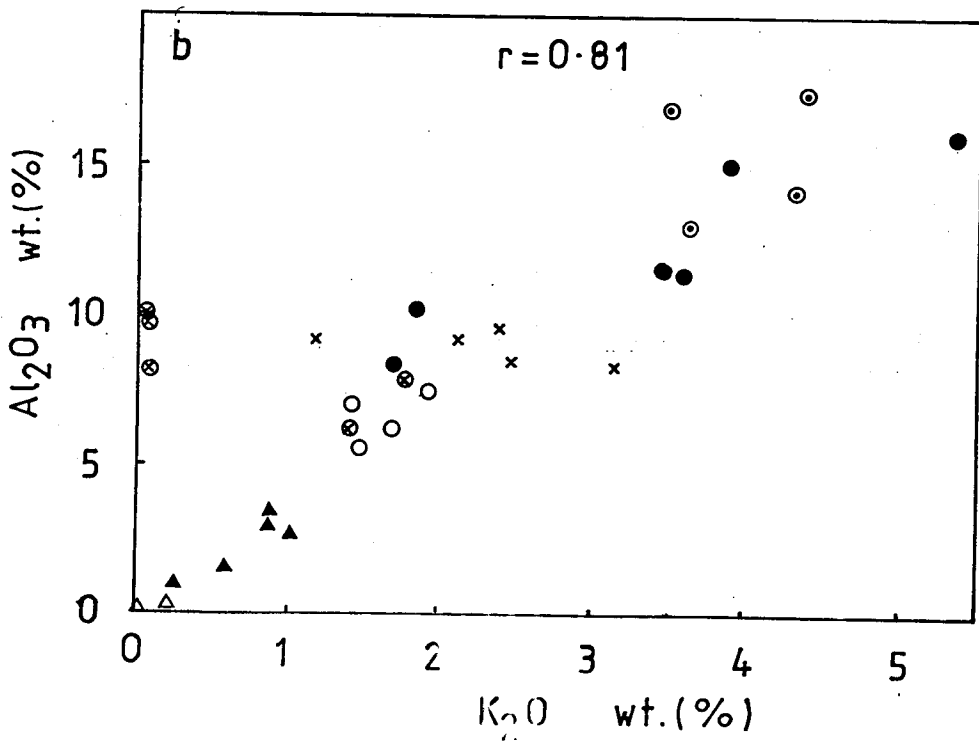


Figure 3.3. Plots of Al₂O₃ weight per cent against (a) Na₂O and K₂O weight per cent for the calc-silicate rocks and marbles. Symbols as for Figure 3.1.

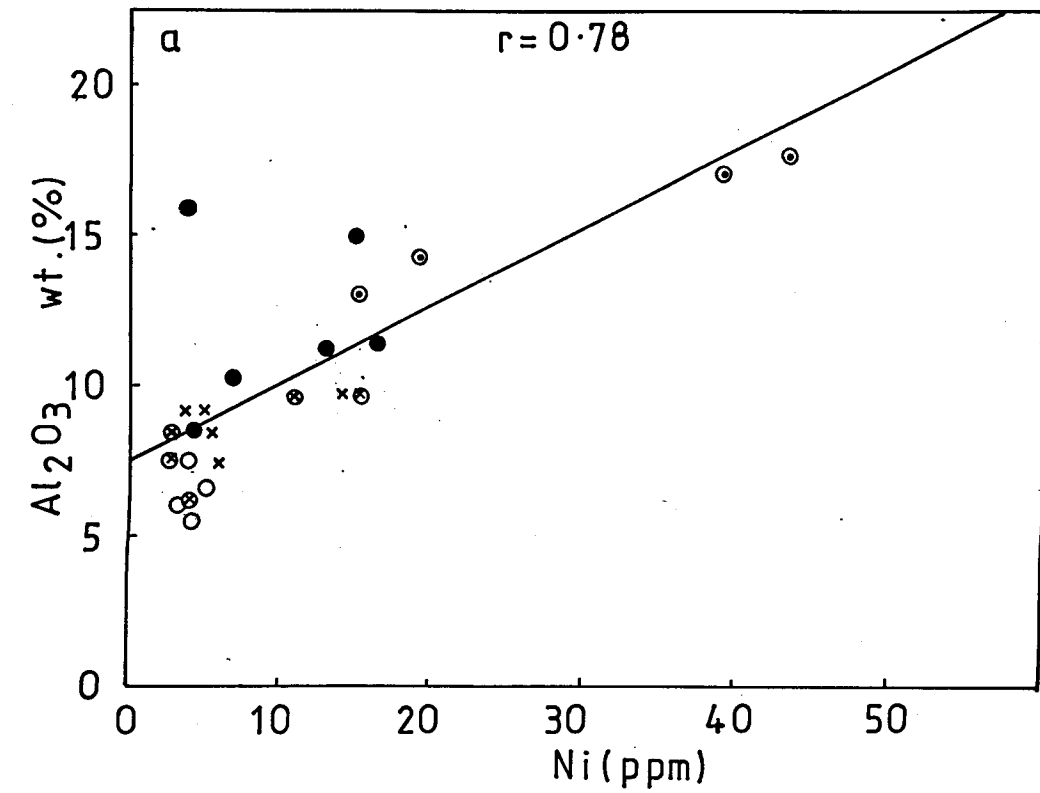
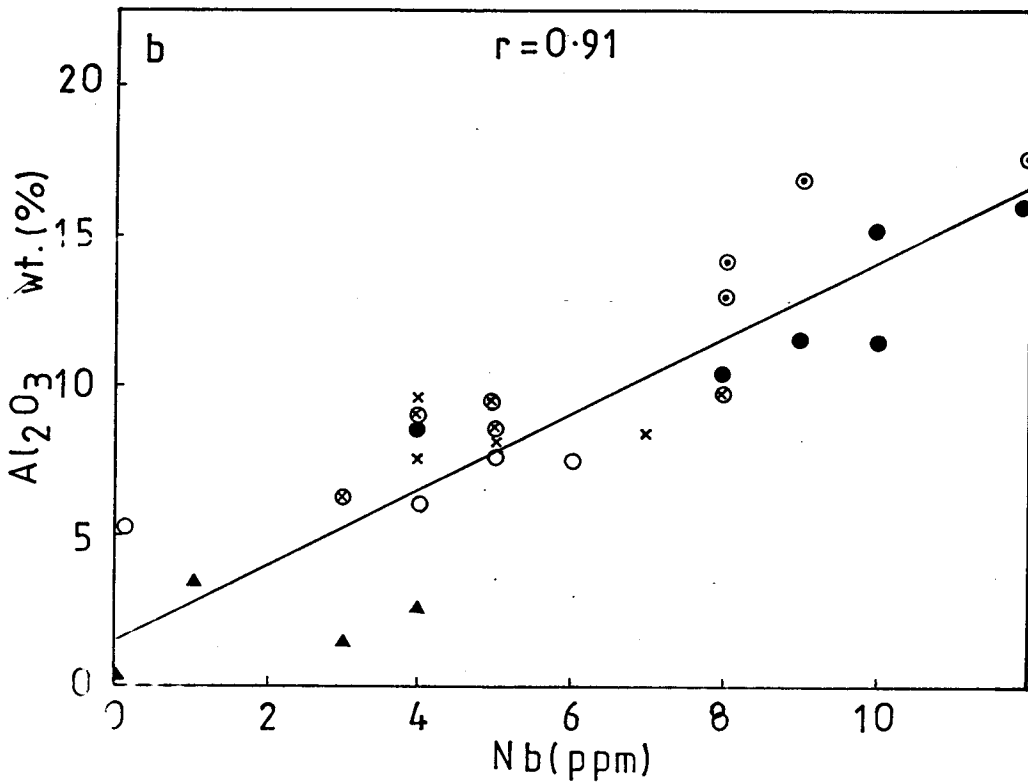


Figure 3.4. Plots of Al_2O_3 weight per cent against (a) Ni and (b) Nb (ppm) for the calc-silicate rocks and marbles. Symbols as for Figure 3.1.

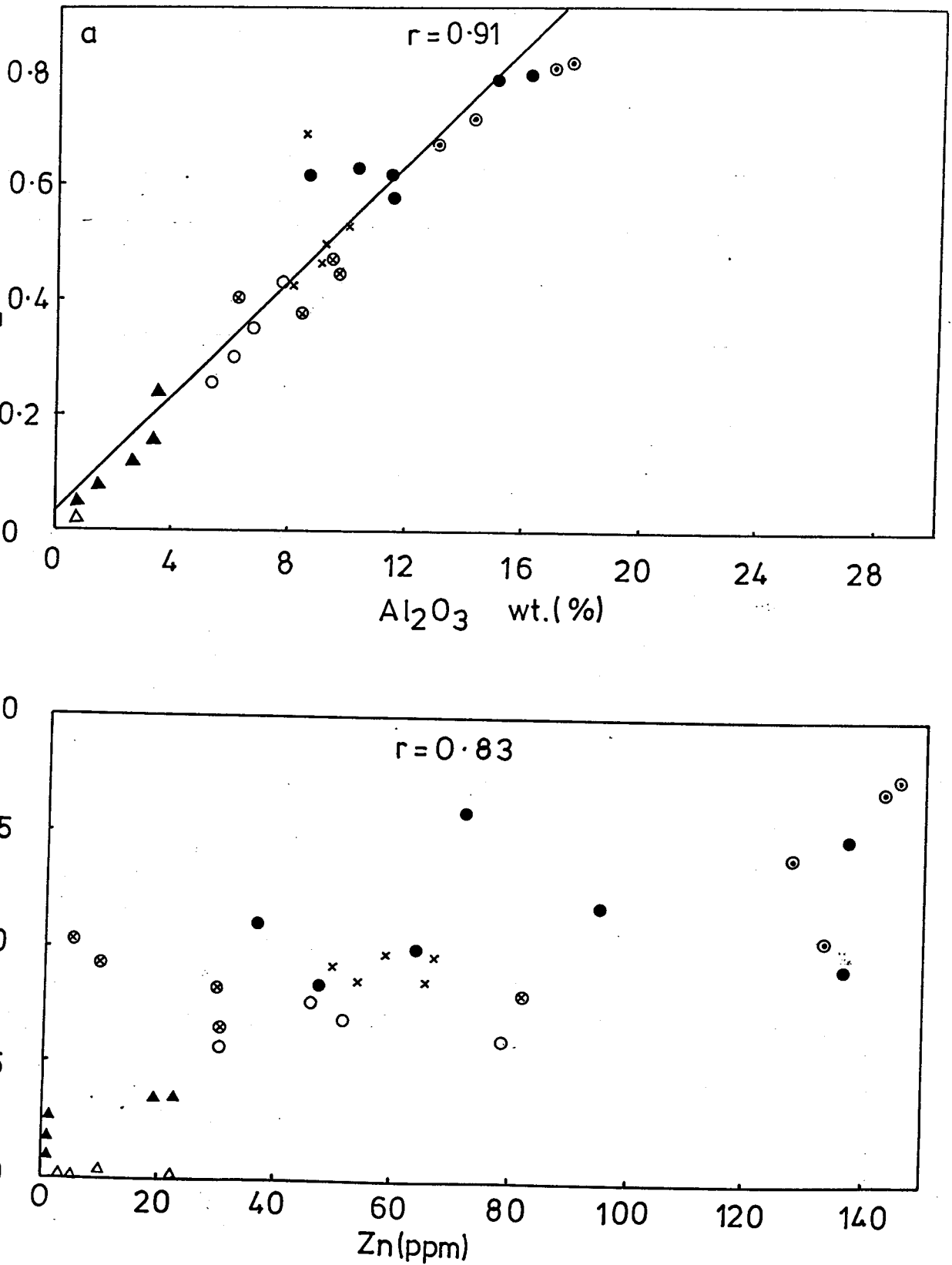


Figure 3.5. Plots of Al_2O_3 weight per cent against (a) TiO_2 weight per cent and (b) Zn(ppm). Symbols as for Figure 3.1

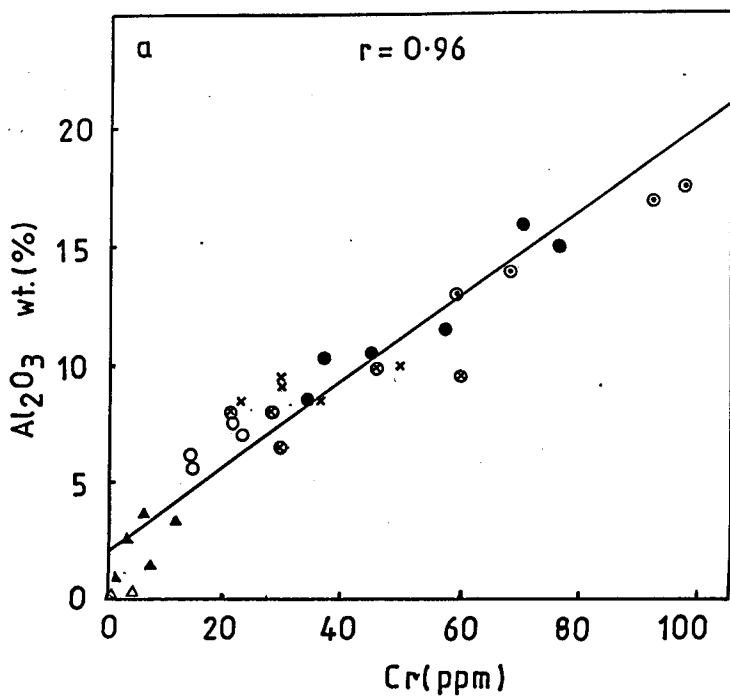
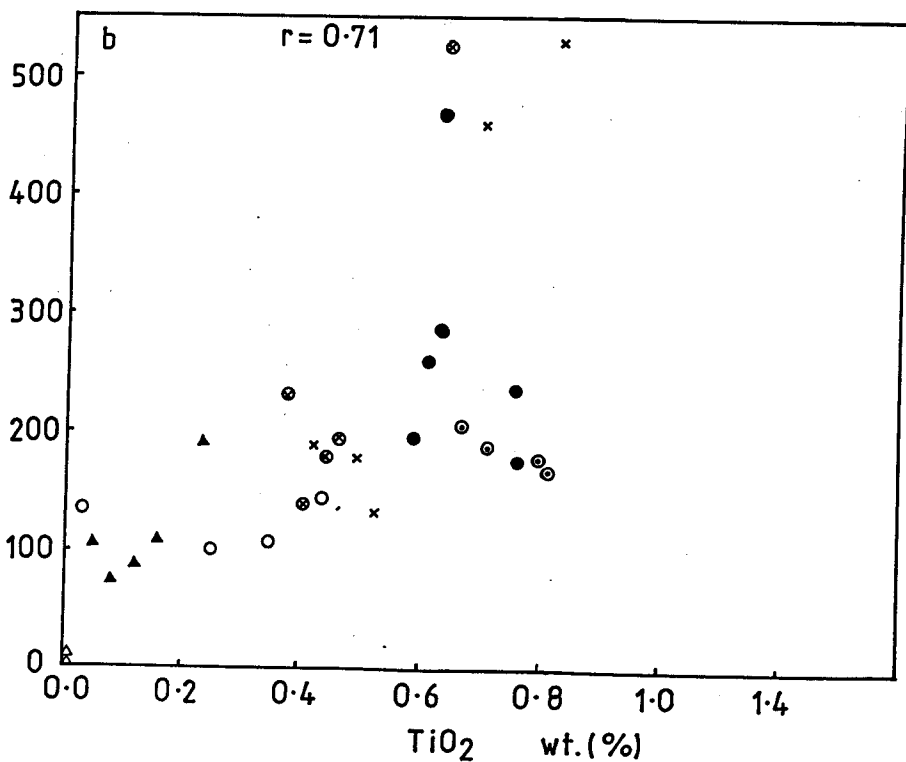


Figure 3.6, Plots of (a) Al_2O_3 weight per cent against Cr (ppm) and (b) Zr (ppm) against TiO_2 weight per cent for the calc-silicate rocks and marbles. Symbols as for Figure 3.1.

