THE GEOLOGICAL AND GEOCHEMICAL EVOLUTION OF TONALITE-TRONDHJEMITE GNEISSES AND MIGMATITES IN THE BARBERTON REGION, EASTERN TRANSVAAL

by

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DECLARATION

I declare that this thesis is my own work. It is being submitted for the degree of Doctor of Philosophy in the University of the Witwatersrand, Johannesburg and has not been submitted before for any degree or examination in any other University.

L.J. ROBB

April, 1981

FOR MY WIFE VICKI,

WHO MADE IT ALL POSSIBLE

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ABSTRACT

Tonalite-trondhjemite gneisses and migmatites generally constitute the oldest granitoid suite in typical Archaean terranes. These rocks occur either as discrete bodies or plutons characterized by a homogeneous appearance and pervasive mineral fabric, or form intrinsic components in migmatites which may be complexly deformed and often typified by anatexis or sub-solidus differentiation. This thesis examines geological and geochemical features associated with tonalite-trondhjemite gneisses and migmatites in the Barberton Mountain Land and compares them briefly to similar rock types in the Ancient Gneiss Complex of Swaziland.

Migmatites occurring to the southwest of the Barberton greenstone belt can be viewed conceptually as representing, either a basement complex to a [illegible] greenstone succession, or the products of interaction between an [illegible] greenstone assemblage and younger, intrusive tonalite-trondhjemite magmas. Detailed mapping reveals that a simple choice between these alternatives is unrealistic. In certain instances tonalite and trondhjemite magmas have intruded greenstone remnants that can be correlated with a range of lithologies from the Barberton greenstone belt itself. In other cases, trondhjemite gneisses are intruded by early, deformed mafic dykes which may represent the intrusive equivalents of volcanic successions deposited during later stages in the development of the greenstone belt. In addition, the migmatites are invariably characterized by anatexis, a process which places well-defined constraints on P, T and f_{H_2O} conditions prevailing in the Archaean crust during the formation of these mixed rocks. The migmatitic rocks examined also reflect processes such as palingenesis and granitization/assimilation as well as recording, on a small scale, the effects of successive deformational increments in the broader region.

Detailed studies were made of the Kaap Valley and Doornhoek plutons, both of which abut directly against southwesterly portions of the Barberton greenstone belt. The Kaap Valley tonalite body is characterized by bulk compositions which reflect higher than normal hornblende and biotite contents.

The body also exhibits a pronounced crystal fractionation trend which can be modelled by decreasing hornblende contents and the late introduction of biotite on the liquidus during progressive solidification. The distribution and abundance of trace elements in this body is shown to possibly reflect an origin akin to zone melting. The Doornhoek trondhjemite pluton is markedly more felsic than the Kaap Valley body and is characterized by an extensive zone of neutral strain. From this, and other observations, it is suggested that many of the tonalite-trondhjemite plutons in the region were emplaced structurally, as diapirs, at least to their present positions.

Studies of a more regional nature over the entire tonalite-trondhjemite gneiss terrane southwest of the Barberton greenstone belt, show that many of the plutons or "cells" in the area have a distinctive chemical signature. This is particularly evident in terms of Sr which is shown to vary by a factor of five from one body to another. The tonalite-trondhjemite gneisses from the study area are also compared with data available from the Ancient Gneiss Complex in Swaziland which has many of the characteristics of the Barberton terrane. Two sub-groups of tonalite-trondhjemite gneisses emerge from the combined data; the first (occurring predominantly in the Barberton region) is characterized by high Sr and low Rb/Sr and ΣREE, whereas the second (occurring predominantly in the Ancient Gneiss Complex) has lower Sr and higher Rb/Sr and ΣREE. It is suggested that the former sub-type formed from a melt which equilibrated with a dominantly amphibole-bearing residue, whereas the latter was derived at a deeper crustal level where the parental magma equilibrated with a dominantly clinopyroxene-bearing (eclogitic) residue. This scheme obviates the need to genetically distinguish between the gneisses of the two regions and is consistent with generally higher metamorphic grades in the Swaziland terrane.

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CHAPTER 1

INTRODUCTION

INTRODUCTION

1. THE GEODYNAMICS PROJECT IN SOUTH AFRICA

The work contained in this thesis has been carried out under the auspices of the South African contribution to the International Geodynamics Project. The latter is a world-wide programme of research into the "...... dynamic history of the earth with emphasis on deep-seated foundations of geological phenomena" (The Geodynamics Project in South Africa, 1975). With its dynamic theme, the project has concentrated in those areas now exposed on the Earth's surface, that have been subjected to intense and prolonged deformational histories, i.e. the so-called "mobile belts". Complementary to this theme, however, has been the study of the early history of the large, stable cratonic platforms of southern Africa, as one such fundamental geological phenomenon revolves around understanding the processes whereby sialic foundation rocks were originally generated. On the Kaapvaal Craton (Figure 1) the best exposed and most widely understood area that might qualify for a study of this nature is the Barberton Mountain Land. As a result, this area was selected for participation in the Geodynamics Project under the general heading of "Evolution of the Earth's Crust in the Cratons" (The Geodynamics Project in South Africa, 1975). Clearly, the geodynamic theme implied that the Barberton project should concentrate on understanding the secular processes whereby the proto-Archaean crust, characterized by a thin and unstable lithosphere, was gradually transformed into stable continental crust that was at least as thick by the end of the Archaean as it is at present. With this view in mind the Barberton study strip was selected in order that it traversed as wide as possible a selection of the granitic terrane in the region (Figure 1). Besides affording an opportunity of study within the confines of the geodynamic theme, this traverse section also provided opportunities for studies of a complementary nature to those carried out by the Upper Mantle Project which had concentrated on a detailed understanding of the Barberton greenstone belt. The stratigraphically lowermost components of the latter consist of a suite of essentially volcanic rocks that are ensimatic in character and considered representative of a, once extensive, oceanic basin. The granites that surround the Barberton greenstone belt, therefore, represent the principal components responsible for the transformation of an ensimatic crust into a stable continental sialic environment.

Figure 1 : *Locality map showing the extent of the Geodynamics study strip in the Barberton region. The study strip is shown in relation to a generalized classification scheme which subdivides the Archaean granites in the area into three magmatic cycles (Anhaeusser and Robb, 1983b). Components of all three cycles are located in the study strip. The areas of interest of the various workers that have participated in the Barberton project are also shown.*

The understanding of the processes whereby this transformation took place can, in a broad sense, be viewed as the goal of the current Barberton Geodynamics Project.

2. THE GEODYNAMICS PROJECT APPROACH IN THE BARBERTON STUDY AREA

As illustrated in Figure 1, the Barberton study strip is orientated about a north-south trending axis and extends from Bushbuckridge southwards to a latitude of approximately $26^{0}30'$S. In Figure 1 it will be noticed that the granite terrane in the region is sub-divided into three sections, termed "magmatic cycles". These cycles, which represent a simplified genetic breakdown of the granites in the area, are all found in the granitic terrane underlying the study strip which can, therefore, be said to encompass a representative section of the entire evolutionary cycle of this portion of the crust. A detailed account of the magmatic cycle concept is presented in the concluding chapter of this thesis.

The initial approach undertaken by workers in the Barberton study strip was that of careful regional mapping using aerial photographs on a scale of either 1:30 000 or 1:10 000 depending on the complexity of the area. The study commenced officially in January, 1975 when the project co-ordinator Professor C.R. Anhaeusser continued his existing regional mapping programme in the area southwest of the Barberton greenstone belt (Figure 1). In April, 1975 the writer became involved in a regional mapping exercise in the granitic terrane north of the Barberton greenstone belt, between Nelspruit and Buchbuckridge. This study recognized the existence of a large multi-component batholith in the area, detailed descriptions of which are presented in an M.Sc. thesis (Robb, 1977) and several publications (McCarthy and Robb, 1978 and Robb, 1978; 1979). By the beginning of 1977, therefore, large portions of the northern, and also the southern, portions of the study strip had been mapped on a regional scale.

In February, 1977 this mapping programme was augmented by a study of the central strip of the Barberton traverse section undertaken by Mr. D.A. van Nierop (Figure 1). This study extended the recognition of the potash-rich batholith described in Robb (1977) and also examined the characteristics of a younger, post-tectonic pluton of the third magmatic cycle that occurred in this area; the results of this work are included in a thesis that has yet to be completed (D.A. van Nierop, in preparation).

Thus, at the beginning of 1978 the northern half of the Barberton study strip had been examined albeit on a regional scale. Detailed mapping in the southern portion of the study area had by this time progressed to an advanced stage and numerous xenolithic remnants of the Barberton greenstone belt had been identified and correlated with the main greenstone belt itself (Anhaeusser, 1980; Anhaeusser and Robb, 1980a). At this stage of the project, therefore, it was decided that attention should be focused on more detailed studies that would be responsible for elucidating problem areas as well as supplying the type of information that would lead to an understanding of the petrogenesis of the rocks occurring in this area. During 1978-79, Dr. J.M. Barton of the Bernard Price Institute of Geophysical Research, University of the Witwatersrand, undertook isotopic analyses of approximately fifteen individual granitic units from the study area, which resulted in Rb-Sr whole rock and Rb-Sr biotite ages, as well as initial $^{87}Sr/^{86}Sr$ ratios being obtained, for each. Much of this data has been presented in summary form by Barton (1980). In addition, Mrs. E. Barton, also of the Bernard Price Institute, was responsible for providing Rb-Sr age determinations for three discrete units from the multi-component potash-rich batholith that occurs in the northernmost portion of the study strip (Figure 1). This data has now been supplemented by U-Pb isotopic analyses and the combined Rb-Sr and U-Pb ages will be published shortly (Barton et al., in preparation).

From a geological point of view, additional detailed studies were initiated in February, 1978 by the writer and this thesis presents most of the results arising out of this effort. In addition, certain of the preliminary results of these studies have been published by Anhaeusser and Robb (1980 a, b) and Robb (1980). This particular project was carried out in close collaboration with Professor C.R. Anhaeusser whose mapping programme had been responsible for the recognition of numerous problem areas. The broad aims of the study centred around an examination of aspects of the evolution of the tonalite and trondhjemite gneisses to the southwest of the Barberton greenstone belt, the latter representing the principal components of the first magmatic cycle (Figure 1). Specifically, the project was concerned with four aspects : (i the detailed mapping of migmatitic rocks spatially related to the tonalite-trondhjemite gneisses, (ii) the petrographic and chemical characterization of the various components encountered in typical migmatite exposures, (iii) the regional mapping of tonalitic and trondhjemitic plutons that required detailed study in view of their prominent occurrence within the confines of the study strip and (iv) an evaluation of petrogenetic aspects related to all components of the first magmatic cycle.

The remainder of this introductory chapter provides a general summary of some of the previous work that is directly applicable to the Geodynamics Project in the Barberton area. Individual chapters in the text of the thesis provide more relevant review summaries that deal specifically with the topics being discussed. In addition, this introductory section also briefly discusses the current, and somewhat controversial state of knowledge regarding the evolution of the Earth's early Archaean crust - a topic that has direct relevance to points dealt with in the text.

A SUMMARY OF PREVIOUS WORK CARRIED OUT IN THE BARBERTON REGION

Most of the very early work undertaken in the Barberton Mountain Land received its impetus, either from interest in the economic potential of the area or through the involvement of the Geological Survey of South Africa's regional mapping programmes. Comprehensive summaries of this early work have been written on a number of previous occasions (e.g. Anhaeusser, 1969; Robb, 1977) and an exhaustive bibliography of all publications related to the Barberton region in the period 1884-1976 is also available (Anhaeusser, 1976a). By 1960 a number of broad regional accounts were available that generally reflected the state of knowledge regarding the area at that time (Hall, 1918; du Toit, 1926; van Eeden, 1941; Visser, compiler, 1956; Visser and Verwoerd, 1960). However, in spite of the fact that, at this stage the Barberton greenstone belt had been mapped in detail, the nature of the stratigraphic succession as well as its geological significance, was largely misunderstood. The granites in the area, with little or no economic potential, had only been cursorily examined although it was widely appreciated that they represented the ancient basement.

During the 1960's, however, enormous advances were made in understanding the geology of the Barberton Mountain Land. This progress was engendered, firstly, by the participation of workers from the Economic Geology Research Unit, University of the Witwatersrand, who undertook mapping, as well as structural and economic studies along the northern flank of the Barberton greenstone belt and, secondly, by the inception of the international Upper Mantle Project (1964-1969) which sponsored further detailed stratigraphic studies over the belt as a whole. The first project achieved, amongst other things, a better understanding of the gold mineralization in the Barberton greenstone belt, the results of which are found in a number of theses and reports (Anhaeusser, 1963; Gay, 1963; Viljoen, 1963 and van Vuuren, 1964). The results of the Upper Mantle Project had particularly far-reaching implications in terms of both the understanding and significance of greenstone belts in general, and are summarized in a series of publications by Viljoen and Viljoen (1969 a-j). In this work, for the first time, a viable stratigraphic column was erected whereby the secular evolution of the greenstone lithologies could be understood. The base of the volcano-sedimentary pile was shown to consist of volcanic extrusive rocks and minor chemical sediments, which together, comprised the Onverwacht Group. The base of this Group, i.e. the Tjakastad Subgroup, was shown to consist dominantly of mafic and ultramafic lavas which graded upwards into the Geluk Subgroup, comprising calc-alkaline volcanics ranging from tholeiitic to dacitic and rhyolitic in composition. This volcanic pile showed evidence of extrusive ultramafic magmas and sub-aqueous quench textures that suggested the preservation of an ancient relic of ocean floor. The granitic rocks surrounding the Barberton greenstone belt were also examined (Viljoen and Viljoen, 1969 f,g) and classified in a scheme which did not recognize the existence of any granites in the area pre-dating the greenstone belt itself. As a result, the volcano-sedimentary pile was regarded as an ensimatic assemblage representative of the earliest crust in the area. Considerations regarding the evolution and transformation of this early oceanic crust to one represented by a stable, continental sialic basement, formed the culmination of the studies in the decade of the 1960's and are presented in a series of classic papers by Anhaeusser et al.. (1969); Anhaeusser (1973) and Anhaeusser (1975). The views expressed in these papers became controversial, however, in the light of the considerable amount of work that was accumulating in Archaean terranes from other parts of the world. A summary of the controversies existing in terms of the evolution of the Archaean crust in general, is presented in a following section.

In the 60's and early 70's, geochronological work was responsible for quantifying the ancient nature of the Barberton Mountain Land. The oldest granitic rocks in the area were variously dated by Rb-Sr and U-Pb techniques to give a range in ages of between 3,44 - 3,17 b.y. (Allsopp et al., 1962, 1969; Oosthuyzen, 1970). As these granites were considered to intrude the Barberton greenstone belt, this suggested that the volcanics of the Onverwacht Group should be at least 3,5 b.y. or older. In general, however, questions relating to the relative ages of various units in the region, at this time, lent themselves to complicating the issues at hand. This was particularly the case where ideas regarding the evolution of the Archaean terrane in adjacent Swaziland (Figure 1) were amalgamated with the data from the Barberton region. Work in Swaziland had revealed the presence of a complex suite of tonalite-trondhjemite gneisses, migmatites and mafic xenoliths, that was considered, largely on the basis of structural reasoning, to be older than the Barberton greenstone belt (Hunter, 1973, 1974). Although this was not confirmed by geochronological studies (Allsopp et al., 1969; Davies and Allsopp, 1976), the Ancient Gneiss Complex, as it was called, has been the object of a continued debate in Archaean studies comparing the two regions from the point of view of crustal evolution.

With the completion of the Upper Mantle Project, the investigations carried out in the early 1970's (i.e. prior to the Geodynamics Project) were sporadic and did not form part of any concerted programme of research. Attempts were made to understand the petrogenesis of both the mafic and ultramafic volcanics on the one hand, and the various granitic components, on the other. Petrogenetic aspects of peridotitic komatiites of the Barberton greenstone belt were discussed in Green et al., (1975) whilst a detailed account of the geochemistry of basaltic flows was presented by Smith et al., (1978). The origins of various granitic rocks in the Barberton and Swaziland regions were discussed mainly from the point of view of their trace element characteristics (Condie and Hunter, 1976; Glikson, 1976a). This work contributed towards an understanding of the origins of Archaean tonalite-trondhjemite gneisses which have come to be viewed as representing partial melts of basaltic precursors. This idea lent credence to those evolutionary models that envisaged a secular transformation from an early ensimatic crust to one of sialic character (e.g. Glikson, 1972; Anhaeusser, 1973).

With regard to the Barberton greenstone belt itself, recent contributions have tended to both agree and disagree with past findings. Hamilton et al. (1979) have obtained a precise Sm-Nd isochron on various mafic and ultramafic rocks of the lower portion of the Onverwacht Group.

This age, of approximately 3,51 b.y., confirms the minimum expected age for the lower greenstones on the basis of previous age determinations carried out on the intrusive granitic plutons. From a geological view-point, recent re-mapping of portions of the Onverwacht Group type-area has led to suggestions that the thickness of certain stratigraphic units was originally overestimated as the result of duplication in tight isoclinal folds (Williams and Furnell, 1979). This has been contested by Viljoen and Viljoen (1979) with the result that quantified structural interpretation of the Barberton greenstone belt remains an unresolved parameter.

The above sections provide a brief framework to the not inconsider-able amount of geological knowledge pertaining to the Barberton Mountain Land. It is evident that much of the effort in the past has been concentrated on the greenstone belt and it is, therefore, pertinent that the efforts pertaining to the Geodynamics Project should have been devoted to investigations on aspects of the surrounding granitic terrane. Clearly, some of the ideas that have been generated in previous studies have proved to be contentious, particularly those relating to the evolution of this Archaean terrane. The following section attempts to show that this controversy is not restricted to the Barberton region, but applies to Archaean terranes world-wide; an understanding of the nature of these discordant view-points is shown to be necessary in terms of appreciating some of the motives behind the present study.

4. IDEAS AND CONTROVERSIES RELATING TO THE EVOLUTION OF THE ARCHAEAN CRUST

Any discussion that is concerned with the evolution of the Archaean crust must necessarily be primarily concerned with that "....vestige of a beginning...." which so eluded James Hutton over two centuries ago. A considerable portion of Earth history is no longer discernible in view of the fact that the origin of the earth can be placed at approximately 4,7 b.y.ago, whereas the oldest rocks yet dated yield isotopic ages of 3,7 - 3,9 b.y. (for example, Moorbath, 1975: Barton et al., 1977). As a result, development of the Earth's crust in the proto-Archaean (i.e. > 3,9 b.y.) is based, either on terrestrial-based inference or, in more recent times, on comparative planetary evolution, or planetology. The latter discipline is responsible for the most meaningful indications of the nature of the Earth's earliest Archaean crust and is based on the precept that the inner silicate planets (i.e. Mercury, Venus, Earth-Moon and Mars) have evolved along more or less similar lines. It is clear that the smaller, less-active planets, which, in contrast to Earth did not develop a substantial atmosphere, have preserved their early crustal histories to a much greater extent.

One of the principal working hypotheses derived from comparative planetology is the fact that the Earth cannot have escaped the intense impact cratering that is so characteristic of the other inner planets (Grieve, 1980; Frey, 1980). As a result many workers have come to include a period of meteoritic bombardment in the period ≈ 4,0 - 3,9 b.y. as an intrinsic component of Archaean evolutionary models and attribute to this event both the non-preservation of a primordial crust and the triggering of subsequent magmatic events (Green, 1972; Glikson, 1976b; Lowman, 1976 and Shaw, 1976). In spite of this catastrophic meteorite flux however, recent geological studies of the Moon indicate that the smaller silicate planets in general, appear to preserve geological features that formed in pre-impact times. The oldest rocks on the Moon (4,6 - 4,3 b.y. old) are preserved in the lunar highlands which have been shown to be essentially intermediate in composition (Lowman, 1976). This feature, which is the result of substantial amounts of plagioclase in these rocks, accounts for the higher albedo in highland areas as opposed to the lower-lying basaltic maria. Most of the younger rocks on the Moon (i.e. ≅ 4,0 b.y. and younger) are represented by maria of basic and ultrabasic composition that were emplaced as countless intrusive and extrusive units resulting from intense meteoritic bombardment.

In the light of this knowledge Lowman (1976) proposed a similar scenario for the evolution of the Earth's crust in the proto-Archaean. In the period 4,7 - 4,0 b.y. ago it was envisaged that a period of "first differentiation" resulted in the formation of a global andesitic crust with minor associated anorthosites and more basic residual phases. Although the peak flux of meteorite impacting occurred approximately 4,0 b.y. ago, remnants of both the first differentiation and the impact cratering are no longer preserved on Earth. The reason for this is related to the higher internal energy (i.e. heat flow, magmatism etc.,) inherent in the Earth system as well as the higher volatile content, which resulted both in the formation of the hydrosphere and atmosphere and in facilitating the melting of pre-existing solid material. Although not substantiated by direct evidence, the 4,0 b.y. meteorite impacts may have triggered a period of second differentiation which resulted in the generation and eruption of large volumes of basic and ultrabasic magmas which are now manifest in the form of Archaean greenstone belts (Green, 1972).

The above discussion illustrates briefly some of the ideas pertaining to crustal evolution in the period prior to 3,9 b.y. ago. Ideas on crustal evolution subsequent to this date are based largely on terrestrial experience and, hence, considerably better control is available. At the outset, however, it is apparent that the planetologists' view that the Earth's primordial crust was global in extent is not in keeping with certain terrestrially-based views. Glikson (1972) and Windley (1977) have, for example, envisaged the lateral growth of Archaean crust from the coalescence of "mini-continents" or "sialic nuclei", whereas Clifford's (1972) study of the evolution of the African crust implied extensive (perhaps global ?) sialic crust and progressive cratonization, or stabilization, with time. The roots of this problem, and indeed possibly that of Archaean crustal evolution in general, are twofold and stem from (i) lack of consensus as to the oldest recognized lithological unit in the *existing* Archaean rock record and, (ii) differences in opinion as to whether the Archaean is more profitably viewed in terms of unique tectonic processes or whether a uniformitarian approach to the New Global Tectonics is more relevant.

Most meaningful Archaean tectonic models have been postulated since 1968 when a surge of interest in this topic arose out of the completion of the international Upper Mantle Project. The controversies that arose initially were mainly involved with the questions of whether greenstone belts represented primordial crust and were ensimatic in nature, or whether a granitic proto-crust of global extent existed prior to the development of the earliest recorded greenstone belts. This has led to two schools of thought; the first (the North Atlantic school of Glikson, 1979a) supports the development of early sial prior to the formation of any greenstone belts and regards highly metamorphosed and structurally complex mobile belts as distinct (probably older) units from the granite-greenstone shield areas, and the second (the Barberton-Pilbara school of Glikson, 1979a) which views the early mafic-ultramafic greenstones as primordial and ensimatic, with mobile belts representing a deeper level in the subsequently granitized crust. In southern Africa, for example, the two schools are typified by the views of Hunter (1973, 1974) who regarded the Ancient Gneiss Complex in Swaziland as an entirely discrete, and older, sialic basement upon which the Barberton greenstone belt was deposited, whilst Anhaeusser (1973, 1975) viewed the latter as ensimatic, regarding all granites in the area as intrusive and, therefore, younger.

Both points of view can be corroborated with a substantial amount of evidence; for example, the first school can point to typical greenstone assemblages unconformably overlying a granitic basement (Bickle et al., 1975; Ermanovics and Davison, 1976), to very old radiometric ages in mobile belts possibly representative of granitic basement (Barton et al., 1977) and to lithological successions in such mobile belts that are not easily correlatable with those in, supposedly younger, granite-greenstone terranes. In regard to the latter point, Windley (1977) has drawn attention to shelf-type arenites and shallow-water marbles and pelites in mobile belts, by comparison with the deep-water greywacke-turbidite associations of the oceanic greenstone belts. The second school of thought, on the other hand, can point to the lack of direct evidence for granitic phases pre-dating the *oldest* recognized greenstone assemblages and refer, for example, to the 3,7 b.y. old Amitsoq gneisses in West Greenland that contain inclusions of the Isua supracrustals (McGregor, 1979). Proponents of this view also point to the fact that where unconformities exist between granite and overlying greenstones, the latter are represented by stratigraphically younger units that are underlain by older greenstones in other areas. In Zimbabwe for example, at least two stages of greenstone belt development have recently been recognized (Wilson, 1979). The ensimatic nature of the earlier developed greenstone belts is also inferred from the primitive nature of the komatiitic basic and ultrabasic rocks that form such a significant component of these assemblages (in comparison to Proterozoic and Cenozoic volcanics) and whose petrogenetic characteristics militate against their having been emplaced through an ensialic basement. A final, and particularly convincing, argument for a primordial basaltic crust is related to the chemistry of early Archaean tonalites and trondhjemites. Experimental and petrogenetic modelling has been able to show that these rocks were derived by partial melting of a basic precursor (Arth and Hanson, 1972; Lambert and Wyllie, 1972; Arth and Barker, 1976, Glikson, 1979a). As such, it is difficult to conceive of the presence of a *primordial* tonalitic-trondhjemitic crust that has not itself been derived from pre-existing mafic material.

The above controversies are further complicated if one takes into account the variety of tectonic processes that have been envisaged in the development of the Archaean crust. Earlier geotectonic models (i.e. derived between approximately 1968-1973) were not subjected to the onslaught of ideas generated through the new global tectonics concept and it is only in more recent times, therefore, that plate tectonic processes have been extrapolated into the Archaean. On this basis, the two schools became further polarized in that proponents of ensimatic greenstones found themselves unable to readily extend modern plate tectonic ideas into an Archaean scenario which envisaged an extensive primordial mafic crust. As a result this school envisaged a dominantly vertical mode of tectonics whereby the dense primordial crust gradually foundered under its own weight, initiating partial melting and gravitationally induced diapirism of early tonalitic bodies, the latter resulting in the formation of the initial sialic nuclei (Anhaeusser et al., 1969; Green and Baadsgaard, 1971; Glikson, 1972; Anhaeusser, 1973, 1975; Hargraves, 1976).

The proponents of a primordial granitic crust, however, had little difficulty in envisaging plate tectonic processes operating in the Archaean. These ideas took a number of forms with greenstone belts forming intra-cratonically on thin mafic crust between small continents of sialic composition (Goodwin and Ridler, 1970), with greenstones represented as island-arcs (Folinsbee et al., 1968; Anhaeusser, 1973) and also as fossilized marginal back-arc basins (Burke et al., 1976). The latter idea, in particular, has been closely examined with regard to a Cretaceous ophiolite complex in southern Chile where the association and distribution of rock types is very similar to that of typical Archaean greenstone belts (Tarney et al., 1976). If this comparative model were to prove correct it would certainly provide a valuable insight into the tectonic processes that prevailed in the Archaean. Unfortunately, however, certain key similarities between the two tectonic settings are lacking. Foremost amongst these are the absence of intrusive sheeted dyke complexes in the typical greenstone assemblages and the paucity of komatiitic basic and ultrabasic lavas in the modern ophiolite settings (Anhaeusser, 1981). Whether these discrepancies are real, or merely the result of inconsistencies in the recognition and interpretation of rock textures from one setting to the other (M.J. de Wit, personal communication), is a decision which awaits further work. If it is to be said that a form of plate tectonics applies to the Archaean, it is likely that such processes were considerably different to those prevailing in modern times as little evidence exists for the global continental crust indicated by comparative planetology. Tectonic processes in the Archaean were probably constrained by the presence of smaller, incipient continental masses that were characterized by more complex and less definitive relative motions.

In conclusion, it is pertinent, in the light of the above discussion, to speculate on where the oldest possible rocks on earth might be found. In terms of the primordial sialic crust option, it would appear that old, complex mobile belts adjacent to Archaean granite-greenstone cratons might provide the terrane where such material could be located. Alternatively, if the greenstone belts themselves were ensialic and were now found adjacent to, or were deposited directly on top of, early continental crust, then, in the cratonic areas, the oldest material would be preserved in immediate juxtaposition with the oldest (now vertical) greenstone accumulations. In the present study, this reasoning was one of the motives behind the examination of migmatites in the Barberton Mountain Land. This complex suite of rocks, which in the study area contains components of both granite and greenstone, may preserve indications suggestive of the fundamental relationships between possible contestants for the primordial crust. It is the writer's opinion, however, that the final answer to the Archaean controversy will have to await considerably more detailed geological studies of the inner silicate planets and the extrapolation of this data to the much later processes now manifest in the Archaean of the Earth system.

5. THE PRESENT STUDY

This thesis is concerned with facets of the geological and geochemical evolution of tonalite-trondhjemite gneisses and migmatites in the Barberton Mountain Land. As illustrated briefly in Figure 1 and also described in more detail in Chapter 7, the tonalites and trondhjemites of the granitic terrane in this region form one component of three generalized granitic magmatic cycles considered responsible for the evolution of this portion of the Earth's continental crust. In terms of geological relationships, the tonalite and trondhjemite gneisses collectively represent the oldest suite of granitic rocks in the area and, thus, constitute the first magmatic cycle. It is also within this suite of rocks that the migmatitic rocks, described in subsequent chapters, occur and where indications, if any, of a primordial sialic basement are likely to be located.

The following text is divided into three distinct parts; Part 1 describes in detail the geology, petrography and chemistry of a number of migmatitic outcrops that were mapped in the study area, as well as dealing with the petrogenesis of individual components that make up these migmatites; Part 2 discusses the regional geological and chemical characteristics of two discrete tonalite and trondhjemite plutons (i.e. the Kaap Valley tonalite pluton and the Doornhoek trondhjemite pluton) in the study area and also considers petrogenetic aspects related to both of these bodies; Part 3 examines the broad chemical and petrogenetic characteristics of a number of tonalite-trondhjemite bodies in the area southwest of the Barberton greenstone belt in the light of new chemical data obtained from samples collected in collaboration with Professor C.R. Anhaeusser. The latter section also compares and contrasts the trace element data from this suite of rocks with similar components from the Ancient Gneiss Complex in Swaziland.

The initial stages of this project entailed field studies and the mapping of the various units discussed later in the thesis. In regard to the study on migmatites, the mapping was of an extremely detailed nature and involved the careful assessment of a number of select outcrops (see Chapter 2). Once an outcrop had been selected for appraisal, a string-line and chalk grid was superimposed on it and the mapping of discrete components of the migmatite was undertaken on a scale of 1:50. All the relevant migmatite components were subsequently sampled and prepared for petrographic study and chemical analysis. The mapping of the tonalite-trondhjemite plutons was carried out on a much larger scale with the aid of aerial photographs; the Kaap Valley pluton was mapped at a scale of 1:30000, whereas the smaller Doornhoek pluton was mapped using aerial photographs enlarged to a scale of approximately 1:8000. These bodies were also extensively sampled so as to acquire subsequent geochemical analyses that were representative of the body as a whole. The geological ground control for the samples referred to in Part 3 of the thesis was provided by detailed 1:10000 mapping undertaken by Professor C.R. Anhaeusser (see Anhaeusser, 1980; Anhaeusser and Robb, 1980a).

The subsequent stages of the project involved the examination and analysis of approximately 110 individual samples. The analytical procedure was broken down into three separate stages: (i) all the samples were analysed for full major elements as well as select trace elements (namely rubidium, strontium and barium) by X-ray fluorescence spectrometry; (ii) approximately one half of the samples were selected for rare-earth element analysis using neutron activation techniques; and (iii) a few select samples underwent individual mineral analyses using an electron microprobe. Details of these various procedures are presented in Appendix 1.

In the descriptive sections of this thesis routine taxonomic considerations, classification of rock types and comparisons with the voluminous data in the literature, were kept to a minimum in view of the fact that this approach tends to be repetitive and, on its own, not conducive towards a detailed understanding of the rocks. As a result, emphasis was placed on considerations dealing with petrogenetic aspects of the various rock units, particularly in terms of trace element modelling. Such procedures are open to numerous criticisms but nevertheless afford the petrologist with a relatively simple technique for placing constraints on the origin and formation of igneous rocks.

Uncertainties in both trace (Rb, Sr and Ba) and rare-earth element modelling revolve around; (i) the suspected mobility of these elements in a metamorphic environment (Condie et al., 1977); (ii) uncertainties in certain partition coefficients, some of which are derived experimentally, others by phenocryst-groundmass analysis; (iii) changes in the magnitudes of known partition coefficients as a function of variables such as magma composition, temperature, pressure and oxygen fugacity; and (iv) the uncertainties in actual analytical data with which trace element models are compared (Arth, 1976). In spite of these points the writer is of the opinion that the *systematic behaviour* of trace elements in fresh, unaltered rock, must, to a large measure, reflect the primary igneous processes that the rock was originally subjected to. As such, the complementary behaviour of major, trace and, where available, rare-earth elements in a particular rock system is viewed in this thesis as reflecting the origin and mode of formation of that rock. Where the three sets of data do not behave cohesively or are characterized by extreme relative variations, the data was regarded as suspect.

The trace element models described in the text were carried out with two objectives in mind; the first placed constraints on the possible parentage of certain granitic rock-types and was concerned with the process of partial melting or anatexis; the second examined the process of crystallization or solidification in a granitic melt with a view to explaining chemical variations in the subsequently formed body of rock. The formulation of trace element models was undertaken by assuming that trace elements behave according to Henry's law and do not represent a stoichiometric constituent of any mineral phase (i.e. certainly true in the case of Rb, Sr, Ba and the rare-earth elements). Partial melt considerations in the text were always evaluated in terms of "batch melting", the equations for which were derived by Shaw (1970) and are outlined in Appendix 2. Batch melting is considered the most realistic melting process (Arth 1976) and involves the continual equilibration of a liquid phase with a residual solid phase, until complete removal of the melt from the residue. In this process the distribution of trace elements between melt and residue is dependent on the nature of mineral phases present in the residue at the time of extraction of the melt, and not on the mineral phases originally present in the parental material (Hanson, 1978). Considerations of crystallization are evaluated in terms of the Rayleigh fractionation law, the relevant equations for which were originally applied to the earth sciences by Neumann et al. (1954). The equations for equilibrium crystallization as well as for fractional crystallization are also provided in Appendix 2. All the trace element models considered in the text apply specifically to Rb, Sr, Ba and the rare-earth elements as the partition coefficients for these elements into the common rock-forming minerals are readily available; the partition coefficient is defined here as the concentration of a given trace element in a mineral divided by the concentration of the same element in a co-existing melt (Hanson, 1978). The partition coefficients used in this study were assembled from a number of sources and are presented in Appendix 2. Finally, a detailed worked example of how the trace element models were calculated and applied is also presented in Appendix 2.

The above discussion considers very briefly the motives and techniques behind the present study. The latter is offered as a contribution to the understanding of the geological evolution of the oldest recognized granitic *(sensu lato)* phase in the Barberton Mountain Land and an evaluation of the role that this magmatic event has played in the generation, development and subsequent stabilization of the continental crust in the area. The following scheme represents the breakdown of the subject matter in the remainder of the thesis:-

Chapter 2 -	Detailed studies of select migmatite outcrops to the north and southwest of the Barberton greenstone belt - systematic description.	PART 1
Chapter 3 -	Petrogenetic aspects related to the various components identified from the migmatite outcrops in the Barberton Mountian land.	
Chapter 4 -	The Kaap Valley tonalite pluton - its geology, chemistry and mode of formation.	PART 2
Chapter 5 -	Geological and geochemical characteristics of the Doornhoek pluton.	
Chapter 6	Chemical and petrogenetic characteristics of tonalite and trondhjemite plutons in the area southwest of the Barberton greenstone belt.	PART 3
Chapter	Discussion and conclusions.	

* * *

PART 1

MIGMATITIC ROCKS IN THE

BARBERTON MOUNTAIN LAND

CHAPTER 2

DETAILED STUDIES OF SELECT MIGMATITE OUTCROPS TO THE NORTH AND SOUTHWEST OF THE BARBERTON GREENSTONE BELT –SYSTEMATIC DESCRIPTION

DETAILED STUDIES OF SELECT MIGMATITE OUTCROPS TO THE NORTH AND SOUTHWEST OF THE BARBERTON GREENSTONE BELT - SYSTEMATIC DESCRIPTION

1. INTRODUCTION

The major portion of this thesis deals with a detailed study of select, well-exposed migmatite outcrops in the Barberton Mountain Land. Ten individual sites were mapped in considerable detail (on a scale of 1:50) and the description and interpretation of these localities forms the bulk of this chapter. Nine of the sites are located to the southwest of the Barberton greenstone belt, whereas the tenth is found to the north of the belt (Figure 2). The migmatites occurring to the southwest of the belt are intimately associated with greenstone xenoliths of varying lithology as well as being spatially related to the tonalite and trondhjemite gneisses of the first magmatic cycle; the single migmatite outcrop mapped to the north of the greenstone belt is located in the marginal, K-rich migmatite and gneiss terrane flanking the Nelspruit batholith, the latter making up one component of the second magmatic cycle.

In order to view these migmatites and the granites *(sensu lato)* with which they are spatially associated, in the correct perspective it is first necessary to consider both past and present ideas relating to the understanding of both granite and migmatite genesis. The following sections comprise a brief apporaisal of the often controversial ideas relating to this topic.

1.1. The "Granite Controversy"

Undoubtedly the single most contentious issue in the history of geological science has been the question of the origin and genesis of granites *(sensu lato)*. Discussion regarding the origin of granites is known to date back to the beginnings of geology when Hutton referred to granitic textures as prima faciae evidence against the, then all-powerful, Neptunistic doctrine. As geology evolved into a specific discipline arguments concerning granites remained in the forefront of the subject and over the last century of geological discussion it can be stated that many of the milestones marking the development of earth-sciences can be directly related to advancements made in the understanding of granite genesis. Granites, in a broad sense, represent the most abundant rock types available for study on the earth's crust; they form the basement on top of which most sediments were deposited and also form the provenance from which many sediments were derived; finally, older granites commonly constitute the parent material from which younger orogenic granites were formed. Clearly, the reason that granites are so abundant in the earth's crust is a function of the mechanism by which they have formed; this notion, together with the fact that granites exist in a variety of different tectonic environments, explains the existence of a granite controversy in geological history. Is the mechanism by which granites have formed a common denominator to all types of tectonic environment, or have they formed by specialized processes directly relatable to their setting in time and space? The sections below describe the historical development of ideas relating to the origins and genesis of granites, in this light.

1.2. The early geological controversies

The earliest geological controversy was undoubtedly the one which, in effect, decided the direction along which all future geological thought was channelled. Up until 1795, when James Hutton published his work entitled "The Theory of the Earth", geological thought had been dominated by the Neptunistic doctrine of Werner. This dominantly religious school believed that all rocks present on the earth, both igneous and sedimentary, were deposited together during the biblical "primordial flood" which was supposed to have covered the entire surface of the earth. Sedimentary successions were, thus, easily accounted for whereas igneous rocks, although more complex in origin, were nevertheless regarded as a chemical precipitate from this universal ocean. One presumes that the surface on top of which the flood took place represented the ".... vestige of a beginning ...." which subsequent geologists found so difficult to detect.

By the 19th Century, Hutton's Plutonistic doctrine was widely accepted and geological science had achieved its stable foundation upon which it could subsequently evolve. Much of this century was devoted to outlining the fundamental principles of geology with the broad outlines of Uniformitarianism, as propounded by Charles Lyell (1875), becoming well-entrenched. These ideas, the basic tenet of which stated that

".... the present is the key to the past" represented a great stride forward in geological thinking, so much so that this persuasion is still used as a forcible argument in present times.

