THE GEOLOGY OF THE MOZAMBIQUE BELT AND THE ZIMBABWE CRATON AROUND MANICA, WESTERN MOZAMBIQUE.

Chapter 1

INTRODUCTION

1.1 Introduction

The geology of Mozambique is poorly known. Published geological maps include the 1987 1:1000 000 map of the whole country, the 1969 1:250 000 maps which largely cover the Precambrian terrains and several generations of 1:50 000 maps of mining districts. For some of the mines 1:10 000 maps were produced. In general, detailed studies have been confined to the mines themselves, emphasising largely economic aspects with little or no extension to the surrounding areas. Few specialized studies concentrating on tectonics and structural geology have so far been undertaken. This situation has inhibited correlation of the geology of Mozambique with that of surrounding countries such as South Africa, Zimbabwe, Swaziland, Zambia and Tanzania.

The geographic position of Mozambique in the framework of Gondwana, makes the country a geologically important terrain particularly because it contains boundaries between cratonic and mobile belt terrains. The deformation and metamorphism contributing to the Mozambique Metamorphic Province is viewed as originating during the amalgamation of Gondwana (Moyes *et al.*, 1993; Dalziel, 1991).

It was decided, therefore, that a study of the geology of the boundary between the Zimbabwe Craton and the Mozambique Metamorphic Province with emphasis on the Mozambique Metamorphic Province, would make a valuable contribution towards the understanding of geological processes that took place in the region and in Gondwana.

1.2 Regional geological setting

The study area includes part of the Archaean to Early Proterozoic-age Zimbabwe Craton and the Late Proterozoic-age Mozambique Metamorphic Province (Fig. 1.1). The Zimbabwe Craton forms part of the Kalahari Craton which also includes the Archaean-age Kaapvaal Craton and Limpopo Metamorphic Province. These entities stabilised far earlier than the central, northeastern and northwestern African cratons that stabilised during the Proterozoic (Petters, 1991, p.10-11). The Mozambique Metamorphic Province forms part of a Grenvillian-age (~1100 Ma±100 Ma) metamorphic terrain which was accreted onto the Kalahari Craton in southern Africa at that time (Fig. 1.1).

Reconstructions of Gondwana suggest that this Grenvillian-age belt continues southwards through western Dronning Maud Land, Antarctica, where it changes to a south-easterly direction and continues

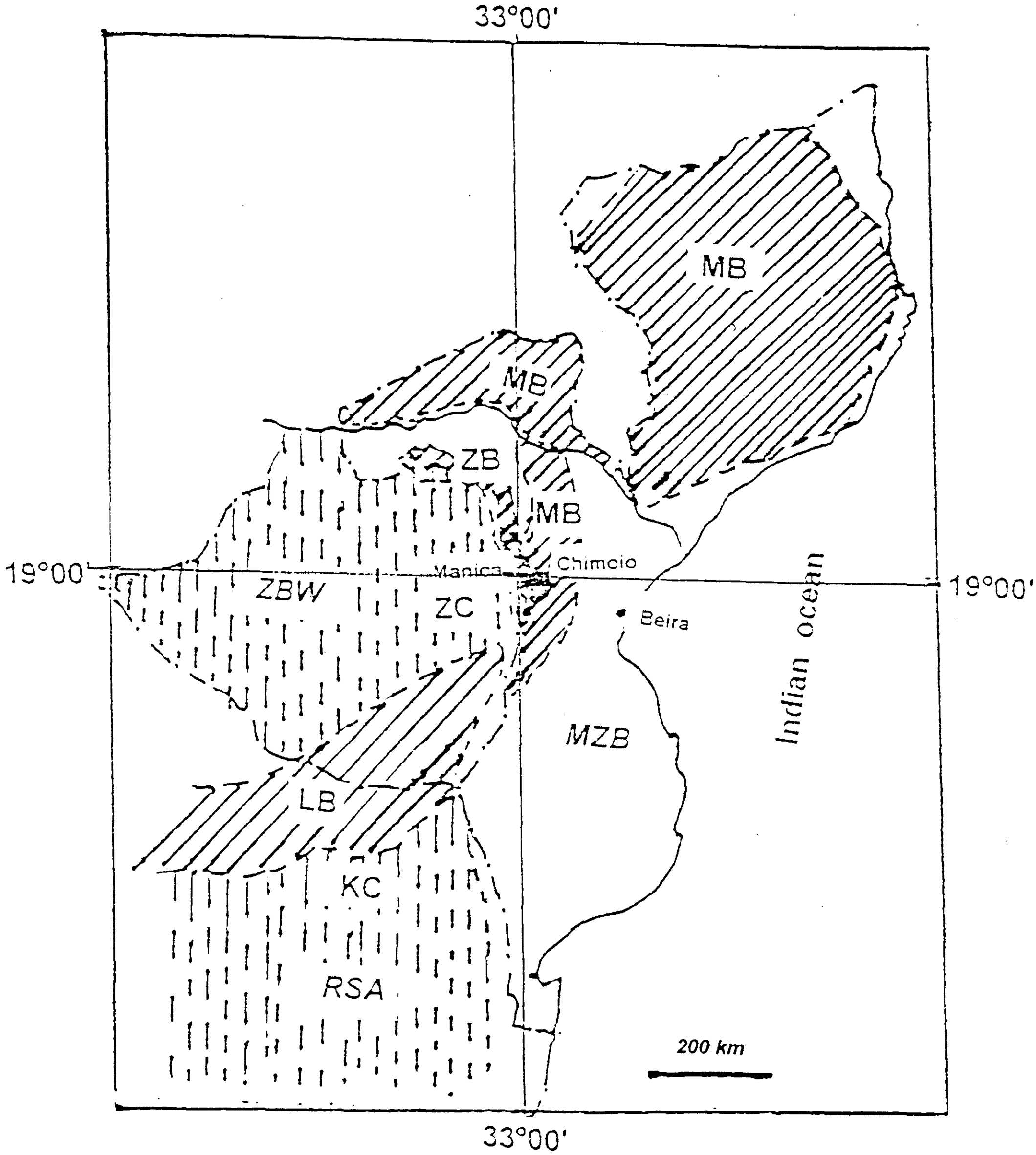

Figure 1.1: Location of the study area shown in the context of the regional geological structure of southern Africa. Adapted from Afonso (1978), Petters (1991) and Dirks *et al.* (1998) data. LB- Limpopo Metamorphic Province MB- Mozambique Metamorphic Province, ZB- Mid-Zambezi Metamorphic Province, ZC- Zimbabwe Province and KC- Kaapvaal Province. ZBW- Zimbabwe, RSA- South Africa and MZB- Mozambique.

into the Natal Metamorphic Province where the rocks become obscured by later Phanerozoic cover sequences (Grantham *et al.* 1988; Groenewald *et al.*, 1991).

1.3 Previous geological work

The study area has been the subject of several geological and metallogenic studies since the beginning of the 20th century, particularly concentrating on Archaean gold deposits which are hosted in the Manica Greenstone Belt. Few of these studies have been formally published.

Phaup (1937), gives an outline of the geology of the Umtali (Zimbabwe) area which describes extensions into Zimbabwe of the Manica (Mozambique) gold belt. In this outline he describes the rock types, structure, tectonics and genesis of the belt. Phaup (1937) reported the main lithological units as comprising the Archaean Greenstone Series which included talc-schist and serpentinites, the M'Beza Sedimentary Series, comprising successively a basal conglomerate, grits, greywacke, arkose, phylites, slates and conglomerate composed of greywacke pebbles. He also described granite batholiths with fine-grained margins grading to coarse grained gneissic granite at the centre of the batholiths. Vail (1964) described the Umkondo System adjacent to the southern part of study area and indicated that it consisted of undeformed, unmetamorphosed sediments. Oberholzer (1964) described the lithostratigraphy of the Archaean Manica Group as consisting of the Macequece Formation which is composed of ultrabasic rocks correlated with the Bulawayan Group in Zimbabwe, and the M'Beza/Vengo Formation, a metasedimentary sequence correlated with the Shamvaian Group of Zimbabwe. Vail (1965) used the K-Ar method to determine ages of biotite in the Gairezi Group gneiss and in the Frontier Formation schist in Macossa (localities adjacent to the study area) and obtained mineral resetting ages of 525±20 and 526±30 respectively. A mineral resetting age of 465±20 in muscovite from the Chicamba quartzite (Frontier Formation, within the study area) was also determined by Vail (1965). A comprehensive geologic investigation involving photogeology and field mapping of Precambrian terrains in the Manica province was undertaken during the 1960's by Araujo and Gouveia (1965) and culminated with the publication of a map. On this map the Precambrian geology is subdivided into (1) the greenschist facies or low grade Archaean Manica System, which includes talc-schists, serpentinites, greenstones and gneisses as well as banded quartzites of the Macequece Series and conglomerates, greywackes and schists of the Vengo Series, (2) the medium to high grade Proterozoic Barue Formation which is composed of granitoid gneisses, metadolerites and amphibolites and (3) the Umkondo System which includes micaschists, quartzites and schists of the Frontier Formation and carbonates, hornfels, schists and quartzites of the Umkondo Formation. They distinguished three types of gneisses, namely, migmatitic, granitic and granite gneisses.