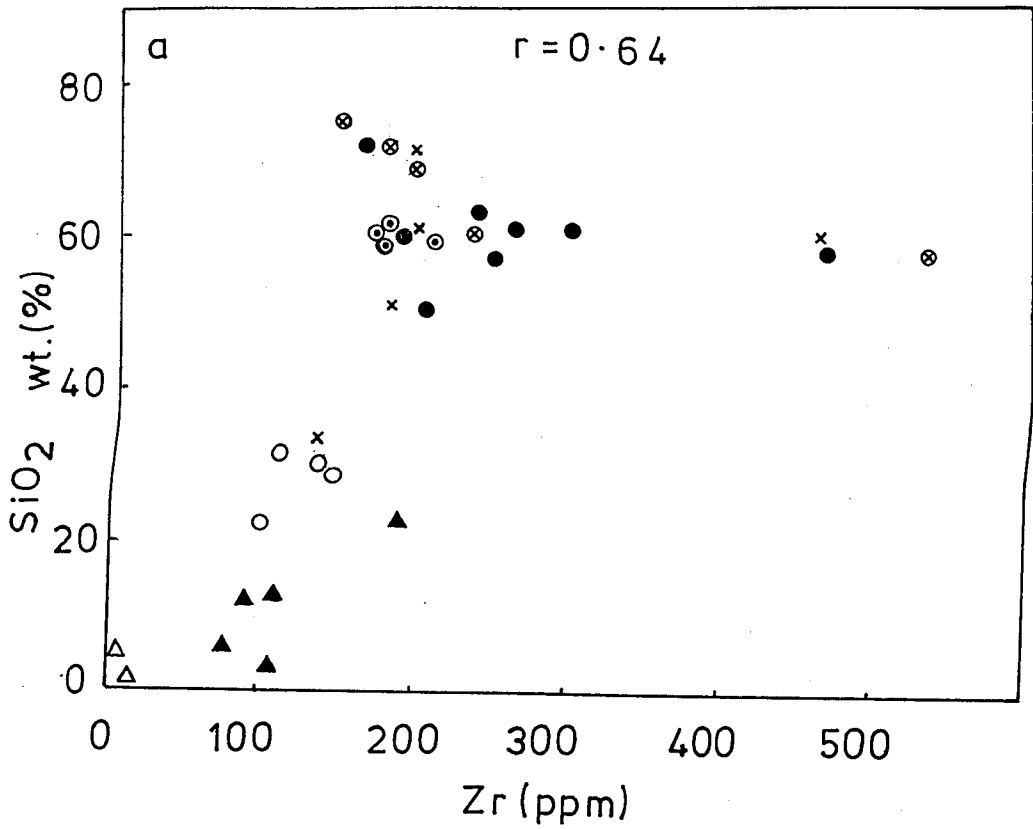
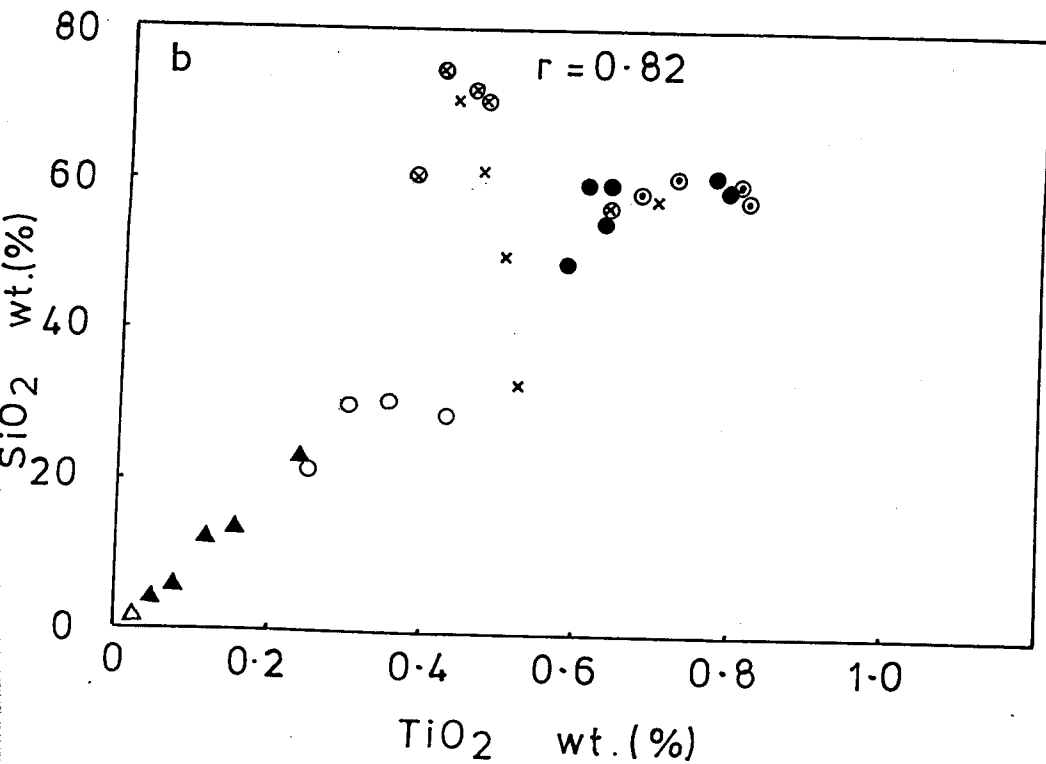


Figure 3.7. Plots of SiO_2 weight per cent against (a) Zr (ppm) and (b) TiO_2 weight per cent for the calc-silicate rocks and marbles. Symbols as for Figure 3.1.

3.5.4 CaO, Sr and Al_2O_3

The concentration of Sr follows that of CaO as shown on Figure 3.8a. This is expected on the basis of their similar atomic radii⁽³⁹⁾. The dolomite marbles cluster together with low Sr values, whereas high Sr values are present in the calcite marbles. A considerable amount of scatter in Sr and CaO is exhibited by the calc-silicate rocks. This possibly at least partly reflects variation in modal calcite in these rocks, but also introduces the possibility that during metamorphism, Sr suffered some metasomatic movement relative to CaO.

Both CaO and Sr show negative correlations with Al_2O_3 (Fig. 3.9a and b). That of CaO with Al_2O_3 is however much stronger than that of Sr with Al_2O_3 , possibly further indicating mobility of Sr relative to CaO during metamorphism,

3.6 Interpretation of the Geochemistry

As previously pointed out, the variation in the chemical compositions of the calc-silicate rocks and marbles reflects variations in the mineralogical compositions of these rocks.

There are two main possibilities for the origin of the chemical variations. One possibility is that they reflect extensive metasomatism occurring during metamorphism. A more likely possibility is that they reflect original differences in the compositions of the protoliths.

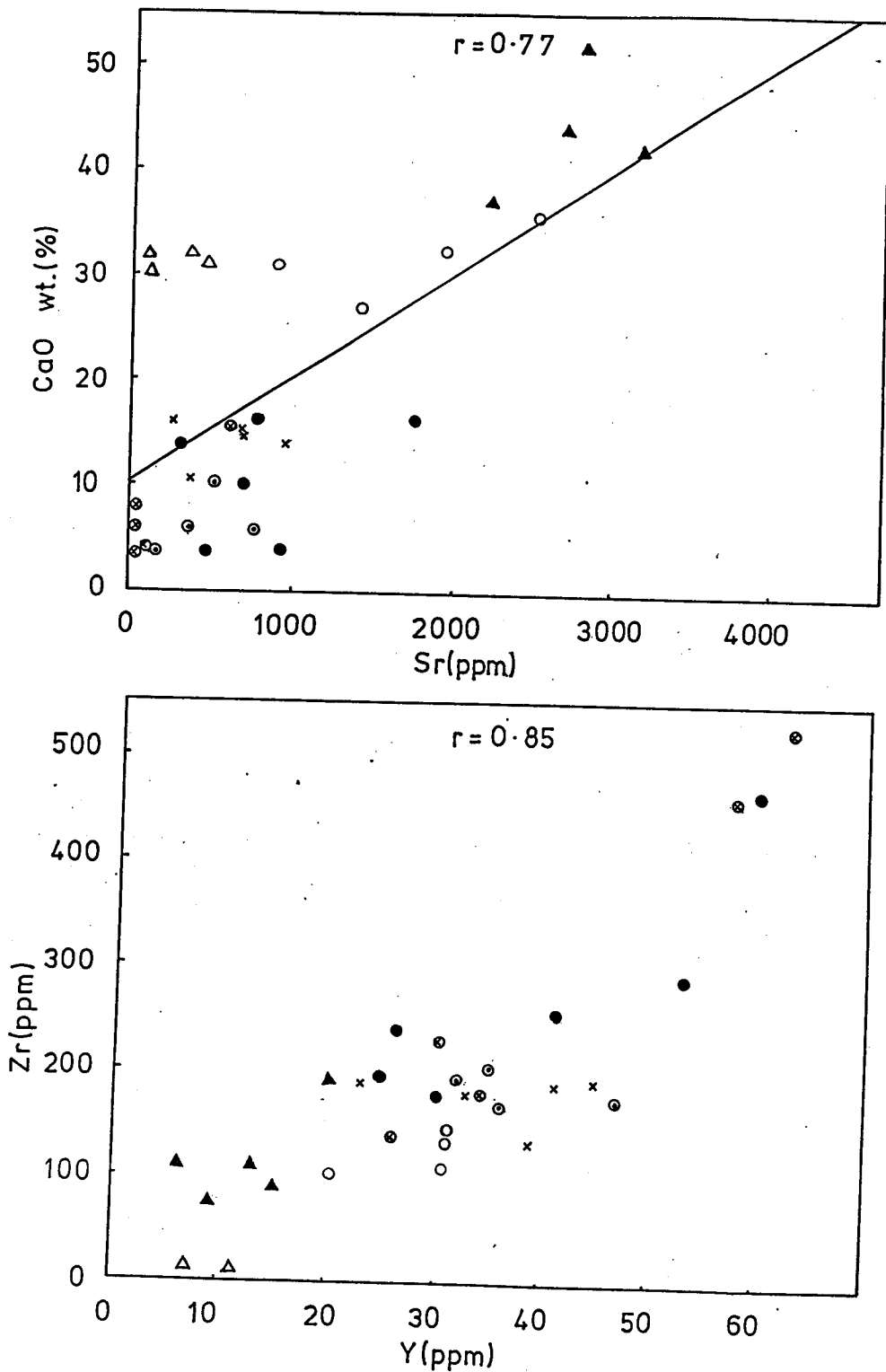


Figure 3.8. Plot of (a) CaO weight per cent against Sr(ppm) and (b) Zr against Y(ppm) for the calc-silicate rocks and marbles. Symbols as for Figure 3.1.

In all of the plots shown above, the calc-silicate schists and fine-grained layers of the calc-silicate gneisses tend to plot farthest from the marbles. The coarse-grained layers of the gneisses tend to plot in an intermediate position between these rock types and the marbles. The massive calc-silicate rocks show more scatter, but in many cases they plot along the same trends. Together with the general strong correlations between the various elements, this suggests that the chemical variations within the calc-silicate rocks and the marbles reflect variations in the amount of detrital phases admixed with carbonate during deposition.

Because the calc-silicate schists and the fine-grained layers that plot farthest from the marbles are rich in Al_2O_3 and K_2O and in modal biotite, this suggests that much of the detrital material admixed with carbonate may have been introduced in the form of clays and detrital micas. This would be consistent with the generally strong positive correlations of the other elements with Al_2O_3 , as the latter is a major component in phyllosilicates.

This hypothesis may be tested by the use of Niggli parameters^(37,38,40). In particular, in metasedimentary rocks, the parameter al-alk (see Appendix III) provides a measure of the Al contained in the original sediment in clay minerals and micas rather Al contained in alkali feldspar, because al-alk in albite and K-feldspar is zero. In the present case, the possibility that significant amounts of Al were added in detrital anorthite-rich feldspar is excluded by the negative correlation of CaO and Sr with al-alk (Fig. 3.10).