The culmination of the 19th Century saw the emergence of another major controversy, in this case directly related to the origin of granite. This clash of ideas, commonly described as the debate between the "injectionists" and the "transformists" was presided over by a German school on the one hand, represented in the main by Rosenbusch of Heidelberg, and a French school on the other. The latter, represented by geologists such as Michel-Levy and Termier, were the "transformists" who believed that all granites were originally sediments that had been metamorphosed to their present state by the interaction of an ichor of somewhat devious origin. The German school were magmatists and, like Hutton, believed that granites had crystallized from an igneous melt derived from the earth's interior and injected to the surface.

Coming at a time when German and French nationalistic fervour undoubtedly penetrated the ranks of academia, it is likely that this debate was fired more by political thoughts than objective scientific reasoning. This fact, coupled with restricted communication and a language barrier meant that the debate was never resolved and that significant advances in knowledge that may have resulted from it, were stinted by a hard-headed approach on both sides (Read, 1957 pages 4-5). As a result, in the early part of the 20th Century, at a time when important work was being carried out on the description and realization of the signficance of the migmatitic terranes of Scandinavia, there were still two contradictory views regarding the origin and formation of granites.

1.3. Early ideas relating to the definition and significance of migmatitic rocks

The original definition and early ideas regarding migmatitic rocks were inextricably linked to the controversy regarding the origin of granites at that time. Without a doubt the pioneer in the field of migmatite geology was J.J. Sederholm who carried out a life-time's work mapping the Precambrian basement of Finland. In 1907, in a publication entitled "On Granite and Gneiss" Sederholm first used and defined the word "migmatite". He stated "Because the mixture of different constituents is the characteristic feature of all these different rocks, I would suggest for them the name migmatites, from μῖγμα, a mixture. This rock group occupies, in a sense, a transitional position between the granites and the crystalline schists of partly sedimentary, partly igneous eruptive origin ....". From this early definition it is clear that Sederholm was, in essence, a transformist and he was to remain so in his later ideas published in the well-known trilogy, "On migmatites and associated Precambrian rocks of southwestern Finland (Sederholm, 1934)". Thus, the earliest definition of migmatite had a clear genetic connotation and no consideration was given to alternate modes of formation.

In later publications Sederholm was to have a strong influence in propagating the transformistic or metasomatic approach to the origin of granite and there is no doubt that this became the prevailing doctrine in Europe during the early part of this century. Although Sederholm believed in a granite "ichor" he also described, in great detail, the effects of palingenesis on the formation of migmatites. In terms of a more modern approach to migmatite terminology, he was, therefore, a proponent of the arteritic origin of migmatites. This view brought him into direct conflict with the Swedish school of thought led by Holmquist. This school had remained neutral in the major transformist-magmatist controversy but maintained that migmatites could be formed by means other than the strictly arteritic approach of Sederholm. Working in the Precambrian of Sweden, Holmquist had recognized migmatites and veined gneisses which he considered to have formed by the internal reorganization of mafic and felsic constituents. This mechanism, now known as segregation or metamorphic differentiation, was not readily accepted initially, but today is considered as an important parameter in the formation of migmatites. Thus, prior to the Second World War, there is no doubt that the "Granite Problem" was biased towards a transformist or a metasomatic approach, particularly in Europe. The numerous textural variations within migmatitic rocks were considered to point strongly in this direction and, as a result, ardent magmatists were few and far between. However, the igneous approach to the granite problem did have its spokesmen, particularly prominent in the form of Niggli in Europe and N.L. Bowen in the United States. After the war, with the onset of experimental petrology, particularly in the U.S.A., the magmatists were to become extremely prolific and the fifties and sixties saw a renewed interest in the granite controversy.

1.4. The contribution of experimental petrology to the granite problem

Stemming from the fact that not all granites have migmatitic and gneissic textures and that many adamellites and granodiorites are massive and exhibit typical igneous textures, it became apparent that such bodies must have been derived from magma or melt. With the advent of experimental petrology came the means of demonstrating how, and from where, a granitc magma could be formed; as a result, once the phase equilibria of minerals in the granite system was understood, the magmatists had a powerful tool to counter the traditional transformist approach.

The modern form of the granite controversy, although debated at many levels, is typified by the arguments between H.H. Read, representing the transformists, and N.L. Bowen representing the magmatist school. The argument was often heated and sometimes assumed personal proportions and the typical views of the disputants are well expressed in two quotations. Bowen is said to have once described Read as ".... an old soak seeking the penitents bench" whereas Read's view of Bowen and the experimental petrologists' viewpoint was that, "At my time in life I do not propose, in Hutton's prophetic words, to .... judge of the great operations of the mineral kingdom from having kindled a fire, and looked into the bottom of a little crucible." Notwithstanding these comments this modern debate saw great strides made, the final outcome of which was the realization that both magmatic and metasomatic granites existed. In fact it had taken over half a century before the words of A.H. Green, who, in 1882 stated, "There are granites and granites, ... some formed in one way and some in another", came to be recognized.

In a sense this modern debate was a victory for the new magmatists who were able to convincingly prove the partial melting and fractional crystallization could result in the formation of granitic magma. The victory was, however, Pyrrhic in that the transformist school could, and still can, point to a number of phenomena that are difficult to explain by the magmatists' approach. Read (1948) points, for example, to the question of the volume of granitic magma that is likely to have been formed by the fractional crystallization of a basic liquid, referring to the Skaergaard complex, with its lack of granitic mesostasis, as a case in point. However, in attempting to refute the magmatists and show that this concept could not have produced the vast volumes of granite now present, Read has overlooked the effects of partial melting, particularly of sediments. Read (1948) has also pointed to the space problem created by the emplacement of enormous volumes of granitic magma and questioned the ability of this magma to structurally readjust, or stope, the overlying country rock. However, the concepts of zone melting and crustal underplating now provide an answer to these once valid objections, at least in part.

1.5. The modern approach to the origin of migmatites and granites

It can safely be said that the modern approach to the petrogenesis of migmatites and granites is entirely different from that of some thirty years ago. Generally speaking the granite petrologist of today will attempt to establish which, of a number of petrogenetic possibilities, is best suited to overall characteristics of the unit in question. This is in contrast to the period of heated, often nationalistic, debate where facts in the field were collected in order to try and fit an, often preconceived, idea on the formation of a granite. It is, therefore, not uncommon to page through modern literature and find descriptions of migmatites that have formed by *in situ* partial melting (von Platen, 1965; Mehnert, 1968), by subsolidus metamorphic differentiation (White, 1966; Hedge, 1972), by metasomatism (King, 1965; Misch, 1968; Viljoen and Viljoen, 1969g) and by the physical emplacement of an externally derived magma (Lowman, 1965; Van Schmus and Anderson, 1977). In addition workers in highly deformed areas have demonstrated that a relationship exists between intensity of deformation and genesis and texture of migmatites (Mackenzie, 1957; Myers, 1978).

However, notwithstanding this objective approach, discrepancies and arguments still remain in the modern literature, albeit the clashes are not as pronounced as they were in the days of the so-called "granite controversy". Many granite petrologists still maintain that the modern approach to granites and migmatites is by no means all-encompassing and have stated that the conclusions derived from experimental data" .... represent an over-simplication and indeed a naive approach to a major aspect of petrogenesis". (King, 1965). This attitude was adopted by King with reference to a study he made on migmatites in the Archaean basement of Zimbabwe where certain of the observed textures could, in his view, only be described as being the result of metasomatism and granitization.

It is interesting to note that a re-examination of the identical migmatite exposures described by King (1965) were recently interpreted as being largely the result of anatexis and assimilation (Condie and Allen, 1980). In all fairness, however, there is no doubt that in the last decade the literature dealing with the petrogenesis of migmatites has seldom, if ever, called upon metasomatism as being the mechanism of formation and the latter process is rarely resorted to in genetic interpretations. This is undoubtedly due to the fact that the processes by which metasomatism is supposed to take place and the origin of the so-called "ichor" is not easily quantified.

In addition to the above case, recent literature on migmatite petrogenesis is often characterized by discrepancies and irregularities in the various approaches adopted. For example, migmatites from the Front Range, Colorado have been ascribed to both sub-solidus metamorphic differentation as well as to an arteritic origin (cf. Hedge, 1972; Lowman, 1965) whilst studies of migmatite genesis in Greenland have been carried out using structural techniques without recourse to the standard geochemical procedures generally used elsewhere (Myers, 1978). However, in view of the complexity of migmatite terranes, it is quite probable that a variety of processes may be applicable to any one area. This fact necessarily places a constraint on the modern objective approach and the tremendously detailed work that is required to carry it out. It is necessary to be aware of the dangers of attempting to interpret entire areas on the basis of a study, the samples for which may only have been taken over a limited outcrop area. Successful interpretations in modern times will, therefore, depend on establishing a balance between regional and detailed studies and hence collaborative work is likely to become increasingly necessary. It will become apparent that the present study has resorted exactly to this collaborative approach in an attempt to understand the regional significance of the granites and related migmatites in the study area.

1.6. The genesis of migmatites and a definition of terms

Recent detailed studies of migmatites generally concur in the view that there are four basic processes whereby these rocks may form (White, 1966; Misch, 1968; Yardley, 1978). These are:-

(i) Igneous injection of magma; this process may result in a variety of migmatitic textures and can occur with respect to any type of country rock, for example, the margins of an intrusive pluton may contain numerous xenoliths giving the outcrop a migmatitic aspect (e.g. the Thorr pluton of Donegal, Pitcher and Berger, 1972).

(ii) Partial melting or anatexis; numerous laboratory melting experiments (von Platen, 1965; Winkler, 1974; Helz, 1976; Drake, 1976) have indicated that rocks of variable composition can melt at geologically feasible temperatures, especially in the presence of H_2O. As a result of these studies, anatectic products can easily be recognized by features such as their minimum-melt compositions in terms of the granite tetrahedron, or the more sodic aspect of plagioclase in the rocks derived therefrom. Examples of migmatites that have formed principally by anatectic processes are described from the Dalradian in Scotland by Ashworth (1976) and from the Zimbabwean Archaean by Condie and Allen (1980).

(iii) Sub-solidus metamorphic differentiation; the formation of numerous migmatitic terranes has recently been attributed to this process, which differs from *(ii)* in that melting, and hence a liquid phase, is not involved. As a result this process is best tested for by considering the equilibration of trace elements between co-existing minerals in each of the differentiated portions of the rock. Examples of migmatities derived by metamorphic differentiation are those of the Palmer region in Australia, (White, 1966); those of the Sinai (Amit and Eyal, 1976); and the Skagit Gneiss of Washington State (Misch, 1968 and Yardley, 1978).

(iv) Metasomatism; this ill-defined process is now generally regarded as having only a limited influence in granite/migmatite petrogenesis (e.g. the minor felspathization seen in xenoliths contained within large granitic bodies) and the process is no longer a plicable to the formation of granite bodies in their entirety. An example where metasomatism was considered to have taken place is described from the complex and nebulous migmatites of the Gwenoro Dam outcrop in the Archaean basement of Zimbabwe, in King (1965). Portions of the similarly complicated Skagit Gneisses of Washington State have also been ascribed to metasomatism by Misch (1968).

Besides the above processes, it is now generally recognized that, in most cases, structural deformation accompanies the genesis of migmatites. Mackenzie (1957) and Myers (1978) have both, for example, emphasized the relationship between intensity of deformation and the development of migmatitic textures and there is little doubt that whichever process of migmatization is operative it will be accompanied, to a variable extent, by stress and strain. Recently, for example, a theory of sub-solidus metamorphic differentiation has been proposed whereby it is envisaged that the development of compositional banding in rocks arises directly from the diffusion of elements responding to a stress-induced pressure gradient (Robin, 1979). In short, it is unlikely that the formation of a migmatitic terrane will result from only one of these complex process, but whereas a single process may be *dominant*, a combination of two, or more, is most likely to have been operative.

Before describing the individual migmatite outcrops examined in this study it is necessary to define some of the terms in the context that they are used in this thesis. Many of the terms used are broadly in accordance with the definitions outlined by Mehnert (1968).

<u>Migmatite</u> - is used in the broadest possible sense to mean a mixed rock or outcrop comprising two or more distinct components.

<u>Anatectite</u> - any rock that has formed by the partial or total melting of a pre-existing rock; dominantly quartzo-felspathic in the descriptions that follow.

<u>Gneiss</u> - usually a granitic *(sensu lato)* rock with a parallel structure or texture such as foliation, lineation or schistosity.

<u>Agmatite</u> - migmatite with brecciated or "broken apart" texture.

<u>Schlieren</u> - irregular streaks of mafic material resulting from an advanced stage of assimilation.

<u>Restite/ Residue</u> - that portion of a rock that is not melted during anatectic processes.

<u>Mesostasis</u> - the final differentiated liquid that usually accumulates in the spaces between earlier-formed crystals, but may appear as a discrete vein as the result of filter-pressing.

Leucosome - leucocratic veins that form during the process of migmatization; may be anatectites.

Assimilation/ Contamination/ Hybridization - the process whereby the composition and appearance of a pre-existing rock type (usually mafic in the descriptions that follow) is digested and altered by a later, intrusive magma of different composition (usually felsic).

Arteritic - refers to the process where migmatites have formed by the injection of magma into a pre-existing rock type.

Venitic - refers to the process where migmatites have formed in situ, by either sub-solidus means or partial melting.

Metamorphic Differentiation - refers to the formation and growth of bands of differing bulk composition from an originally homogeneous rock in the sub-solidus state.

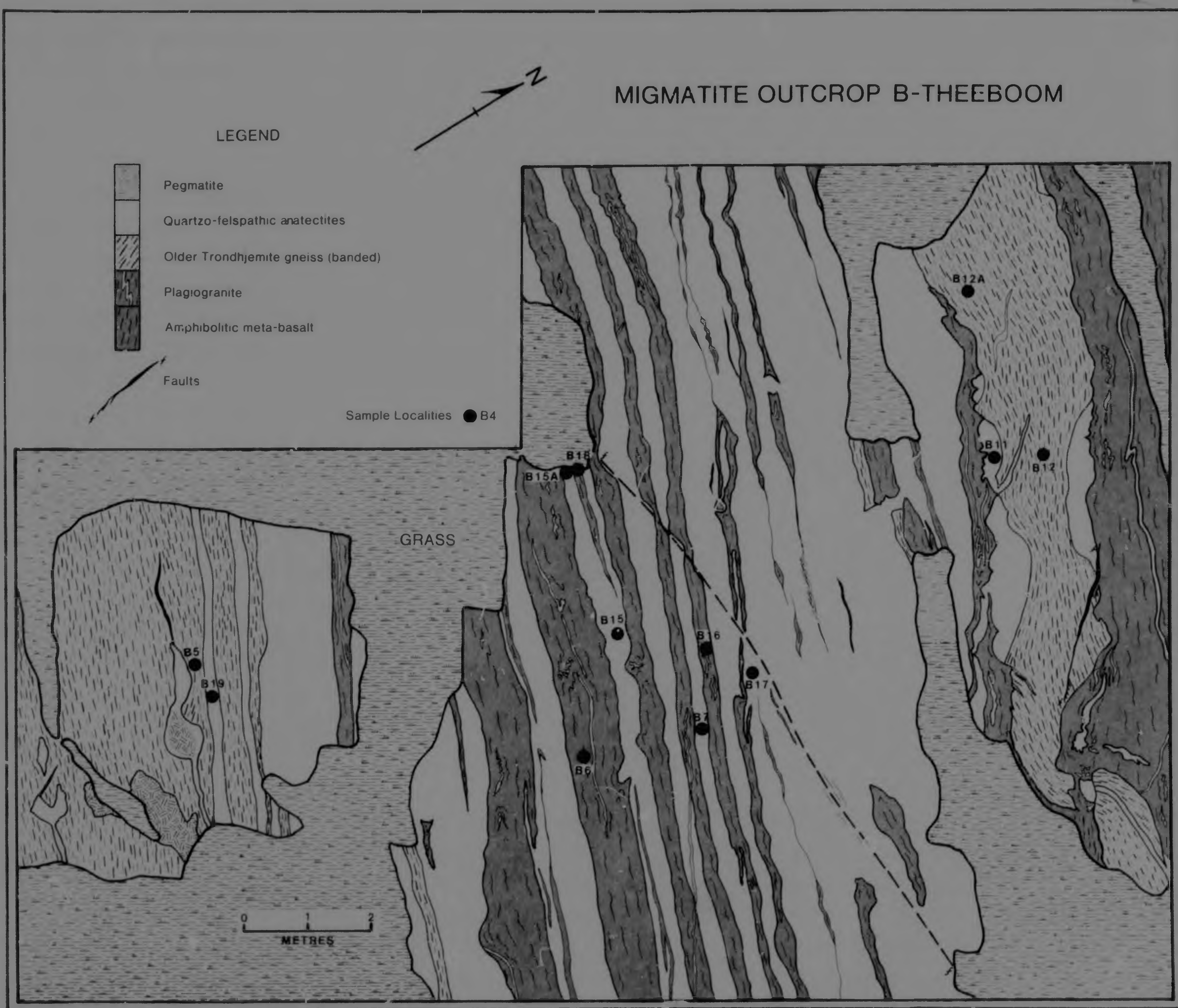
Palingenesis - normally refers to the emplacement of dykes which have locally remelted their host rocks so that the dykes themselves appear to have been intruded by a remobilized magma.

Metasomatism - alteration of a pre-existing rock by the introduction of material in solution or by diffusion of migrating ions.

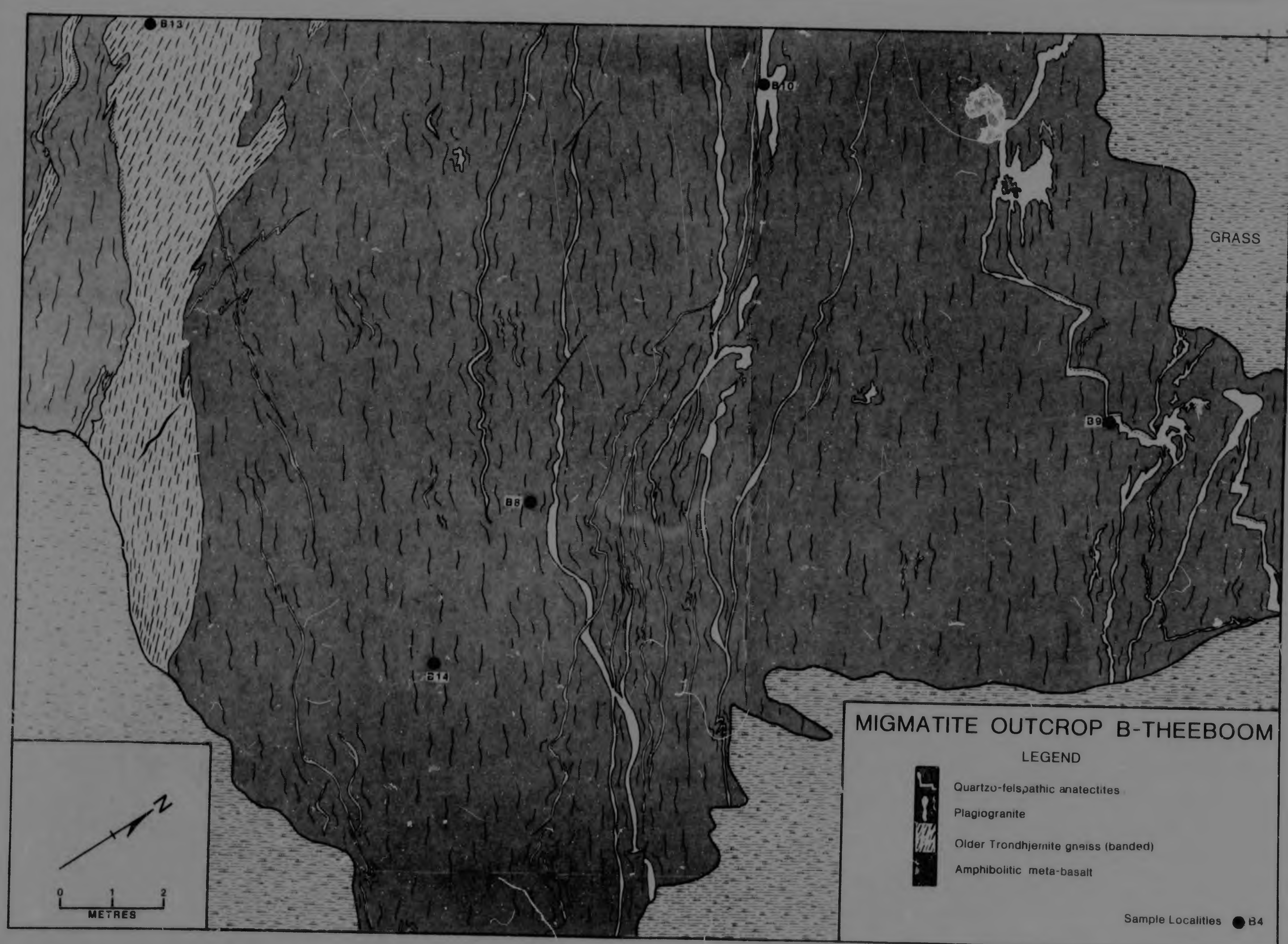
Meta - this prefix is added to the description of a rock type if its composition is still recognizable in terms of that envisaged for the original rock; its texture, appearance and mineralogical constitutents may have changed, however, because of metamorphism or recrystallization (e.g. metabasalt, metatuff).

Tonalite/ Trondhjemite - these terms are used synonomously in the course of this thesis; where a chemical analysis has been carried out, however, tonalite refers to the rock


MIGMATITE OUTCROP B-THEEBOOM
Aplitic veins
Younger Trondhjemite gneiss
Pegmatite
Quartzo-felspathic anatectites
Amphibolitic meta-basalt
Older Trondhjemite gneiss (banded)
N
Fractures
Sample Localities B4
0 1 2 metres
B21
B22
B23
B20
B24
Mafic selvedge

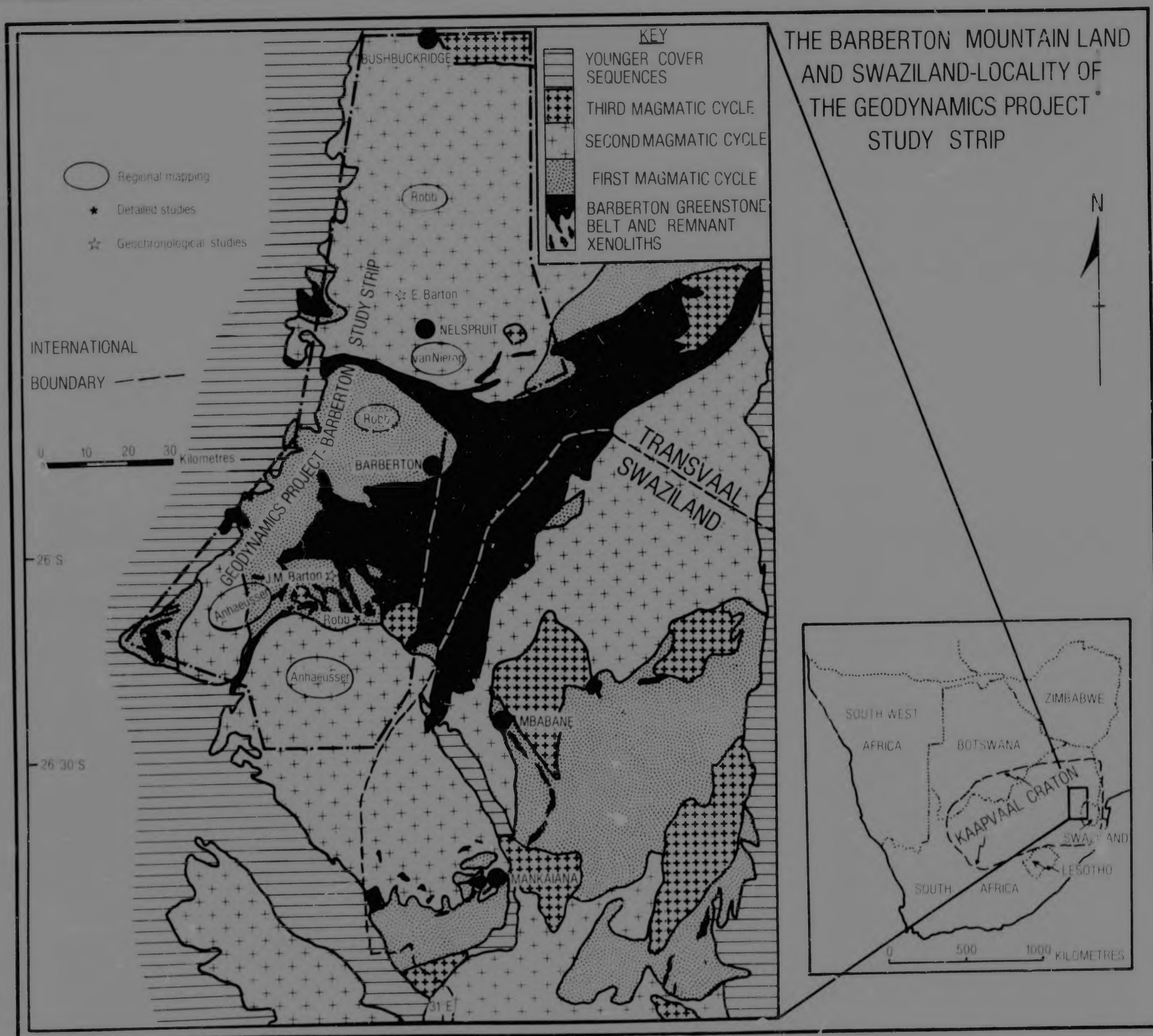


MIGMATITE OUTCROP B-THEEBOOM
N
LEGEND
Pegmatite
Quartzo-felspathic anatectites
Older Trondhjemite gneiss (banded)
Plagiogranite
Amphibolitic meta-basalt
Faults
Sample Localities B4
GRASS
B5
B19
B18
B15A
B15
B16
B17
B7
B6
B12A
B11
B12
0
1
2
METRES


B13
B10
GRASS
B9
B8
B14
0
1
2
METRES
MIGMATITE OUTCROP B-THEEBOOM
LEGEND
Quartzo-felspathic anatectites
Plagiogranite
Older Trondhjemite gneiss (banded)
Amphibolitic meta-basalt
Sample Localities B4

2
3
1
A8
A4
A6
A2
A1
A7
GRASS
GRASS
LEGEND
Quartz veinlets fractures
Aplitic veinlet
Quartz-diorite dyke
Trondhjemite Gneiss
Quartz-felspar porphyry
Plagiogranite
Amphibolitic meta-basalt
Sample Localities ● A8
N
0 1 2
METRES
MIGMATITE OUTCROP A-BOEKENHOUTRAND

REGIONAL GEOLOGY OF THE GRANITE-GREENSTONE TERRANE
SOUTHWEST OF THE BARBERTON GREENSTONE BELT
LEGEND
Proterozoic Cover
Later syenitic, granodioritic, adamellitic plutons or batholiths
Tonalite / Trondhjemite Gneisses
Migmatites
Kromberg Formation
Hooggenoeg Formation
Geluk Subgroup
Onverwacht Group
Komati Formation
Theespruit Formation
Sandspruit Formation
Tjakastad Subgroup
Undifferentiated (probably Tjakastad Subgroup)
E Outcrop studied in detail
0 1 2 km
N
NELSHOOGTE PLUTON
NELSHOOGTE SCHIST BELT
BARBERTON GREENSTONE BELT
MIDDLE MARKER UNIT
STOLZBURG PLUTON
THEESPRUIT PLUTON
DOORNHOEK PLUTON
HEERENVEEN BATHOLITH
BOESMANSKOP PLUTON
MPULUZI BATHOLITH
DALMEIN PLUTON
ROOIHOOGTE
BATAVIA
THEEBOOM
WEERGEVONDEN
BRANDYBAL
Komati River
Theespruit River
To Badplaas
To Carolina
To Lochiel
To Tjakastad
To Msauli Mine
A
B
C
D
E
F
G
H
I
J
Barberton
0 50 Km
A–J



THE BARBERTON MOUNTAIN LAND AND SWAZILAND-LOCALITY OF THE GEODYNAMICS PROJECT STUDY STRIP
KEY
YOUNGER COVER SEQUENCES
THIRD MAGMATIC CYCLE
SECOND MAGMATIC CYCLE
FIRST MAGMATIC CYCLE
BARBERTON GREENSTONE BELT AND REMNANT XENOLITHS
Regional mapping
Detailed studies
Geochronological studies
INTERNATIONAL BOUNDARY
0 10 20 30 Kilometres
BUSHBUCKRIDGE
NELSPRUIT
BARBERTON
MBABANE
MANKAIANA
GEODYNAMICS PROJECT - BARBERTON STUDY STRIP
TRANSVAAL
SWAZILAND
Robb
E. Barton
van Niekerk
J.M. Barton
Anhaeusser
26°S
26°30'S
31°E
N
SOUTH WEST AFRICA
BOTSWANA
ZIMBABWE
KAAPVAAL CRATON
LESOTHO
SOUTH AFRICA
0 500 1000 KILOMETRES

of relevant composition that has SiO_2 generally less than 68%, whereas trondhjemite is used for the same rock but with $SiO_2 > 68\%$. A more rigid definition of these two terms is provided in Chapter 6.

2. MIGMATITES TO THE NORTH AND SOUTHWEST OF THE BARBERTON GREENSTONE BELT - SYSTEMATIC DESCRIPTION

A total of ten geographically distinct outcrops were selected for detailed mapping and interpretation during this study. Each of the ten outcrops is allocated a letter (i.e. A to J) but is also described in the text, by the name of the farm on which the exposures occur. The geological features in each of the migmatite outcrops studied is systematically described in the sections that follow; in addition the geochemical characterization of the numerous and varied components that make up these rocks is provided. It is necessary to stress that this chapter provides only the descriptive details regarding the various migmatite exposures and that all petrogenetic considerations regarding the various components and processes that make up these rocks are presented in Chapter 3. Accompanying each description is a map, or series of maps, which illustrates as clearly as possible, the physical appearance of the migmatite as well as the geological relationships between the individual components of the outcrop. All of these maps were originally drawn at a scale of 1:50 but have subsequently been reduced for presentation.

2.1. The location of migmatite outcrops in relation to the regional geology of the area

The locality of each of the ten migmatite outcrops described in the following sections is shown in relation to the regional geology of the area in Figure 2. Nine of the ten outcrops (i.e. A-C, E-J in Figure 2) occur in the area southwest of the Barberton greenstone belt and are intimately associated with tonalite - trondhjemite gneisses and shredded remnants of the main greenstone belt succession (Figure 2). The tenth outcrop (D) occurs to the north of the Barberton greenstone belt and its locality is only approximately located in the inset diagram of Figure 2. The migmatites and gneisses at this locality differ markedly from the

Figure 5 : The geological setting of migmatite outcrops described in the text, in relation to the principal lithological units occurring in the southwest portion of the Barberton greenstone belt. Most of the migmatite outcrops are spatially related to greenstone remnants that are correlatable with the lower successions in the Onverwacht Group (i.e. the Sandspruit, Theespruit and Komati formations of the Tjakastad Subgroup). None of the outcrops is unequivocally correlatable with the upper formations of the Onverwacht Group (which overlie the prominent chemical sedimentary unit known as the Middle Marker) which consists of the Hooggenoeg, Kromberg and Swartkoppie formations of the Geluk Subgroup. Note that the uppermost Swartkoppie Formation does not appear on this map. Geological details are taken from Viljoen and Viljoen (1969c, d, e) and Anhueusser and Robb (1980a).

remainder of the outcrops in that they are located on the fringes of the large, dominantly potash-rich Nelspruit batholith, detailed descriptions of which are found in Robb (1977; 1978; 1979) and Anhaeusser and Robb (1980b). These migmatites are not, therefore, related to tonalites-trondhjemitic gneisses but are more potassic in nature; the description of this single exposure is included in the present study for comparative purposes.

In Figure 2, the stratigraphic breakdown of the Onverwacht Group (with the exception of the uppermost Swartkoppie Formation which does not appear in the map area) in the southwestern portion of the Barberton greenstone belt is shown. In addition, an attempt has been made to correlate certain of the greenstone remnants occurring in the granitic terrane with lithologically similar formations in the greenstone belt itself. This correlation is possible where detached greenstone remnants are close enough to the greenstone belt as to make a matching of lithologies unequivocal. Also where a distinctive lithological assemblage is preserved such as the felsic schists characteristic of parts of the Theespruit Formation (Viljoen and Viljoen, 1969c), then a correlation can be made with a fair degree of certainty. A case in point refers to the greenstone remnants occurring immediately to the south of the Boesmanskop pluton (Figure 2) in the Weergevonden area, where the presence of felsic schists and tuffaceous units (shown in black) suggests a correlation with the Theespruit Formation (Anhaeusser, 1980). It should be noted, however, that most of the greenstone xenoliths in the study area show only broad lithological similarities with the Tjakastad Subgroup and, therefore, can only be broadly correlated with the latter (Figure 2).

The distribution of studied migmatite exposures in Figure 2 suggests that most are related to greenstone remnants that can only be broadly correlated with the Tjakastad Subgroup and not with a specific formation in the latter. Possible exceptions occur in the case of outcrop C where the characteristics described later suggest that certain of the migmatitic components have affinities with the Theespruit Formation. Also outcrop J is located in a position that is close to the contact zone between trondhjemite gneisses and the lowermost unit of the Geluk Subgroup, namely the Hooggenoeg Formation. As suggested in the relevant description, this particular geological setting is of consequence in interpreting the migmatite outcrops in this area.

It is particularly instructive, in Figure 2, to comment on the distribution of migmatitic rocks (and the subsequent location of the outcrops described in the following sections) in terms of the regional geology of the area. It is seen that migmatites are developed in areas that are intimately associated with, or marginal to, the numerous, scattered greenstone remnants in the region (Anhaeusser and Robb, 1980a). Migmatitic textures are not randomly distributed with respect to the tonalite-trondhjemite plutons and are generally, but not always, marginal to these relatively homogeneous bodies. This distribution has two possible implications; firstly, that the migmatites *in toto*, represent the remnants of an early sialic basement on top of which the greenstone assemblages were deposited and through which the younger, homogeneous tonalite and trondhjemite plutons were emplaced, or secondly, that migmatitic rocks were developed where ensimatic greenstones have been intruded by, and have interacted with, wide-spread younger sialic material. The interpretation of these, often complex, migmatitic rocks and a selection between these dichotomous viewpoints is the prime function of the first part of this thesis. Successful resolution of this objective must certainly contribute towards a better understanding of the geological evolution of the study area.

The sections that follow present detailed geological descriptions of the ten migmatite outcrops mentioned above. The individual migmatite outcrops are described in the following sequence:-

(i) Migmatite outcrop A - where the contact zone between amphibolitic meta-basalts of the Barberton greenstone belt and an intrusive trondhjemite gneiss is exposed.

(ii) Migmatite outcrops B, E and I - where complex relationships between amphibolites, trondhjemite gneisses and quartzo-felspathic anatectites are preserved.

(iii) Migmatite outcrops C and F - where tonalite and trondhjemite gneisses interact with a variety of felsic and quartz-dioritic components.

(iv) Migmatite outcrops G, H and J - where syn-tectonic dykes of amphibolitic material interact with trondhjemite gneisses and quartzo-felspathic anatectites.

(v) Migmatite outcrop D - where amphibolitic xenoliths are migmatized and assimilated by the emplacement of potash-rich magma associated with the Nelspruit batholith to the north of the Barberton greenstone belt.

3. MIGMATITE OUTCROP A - BOEKENHOUTRAND

3.1. Geological description

The Boekenhoutrand outcrop occurs at the contact between the southwestern extremity of the Barberton greenstone belt, where rocks of the Theespruit Formation crop out, and intrusive trondhjemite gneisses of the Stolzberg pluton (Figure 2). The mapped outcrop shown in Figure 3 actually straddles the contact described above; it is evident, however, that the outcrop illustrated here is not "migmatitic" in the commonly accepted sense of the word but nevertheless does contain numerous distinct components and it is, therefore, described in this context. The outcrop was selected for study as it represents a well-exposed site where the contact relationships between granite (trondhjemite gneiss) and greenstone (amphibolitic meta-basalt) are well-preserved.

The trondhjemite gneiss in the vicinity of the granite/greenstone contact is moderately foliated with a distinct strengthening of a planar fabric as the contact is approached (Figure 3). A lineation is not markedly evident in the outcrop. The gneiss is also characterized by numerous disorientated fractures which have been in-filled with "sweat" quartz veinlets (Plate 1A). These fractures appear to be a function of stresses generated at the pluton-edge as they are not pervasive throughout the body. The quartz fill appears to have formed in the fractures themselves and in many cases it is possible to follow a quartz veinlet laterally into a fracture. Certain portions of the outcrop appear to have a preferred fracture orientation which is generally perpendicular to the granite-greenstone contact. Some of the fractures post-date others and there are also two generations of quartz veinlet (Figure 3). In thin section the mineral components of the trondhjemite gneiss reflect the severe stresses that have obviously caused the intense fracture pattern at the outcrop, with quartz being recrystallized and showing intense undulose extinction and plagioclase twin-laths being severely dislocated.

Figure 3 : Detailed map of migmatite outcrop A on the farm Boekenhoutrand 732 JT. The outcrop exposes some of the details that are typical of the contact zone between a large gneiss pluton (i.e. the Stolzburg pluton) and the Barberton greenstone belt. The locality of the outcrop is shown in Figure 2.

The trondhjemite gneiss has been intruded by two distinct phases; the first of these is a medium-fine grained dyke-like body of well-foliated quartz-diorite. This body is clearly syn-tectonic and judging by the nature of its contact with the trondhjemite (Figure 3), may have been emplaced contemporaneously with respect to the latter. The second phase is a fine-grained aplite, with no apparent foliation and which intrudes the trondhjemite a few metres away from the granite-greenstone contact.

The amphibolitic meta-basalt which constitutes the greenstone component of the outcrop consists dominantly of greenish hornblende together with a lesser amount of quartz. Minor plagioclase and opaque oxides also occur. The rock is characterized by a poorly developed fabric which appears obliquely orientated to the trondhjemite-greenstone contact. The amphibolite has been intruded by numerous quartzo-felspathic veinlets (Figure 3) and two distinct leucocratic components occur. The first is a small, metre-wide vein of foliated quartz-felspar porphyry which is emplaced parallel to the fabric in the amphibolite. This rock consists of large phenocrysts of plagioclase and quartz set in a groundmass of the same minerals. Small amounts of muscovite and biotite also occur, the latter exhibiting a strongly preferred orientation. Also intrusive into the amphibolite, and cutting across the fabric are at least two phases of plagiogranitic veinlets. These veinlets consist dominantly of plagioclase and quartz together with traces of sphene, apatite, muscovite and opaque oxides. Both the quartz-felspar porphyry and the plagiogranitic veinlets bear no resemblance to the adjacent trondhjemite gneiss so that there is no direct evidence for the magmatic intrusion of the latter into the greenstones.