As a result of work done by a multidisciplinary team in the mid sixties, the Servicos de Geologia e Minas da Provincia de Mocambique (1969), Published the "Carta Geologica da Regiao de Vila Manica-Vila Gouveia, Grau Quadrado 1833, scale 1: 250 000". This map shows a detailed distribution and relationship of lithological units and was taken as the main reference in selecting the present study area. Obretenov (1977) described the geology of Manica as part of a survey into the mining in the region. His study mostly confirmed data from previous authors and correlated the Manica Group with the Shamvaian Group in Zimbabwe. He described the rocks of the M'Beza/Vengo Formation as being meta-argilites, black schist, sericite schist and argillaceous schist, metagreywacke, meta-arkose and meta-conglomerate. In addition, he included a quartzitic unit at the top of Macequece Formation but conceded this to be controversial and suggested the existence of at least three types of these quartzites. As part of a large scale geologic survey, the area was studied by Hunting, a consulting company, in 1984. The study included aerogeophysics and photogeology with ground control and defined the Matambo Group (Barr *et al.,* 1983). Pinna *et al.* (1986) distinguished greenstones, granitoids and metasediments of the Archaean Manica Group, metasediments of the Frontier Formation which is included in the Gairezi Group, and granitoids of the Madzuire and Matambo Groups which are included in the Mozambique Belt in the study area. More recently a PhD study on the Manica Greenstone Belt and adjacent granitoids by Manuel (1992) describes the geology, petrography, geochemistry and ore deposits. Using chemistry and petrography, he subdivided the granitoid rocks into tonalites, granodiorites and adamellites and further showed the granitoids as being Middle to Late Archaean in age. He also described the basic to ultrabasic rocks of the Manica Greenstone belt as peridotitic and basaltic komatiites, serpentinites, metabasalts and gabbros and confirmed their low grade metamorphism. Based on these age determinations and other several Late Archaean ages of granites, felsites and stromatolites, a stratigraphic column for the Manica region was produced and a correlation with the Zimbabwe Craton ages made. Thus, the older granitoids are correlated with the Sebakwian whereas the younger granitoids as well as felsites and greenstones are correlated to the Bulawayan Group. Manuel (1992) describes conglomerate occurrences in the Zambuzi Valley, monomictic metaconglomerate of serpentinite in the Isitaca and Seymour areas and polymictic conglomerate of metabasalt, serpentinite, komatiite, schist, quartzite and granites in the Penhalonga, Monarch and Chua areas. Schwarz (1994), studied a detailed section through the "Vengo Group" and reported the following lithological sequence from top to bottom:

4. Dolostone sequence, with stromatolites and archaeocyathids,
3. Unit of weathered residue enriched in manganese (Mn),
2. Metaclastic rocks,
1. Metavolcanic rocks

The metaclastic rocks are characterized by an alternating sequence of fine and coarse grained layers that include volcanic rocks.

In conclusion, it is apparent that much of the previous work conducted in the study area concentrated largely on the Manica Greenstone Belt and to a lesser extent on its surrounding granitoid gneisses. Consequently this study will devote more attention to the boundary relationships between the Zimbabwe Craton and the Mozambique Metamorphic Province and to the geology of the latter.

Chapter 2

LITHOSTRATIGRAPHY

2.1 Introduction

This chapter describes the stratigraphic framework used in this thesis. The stratigraphic framework and nomenclature used are based on the previous work done in the study area and described in the previous chapter, as well as those field relationships recorded in this study. The field relationships are described in this chapter. Figure 2.1 (p. 6) shows the distribution of the lithological units. Sample localities are shown on Figure 2.2 and the actual samples are indicated in Appendix 1. The stratigraphic framework is outlined in Table 2.1.

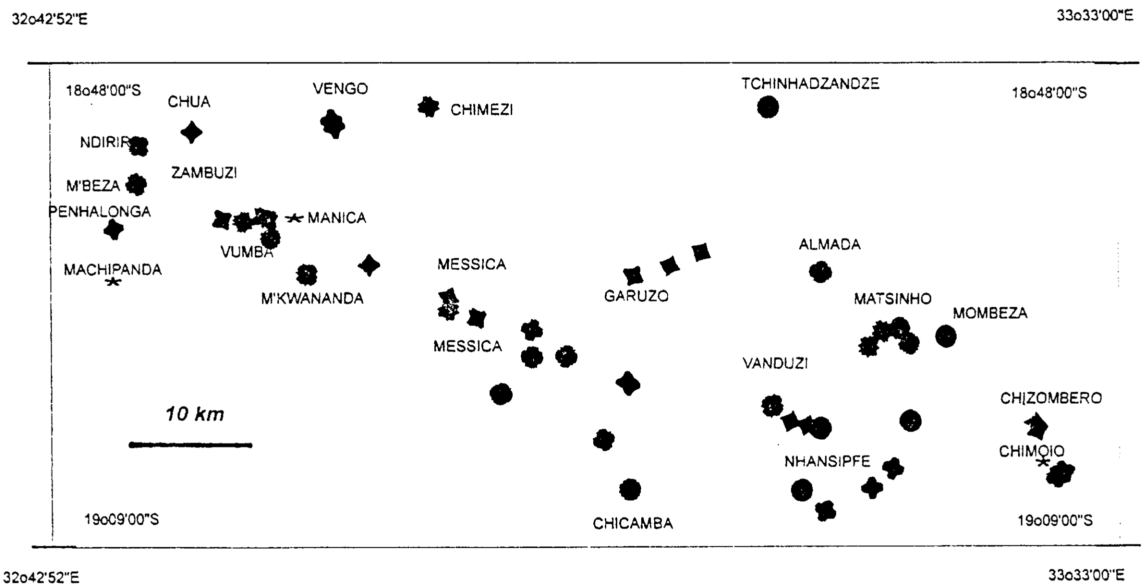

Figure 2.2: Sampling locality map. Locality names are those known to the locals and may be different from the official denominations. Star symbols represent main towns. The others represent sampling localities and due their differences to the number of samples taken in each locality.

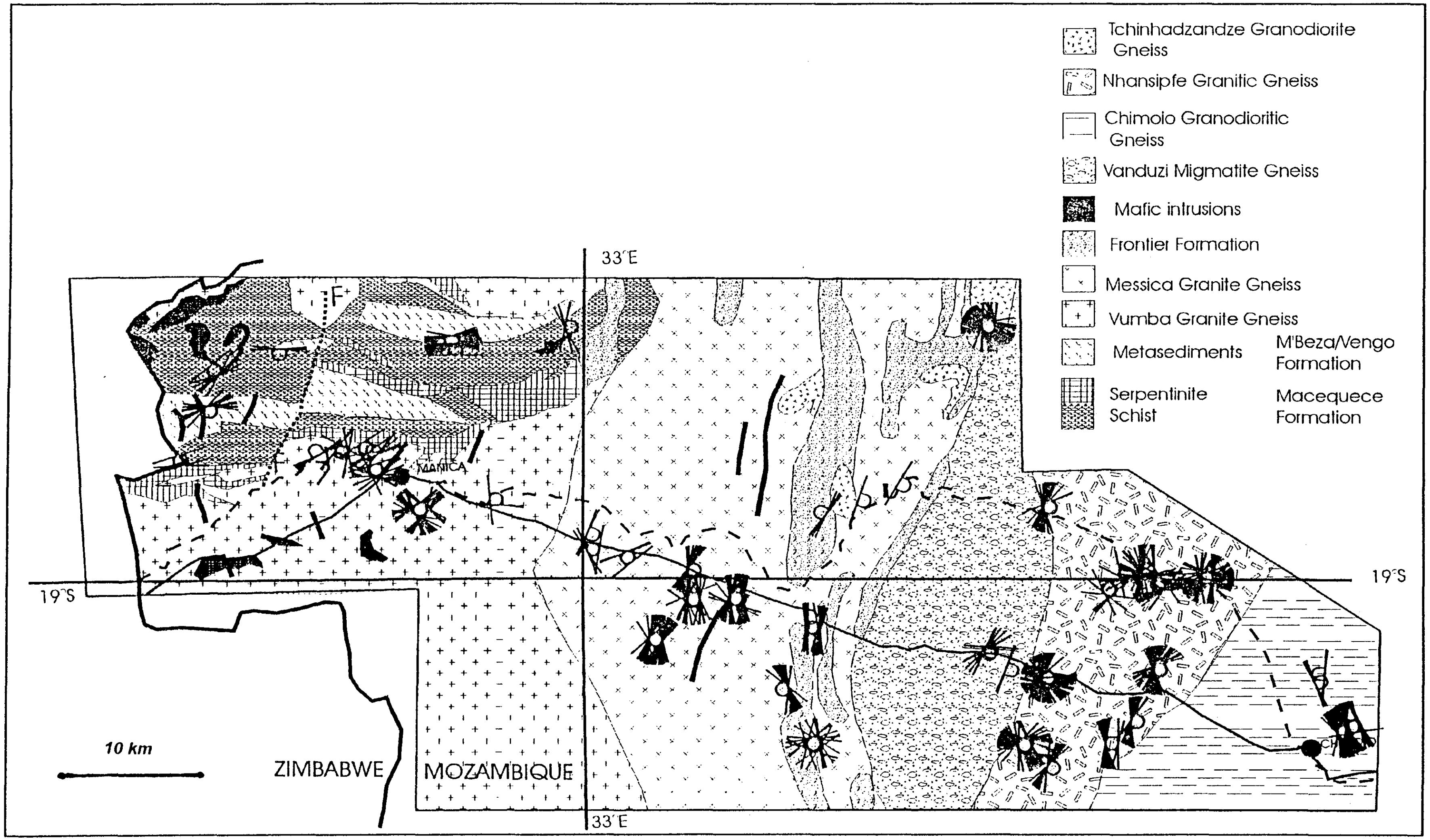

Figure 2.1: Major lithological units and planar fabrics directions within the study area. Broken and full lines across the map represent the railway and the main road respectively. Geologic map after Gouveia *et al.* (1968) with additions from present study.