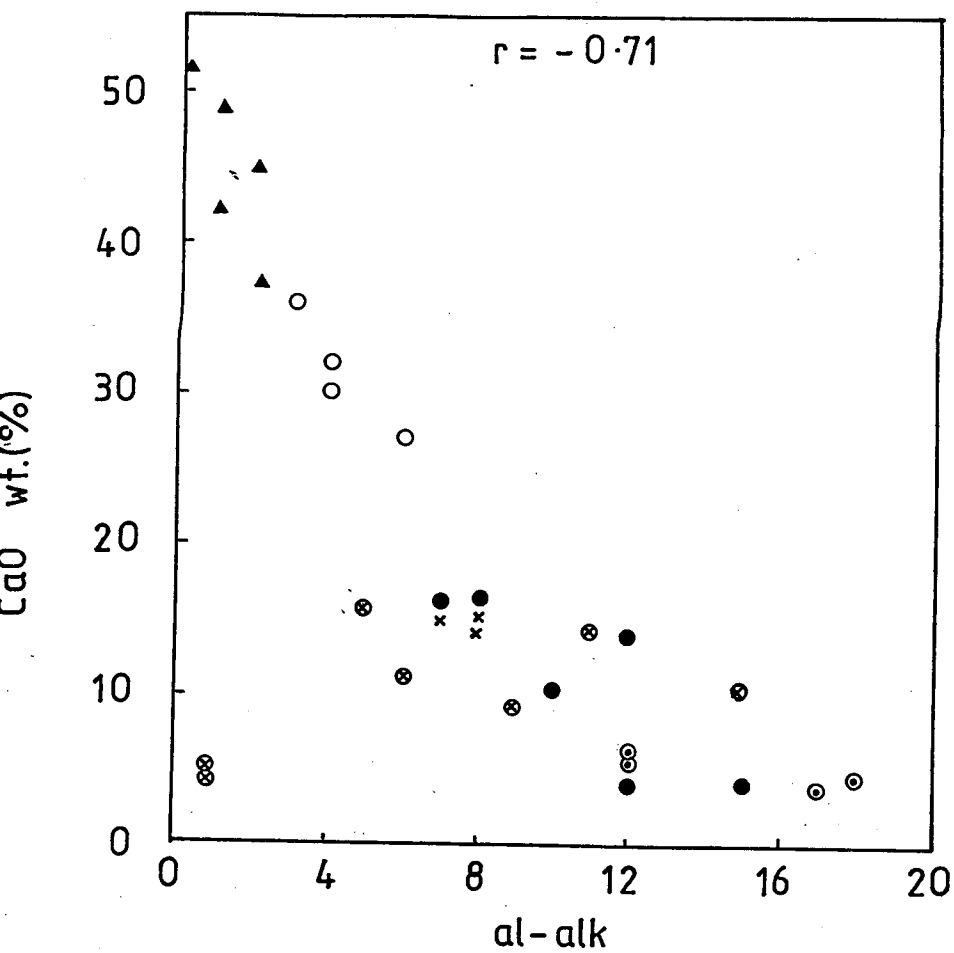
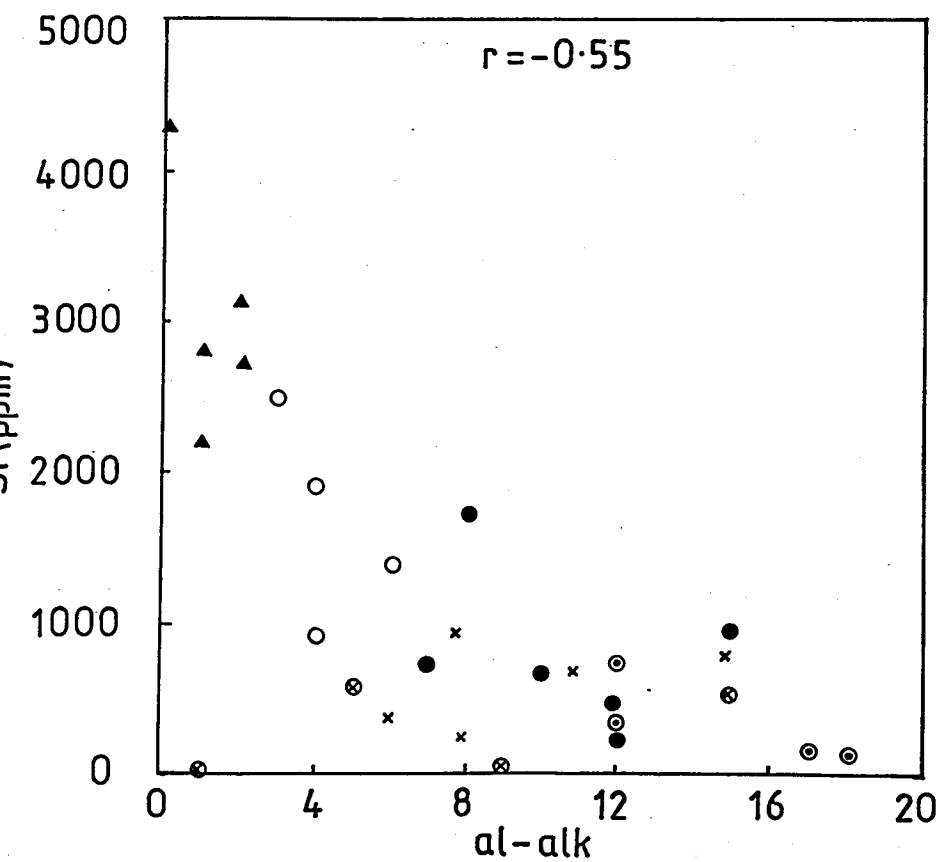


Figure 3.10. Plots of (a) CaO weight per cent and (b) Cr (ppm) against al-alk for the same samples as in Figure 3.9.

As examples, plots of Ba, Cr, Ni, Nb, TiO_2 and Zn against the parameter al-alk are shown on Figures 3.11 through 3.13, where it is evident that these elements show positive correlations with al-alk. As in the inter-element correlations discussed above, the calc-silicate schists and fine-grained layers of the calc-silicate gneisses in general plot farthest from the marbles, and the coarse-grained layers of the gneisses fall in an intermediate position. As expected, the same elements that are positively correlated with Al_2O_3 show a statistically valid correlation with al-alk and this confirms that these elements were predominantly incorporated in the original sediment in the form of clay minerals and detrital micas. This is consistent with the fact that these trace elements in impure carbonate sedimentary rocks are generally carried by non-carbonate phases⁽⁴¹⁾ and the main carriers are fine-grained clays, to which these elements are adsorbed⁽⁴²⁾.

Sr shows a weak but statistically valid negative correlation with al-alk (Fig. 3.10b), which suggests that much of the Sr was originally contained in the carbonate component in the sediments. This is supported by the high concentrations of Sr in the calcite marbles and coarse-grained layers of the calc-silicate gneisses, and by the positive correlation of Sr with CaO (Fig. 3.8a).

The hypothesis that most of the present variations in chemical composition within the calc-silicate rocks and marbles are due to variations in the proportions of detrital clays and micas admixed with carbonate during deposition is further confirmed in the plot

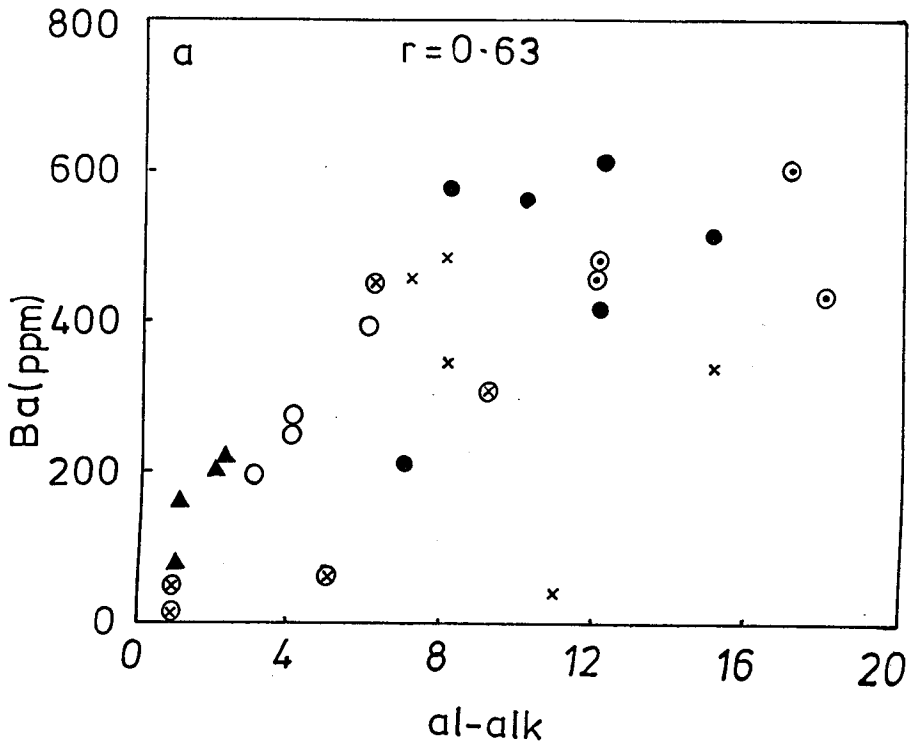
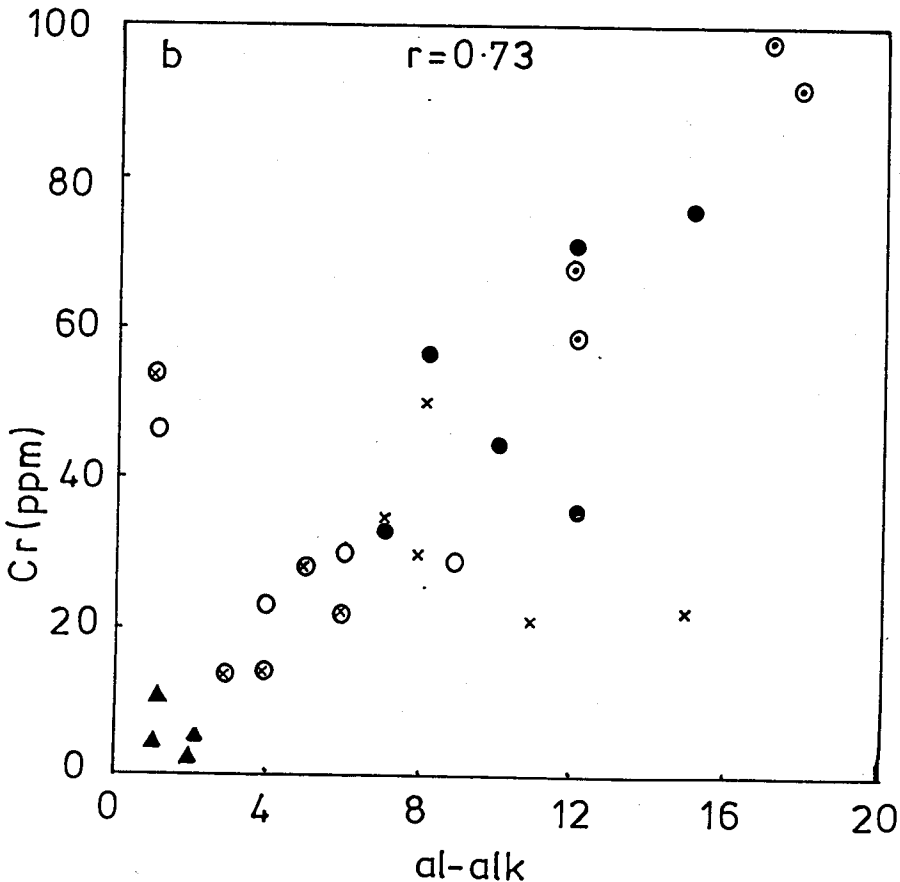


Figure 3.11. Plots of (a) Ba and (b) Cr (ppm) against al-alk for the calc-silicate rocks and marbles. Δ represents dolomite marbles; $\bullet$, calcite marbles; $\otimes$, massive calc-silicate rocks; $\odot$, undifferentiated calc-silicate gneisses; $\bullet$, fine-grained layers; $\circ$, coarse-grained layers of the calc-silicate gneisses; $\times$, calc-silicate schists. r is the correlation coefficient.

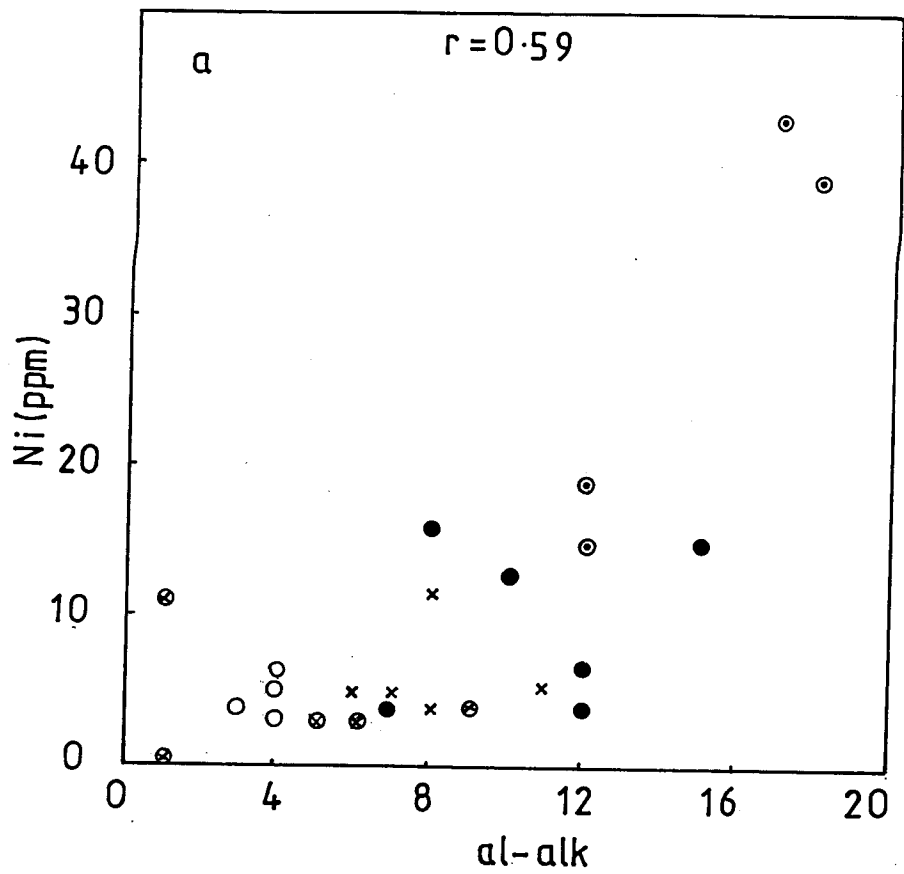
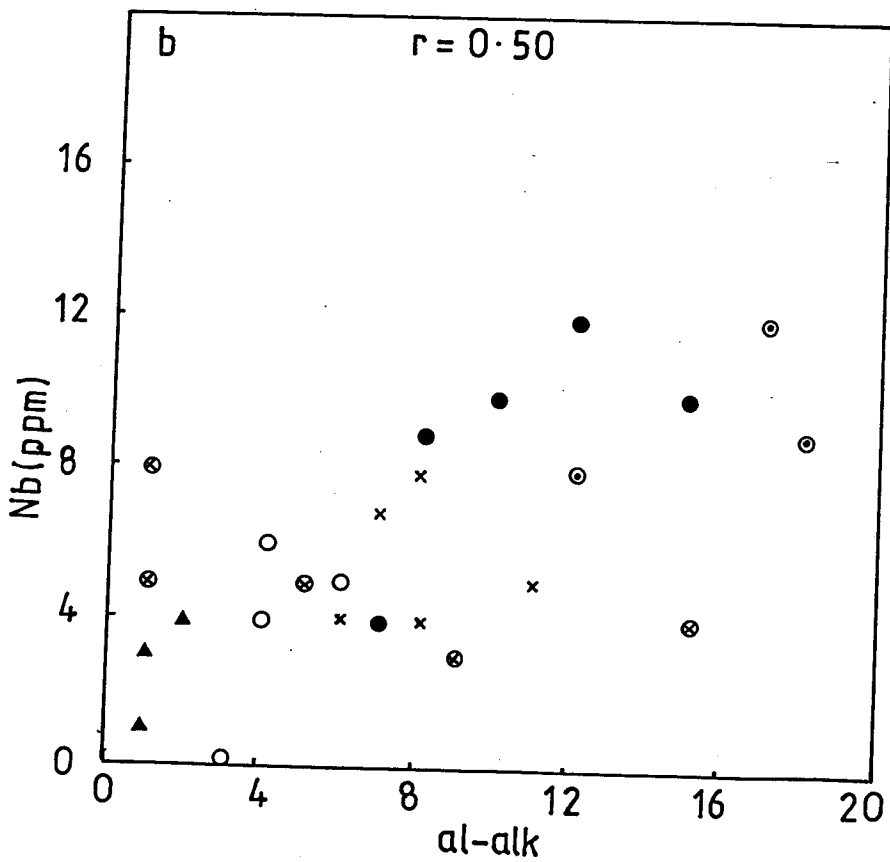