The latter observation, together with the description of the numerous quartz-filled fractures mentioned above, presents a clue as to the style of emplacement of trondhjemite into greenstone at this particular outcrop. Although not necessarily applicable to the entire edge of the Stolzburg pluton, the above evidence suggests that the latter was rigidly emplaced into its present position with respect to the adjacent greenstones. If this mechanism is correct, one would expect no evidence for the magmatic intrusion of trondhjemitic magma into the amphibolites so that it is unlikely that the primary relationships between the two units are preserved.

Further examples, as well as the significance, of the structural emplacement of tonalite and trondhjemite plutons in the Barberton region have been alluded to in subsequent sections of this thesis (i.e. Chapters 4, 5, 6 and 7).

3.2. Geochemistry

The following section briefly describes the chemical attributes of the various rock types described above. It should be stressed once more that this section, as well as the equivalent sections in the descriptions of the other migmatite outcrops, is purely taxonomic in character; the detailed petrogenetic considerations of these rock types are presented in Chapter 3.

The trondhjemitic gneisses at the Boekenhoutrand outcrop are characterized by $SiO_2 > 70\%$ and $K_2O/Na_2O < 0{,}5$ (Table 1); these characteristics conform in all respects to the trondhjemite definition provided in Chapter 6. The rare-earth element (REE) content of the trondhjemite gneiss is typical of other Archaean trondhjemites analysed from various regions and is characterized by light rare-earth element (LREE) enrichment, depleted heavy rare-earth elements (HREE) and no significant Eu anomaly (Table 1; Figure 20).

The quartz-diorite dyke which intrudes the trondhjemite gneiss (Figure 3) has a similar composition to the latter, but is slightly depleted in SiO_2 and enriched in $Fe_2O_3^* + MgO$ (†). The rock is also enriched in the LREE with respect to the trondhjemite but contains very similar Rb, Sr and Ba contents. The quartz-diorite dykes are referred to by this term mainly for the sake of distinguishing them from their trondhjemitic hosts(*), the intimate, syn-tectonic association of these two rock types and their similar compositions suggest that they may be genetically related.

The aplite vein which also intrudes the trondhjemite gneiss in Figure 3 has a high SiO_2 content but differs from the latter in having a higher K_2O/Na_2O ratio ([illegible] 1) as well as higher Rb and lower Sr contents (Table 1). The "sweat" quartz veinlets have also been analysed and are characterized by $SiO_2 > 99\%$ with a small amount of $Fe_2O_3^*$ being attributed to iron-staining (Table 1).

Footnote (†): The symbol $Fe_2O_3^*$ refers to the total iron content of the rock analysed as Fe_2O_3; all iron analyses carried out by the writer in this thesis are referred to in the above form.

(*): In a strict sense the quartz-diorite dykes referred to in this thesis may be tonalitic or trondhjemitic in composition.

TABLE 1

CHEMICAL ANALYSES OF COMPONENTS FROM
MIGMATITE OUTCROP A - FARM BOEKENHOUTRAND 722JT

		1	2	3	4	5	6	7	8	9
		A1	A3	A2	A7	A8	A5	A9	A4	A6
wt.%	SiO_2	71,74	73,80	71,47	99,20	76,19	70,99	78,26	52,17	51,70
	TiO_2	0,14	0,15	0,21	0,01	0,06	0,19	0,05	0,68	0,67
	Al_2O_3	15,32	14,40	15,16	0,32	12,99	15,67	13,48	15,38	14,10
	Fe_2O_3*	0,69	1,27	1,26	0,46	0,71	1,60	0,45	12,01	11,30
	MnO	0,01	0,02	0,01	<0,01	<0,01	<0,01	0,01	0,18	0,16
	MgO	0,12	0,60	0,41	0,32	0,36	0,64	0,13	8,34	7,70
	CaO	1,60	1,10	1,97	0,04	0,35	1,76	0,91	9,56	9,90
	Na_2O	5,78	6,30	5,95	<0,01	4,68	6,19	7,34	1,12	2,80
	K_2O	2,60	1,82	1,85	0,07	3,54	0,87	0,13	0,48	0,25
	P_2O_5	0,07	0,04	0,09	0,03	0,03	0,09	0,02	0,08	0,12
	L.O.I.	0,61	0,83	0,79	0,13	0,33	0,92	0,41	1,18	0,55
	TOTALS	98,68	100,33	99,17	100,58	99,51	98,92	101,19	101,18	99,25
ppm	Rb	61	53	48	<1	95	22	<1	17	5
	Sr	553	600	610	4	39	602	89	353	150
	Ba	8	770	453	<1	<1	6	52	133	100
	La	8,9	-	13,9	-	-	15,8	6,4	4,0	-
	Ce	17,1	-	23,7	-	-	30,5	15,0	9,6	-
	Nd	-	-	8,3	-	-	10,3	-	-	-
	Sm	0,91	-	1,46	-	-	1,86	0,80	1,49	-
	Eu	0,28	-	0,48	-	-	0,57	0,06	0,77	-
	Tb	0,30	-	0,20	-	-	0,23	0,10	0,64	-
	Yb	0,30	-	0,64	-	-	0,56	0,62	1,33	-
	Lu	0,02	-	0,05	-	-	0,06	0,06	0,28	-

(Analysts: Columns 1, 3-8 - L.J. Robb
Columns 2 and 9 - Bergström and Bakker, Johannesburg
Fe_2O_3* - Total iron as Fe_2O_3)

Columns 1 - 2 - Trondhjemite gneiss
3 - Quartz - diorite dyke
4 - "Sweat" quartz veinlet
5 - Aplitic vein
6 - Quartz-felspar porphyry dykelet
7 - Plagiogranite vein
8-9 - Amphibolitic meta-basalt

Sample localities shown in Figure 3

The amphibolitic meta-basalts at Boekenhoutrand have a composition that is similar to meta-tholeiites previously analysed from the Barberton greenstone belt (see Chapter 3). These meta-tholeiites are typified by $CaO/Al_2O_3 < 1$ and MgO contents between 7-8%. They have flattish REE traces when plotted on a chondrite normalized diagram but with total rare-earth element contents (ΣREE) somewhat higher than those characteristic of basaltic komatiites (Figure 33).

The quartz-felspar porphyry vein that intrudes the amphibolite has a composition that is broadly similar to that of the adjacent trondhjemite gneisses (Table 1). However, the K_2O/Na_2O ratio is slightly lower and the LREE content slightly enriched with respect to the latter, so that the two are unlikely to be related, particularly in view of their totally different textures. The plagiogranitic veins are characterized by an unusual chemistry with a high SiO_2 content ($\approx$ 78%), low Fe_2O_3* + MgO content and K_2O/Na_2O ratio, as well as a depleted ΣREE content (Table 1). Such rock types have not previously been described in the Barberton area and are considered again in Chapter 3.

3.3. Summary statement

The Boekenhoutrand exposure illustrates in detail the nature of the contact between the Stolzburg pluton and Barberton greenstone belt. A trondhemite gneiss intrudes amphibolitic meta-basalts of tholeiitic bulk composition, the latter being correlated with the Theespruit Formation. No evidence for the magmatic intrusion of gneiss protoliths into the adjacent greenstones is present at this exposure, suggesting that the Stolzburg pluton as a whole may have been structurally emplaced into its present position. The outcrop also comprises dykes and veins of quartz-dioritic, aplitic, plagiogranitic and quartz-felspar porphyry material.

4. MIGMATITE OUTCROP B - THEEBOOM

4.1. Geological description

The Theeboom outcrop is located along a well-exposed river-section that cuts across a linear amphibolitic remnant some 4 km southwest

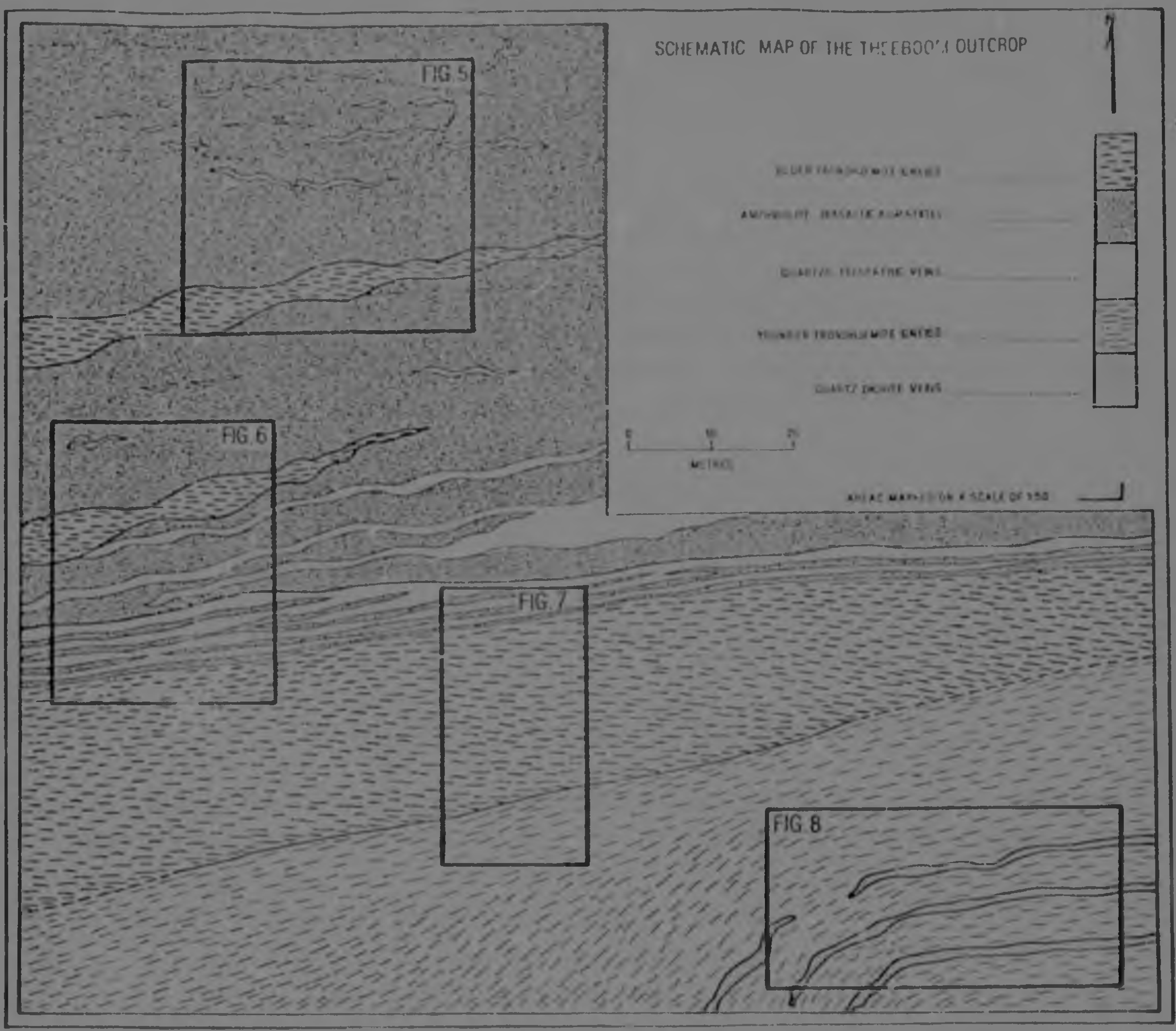


Figure 4 : *Schematic map showing the distribution of the principal components of migmatite outcrop B on the farm Theeboom 729 JT. Also shown are the relative positions of the four mapped sheets presented in Figures 5, 6, 7 and 8.*

of the Barberton greenstone belt (Figure 2). The outcrop was selected for mapping as it contains extremely well-preserved relationships between a greenstone remnant and enveloping trondhjemite gneisses. Four separate sections from this exposure were mapped in detail and these are presented in Figures 5, 6, 7 and 8 respectively. The relationships between the four mapped sections are illustrated in a schematic map of the Theeboom outcrop which also shows the principal geological components at the site (Figure 4). The four mapped sections are seen to progress separately from the centre of the amphibolitic unit (Figure 5) to the contact zone between the latter and an older banded trondhjemite gneiss unit (Figure 6) and then to the contact between the older gneiss and a younger trondhjemite phase (Figure 7). The fourth section (Figure 8) illustrates the relationship between the younger trondhjemite gneiss and intrusive quartz-diorite dykes. Each of the mapped sections are described consecutively in the following discussion.

4.1.1. *Theeboom outcrop - Figure 5*

This section of the outcrop consists dominantly of a black, well-foliated amphibolitic meta-basalt. In thin-section this rock is seen to contain approximately equal amounts of hornblende and clinopyroxene although in most samples the former is more abundant. The compositions of co-existing hornblende and clinopyroxene for an amphibolite at this outcrop are discussed in Chapter 4 and presented in Table 26. The clinopyroxene component of these meta-basalts does not appear to be primary, being markedly poikiloblastic and containing inclusions of quartz and minor plagioclase. The amphibolite unit has been intruded by at least two phases of quartzo-felspathic veins (Figure 5 and Plate 1B, 1C and 1D); the earlier phases, termed plagiogranites, are generally conformable with the fabric in the amphibolites and have been boudinaged and attenuated together with the latter (Plate 1D). These veins have also been subjected to a mild phase of open folding that has resulted in a compression of boudins and a crenulation of the original fabric (Plate 1C). The second phase of veining, (the quartzo-felspathic anatectites in Figure 5) clearly truncate earlier veins as well as the fabric in the amphibolite. The anatectites commonly contain a coarser, pegmatitic margin (Plate 1B) which appears to have formed as the result of localized marginal concentrations of volatiles and a subsequent depression of the solidus temperature in these areas (see light stipple in the vicinity of sample B9, Figure 5).

Figure 5 : Detailed map of a portion of migmatite outcrop B on the farm Theeboom [illegible]. The map illustrates the complex nature of quartzo-feldspathic veining in amphibolitic meta-basalts at the outcrop. The relative position of this section of the outcrop in relation to the other sections shown in Figures 6, 7 and 8, is demonstrated in Figure 4. The regional locality of the Theeboom outcrop is shown in Figure 1.

In addition to the two phases of quartzo-felspathic veining, the amphibolite envelops a large boudin of strongly foliated, banded trondhjemite gneiss. The relationship of this lens of gneiss to the amphibolite is enigmatic as the boudinaging has been responsible for disconformities between the fabric in the gneiss and the enveloping amphibolite. A similar relationship is described in more detail in the following section. The gneiss, however, can be described as being syntectonic with respect to the total strain history of the outcrop and is also characterized by a distinct compositional banding.

4.1.2. Theeboom outcrop - Figure 6

This section reveals a well-preserved contact zone between the amphibolitic meta-basalt on the one hand and a strongly-foliated, banded trondhjemite gneiss, identical to the gneiss boudin described above, on the other. The zone is complicated by the lit-par-lit intrusion of a series of parallel anatectic veins that obscure, to a large extent, the primary relationship between banded gneiss and amphibolite (Figure 6 and Plate 1E). In one part of the outcrop, however, a boudinaged lens of trondhjemite gneiss abuts directly against amphibolite, providing an opportunity for direct interpretation of the relative ages of these two units. As seen in Figure 6 the foliation in the banded gneiss unit is abruptly truncated by the amphibolite in a number of places, suggesting that the latter post-dates the trondhjemite (Plates 1F and 2A). However, because of the obvious deformation prevalent in the outcrop this interpretation needs to be carefully assessed in terms of two possibilities:-

(a) In certain places where the trondhjemite gneissocity is truncated by the amphibolite, the former is curved in towards the gneiss-amphibolite contact (Plate 2C), a phenomenon which suggests that boudinaging may have had a rotational aspect such that the trondhjemite gneiss itself represents an incipient "lozenge-shaped boudin" (Rast, 1956; Charlesworth and Evans, 1962). The formation of these boudins is schematically illustrated in Figure 9 where rotation of the boudinaged layer is seen to be caused by an orientation of the maximum principal stress that is oblique to the layering under consideration. It is clear from this diagram that the truncation

Figure 6 : *Detailed map of a portion of migmatite outcrop B on the farm Theeboom 729 JT. The map illustrates the complex relationships between banded trondhjemite gneiss, quartzo-felspathic anatectic material and amphibolitic meta-basalt at the outcrop.*

of a foliation in a "necked" rock may be due to features similar to this (W.M. Schwerdtner, personal communication) and need not necessarily reflect a primary discordancy between any two rock units.

(b) In other places, however, discrete compositional bands (probably of metamorphic origin) in the trondhjemite gneiss are themselves truncated by the amphibolite (Plate 2A). This may be more significant than the mere truncation of foliation as the development of a gneissocity in a more competent layer may have actually occurred during the boudinaging event. With respect to the truncation of compositional layering, however, this feature may be preserving a primary relationship that has been maintained in spite of the overall concordancy now existing between the two units. Short lengths of discordant contact such as these, are often the only evidence that exists in highly deformed terranes for the presence of dyke-like intrusives (Dearnley and Dunning, 1968).

In the light of these arguments, the interpretation placed on the relative ages of the banded trondhjemite gneiss and the amphibolite at this outcrop must remain equivocal. As will be shown in a following section, the composition of the amphibolite in question here is komatiitic and the outcrop as a whole, therefore, becomes particularly important in view of the fact that it represents the sole example in the Barberton region of where a basaltic komatiite has a tentatively intrusive character. Depending on the choice of interpretation, the Theeboom outcrop may provide evidence for the existence of remnants of ancient sialic material that pre-date amphibolitic meta-basalts that, in terms of their composition at least, are correlatable with the lower Onverwacht Group. Unfortunately, as seen in Figure 6, the trondhjemite/amphibolite contact is largely obscured by a series of linear, parallel anatectic veins that intrude both units and, as such a lengthy exposure of the two key rock-types does not occur.

The anatectic veins that intrude both amphibolite and trondhjemite, form a spectacular ser[illegible] parallel lit-par-lit intrusives, particularly where they intrude the [illegible] (Figure 6). The veins are white and contain few, if any mafic materials; a pronounced fabric is nevertheless visible in the rock, mainly in the form of elongated aggregates of quartz. The anatectic veins in Figure 6 consist dominantly of quartz, K-felspar (microcline) and plagioclase in approximately equal proportions (see Plate 6A), together with small amounts of secondary muscovite/sericite, small clusters of radial sillimanite and minor epidote. The rock is mineralogically heterogeneous in thin section containing irregular zones which are preferentially enriched either in plagioclase or microcline; this distinction is not evident in hand-specimen. The anatectic veins differ substantially from the trondhjemite gneisses which they intrude, the latter consisting dominantly of plagioclase and quartz with lesser amounts of biotite (5-10%) and only minor K-felspar (1-5%). The anatectic veins are considered to represent the partial melt products of a trondhjemite gneiss and the petrogenesis of these rocks is considered in detail in Chapter 3.

4.1.3. *Theeboom Outcrop - Figure 7*

This section of the Theeboom outcrop illustrates the transition from the broad contact zone described above, into a younger, homogeneous, trondhjemite gneiss phase that intrudes both the older banded gneiss unit and the amphibolite (Figure 7). The contact zone shown in Figure 6 is represented again in Figure 7 as a parallel series of anatectic veins intruded, in a lit-par-lit fashion, into both the amphibolite and the banded gneiss. It is interesting to note that in this zone a small lens of older trondhjemite gneiss appears as a xenolith that is largely enveloped by amphibolite and to a lesser extent, the anatectite. This may be construed as evidence in support for the trondhjemite pre-dating the amphibolite. The banded trondhjemite gneiss consists here of a number of quartzo-felspathic and pegmatoid veins which have intruded parallel to the fabric in the gneiss. These quartzo-felspathic veins (shown as aplites in Figure 7) are similar to the anatectites described above but contain less microcline and may contain small amounts of biotite. It is apparent that a number of discrete quartzo-felspathic intrusions have occurred during the development of this complex outcrop (see later). As the contact between the younger and older gneiss phases is approached, the latter becomes increasingly banded with the strongest development of these leucocratic segregations at the contact itself (Plate 2D). The division between the older and younger gneissic units is extremely well-defined and demarcated by a mafic selvedge within the former unit. As

Figure 7 : Detailed map of a portion of migmatite outcrop B on the farm Duelboom 789 JT. The map illustrates the transition from amphibolitic meta-basalt through an older, banded trondhjemite gneiss phase into an intrusive younger trondhjemite gneiss. The southern portion of the map shows a clearly defined contact where compositional banding in the older gneiss is truncated by the younger trondhjemite phase. The asterisk marks the site of what appears to be a small xenolith of older gneiss partially enveloped by amphibolitic meta-basalt (see text).

seen in Figure 7 and Plate 2D, the younger, homogeneous trondhjemite gneiss truncates both the compositional banding and the foliation in the older unit and itself contains no such banding and a much weaker foliation.

A realistic explanation of the compositional banding in the older trondhjemite gneiss is difficult in terms of the relationships present at the exposure. In view of the increasing frequency with which banding occurs towards the contact of the two units, it is possible that the latter may have been caused by a thermal effect emanating from the younger gneiss. However, the banding is, itself, truncated by the younger gneiss and appears to pre-date it. It is more likely that this segregation occurred in response to stress-induced diffusion processes (Robin, 1979) arising from a structural event that was operative prior to the emplacement of the younger gneiss. The individual leucocratic bands have constituents that are very similar to the enveloping gneisses (i.e. plagioclase and quartz with lesser amounts of biotite and microcline) but generally contain lesser amounts of biotite and slightly more microcline. The finely-banded and regular nature of the compositional layering in the older gneiss unit suggests that they were derived by a sub-solidus process such as metamorphic differentiation but this statement needs to be quantified before an unequivocal interpretation is made.

In summary, this section of the Theeboom outcrop represents the best-exposed example of the co-existence of two physically distinct phases of trondhjemite gneiss in contact with each other. The occurrence of this relationship adds credence to the suggestion made in the previous section, that the older trondhjemite gneiss, with its ambiguous relationship to the amphibolite, may represent a small segment of pre-amphibolitic sialic crust. The impression is gained by viewing the sliver of older trondhjemite gneiss as a fortuitously preserved remnant into which the meta-basalt may have been intruded. Irrespective of whether this interpretation is correct or not, amphibolite and the older, banded trondhjemite gneiss can both be viewed simply as xenoliths occurring within the homogeneous younger gneiss.

4.1.4. *Theeboom outcrop - Figure 8*

This map illustrates the relationship between the younger, homogeneous trondhjemite gneiss and a series of intrusive quartz-diorite and quartzo-felspathic veins and dykelets (Figure 8). As mentioned above

Figure 6 : *Detailed map of a portion of migmatite outcrop B on the farm Theeboom 729 JT. The map illustrates the nature of intrusive quartz-diorite dykes with respect to the younger trondhjemite gneiss at the Theeboom outcrop.*

the younger trondhjemite gneiss unit does not have the pronounced metamorphic banding characteristic of the older gneissic phase. The rock consists predominantly of quartz and plagioclase together with lesser amounts of biotite and microcline (together totalling about 10% of the rock). Intrusive into the trondhjemite gneiss are a series of sub-parallel quartz-diorite dykes that are generally conformable with the foliation in the gneisses (Plate 2B). Slight discordancies do, however, exist between the gneiss fabric and the quartz-diorite dykes suggesting that the latter are in fact intrusive. In another portion of the Theeboom outcrop that is removed from the mapped section in Figure 8, these discordancies are far more pronounced and the intrusive nature of the quartz-diorites is unequivocal. The quartz-diorites themselves, however, are weakly foliated so that they have been intruded syn-tectonically and have also been mildly folded together with the gneiss fabric. This folding corresponds to the compression of boudins and crenulation in the amphibolite fabric mentioned in the description of the first Theeboom map (i.e. Figure 5). The quartz-diorite veins are generally finer-grained and more mafic than the trondhjemite gneisses that they intrude, but otherwise have very similar mineral constituents and compositions (see below). The rock consists dominantly of plagioclase, quartz and biotite together with lesser amounts of microcline and traces of apatite. The possibility that the quartz-diorite dykes represent xenoliths of granitized or assimilated amphibolitic meta-basalt is not consistent with the petrographic characteristics of the rock, which shows no evidence for the break-down of hornblende to biotite. The rock has an equigranular texture and, in addition contains numerous disorientated laths of biotite, the latter having clearly crystallized from a melt.

Both the quartz-diorite dykes and the trondhjemite gneiss have been intruded by at least four phases of quartzo-felspathic or pegmatite veins (Figure 8). All these phases post-date the deformation that has affected the earlier quartz-diorites and trondhjemites. The veins are randomly intruded into the earlier units and do not appear to have been controlled by the later fractures and joints that pervade the outcrop. These veins, or anatectites, vary somewhat in term of their composition and mineral constituents; most consist essentially of quartz and plagioclase with variable amounts of microcline (between 10-30%). Biotite occurs in variable quantities (usually $< 5\%$) but some of the veins are

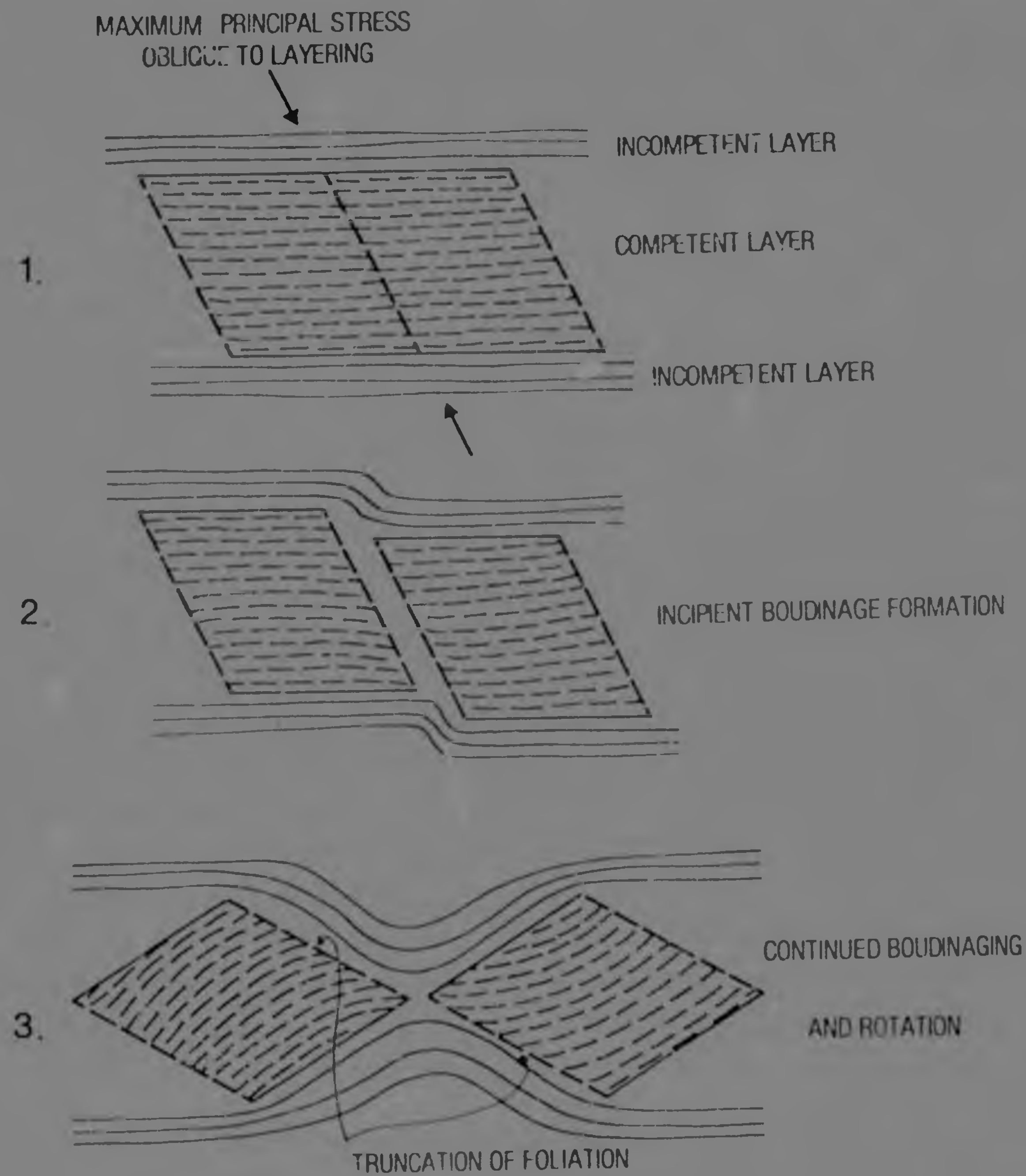


Figure 9 : A schematic diagram illustrating the formation of "lozenge shaped" or rotated boudins (after Rast, 1956 and Charlesworth and Evans, 1962).

aplitic in the sense that they contain very few mafic minerals. These low ferromagnesian anatects are similar to those mentioned in the description of Figure 6 and are characterized by a medium-fine grained equigranular texture that may be the result of the simultaneous crystallization of quartz, plagioclase and K-felspar on the granite cotectic.

This section of the Theeboom outcrop has been disrupted by a late fault which has clearly displaced the quartz-diorite dykes shown in Figure 8; the fault is located along the course now occupied by the stream flowing through the mapped section.

4.2. Geochemistry

In the Theeboom outcrop the older and the younger trondhjemite gneiss phases are indistinguishable in terms of their major element compositions (Table 2) in spite of the fact that the one clearly intrudes and post-dates the other. Both rock types have $SiO_2 > 70\%$, $Fe_2O_3^* + MgO$ in the range 1,0 - 2,5% and $K_2O/Na_2O < 0,5$; these characteristics are all consistent with the trondhjemite definition provided in Chapter 6. The Rb and Ba contents of the two gneiss units are also indistinguishable and the only systematic differences are found in the Sr contents of the two rock types (Table 2). The older banded gneiss has an average Sr content of 618 ppm by comparison with a higher average value of 761 ppm for the younger, homogeneous gneiss (see also Anhaeusser and Robb, 1980a). The full signifiance of variations in the Sr contents of tonalite and trondhjemite gneiss bodies in the study area is discussed in Chapter 6. Both the older and younger gneiss units have similar LREE enriched traces but, in keeping with the Sr values, the younger gneiss has a slightly higher ΣREE content than the older unit.

The amphibolitic meta-basalts at the Theeboom outcrop have compositions that are similar to the category of Barberton-type basaltic komatiites as originally defined from within the Barberton greenstone belt itself (Viljoen and Viljoen, 1969c). These amphibolites have MgO in the range 10-12%, $CaO/Al_2O_3 > 1$ and $TiO_2 < 0,7\%$ (Table 2); these characteristics, together with relatively low concentrations of Rb, Sr and Ba, indicate that these meta-basalts have remained remarkably isochemical during the metamorphic events through which they have been subjected. The meta-basalts are also

PLATE 1

A. Trondhjemite gneiss at the Boekenhoutrand outcrop; characterized by [illegible] fractures and quartz-veins of which at least three discrete episodes are seen in the photograph.

B. Quartzo-felspathic anatectite intruding amphibolite at the Theeboom outcrop. The vein truncates earlier plagiogranites seen in Plates C and D and is characterized by a marginal pegmatite phase in the "horizontal" segments of the intrusion.

C. Plagiogranitic veins at the Theeboom outcrop that have been subjected to a mild phase of open folding. The veins are generally concordant with respect to the amphibolite foliation.

D. Boudins in plagiogranitic veins at the Theeboom outcrop; the boudinaging occurred prior to the folding demonstrated in Plate C.

E. Veins of [illegible] quartzo-felspathic anatectite intruded in a lit-par-lit fashion into the amphibolitic meta-basalt at the Theeboom outcrop.

F. Truncation of foliation and compositional banding in the older trondhjemite gneiss unit at the Theeboom outcrop, by amphibolitic meta-basalt containing anatectic veins. This structure may, in part reflect a primary relationship but may also be related to a boudinaging process.

PLATE 1

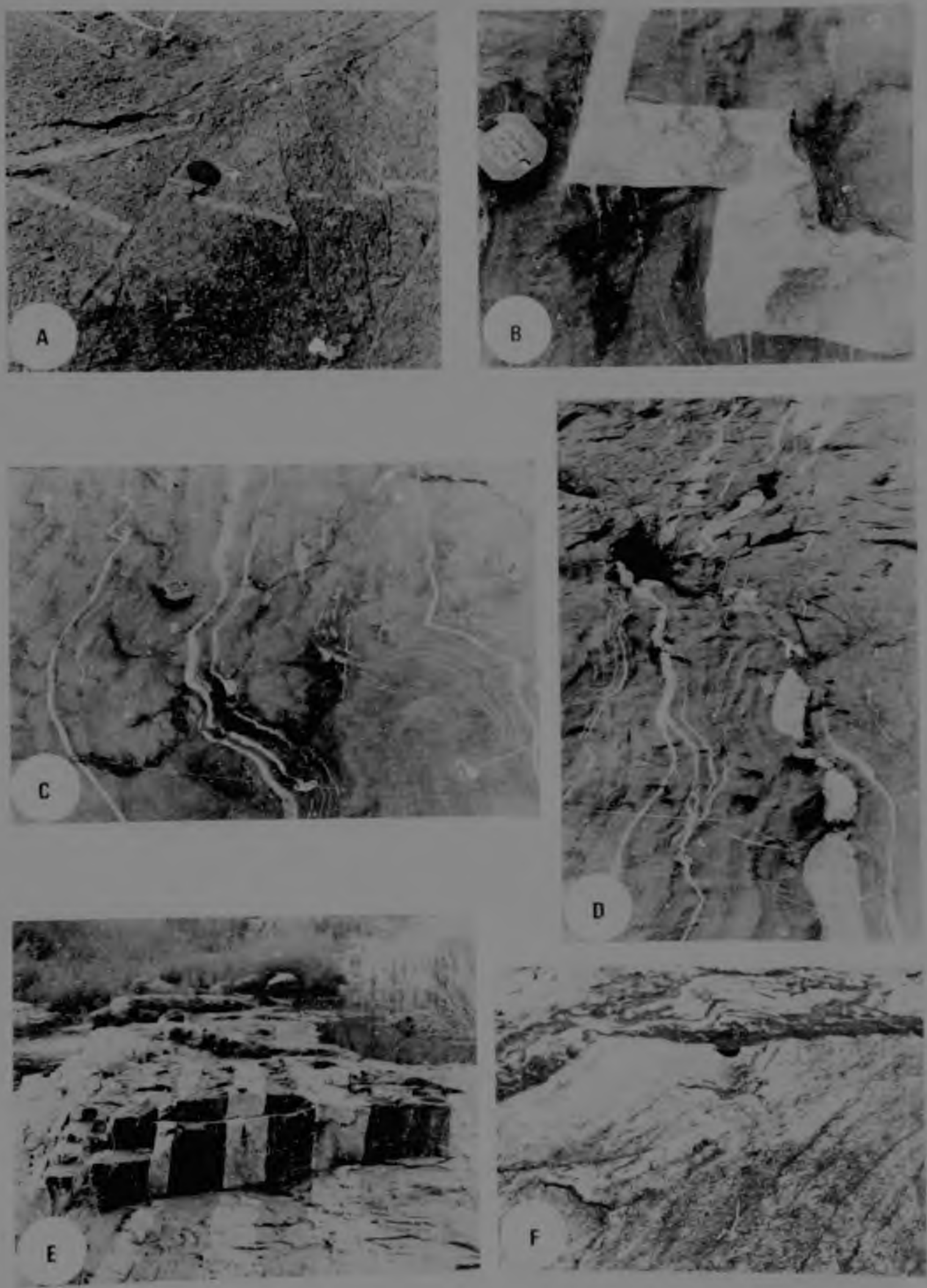


TABLE 2

CHEMICAL ANALYSES OF COMPONENTS FROM MIGMATITE OUTCROP B - FARM THEEBOOM 722JT

		1	2	3	4	5	6	7
		B2	B20	B1	B3	B4	B5	B12(A)
Wt.%	SiO_2	72,70	71,54	71,37	73,78	72,42	73,43	71,50
	TiO_2	0,25	0,38	0,37	0,15	0,22	0,19	0,15
	Al_2O_3	15,42	16,48	14,91	22	14,80	15,20	15,60
	Fe_2O_3*	1,56	2,43	2,30	0,60	1,11	1,21	1,30
	MnO	0,12	<0,01	0,04	<0,01	<0,01	0,09	0,01
	MgO	0,46	1,04	1,35	0,32	0,31	0,51	0,40
	CaO	2,30	2,55	1,94	1,53	1,80	1,87	1,79
	Na_2O	5,32	4,26	4,30	4,47	5,94	4,73	5,90
	K_2O	1,45	1,92	2,84	3,76	2,26	2,22	2,12
	P_2O_5	0,11	0,15	0,23	0,01	<0,01	0,08	0,04
	L.O.I.	1,41	0,36	0,41	0,36	0,64	0,26	0,42
	TOTALS	101,10	101,11	100,06	99,20	99,50	99,79	99,23
ppm	Rb	52	60	49	76	57	53	46
	Sr	712	810	654	357	541	674	604
	Ba	226	584	518	593	372	390	620
	La	15,9	-	32,2	-	32,9	-	-
	Ce	31,8	-	38,3	-	22,0	-	-
	Nd	7,9	-	11,6	-	6,4	-	-
	Sm	1,87	-	4,08	-	2,37	-	-
	Eu	0,64	-	0,77	-	0,54	-	-
	Tb	0,17	-	0,23	-	0,20	-	-
	Yb	0,24	-	0,24	-	0,37	-	-
	Lu	0,04	-	0,04	-	0,04	-	-

(Analysts: Columns 1-6, L.J. Robb
Column 7, Bergström and Bakker, Johannesburg
Fe_2O_3* - Total iron as Fe_2O_3)

Columns 1 - 2 - Younger trondhjemite gneiss
3 - Quartz-diorite dyke within the younger trondhjemite gneiss
4 - 5 - Quartzo-felspathic vein (anatectites) within the younger trondhjemite gneiss
6 - 7 - Older trondhjemite gneiss

Sample localities shown in Figures 5-8

TABLE 2 (Continued)

		8	9	10	11	12	13	14
		B13	B21	B23	B19	B22	B24	B7
	SiO_2	74,62	72,08	71,92	74,28	73,47	73,35	73,93
	TiO_2	0,19	0,16	0,18	0,13	0,08	0,10	0,12
	Al_2O_3	14,95	15,61	15,84	15,24	16,36	15,31	14,87
	Fe_2O_3*	1,47	1,39	0,73	0,91	1,02	0,43	1,05
	MnO	0,04	<0,01	0,01	0,01	<0,01	0,01	0,04
Wt.%	MgO	0,38	0,19	0,13	0,27	0,50	0,01	0,51
	CaO	1,76	2,11	1,41	1,64	1,89	1,56	1,51
	Na_2O	5,23	5,41	5,18	4,77	4,78	5,41	4,69
	K_2O	1,44	1,52	1,98	2,90	2,46	2,91	4,24
	P_2O_5	0,08	0,05	0,07	0,07	0,05	0,06	0,07
	L.O.I.	0,48	0 44	0,89	0,47	0,41	0,50	0.64
	TOTALS	100,64	98,96	98,34	100,70	101,02	99,65	101,68
	Rb	69	51	34	59	59	61	140
	Sr	660	574	581	515	626	476	337
	Ba	458	216	512	578	754	617	409
	La	-	-	11,4	-	-	-	-
	Ce	-	-	12,9	-	-	-	-
ppm	Nd	-	-	-	-	-	-	-
	Sm	-	-	1,20	-	-	-	-
	Eu	-	-	0,24	-	-	-	-
	Tb	-	-	0,08	-	-	-	-
	Yb	-	-	0,28	-	-	-	-
	Lu	-	-	0,02	-	-	-	-

(Analyst: Columns 8-14, L.J. Robb)

Columns 8 - 10 - Older trondhjemite gneiss

11 - 12 - Anatectic veinlets intimately associated with the older trondhjemite gneiss

13 - Discrete aplite-like vein within the older trondhjemite gneiss

14 - Quartzo-felspathic (anatectic) veins at the contact between amphibolite and older gneiss

TABLE 2 (Continued)

		15	16	17	18	19	20	21	22
		B11	B15	B17	B9	B10(A)	B6	B14	B16
	SiO_2	75,31	73,43	70,39	73,85	77,52	50,54	50,14	50,15
	TiO_2	0,03	0,12	0,15	0,13	0,06	0,73	0,47	0,58
	Al_2O_3	14,67	14,96	13,81	15,17	14,19	9,40	10,40	8,14
	Fe_2O_3*	0,57	0,88	1,81	0,01	0,19	13,47	11,82	12,66
	MnO	0,08	0,01	0,09	0,13	0,01	0,46	0,45	0,34
Wt.%	MgO	0,09	0,44	1,80	0,20	0,06	10,47	11,31	11,87
	CaO	1,11	1,12	1,85	2,34	1,54	11,52	12,38	11,62
	Na_2O	4,44	4,59	3,17	4,47	6,46	1,75	1,86	1,82
	K_2O	4,25	4,10	4,41	2,13	0,53	0,79	0,36	0,69
	P_2O_5	0,03	0,07	0,17	0,04	0,02	0,01	0,10	0,02
	L.O.I.	0,36	0,60	1,29	0,42	0,39	1,02	1,27	1,11
	TOTALS	100,94	100,32	98,94	98,89	100,96	100,15	100,56	99,00
	Rb	90	97	136	73	12	14	15	15
	Sr	131	339	214	414	84	184	130	82
	Ba	42	655	925	843	5	81	18	34
	La	-	9,1	-	-	9,4	-	1,5	-
	Ce	-	12,4	-	-	9,4	-	8,6	-
ppm	Nd	-	-	-	-	2,8	-	-	-
	Sm	-	1,28	-	-	0,54	-	1,54	-
	Eu	-	0,29	-	-	0,08	-	0,48	-
	Tb	-	0,09	-	-	0,05	-	0,45	-
	Yb	-	0,27	-	-	0,17	-	1,10	-
	Lu	-	0,04	-	-	0,02	-	0,24	-

(Analyst: Columns 15 - 22, L.J. Robb)

Columns 15 - 17 - Quartzo-felspathic (anatectic) veins at the contact between amphibolite and older gneiss

18 - Late, post-tectonic veinlet within the amphibolite unit

19 - Syn-tectonic plagiogranitic veinlet within the amphibolite unit

20 - 22 - Amphibolitic meta-basalt

characterized by a relatively constant normalized REE content that is approximately 10-15X enriched with respect to chondritic values (see Figure 33). The similarity between the compositions of the amphibolitic meta-basalt from the Theeboom outcrop and basaltic komatiites from the Barberton greenstone belt suggests that the former may be correlated with uni[illegible]om the lower formations of the Onverwacht Group (see Figure 2).