Table 2.1: Stratigraphic framework of lithological units. Compiled using present study data and data from Oberlholzer (1964), Gouveia *et al.* (1968), Pinna *et al.* (1986) and Manuel (1992).

tectonic block	geologic formation	lithological unit	age
Late-Mozambique Belt	Young Granite	Tchinhadzandze Grano-diorite Gneiss Mafic Dykes	?
Mozambique Belt	------------------- ? Madzuire Group Matambo Group	Nhansipfe Granitic Orthogneiss Chimoio Granodioritic Gneiss Vanduzi Migmatite Gneiss	~980 Ma ~1200 Ma
Pre-Mozambique belt	Gairezi Group	Frontier Formation pelitic schist, quartzite	?
Zimbabwe Craton		Messica Granite Gneiss	~2300 Ma
		M'Beza/Vengo Formation greywackes, shales, pelitic schists, congolmerates metaconglomerates	?
		South Vumba Granite Gneiss	~2500 Ma Manuel (1992)
	Manica Group	Macequece Formation mafic to ultramafic schists, felsic schists, serpentinites	~2800 Ma Manuel (1992)
		North Vumba Granitic Gneiss	~3400 Ma Manuel (1992)

Outcrops in the study area are very poor with few relationships between the various units being exposed. Access is also severely restricted because of a limited road network and the uncertainty of the distribution of landmines.

The Archaean granite-greenstone terrain occupies about one third of the study area in the western part. The greenstone lithological units include the M'Beza/Vengo and Macequece Formations which strike approximately E-W to NE-SW in the north-western part of the study area (Fig. 2.1). Exposures of the Vumba Granite Gneiss are found north and south of the greenstone (Fig. 2.1). Both the greenstones and the Vumba Granite Gneiss form steep hilly topography. East of the greenstones and the Vumba Granite Gneiss, the Messica Granite Gneiss is exposed and forms more subdued topography. The metasediments of the Frontier Formation locally overly the greenstone lithologies, the Vumba Granitic Gneiss and the Messica Granite Gneiss. The main exposures of the Frontier Formation form prominent N-S ridges, particularly as a consequence of highly resistant quartzites. East of the Messica Granite Gneiss, migmatitic gneisses of widely varying composition which constitute the

Vanduzi Migmatite Gneiss are exposed. To the east of the migmatites, the megacrystic Nhansipfe Granitic Orthogneiss forms an extensive body. Finally, the eastern extremity of the area is underlain by the Chimoio Granodioritic Gneiss. Small (1-2 km in diameter) plutons of Tchinhadzandze Granodiorite Gneiss are distributed in the centre of the study area and are hosted by the Messica Granite Gneiss although no intrusive contacts were seen. The planar fabric in the granite is variable and is weakly developed compared to the surrounding Messica Granite Gneiss and consequently the Tchinhadzandze Granodiorite Gneiss is viewed as being emplaced either after the fabric-forming event or as being late syn-tectonic.

2.2 Field Distribution and Age of Major Lithostratigraphic Units

The oldest rocks dated in the study area are the northern Vumba granitoids (Manuel, 1992). However, because enclaves of the Macequece Formation rocks are seen in the surrounding granitoids (Phaup, 1937), the former must, at least in part, be even older. In addition Phaup (1937) recorded fine-grained granite where the granites are in contact with the ultramafic rocks of the Macequece Formation which he interpreted to represent a chilled margin and he also reported two generations of granitic rocks. Manuel (1992) also determined two ages of granites from the Vumba granitoids using the Rb/Sr method. A suite of samples from granitoids exposed north of the Manica Greenstone Belt yielded an age of 3385±255 Ma whereas samples from granitoids south of the Manica Greenstone Belt yielded 2527±632 Ma (Manuel, 1992). Meta-volcanic horizons within the Manica Greenstone Belt have yielded a Rb/Sr date of 2801±42 Ma. Age relationships within the ultramafic rocks of the Macequece Formation in the Manica Greenstone belt are difficult to determine due to structural complexity. However, Manuel (1992) suggested that the ultramafic rocks are older than the pelitic schist because the latter schists contain granite clasts. The metasediments of the Mbeza/Vengo Formation are obviously younger than the oldest granitoids because the meta-conglomerates contain clasts of the granitoids. Oberholzer (1964) indicated that the second generation of granitoids is younger than the metasediments of the Mbeza/Vengo Formation because the granites intrude the metasediments. A Rb/Sr study of the Messica Granite Gneiss suggests an age 2348±267 Ma and therefore represents a younger, Early Proterozoic-age granite. No contacts between the Messica Granite Gneiss and the Vumba granitoids were seen. However the style of deformation in the former is simpler suggesting that it is less deformed and consequently is probably younger than the Vumba granitoids. Figure 2.1 shows that the metasediments of the Frontier Formation are restricted to areas underlain by the Macequece Formation, the Vumba Granite Gneiss and the Messica Granite Gneiss. Afonso (1974) described an angular unconformity between rocks of the Umkondo Group and the underlying folded and metamorphosed strata of the Frontier Formation. Barr *et al.* (1983) confirmed the age relationship during photogeological studies which established that the Umkondo overlies part of Gairezi Group which includes the Frontier Formation. Allsopp *et al.* (1989) suggested that the Umkondo Group has a minimum age of ~1089Ma based on Rb/Sr ages of biotite in mafic intrusions into the Umkondo Group. Mafic dykes intrude the Manica Greenstone Belt, the surrounding granitoids and the metasediments of

the Frontier Formation (Carta Geologica Vila Manica-Vila Gouveia 1:250 000). More recently, Pinna *et al.* (1986) indicates that the age of post- Umkondo dolerites vary between 1100-500 Ma (K/Ar dating) and suggested that the Umkondo Group may be the southern equivalent of the Roan Supergroup in Zambia formed at
~1150 Ma. Given the present uncertainty, all that can be said is that the Frontier Formation has an emplacement age younger than the ~2300 Ma of the underlying Messica Granite Gneiss and older than the ~1089 Ma Umkondo which overlies it.

The Chimoio Granodioritic Gneiss gave an age of 1236±202 Ma, older than the Nhansipfe Granitic Orthogneiss with an age of 981±83 Ma, and is incorporated into the Madzuire Group. The younger granitic intrusions are termed the Tchinhadzandze Granodiorite Gneiss.

Chapter 3

MANICA GREENSTONE BELT

3.1 Introduction

The Manica Greenstone Belt comprises rocks of the Macequece and M'Beza/Vengo Formations and both units belong to the Archaean Manica Group and constitute the continuation into Mozambique of the Zimbabwe's Mutare greenstone belt. The M'Beza/Vengo Formation comprises two units, namely, M'Beza and Vengo sequences and lies discordantly on schists and serpentinites of the Macequece Formation. The M'Beza/Vengo Formation comprises pelitic schist, conglomerates, greywackes, shales and their metamorphic equivalents.

3.2 Field Description

3.2.1 Macequece Formation

The Macequece Formation (Fig. 2.1) consists of interlayered Mg-rich and pelitic rocks which show varying degrees of deformation. The highly strained varieties have strong schistose planar fabrics whereas in some areas the rocks are undeformed but metamorphosed to low grades.

The schists occur in the central part of the greenstone belt and share boundaries with metasediments, quartzite, serpentinite and granitoid rocks towards the centre and periphery respectively. The schists are cut by mafic intrusions and are interlayered with banded iron formation (BIF). Four different types of schist were identified, namely, talc-chlorite, quartz-sericite, andalusite-chloritoid and actinolite schists.

The talc-chlorite schists are green with white streaks consisting of talc. Mineralogically they contain talc, chlorite, carbonate and opaque minerals. Two alternating layers are commonly distinguishable, namely, greenish layers, composed of chlorite and light brown layers composed of carbonate. The thicknesses of these layers are $\leq$3 mm . Talc occurs within these layers as a fine material locally forming small lenses. Carbonate, talc and chlorite are fine-grained with the phyllosilicates exhibiting a preferred orientation defining a strong schistosity.

The actinolite/tremolite schist occurs as layers of generally greenish colour and is commonly associated and intercalated with talc-chlorite schist. Mineralogically it contains actinolite/tremolite, talc and chlorite and opaque minerals. It is medium-grained.

The major occurrences of the serpentinite and serpentine-talc-magnesite hornfels are exposed in the southern part of the granite-greenstone belt and commonly occur associated with schists with which they share geological boundaries (Fig.2.1). They are also intruded by mafic rocks. Mineralogically the serpentinite contains serpentine minerals (mostly antigorite), chlorite, carbonate and opaque minerals. It is massive, equigranular and fine-grained. Serpentine-talc-magnesite hornfels have the same mineralogical composition as serpentinite but exhibit a porphyroblastic texture whereby medium-grained antigorite and carbonate are set in a fine matrix of talc.