Figure 3.12. Plots of (a) Ni and (b) Nb (ppm) against al-alk for the cal-silicate

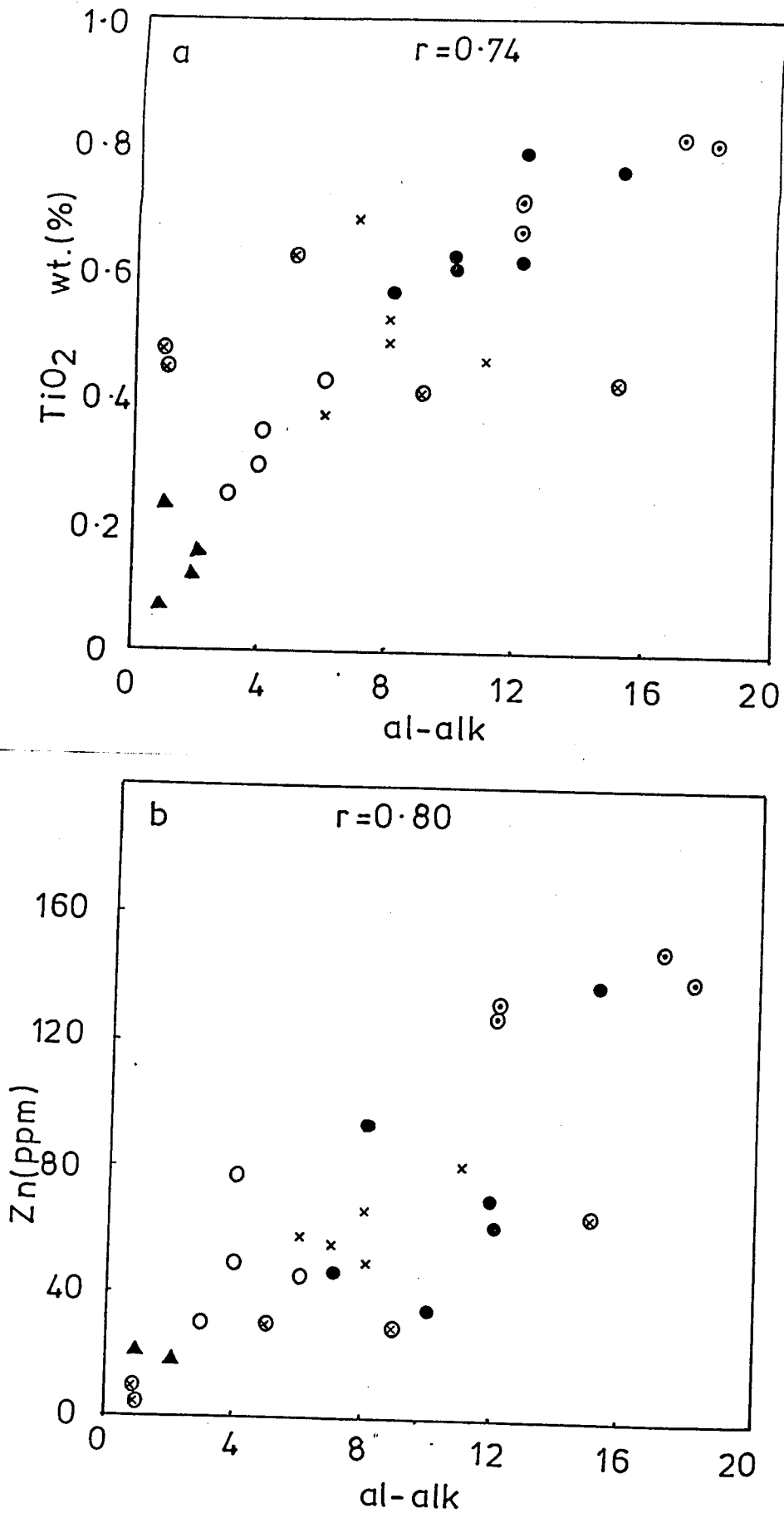


Figure 3.13. Plot of (a) TiO₂ weight per cent and (b) Zn(ppm) against al-alk for the calc-silicate rocks and marbles. Symbols as for Figure 3.12.

of al-alk against Niggli C (Fig. 3.14) developed by Burri (quoted in 40). The diagram shows the dolomite marbles to cluster close to ideal dolomite reflecting their close approach to pure dolomite, whereas the calcite marbles show some deviation from an ideal limestone due to the presence of silicate impurities in these rocks. Their positions on the diagram are consistent with an origin as limestone containing small amounts of clays. It is also evident from this plot that most of the calc-silicate rocks could have originated as mixtures of pelite/carbonate in varying proportions. The calc-silicate schists plot closest to the pelite field. This is in accordance with the other plots and field evidence, since most of these rocks are located at the southern extremity of the Muzuma Calc-silicate Formation. There, the rocks grade imperceptibly into the quartz-biotite schists of the Sachenga Formation ⁽¹³⁾, indicating that abundant pelitic component were admixed with calcareous sediment during deposition.

As in the other plots, the coarse-grained layers of the calc-silicate gneisses are closer to the calcite marbles than are the fine-grained layers, some of which plot together with the calc-silicate schists close to the pelite field. This suggests that the calc-silicate gneisses most likely originated by interbedding of carbonate-rich and clay-rich layers.

The derivation of most of the calc-silicate rocks by intermixing of carbonate and pelite in the protolith is also suggested by comparison of their major element chemistry with that of unmetamorphosed

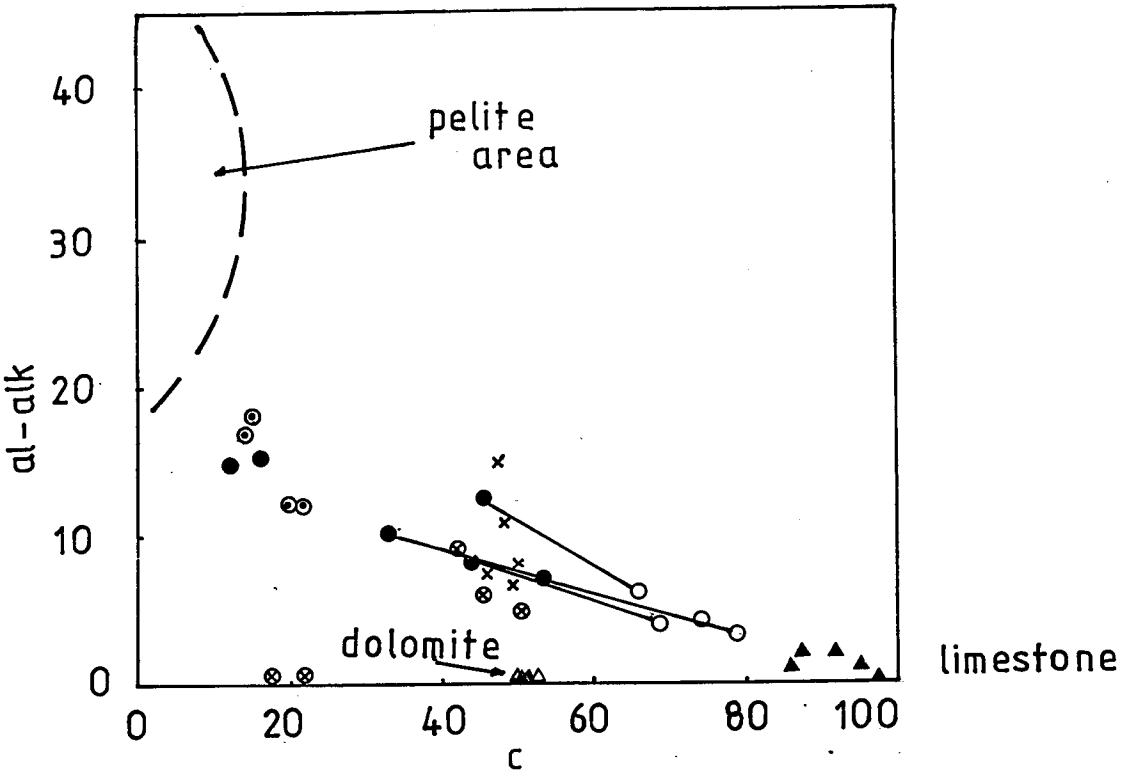


Figure 3.14. Plot of Niggli al-alk against Niggli c for the calc-silicate rocks and marbles. Lines connect adjoining layers in the calc-silicate gneisses. Pelite field from Van de Kamp⁴³. Computed points for ideal dolomite and limestone are also shown. Symbols as for Figure 3.11.

Table 3.8 Average concentrations of minor elements in the calc-silicate rocks and marbles compared to common sedimentary rocks (ppm) (44,45).

	Limestones	Shales	Sandstones	Calcite marbles	Massive calc-silicate rocks*	Coarse-grained, Calcite-rich layers in calc-silicate gneiss	Fine-grained Biotite-rich layers in calc-silicate gneiss	Calc-silicate schists
Ba	90	630	100	147	198	276	423	491
Cr	11	100	35	5	37	18	76	79
Zr	19	180	220	92	253	122	134	185
Sr	610	400	20	3028	253	1680	721	352
Rb	3	140	60	22	39	56	95	189
Y	30	35	40	13	40	28	29	38
Zn	20	90	16	14	28	51	81	137
Ni	20	80	2	14	7	4	51	29

*the mottled-varieties were not analysed.

and calc-silicate rocks within the Zambezi belt.

In all the rock types, Zr and Y do not correlate with either Al_2O_3 or al-alk (Fig. 15). This indicates that originally these elements were not contained in phyllosilicates in significant amounts. The distribution of Zr, however, is related to that of SiO_2 and TiO_2 (Figs. 3.6b and 3.7a), most likely implying the addition of Zr, SiO_2 and some TiO_2 in other detrital phases, such as zircon, quartz, and rutile, which were added together during deposition. Small zircon grains are present in some of the massive calc-silicate rocks, and rutile also occurs in a few samples of the calc-silicate rocks and marbles (Tables 2.2 and 2.3). It is possible that these are at least partly relict detrital grains. Sporadic intercalations of quartzites are present in the Muzuma Calc-silicate and Mapanza Carbonate Formations, indicating that detrital quartz and probably other stable heavy minerals as well were indeed supplied to the original sediment in the basin.

Zircon may contain up to 14,000 ppm Y in its crystal lattice⁽⁴⁶⁾. It is therefore possible that the strong correlation between Zr and Y (Fig. 3.8b) reflects incorporation of Y in detrital zircon.

The massive calc-silicate rocks are generally much higher in SiO_2 than the other rock types, and the high SiO_2 values are comparable to those of certain types of sandstones such as arkoses or greywackes⁽⁴⁷⁾. This suggests that calcareous sandstone was the protolith for these rocks. Their trace element contents are compatible

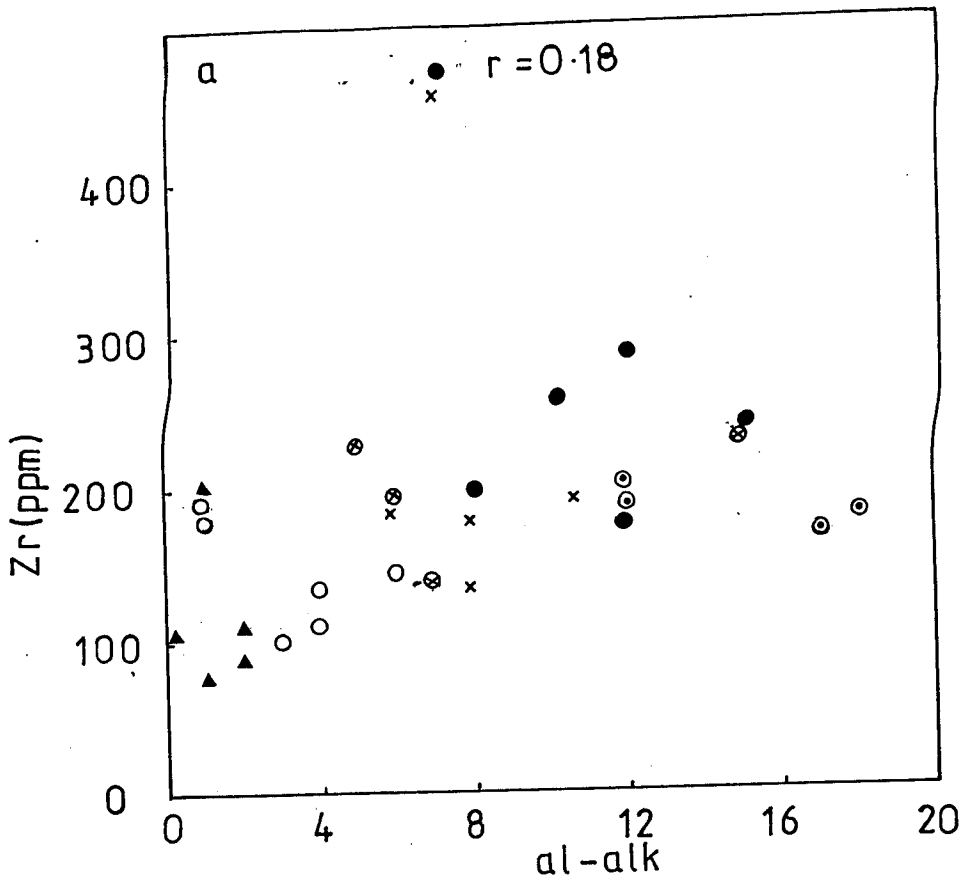
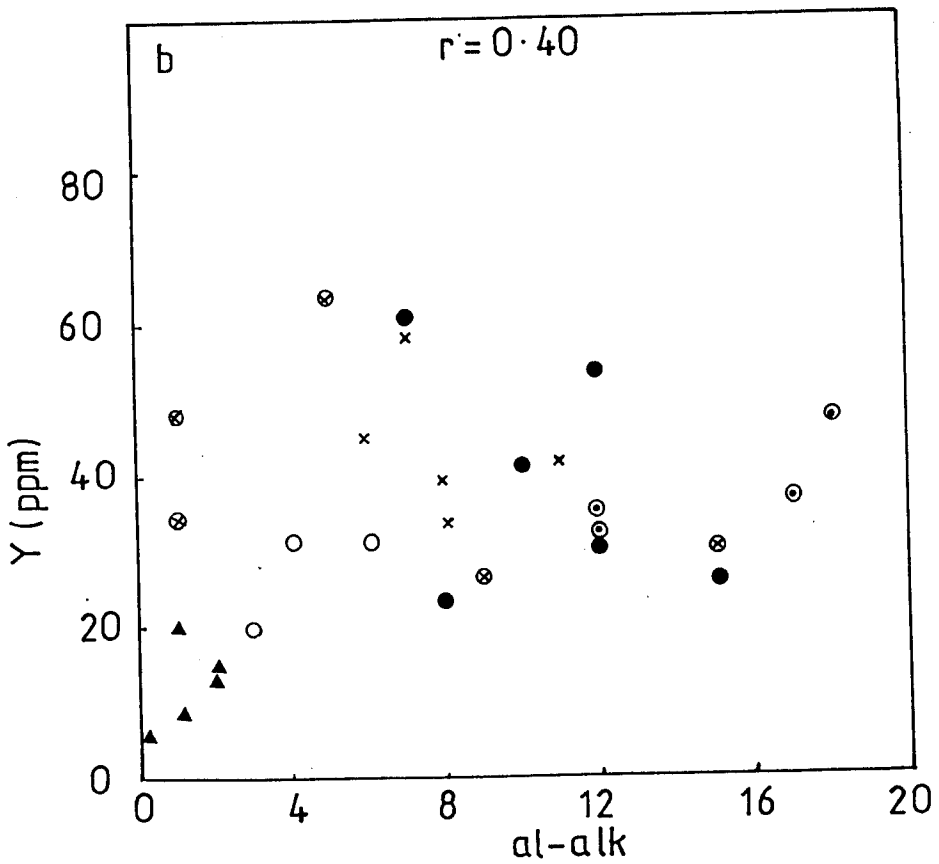