Plagiogranitic veins that intrude the amphibolite at Theeboom have SiO_2 > 77[illegible], K_2O/Na_2O < 0,1 and very low Fe_2O_3* + MgO contents (Table 2). These veins are also characterized by low Rb, Sr, Ba and ΣREE contents and are very similar, therefore, to the plagiogranitic veinlets occurring at the Boekenhoutrand outcrop (Figure 3 and Table 1). The trace element contents of these rocks, which are essentially similar to those of the amphibolitic meta-basalts, suggest a possible genetic link between the two.

The quartzo-felspathic anatectites are characterized by SiO_2 > 70%, K_2O/Na_2O in the range of 0,4 - 1,4 and low Fe_2O_3* + MgO (usually less than 1,5%). These rocks differ from the trondhjemite gneisses mainly in their higher K_2O/Na_2O ratios and lower ferromagnesian contents. The anatectites also have higher Rb contents than the trondhjemites and are characterized by LREE enriched patterns which commonly have pronounced Eu anomalies (see Figure 26). Aplitic and other post-tectonic veinlets listed in Table 2 have similar broad characteristics to the anatectites described above.

Quartz-diorite dykes intrusive into the younger trondhjemite gneiss at Theeboom are characterized by lower SiO_2 and higher Fe_2O_3* + MgO contents than their host rocks. Their REE patterns are similar to those of the trondhjemites on a chondrite normalized diagram, but ΣREE contents are marginally higher.

4.3. Summary statement

The Theeboom outcrop illustrates excellently preserved relationships depicting the nature of interactive processes between amphibolitic meta-basalts of komatiitic affinity and two discrete phases of enveloping trondhjemitic gneiss. A fourth major component of the outcrop is anatectic material which, although emplaced syn-tectonically, intrudes both gneiss and amphibolite.

PLATE 2

A. *Truncation of the compositional banding in the older trondhjemite gneiss at the Theeboom outcrop by amphibolite in an area where the effects of boudinaging are minimal.*

B. *Syn-tectonic diorite dykes intrusive into the younger trondhjemite gneiss unit at the Theeboom outcrop.*

C. *Composite photograph illustrating the same effects as those described in Plate A but where the effects of boudinaging may have contributed to this relationship; from the older trondhjemite gneiss boudin in Figure 6.*

D. *The contact between the older trondhjemite gneiss (right) and the younger trondhjemite gneiss (left) at the Theeboom outcrop. The older gneiss is characterized by a distinct mafic selvedge at its contact and also by compositional banding that is absent in the younger unit. The contact plane truncates both the foliation and compositional banding in the older unit.*

PLATE 2

The exposure as a whole has been subjected to a compressive stress so that boudinaging between juxtaposed units of differing competency is commonplace. The older trondhjemite gneiss phase, which has a pronounced compositional layering, is juxtaposed with the amphibolite in certain key areas where the interpretation of the relative ages of these two units is equivocal. The effects of boudinaging produces discordancies which appear to make the trondhjemite gneiss older than the adjacent amphibolite. On the other hand the compositional layering in this gneiss is also truncated in places by the amphibolite, which suggests that, in these areas, a primary discordancy may be preserved. The older gneiss itself is preserved as a thin sliver between the amphibolite and a younger, intrusive trondhjemite gneiss that does not contain the compositional layering characteristic of the older gneiss. Both the older gneiss and the amphibolite can be regarded as xenoliths within the younger trondhjemitic gneiss. Until such time as geochronological work still in progress evaluates the relationship between the older gneiss and the amphibolite, interpretation must remain equivocal. The possibility remains, however, that the amphibolite may originally have been intruded into, or extruded on top of, the older trondhjemitic gneiss unit.

5. MIGMATITE OUTCROP E - BATAVIA

5.1. Geological Description

On the farm Batavia 151 IT, immediately to the west and northwest of the Boesmanskop syenite pluton, good exposures of tonalite and trondhjemite gneisses, shredded and deformed greenstone remnants and complex migmatites are preserved (Figure 2). This belt is portrayed in Figure 2 as possibly representing an extension of that portion of the Barberton greenstone belt known as the Nelshoogte schist belt (Anhaeusser, in preparation). This schist belt consists essentially of rocks that are correlatable with the lower portion of the Onverwacht Group (i.e. the Tjakastad Subgroup) and consists dominantly of komatiitic and tholeiitic meta-basalts with minor serpentinitic, calc-silicate and chert units. The extension of this schist belt (referred to in all following descriptions as the Batavia section, and which is outlined by outcrops H-E-F-G in Figure 2) has been intruded by a number of phases of tonalite and trondhjemite gneiss, which, together with quartz-diorite and anatectic

Figure 10 : Detailed map of migmatite outcrop E on the farm Batavia 151 IT. The map illustrates the relationships existing between amphibolitic xenoliths and tonalitic gneiss after both units have been deformed and appear, in most places, structurally concordant. The asterisk depicts the single occurrence of a discordant relationship between gneissosity and lithological boundaries in the outcrop. The locality of the outcrop is shown in Figure 8.

veins, have migmatized and shredded the pre-existing greenstone successions in the area. The description of outcrop E, together with the descriptions of other outcrops from the Batavia section, collectively serve to illustrate the extremely complex nature of the geological processes that have resulted in the formation of migmatitic rocks in this belt. The Batavia section, in fact, represents a possible type section for the development of tonalite-associated migmatitic rocks in the Barberton Mountain Land and is referred to in this light again, at the end of Chapter 3.

The two mapped sections of outcrop E (Figure 10 A and B) serve to typify one facet in the complex nature of this migmatite zone. In this outcrop a remnant of amphibolitic meta-basalt is enveloped by a well-foliated banded tonalite gneiss and both units are seen to be cohesively deformed (Plate 3A). In spite of the deformation and the resultant concordancy between the gneissocity and lithological contacts, it is nevertheless possible to identify the intrusive nature of the tonalite gneiss protolith. In section B of Figure 10, at the locality marked by an asterisk, the banding (possibly of metamorphic origin) and foliation that occurs within the meta-basaltic unit has been truncated by the tonalite gneiss. The meta-basalt is, therefore, interpreted as representing a greenstone xenolith that has been deformed together with the tonalite gneiss that intruded it.

The tonalite gneiss consists predominantly of plagioclase and quartz together with lesser amounts of biotite and hornblende. These two minerals commonly occur as small clots in the rock which are occasionally associated with minor epidote, apatite and garnet (Plate 6F). Both biotite and hornblende are probably primary constituents of the tonalite as they are commonly juxtaposed and are characterized by a euhedral-to-subhedral crystal habit.

In addition to the tonalite gneiss, the meta-basaltic unit has been intruded and fragmented by numerous syn-tectonic anatectic veins (Plate 3B). These white coloured quartzo-felspathic veins are invariably less mafic than the tonalite gneiss and are usually complexly folded together with the amphibolite (Figure 10). In many places, the migmatitic appearance of the outcrop is the result of the intrusion of the anatectite into pre-existing amphibolitic remnants. The more pervasive intrusive nature of the anatectic fluid is the result of it being less viscous than

PLATE 3

A. *Tonalite gneiss enveloping bands of amphibolite, both of which have been folded together in such a way that dome-like interference structures have formed. The exposure is from the Batavia section, outcrop E, where, despite the deformation, the amphibolitic components are nevertheless recognizable as xenolithic remnants originally intruded into by the tonalite gneiss protoliths.*

B. *A complex array of intrusive anatectites in amphibolite from outcrop [illegible], Batavia section.*

C. *Quartz-diorite veins folded about two mutually perpendicular axes in outcrop F, Batavia section.*

D. *Blocky agmatitic texture formed by the intrusion of a quartzo-feldspathic anatectite into amphibolite at the Rooihoogte outcrop.*

E. *Agmatite formed by the lit-par-lit intrusion of anatectic material in outcrop [illegible], Rooihoogte.*

F. *Complex agmatite probably developed by the forcible or explosive injection of anatectic material into an amphibolitic remnant preserved on the western margin of the Theespruit pluton.*

PLATE 3

the tonalite magma, probably because of the higher volatile content in the former. This feature is apparent in the fact that the anatectites can occasionally be seen to have a pegmatitic or coarser-grained, texture (Figure 10 A and B). The anatectic veins consist predominantly of quartz and plagioclase and contain only minor interstitial biotite, much of which may represent an entrained restite phase. The anatects at this outcrop, in contrast to the Theeboom outcrop, do not contain a significant K-felspar component and, as a result, are unlikely to represent small degrees of partial melting (see Chapter 3).

The amphibolitic meta-basalt at outcrop E has been migmatized and intruded by numerous quartzo-felspathic veinlets which are responsible for imparting an heterogeneous aspect to this unit (see Plate 3B). The meta-basalts consist predominantly of euhedral, medium-to-coarse grained, greenish hornblende. This texture becomes altered, however, in the vicinity of intrusive quartzo-felspathic veinlets, where the hornblende becomes finer-grained with a tendency for anhedral outlines. Furthermore, in areas immediately adjacent to the anatectic veinlets the amphibolite itself contains locally, more plagioclase and quartz than on average and this is considered to reflect the progressive assimilation of the meta-basalt on a small scale. The fact that the anatectic veinlets in the amphibolite do not exhibit a mafic selvedge is indicative of a derivation from an external source, as the result of anatexis, and not by a process of *in situ* metamorphic differentiation.

5.2. Geochemistry

The well-foliated tonalite gneiss at outcrop E is characterized by $SiO_2 \cong 67\%$, an $Fe_2O_3^* + MgO$ content of approximately 4,5 and a K_2O/Na_2O ratio of 0,21 (Table 3). This gneiss is more highly ferromagnesian than those described from the previous two migmatitic outcrops and its composition is compatible with that of a tonalite, as defined in Chapter 6. The tonalite gneiss is also characterized by relatively low Rb and Ba contents but the concentration of Sr is typical of this suite of rocks. The REE pattern of the gneiss is similar to that of other tonalites and trondhjemites in the region (see Figure 20) with typical LREE enrichment and no significant Eu anomaly. HREE are depleted despite the fact that small amounts of garnet occur in the rock.

TABLE 3

CHEMICAL ANALYSES OF COMPONENTS FROM MIGMATITE OUTCROP E - FARM BATAVIA 151IT

		1	2	3	4	5
		E1	E2	E3	E4	E5
Wt.%	SiO_2	74,63	67,62	53,49	48,95	75,21
	TiO_2	0,12	0,30	1,02	1,22	0,03
	Al_2O_3	12,79	17,86	11,67	14,97	13,52
	Fe_2O_3*	1,73	3,08	11,58	11,40	0,76
	MnO	0,01	0,06	0,16	0,17	0,01
	MgO	1,07	1,23	8,36	6,14	0,22
	CaO	3,46	4,35	10,31	11,49	1,94
	Na_2O	4,51	4,69	2,89	3,33	5,53
	K_2O	0,29	0,99	0,68	0,58	0,72
	P_2O_5	0,06	0,09	0,08	0,08	0,01
	L.O.I.	0,41	0,48	0,70	0,53	0,54
	TOTALS	99,08	100,74	100,94	98,86	98,49
ppm	Rb	2	17	37	5	12
	Sr	298	549	182	148	231
	Ba	24	159	26	10	82
	La	-	8,8	4,8	-	1,6
	Ce	-	17,8	11,0	-	2,5
	Nd	-	10,8	-	-	-
	Sm	-	1,31	2,98	-	0,21
	Eu	-	0,60	1,09	-	0,24
	Tb	-	0,31	1,05	-	0,06
	Yb	-	0,46	2,31	-	0,11
	Lu	-	0,04	0,28	-	0,02

(Analyst: L.J. Robb.
Fe_2O_3* - Total iron as Fe_2O_3)

Columns 1 and 5 - Quartzo-felspathic veins intrusive into amphibolitic unit
2 - Tonalite gneiss
3 - 4 - Amphibolitic meta-basalt

Sample localities shown in Figure 10

The anatectic veins at outcrop E have a significantly different composition to those analysed from, for example, the Theeboom outcrop, even though both sets of veins are similar in appearance and style of emplacement. The Batavia anatectites have high SiO_2 (> 74%), low Fe_2O_3* + MgO (between 1-3%) and very low K_2O/Na_2O ratios of between 0,05 and 0,15. These characteristics closely resemble the plagiogranites described previously except that their REE contents are significantly different (compare Table 3 with the relevant analyses in Tables 1 and 2). The anatectic veins from Batavia do not, therefore, reflect the cotectic, or minimum-melt, compositions of the Theeboom equivalents and these divergent characteristics are discussed fully in Chapter 3. The REE contents of the Batavia anatectites are also significantly different to those of the Theeboom anatectic veins with the former having a lower ΣREE content and a significant positive Eu anomaly. It is the latter characteristic which distinguishes between the anatectites and the plagiogranites described previously from the Boekenhoutrand and Theeboom outcrops.

The amphibolitic meta-basalts at outcrop E have a tholeiitic bulk composition with MgO in the range 6-8% and CaO/Al_2O_3 < 1 (Table 3). These rocks also have relatively high Al_2O_3 (12-15%) and Na_2O (≅ 3%) contents which are the result of the intrusion of numerous, small anatectic veins. The REE trace of the amphibolite is typically flat on a chondrite normalized diagram but the ΣREE content is higher than that for amphibolites with komatiitic affinities (Figure 33).

5.3. Summary statement

Migmatite outcrop E on the farm Batavia illustrates the relationship between a tonalitic gneiss and an amphibolitic remnant of tholeiitic composition. The preservation of a discordancy between compositional layering in the meta-basalt and the surrounding gneisses indicates that protoliths of the latter originally intruded and migmatized remnants of amphibolite, which are probably, therefore, relics of a pre-existing greenstone belt. Both the tonalite gneiss and amphibolite have subsequently been complexly folded so that felsic and mafic units together define interference-type basin and dome structures. Migmatization processes have been complicated by the syn-tectonic intrusion of quartzo-felspathic anatectic veins which tend, locally, to hybridize the pre-existing amphibolites.

6. MIGMATITE OUTCROP I - ROOIHOOGTE

6.1. Geological description

Unlike most of the other migmatite outcrops described in this study which occur within 5 km or less of the Barberton greenstone belt, the Rooihoogte outcrop is situated at least 30 km from its most south-westerly tip. The outcrop is located to the west of the Heerenveen batholith, in a triangular window consisting of tonalitic gneisses, migmatites and greenstone remnants, and flanked by Proterozoic cover on two sides and the batholith on the third (Figure 2). The greenstone remnants in the vicinity of the Rooihoogte outcrop are aligned approximately east-west and form an array of long, linear bodies whose geometry is the result of either lit-par-lit emplacement of granite *(sensu lato)*, or repetition due to tight isoclinal folding. The greenstone remnants in the area are lithologically variable and consist predominantly of amphibolites with minor serpentinites, talc schists and felsic agglomerates (C.R. Anhaeusser, personal communication). In spite of their distance from the Barberton greenstone belt, these greenstone remnants are, nevertheless, correlatable with similar lithologies from the Tjakastad Subgroup. The migmatite outcrop I is located on the flanks of one such linear, dominantly amphibolitic, remnant (Figure 2).

Details of the Rooihoogte outcrop are presented in Figure 11 where it is seen that a banded trondhjemite gneiss unit is intimately associated with remnants of amphibolitic meta-basalt. An agmatitic texture has developed not, however, by the interaction of trondhjemitic magma with amphibolite, but by the intrusion of a quartzo-felspathic anatectite into the latter (Plate 3D and 3E). The formation of a migmatite at this outcrop, therefore, is the result of anatexis and, as at the Theeboom outcrop, the primary relationships between trondhjemite gneiss and amphibolitic meta-basalt are largely obscured by this palingenetic effect.

In contrast to the Theeboom exposure where dykes of anatectic material had been emplaced in a linear, lit-par-lit array (Figure 6), the anatectite at Rooihoogte has intruded the amphibolites in a random, anastomosing fashion. The result of this has been the pronounced disruption of what was originally a single amphibolitic unit and the subsequent formation of an agmatitic texture (Plate 3E and F). It is apparent

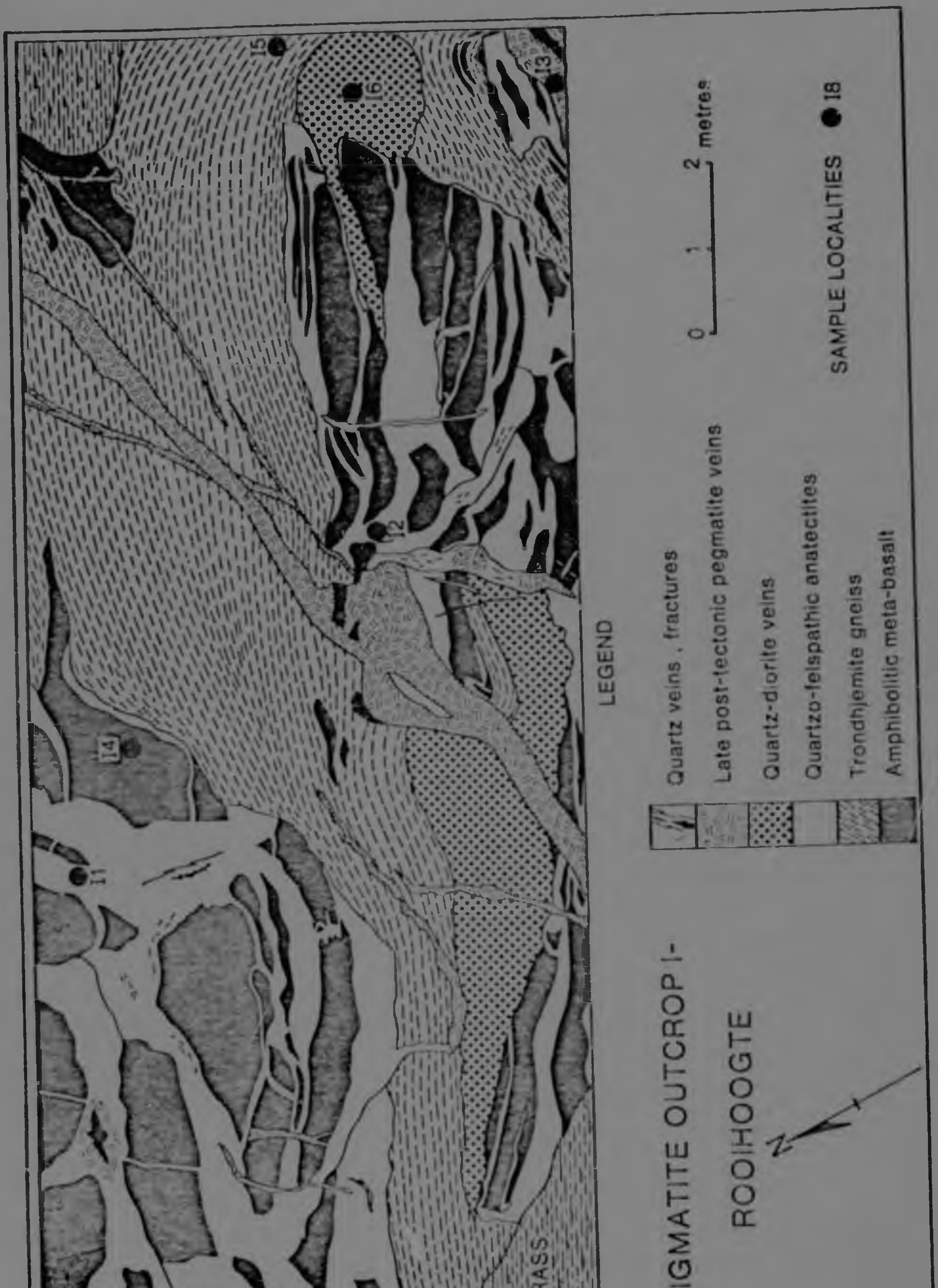


Figure 11 : Detailed map of migmatite outcrop 1 in the vicinity of the Rooihoogte Fuse. The locality of the outcrop is shown in Figure 2.

from Figure 11 that the intrusion of anatectic veins and the resultant migmatization process, was a multi-stage event and not restricted to a single episode. It is also clear that the palingenetic nature of this outcrop does not assist in an interpretation of the primary relationships between trondhjemite gneiss and amphibolite, particularly in the absence of a detailed understanding of the structural history of the region. Whether the amphibolitic meta-basalts are infolded supracrustal remnants or xenoliths is impossible to say at this outcrop, although, in the light of the description of migmatite outcrop E, the latter suggestion may be more feasible.

The amphibolite at Rooihoogte consists dominantly of subhedral hornblende with lesser amounts of highly sericitized plagioclase and quartz. In spite of the intrusion of anatectites and its intimate association with these felsic veins, the amphibolite has not suffered from hybridization or contamination; as a result, metamorphic effects have been isochemical and the amphibolite has retained its original composition (see below). Likewise, the anatectites contain no significant mafic component and their mineralogy is dominated by quartz, plagioclase and highly sericitized orthoclase. Minor chlorite and muscovite occur together with radial clusters of sillimanite. The trondhjemite gneiss is characterized by an irregular compositional layering that is parallel to a very pronounced mineral fabric in the rock (similar, for example, to the older gneiss unit at the Theeboom outcrop). The gneiss consists dominantly of quartz and plagioclase together with strongly aligned, interstitial biotite euhedra.

The Rooihoogte outcrop is also transected by several phases of felsic intrusives which include a syn-tectonic quartz-diorite and at least two episodes of post-tectonic pegmatite veining (Figure 11). The quartz-diorite vein is slightly more mafic and also finer grained than the adjacent trondhjemite gneiss. It consists essentially of plagioclase and quartz with the former mineral exhibiting complex albite-pericline twinning. Biotite is the dominant mafic mineral and, as in the trondhjemite gneiss, is strongly aligned. The quartz-diorite is very similar in appearance to those described from the Boekenhoutrand and Theeboom outcrops. The pegmatitic veins are characterized by a bimodal grain-size distribution with large grains of quartz and plagioclase set in an interstitial groundmass of finer quartz, plagioclase and minor microcline. The larger plagioclase grains are anti-perthitic and contain inclusions of microcline and quartz. The pegmatites clearly post-date the anatectic veins and, as a result, are probably not genetically related to the earlier melt episode, but rather to the emplacement of the Heerenveen batholith, which is located approximately one kilometre to the east of the outcrop.

6.2. Geochemistry

The composition of the amphibolitic meta-basalt at outcrop I is identical to the category of Barberton-type basaltic komatiites defined in the Barberton greenstone belt by Viljoen and Viljoen (1969c). This rock has low SiO_2 (51), high MgO (14), low TiO_2 (0,27) and a CaO/Al_2O_3 ratio that is greater than unity (Table 4). This composition is consistent with the suggestion made above, that the amphibolite represents a greenstone remnant; its relationship, however, to the trondhjemite gneiss cannot be assessed unequivocally in terms of the relationships preserved at this outcrop. The flat REE pattern on a chondrite normalized diagram is typical of that in basaltic komatiites and the ΣREE content is seen to be somewhat lower than the average pattern obtained from other migmatite-related amphibolites in the study area (Figure 33).

The anatectites from the Rooihoogte outcrop are very similar in composition to those from Theeboom and have high SiO_2 (72-73), low Fe_2O_3* + MgO (0,6 - 0,9) and a high K_2O/Na_2O ratio of between 0,8 - 1,2 (Table 4). These characteristics reflect eutectic, or minimum-melt, compositions in the granite system and are consistent, therefore, with magma derived by anatexis. The anatectites are characterized by LREE enrichment and a pronounced negative Eu anomaly (Figure 26), suggesting equilibration of the melt with a plagioclase-enriched residue.

The trondhjemite gneiss at Rooihoogte is typical of other trondhjemites in the Barberton Mountain Land and is characterized by SiO_2 > 70%, Fe_2O_3* + MgO 3% and a low K_2O/Na_2O ratio (0,2). The Rb content of the gneiss is lower than average (Table 4) and it is not certain whether this factor is real or a reflection of the mobility of this element during alteration. The REE show a typical pattern on a chondrite normalized diagram with LREE enrichment and no significant Eu anomaly (Figure 20).

The syntectonic quartz-diorite vein has a similar composition to the trondhjemite gneiss but, as with other quartz-diorites from previously

TABLE 4

CHEMICAL ANALYSES OF COMPONENTS FROM MIGMATITE OUTCROP I - ROOIHOOGTE PASS

		1	2	3	4	5	6
		I1	I2	I3	I4	I5	I6
Wt.%	SiO_2	71,89	73,07	71,79	51,10	71,70	69,32
	TiO_2	0,01	0,01	0,01	0,27	0,20	0,29
	Al_2O_3	15,75	15,21	17,11	10,52	15,62	17,23
	Fe_2O_3*	0.59	0,41	0,64	9,25	2 19	2,43
	MnO	0,01	0,02	0,01	0,17	0,01	0,03
	MgO	0,27	0,15	0,26	13,98	0,85	0,96
	CaO	1,31	1,35	1,00	11,95	3,05	3,63
	Na_2O	5,00	4,04	6,72	2,36	4,29	4,77
	K_2O	4,08	4,58	1,05	0,61	0,91	1,11
	P_2O_5	0,01	0,01	0,02	0,01	0,06	0,09
	L.O.I.	0,42	0,30	0,40	0,71	0,63	0,46
	TOTALS	99,34	99,15	99,01	100,93	99,51	100,32
ppm	Rb	49	47	14	57	14	20
	Sr	95	134	55	110	434	499
	Ba	74	167	5	5	120	151
	La	-	4,0	-	1,3	10,9	-
	Ce	-	9,1	-	3,7	25,3	-
	Nd	-	5,8	-	-	10,2	-
	Sm	-	2,04	-	0,62	1,55	-
	Eu	-	0,12	-	0,35	0.62	-
	Tb	-	0,62	-	-	0,17	-
	Yb	-	0,58	-	0.53	0,16	-
	Lu	-	0,07	-	0,06	0,03	-

(Analyst: L.J. Robb

Fe_2O_3* - Total iron as Fe_2O_3)

Columns 1 - 2 - Anatectites
3 - Pegmatitic vein
4 - Amphibolitic meta-basalt
5 - Trondhjemite gneiss
6 - Quartz-diorite dykelet

Sample localities shown in Figure 11

described migmatite outcrops, has a lower SiO_2 content (≅69%) and higher Fe_2O_3* + MgO (≅4%) than the gneisses which they intrude (Table 4). The coarse-grained pegmatite veins have high SiO_2 contents (≅72%) but a low K_2O/Na_2O ratio (0,15) that is not typical of pegmatites analysed from other migmatite outcrops (e.g. outcrops D and F). This may, however, be the result of a sampling bias in a vein with heterogeneous characteristics.

6.3. Summary statement

The Rooihoogte migmatite outcrop illustrates the complex interaction between remnants of amphibolitic meta-basalt of komatiitic composition, trondhjemitic gneisses and anatectically derived material. The intrusion of anatectite into the amphibolite creates an agmatitic texture indicating that the migmatite was formed largely by arteritic processes. The primary relationship between trondhjemite gneiss and amphibolite at this outcrop is mostly obliterated by the palingenetic effects of the anatectite; the amphibolite may either, represent xenoliths of pre-existing greenstone material (as suggested for outcrop E) or, structurally infolded remnants that once unconformably overlay the gneisses. Little, or no, direct evidence exists for the latter possibility, suggesting that the former may be the more viable.

7. MIGMATITE OUTCROP C - WEERGEVONDEN

7.1. Geological description

The Weergevonden exposure (outcrop C) occurs to the southeast of the Boesmanskop syenite pluton, in an area where numerous small and shredded greenstone remnants are found intimately associated with tonalite and trondhjemite gneisses (Figure 2). Immediately to the south of the Boesmanskop body a large greenstone remnant is preserved, which comprises a succession of basalts, serpentinites and felsic schists, the latter being characterized by agglomeratic and tuffaceous textures. The presence of felsic volcanics in this greenstone remnant, as well as in a number of the smaller remnants in this area, suggests that these units are most likely correlated with the Theespruit Formation in the Barberton greenstone belt (Anhaeusser, 1980). The Weergevonden migmatite outcrop preserves the relationships that exist between a small greenstone remnant consisting

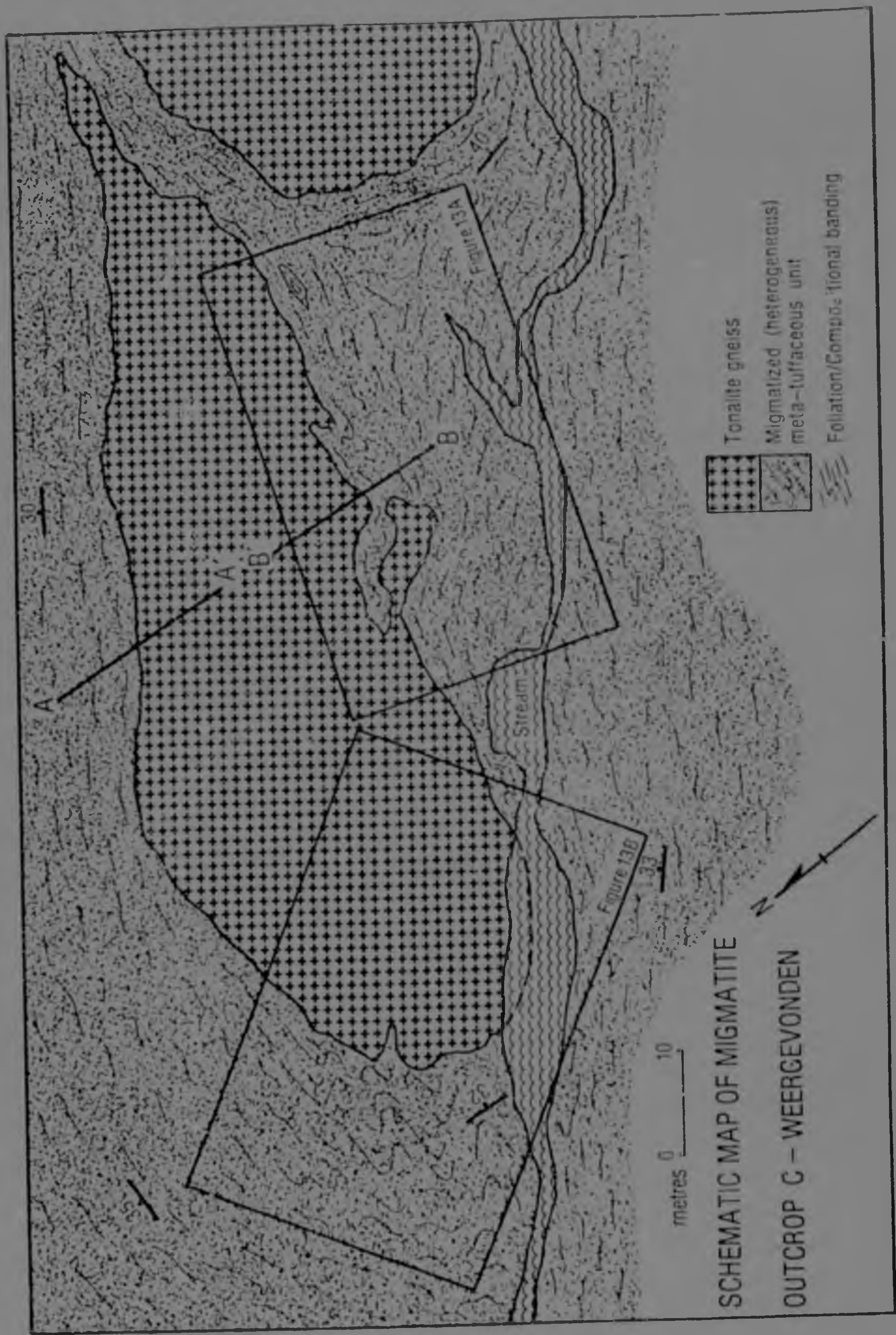


Figure 12 : *Schematic map of migmatite outcrop C on the farm Weergevonden 173 IT. The diagram shows the broad structural relationships between migmatized felsic tuffaceous schists and tonalite gneiss as well as the two sectors mapped in detail in Figure 13.*

f felsic schists, and an intrusive tonalite gneiss. As such, the outcrop provides a contrast to the previous descriptions where mafic meta-volcanics formed an essential constituent of the outcrops.

A schematic illustration of the Weergevonden outcrop is presented in Figure 12, where it is seen that two main components make up the exposure. Along the traverse A-A' the greenstone remnant comprises a sequence of amphibolites and felsic schists before being intruded by tonalite material. In traversing from B to B' (where the outcrop is excellent due to a polished, water-worked platform exposure) the tonalite-greenstone contact is again exposed but the felsic schists are seen to have become intensely migmatized and deformed. The nature of this contact and the processes of migmatization of the felsic schist are represented in detail in Figure 13, and also discussed below.

The schematic map in Figure 12 also illustrates the fact that the outcrop as a whole has been complexly deformed. The body of tonalite gneiss at the outcrop is totally enveloped by felsic schists in various stages of migmatization; the flow lines in the latter unit represent the geometry of veinlets and anatectites and outline minor fold structures within a much larger fold, the full extent of which is not visible because of poor exposure away from the river bed. The Z and M structures in Figure 12 indicate that the mapped outcrop (represented by Figure 13 A and B) contains a portion of the limb and hinge zone of this larger fold structure, which reflects a complex deformational history in this area. Increments of this deformational sequence could be related to the intrusion of the tonalite and later, also, to the emplacement of the Mpuluzi batholith, the northernmost limit of which occurs only one kilometre to the south of the outcrop (Figure 2).

The nature of the migmatized felsic meta-tuff(*) is illustrated in detail in Figure 13 and has also been described in Anhaeusser and Robb (1980a). In section A of this figure the sharp, well-defined contact between

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Footnote (*) : The term "meta-tuff" is used here to describe the felsic schists that have been extensively migmatized and metamorphosed. The tuffaceous connotation to these rocks is derived from Anhaeusser (1980) who referred to bedded lapilli textures in relatively unaltered felsic schists from the large greenstone remnant adjacent to the Boesmanskop syenite pluton (see Figure 2). The chemical similarities between relatively unaltered felsic tuffs and the migmatized meta-tuff described above, are demonstrated in section 7 of Chapter 3.

Figure [illegible] : [illegible] map of migmatite outcrop C on the farm Weergevonden [illegible]. The map illustrates the contact relationships between metamorphosed and migmatized felsic tuffaceous schists and an intrusive tonalite gneiss. The locality of the outcrop is shown in Figure [illegible].

the latter and the tonalitic gneiss shows clearly that gneiss protoliths have rafted off, and incorporated, small segments of the meta-tuff (Plate 4A). The tonalite gneiss consists essentially of plagioclase and quartz in approximately equal proportions, in addition to biotite (~10%) and a small amount of microcline. The felsic meta-tuff, on the other hand, is much finer-grained than the tonalite and contains significant amounts of microcline (20 - 30%) in addition to plagioclase, quartz and biotite. The rock has a markedly equigranular texture and grain contacts appear recrystallized (i.e. polygonal). In section A of Figure 13, individual anatectic veinlets that intrude the meta-tuffaceous unit, are generally aligned parallel to the fabric in the latter and are commonly ptygmatically folded (Plate 4B). In thin section components of these veinlets are coarser-grained than their host-rock and also contain considerably less biotite than the latter. The small amount of biotite that does occur is invariably chloritized. The contacts between felsic meta-tuff and anatectic veins are usually characterized by a concentration of chloritized biotite that resembles a mafic selvedge resulting from the segregation of the more felsic vein from its host.