The quartz-sericite schists occur in several localities in the Manica Greenstone belt, and in the Penhalonga locality (Fig. 2.2) are associated with banded iron formation (BIF). They vary in colour from greenish to pink with white patches of quartzo-feldspathic material (Fig. 3.1). Two group of minerals form the bulk of the rock, namely, the fine-grained pinkish quartz+sericite with subordinate green chlorite. Texturally the rocks exhibit medium- to coarse-grained quartzo-feldspathic mineral fragments in a fine-grained schistose matrix consisting of quartz, sericite and chlorite.

The andalusite-chloritoid schists are exposed around the Ndirire locality (Fig. 2.2) as loose blocks of float up to 3 metres in size. These blocks overly talc-chlorite schist, but their position in the stratigraphy is uncertain. The rock is greenish, being composed of layers of fuchsitic quartzite separated by thin (up to 5 mm thick) layers of brownish chloritoid and andalusite. The crystals of andalusite are long and prismatic. Mineralogically the rock contains fine-grained quartz and fuchsite with medium to coarse-grained chloritoid and andalusite. The rock is intensely deformed (Fig. 3.2).

Figure 3.1: Pinkish quartz-sericite schist intercalated with dark brown banded iron formation in the foreground.

Figure 3.2: Folding in the andalusite-chloritoid schist. Note the fine brownish layers containing the andalusite and chloritoid.

3.2.2 M'Beza/Vengo Formation

The M'Beza/Vengo Formation is a metasedimentary sequence that discordantly overlies the Macequece Formation in the southern and northern parts of the Manica Greenstone Belt (Fig. 2.1) (Oberlholzer, 1964, p. 2-3). Lithologically, the M'Beza/Vengo Formation is characterized by a layered sequence of polymictic metaconglomerate containing clasts of schist, serpentinite, quartzite and granite pebbles with chloritic argillaceous cement (Manuel, 1992), meta-argilites, black schist, sericite and argillaceous schists, metagreywackes and metarkoses (Obretenov, 1977, p.11-12). Locally carbonate lenses occur intercalated with the schist. The metashales are laminated with the laminae being defined by different colours and composition and vary from whitish through yellow to greenish and are of variable thickness (from less than to 4 millimeters). Intercalated in the metashales are thin layers of metagreywacke up to 10 mm thick . Towards the middle part of the Vengo area (Fig. 2.2), a sequence of very fine-grained brownish to black rocks interlayered with metaconglomerate are exposed. The fine-grained rocks are foliated with the foliation dipping towards the S. Locally, the rocks have undergone polyphase deformation seen as early symmetric folds of an earlier stage that were subsequently overturned to form recumbent folds which in turn were deformed to cylindric, open and box folds. At the Chua locality the sequence contains concordant whitish lenses of carbonate. Locally, the metaconglomerate clasts are deformed and define an E-W foliation with steep dips towards the south.

3.3 Petrography

Undeformed hornfels, schists and shales were investigated. The grain sizes of these rocks vary from very fine-grained (<0.25 mm) through medium (≥1≤2 mm) to coarse-grained (≥2 mm) rocks. XRD was used in determining the mineralogy of the fine-grained rocks and in discriminating between the carbonates and serpentine bearing varieties. Compositionaly the greenstone rocks comprise talc-chlorite schists, quartz-sericite schists, chloritoid-andalusite schists and carbonate-antigorite hornfels within the Macequece Formation and pelitic schist and metashales (phyllites) within the M'Beza/Vengo Formation.

Talc-Chlorite Schists and Carbonate-Antigorite Fels

Mineralogically (Table 3.1) the schists consist of fine grained chlorite, carbonate and opaque minerals. The last two occur in a fine-grained matrix of talc and chlorite.

Table 3.1: Mineralogical composition of talc-chlorite schists and carbonate antigorite fels. Atg-antigorite, Chl- chlorite, Dol- dolomite, Tr- tremolite/actinolite, Tlc- talc and Opm- opaque minerals. Numbers inside the cells represent mineral proportions in percentage.

Sample	Atg	Chl	Dol	Tr	Tlc	Opm	rock type
ba	75	10	10	-	-	5	fels
ma	75	15	5	2	-	4	fels
mb	80	10	5	-	-	5	fels
mc	70	20	8	-	-	2	fels
scg	65	-	15	-	15	5	fels
8	60	-	20	-	15	5	fels
epsc1	-	50	10	-	39	1	schist
26aga	-	50	10	-	38	2	schist
26agb	-	46	12	-	40	2	schist

Chlorite occurs as flakes and/or fibrous aggregates, and in non-sheared rocks the crystals lie in criss-cross directions. Twinned carbonate, which consists of dolomite that predominates over magnesite, occurs as isolated xenoblastic grains in general, but also as interlocking, locally elongated grains when in veins. Opaque minerals are generally associated with chlorite and exhibit sub- to idiomorphic habit (Fig. 3.3). The schistosity is defined by the preferred orientation of chlorite and talc which form fine alternating bands. Chlorite wraps around pre-tectonic opaque minerals and, where microfractures are present, it invades these minerals and, together with carbonate minerals, forms pressure shadows around them (Fig. 3.4), which suggests that the schists have been polymetamorphosed (Spry, 1969, p. 309).

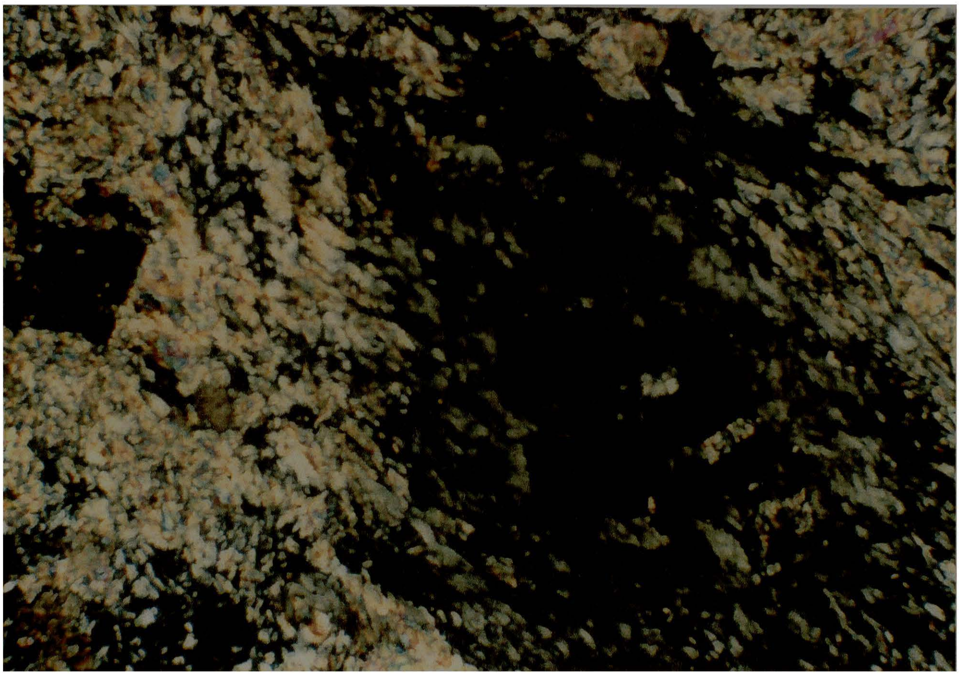

Figure 3.3: Sub-to idioblastic opaque minerals associated with fine-grained chlorite (dark grey) and talc (high birefringence). Crossed nicols, width of field 3 mm.

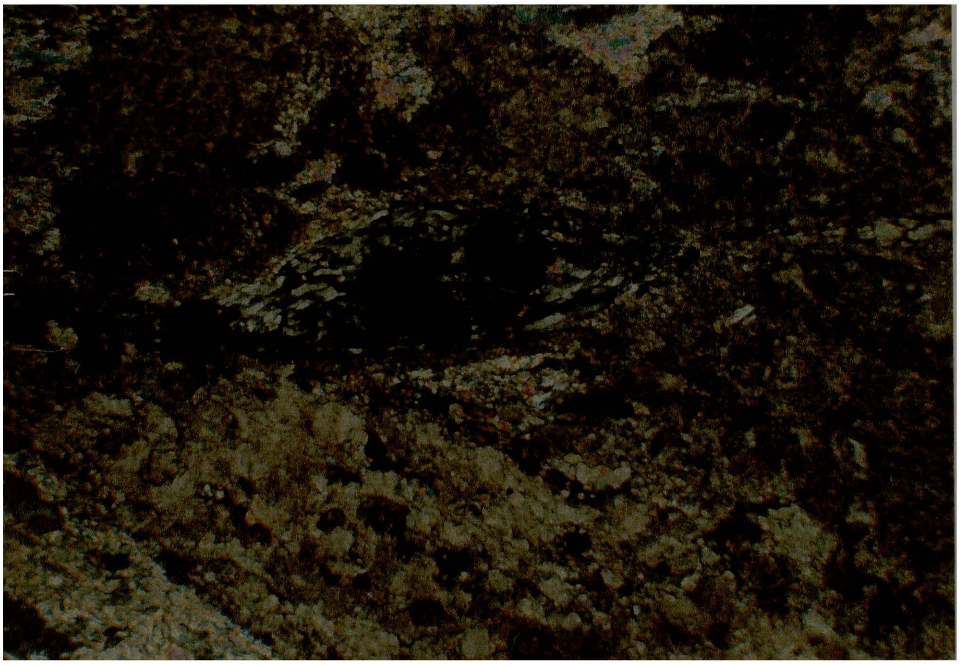

Figure 3.4: Chlorite and carbonate wrapping around and invading opaque minerals. Highly birefringent talc at the top of the picture. Crossed nicols, width of field of view 7 mm.