Figure 3.15. Plots of (a) Zr and (b) Y (ppm)

with such an origin, and in particular their Zr, Y, Cr and Ni contents compare fairly well with average values for sandstones (Table 3.8).

In some cases the massive calc-silicate samples fall along the same trend as the other rock types in the plots presented above, which suggests that addition of detrital clays and micas still played an important role in governing element distribution patterns in these rocks. Where some samples plot off the main trends, element patterns were probably controlled less by clays and detrital micas and more by addition of quartz and other phases (e.g. feldspar?).

3.7 Element immobility during metamorphism

Evidence of element mobility during metamorphism of carbonate and calc-silicate rocks has been documented in a number of studies (48, 49, 50, 51). In particular, progressive loss of Na_2O and K_2O with increasing grade of metamorphism has been cited (47, 48, 49). In these studies, Al_2O_3 , TiO_2 and to some extent FeO , MgO and CaO were found to be relatively immobile during metamorphism from the chlorite through the sillimanite zone. The behaviour of trace elements during progressive metamorphism, however, was not investigated by these workers.

The calc-silicate rocks and marbles of the present study were metamorphosed at uniform grade in the amphibolite facies, as will be discussed below. They do not therefore afford an opportunity to test the behaviour of the elements with increasing grade of . . .

metamorphism. However, it is possible to make inferences regarding general element mobility during metamorphism of these rocks.

The fairly close similarity of the abundances of TiO_2 , Al_2O_3 , MgO , CaO and FeO total in the calc-silicate and carbonate rocks with those of probable sedimentary protoliths (Tables 3.4 and 3.6) is another indication that these elements were not significantly mobilized during metamorphism. In the case of TiO_2 and Al_2O_3 , this is in accord with the general geochemical behaviour of these elements, which typically act as immobile components during metamorphism of diverse rock types.

The preservation of these primary chemical variations within these rocks into the amphibolite facies implies that the elements in question were relatively immobile during metamorphism.

The alkalis (Na_2O and K_2O) are typically highly mobile during metamorphism. However, it is interesting to note that in the present case, the alkalis apparently show the same primary variations as the other elements, and this suggests that the alkalis were also relatively immobile.

Cann⁽⁵²⁾, Pearce and Cann⁽⁵³⁾ and Floyd and Winchester⁽⁵⁴⁾ have shown that during alteration and metamorphism of basalts, the elements Zr, Nb and Y remain relatively stable. Lambert and Holland⁽⁴⁶⁾ have also concluded independently that Y behaves as an inert element during metamorphism. This is consistent with the assumption that Zr, Nb and

Y were also stable during metamorphism of the calc-silicate rocks and marbles discussed here.

The conclusion that the other trace elements (Ba, Rb, Zn, Sr, Cr and Ni) were also relatively immobile during metamorphism may be tested by plots of these elements against any one element believed to have been immobile during metamorphism. This has in effect already been shown by plotting these elements against Al_2O_3 . Here it is further tested by plotting the elements against TiO_2 (Figs. 3.16 through 3.18). In all cases, there is a fairly strong positive or negative correlation of each element with TiO_2 , which strongly suggests that all of these elements were in general relatively immobile during metamorphism. This is also suggested by the fact that these elements in general show a fairly strong correlation between each other (e.g. Figs. 3.19 and 3.20) which is expected since the elements correlate with Al_2O_3 and TiO_2 . In cases where elements with markedly different geochemical properties are strongly correlated (e.g., Rb versus Cr, Fig. 3.20a), it is highly unlikely that the variation reflects a similar degree of mobilization during metamorphism, and it must instead reflect variations in the protolith composition which have survived metamorphism.

Some of the scatter in the plots may reflect limited mobilization of the elements relative to each other. At least some of the scatter, however, probably reflects original variations in the exact proportions and compositions of detrital phases admixed with

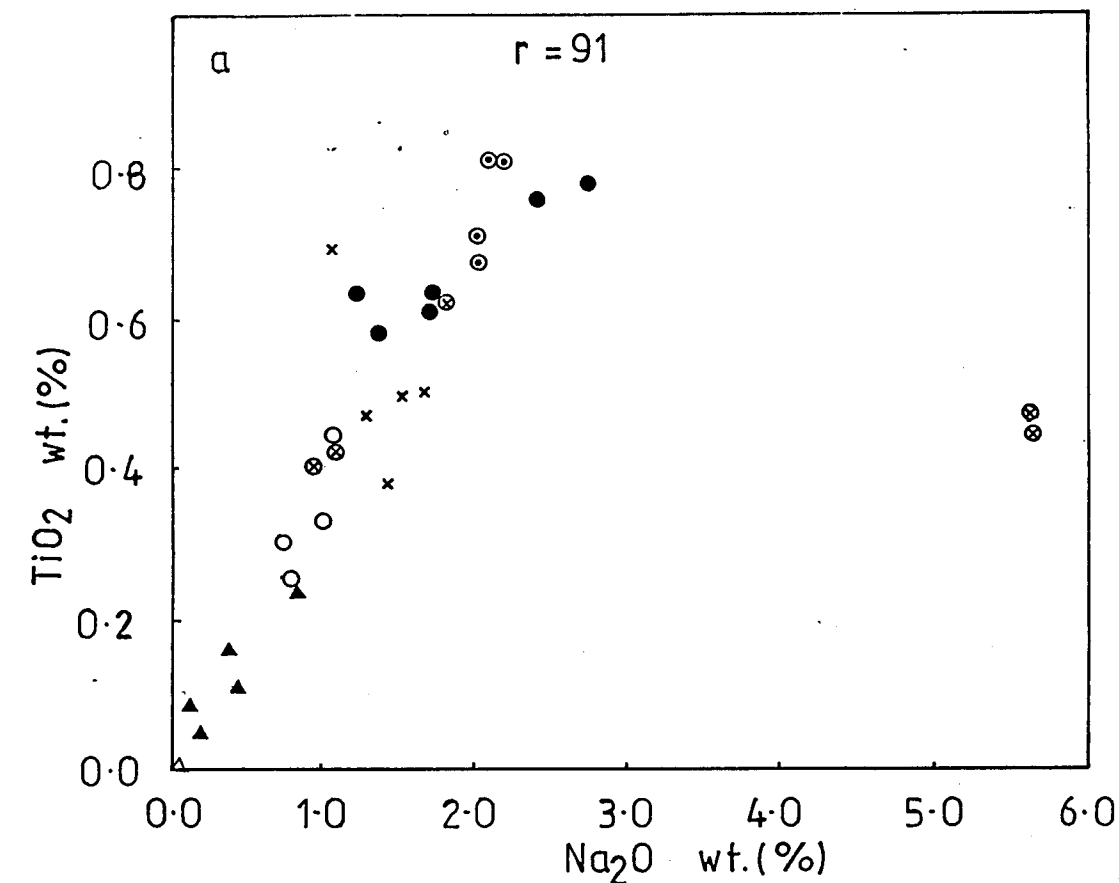
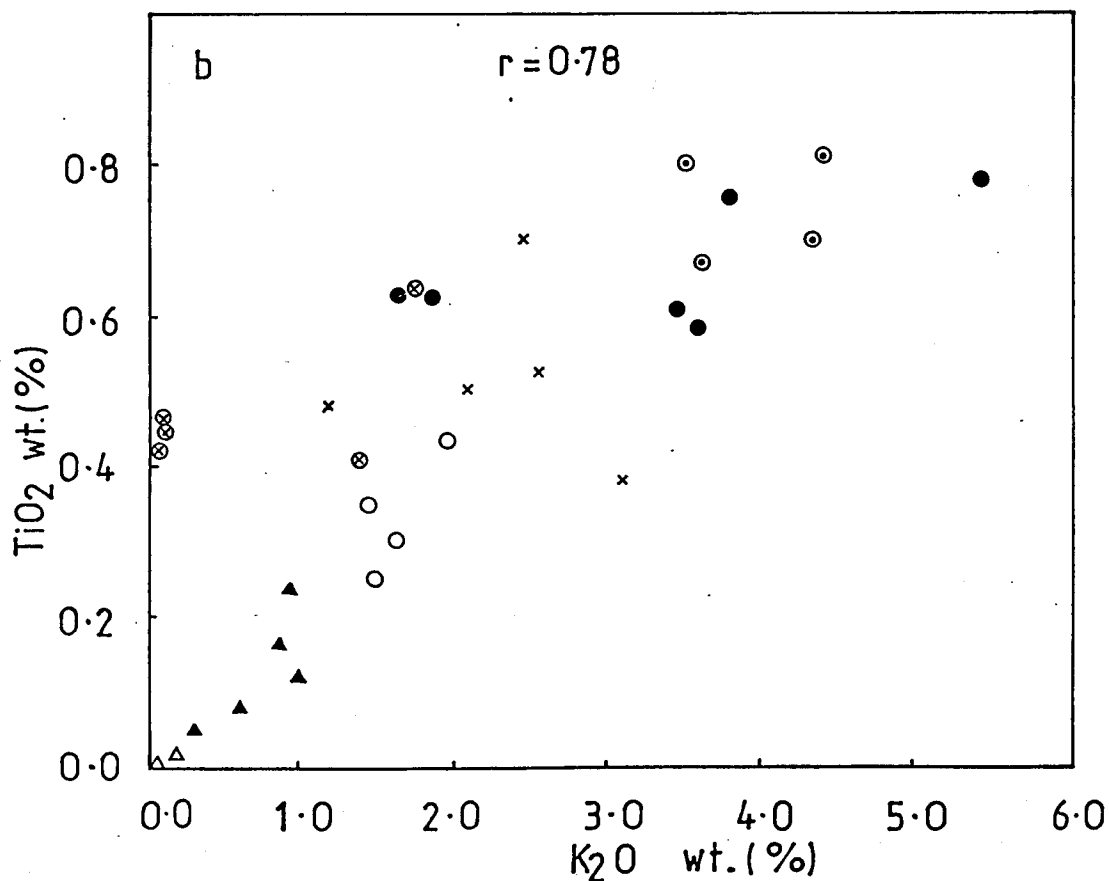


Figure 3.16. Plots of TiO₂ weight per cent against (a) Na₂O and (b) K₂O weight per cent for the calc-

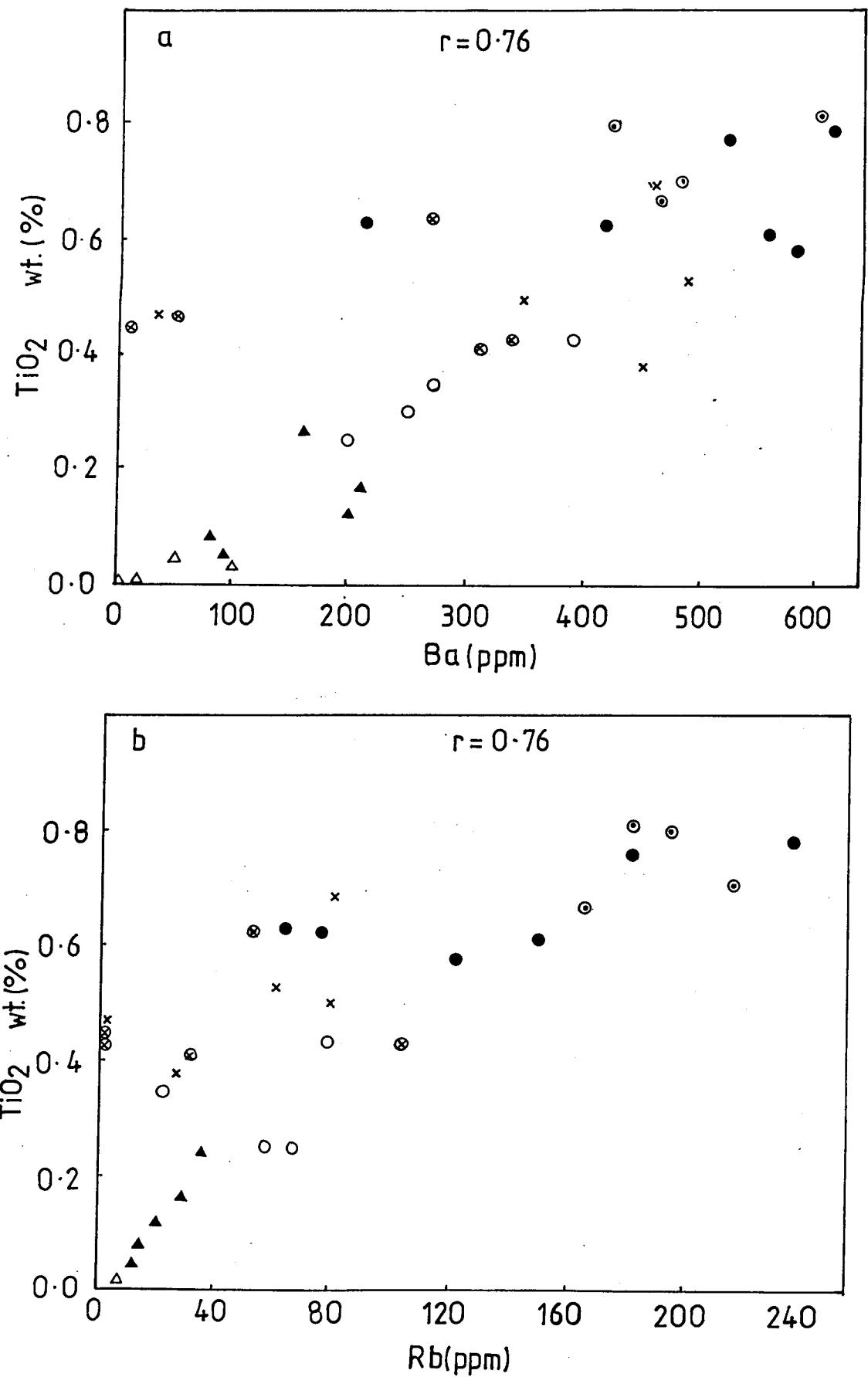


Figure 3.17. Plots of TiO_2 weight per cent against (a) Ba and (b) Rb(ppm) for the Calc-silicate rocks and marbles. Symbols as for Figure 3.11.