Section B of Figure 13 represents a portion of the outcrop that is further west along strike from that shown in section A. A marked change in the nature of the migmatized meta-tuffaceous unit takes place as one progresses from east to west and, both the fabric and the more numerous anatectic veinlets within this unit, become strongly folded. often into tight isoclinal structures. Whereas, in section A of this map, the density of occurrence of anatectic veinlets is such that each anatectite is easily recognizable as a discrete individual unit (e.g. Plate 4B), in the folded zone, numerous anastomosing anatectic veins occur, many of which are indistinguishable one from the other (Plate 4 C and D). The geometry of minor folds in section A defines a series of Z structures indicative of a fold-limb, whereas in section B, more symmetrical M structures are observed, indicating a fold hinge (Plate 4C). The textural change that takes place in the felsic meta-tuff can probably, therefore, be attributed to the influence of structure on the process of migmatization. Similar effects have been noted by Mackenzie (1957) in the mid-Strathspey region of Scotland, where the onset of migmatization in quartzo-felspathic and pelitic gneisses of the Moine Series has been controlled by the degree of structural deformation in the area. Mackenzie

(1957) stated that the ".... development of felsic material in the gneisses can be directly correlated with a high intensity of folding" and also that a close relationship exists between, ".... the deformation of the gneisses and the formation of the various quartzo-felspathic bodies whose presence distinguishes the gneisses as migmatites". The heterogeneous, intensely migmatized felsic meta-tuff in Figure 13B, is coarser-grained than its less-altered equivalent and consists dominantly of quartz, microcline and plagioclase in approximately equal proportions. In addition, biotite also occurs often together with muscovite, the latter not having been detected in the meta-tuff from the fold-limb region of the map. The presence of muscovite is possibly indicative of anatexis, forming by the break-down of K-felspar along the lines of the following equilibrium reaction:-

$$\text{muscovite} + \text{quartz} \rightleftharpoons \text{K-felspar} + Al_2SiO_5 + H_2O$$

(after Winkler, 1967)

In terms of the above description, the Weergevonden outcrop probably represents a scaled-down example illustrating the effects of structure on the process of migmatization. Anatexis or sub-solidus metamorphic differentiation within the felsic meta-tuff appears to have been initiated by the intrusion of tonalitic gneiss, the emplacement of which was probably, in part, responsible for the deformation of this unit. A pressure gradient that evidently existed between fold limbs and hinges was responsible for the concentration, by either process, of leucosomes into the lower-pressure hinge zones. Thus, along short distances of strike both the texture and character of a migmatitic rock can undergo a drastic change, which is strongly influenced by the nature of structures in the areas under consideration. Without either, detailed examination, or, complete exposure an incorrect interpretation of such an outcrop might easily ensue. A petrogenetic assessment of the mechanism of migmatization (i.e. either anatexis or metamorphic differentiation) at this outcrop is provided in section 7 of Chapter 3.

A number of additional minor rock-types also occur in the Weergevonden outcrop; an unusual biotite-hornblende-quartz-plagioclase dykelet is seen intruding both the felsic meta-tuff and tonalite gneiss in Figure 13. This dykelet is clearly syn-tectonic and behaves differently in various portions of the outcrop; in the attenuated fold-limbs section (Figure 13A) the dykelet is linear and segmented, whereas in the tightly

PLATE 4

A. *Contact between intrusive tonalite gneiss and the meta-tuffaceous unit at the Weergevonden outcrop. Small slivers of the latter appear as xenoliths in the intrusive unit.*

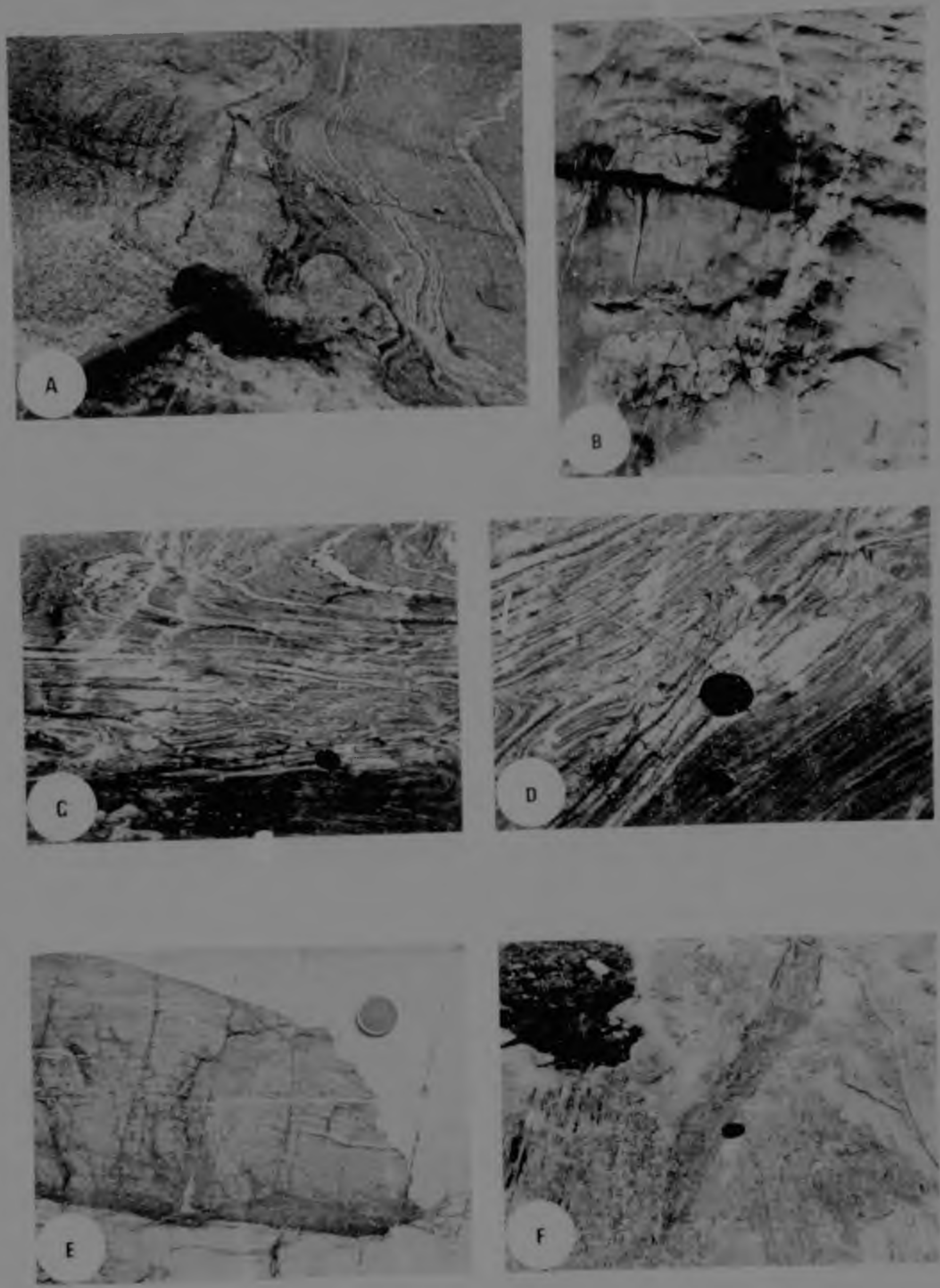
B. *Ptygmatic vein occurring in the fold-limb section of the meta-tuffaceous unit at Weergevonden. The frequency of occurrence of anatectic veins or leucosomes in this part of the outcrop is clearly not as pronounced as those in Plates 4 C and D.*

C. and D. *The nature and physical appearance of the heterogeneous, migmatized meta-tuffaceous unit at the Weergevonden outcrop. This part of the outcrop is characterized by minor structures that reflect a fold-hinge zone, the latter having been intensely pervaded with anatectic leucosomes.*

E. *Amphibolitic meta-basalt from the Batavia section (near outcrop F) that is totally enveloped by trondhjemite gneiss; the former has the unequivocal appearance of a xenolith that has been rafted off a larger greenstone remnant by invading trondhjemitic magma.*

F. *An unequivocally recognizable amphibolitic dyke intruding banded trondhjemite gneisses in the Batavia section near outcrop G. Although assimilated and affected by crustal residence contamination (in much the same way as the xenolith in Plate E) the dyke retains a recognizable discordancy with respect to the gneiss in spite of having been involved in much of the tectonic history of the rock. Dykes that do not retain this feature may be difficult to differentiate from amphibolitic xenoliths.*

PLATE 4



folded portion of the outcrop (Figure 13B), the dykelet is sygmoidal, but nevertheless maintains a discordant relationship with respect to the heterogeneous meta-tuffaceous unit. The dykelet is, in turn, cut by post-tectonic aplite and pegmatite veins which are probably related to the emplacement of the nearby Mpuluzi batholith (Figure 2). Finally, the river course in the Weergevonden outcrop is controlled by a diabase dyke of Proterozoic age which cuts across all other components in the area.

7.2. Geochemistry

The intrusive tonalite gneiss at the Weergevonden outcrop is characterized by a lower SiO_2 (≈69%) and higher Fe_2O_3* + MgO content (> 4%) than the more leucocratic trondhjemite gneisses from previously described migmatite outcrops. The rock is termed a tonalite because of its high ferromagnesian content (i.e. > 3,4%, see Chapter 6) and in spite of the fact that its silica content is marginally higher than the cut-off limit for the tonalite-trondhjemite definition. The tonalite gneiss has Rb, Sr and Ba contents that are typical of other units from the Barberton region, but the ΣREE content of this rock is considerably higher than that indicated from other analyses presented in this thesis (Figure 20).

Analyses of relatively unaltered felsic meta-tuff (i.e. samples C1 and C3 in Table 5, which come from the fold-limb portion of the outcrop in Figure 13A) show a high SiO_2 content (> 72%), Fe_2O_3* + MgO of between 3 - 4% and K_2O/Na_2O ratios of > 1. This rock is, clearly, quite different from tonalite-trondhjemite gneisses in the Barberton Mountain Land and is also characterized by higher Rb and Ba contents and generally lower Sr concentrations (Table 5). The composition of the felsic meta-tuff at Weergevonden is very similar to that of felsic schists from nearby greenstone remnants, with respect to both major and trace elements (Table 19). This corroborates the field relationships described above which suggest that the migmatized meta-tuff was originally a felsic volcanic rock that once formed part of the lithological succession in a greenstone belt. The meta-tuff is also characterized by a rare-earth element pattern that is LREE enriched, has a marked negative Eu anomaly and a higher ΣREE content with respect to the adjacent tonalite gneiss (Table 5).

TABLE 5

CHEMICAL ANALYSES OF COMPONENTS FROM MIGMATITE OUTCROP C - FARM WEERGEVONDEN 173IT

		1	2	3	4	5	6	7
		C1	C3	C4	C6	C2	C5	C7
	SiO_2	72,65	74,29	71,39	73,89	68,77	52,31	52,50
	TiO_2	0,21	0,20	0,26	0,07	0,52	0,89	0,92
	Al_2O_3	13,45	12,66	14,91	15,14	17,18	13,07	13,30
	Fe_2O_3*	2,18	2,18	2,99	0,71	3,22	11,58	10,50
	MnO	0,03	0,01	0,08	<0,01	<0,01	0,33	0,16
Wt.%	MgO	1,01	0,78	0,87	0,35	1,14	6,72	6,80
	CaO	0,68	0,87	1,04	0,98	3,09	7,07	8,00
	Na_2O	3,37	3,77	2,73	3,63	4,45	0,97	1,60
	K_2O	5,36	3,86	4,77	3,95	1,51	3,66	3,80
	P_2O_5	0,08	0,06	0,07	0,04	0,18	0,05	0,93
	L.O.I.	0,47	0,49	1,12	0,72	0,85	2,09	0,96
	TOTALS	99,51	99,17	100,23	99,48	100,91	98,74	99,47
	Rb	69	83	128	117	58	357	110
	Sr	148	95	180	179	754	237	1130
	Ba	1170	817	1193	923	220	1141	3000
	La	66,1	-	69,6	-	32,9	-	-
	Ce	118,2	-	137,7	-	70,2	-	-
ppm	Nd	36,0	-	35,0	-	22,5	-	-
	Sm	6,22	-	8,53	-	4,56	-	-
	Eu	0,90	-	1,17	-	1,48	-	-
	Tb	0,99	-	1,71	-	0,55	-	-
	Yb	3,06	-	5,33	-	2,17	-	-
	Lu	0,42	-	0,63	-	0,28	-	-

(Analyst: L.J. Robb

Fe_2O_3* - Total iron as Fe_2O_3)

Columns 1 - 2 - Felsic meta-tuffaceous unit
3 - Heterogeneous felsic meta-tuffaceous unit
4 - Single anatectic veinlet from the meta-tuffaceous unit
5 - Tonalitic gneiss
6 - 7 - Syn-tectonic biotite-hornblende dykelet

Sample localities shown in Figure 13

The bulk composition of the more markedly migmatized and heterogeneous felsic meta-tuff (i.e. sample C4, Table 5) from Figure 13B is not significantly different from the relatively unaltered equivalents, with a high SiO_2 content (> 71%) and a K_2O/Na_2O ratio > 1. This similarity suggests that, in spite of the textural differences, the processes of migmatization took place *in situ* with insignificant changes in the bulk chemistry of the system. The Rb content of the more severely migmatized unit is, however, considerably higher than that of the less altered material; likewise the ΣREE content in the former is marginally higher, although the respective patterns on a chondrite normalized diagram are very similar (Figure 44).

An analysis of a single anatectic veinlet (sample C6, Table 5) that occurs within the felsic meta-tuff, is characterized by high SiO_2 (~74%), low Fe_2O_3* + MgO (< 1%) and a K_2O/Na_2O ratio of > 1. These characteristics are typical of anatectites described from the Theeboom and Rooihoogte outcrops and reflect eutectic or mimimum-melt compositions in the granite system. In spite of this, however, it is feasible that these veins may have been derived by a sub-solidus process such as metamorphic differentiation and, as a result, a detailed assessment of the migmatization process within the meta-tuffaceous unit is provided in section 7 of Chapter 3.

The composition of the syn-tectonic hornblende-biotite dykelet at Weergevonden is unusual in comparison to other amphibolitic dykes or xenoliths in the region. The dykelet has MgO in the range 6 - 7%, a CaO/Al_2O_3 ratio ~0,6 and an anomalously high K_2O content of > 3,6% (Table 5). This composition is atypical of either tholeiitic or komatiitic chemistries in the sense that they have been defined elsewhere in the Barberton Mountain Land and, hence remains anomalous in terms of a regional comparison. The dyke is also characterized by very high Rb (110 - 350 ppm) and Ba (1100 - 3000 ppm) contents which reflect the presence of primary biotite, for which Rb and Ba both have high partition coefficients (see Appendix 2).

7.3. Summary statement

The Weergevonden outcrop illustrates the relationships between felsic volcanic remnants from a portion of a pre-existing greenstone belt (possibly correlatable with the Theespruit Formation in the Barberton greenstone belt) and the intrusive protoliths of a tonalitic gneiss. The outcrop has been complexly deformed with minor structures reflecting a large-scale folding episode. The felsic meta-tuffaceous unit has been severely altered (metamorphosed) and migmatized during various stages in the tectonic history of the outcrop. The development of anatectic leucosomes is controlled by the fold geometry, with the apparent migration of these phases into the low-pressure hinge-zones of the major fold structure. The fact that both tonalite and meta-tuff have been involved together in the tectonic deformation is evidenced by the emplacement of a mafic dykelet into both units, with the latter having been involved in, at least, the final increments of deformation. The meta-tuff is unlikely to represent a migmatized remnant of pre-existing sialic crust because of both, chemical similarities, and a close spatial link, with felsic schists in adjacent greenstone remnants.

8. MIGMATITE OUTCROP F - BATAVIA

8.1. Geological description

During the course of the detailed mapping of migmatite outcrops in the Barberton Mountain Land, a number of enigmatic exposures were encountered, the interpretation of which remains equivocal in spite of the careful examination that each outcrop was subjected to. This fact points to the complex nature of the processes that have led to the formation of migmatites in the region and stresses the need for careful consideration on the scale of the individual outcrop, before attempting to evaluate the evolution of the area as a whole. Outcrop F, which is located in the complex belt of migmatites developed immediately to the northwest of the Boesmanskop syenite pluton (i.e. the Batavia section H-E-F-G, Figure 2) is one such area where the nature of the migmatite is somewhat unusual and the interpretation of which is not particularly clear.

This outcrop, like others in the vicinity (e.g. outcrop E, Figure 10) is complexly deformed. It consists of a series of irregular quartz-diorite bodies that are enveloped by well-foliated trondhjemite gneisses and syn-tectonic, anatectic veins. The relative volumes of enveloping gneiss, as opposed to anatectite, are seen to be highly variable from one part of the outcrop to another (Figure 14, A and B).

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Figure 14 : *Detailed map of migmatite outcrop F, on the farm Batavia 151 IT. The map illustrates the relationship between deformed quartz-diorite dykes, palingenetic anatectites and trondhjemite gneiss. The locality of the outcrop is shown in Figure 2.*

In Figure 14A, deformed quartz-diorite bodies are enveloped by trondhjemite gneisses (Plate 3C) which themselves are intruded by numerous, folded and contorted anatectic veins. The quartz-diorite bodies consist predominantly of equigranular quartz and plagioclase which occur together with small, interstitial euhedra of biotite. The laths of biotite have a preferred orientation which testifies to the syn-tectonic nature of the quartz-diorite veins. In spite of the deformed nature of the quartz-diorite, these bodies are considered to have intruded the trondhjemite gneiss and in certain places they clearly truncate the small folded and buckled anatectic veins that occur within the latter (Figure 14A). In addition, the quartz-diorite veins are usually accompanied by a thin selvedge represented by quartzo-felspathic veinlets which serve to outline the distroted boundaries of these veins. This is suggestive of the fact that the intrusion of the quartz-diorite veins was accompanied by localized re-melting of the host trondhjemite gneiss and that the anatectic melt thus derived was not mobilized, but remained intact at the site in which it was generated. These marginal anatectic veins are coarse-grained (they may be almost pegmatoid in character, in certain places) and consist dominantly of plagioclase and quartz with interstitial biotite and minor microcline. In places the biotite is altered to chlorite.

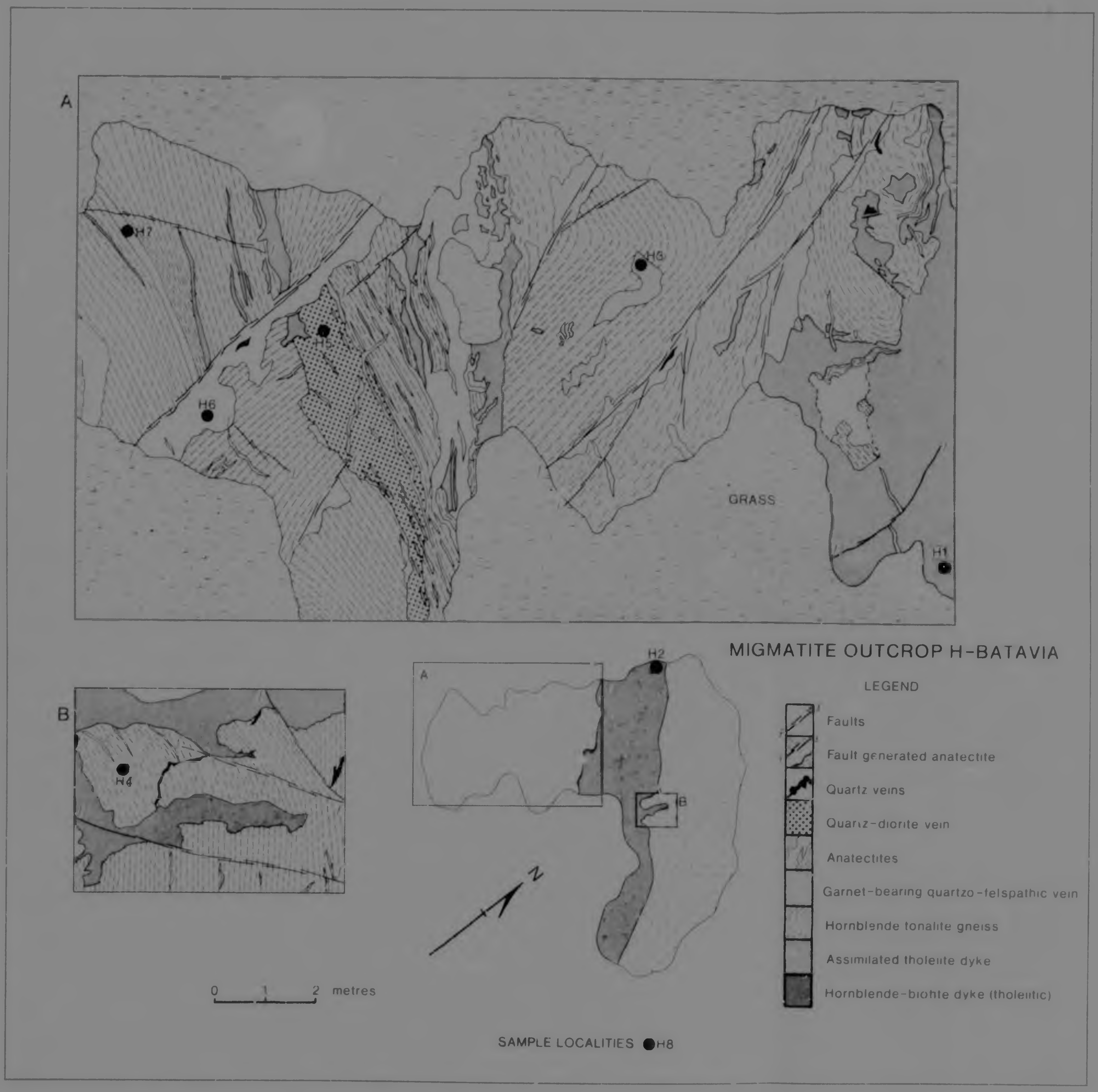
The trondhjemite gneiss has a markedly different texture to the intrusive quartz-diorite veins; it is much coarser-grained and consists dominantly of plagioclase and quartz together with lesser amounts (10 - 15%) of coarse-grained biotite, much of which is chloritized. Minor apatite also occurs in the rock. The distorted anatectic veinlets that occur within the trondhjemite gneiss are coarser-grained than the latter and also contain significantly less biotite (i.e. < 5%). There is little distinction between these anatectites and those that occur as a selvedge to the quartz-diorite veins.

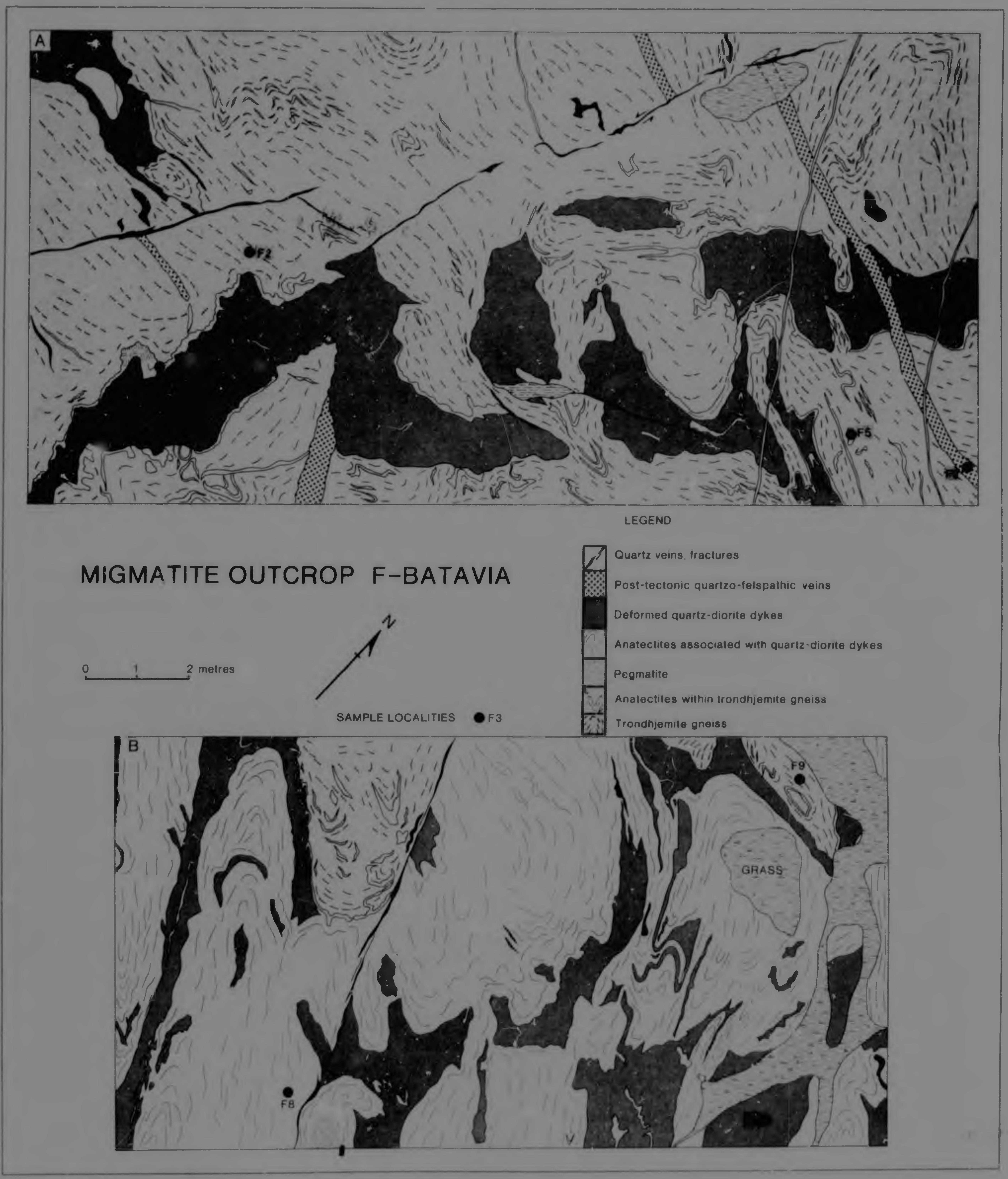
In Figure 14B, a different situation prevails to that described for the accompanying mapped section, although the components in the two outcrops (which are situated no more than twenty metres apart) are similar. In this section the highly deformed quartz-diorite veins are totally enveloped by quartzo-felspathic material that is similar in appearance to the anatectites described above. The quartz-diorite veins are identical to those enveloped by the trondhjemite gneisses and, in places, clearly demonstrate the presence of at least two fold increments (e.g. in Figure 14B, an early fold closure is seen to be re-folded about an axis that is orientated at right angles to the earlier event; see also Plate 3C.) The quartzo-felspathic anatectic material which in this case, totally envelopes the bodies of quartz-diorite, has a different texture to the smaller, marginal anatectic veinlets described above. The former consists of medium-to-coarse grains of plagioclase and quartz which are surrounded by finer-grained interstitial material consisting also of plagioclase and quartz, together with minor chlorite, muscovite and microcline. This texture suggests that the rock may originally have been a crystal-mush and that the finer-grained assemblage represents the chilled liquid (anatectic) component. The presence of this extensively developed anatectic phase suggests that the quartz-diorite veins in Figure 14B, although originally intrusive into the trondhjemitic gneisses, were subsequently reintruded by an anatectite that itself, was derived from the trondhjemite gneisses (*). The outcrop appears, therefore, to represent an example of *palingenesis*, where the oldest component of the outcrop (i.e. the trondhjemite gneisses) has, in the words of Sederholm (1926) ".... received a new eruptivity" and reintruded an effectively younger component (i.e. the quartz-diorite). The nature of palingenetic processes is illustrated in an analagous situation, but on a smaller scale, in Plate 5F.

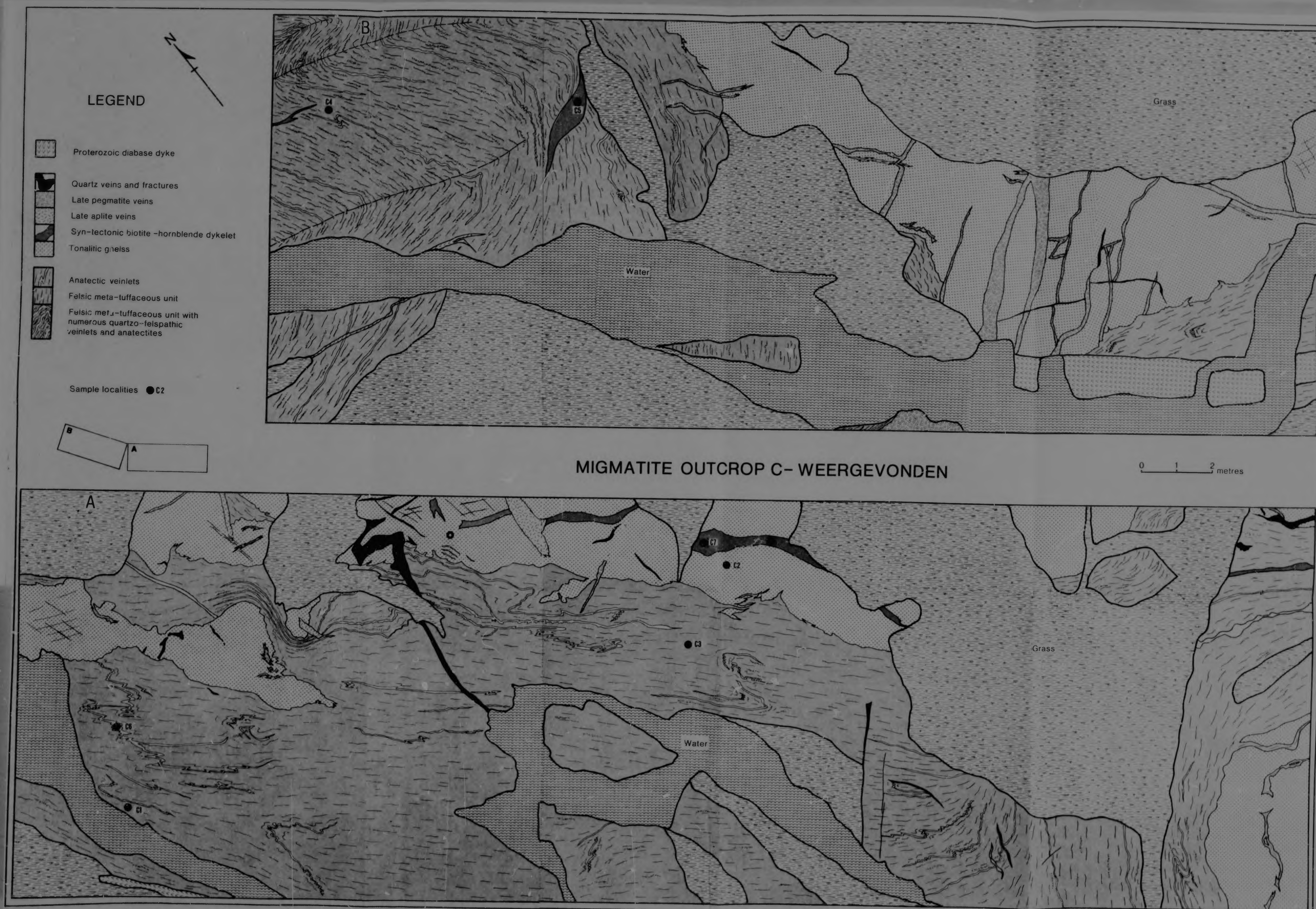
The deformation sequence at this outcrop has resulted in the occurrence of significant faulting which has taken place subsequent to the emplacement of post-tectonic quartzo-felspathic and pegmatitic veins. These veins form straight, undeformed dykes which cut across the older components of the outcrop, but are, in turn, displaced (often by 2 - 3 metres) by these faults. The latter are now invariably filled with milky-white quartz material. The post-tectonic quartzo-felspathic veins have a similar composition and contain the same mineral constituents as they syn-tectonic anatectites described above; the pegmatite veins, however, consist predominantly of coarse-grained microcline-perthite, interstitial to which finer-grained quartz, plagioclase and muscovite is developed.

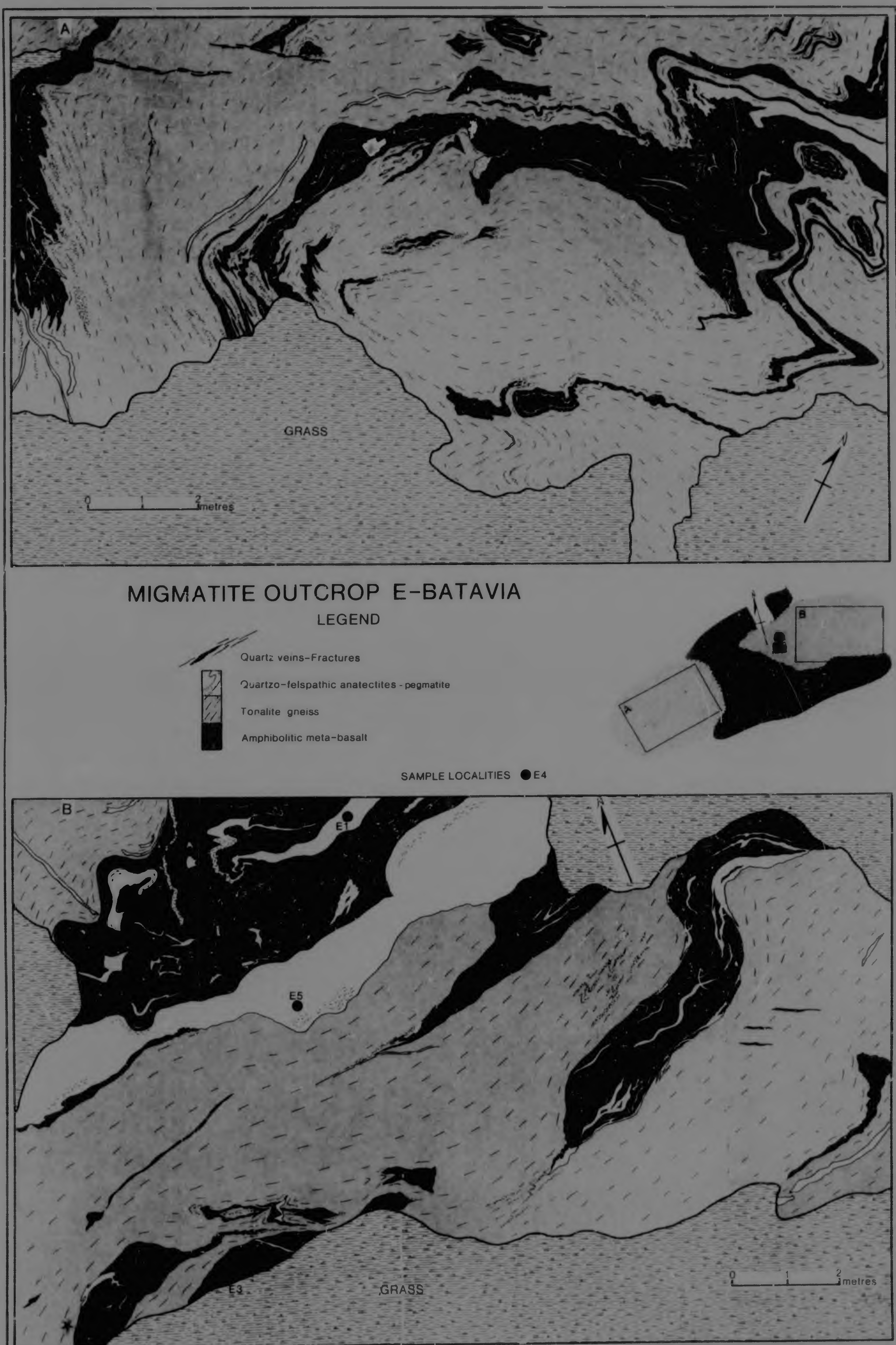
Footnote (*) : it is necessary to stress at this stage that the petrogenesis of anatectites in the study area is considered in detail in section 3 of Chapter 3. Model considerations indicate that the chemical characteristics of these rocks are compatible with an origin by partial melting of tonalitic-trondhjemitic precursors.