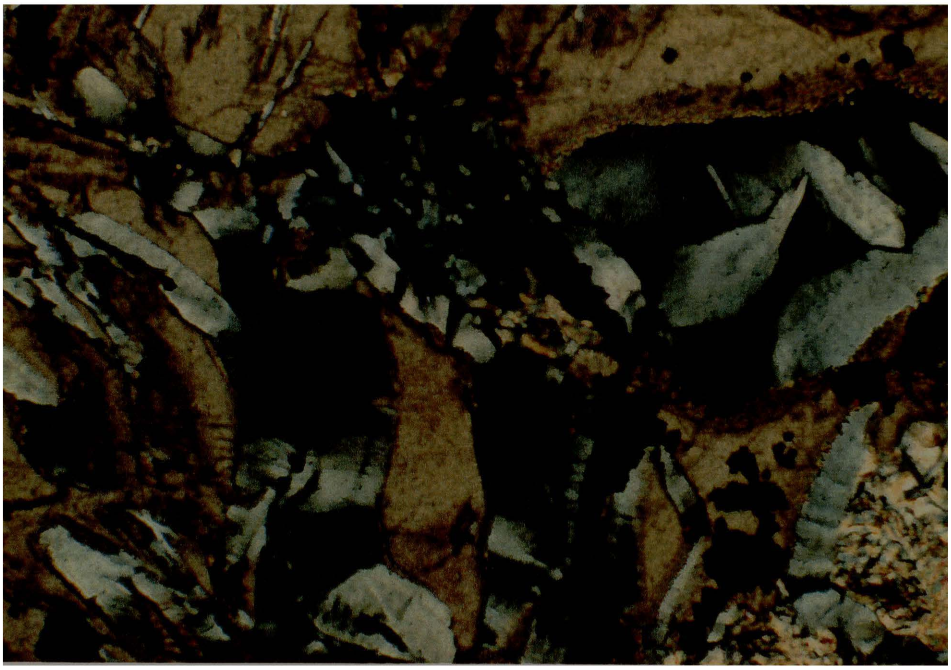

Figure 3.5: Medium-grained carbonate (brown), antigorite (light to dark grey), fine-grained chlorite (grey, top centre) and fine-grained idioblastic opaque minerals (black) locally filling cracks. Crossed nicols, width of field 3 mm.

The carbonate-antigorite serpentinite exhibits a very uniform mineralogical composition (Table 3.1) throughout the study area. The samples vary from massive fine (ma, mb, mc and ba) to medium (scg and 8) grained. Antigorite is fine to medium-grained with varying morphology. In the fine-grained serpentinite, antigorite forms the matrix. Carbonate, mostly dolomite, occurs as isolated grains, as fine- to medium-grained aggregates and locally, small veins. Chlorite occurs as scattered flakes. Rare fibrous chrysotile occurs within antigorite. Actinolite is very rare and occurs as fine prismatic crystals. Talc is represented by fine grains and, together with fine-grained antigorite, forms the matrix in the medium-grained serpentinite (Fig. 3.5). Opaque minerals vary in shape from idioblastic to xenoblastic and commonly fill cracks in serpentine and carbonate (Fig. 3.5) but also occur as isolated grains.

<u>Quartz-Sericite and Chloritoid-Andalusite Schists</u>

The mineralogy of these rocks is shown in Table 3.2.

Quartz-sericite schists consist of angular quartz, sub- to idioblastic chloritoid, chlorite and xenoblastic opaque minerals set in a schistose matrix of very fine-grained quartz and sericite. Chloritoid exhibits polysynthetic twinning and hour glass zoning. Quartz occurs in veins as fine and coarse grains and as granoblastic-polygonal aggregates which represent crushed pre-existing quartz grains. Evidence of this is the presence of strained quartz with some coarse grains having recrystallized to form finer grained aggregates.

Table 3.2: Mineralogical assemblages of quartz-sericite and chloritoid-andalusite schist.

Sample	Qtz	And	Cld	Chl	Ser	Fuc	Opm	rock type
fsc1	54	-	10	5	30	-	1	Qtz-sericite schist
fsc2	65	-	2	20	12	-	1	Qtz-sericite schist
qznd1	20	5	25	2	18	25	5	Cld-andalusite schist

Cld- chloritoid, And- andalusite, Qtz- quartz, Ser- sericite Fuc- fuchsite and Opm- opaque minerals. Numbers inside the cells represent mineral proportions in percentage.

Chloritoid-andalusite schists consist of coarse-grained idioblastic chloritoid and andalusite randomly distributed in a schistose matrix of fuchsite (chromium bearing green mica) and very fine-grained quartz, chlorite, sericite and opaque minerals (Fig.3.6). Quartz occurs as elongate grains in fine bands and as equant grains in aggregates. Fuchsite forms very fine bands that flow around the quartz grains and define the schistosity. Chloritoid exhibits polysynthetic twinning and hour glass zoning (Spry, 1969, p.169-170) and, along cracks, is altered to green mica which forms the matrix (Fig.3.6). It also contains inclusions of fuchsite and quartz. Andalusite, occurring in much smaller proportions than chloritoid, exhibits idiomorphic habits. Locally, it is altered to very fine-grained sericite.

Figure 3.6: Medium-grained idiomorphic chloritoid grain exhibiting hour glass zoning (faintly visible) in a matrix of fuchsite. Crossed nicols, width of field 3 mm.

Pelitic Schist and Metashale

The mineralogy of these rocks is shown in Table 3.3.

Table 3.3: Mineralogical composition of some samples of M'Beza/Vengo Formation.

sample	Qtz	Chl	Ser	Gr	Mag
21sc	x	-	x	x	-
mbsh	x	x	-	-	x
zash	x	x	-	-	x

Mineral abbreviation as in Table 3.2. Mag- magnetite and Gr- graphite. X indicate mineral occurrence.

A common characteristic of these rocks is their very fine grain size and because of this textural characteristic, XRD (X-ray diffraction) was used for qualitative mineralogical identification (Table 3.3). Quartz predominates over sericite and chlorite. Samples from the M'Beza sequence (mbsh and zash) have chlorite as the other major component whereas in the Vengo sequence it is sericite. The rocks from the Vengo sequence are graphitic.

3.4 Chemistry

Four analyses from the present study and 13 from Manuel (1992) of mafic to ultramafic rocks will be used to describe the chemistry of these rocks (Table 3.4). Due to high contents of volatiles, the analyses from this study have yielded low totals varying from 96 to 98 wt% and, therefore, they have been recalculated to 100 wt%.

In general, the rocks are characterized by low SiO_2 and Al_2O_3 contents and high but variable MgO contents which is compatible with their mafic to ultramafic character. The mafic to ultramafic character is also reflected in high Ni and Cr contents and low Li, Sr, Rb, Ba, Y, Nb and Zr contents.

Table 3.4: Chemical composition of Macequece Formations rocks.

Samp	MA	EPSC	SCG	8	20340	A	152	119	104	95	14279	140	1	413	20428	69	192
SiO_2	47.56	48.26	45.71	48.09	47.69	45.94	46.44	47.02	53.39	55.67	48.55	46.64	50.16	45.4	51.59	51.36	51.3
Al_2O_3	2.87	1.91	0.37	3.27	3.6	2.81	7.0	2.46	3.95	5.15	3.76	4.28	7.11	7.8	5.12	7.05	5.98
Fe_2O_3	1.74	2.12	1.77	2.05	4.56	4.41	2.58	2.29	2.84	3.10	2.56	2.88	3.03	2.22	2.53	3.11	2.64
FeO	7.77	7.27	8.10	9.17	12.20	11.64	7.10	6.20	4.33	4.85	6.75	7.63	7.59	6.18	6.22	7.66	6.54
MgO	39.41	36.20	43.81	34.35	20.49	25.62	32.14	40.02	32.67	28.17	33.79	33.49	24.42	30.6	21.56	21.46	25.81
CaO	0.39	3.86	0.02	2.71	8.36	6.67	3.47	0.05	0.06	1.28	2.28	2.5	5.6	6.4	10.89	7.49	5.74
Na_2O	0.00	0.00	0.00	0.00	0.41	0.47	0.07	nd	nd	nd	0.04	0.26	0.18	0.1	0.11	0.1	0.07
K_2O	0.04	0.00	0.00	0.00	0.04	0.06	0.02	0.1	4.63	3.9	0.02	0.09	0.02	0.09	nd	0.02	0.01
TiO_2	0.11	0.17	0.07	0.21	0.69	0.59	0.16	0.13	0.15	0.24	0.2	0.26	0.22	0.2	0.17	0.31	0.17
P_2O_5	0.01	0.01	0.00	0.01	0.03	0.05	0.02	nd	nd	0.02	0.02	0.03	0.05	nd	0.02	0.01	nd
MnO	0.11	0.18	0.15	0.15	0.27	0.21	0.13	0.05	0.07	0.07	0.15	0.15	0.17	0.1	0.17	0.7	0.1
Total	100.00	100.00	100.00	100.00	98.34	98.47	99.13	98.32	102.09	102.45	98.12	98.21	98.55	99.09	98.38	99.27	98.36
Ba	5	10	10	12	20	22	22	28	44	7	37	36	18	100	15	21	16
Co	103	66	120	106	105	101	62	77	72	57	74	79	76	92	68	24	62
Cr	4106	1783	1545	2389	2310	2040	2730	2040	3350	2670	2910	2960	1750	2600	2150	110	100
Cu	17	5	9	19	82	31	nd	6	17	6	nd	nd	nd	nd	172	9	106
Li	1	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Nb	1	2	0	3	40	0	3	3	3	3	3	4	3	0	3	3	3
Ni	1883	1723	2668	1715	1862	2557	1486	2139	2019	1606	1689	1587	742	1600	1204	790	1050
Sc	17	15	12	17	Nd	Nd	Nd	Nd	Nd	Nd	Nd	Nd	Nd	Nd	Nd	Nd	Nd
Sr	0	40	0	19	51	67	5	3	3	5	21	12	3	50	7	7	5
Rb	1	0	2	1	4	2	2	1	1	2	1	3	2	nd	2	2	2
V	71	62	36	69	150	200	101	50	80	90	70	70	130	50	100	110	100
Y	3	4	2	6	8	12	3	2	3	25	4	5	8	nd	5	3	3
Zn	45	44	43	45	93	78	63	36	44	63	46	60	130	70	79	569	66
Zr	13	14	10	18	31	30	12	9	13	16	20	28	13	nd	11	23	14