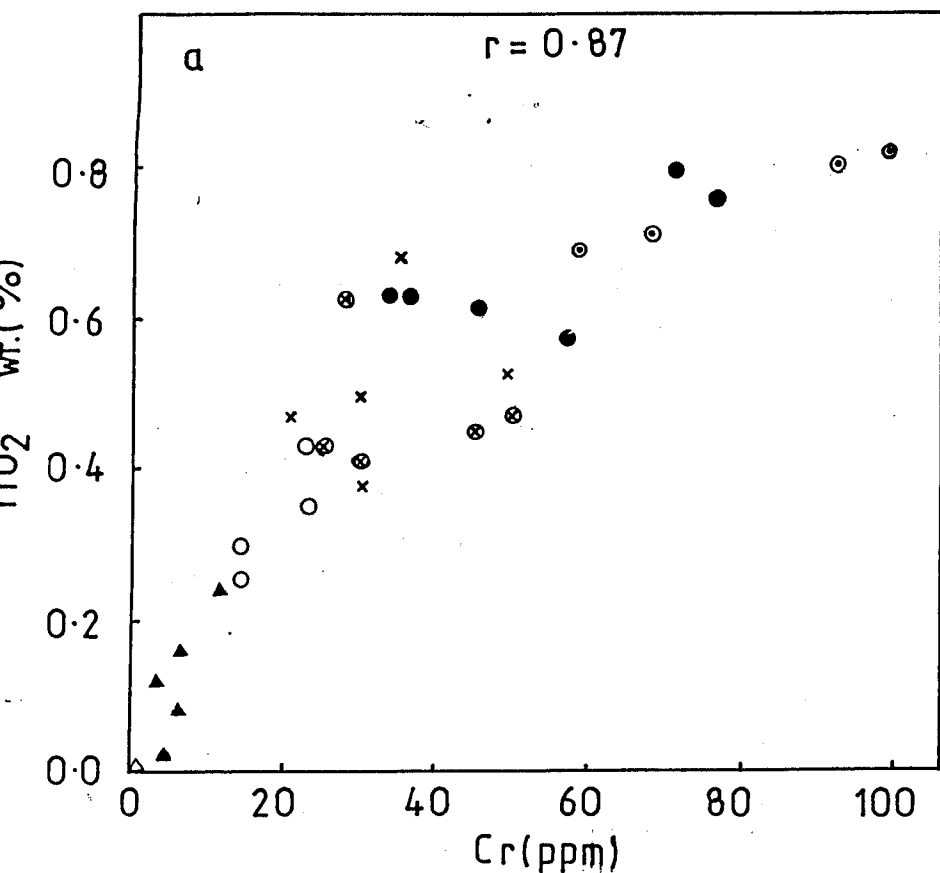
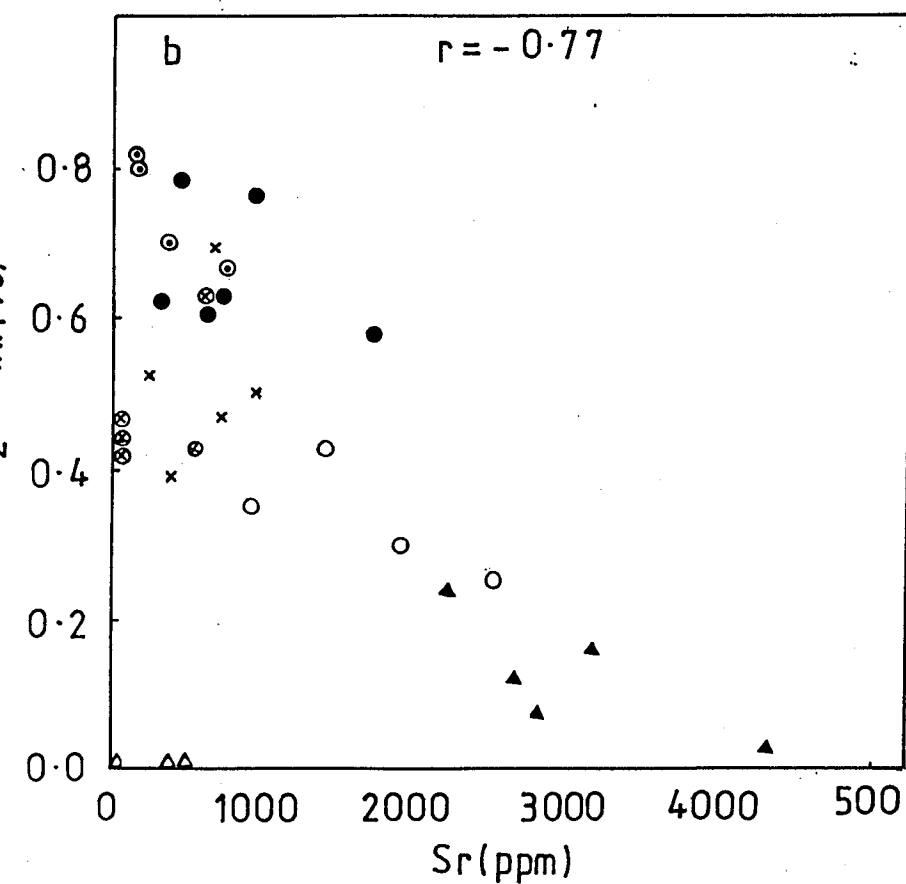


Figure 3.18. Plots of TiO_2 weight per cent against (a) Cr (ppm) and (b) Sr (ppm) for the

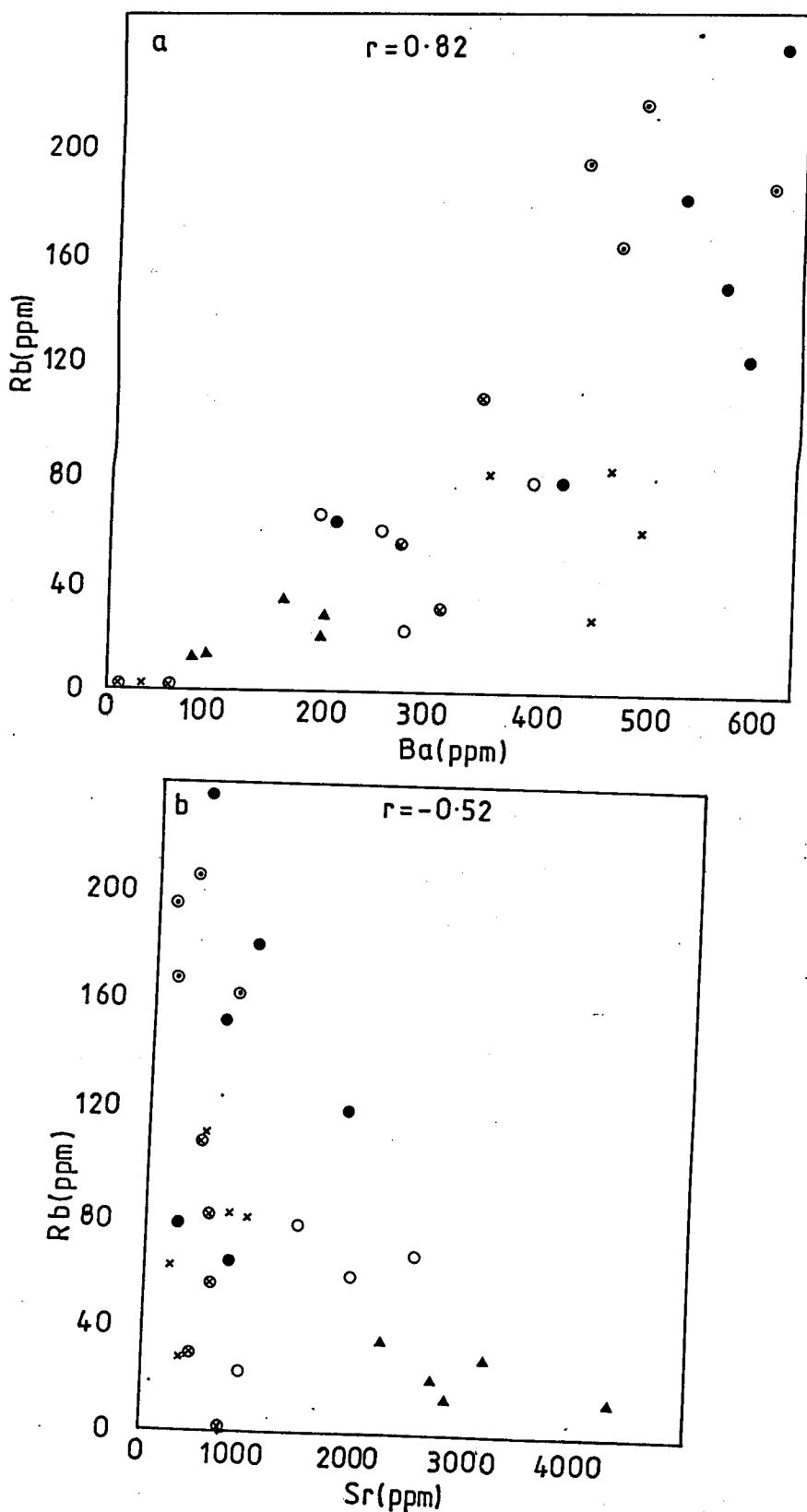


Figure 3.19. Plot of Rb(ppm) against (a) Ba(ppm) and (b) Sr(ppm) for the calc-silicate rocks and marbles. Symbols as for Figure 3.11.

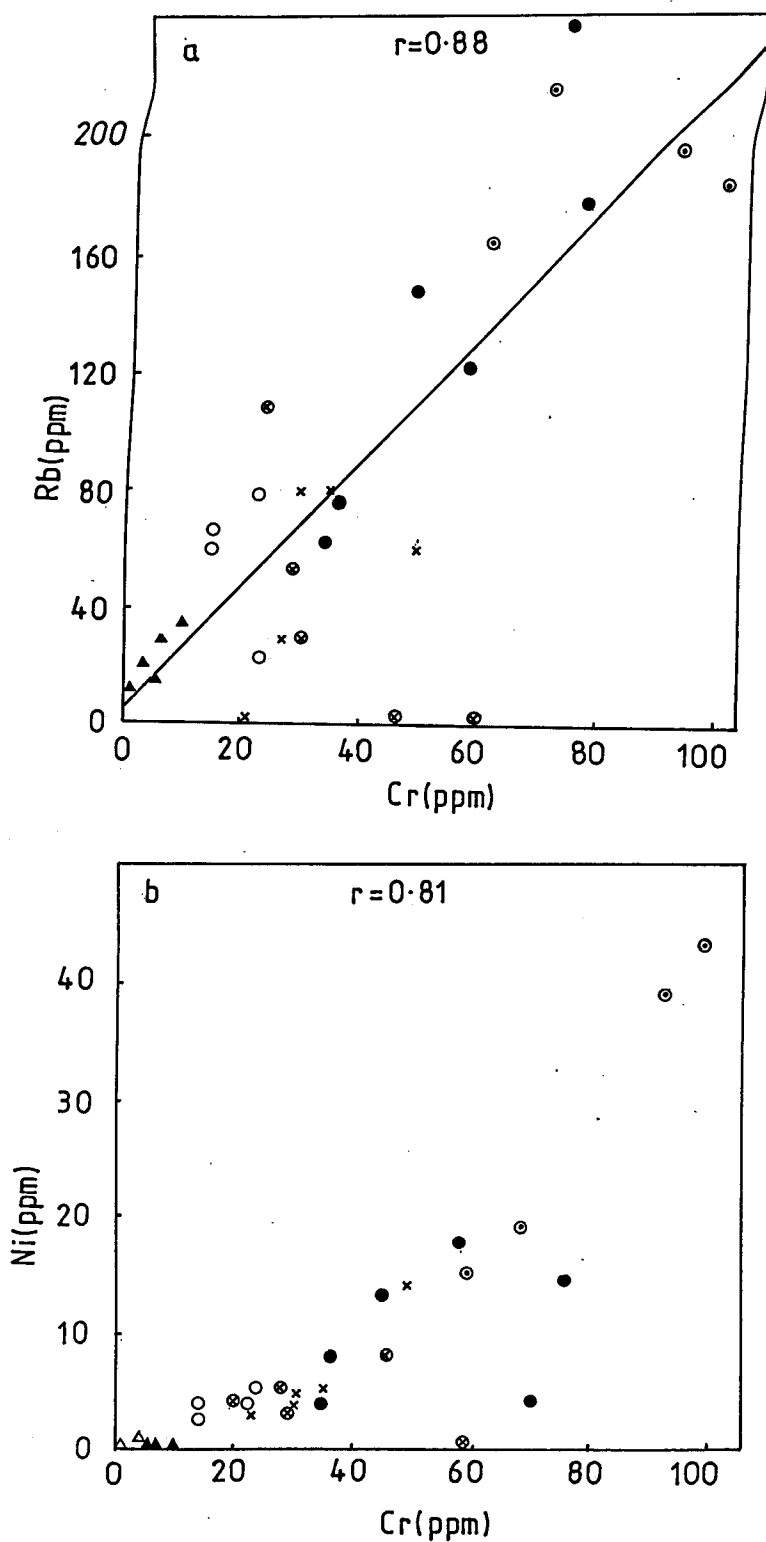


Figure 3.20. Plot of (a) Rb(ppm) and (b) Ni(ppm) against Cr(ppm) for the calc-silicate rocks and marbles. Symbols as for Figure 3.11.

carbonate during deposition. This may be particularly true for a few of the massive calc-silicate rocks, which plot well off the main trend in several of the plots (see earlier discussion of these rocks).