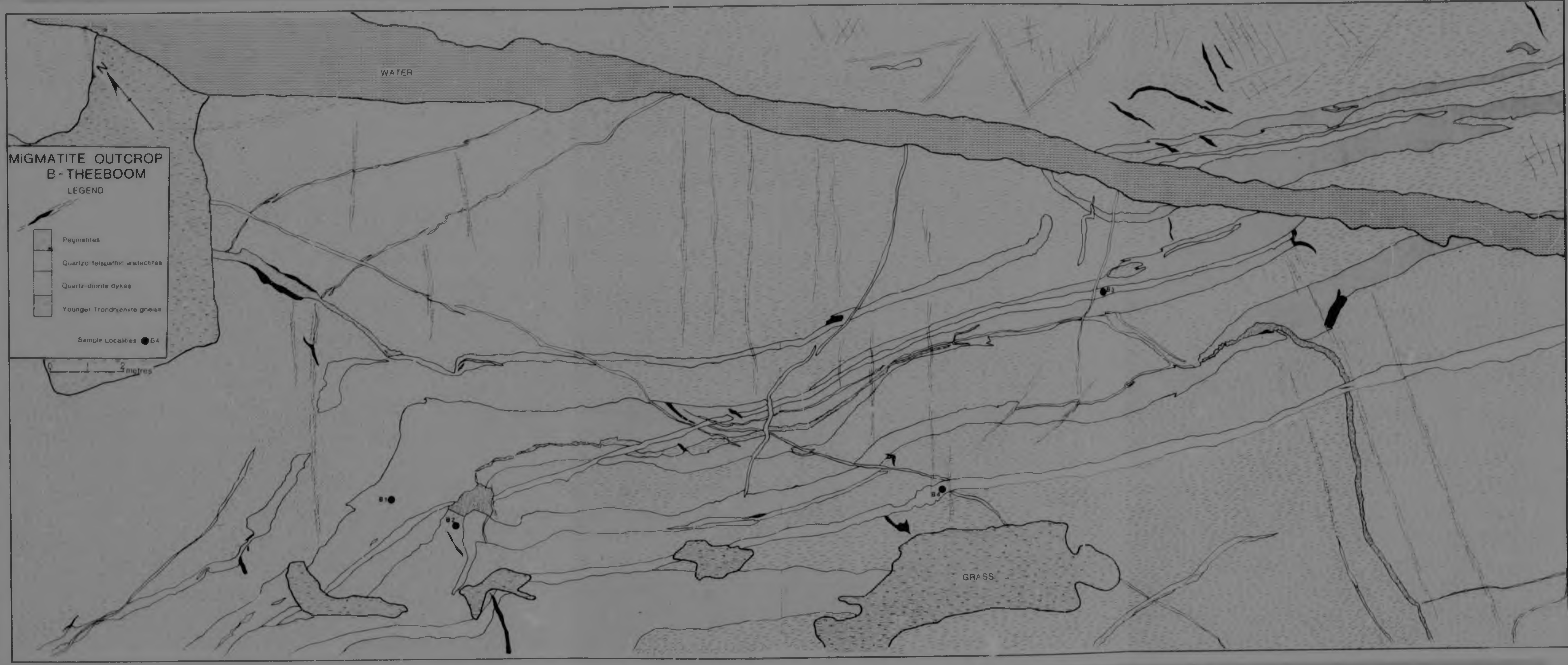

GRASS
GRASS
FENCE
MIGMATITE OUTCROP D–MARA
LEGEND
Early pegmatite veins
Intermediate pegmatite veins
Late pegmatite veins
Schlieric potassic gneiss
Diorite, assimilated equivalent of amphibolite D2
Amphibolitic meta-basalt
Sample Localities D4
N
0
1
2
METRES
D4


A
H7
H5
H3
H6
GRASS
H1
B
H4
A
H2
B
N
0 1 2 metres
MIGMATITE OUTCROP H-BATAVIA
LEGEND
Faults
Fault generated anatectite
Quartz veins
Quartz-diorite vein
Anatectites
Garnet-bearing quartzo-felspathic vein
Hornblende tonalite gneiss
Assimilated tholeiite dyke
Hornblende-biotite dyke (tholeiitic)
SAMPLE LOCALITIES H8


A
F2
F5
LEGEND
MIGMATITE OUTCROP F-BATAVIA
Quartz veins, fractures
Post-tectonic quartzo-felspathic veins
Deformed quartz-diorite dykes
Anatectites associated with quartz-diorite dykes
Pegmatite
Anatectites within trondhjemite gneiss
Trondhjemite gneiss
0 1 2 metres
N
SAMPLE LOCALITIES F3
B
F9
GRASS
F8


MIGMATITE OUTCROP C- WEERGEVONDEN
LEGEND
N
Proterozoic diabase dyke
Quartz veins and fractures
Late pegmatite veins
Late aplite veins
Syn-tectonic biotite -hornblende dykelet
Tonalitic gneiss
Anatectic veinlets
Felsic meta-tuffaceous unit
Felsic meta-tuffaceous unit with numerous quartzo-felspathic veinlets and anatectites
Sample localities C2
B
A
0 1 2 metres
Grass
Water
C1
C2
C3
C4
C5
C6
C7


A
GRASS
0 1 2 metres
MIGMATITE OUTCROP E-BATAVIA
LEGEND
Quartz veins-Fractures
Quartzo-felspathic anatectites - pegmatite
Tonalite gneiss
Amphibolitic meta-basalt
SAMPLE LOCALITIES ● E4
A
B
B
E1
E5
E3
GRASS
0 1 2 metres


WATER
MIGMATITE OUTCROP
B - THEEBOOM
LEGEND
Pegmatites
Quartzo felspathic anatectites
Quartz diorite dykes
Younger Trondhjemite gneiss
Sample Localities B4
0 1 2 metres
GRASS

8.2. Geochemistry

The quartz-diorite veins from outcrop F in the Batavia section have similar chemical attributes to quartz-diorites that occur in the previously described migmatite outcrops. These rocks are generally characterized by a lower SiO_2 content than the tonalite or trondhjemite gneisses that they intrude (≈67%) and a concomitantly higher Fe_2O_3* + MgO content (≈4 - 5%). The K_2O/Na_2O ratios of the quartz-diorite bodies are similar to those of the trondhjemites but at this particular outcrop the sodium contents are lower than average (3 - 4%) with CaO contents being somewhat high, in the range 3 - 4%. (Table 6). The Rb, Sr and Ba contents of the quartz-diorite veins are indistinguishable from those of the adjacent trondhjemite gneiss. The quartz-diorite dykes have a very similar REE pattern, on a chondrite-normalized plot, to those of other quartz-diorite veins (Figure 36, Chapter 3) and are characterized by LREE enrichment and no detectable Eu anomaly; these characteristics are also indistinguishable from those in the trondhjemite gneisses, suggesting a genetic link between these two units.

The anatectic veins from outcrop F are characterized by a range in both major and trace element compositions. Silica contents vary between 69 - 74% with Fe_2O_3* + MgO contents in the range 1 - 4% (see Columns 4, 5 and 6, Table 6). The high ferromagnesian content of certain of the anatectic veins is not characteristic of similar rock types from the previously described migmatite outcrops. In this regard, the chloritized aspect of biotites from these rock types suggests that this mineral may represent an entrained restite phase, so that the high iron and magnesium contents do not necessarily reflect the primary anatectic compositions. The low K_2O/Na_2O ratios (between 0,1 - 0,6) of the anatectites at outcrop F are similar to those from the quartzo-felspathic veins at outcrop E, also in the Batavia section. As previously mentioned, these ratios differ from the $K_2O/Na_2O > 1$ that characterizes the anatectites from the Theeboom and Rooihoogte outcrops; this topic is discussed in more detail in Chapter 3. The Rb contents of these anatectites are generally low with Rb/Sr ratios also being lower than those usually characteristic of the trondhjemite gneisses (Table 6). The single REE analysis of anatectic material from the zone of palingenesis is characterized by a pronounced positive Eu anomaly on a chondrite normalized diagram (Figure 26) suggesting the presence of cumulus plagioclase in the rock.

TABLE 6

CHEMICAL ANALYSES OF COMPONENTS FROM MIGMATITE OUTCROP F - FARM BATAVIA 151IT

		1	2	3	4	5	6	7	8
		F1	F7	F9	F5	F6	F8	F3	F4
	SiO_2	67,93	67,76	69,85	68,76	69,92	74,38	72,33	70,65
	TiO_2	0,26	0,41	0,31	0,36	0,21	0,05	0,11	0,02
	Al_2O_3	17,66	15,78	15,56	15,48	15,85	14,94	14,97	16,10
	Fe_2O_3*	3,00	4,02	3,23	3,50	2,30	0,81	1,04	0,46
	MnO	0,01	0,04	0,01	0,03	0,02	0,02	0,01	0,01
Wt.%	MgO	0,94	1,43	1,23	1,08	0,62	0,21	0,22	0,10
	CaO	3,37	3,86	2,93	2,7[illegible]	2,96	2,54	1,80	0,39
	Na_2O	3,93	3,69	4,08	3,61	4,61	5,26	4,87	2,61
	K_2O	1,62	1,35	1,22	2,24	0,96	0,57	2,15	8,46
	P_2O_5	0,08	0,13	0,07	0,08	0,01	0,01	0,02	0,01
	L.O.I.	0,38	0,37	0,75	0,66	0,64	0,45	0,60	0,33
	TOTALS	99,18	98,84	99,24	98,53	98,10	99,24	98,12	99,14
	Rb	21	18	25	36	14	2	16	143
	Sr	557	174	386	320	467	346	395	89
	Ba	314	142	237	343	200	73	312	128
	La	21,7	-	33,6	-	-	2,5	-	-
	Ce	40,8	-	54,5	-	-	2,9	-	-
ppm	Nd	14,1	-	25,3	-	-	-	-	-
	Sm	2,85	-	3,73	-	-	0,23	-	-
	Eu	0,90	-	0,86	-	-	0,45	-	-
	Tb	0,51	-	0,52	-	-	0,01	-	-
	Yb	0,58	-	0,59	-	-	0,12	-	-
	Lu	0,07	-	0,06	-	-	0,02	-	-

(Analyst: L.J. Robb

Fe_2O_3* - Total iron as Fe_2O_3)

Columns 1 - 2 - Syn-tectonic quartz-diorite dykes
3 - Trondhjemite gneiss
4 - 5 - Anatectic veins intimately associated with the trondhjemite
6 - Anatectite from zone of palingenesis
7 - Post-tectonic quartzo-felspathic vein
8 - Post-tectonic pegmatitic vein

Sample localities shown in Figure 14

The trondhjemite gneiss at outcrop F is characterized by silica $\approx 70\%$, $Fe_2O_3^* + MgO < 4\%$ and a low K_2O/Na_2O ratio ($< 0,2$). The Rb, Sr and Ba contents are typical of similar rock types analysed from the study area. The REE pattern, likewise, is typically LREE enriched with no significant Eu anomaly; the ΣREE content, however, is marginally higher than that for trondhjemite gneisses from other migmatite outcrops described (Figure 20).

The post-tectonic veins at outcrop F vary in composition, with one (i.e. F3, Table 6) closely resembling the anatectites described above and possibly being genetically related to the latter. The pegmatite vein is characterized by high K_2O/Na_2O (> 3) and Rb/Sr ($> 1,5$) ratios. This vein is probably related to the emplacement of the Mpuluzi batholith (Figure 2) the peripheral effects of which may be seen 2 - 3 kilometres from its edge.

8.3. Summary statement

Outcrop F in the Batavia section illustrates the complex effects of anatexis and palingenesis in the development of migmatitic rocks in the Barberton Mountain Land. A foliated trondhjemite gneiss has been intruded by quartz-diorite veins, the latter possibly being genetically related to the gneiss. Both units have been deformed and folded together by at least two successive increments of strain. Either, during these tectono-thermal processes or, at the time of emplacement of the quartz-diorite veins, temperature and pressures were sufficiently high that partial melting was initiated. It is suggested that anatectites, probably generated from a trondhjemitic precursor, were themselves intruded into the sites where the quartz-diorite veins had been emplaced. These effects appear to be subordinate in one portion of the outcrop where anatectites form selvedges to the quartz-diorite bodies. In another part, however, the latter appear to have been totally enveloped by anatectic material so that the original intrusive bodies are themselves palingenetically re-intruded. Migmatites derived by processes such as these can be regarded as having an arteritic origin in spite of the fact that the anatectites were probably locally derived.

9. MIGMATITE OUTCROP G - BATAVIA

9.1. Geological description

Facets of the complex and deformed zone of migmatites that are developed in the Batavia section (i.e. the section H-E-F-G, Figure 2) have

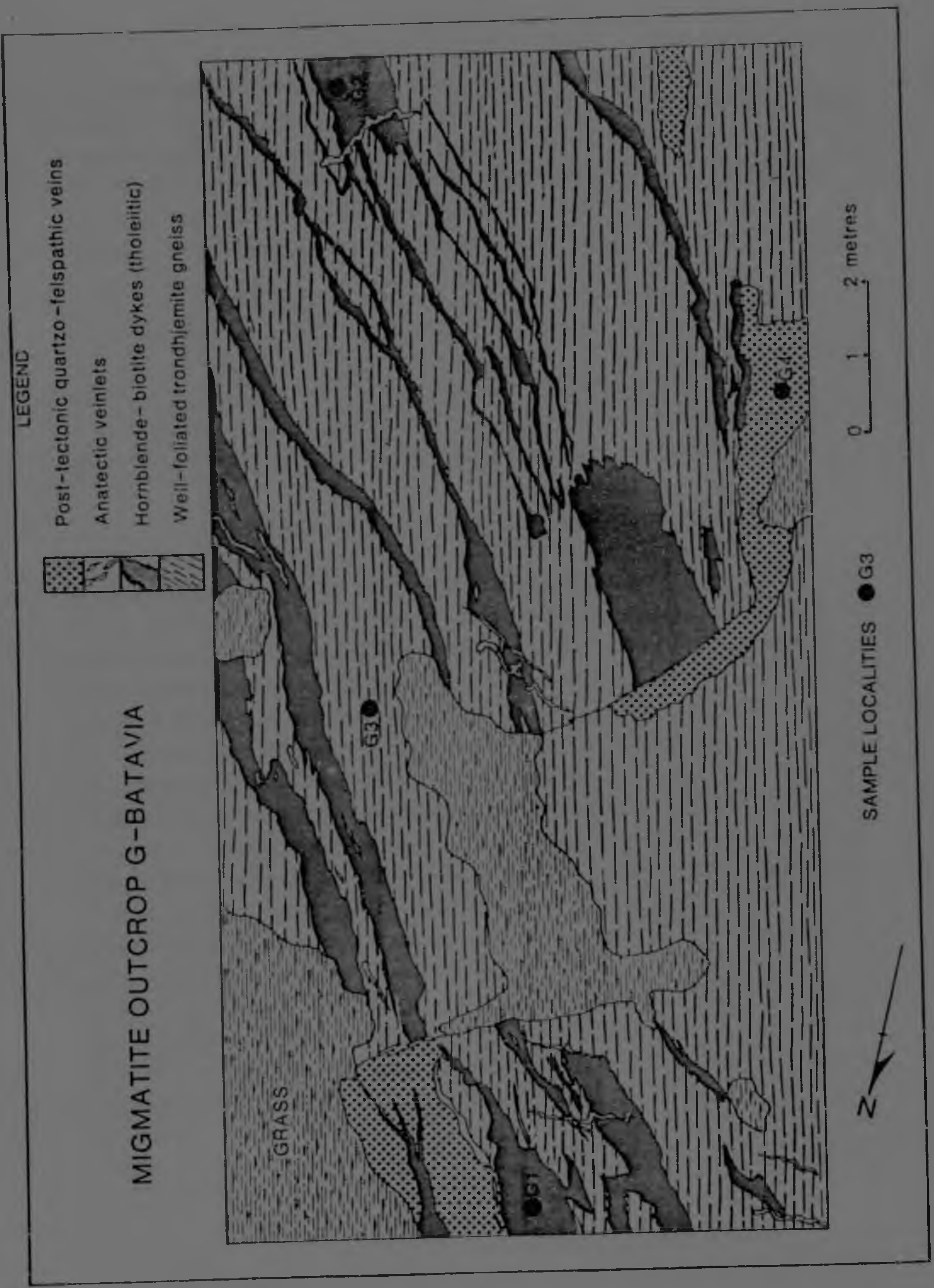


Figure 15 : A detailed map of migmatite outcrop G on the farm Batavia 151 IT. The map illustrates the relationship between discordant, migmatized tholeiite dykes and a well-foliated trondhjemite gneiss. Locality of the outcrop is shown in Figure 2.

been alluded to above in the descriptions of outcrops E and F. These two exposures illustrate the deformed nature of the various components that make up these migmatite outcrops and also refer to the processes of anatexis and palingenesis that have characterized their formation. At outcrop G, however, a migmatitic exposure has been mapped that is significantly different in character to those encountered in the previous descriptions. In this outcrop, bands of mafic material clearly transgress the gneissocity of the enveloping trondhjemite gneiss (Figure 15), a feature which is in marked contrast to the more common situation where amphibolitic remnants are generally structurally concordant with the trondhjemite foliation, or can be recognized as xenoliths. The salient features which distinguish between amphibolitic dykes and xenoliths, both of which occur in the Batavia section, are illustrated in Plate 4 E and F.

The meta-basaltic bands at this outcrop have been migmatized, assimilated and deformed in much the same way as have the amphibolitic xenoliths at, for example, outcrop E in the Batavia section (Plate 5B). In this sense the meta-basaltic bands might closely resemble these xenoliths were it not for the fact that they are markedly discordant with respect to the trondhjemite gneissocity. This feature is illustrated in Figure 15 where it is apparent that the meta-basaltic bands must originally have been intrusive into the trondhjemite. This outcrop, therefore, is particularly important in understanding the genesis of migmatites in the study area as it demonstrates the presence of intrusive syn-tectonic amphibolite dykes the latter contrasting with the previously described amphibolitic bodies that are correlated with the greenstone successions and which are considered extrusive in origin.

The meta-basaltic dykes may have irregular shapes and are invariably shredded apart by numerous small anatectic veinlets. These characteristics are illustrated in Plate 5 A and B where it is seen that a discordancy of between 10 - 20^{o} exists between the dykes and the trondhjemite foliation. In thin section the dykes consist predominantly of subhedral hornblende and biotite together with highly sericitized plagioclase. The rock also consists of minor sphene, quartz, magnetite and muscovite. The biotite in the rock is highly chloritized and the hornblende is usually preserved in various stages of alteration and disintegration. The margins of individual hornblende grains are invariably eroded and in places the hornblende can be seen to be disintegrating along cleavage planes where micro-veinlets

<u>PLATE 5</u>

A. *Migmatized and assimilated amphibolitic dyke intrusive into banded trondhjemite gneiss at outcrop G, Batavia section.*

B. *Irregularly shaped and deformed amphibolitic dyke from the same locality as Plate 5A; this unit might easily have been incorrectly interpretted as an amphibolitic xenolith were it not for discordancies preserved between it and the enveloping gneiss.*

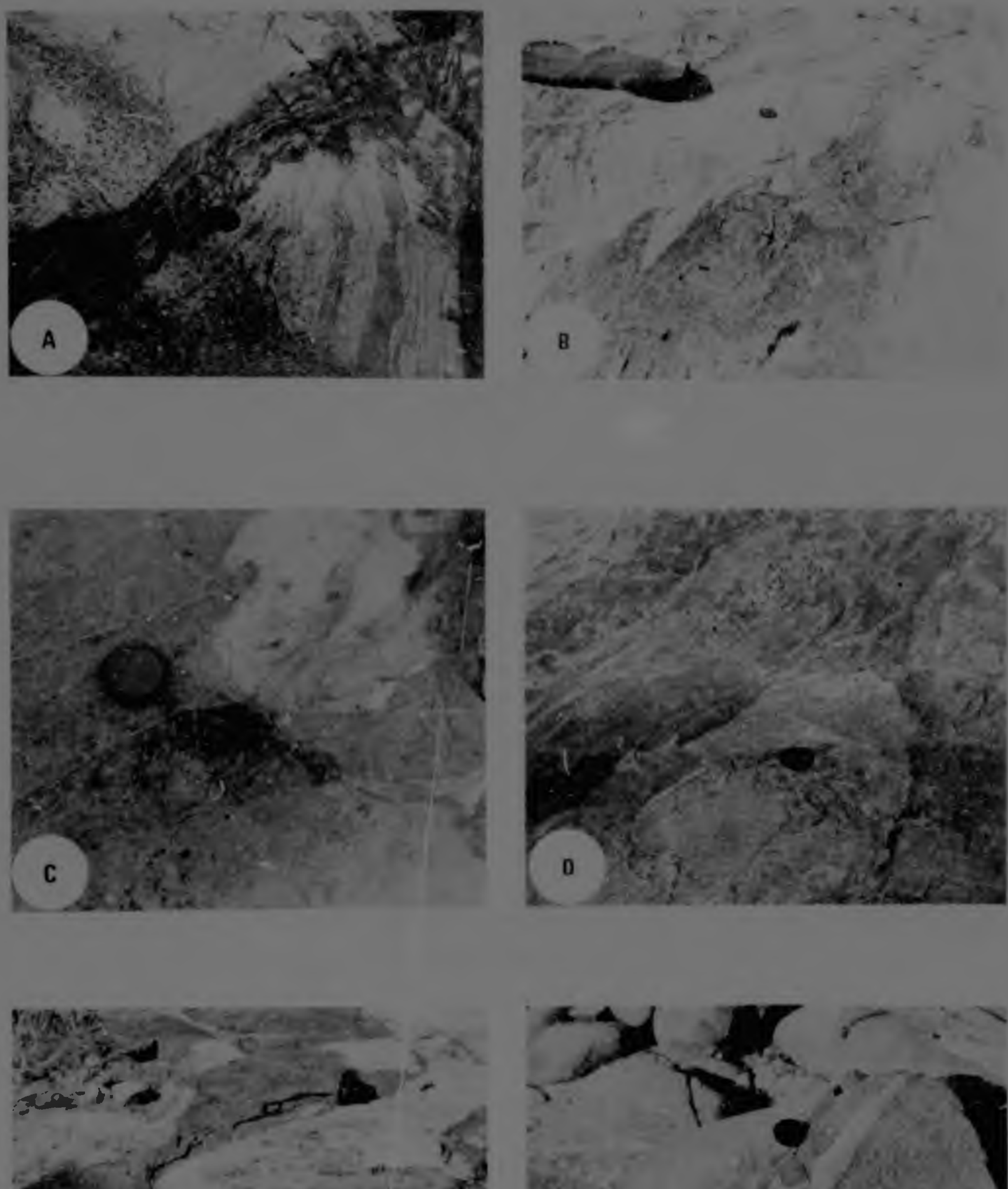
C. *Possible intrusive relationship between amphibolite and banded trondhjemite gneiss at the Mooiplaats outcrop. The interpretation of the amphibolite as a dyke is equivocal due to the presence of a fracture which may either, have resulted in the observed discordancy or, have controlled the original emplacement of the dyke.*

D. *"Horned" structure, typical of the intrusion of mafic dykes into granitic material. Structures such as these from the Mooiplaats outcrop, again suggest that the amphibolite bodies in this area were intruded as dykes.*

E. *Possible linear dyke-like features in amphibolites from the Mooiplaats outcrop; the amphibolite body in the right foreground contains a felsic remnant which is possibly a xenolith from the host trondhjemite gneiss.*

F. *Palingenetic effects of a small mafic dyke being reintruded by anatectic material which was formed locally during the actual emplacement of the dyke into its tonalitic host rock. This occurrence was photographed in the Tuross Heads tonalite, a ≈ 400 m.y. body forming one component of the Moruya batholith in the southern part of New South Wales, Australia.*

PLATE 5



of quartz and plagioclase have penetrated the grain. These petrographic characteristics indicate that the rock has reached an advanced state of alteration which is a combination of residence contamination and the effects of intrusion by small anatectic veinlets. The dykes have clearly been present during a substantial portion of the tectonic and metamorphic history that has accompanied the deformation of the trondhjemite gneiss.

The trondhjemitic gneiss which the meta-basaltic dykes intrude, is characterized by a very pronounced foliation. In thin-section this fabric is reflected in long stringers of plagioclase and quartz which occur together with minor microcline; a minor amount of biotite is also present in the rock and occurs with a strongly preferred orientation that parallels the compositional banding. A third component of the outcrop is a post-tectonic quartzo-felspathic vein which cuts both the trondhjemite and meta-basaltic dykes (Figure 15). This vein is devoid of biotite or hornblende and consists predominantly of sericitized plagioclase, quartz and small amounts of epidote.

When viewed in terms of the structural characteristics of migmatites at the nearby outcrops E and F (Figures 10 and 14), the nature of the meta-basaltic dykes at outcrop G provide an indication as to the timing of their emplacement. The components of both E and F outcrops were described as having been complexly deformed, possibly in response to two, or more, discrete stress increments. At outcrop E, for example, amphibolitic xenoliths, interpreted as representing a remnant greenstone, have been folded such that small-scale dome/basin structures have formed (Figure 10). By contrast, the meta-basaltic dykes discussed here, although much altered and migmatized, have not been subjected to all the strain increments that characterize the outcrops at E and F. Whereas the amphibolitic xenoliths described previously were generally structurally concordant with respect to the trondhjemite gneissocity, the amphibolitic dykes post-date at least the early fabric-forming episode and, hence, also post-date the greenstone remnants in the area. These dykes could not, therefore, represent feeders to the earlier developed greenstone successions, the latter being characterized dominantly by mafic and ultramafic volcanics with komatiitic affinities.

9.2. Geochemistry

Where relatively unaltered, the meta-basaltic dykes at outcrop G have a composition that is very similar to meta-basaltic tholeiites that have

TABLE 7

CHEMICAL ANALYSES OF COMPONENTS FROM
MIGMATITE OUTCROP G - FARM BATAVIA 151IT

		1	2	3	4
		G1	G2	G3	G4
	SiO_2	49,13	51,46	69,96	68,91
	TiO_2	0,88	0,67	0,16	0,21
	Al_2O_3	16,60	15,83	17,06	16,41
	Fe_2O_3*	10,31	7,70	1,68	2,28
	MnO	0,14	0,15	0,01	0,03
Wt.%	MgO	8,10	6,00	0,52	0,65
	CaO	9,70	6,59	3,25	3,29
	Na_2O	3,14	3,26	4,71	5,48
	K_2O	1,46	3,15	1,01	1,36
	P_2O_5	0,42	0,23	0,04	0,05
	L.O.I.	0,97	5,52	0,29	0,66
	TOTALS	100.85	100,56	98,69	99,33
	Rb	64	110	15	16
	Sr	434	404	620	219
	Ba	223	647	187	149
	La	18,2	-	10,3	-
	Ce	44,2	-	11,6	-
ppm	Nd	26,3	-	5,3	-
	Sm	4,83	-	1,05	-
	Eu	1,80	-	0,41	-
	Tb	1,26	-	0,17	-
	Yb	1,80	-	0,30	-
	Lu	0,21	-	0,03	-

(Analyst: L.J. Robb
Fe_2O_3* - Total iron as Fe_2O_3)

Columns 1 - 2 - Amphibolitic dykes
3 - Trondhjemite gneiss
4 - Intrusive quartzo-felspathic vein

Sample localities shown in Figure 15

been described predominantly from the upper portions of the Onverwacht Group in the Barberton greenstone belt (Viljoen and Viljoen, 1969c). The dykes are characterized by SiO_2 ≈50%, low MgO contents between 6 - 8% and a low CaO/Al_2O_3 ratio (between 0,4 - 0,6, see Table 7). The tholeiite dykes also differ significantly from typical basaltic komatiites in the Barberton area in that they have a much higher K_2O content, in the range 2 - 3%. This factor is a reflection of both the biotite content of the rock as well as the contaminated nature of the dykes. The tholeiite dykes are also characterized by much higher Rb, Sr and Ba contents than typical komatiites and, likewise, have a REE content that is higher than the latter. Furthermore, on a chondrite normalized diagram (Figure 33) these amphibolites have more evolved pattern than the flat-trending komatiites and the dykes are slightly LREE enriched with a Ce_N/Yb_N ratio of approximately 5 (Table 7). A detailed assessment of the chemical differences between the amphibolitic dykes and meta-basaltic xenoliths from the various migmatite outcrops described, is presented in section 4 of Chapter 3.

The trondhjemite gneiss at outcrop G is typical of other trondhjemites in the area with a SiO_2 content of approximately 70%, Fe_2O_3* + MgO ≈3% and a low K_2O/Na_2O ratio (≈0,2). The gneiss is typically LREE enriched, with no significant Eu anomaly and a Ce_N/Yb_N ratio of approximately 10 (Table 7). The quartzo-felspathic vein at this outcrop is chemically similar to other anatectites from the Batavia section and has SiO_2 ≈69% and a low K_2O/Na_2O ratio of 0,25. The ferromagnesian content of the vein is approximately 3% and, as in the case of outcrop F, this may be due to the presence of an entrained restite phase.

9.3. Summary statement

Migmatite outcrop G in the Batavia section proves the existence of a very early phase of mafic dykes in the Barberton Mountain Land. Dykes of this nature have, in fact, been recognized previously by Anhaeusser (1966) who commented on their syn-tectonic character. These dykes, of tholeiitic composition, are clearly different from other amphibolitic bodies that are related to migmatites in the region and which occur as xenoliths, or structurally infolded remnants, within tonalitic or trondhjemitic gneisses. The dykes, being intrusive in nature, are also significantly different from the amphibolitic remnants that are correlated with the greenstone successions and which must have originally been extrusive. The dykes are also characterized by marked alteration and assimilation which is related to the processes of migmatization and, as a result, may appear indistinguishable from amphibolitic xenoliths in the area. The unequivocal recognition of the dykes, therefore, depends entirely on the preservation of a recognizable discordancy between dyke and trondhjemite gneissocity. The dykes do not, however, appear to have been subjected to the entire structural pre-history that is apparent in other migmatite outcrops adjacent to the one discussed above. They are not, therefore, likely to have been feeders to the oldest greenstone successions in the area (i.e. the Tjakastad Subgroup), but may represent an intrusive counterpart to younger (dominantly tholeiitic) volcanic successions possibly related to the Geluk Subgroup (see Figure 2).

10. MIGMATITE OUTCROP H - BATAVIA

10.1. Geological description

Of the four migmatite outcrops mapped in the Batavia section (i.e. the section H-E-F-G, Figure 2) the present exposure is particularly instructive in demonstrating the complexities which can accompany the formation of migmatitic rocks in this area. The outcrop is illustrated in detail in Figure 16A and B, which also shows a schematic outline of the outcrop as a whole. The latter schematic diagram shows the outcrop to consist of a linear dyke-like amphibolitic body enveloped on both sides by a hornblende tonalite gneiss. In places the amphibolite is clearly discordant with respect to the fabric of the enveloping gneissic material and, in this regard, a similarity exists between this outcrop and that described in the preceding section (i.e. outcrop G).

Details of the contact between amphibolite dyke and tonalite gneiss, as well as the heterogeneous nature of the gneiss, are provided in Figure 16A. The outcrop here is dominated by a well foliated hornblende tonalite gneiss which has been faulted in numerous places. A result of this faulting is that no systematic orientation of the mineral fabric in the tonalite exists and the foliation on one side of a fault may occur obliquely, or even at right angles, to that on the other side. Most of the faults are accompanied by felsic anatectic material which cuts across all other components of the outcrop. The contact between tonalite and mafic dyke is a complex one and enigmatic; in certain places (Figure 16B), the amphibolite dyke is clearly discordant with respect, both to the tonalite fabric and to small quartzo-

Figure 16 : Detailed map of migmatite outcrop H on the farm Batavia 151 LT. The map illustrates the relationship between what is believed to be a tholeiitic dyke and a palingenetic tonalite gneiss. The locality of the outcrop is shown in Figure 2.

felspathic anatectites that occur within the tonalite. In other places, however (Figure 16A) the amphibolite has clearly been assimilated by the tonalite with which it is in contact. The latter feature is also apparent in that the hornblende tonalite has a variable mafic content and contains between 5% and 20% hornblende from one place to the next. The tonalite itself consists predominantly of plagioclase with lesser amounts of quartz and a variable hornblende content. In thin-section the hornblende has a distinctly anhedral and poikilitic texture with severely corroded grain margins. This feature, together with the variable hornblende content of the tonalite, indicates that the rock, as a whole, may be a product of hybridization resulting from processes of assimilation or mixing between the amphibolitic dyke and, what was originally, a hornblende-free anatectite.

The mechanics of this assimilation process are demonstrated in a series of samples (i.e. samples H1, H2 and H3, Table 8) that were collected to illustrate the progressive textural changes that take place from pristine amphibolite (H1) to hybridized equivalent (H3). In thin section, the pristine amphibolite consists predominantly of euhedral-to-subhedral hornblende (≈75%), together with minor light-brown to brown pleochroic biotite and small amounts of plagioclase and quartz. This rock is similar to the tholeiitic dykes described from outcrop G, which also contain a predominantly amphibole-mica assemblage. Sample H2 demonstrates the effects of incipient hybridization and contains significantly less hornblende (≈65%) with greater amounts of plagioclase together with minor quartz and biotite. Unlike the amphibole in H1, the hornblende in sample H2 is subhedral, is characterized by weak twinning and has corroded grain margins. In addition, certain hornblende grains have started to physically disintegrate, particularly along cleavage planes where minute veinlets of plagioclase and quartz have permeated (Plate 6C). In sample H3 the same effects are seen and hornblende, which now makes up only ≈55% of the rock, has, in some instances, been markedly dismembered and chloritized. A significant component of the felsic contaminant is also recognized in this sample as large plagioclase grains which poikilitically enclose smaller plagioclase and hornblende grains, the latter presumably derived from the mafic dyke.

These textural and petrographic observations are clearly consistent with the process of hybridization or assimilation between two end-member components of the outcrop; one, an amphibolitic dyke and the other, a quartzo-felspathic intrusive. As the latter (possibly an anatectite) can be regarded as the contaminant in this case, it is logical to assume that it was intrusive into the amphibolitic component. However, as mentioned above, and as demonstrated in Figure 16B, the amphibolite has a dyke-like appearance and apparently *post-dates* the hybridized hornblende tonalite described above. This contradiction can best be explained by consideration of two factors; firstly, the disruptive effect of faulting on the orientation of the mineral fabric in the tonalite and, secondly, the possible palingenetic effects caused by the emplacement of a substantial mafic body into a felsic host rock.

With regards the latter point, it is quite feasible that the emplacement of a mafic dyke at near-liquidus temperatures will have the effect of locally re-melting the country rock into which it intruded. This palingenetic process, which has already been described in the account of outcrop F, can take place on a variety of scales and generally transforms a dyke from an intrusive object into a series of, often disrupted, xenoliths. This process (which is occasionally referred to as the "Sederholm effect") is illustrated on a small scale in Plate 5F where a mafic dyke intrudes a tonalite, but is itself reintruded by anatectic material that is derived virtually *in situ*. In the context of outcrop H, therefore, it is probable that the intrusion of a large amphibolite dyke (with a similar mineralogy and composition to other, unequivocally recognized dykes in the Batavia section) prompted the melting of the tonalite or trondhjemite gneisses through which it was being intruded. Subsequently, it is envisaged that physical mixing between the *in situ* derived melt and the dyke component (possibly whilst both were in a crystalline mush state), ultimately gave rise to the range of hybridized products now observed. Deformation *subsequent* to the emplacement of the dyke was responsible for the imposition of a mineral fabric in the system which was, in turn, modified and disrupted (particularly in the hornblende tonalite) by faulting (see Figure 16A). This complex series of events is particularly well demonstrated at outcrop H, but may be effective in one form or another, in most migmatitic zones in the study area.

As seen in Figure 16A, this outcrop consists of other components besides the amphibolite dyke and hornblende tonalite described above. As mentioned previously, the numerous faults that cut the outcrop are in-filled by sheared anatectic material. This anatectite has exactly the same mineral constituents as the hornblende tonalite but is finer-grained, recrystallized and generally has a more pronounced mineral fabric. Another rock-type that is intimately associated with the hornblende tonalite is a quartz-diorite dykelet. This rock is highly altered and consists predominantly of plagioclase, quartz and chlorite together with minor muscovite. The rock has evidently been deformed and sheared and mineral grain boundaries are irregular and anhedral; plagioclase twinning is often dislocated and quartz has been recrystallized. A third discrete component of the outcrop is a garnet-bearing anatectic veinlet that is aligned parallel to the fabric in the hornblende tonalite. This rock consists essentially of plagioclase and quartz together with discrete clots of coexisting garnet, biotite and hornblende. Garnet is markedly poikiloblastic and may contain inclusions of hornblende, quartz and plagioclase.

10.2. Geochemistry

The composition and mineralogy of the pristine amphibolite (hornblende-biotite) dyke at outcrop H is very similar to that of dykes described from outcrop G. The uncontaminated dyke material at outcrop H has SiO_2 ≈50%, a relatively high MgO content (11,4%) and $CaO/Al_2O_3 < 1$ (Table 3). This composition is also similar to that of typical meta-tholeiites from the Onverwacht Group (Viljoen and Viljoen, 1969c) with the exception of the MgO content of the dyke which is somewhat higher. One anomalous feature regarding the amphibolitic dykes at both outcrops G and H, is their high Rb contents (e.g. 49 ppm, Table 8) which is undoubtedly due to the presence of biotite in these rocks.

The effects of assimilation on the contaminated amphibolite dykes (i.e. samples H2 and H3) involve a systematic increase in SiO_2, Al_2O_3 and alkalis, and a decrease in Fe_2O_3, CaO and MgO, with increasing hybridization. These effects will not be discussed here as a detailed account of the process of assimilation at this outcrop, as well as others in the study area, is presented in Chapter 3.

The composition of the hornblende tonalite gneiss at outcrop H is somewhat unusual, particularly in terms of other hornblende-bearing tonalites in the region. This hornblende tonalite has low SiO_2 (≈62%), high CaO (≈5%) and an Al_2O_3 content of approximately 22% (Table 8). This is considerably higher than the alumina content of the Kaap Valley tonalite, for example, which contains between 14 - 17% Al_2O_3 (see Table 21, Chapter 4). This high Al_2O_3 content may be related to the presence of anorthite-enriched plagioclases in the hornblende tonalite, a feature which may also

TABLE 8

CHEMICAL ANALYSES OF COMPONENTS FROM MIGMATITE OUTCROP H - FARM BATAVIA 151IT

		1	2	3	4	5	6	7
		H1	H2	H3	H4	H5	H6	H7
	SiO_2	50,26	52,40	51,42	61,97	65,66	64,50	68,09
	TiO_2	1,13	0,88	0,70	0,12	0,32	0,60	0,43
	Al_2O_3	12,10	15,76	17,61	21,96	18,16	17,58	16,91
	Fe_2O_3*	11,62	8,89	9,14	1,36	2,40	4,50	3,46
	MnO	0,09	0,06	0,06	0,01	0,01	0,06	0,06
Wt.%	MgO	11,40	8,58	7,33	0,87	1,74	1,64	1,56
	CaO	9,10	9,09	8,53	5,31	2,02	5,03	4,28
	Na_2O	3,71	3,47	4,90	5,99	6,41	4,16	3,92
	K_2O	0,66	0,60	0,48	0,68	1,00	0,64	0,82
	P_2O_5	0,06	0,08	0,03	0,05	0,09	0,14	0,09
	L.O.I.	0,65	0,70	0,92	0,74	1,36	0,79	0,50
	TOTALS	100,78	100,51	101,12	99,06	99,17	99,64	100,12
	Rb	49	40	7	12	19	13	-
	Sr	190	433	518	801	344	398	397
	Ba	34	31	51	19	186	96	154
	La	-	-	3,1	4,7	-	8,7	-
	Ce	-	-	10,4	7,1	-	19,9	-
ppm	Nd	-	-	10,5	-	-	8,7	-
	Sm	-	-	2,31	0,69	-	2,37	-
	Eu	-	-	1,06	0,53	-	0,92	-
	Tb	-	-	0,59	0,19	-	0,77	-
	Yb	-	-	0,85	0,23	-	1,22	-
	Lu	-	-	0,16	0,04	-	0,16	-

(Analyst: L.J. Robb

Fe_2O_3* - Total iron as Fe_2O_3)

Columns 1 - Amphibolitic dyke
2 - 3 - Contaminated/assimilated amphibolitic dyke
4 - Hornblende [illegible]te gneiss
5 - Quartz-dior[illegible]
6 - Shear/fault-generated anatectic material
7 - Garnetiferous quartzo-felspathic veinlet

Sample localities shown in Figure 16

be reflected in the high CaO content of the rock. As mentioned previously it is considered likely that the effects of assimilation have altered the original nature of the hornblende tonalite. It was suggested that the rock may originally have been an anatectite that formed from the localized partial melting of a tonalitic or trondhjemitic gneiss precursor. A comparison of the hornblende tonalite composition (i.e. sample H4 in Table 8) with the typical characteristics of anatectites from the other migmatite outcrops (e.g. outcrops B, E, I and F), shows that this rock differs in many respects. The hornblende tonalite has lower SiO_2 and higher CaO and Al_2O_3 contents than any of the typical anatectites previously described. The full reason for this discrepancy is not clear but may, in part, be due to the presence of the hornblende contaminant in the rock. However, if the hornblende tonalite bulk composition is recalculated after removing its hornblende component then it is certainly characterized by a chemistry that is more typical of certain of the anatectites previously described. In the section dealing with the petrogenesis of anatectites in Chapter 3, the composition of sample H4 is recalculated hornblende-free and compared with that of typical anatectites from other migmatite outcrops. Although discrepancies (i.e. a high Al_2O_3 content) still exist in spite of these considerations the overall characteristics of the rock are, nevertheless, consistent with it having a partial melt origin. The Sr content of the hornblende tonalite (i.e. ≈800 ppm, Table 8) is also considerably higher than that generally found in anatectites from the area but this may reflect either, an anomalously high Sr content in the source material or, the degree of partial melting involved in generating the rock. The REE content of H4, on the other hand, is similar to that of the orthoclase-depleted anatectites described in Chapter 3. On a chondrite normalized plot (Figure 26), the REE pattern of the hornblende tonalite shows a similar pattern, with the flattish trend and positive Eu anomaly that is characteristic of the low K_2O/Na_2O, plagioclase-dominated anatectites.