The first four samples were collected and analysed during the present study whereas the remaining data are from Manuel (1992). Nd=not determined and nd=not detected

Al_2O_3, and CaO show an inverse correlation with MgO whereas FeO shows a scatter of data points (Fig. 3.7). The enrichment of samples in Cr and Ni in contrast to V is reflected in the plot of these elements versus MgO (Fig. 3.8). The trend of data is that of positive correlations for Cr and Ni, whereas V is not correlated with MgO or with the other major elements.

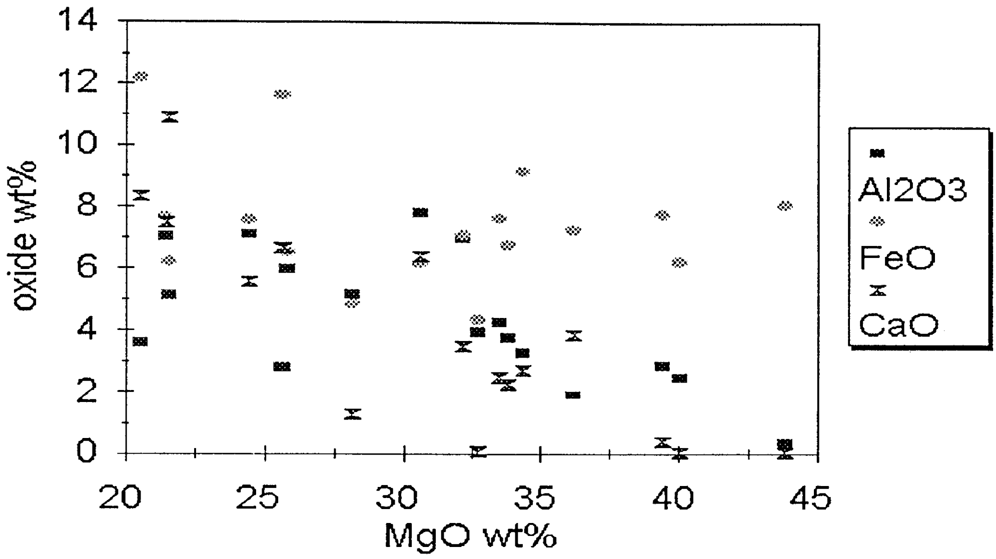

Figure 3.7: Al_2O_3, FeO and CaO versus MgO variation diagram of the mafic to ultramafic rocks.

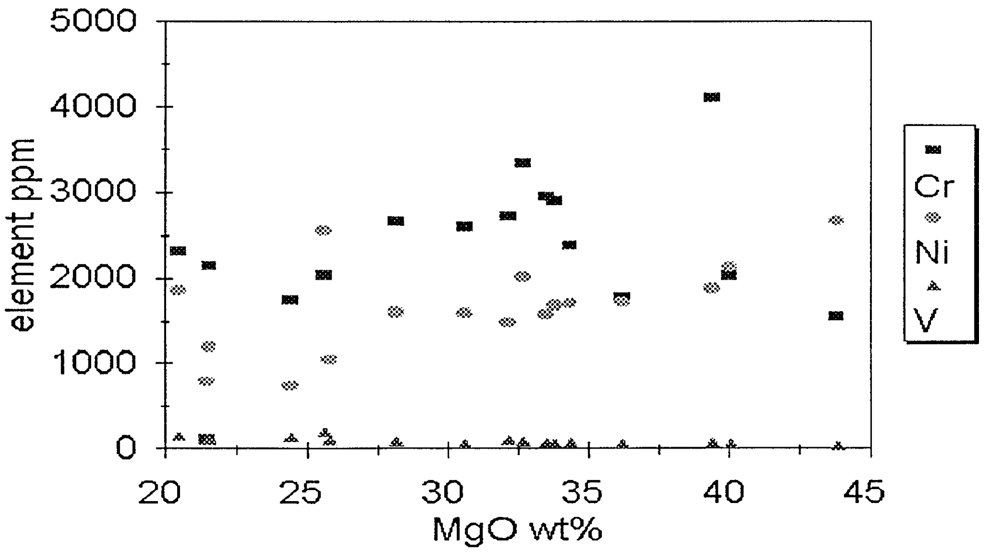

Figure 3.8: Variation diagram of Cr, Ni and V versus MgO of the mafic to ultramafic rocks.

3.5 Interpretation of Metamorphism and Chemistry of Rocks

Based on the mineralogy described above, the rocks of the Macequece Formation can be subdivided into a mafic to ultramafic suite containing chlorite+carbonate+serpentine+talc+tremolite+magnetite and a pelitic suite characterized by quartz+sericite+chloritoid+chlorite+andalusite+fuchsite (Winkler, 1974, p. 151, 206). In Figure 3.9, an ACF diagram confirms that the rocks are rich in magnesium and aluminum respectively, so that they agree with the corresponding fields of meta-ultramafites and metapelites.

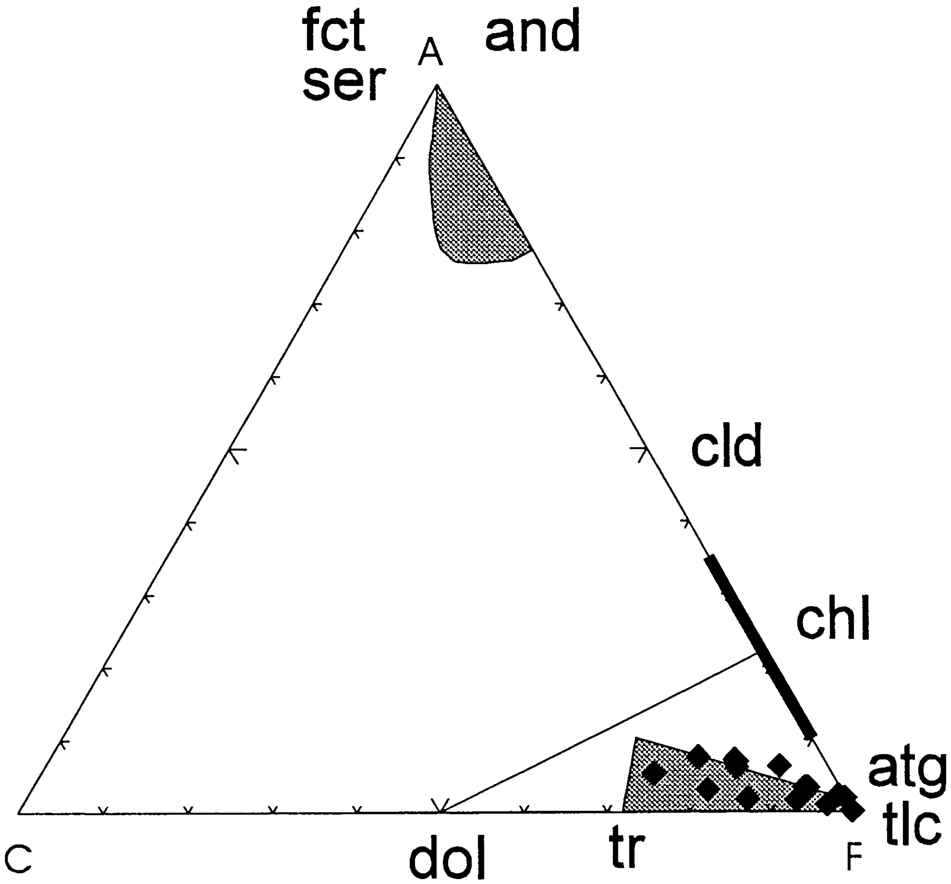

Figure 3.9: ACF diagram of mineralogy and chemistry of ultramafic and pelitic rocks. Shaded areas show field of pelitic and ultramafic compositions. The relevant compositions of the pelitic samples are: 21Sc (SiO_2-67.97; Al_2O_3-20.33; MgO-1.38 and CaO-0.01) and Ndqtz (SiO_2-48.1 and Al_2O_3-40.93). Mineral abbreviations as in Table 3.2. Fct- fuchsite.

3.5.1 Metamorphism

Mafic to Ultramafic Association

The temperature of metamorphism of the association can be constrained using Figure 3.10 and Figure 3.11 in which the phase relationships for ultramafic rocks are shown on TX diagrams (Winkler, 1974, p. 151 ; Bucher and Frey, 1994, p. 165).