In the case of Sr, it is significant that Veizer (Pers. commun., 1985) has pointed out that ancient marbles rarely have Sr contents as high as 3000 ppm. Two of the calcite marbles samples have Sr in excess of this, which suggests that Sr may have been metasomatically added in these cases. The low correlation coefficients in Figures 3.9b, 3.10b above also suggests metasomatic disturbance of Sr. However, the abundance of this element in the calcite marbles and hence its correlation with CaO suggests that Sr was originally concentrated in the calcite-rich sediment.

Other geochemical studies of metamorphosed calc-silicate and carbonate rocks have also shown that many elements were immobile during metamorphism and that original variations in composition of the protolith survived metamorphism.

Senior and Leake⁽³⁸⁾ have concluded from extensive geochemical study of the amphibolite facies Connemara calc-silicate rocks, marbles, pelites and semipelites that chemical variations exhibited by the rocks were mainly primary, reflecting variations in the original sediment. They correlated the original clay mineral component with the elements Ti, K, Rb, Zr, Zn, Y, Ni, Nb, Cr, Ga, and Fe. They inferred that a similar, illite-rich clay mineral was added to all sediments,

and based on crustal abundances of these elements, they also drew a general conclusion that the control of these elements by clay minerals was common in most sediments. Leake et al.⁽³⁷⁾ also arrived at the same conclusion, correlating the trace element concentrations of the Connemara ophicalcite and dolomitic marbles with the clay mineral content originally in the sediment. Similarly Yardley⁽⁵⁵⁾ has found that Connemara metapelites showed isochemical behaviour during metamorphism.

In the Churchill structural province of the Precambrian Canadian Shield, Hogarth and Griffin⁽⁵⁶⁾ concluded that no significant movement of SiO_2 , Al_2O_3 , MgO , Na_2O and K_2O had occurred during granulite facies metamorphism of lapis lazuli deposits. They interpreted lapis lazuli layers having high contents of SiO_2 and Al_2O_3 and surrounded by marbles as originally clay-rich layers.

From the geochemical data of the calc-silicate rocks and marbles presented above, it seems clear that the compositions of these rocks do not vary in any random fashion. Such consistent chemical variations are mainly primary and largely reflect chemical differences inherited from the original sediment. The clay mineral content of the protolith largely or entirely controlled the distribution of the elements Al, K, Na, Ti, Fe, Ba, Cr, Ni, Rb, Zn and Nb. Sr was concentrated mainly in calcareous-rich sediment whereas Zr and Y were mostly likely introduced as detrital zircon.

3.8 Origin of banding in the calc-silicate gneisses

In metamorphic petrology, an interesting problem which is quite often encountered is whether the compositional layering present in certain gneisses represents relict sedimentary bedding or was formed by metamorphic differentiation.

Criteria for recognition of layering formed during segregation processes include (38,57):

1. Presence of incompatible phases in adjacent layers such as forsterite and quartz, corundum and quartz, and in high grade marbles dolomite and quartz, which would not normally coexist in a single layer.
2. Evidence of compositional control of certain layers by one or a few metamorphic minerals whose total bulk composition is difficult to match with unaltered sediments or with a likely mixture of sediments.
3. Presence of compositional layering which can be seen to cut across the bedding.

None of the above criteria are shown by the compositional layering in the calc-silicate gneisses, and the geochemical trends discussed above strongly suggest that the layering represents relict bedding.

Calc-silicate bands formed between pelite and carbonate rocks and thought to have developed by diffusion of elements during metamorphism have been documented in a number of studies (58,59).

The formation of calc-silicate bands by metamorphic differentiation has also been experimentally demonstrated⁽⁶⁰⁾. However, these bands are commonly thin (on the scale of a few centimeters) and are typically developed in a relatively small area. In regions where the compositional layering is very widespread, such as is the case for the calc-silicate gneisses in Southern Province, it is difficult to explain the formation of the banding by metamorphic differentiation⁽⁶¹⁾. It has also been pointed out that a compositional layering which appears to be relict bedding is well-preserved in some other calc-silicate rocks⁽⁶²⁾.

From the geochemistry of the calc-silicate rocks and marbles, it has been possible to deduce that during metamorphism, the chemical compositions of the rocks were not modified to a large extent. It thus follows that the conspicuous compositional layering in the calc-silicate gneisses originated as sedimentary bedding, which was most likely later modified and accentuated during metamorphism.

CHAPTER FOUR

GEOCHEMISTRY AND ORIGIN OF THE AMPHIBOLITES

4.1 Introduction

Geochemistry of the Mapanza amphibolites is presented and whole-rock chemical analyses of six amphibolites by X-ray fluorescence spectrometry (Appendix II) are given. The chemical data is relevant inasmuch as it has some significance for the petrogenesis of these rocks. Techniques often used to distinguish amphibolites of different sources have been used in an attempt to elucidate the nature of the protolith for the Mapanza amphibolites.

4.2 Chemical variations within the amphibolites

Chemical analyses of six Mapanza amphibolites are listed in Table 4.1. The garnet amphibolites differ markedly from the garnet-free amphibolites in some of the major and trace element contents.

The garnet amphibolites are enriched in the trace elements Zr, Sr, Rb, Y, Nb and Zn relative to the garnet-free amphibolites, which in turn show higher Ba, Cr, and Ni content than the garnet amphibolites.

The garnet-free amphibolites also have higher CaO , Al_2O_3 and MgO than the garnet-bearing types and are therefore the more mafic. TiO_2 is significantly higher in the garnet amphibolites than in the garnet-free varieties. The former also have distinctly higher $\text{Fe}/(\text{Fe} + \text{Mg})$ ratios than the garnet free amphibolites (Table 4.1).

Table 4.1 Chemical analyses of the amphibolites
Major elements (wt.%)

	<u>Garnet amphibolites</u>		<u>Garnet-free amphibolites</u>			
	MA19	MA19A	MA15	MA13A	MA8	MA14
SiO	48.94	48.94	46.28	47.28	48.58	49.28
TiO ₂	2.02	2.03	0.87	0.85	0.83	0.82
Al ₂ O ₃	14.09	14.24	16.74	15.98	15.36	16.26
*FeO	12.99	13.18	10.62	9.98	8.91	9.34
MnO	0.20	0.20	0.19	0.17	0.14	0.14
MgO	6.59	6.52	10.61	9.17	8.82	8.95
CaO	10.68	10.57	12.16	14.53	12.35	12.78
Na ₂ O	2.55	2.55	1.84	1.09	2.34	2.30
K ₂ O	0.27	0.27	0.10	0.11	0.14	0.15
P ₂ O ₅	0.06	0.05	n.d	n.d	n.d	n.d
S	0.02	0.04	n.d	0.10	n.d	0.01
Fe/(Fe+Mg)	0.525	0.531	0.360	0.379	0.362	0.369
<hr/>						
Trace elements (ppm)						
Ba	n.d	15	61	37	45	35
Cr	90	83	311	134	505	446
Zr	156	157	52	53	55	63
Sr	1043	1058	375	679	719	780
Rb	4	4	n.d	n.d	n.d	n.d
Y	44	45	31	33	29	31
Nb	5	9	n.d	n.d	n.d	1
Zn	88	101	56	74	57	65
Ni	52	57	207	66	95	109

*Total iron as FeO

n.d. not detected

This compositional variation is illustrated on an 'A' F M diagram (Fig. 4.1) projected through the epidote point in the system Al_2O_3 -FeO-MgO-CaO on to the plane $\text{A}(\text{Al}_2\text{O}_3) - \text{F}(\text{FeO}) - \text{M}(\text{MgO})$ ⁽⁶³⁾. This shows how an increase in FeO relative to MgO controls the appearance of garnet in the phase assemblages. Samples which contain garnet fall to the left of the plagioclase hornblende tie line whereas garnet-free amphibolites fall to the right of the plagioclase - hornblende tie line.

The garnet amphibolites also have higher K_2O and Na_2O than the garnet-free types. This suggests that the appearance of biotite in the former is also a function of bulk chemical composition. Biotite is the main K-bearing mineral in these rocks and some of the Na is in solid solution with K in biotite. Such a compositional control on the appearance of garnet and biotite in amphibolites is common and has been documented in many studies ^(64,65,66).

However, despite the compositional variation shown by these amphibolites, their major and trace element chemistry in general compares reasonably well with that of other rock suites of basic composition (Table 4.2).

4.3 Origin of the amphibolites

It is generally acknowledged that amphibolites may form by the following mechanisms ^(67, 35, 36, 43, 68):

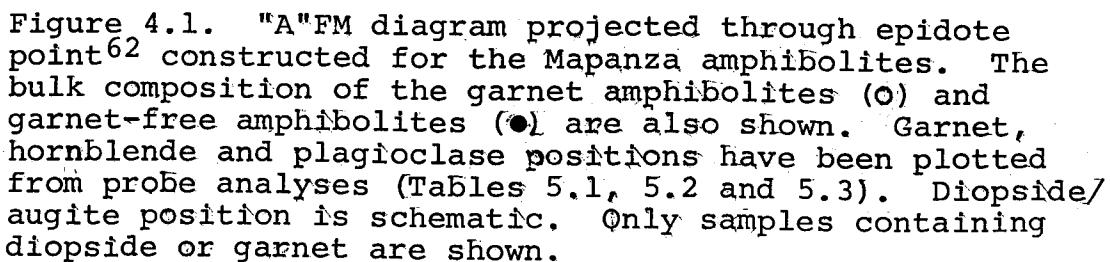


Table 4.2 Mean compositions and standard deviations(s.d) of Mapanza amphibolites compared to typical ortho-amphibolites and basalts

	Major elements (wt.%)							
	Mean of Wankie		Mean of		Mean of		Mean of Alabama	
	Karoo		Swaziland		Mapanza		Piedmont	
	basalts(69)		Karoo		amphibolites		orthoamphibolites (	
	(n=8)		basalts (69)		(n=6)		(n=27)	
	Mean	S.d	Mean	S.d	Mean	S.d	Mean	s.d
SiO ₂	51.28	0.31	50.21	2.56	48.22	1.98	49.02	3.13
TiO ₂	3.17	0.13	1.61	0.46	1.24	0.61	1.23	0.31
Al ₂ O ₃	13.09	0.30	14.93	1.04	15.54	1.09	15.47	1.60
* FeO	12.77	0.86	11.36	1.00	10.84	1.84	11.78	2.00
MgO	5.42	0.31	5.41	0.64	8.44	1.60	6.77	1.03
CaO	9.28	0.49	10.02	1.87	12.18	1.47	11.10	1.84
Na ₂ O	2.41	0.17	2.87	0.77	2.11	0.56	2.20	1.14
K ₂ O	1.06	0.34	0.35	0.29	0.17	0.08	0.38	0.22
	Trace elements (ppm)							
	Mean	S.d	Mean	S.d	Mean	S.d	Mean	S.d
Ba	590	149	184	123	32	22	36	9
Cr	n.d	-	156	65	261	186	248	178
Sr	576	140	294	84	776	255	183	75
Zr	352	98	70	25	89	52	**	
Ni	68	8	86	22	98	58	78	27
Rb	33	4	n,d		1	2	**	
Y	n.d		22	10	35	7	**	
Nb	10	2	18	11	2	4	**	

*Total iron as FeO

**not analysed

n.d not detected

1. Metamorphism of basic igneous rocks.
2. Metamorphism of calcareous or dolomitic shale.
3. *Metasomatism involving exchange of significant amounts of non-volatile constituents with the surrounding rocks.*
4. Metamorphism of graywackes containing appreciable amounts of basic igneous debris.

Amphibolites resulting from metamorphism of basic igneous protoliths have been termed ortho-amphibolites whereas those produced by metamorphism and/or metasomatism of sediments have been called para-amphibolites (35,36).

It has already been inferred from field relations (Chapter 2) that the garnet-free amphibolites are ortho-amphibolites.

Geochemical methods by which ortho-amphibolites may be distinguished from para-amphibolites have been developed⁽³⁵⁾. A particularly useful technique involves comparison of Niggli parameters mg , c and $al-alk$ for amphibolites with trends of unmetamorphosed basic igneous rocks.

Niggli parameters for the Mapanza amphibolites are given in Table 4.3 and have been plotted on the diagrams recommended by Evans and Leake⁽⁶⁷⁾ and Leake⁽³⁵⁾ in Figures 4.2, 4.3 and 4.4. In all three plots, the data are consistent with an igneous origin for the amphibolites.

Table 4.3 Niggli parameters of the Mapanza amphibolites

<u>Garnet amphibolites</u>			<u>Garnet-free amphibolites</u>			
MA19	MA19A		MA14	MA13A	MA15	MA8
al	19	20	21	20	20	20
alk	6	6	5	2	3	5
fm	48	48	45	46	50	46
c	27	26	29	32	27	29
mg	0.47	0.46	0.63	0.62	0.64	0.63
k	0.07	0.07	0.04	0.06	0.04	0.04
al-alk	13	14	16	18	17	15

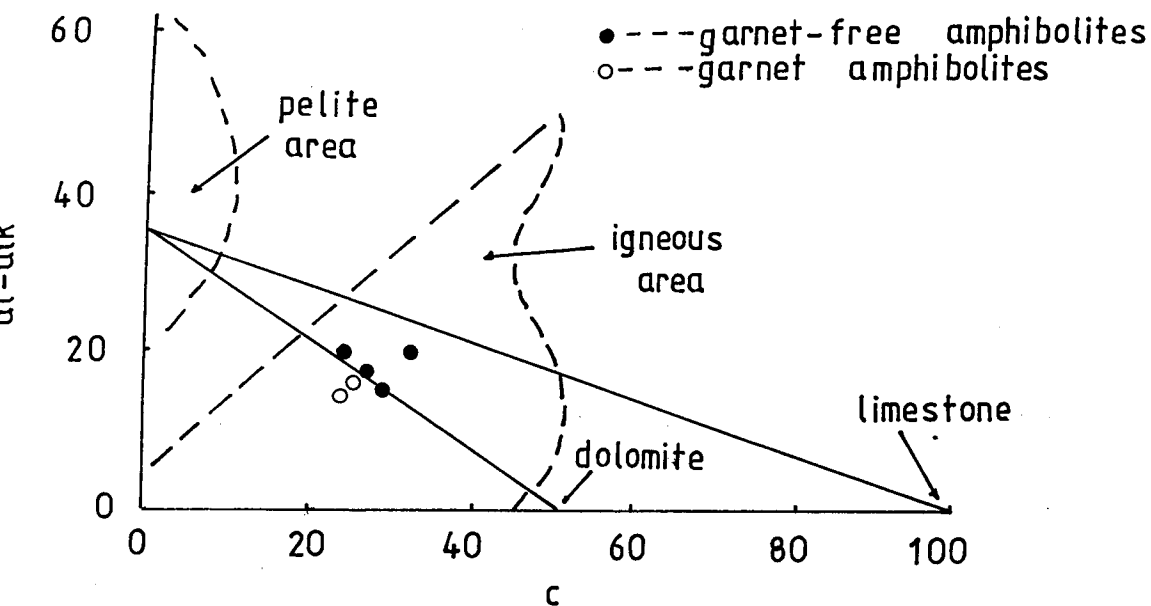


Figure 4.2, Niggli al-alk versus Niggli c (after Evans and Leake⁶⁷) for the Mapanza amphibolites.