The composition of the fault-generated anatectic material (sample H6, Table 8) is very similar in terms of both major and trace elements to that of the hornblende tonalite. The former also has low SiO_2 (≈64%), a low K_2O/Na_2O ratio (0,15), as well as low Rb and Ba contents which are in keeping with the typical characteristics of plagioclase-dominated anatectites. The garnetiferous anatectic vein (sample H7) is characterized by higher SiO_2 (≈68%), lower Al_2O_3 (≈17%), low K_2O/Na_2O (≈0,2) and an anomalously be reflected in the high CaO content of the rock. As mentioned previously it is considered likely that the effects of assimilation have altered the original nature of the hornblende tonalite. It was suggested that the rock may originally have been an anatectite that formed from the localized partial melting of a tonalitic or trondhjemitic gneiss precursor. A comparison of the hornblende tonalite composition (i.e. sample H4 in Table 8) with the typical characteristics of anatectites from the other migmatite outcrops (e.g. outcrops B, E, I and F), shows that this rock differs in many respects. The hornblende tonalite has lower SiO_2 and higher CaO and Al_2O_3 contents than any of the typical anatectites previously described. The full reason for this discrepancy is not clear but may, in part, be due to the presence of the hornblende contaminant in the rock. However, if the hornblende tonalite bulk composition is recalculated after removing its hornblende component, then it is certainly characterized by a chemistry that is more typical of certain of the anatectites previously described. In the section dealing with the petrogenesis of anatectites in Chapter 3, the composition of sample H4 is recalculated hornblende-free and compared with that of typical anatectites from other migmatite outcrops. Although discrepancies (i.e. a high Al_2O_3 content) still exist in spite of these considerations the overall characteristics of the rock are, nevertheless, consistent with it having a partial melt origin. The Sr content of the hornblende tonalite (i.e. ≅800 ppm, Table 8) is also considerably higher than that generally found in anatectites from the area but this may reflect either, an anomalously high Sr content in the source material or, the degree of partial melting involved in generating the rock. The REE content of H4, on the other hand, is similar to that of the orthoclase-depleted anatectites described in Chapter 3. On a chondrite normalized plot (Figure 26), the REE pattern of the hornblende tonalite shows a similar pattern, with the flattish trend and positive Eu anomaly that is characteristic of the low K_2O/Na_2O, plagioclase-dominated anatectites.

The composition of the fault-generated anatectic material (sample H6, Table 8) is very similar in terms of both major and trace elements to that of the hornblende tonalite. The former also has low SiO_2 (≅64%), a low K_2O/Na_2O ratio (≅0,15), as well as low Rb and Ba contents which are in keeping with the typical characteristics of plagioclase-dominated anatectites. The garnetiferous anatectic vein (sample H7) is characterized by higher SiO_2 (≅68%), lower Al_2O_3 (≅17%), low K_2O/Na_2O (≅0,2) and an anomalously high Fe_2O_3* + MgO content (5) for a rock considered to be derived by partial melting. Other anatectites described from the Batavia section have also shown high ferromagnesian contents and, as previously mentioned, this can probably be attributed to the presence of an entrained restite phase. This is particularly relevant in terms of the garnetiferous vein at this outcrop, as the latter contains clots of coexisting garnet-hornblende-biotite which possibly reflect the nature of stable mineral assemblages in the anatectic source environment. Finally, the composition of the quartz-diorite dykelet is similar to quartz-diorites from the remainder of the study area, and is characterized by SiO_2 66%, Fe_2O_3* + MgO > 4 and a low K_2O/Na_2O ratio (0,15; Table 8). Again, this composition is similar to tonalite and trondhjemite gneisses in the area except that the quartz-diorites are invariably more mafic than the latter.

10.3. Summary statement

Outcrop H from the Batavia section serves to illustrate the combined effect of processes prevailing at two previously described migmatitic exposures, namely outcrops F and G, also from Batavia. The hornblende-biotite bearing tholeiite dyke in the outcrop described above, is very similar to the mafic dykes from outcrop G, which are unequivocally intrusive into well-foliated trondhjemite gneisses. In outcrop H, however, the quartzo-felspathic material enveloping the dyke appears to have interacted with the latter so that it has a hybridized appearance with a highly variable hornblende content. Because the original host material into which the dyke intruded is probably not preserved at the outcrop, the hybridized hornblende tonalite is considered to represent an anatectite that is derived from, and subsequently palingenetically injected into, the original, host material. Thus, an apparently contradictory situation whereby a dyke s assimilated by material derived from the host rock which it, itself intruded, appears to apply. This interpretation may be viewed as contentious, particularly in view of the atypical chemical characteristics of the anatectically derived material, but appears the most likely solution in the light of processes described from other migmatite outcrops in the vicinity.

11. MIGMATITE OUTCROP J - MOOIPLAATS

11.1 Geological description

All the migmatite outcrops described in the preceding sections were located in areas immediately southwest of the Barberton greenstone belt where the exposures examined are spatially related to greenstone remnants which have been correlated with the lower formations of the Onverwacht Group (i.e. the Tjakastad Subgroup, see Figure 2). Nowhere in this area were greenstone remnants found that bore any resemblance to the tholeiitic and calc-alkaline meta-volcanic suite that characterizes the upper Onverwacht Group (Geluk Subgroup) as defined by Viljoen and Viljoen (1969e). A possible exception to this is the tholeiitic dykes described from outcrop G which, as mentioned previously, may represent an intrusive counterpart to the volcanism associated with the deposition of these upper greenstone belt formations. Because of this discrepancy a study was made of migmatites in an area where the Hooggenoeg Formation (i.e. the lowermost unit of the Geluk Subgroup) is directly juxtaposed with tonalites and trondhjemites. These migmatites appear to have formed by interaction between the latter and the adjacent greenstones. In the vicinity of outcrop J (Figure 2), units from the Hooggenoeg Formation that strike in a south-southwesterly direction are truncated by tonalitic and trondhjemitic gneisses and migmatites in one of the few areas where early sialic material occurs directly adjacent to the upper volcanic successions in the Barberton Mountain Land.

Details of a small outcrop on the farm Mooiplaats 185 IT are presented in Figure 17 where it is seen that migmatites in the area consist dominantly of two components, namely linear bodies of amphibolite and the enveloping trondhjemite gneisses (Plate 5E). Although well-exposed, the interpretation of these outcrops, however, is equivocal, particularly, in the light of interpretations placed on previously described migmatite outcrops. The close spatial relationship to, and the locality of the outcrop along strike from, units of the Hooggenoeg Formation suggests that the amphibolitic units are most likely correlated with the latter. If the trondhjemite gneiss protoliths in the area are intrusive into the Hooggenoeg volcanics then the amphibolites represent xenolithic remnants similar to those described from outcrop E in the Batavia section. In certain places the

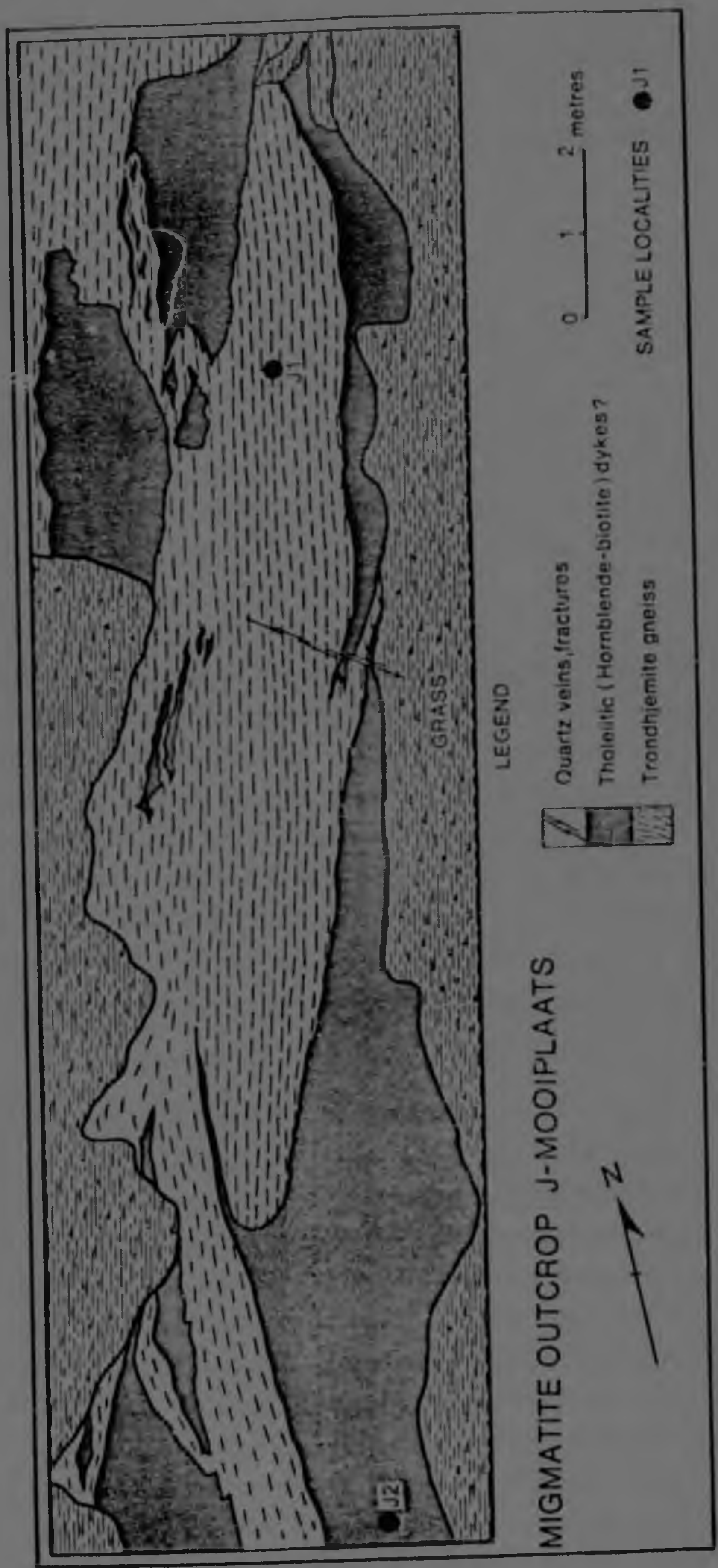


Figure 17 : Detailed map of migmatite outcrop J on the farm Mooiplaats 185 IT. The map illustrates the relationship between a trondhjemite gneiss and tholeiitic remnants which may either be dykes or xenoliths. The locality of the outcrop is shown in Figure 2.

amphibolite bodies appear to have been shredded and assimilated by the trondhjemite, a feature that is diagnostic of their interpretation as xenoliths. However, in another area, a small amphibolitic remnant appears to be discordant with respect to mafic schlieren in the trondhjemite gneiss (Plate 5C) suggesting an intrusive relationship. This intrusive relationship may, however, be contentious in view of the small fault that is associated with the amphibolite and which may either, be responsible for producing the discordancy (as, for example in outcrop H) or, for having controlled the original emplacement of the body. Another dyke-like feature associated with the largest amphibolitic body in Figure 17, is a "horned" structure (Plate 5D) which often accompanies the emplacement of dykes and reflects the orientation of the original fractures along which the dykes were intruded (Currie and Ferguson, 1970; Robb, 1977).

The above observations indicate that the exposures in this area are difficult to interpret unequivocally and the following four possibilities are considered:-

(i) the possible presence of dykes in the area suggests that the amphibolitic bodies could be completely unrelated to the Hooggenoeg volcanics and, instead, represent an early mafic intrusive episode;

(ii) the dykes may, on the other hand, represent an intrusive episode that is genetically related to the lavas extruded in a proximally located greenstone depository;

(iii) if the evidence suggesting intrusive relationships is discounted, the amphibolitic bodies can be viewed as xenoliths that have been rafted-off from the greenstone belt by intruding trondhjemitic magmas; and

(iv) the outcrop may consist of both amphibolitic dykes and xenoliths of genetically unrelated material. Two possibilities present themselves with regards to the latter point; firstly, the xenoliths could be pre-Hooggenoeg Formation with the dykes representing intrusive equivalents of the latter or, secondly, the xenoliths could be correlated with the Geluk Subgroup volcanics with the dykes representing a later unrelated intrusive episode.

Clearly, the selection of one or other of these interpretations is critical to the relative age of the trondhjemite gneiss with respect to the Hooggenoeg Formation. The problem is further complicated, however, by the presence of a discrete tonalite gneiss phase approximately 50 metres to the west of the mapped section. This body consists predominantly of plagioclase and quartz together with lesser amounts of subhedral hornblende. This contrasts markedly with the trondhjemite gneiss (sample J1) from the outcrop in Figure 17, which is more leucocratic and consists of sericitized plagioclase, quartz and a small amount of biotite (< 10%), much of which has been chloritized. The relationship between biotite trondhjemite and hornblende tonalite is not clear due to lack of exposure, but the latter may be younger as it contains no discrete amphibolitic bodies. The tonalite is also characterized by a pronounced schlieric texture suggesting that it intruded and collectively assimilated the pre-existing trondhjemite-amphibolite crust in much the same way as envisaged for the hornblende tonalite at outcrop H.

Because of the lack of complete outcrop in the area, the interpretation of migmatites on the farm Mooiplaats must rely mainly on inference and the conclusions reached from the description of other migmatitic rocks in the origin. The deposition of the Onverwacht Group is likely to have taken several hundred million years so that it is quite feasible that the initial development of sialic crust had occurred before the termination of volcanic activity in adjacent, ensimatic ocean basins. Thus, the existence of an early dyke phase that shows evidence of being deformed and migmatized (i.e. outcrop G) implies that the later episodes of volcanism had intrusive counterparts within the earliest developed tonalite and trondhjemite gneisses. In this light, the preferred interpretation of outcrop J accepts the equivocal evidence for intrusive amphibolitic bodies and views the latter as being emplaced coevally with ongoing volcanism associated with the deposition of the Geluk Subgroup. The presence of amphibolitic xenoliths at this outcrop is accommodated by viewing the latter as remnants of older volcanic successions previously intruded by the trondhjemite gneiss protolith. This interpretation implies, logically, that a geological distinction between xenoliths and dykes is virtually impossible at this outcrop because of the absence of preserved discordancies and the fact that both are likely to have been affected by migmatization and assimilation. The latter processes may have been facilitated by the intrusion of a hornblende tonalite phase which has introduced an additional magmatic component into the area.

TABLE 9

CHEMICAL ANAL[illegible]S OF COMPONENTS FROM MIGMATITE OUTCROP J - FARM MOOIPLAATS 185IT

		1	2	3	4
		J1	J2	J3	J4
	SiO_2	71,30	65,60	51,61	3,89
	TiO_2	0,30	0,52	1,25	0,06
	Al_2O_3	15,20	15,80	13,64	14,65
	Fe_2O_3*	2,77	4,47	15,78	0,92
	MnO	0,02	0,03	0.23	0,01
Wt.%	MgO	0,70	2,10	4,05	0,39
	CaO	2,66	3,45	6,78	1,37
	Na_2O	3,80	4,30	2,30	3,26
	K_2O	1,15	2,39	1,38	6,14
	P_2O_5	0,05	0,08	0.13	0,01
	L.O.I.	1,21	0,95	1,53	0,45
	TOTALS	99,16	99,59	98,68	100,15
	Rb	40	70	30	162
ppm	Sr	240	400	100	138
	Ba	191	506	248	227

(Analyst: L.J. Robb

Fe_2O_3* - Total iron as Fe_2O_3)

Columns 1 - Trondhjemite gneiss

2 - Hornblende tonalite gneiss

3 Amphibolitic dyke phase (?)

4 - Anatectic vein

Sample localities shown in Figure 17, with the exception of J2, which is located approximately 50 metres to the west of the mapped section, and J4 which represents a randomly sampled [illegible] from the Mooiplaats area.

11.2. Geochemistry

The amphibolitic bodies from the Mooiplaats outcrop are characterized by a tholeiitic bulk composition with low SiO_2 (52%) and MgO (4%) contents and a CaO/Al_2O_3 ratio of approximately 0,5 (Table 9). The alkali content of the rock is relatively high with $Na_2O + K_2O$ 3,7%. This composition is markedly different from the amphibolitic meta-basalts with komatiitic affinities that have been described from other migmatite outcrops (e.g. the Theeboom outcrop, Table 2). The Mooiplaats amphibolite is, however, similar in composition to the mafic dykes from outcrop G (Table 7) although $Fe_2O_3^*/MgO$ ratios in the latter are significantly lower. Analyses of meta-tholeiite from the Barberton greenstone belt (Viljoen and Viljoen, 1969 c, e) are also very similar to the amphibolitic bodies at outcrop J.

The trondhjemite gneiss in Figure 17 has high SiO_2 (71%), an $Fe_2O_3^* + MgO$ content of approximately 3,5% and a typically low K_2O/Na_2O ratio (0,3). By comparison, the hornblende tonalite phase that occurs nearby has lower SiO_2 (≈65%) and a significantly higher ferromagnesian content (i.e. $Fe_2O_3^* + MgO$ 6,6%) which may, as suggested previously, reflect assimilation of pre-existing, more mafic material. Although it is not clear precisely what the origin of this rock is, its higher K_2O, Rb and Ba content in relation to the trondhjemite gneiss (Table 9) is consistent with the suggestion that it may have a similar origin to the anatectite described from outcrop H.

A randomly sampled anatectic vein from the Mooiplaats area is included in Table 9 although it has no direct significance to the outcrop being discussed. The anatectite has a high SiO_2 (74%) and low $Fe_2O_3^*$ + MgO (< 1,5%) content with a high K_2O/Na_2O ratio (1,9). These features, together with the high Rb/Sr ratio, are indistinguishable from the anatectic veins from the Theeboom outcrop (see Table 2), the latter being characterized by eutectic or minimum-melt compositions in the granite system.

11.3. Summary statement

The Mooiplaats outcrop represents one of the few localities in the Barberton Mountain Land where volcanic successions of the Geluk Subgroup (more specifically the Hooggenoeg Formation) are preserved directly adjacent to tonalitic and trondhjemitic gneisses. Unfortunately the migmatites that are developed in this area are difficult to interpret because of sporadic exposure and the equivocal relationships existing between amphibolite and trondhjemite. The preferred interpretation of the area considers that both xenoliths and dykes occur but the differentiation of one from the other is extremely difficult without a very much more detailed (possibly chemical) study. Linear dyke-li[illegible] bodies are generally concordant with the trondhjemite gneissocity but occ[illegible]ally exhibit slight discordancies and "horned" structures. Both dykes and amphibolitic remnants appear slightly assimilated and migmatized as a result of their involvement in a significant portion of the tectono-thermal pre-history of the area. The above interpretation also implies that a locally developed ensimatic crust (represented by the lowermost greenstone successions) was gradually transformed into sial by the intrusion of tonalitic or trondhjemitic magmas, but that "nuclei" of this early contintental material were present prior to the deposition of later, more evolved, volcanic successions. This conclusion is in keeping with the indications gained from previously described migmatite outcrops where a similarly complex picture regarding the evolution of the first magmatic cycle is portrayed.

12. MIGMATITE OUTCROP D - MARA

12.1. Geological description

Migmatite outcrop D, on the farm Mara 233 JU, is located to the north of the Barberton greenstone belt (Figure 2) and is fundamentally different to all the other migmatite outcrops described in this chapter. This outcrop is located on the margins of the potash-rich Nelspruit batholith, where the development of migmatites and gneisses is a consequence of peripheral effects resulting from the emplacement of this body (Robb, 1978; Anhaeusser and Robb, 1980b; van Nierop, personal communication). The available data suggests that the margins of these, often porphyritic, adamellitic and granitic batholiths are typified by gneisses and migmatites that reflect the intrusion of these potash-rich phases but nevertheless retain certain of the characteristics, albeit altered and assimilated, of the tonalite-greenstone crust that prevailed prior to this event. This migmatite outcrop differs from the ones described previously in this chapter, as the latter are all intimately involved with processes related to the first magmatic cycle. The Mara outcrop, however, is considered to reflect

<u>*Figure 18*</u> : *Detailed map of migmatite outcrop D on the farm Mara [illegible] JU. The map illustrates the nature of potassic gneisses and migmatites that occur on the margins of the Nelspruit batholith to the north of the Barberton greenstone belt. Approximate locality of the outcrop is shown in Figure 2.*

the processes resulting from the interaction between a K-rich magma related to the Nelspruit batholith (i.e. a component of the second magmatic cycle) and the country-rock into which it was emplaced; the detailed assessment of this migmatite outcrop is aimed at testing this idea on a small scale.

The mapped section at Mara (Figure 18) is seen to consist predominantly of a coarse-grained gneiss with a pronounced schlieric fabric. The gneiss consists of numerous anastomosing and diffuse leucosomes which are interdispersed with more mafic, biotite schlieren. The rock as a whole consists dominantly of plagioclase, quartz and microcline with lesser, but variable amounts of biotite. Alteration, particularly in the form of sericitization of plagioclase, is pervasive. Quartz grains have crenulated boundaries and often appear fragmented, indicative of the high strains that once prevailed in the rock. Biotite is commonly chloritized and minor apatite and zircon occur. Individual leucosome bands contain little or no mafic constituent and contain more microcline than the gneiss as a whole.

In the southwest portion of the outcrop shown in Figure 18 schlieric gneisses envelope a xenolith of amphibolitic meta-basalt, the composition of which is komatiitic (see later). The latter, although intruded by a number of minor pegmatitic veins, is relatively unaffected by the intrusive gneiss and appears to be preserved in an unassimilated condition. The meta-basalt consists predominantly of hornblende together with lesser amounts of clinopyroxene (see Table 26), the latter occurring as discrete bands within the rock. Highly sericitized plagioclase and minor amounts of quartz also occur. In the northeastern section of the outcrop (Figure 18), a melanocratic quartz-dioritic body is also enveloped by schlieric gneisses, as well as being intruded by a number of discrete pegmatite veins. The contact between the quartz-diorite and gneiss is gradational with the former having been intruded and hybridized by protoliths of the gneiss. In the thin-section the quartz-diorite is seen to consist of approximately equal amounts of plagioclase, quartz and chloritized hornblende. The greenish-coloured chlorite is anhedral and commonly associated with scattered grains of opaque oxide (possibly magnetite) and epidote (Plate 6D). This association is indicative of the break-down of either hornblende or biotite to chlorite (Heinrich, 1965) and may be construed as evidence for the assimilation and alteration of a pre-existing, more mafic, rock-type. Minor apatite and rutile also occur in the quartz-diorite. It is envisaged that this quartz-diorite may once have been similar in appearance to the pristine amphibolite occurring at the opposite end of the mapped exposure (Figure 18) but which has been considerably granitized by the passive emplacement of magmatic phases related to the Nelspruit batholith.

The mapped section is also seen to contain at least three phases of pegmatite intrusion. The first is distinctive in that it has been deformed and occurs as irregular and distorted veins (Figure 18). These veins, which also contain chlorite, in addition to microcline, perthite and quartz may be related to the emplacement and subsequent deformation of the schlieric gneiss. The two later phases of white or pinkish coloured pegmatite veining are post-tectonic and form linear dyke-like features that truncate the fabric in the gneisses. These coarse-grained veins consist dominantly of microcline-perthite and quartz although the earlier of the two post-tectonic pegmatite episodes contained discrete, poorly twinned, plagioclase grains that are characterized by a preferred sericitization. The late pegmatite veins do not appear to have significantly contributed to the processes of assimilation and granitization that are envisaged having taken place at this outcrop, as well as in the general area. These veins form discrete units displaying sharp contacts with their host rock and show no direct evidence for having reacted with the surrounding material.

12.2. Geochemistry

Although the gneisses at outcrop D are heterogeneous on the scale of a single hand-specimen, a large sample of this material was selected for analysis; the bulk composition of this rock is granodioritic with SiO_2 > 70%, Fe_2O_3* + MgO < 4% and a K_2O/Na_2O ratio of approximately 0,5 (Table 10). An analyses of a leucosome fraction in the schlieric gneisses reflects the lower mafic content of the more felsic bands and also points to its higher K_2O/Na_2O ratio (i.e. > 1,5). The leucosome also has a higher Rb, Ba and ΣREE content than the bulk schlieric gneiss (Table 10) although the REE patterns of both units are very similar, being LREE enriched and displaying no significant Eu anomaly (Figure 49).

The xenolith of amphibolitic meta-basalt at the Mara outcrop has a composition that is very similar to the Barberton-type basaltic komatiites defined by Viljoen and Viljoen (1969c) from the Barberton greenstone belt.

TABLE 10

CHEMICAL ANALYSES OF COMPONENTS FROM MIGMATITE OUTCROP D - FARM MARA 233JU

		1	2	3	4	5	6	7
		D1	D3	D5	D6	D2	D7	D4
Wt.%	SiO_2	70,39	71,26	73,28	74,46	50,49	53,15	67,06
	TiO_2	0,32	0,29	0,13	0,02	0,43	0,74	0,64
	Al_2O_3	15,83	15,10	14,73	14,51	11,28	7,89	16,52
	Fe_2O_3*	2,90	1,92	1,18	0,37	10,58	13,52	4,50
	MnO	0,01	0,01	<0,01	<0,01	0,10	0,14	0,06
	MgO	1,00	0,73	0,61	0,21	11,21	10,17	1,23
	CaO	2,61	1,59	0,71	0,17	13,56	13,49	3,39
	Na_2O	4,37	2,71	3,18	0,87	0,40	<0,01	4,59
	K_2O	2,21	4,99	6,04	9,22	0,84	0,64	1,49
	P_2O_5	0,17	0,11	0,07	0,03	0,08	0,08	0,21
	L.O.I.	1,03	0,89	1,01	0,44	1,49	1,55	1,13
	TOTALS	100,84	99,60	100,94	100,30	100,46	101,37	100,88
ppm	Rb	10	94	148	272	29	16	59
	Sr	426	292	135	85	228	162	333
	Ba	387	910	287	246	50	89	220
	La	46,9	51,3	-	-	5,4	-	63,4
	Ce	93,3	107,3	-	-	-	-	109,9
	Nd	28,6	33,0	-	-	-	-	33,0
	Sm	5,07	5,77	-	-	1,75	-	8,25
	Eu	1,18	1,30	-	-	0,49	-	1,28
	Tb	0,54	0,56	-	-	0,45	-	0,83
	Yb	0,77	0,71	-	-	1,60	-	1,26
	Lu	0,07	0,06	-	-	0,22	-	0,11

(Analyst: L.J. Robb

Fe_2O_3* - Total iron as Fe_2O_3)

Columns
- 1 - Schlieric potassic gneiss
- 2 - Schlieric potassic gneiss - leucosome
- 3 - 4 - Intrusive pegmatite veins
- 5 - Amphibolitic meta-basalt xenolith
- 6 - Amphibolitic meta-basalt from large greenstone xenolith located 3 km south of outcrop D
- 7 - Quartz-diorite, possibly an assimilated equivalent of D2

Sample localities shown in Figure 18, with the exception of Sample D7.

The amphibolite has SiO_2 ≈50%, MgO ≈11% and a CaO/Al_2O_3 ratio of 1,2 (Table 10). These compositional traits are very similar to pristine basaltic komatiites except that the K_2O content of the Mara amphibolite (i.e. 0,84%) is somewhat high and probably reflects the nature of the host rock. The small amphibolitic xenolith in Figure 18 is also very similar in composition to an amphibolite sampled from a large (1 - 2 kilometres in length) greenstone remnant that occurs approximately 3 kilometres southwest of the Mara outcrop. This supports the contention that the small amphibolitic raft at this outcrop probably represents a xenolith originally derived from a much larger greenstone remnant.

The melanocratic quartz-diorite body has a composition that is, in all respects, intermediate between that of the schlieric gneiss and the amphibolitic meta-basalt in Figure 18. This unit has SiO_2 ≈67%, Fe_2O_3* + MgO ≈7% and $Na_2O + K_2O$ ≈6%; The REE pattern of the quartz-diorite on a chondrite normalized plot is essentially indistinguishable from that of the schlieric gneiss except that the HREE are slightly more enriched (Figure 49). These features are consistent with the derivation of the dioritic unit by assimilation or hybridization of a pre-existing, more mafic, precursor by the protolith of the potassic gneiss. A detailed appraisal of these processes as applicable both to the Mara and other outcrops, is presented in section 8 of Chapter 3.

The post-tectonic pegmatite veins that intrude the Mara outcrop have a distinctive composition with respect to the other components in the mapped section. They have high SiO_2 in the range 73-75%, low Fe_2O_3* + MgO contents (0,6 - 1,8%) and very high K_2O/Na_2O ratios of between 2 and 10 (Table 10). They also have a distinctive trace element content with much higher Rb and lower Sr and Ba contents than the schlieric potassic gneiss.

12.3. Summary statement

The Mara outcrop, located to the north of the Barberton greenstone belt, is the only exposure described in this chapter where migmatites are intimately associated with potash-rich components of the second magmatic cycle. The outcrop occurs within a broad marginal zone related to the Nelspruit batholith, where potassic gneisses, schlieren and small, often assimilated greenstone remnants are developed. At Mara, a small xenolith of amphibolitic meta-basalt with komatiitic affinities is enveloped by a potash-rich schlieric gneiss. In the same outcrop, a body of quartz-diorite appears to have been derived from a more mafic precursor by processes of assimilation or hybridization. The outcrop as a whole, therefore, appears to reflect the "passive" emplacement of a potash-rich magma (of granodioritic to adamellitic composition) into pre-existing crustal components. The latter were probably the tonalitic or trondhjemitic gneisses, migmatites and greenstone remnants that typified the previously described outcrops and form a prominent component of the first magmatic cycle. Thus, the Mara outcrop represents the interactive processes resulting from the emplacement of magmas related to the Nelspruit batholith into the pre-existing, heterogeneous crust that had formed at that time.

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CHAPTER 3

PETROGENETIC ASPECTS RELATED TO THE VARIOUS COMPONENTS IDENTIFIED FROM THE MIGMATITE OUTCROPS IN THE BARBERTON MOUNTAIN LAND

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1. INTRODUCTION

The previous chapter was concerned only with a brief, systematic description of the various migmatite outcrops in the study area that were selected for detailed mapping and examination. It is apparent from these descriptions that many exposures consist of components that are common to other outcrops and are likely, therefore, to have been derived in a similar manner. It is the purpose of this chapter to examine each of the major, discrete, component phases that have been recognized from the various migmatite outcrops in terms of their petrogenesis, the physio-chemical conditions under which they were generated and the role that they have played in the migmatization process.

The earlier sections of this chapter deal systematically with the following rock-types, each of which occurs, either in all, or some, of the migmatite outcrops described previously :-

Tonalite and trondhjemite gneisses
Anatectites
Amphibolitic xenoliths and dykes
Quartz-diorite veins
Plagiogranitic veins

In addition, consideration is also given to certain petrological processes that have a bearing on the formation of migmatitic rocks in the study area. A discussion on assimilation and also a comparison between the processes of partial melting as opposed to sub-solidus metamorphic differentiation is provided in two separate sections following on from the above considerations. The chapter is terminated with a discussion relating to the major findings of the study of migmatites in the Barberton region and presents the conclusions arising from Part 1 of the thesis.

[illegible] TONALITE AND TRONDHJEMITE GNEISSES

The majority of migmatite outcrops described in Chapter 2 contain tonalite and trondhjemite gneisses which occur together with a variety of other intimately related felsic and mafic components. These gneisses exhibit a range in major, trace and rare-earth element concentrations (see Tables 1 - 1[illegible]) which reflect a spectrum of compositions from tonalite to trondhjemite [illegible]. In addition, field evidence exists for the occurrence of discrete, similarly distinct tonalite-trondhjemite phases, suggesting a prolonged emplacement history for the gneiss protoliths. In contrast, however, the tonalite-trondhjemite gneissic plutons that underlie a considerable portion of the terrane southwest of the Barberton greenstone belt (Figure 2) are relatively homogeneous in appearance and do not appear intimately related with other migmatitic components. As described in Chapter 1, these rocks also exhibit a variation in composition that is similar to that in the tonalites and trondhjemites from the migmatite exposures. The purpose of this section is to compare and contrast some of the chemical attributes of tonalites and trondhjemites from the gneiss plutons with similar rock types occurring in the migmatites. Petrogenetic considerations of the tonalite-trondhjemite suite are provided in Chapter 6.

[illegible].1 Major element characteristics

Although broadly similar in bulk composition, tonalite and trondhjemite bodies southwest of the Barberton greenstone belt are characterized by systematic chemical variations that, to a certain extent, serve to distinguish one body from another (Figure 82). In a ternary plot of CaO-NaO-K_2O (Figure 19) data from five tonalite-trondhjemite bodies in the study area (namely the Batavia, Theeboom and Weergevonden cells and the Theespruit and Stolzburg plutons; for identification see Figure 82) serve to delineate fields which represent a range in composition for each of the bodies concerned. Although broadly overlapping, these fields illustrate the compositional differences that can occur in the study area and indicate the fact that certain of the bodies may be significantly different from others. Also plotted on Figure 19 are the individual samples of tonalite and trondhjemite gneisses from the various migmatite outcrops described in

2. TONALITE AND TRONDHJEMITE GNEISSES

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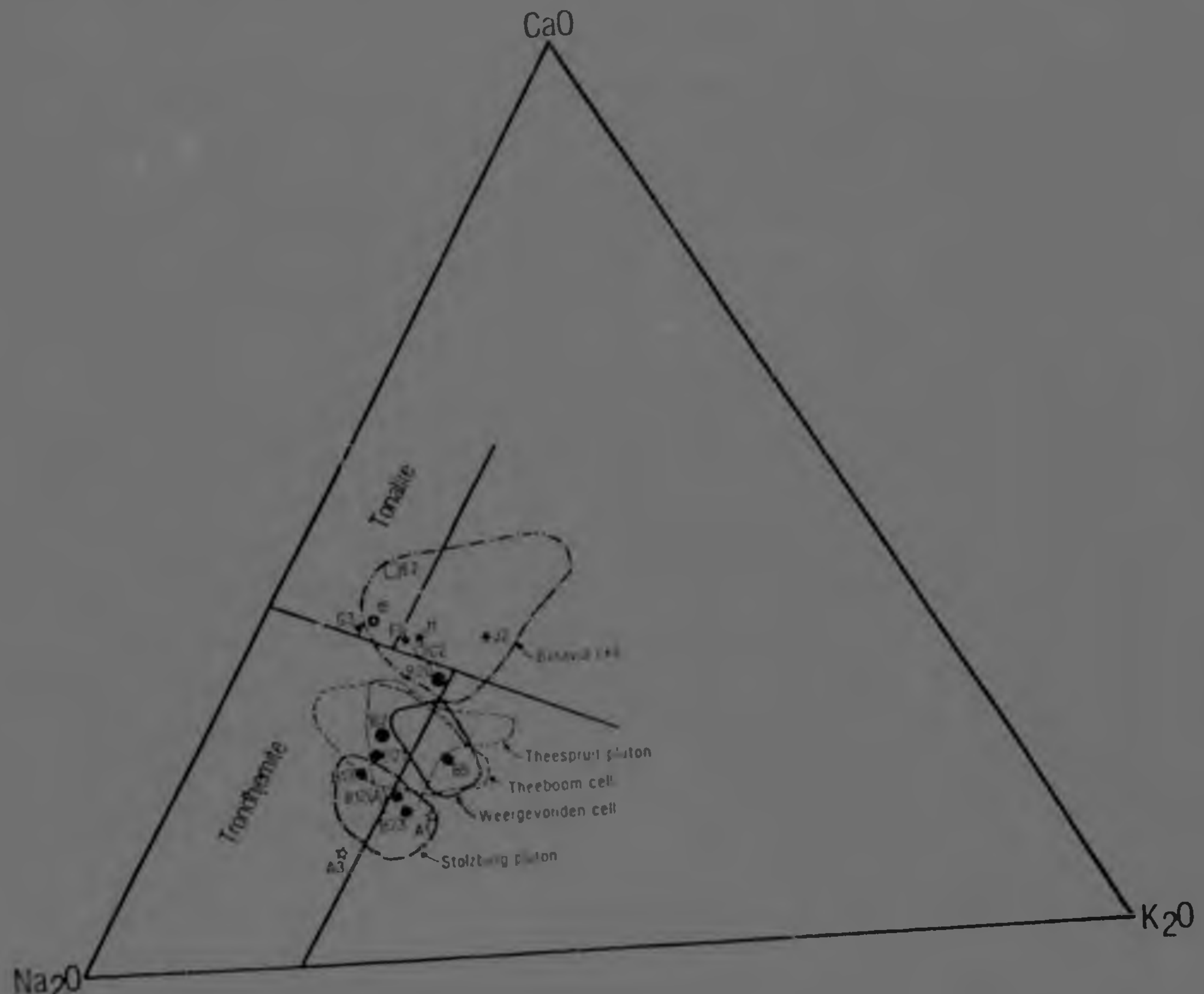

Figure 19 : *Ternary plot of CaO-Na$_2$O-K$_2$O showing the compositional fields of tonalites and trondhjemites, from Glikson (1979a) modified after O'Connor (1965). The data for the individually plotted migmatite-related tonalite and trondhjemite gneisses are from Tables 1-10. The various symbols used for these points differentiate between the eight migmatite outcrops represented in the diagram. Data sources for the Batavia, Theespruit, Theeboom, Weergevonden and Stolzburg pluton fields are given in Table 33, Chapter 6.*

Chapter 2. It is clear from the diagram that most of the migmatite-related tonalites and trondhjemites are similar in composition to the gneissic plutons which are spatially, most closely related to each of the migmatite exposures in question. For example, the compositional field of the Batavia cell embraces the samples E2, F9 and G3, all of which are tonalites or trondhjemites associated with migmatites in the Batavia section (i.e. section H-E-F-G, Figure 2). Likewise, the field of the Stolzburg pluton is located close to samples A1 and A3 which represent trondhjemite gneisses from the Boekenhoutrand outcrop, which itself is located on the extreme margin of the Stolzburg pluton (Figure 2). Thus, in many cases the gneiss protoliths from the homogeneous tonalite-trondhjemite plutons and cells in the study area appear to be represented in the migmatite outcrops suggesting, as previously mentioned, that certain of the latter have formed in response to the intrusion of magma into pre-existing greenstone material.

In certain cases, however, these similarities do not exist, for example, in the case of sample C2 (from the Weergevonden outcrop) which does not plot within the field of the Weergevonden cell (Figure 19). This fact confirms the detailed geological observations in Chapter 2, which show that some migmatitic exposures contain discrete gneissic phases, certain of which may be quite unrelated to the tonalites and trondhjemites from adjacent plutons.

2.2 Trace element considerations

The trace element characteristics of tonalite and trondhjemite gneisses from the study area are considered in detail in Chapter 6 where petrogenetic aspects related to this suite of rocks are discussed. In this chapter considerable emphasis is placed on the varying Sr contents of the gneiss plutons and cells, particularly as differences in the concentration of this element provide the clearest distinction between these bodies (see Figure 85). As with the major elements discussed above, similarities in the Sr contents of tonalite-trondhjemite gneisses from the migmatitic outcrops with those from adjacent gneiss plutons indicate that, in many cases, the two appear to be related (see compilation of Sr data in Table 36). Concentrations of Rb and Ba are insufficiently definitive for similar comparisons to be made.