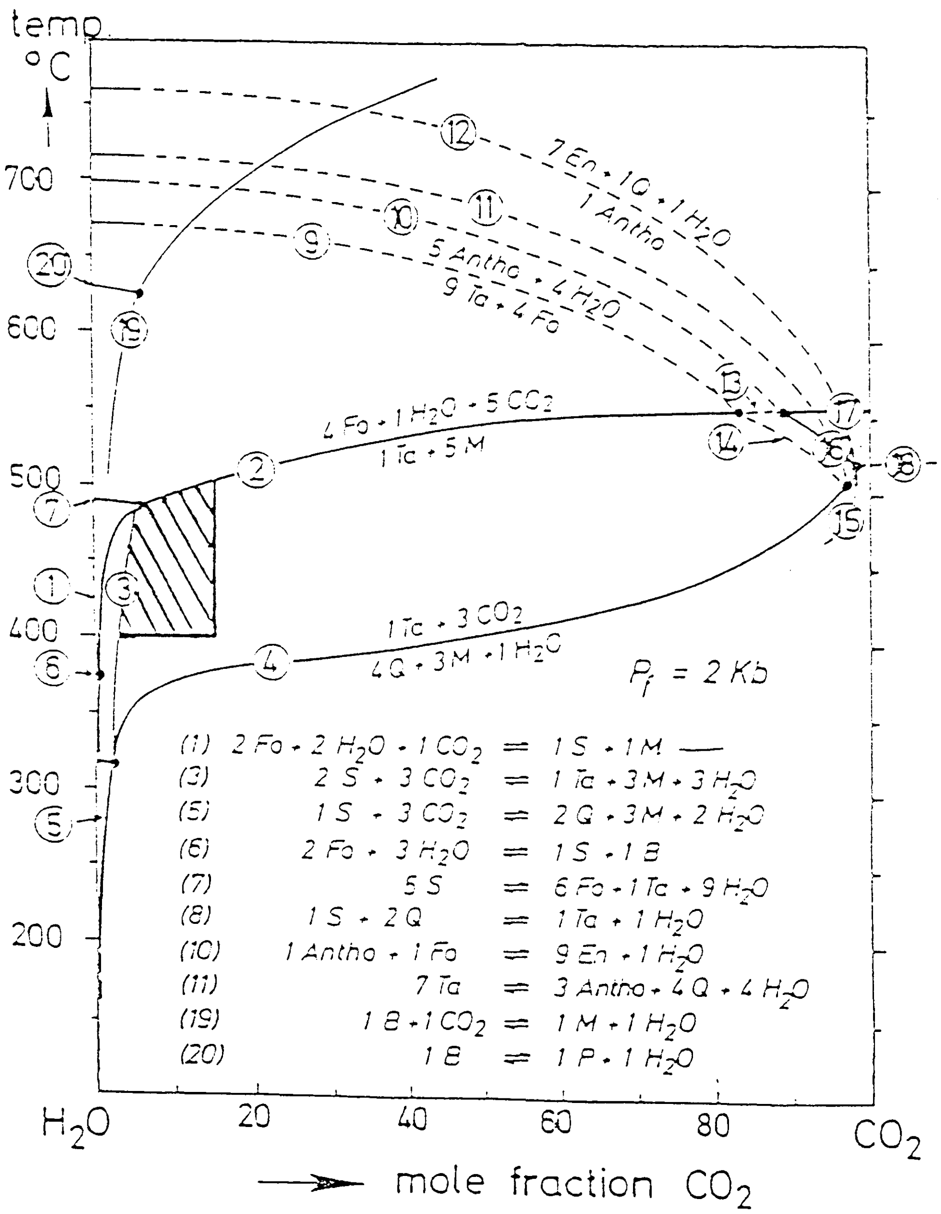

Figure 3.10: Isobaric reaction curves depicting phase relationships in mafic to ultramafic rocks (after Winkler, 1974). The P-T conditions are shown as cross hatched area which is defined by T≥400 °C≤500 °C, XCO_2≤0.14 and the relevant part of reaction 3.

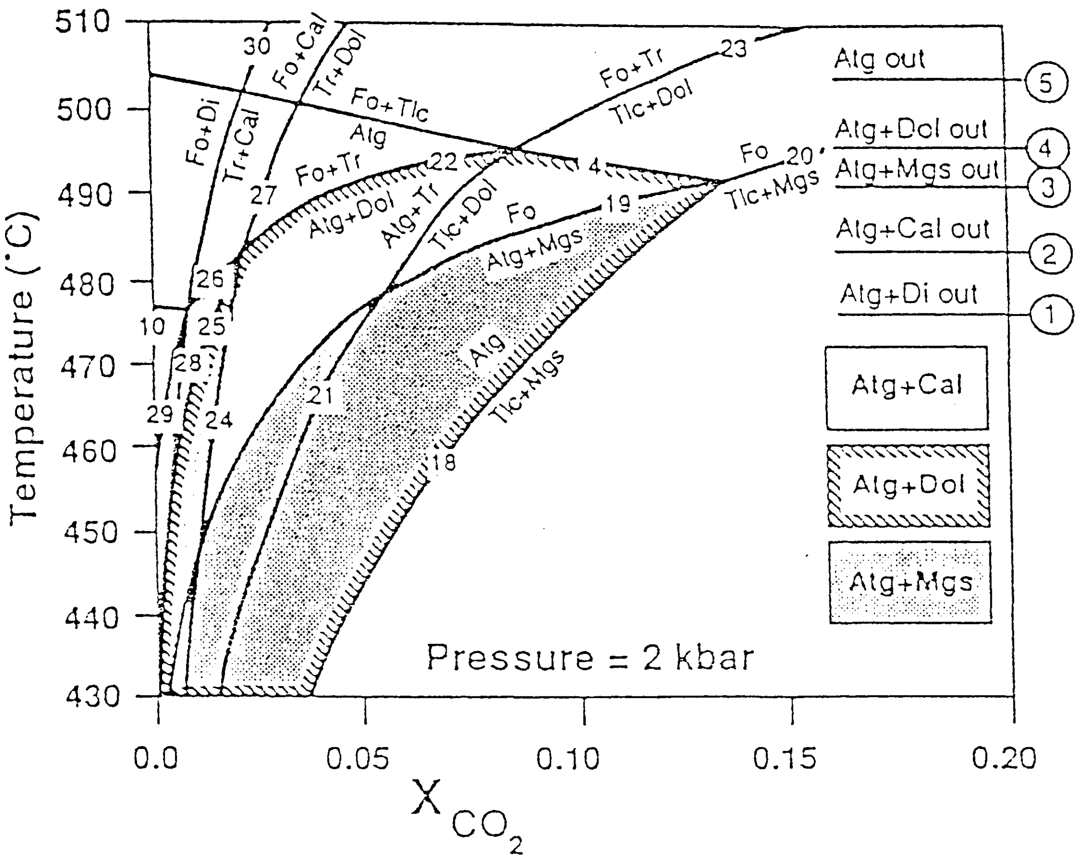

Figure 3.11: Low temperature phase relationship in mafic to ultramafic rocks at isobaric pressure of 2 kbar (after Bucher and Frey, 1994). Relevant P-T conditions are defined by the stippled area.

These figures were selected because they represent relatively low - pressure conditions (2 kbar) as is suggested by the andalusite-bearing pelitic assemblages. The figures show that the minerals recognized are generally stable below 500 °C at 2 Kbar above which olivine would have been expected. In addition, the coexistence of carbonate (dol)+talc+serpentine in some samples (mc, scg, 8) suggests that the fluid phase during metamorphism was a mixture of H_2O and CO_2 with $XCO_2 < 0.14$. These minerals are therefore typical of low grade or greenschist metamorphism.

<u>Pelitic Association</u>

The metamorphic conditions relating to the pelitic association can be interpreted from Figure 3.12 (Yardly, 1989, p. 86) which shows a petrogenetic grid for metamorphosed pelites. The occurrence of andalusite constrains the pressures of metamorphism to below 3.8 kbar and temperatures above ~400 °C below which pyrophyllite would be stable. The occurrence of chloritoid suggests temperatures below ~525 °C above which it would be replaced by staurolite.