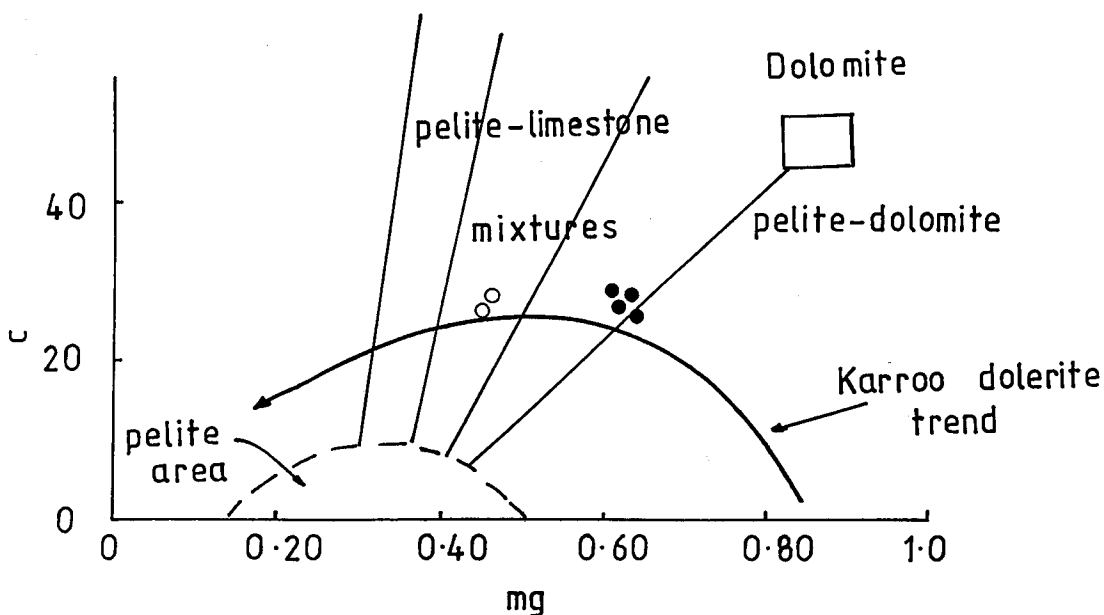


Figure 4.3, Niggli c against mg (after Leake³⁵) for the Mapanza amphibolites. Lines indicate fields where mixture of pelite and carbonate in various proportions plot and were also developed by Leake³⁵.

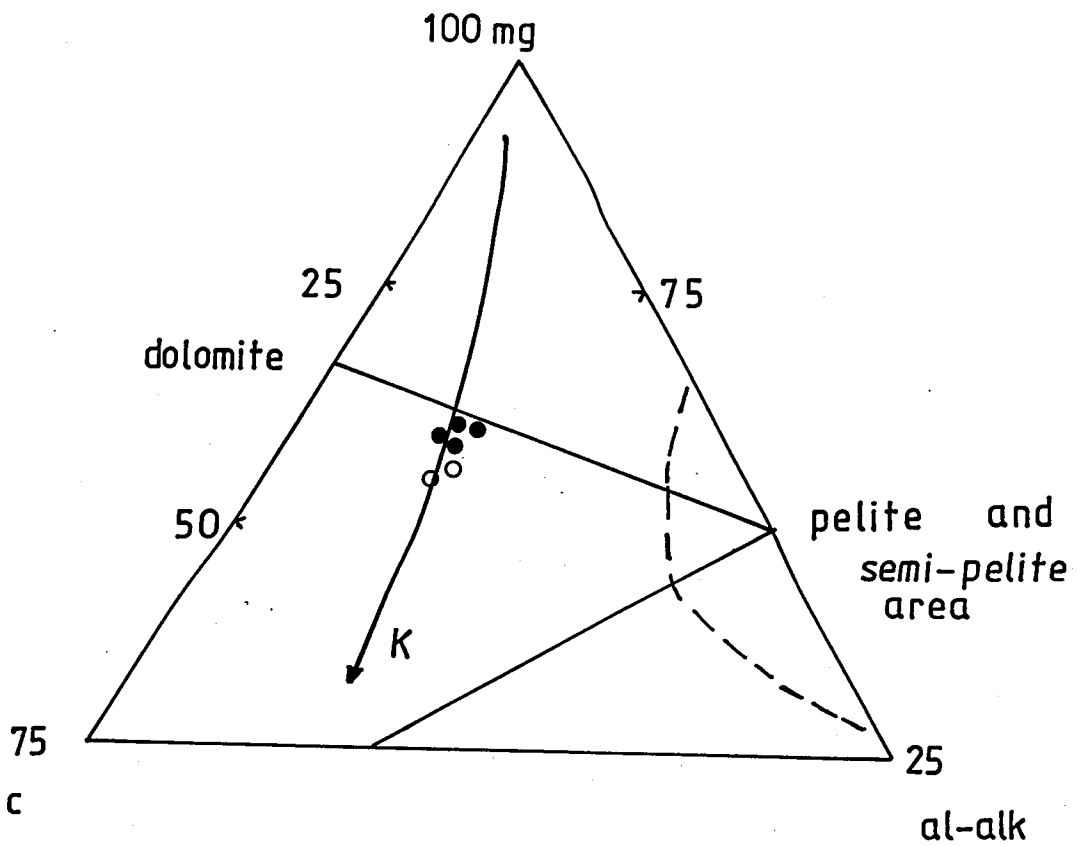


Figure 4.4. Niggli C- (al-alk)- 100mg ternary plot for the Mapanza amphibolites. Karroo dolerite trend is shown as an arrow designated K (after Evans and Leake⁶⁷).

Note that in general the compositions of these rocks could reflect mixture between dolomite and pelite, as well as an igneous protolith. However, an igneous origin for all of the rocks is preferred because in Figures 4.2 and 4.4 they cluster together, and an igneous origin for the garnet-free types has already been inferred based on the field relations.

Niggli k by itself is also said to reveal the nature of amphibolites ⁽⁷⁰⁾, because basic igneous rocks usually have lower k (0.11-0.23) than any possible clay-dolomite mixture (0.63-0.65). The Mapanza amphibolites have very low k values implying a basic igneous origin. This criterion, however, may not be very useful owing to the possible mobility of alkalis during alteration and metamorphism.

The abundances of the trace elements Cr, Ni, and Ti have also been used in attempts to determine the nature of amphibolites. High Cr, Ni and Ti contents accompanied by high Niggli mg are indicative of derivation from basic igneous rocks whereas low values of these elements are inconclusive, indicating derivation from either basic igneous or sedimentary rocks ⁽³⁵⁾. In the present case, the high concentrations of Ni and Cr and high Niggli mg in the garnet-free amphibolites are consistent with an igneous origin for the rocks whereas TiO_2 is low and thus gives no indication as to the nature of the protolith. Low Ni and Cr values in the garnet amphibolites also give inconclusive results for the origin of these rocks.

Plots of the trace elements Ni, Cr, and Ba against mg (Fig. 4.5) as suggested by Leake⁽³⁵⁾, show the garnet-free amphibolites to plot well outside the pelitic field, comparing reasonably well with Leake's ortho-amphibolites. The garnet amphibolites, however, are distinctly separated from the garnet-free amphibolites on all plots, falling closer to the pelite field. They actually plot well within the pelitic field on the Ni against Niggli mg (Fig. 4.5). This possibly reflect a minor sedimentary component in these thin amphibolite boudins and bands. Perhaps they were originally basaltic tuffs.

It is therefore concluded on the basis of the field relations discussed in Chapter 2 and on the geochemistry that the large, discrete bodies of amphibolite within the Mapanza Carbonate Formation were derived from metamorphism of basic igneous rocks. Lack of internal textural variations such as chilled margin and their parallelism with the regional west-northwest trend may suggest that they were syntectonic and were most likely structurally controlled. Thin bands and boudins of amphibolite concordant with the calc-silicate rocks were probably derived by metamorphism of basic igneous rocks admixed with a minor sedimentary component possibly in the form of clay.

Pearce and Cann⁽⁵³⁾ have developed techniques by which the tectonic environment of basaltic volcanic rocks may be established with the use of the trace elements Ti, Y, Zr, Nb and Sr. With exception of Sr, the other elements are generally immobile during alteration and low grade metamorphism⁽⁵³⁾. The nearly constant abundances of

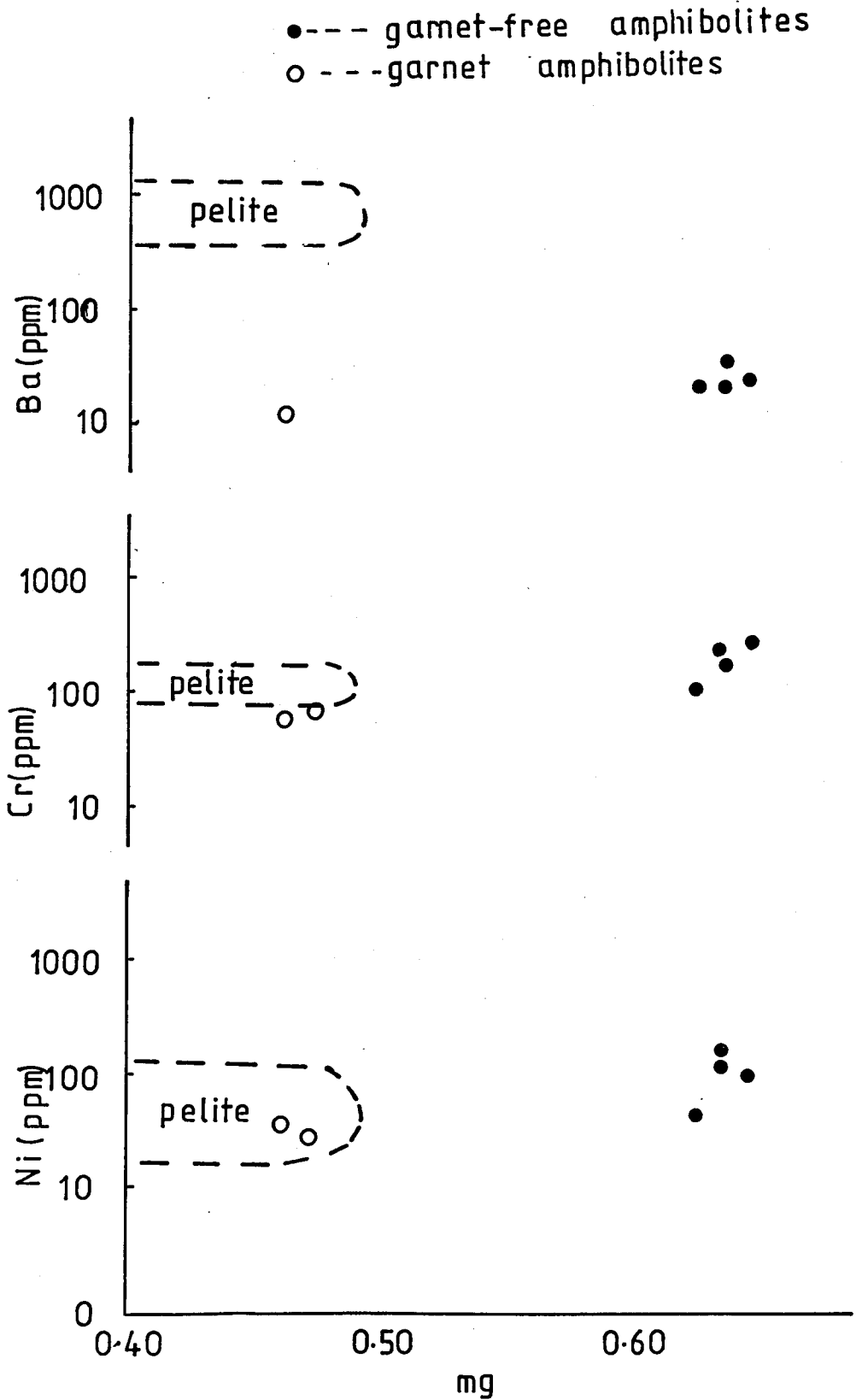


Figure 4.5. Ba, Cr and Ni (ppm) versus Niggli mg for the Mapanza amphibolites (after Leake³⁵).

Zr, Y and Ti within the individual amphibolites implies that these elements were indeed immobile during amphibolite facies metamorphism. The distribution of Sr does not follow that of CaO (Fig. 4.6) as would be expected, suggesting that Sr has suffered metasomatic movement, whereas Nb is mostly below the detection limit in the garnet-free amphibolites (Table 4.1).

Plotting of Ti, Zr, Y and Sr on the diagrams used by Pearce and Cann⁽⁵²⁾ (Figs. 4.7a and b) suggests tholeiitic to calc-alkaline affinities for the Mapanza amphibolites. This result is only tentative, however, for several reasons. Firstly, the diagram in Figure 4.7b uses Sr, which appear to have been mobile during metamorphism of the Mapanza amphibolites, as discussed above. Secondly, Pearce and Cann⁽⁵²⁾ developed their diagrams using data on basalt chemistry from recent geotectonic environments.

It is uncertain whether such diagrams can be used for Precambrian basaltic rocks⁽⁵²⁾. Finally, if a sedimentary component was admixed with the parent rock of the garnet amphibolites, then this may have significantly disturbed their trace element patterns.