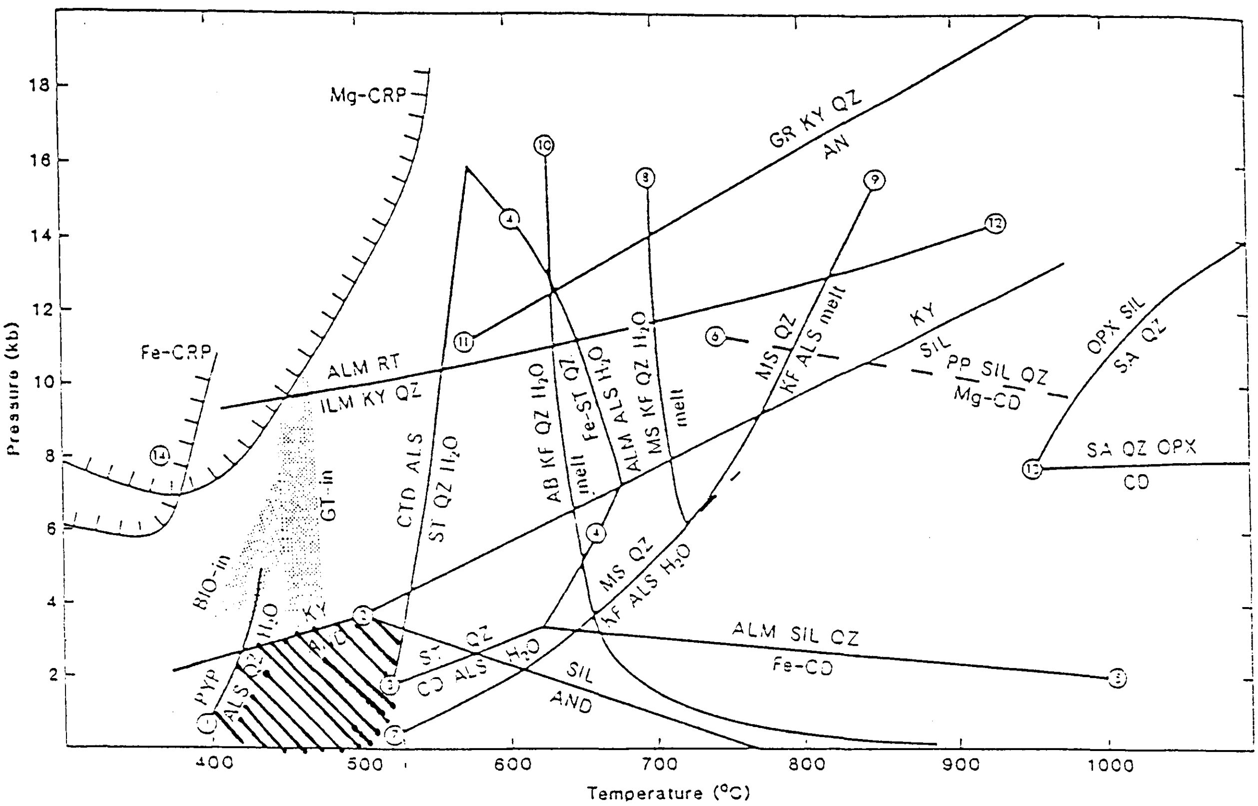

Figure 3.12: Phase relationships in metamorphism of pelitic rocks presented as petrogenetic grid in a PT diagram (after Yardly, 1989).

Considering the intercalated nature of the pelitic and mafic to ultramafic schists, their combined mineral assemblages suggest P-T conditions of between ~400 °C--~500 °C and pressures below 3.8 kbar.

3.5.2 Chemistry

Based on the petrographic data, the chemical composition of samples and the chemical trends described in the previous section, a number of discriminant diagrams are suggested for the interpretation of the nature of the greenstone rocks. Due to limited availability of chemical data, only analyses of mafic to ultramafic rocks will be used.

A plot of chemical data onto the Irvine and Baragar (1971) diagram (Fig. 3.13) shows the trend for MgO enrichment. The analysed samples are characterized by SiO_2 content between 45 and 53 wt% and MgO content above 18 wt%. These parameters are consistent with the definition of the rocks as komatiites (Arndt and Nisbet, 1982). Figure 3.14, after Jensen (1976), supports this with the data plotting in the field of peridotitic komatiites. The low Na_2O+K_2O and TiO_2 contents are also typical of komattiites (Le Maitre, 1989) (Fig.3.15).

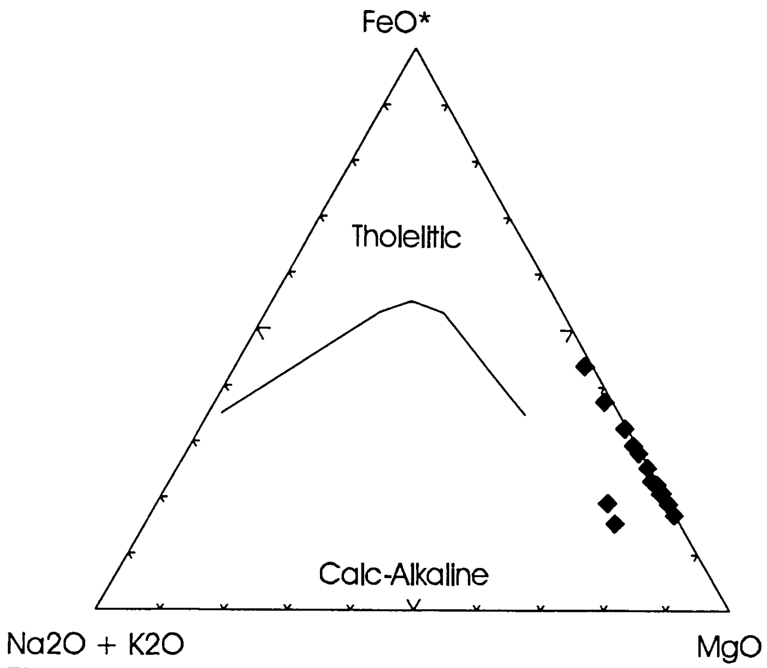

Figure 3.13: Tholeiite versus calc-alkaline series discriminant diagram (after Irvine and Baragar, 1971) of Macequece Formation.

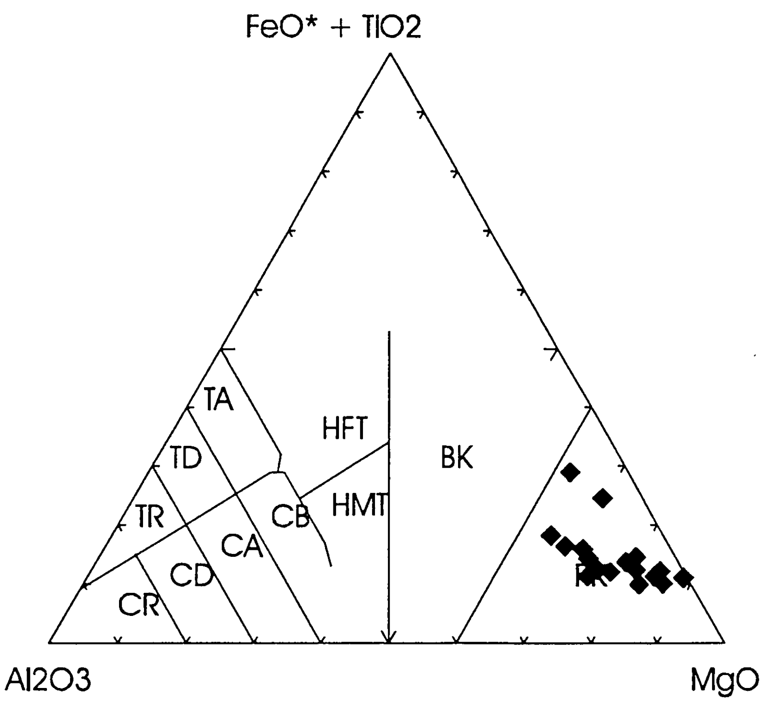

Figure 3.14: Discriminant diagram for tholeiites, komatiites and calc-alkaline fields plotting data of the Macequece Formation (after Jensen, 1976). HF- high iron tholeiites, HM- high magnesium tholeiites, BK- basaltic komatiites, PK- peridotitic komatiites, TR- tholeiitic rhyolites, TD- tholeiitic dacites, TA- tholeiitic andesites, CR- calc-alkaline rhyolites, CD- calc-alkaline dacites, CA- calc-alkaline andesites and CB- calc-alkaline basalts.

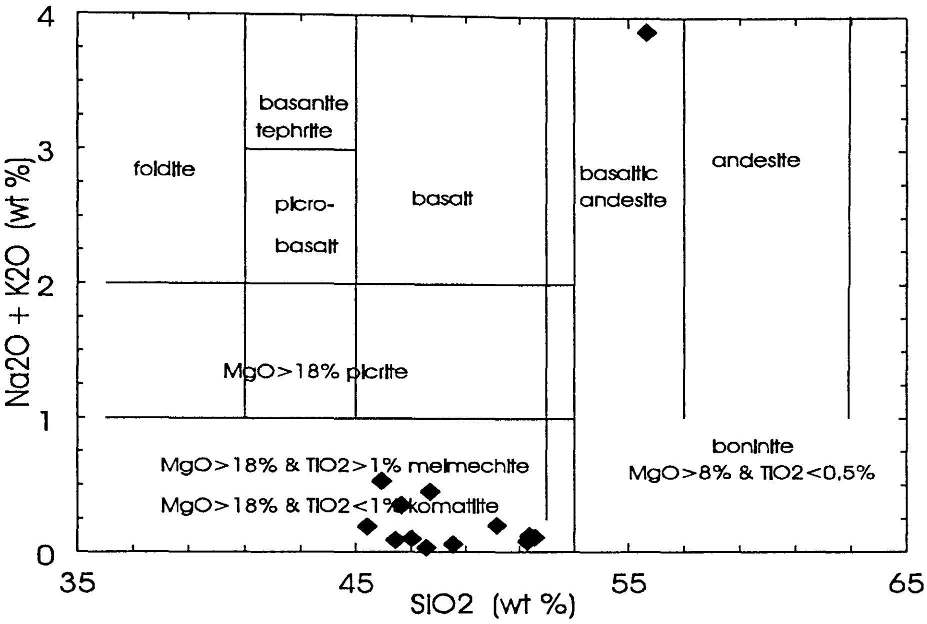

Figure 3.15: Discriminant diagram for various types of basalts (Le Maitre, 1989) of the Macequece Formation.