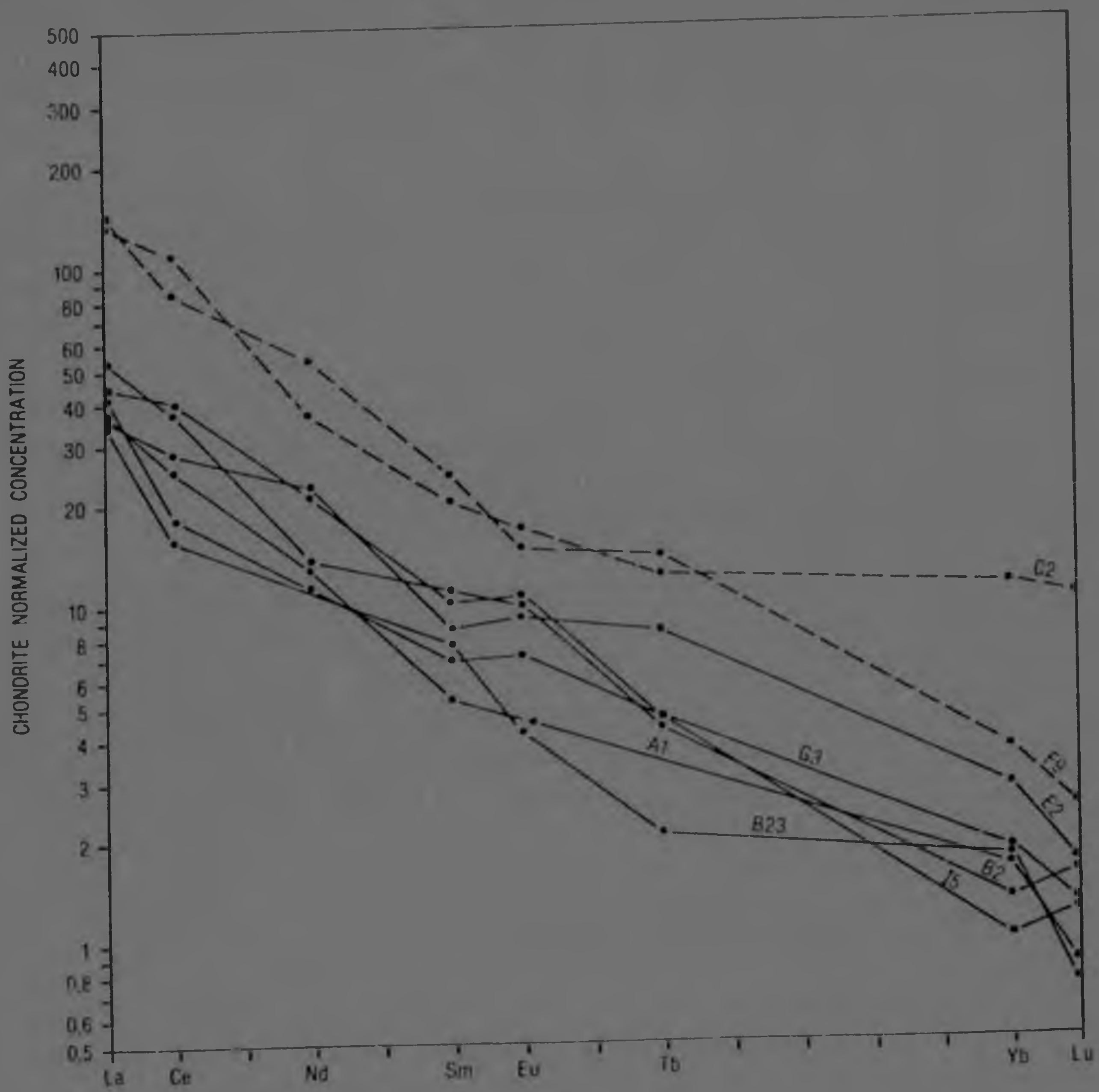

Figure 20 : Chondrite normalized rare-earth element plot for the migmatite-related tonalite and trondhjemite gneisses. The data is listed in Tables 1-10. Samples C2 and F9 (dashed lines) are characterized by a higher ferromagnesian content than the remainder of the samples and, likewise, are seen to have higher ΣREE contents.

A number of tonalite-trondhjemite gneisses from the migmatite outcrops were analysed for their rare-earth element (REE) content, primarily to assess whether these rocks showed any significantly different chondrite normalized patterns to the gneisses analysed from the homogeneous plutons. Such differences might distinguish the migmatite-related gneisses as having a different origin to the more typical gneiss plutons in the area. The chondrite normalized REE content of gneisses from seven different migmatite outcrops are plotted in Figure 20, where it is seen that these rocks have patterns that are, in fact, typical of other Archaean tonalites and trondhjemites. The majority of the samples have light rare-earth elements (LREE) that are 40 - 60 X enriched over chondritic values and no significant Eu anomalies. These patterns are very similar to those compiled for the Theespruit, Stolzburg and Nelshoogte plutons and illustrated in Figure 91. Two of the samples in Figure 20 (i.e. C2 and F9) are characterized by higher total REE contents; these two samples have higher ferromagnesian contents than the remainder of the more leucocratic trondhjemites (see Tables 1 - 10) and are thus, more compositionally akin to the Kaap Valley tonalite pluton (see Chapter 4). In this regard, it is seen that the REE patterns for samples C2 and F9 are also similar to that for the Kaap Valley body as shown in Figure 91, suggesting that the ΣREE content in tonalites and trondhjemites is directly proportional to the ferromagnesian content of the rock.

In summary, the above discussion indicates that most of the tonalite and trondhjemite gneisses that occur as a component of migmatites in the area southwest of the Barberton greenstone belt, are broadly similar in composition to the more homogeneous gneisses situated in adjacent plutons. As indicated from geological relationships, magma protoliths from the homogeneous gneiss plutons have, in certain cases, intruded pre-existing greenstone crust although, as discussed later, much of this emplacement may have been of a structural nature. It is likely, therefore, that petrogenetic considerations relating to the tonalite-trondhjemite kindred (see Chapter 6) will apply equally to both migmatite-related gneisses as well as gneiss plutons.

3. THE ORIGIN OF ANATECTITES IN THE MIGMATITES SOUTHWEST OF THE BARBERTON GREENSTONE BELT

The term "anatectite" is defined in this thesis simply as a rock formed by anatexis, where "anatexis" is the melting of a pre-existing rock (Glossary of Geology, 1977). The detailed descriptions provided in Chapter 2 indicate that anatectites form a significant component of the majority of migmatites in the study area. The following rock samples from the various migmatite outcrops mapped were described as anatectites and these are listed below (analytical data including major, trace, and in certain cases, rare-earth elements are available for each of these samples and are provided in Tables 1-10).

A8
B7, B11, B15, B17, B22, B19, B3, B4
C4, C6
E1, E5
F5, F6, F8
G4
H4, H7
I1, I2
J4

These rocks are typified by certain characteristics which serve to distinguish them from other migmatitic components. These are as follows :-

(i) they invariably occur as veins intrusive into a pre-existing rock which is usually an amphibolite or a tonalite-trondhjemite gneiss;

(ii) they are always *syntectonic* in that they have been involved in all, or part, of the deformational history recorded in any one particular migmatite outcrop: possible exceptions to this rule are A8 and G4 in which a deformation fabric is not readily apparent. This criterion eliminates the cross-cutting (post-tectonic) pegmatite and aplite veins that occur in many of the migmatite outcrops and which are not necessarily genetically related to the physio-chemical processes considered responsible for the development of the migmatites; and

(iii) they are generally devoid of a significant mafic component and, unlike the well-foliated tonalite/trondhjemite gneisses, they contain neither biotite nor hornblende, but may contain minor amounts of chlorite or muscovite; some anatectites contain sillimanite.

3.1 Petrographic characteristics

Petrographically, the 20 samples described above can be divided into two groups, each of which is characterized by a distinct mineral assemblage. Samples A8, B7, B11, B15, B17, C4, I1, I2 and J4 are characterized by the presence of microcline (15-30%) together with plagioclase and quartz in approximately equal proportions. In samples A8, I1 and I2, the K-felspar component is orthoclase rather than microcline. By contrast, samples that occur predominantly from the Batavia section to the west and northwest of the Boesmanskop syenite (E1, E5, F5, F6, F8, H7 and G4), consist dominantly of plagioclase and quartz with no K-felspar. Certain of these anatectites may also contain minor amounts of biotite and chlorite.

Some of the K-felspar-bearing anatectites (specifically those from B and I outcrops) contain small amounts of sillimanite. Winkler (1967) has pointed out that this mineral is a common by-product of anatexis and represents the residue remaining from the incongruent melting of biotite or muscovite to form K-felspar

i.e. $\text{muscovite} + \text{quartz} \rightleftharpoons \text{K-felspar} + \underset{\text{(sillimanite)}}{Al_2SiO_5} + H_2O$

Garnet is not a common phase in the anatectites but was detected in sample H7, where medium-grained porphyroblasts of this mineral occur. As mentioned previously, the presence of garnet and certain mafic phases in the anatectites possibly represent restite phases that have been caught up and emplaced together with the melt fraction.

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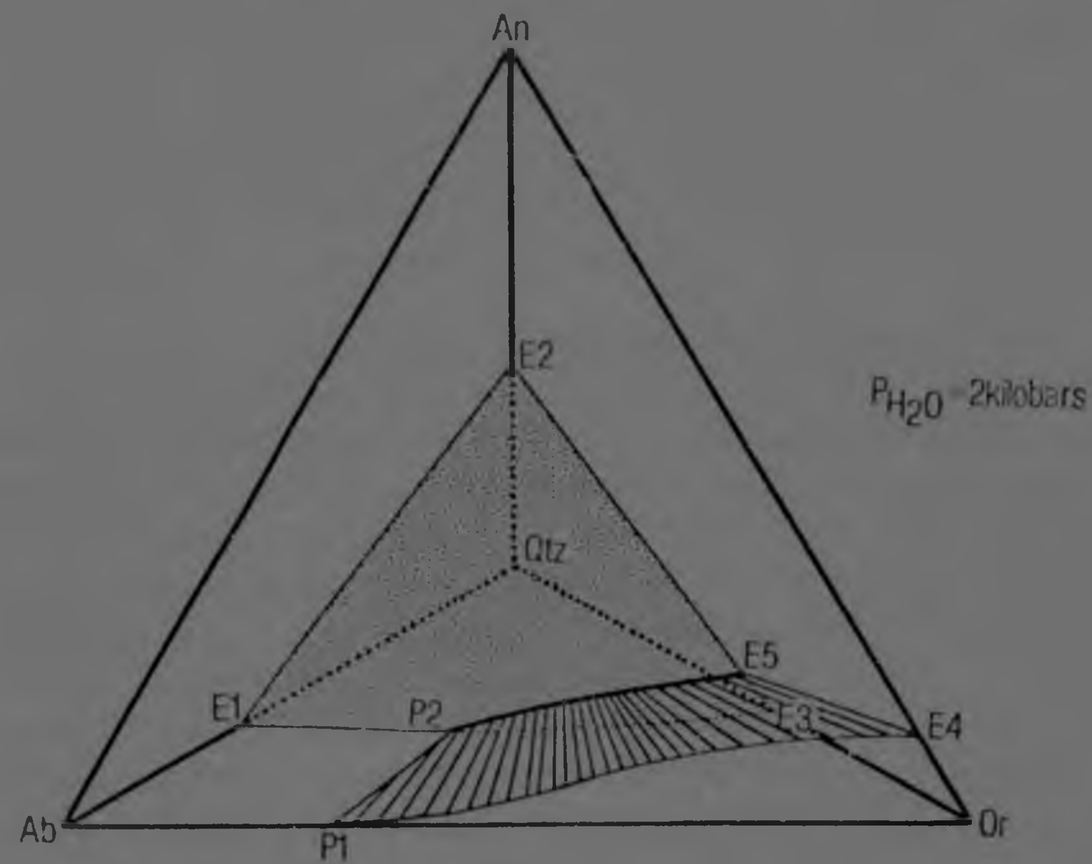


Figure 21 : *The granite tetrahedron showing the locality of the isobaric cotectic line (P2-E5) and the various cotectic surfaces (after Winkler, 1967, page 200).*

3.2 The composition of the anatectites in terms of the granite system

The fact that the anatectites consist dominantly of quartz, plagioclase and alkali felspars, together with only few mafic minerals, means that they can be very suitably represented in terms of the "granite system", Qtz-Ab-An-Or-H_2O. An assessment of the melt origin of these rocks can therefore be made in terms of these components.

The interpretation and recognition of anatectic processes in terms of the granite system has often been contentious for the various reasons discussed in the introduction to Chapter 2. A number of assumptions and precepts need to be outlined prior to the present discussion where anatectic compositions are viewed in terms of their *mesonormative* constituents. The following points are regarded as being important in terms of an appreciation of anatectic compositions in the study area :-

(i) it has been clearly shown by Kleeman (1965) that the normative compositions of rocks can be misrepresented if they are plotted on a ternary diagram that represents only a single two-dimensional section of the granite tetrahedron Qtz-Ab-An-Or-H_2O (Figure 21). For example, normative compositions plotted on the commonly used Qtz-Ab-Or-H_2O ternary diagram can be grossly misleading if the rock contains as little as 2% An. As the anatectites referred to in the following sections invariably contain between 10-20% of the An molecule, plots of Qtz-Ab-Or, Ab-Or-An and Qtz-An-Or were constructed in order to avoid erroneous misrepresentation (Figures 22, 23 and 24);

(ii) in the abovementioned ternary diagrams, isotherms (for P_{H_2O} = 5 kb) are provided so that an impression of the temperatures required to form the anatectites, under these conditions, is given. It is important to realize that small variations in the fusion temperature (± 50°C) are highly significant in terms of the melt origin of these rocks. This is emphasized by the fact that the difference in temperature between the two ends of the cotectic line in Figure 22 is only 40°C (Kleeman, 1965). In order to substantiate this, Winkler and Lindemann (1972) have

...wn that the total temperature range over which isobaric cotectic melting may take place (i.e. where plagioclase-quartz-orthoclase and melt phase are in equilibrium, or coexist) is a mere fraction of 50°C, and probably varies between 5-25°C depending on the composition of the melt in question. These facts indicate that melt compositions are very sensitive to the *final* temperatures at which anatexis takes place;

(iii) Winkler and Lindemann (1972) and Winkler and Breitbart (1978) have emphasized the fact that a rock composition that does *not* coincide with a eutectic or minimum melt composition in the granite system cannot be regarded as evidence precluding that rock from having a magmatic or anatectic origin. Granitic melts have eutectic compositions only in the early stages of anatexis (i.e. within 5-15°C of the inception of melting) where the melt is in equilibrium with three phases (i.e. quartz-plagioclase solid solution - orthoclase solid solution). As it is unlikely that temperature will remain static immediately after the commencement of the partial melting process, it is quite feasible that granitic melts will evolve as the process continues, so that melt compositions may eventually be significantly different from those represented along the isobaric cotectic line. The cotectic line in the granite tetrahedron (Figure 21) is that unique line (P2 - E5) represented by the intersection of three cotectic surfaces (i.e. E2-E1-P2-E5; E5-P2-E3; E5-E4-P1-P2) each of which represents the region in which two phases are in equilibrium with the melt. Thus, the criterion which defines an anatectite is *not* the proximity of its normative composition to this isobaric cotectic line, but will be entirely dependent on the nature of the partial melt process;

(iv) the nature of incipient melt compositions in terms of their position along the length of the isobaric cotectic line (P2-E5, Figure 21) is determined by the compositions of *coexisting* K-felspar and plagioclase with which these melts are in equilibrium. Von Platen (1965) has shown that minimum melt compositions (at 2 kb P_{H_2O}) become enriched in quartz and orthoclase as the Ab/An ratio of the parental material decreases. Winkler and Lindemann (1972) have shown that pressure also affects the incipient melt composition and that a change in P_{H_2O} from 2 kb to 5 kb will raise the An content of the melt from 9% to 14%. Incipient melt compositions that formed from the *same* parental material may, therefore, differ significantly and this point is considered again in section (vi) below;

(v) because the compositions of coexisting plagioclase and K-felspar change with increasing temperature along the isobaric cotectic line, so too will the composition of the melt, in equilibrium with these phases, change. As higher melting temperatures are attained with progressive anatexis, the composition of the melt will change along the cotectic in the direction of E5 (Figure 21), as long as it remains in equilibrium with all three phases. The melt, therefore, becomes enriched in orthoclase and, to a lesser extent, quartz, with these changes becoming more pronounced if the parental material has a higher An content. This point, together with the others made previously, indicates that the generation of anatectic melts is a complex process and it is clear that the most commonly referred to portion of the granite system (i.e. Qtz-Ab-Or-H_2O) has little, if any, petrogenetic significance on its own;

(vi) under natural conditions of regional metamorphism it is likely that P_{H_2O} and the Ab/An ratios of rocks undergoing anatexis are likely to vary considerably. Because eutectic and minimum melt compositions are affected by these variables, it follows that anatectites representing the same degree of cotectic melting may have different compositions. The experimental data of Luth et al. (1964), shows that normative minimum melt compositions will change from Qtz:Ab:Or = 0,39:0,30:0,31 at P_{H_2O} = 0,5 kbs to Qtz:Ab:Or = 0,23:0,56:0,21 at P_{H_2O} = 10 kb. These changes in the normative compositions imply the following differences in the whole rock composition of similarly-formed material that might have been generated under differing P_{H_2O} conditions :-

	P_{H_2O} = 0,5 kb	P_{H_2O} = 10 kb
SiO_2	79,1%	74,8%
Al_2O_3	11,9%	15,2%
Na_2O	4,5%	7,3%
K_2O	3,7%	2,5%

Similarly, the data of von Platen (1965) suggests that minimum melt compositions will change from Qtz:Ab:Or = 0,34:0,40:0,26 when the Ab/An ratio of parental material is ∞ to Qtz:Ab:Or = 0,45:0,15:0,40 when the Ab/An ratio is 1,8. This, likewise, implies the following changes in the whole rock composition of similarly-derived anatectic material :-

	Ab/An = ∞	Ab/An = 1,8
SiO_2	77,9%	80,4%
Al_2O_3	12,9%	10,6%
Na_2O	5,6%	3,0%
K_2O	3,1%	4,8%

Thus, a significant range of compositions can be expected from incipient cotectic melts, whether they be derived from identical parents subjected to different partial pressures of water, or, slightly different parental materials in identical environments. This compositional range may be evident for small degrees of partial melt where anatectic compositions have not strayed from the cotectic by the complete melting out of one of the three coexisting phases;

(vii) with respect to the latter point, it should be emphasized that the composition of early melts will remain on the cotectic line only until such time as one of the phases in equilibrium with the melt is used up. As soon as this happens the melt composition will move away from the isobaric cotectic line (P2-E5, Figure 21) onto one of the cotectic surfaces where two phases are in equilibrium with the melt. For example, if orthoclase is entirely melted as the temperature of fusion increases (as is often the case because orthoclase is the least refractory of the three phases (Kleeman, 1965)) the melt composition will move from the isobaric cotectic (P2-E5) onto the plane E5-E2-E1-P2 in a direction away from the Or apex of the granite tetrahedron. The duration which a melt composition remains on the isobaric cotectic before changing composition off this line depends on the relative proportions of the three phases in equilibrium with the melt. In the case of trondhjemites which contain no more than 5% microcline it is likely

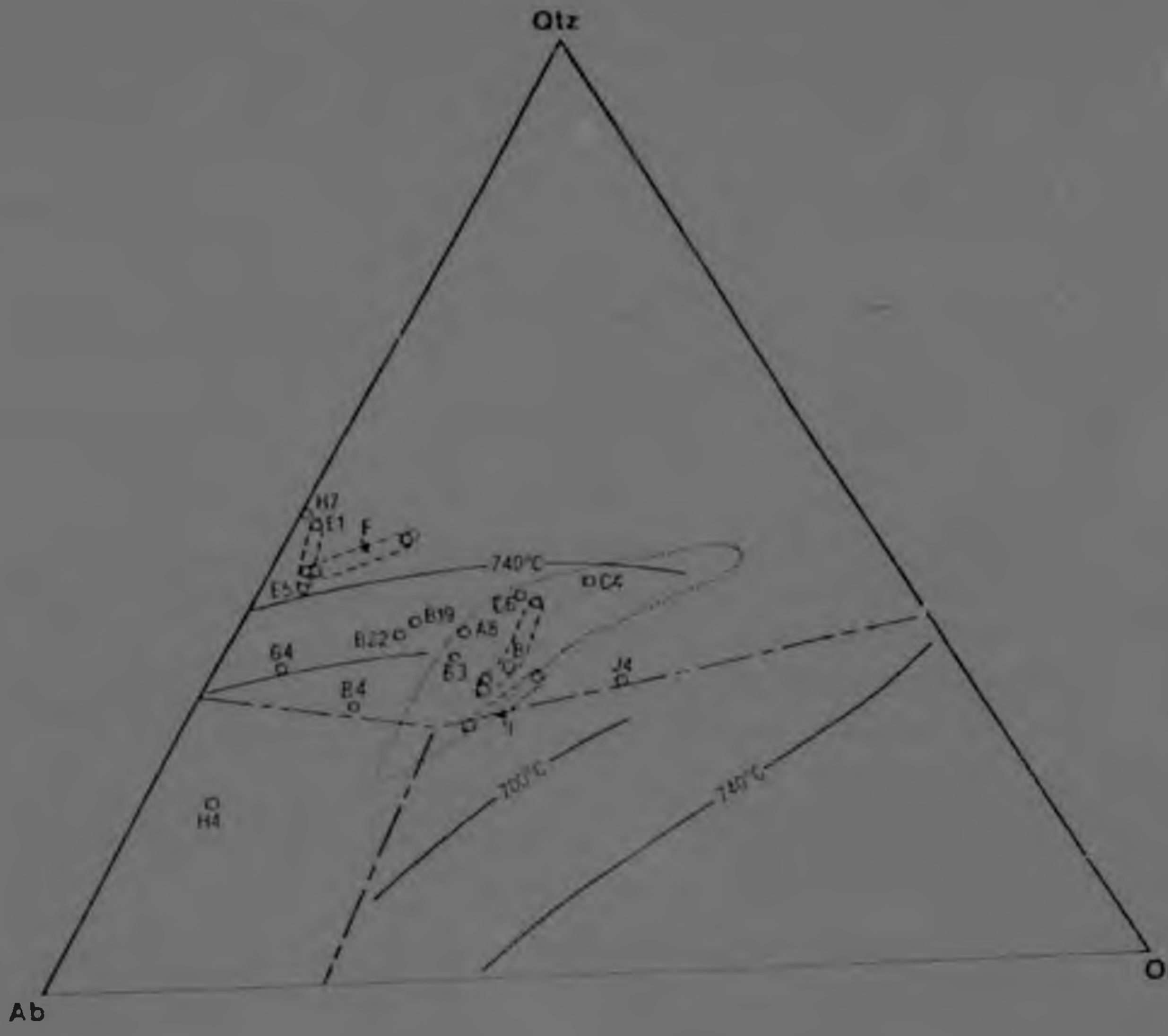


Figure 22 : *Ternary plot of normative Qtz-Ab-Or for anatectites from the various migmatite outcrops described in Chapter 2. Points are plotted from data listed in Table 11. Isotherms and projected cotectic surfaces are from Luth et al. (1964). The dotted field represents a broad envelope of projected eutectic points and thermal minima for a variety of P_{H_2O} and Ab/An ratios from Luth et al. (1964) and von Platen (1965).*

that all the K-felspar will be consumed by the time approximately 15% of the rock has melted. Thus, a significant percentage (> 15%) of trondhjemite melt will have a composition that does *not* lie on the cotectic, but will have evolved into the orthoclase-depleted portion of the tetrahedron to an extent that is dependent on the degree of anatexis that has occurred; and

(viii) a final criterion whereby an incipient melt composition will not lie on the isobaric cotectic, occurs if the parent did not contain any K-felspar, or either of the other cotectic phases. In such a case, melt compositions cannot fall on the cotectic (P2-E5), but will be determined by the nature of the parental composition. In this case, however, the melt may, nevertheless, contain some orthoclase if the incongruent melting of a phase such as biotite or muscovite takes place (e.g. refer to the chemical equation presented above for the breakdown of muscovite and quartz to K-felspar and sillimanite).

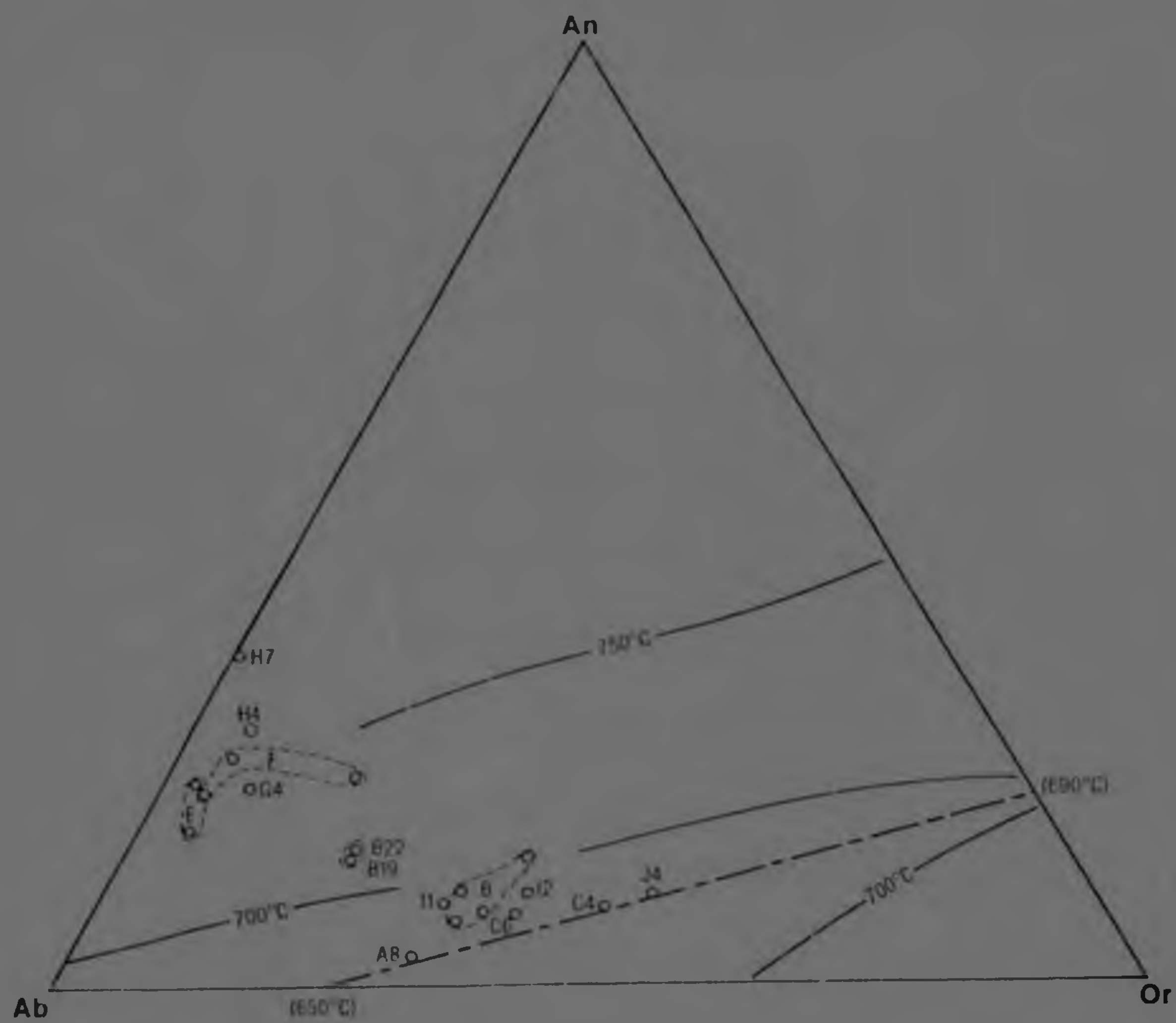
With the above points in mind, the compositions of anatectites from the migmatite outcrops can be assessed in terms of their possible origin. The anatectites exhibit a range of major element compositions with variations between 68-76% SiO_2, 13-16% Al_2O_3, 3-6% Na_2O and 1-5% K_2O (Tables 1-10). This spread indicates that, at least some of the samples will have compositions that do not coincide with minimum melt or eutectic compositions formed during the early stages of anatexis. The mesonormative compositions of the anatectites (Table 11) are plotted on Qtz-Ab-Or, An-Ab-Or and An-Or-Qtz ternary diagrams in Figures 22, 23 and 24 respectively. It is clear from all three of these plots that the anatectites can be subdivided into two broad categories; the first, whose compositions broadly correspond to that of a cotectic melt which has remained in equilibrium (or near-equilibrium) with three coexisting phases (i.e. quartz, plagioclase and orthoclase) and, the second, whose compositions are considerably removed from the quaternary isobaric cotectic (P2-E5, Figure 21). In Figure 22, samples from A, B, C, I and J outcrops all fall within, or close to, an envelope of projected eutectic points and thermal minima for a variety of P_{H_2O} and Ab/An conditions. In Figure 23, the same samples plot on or near the cotectic line between plagioclase and orthoclase solid solution. In both these figures, the isotherms that are plotted indicate that these samples

TABLE 11

MESONORMATIVE COMPOSITIONS OF ANATECTITES FROM MIGMATITE OUTCROPS DESCRIBED IN THE AREA SOUTHWEST OF THE BARBERTON GREENSTONE BELT

	A8	B7	B11	B15	B17	B19	B22	C4	C6	E1	E5	F5	F6	F8	G4	H4	H7	I1	I2	J4
Qtz	35,2	27,2	30,8	29,1	32,6	32,2	32,3	36,0	36,2	39,1	37,0	34,8	34,3	36,7	25,5	13,6	33,3	24.7	29,6	27,7
Ab	40,1	39,4	37,[illegible]	39,0	27,6	40,4	40,3	23,5	31,1	32,8	47,8	31,4	40,2	45,1	47,2	51,7	33,5	42,8	34,6	27,7
An	1,3	6,6	5,2	3,7	7,8	7,2	8,7	3,9	4,4	11,4	9,7	12,1	14,4	12,5	15,5	26,1	19,4	6,4	6,7	6,5
Or	19,9	23,0	24,4	22,[illegible]	21,2	15,9	12,7	24,6	22,4	1,6	3,3	8,8	2,9	2,4	5,2	1,2	0,0	23,4	26,8	35,0
Hb	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	7,6	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Cor	0,1	0,1	0,8	1,3	1,1	1,6	2,6	3,9	3,3	0.0	0,2	2,9	2,2	1,2	0,3	2,0	2,6	0,6	1,2	0,3
Biot	1,9	[illegible],8	1,0	2,4	8,3	1,8	2,7	6,1	1,9	0,2	1,5	7,3	4,5	1,5	4,5	4,4	7,4	1,5	0,9	2,2
Sph	0,2	0,3	0,1	0,3	0,4	0,3	0,2	0,6	0,2	0,3	0,1	0,9	0,5	0,1	0,5	0,3	1,1	0,0	0,0	0,2
Mgt	0,3	0,5	0,3	0,4	0,8	0,4	0,5	1,4	0,3	0,8	0,4	1,6	1,1	0,4	1,1	0,6	1,6	0,3	0,2	0,4
Zirc	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Ap	0,1	0,[illegible]	0,1	0,1	0,3	0,1	0,1	0,1	0,1	0,1	0,0	0,1	0,0	0,0	0,1	0,1	0,2	0,0	0,0	0,0

(Barth mesonorms are calculated using a standard computer programme made available by Dr. R.G. Cawthorn, Department of Geology, University of the Witwatersrand).



<u>*Figure 23*</u> *: Ternary plot of mesonormative An-Ab-Or for anatectites from the various migmatite outcrops described in Chapter 2. Points are plotted from the data listed in Table 11. Isotherms and projected cotectic surfaces are from Kleeman (1965).*

fall in a region of the diagram which corresponds to melt temperatures of $< 700°C$ for $P_{H_2O} = 5$ kb. Thus, in terms of the considerations outlined above, these samples probably correspond to melts that were formed by relatively small degrees of anatexis and whose compositions did not stray significantly from the quaternary cotectic line. If the parental material to these anatectites was a tonalitic or trondhjemitic gneiss, then it is unlikely that they represent much more than about a 15% melt fraction of these rocks. This is because melts of this composition must have remained in equilibrium with a K-felspar phase (together with plagioclase and quartz) which does not generally exceed 5% in tonalites and trondhjemites. Furthermore, the final temperature at which melting took place, although strongly dependent on the P_{H_2O}, could not have exceeded the temperature at which melting was initiated by much more than approximately 30°C, and, in the presence of water, may well have been in the region of 700°C, as indicated in Figures 22 and 23.

In contrast to the above, anatectites from outcrops E, F, G and H all plot in the Or-depleted regions of Figures 22-24. In Figures 22 and 23, it is clear from the isotherms that these samples also plot in a region where melt temperatures correspond to 750°C or greater, at $P_{H_2O} = 5$ kb. These anatectites, therefore, represent one of two possibilities :-

(i) they formed from melts that were not in equilibrium with two felspars and quartz, either because the early stages of anatexis had been surpassed, or they had formed from a parent that contained little or no K-felspar; or

(ii) in terms of a suggestion made by Winkler and Breitbart (1978) they may represent melts which have entrained (or have not effectively separated from) significant portions of the parental material from which they were derived.

The Or-depleted anatectites may, therefore, have formed by two distinct processes; firstly, they may represent a small degree of partial melt (similar to the first category of anatectites) that formed at relatively low temperatures ($\leq$ 700°C) but contain a significant entrained restite component, or secondly, they may have formed at higher temperatures from a significantly higher degree of melting of what was probably a trondhjemitic or tonalitic

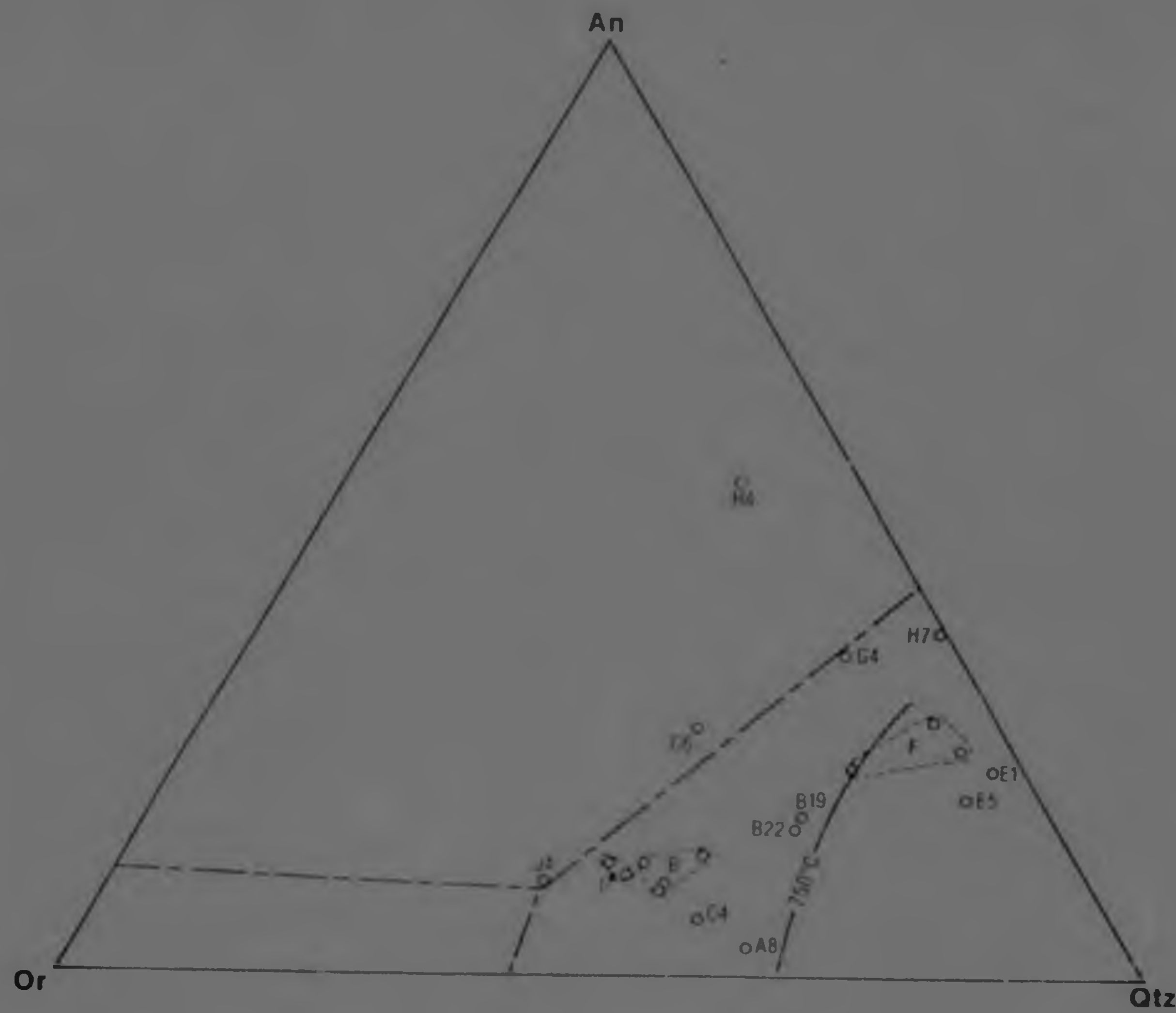


Figure 24 : *Ternary plot of mesonormative An-Or-Qtz for anatectites from the various migmatite outcrops described in Chapter 2. Points are plotted from the data listed in Table 11. Isotherms and projected cotectic surfaces are from Bateman et al. (1963).*

precursor. The petrographic characteristics of the E-F-G-H category of anatectites may help to resolve the dichotomy. Typically, these anatectites do not exhibit textural characteristics that indicate the entrainment of restite material, although they are generally characterized by a higher normative mafic content than the cotectic anatectites (Table 11). Preferentially sericitized calcic cores of plagioclase are not characteristic of the anatectites and the felspars are generally ubiquitously sericitized. However, it is considered likely that the minor chlorite and muscovite that occurs in some of these rocks represents an entrained restite phase. In addition, some samples (e.g. F8), consist of large quartz and plagioclase grains, together with a matrix comprising finer grained, altered and sericitized plagioclase, quartz, minor muscovite and microcline (Plate 6B). It is possible that this finer grained material represents a melt phase whilst the coarser grains constitute the restite, such a texture could equally have formed, however, as the result of subsequent deformation in the rock. It has also been mentioned that some anatectites (e.g. H7), as well as the trondhjemite gneisses themselves in the Batavia section (i.e. H-E-F-G, Figure 2) are garnet-bearing. Stern et al. (1975) showed that experimentally derived tonalitic phase equilibria indicate that garnets are stable only at pressures in excess of 10 kb, which implies that the concomitant temperatures present in this environment may have been somewhat higher than those prevailing in areas where garnets are absent and which are typically characterized by anatectites of cotectic composition. Available evidence suggests, therefore, that the orthoclase-depleted anatectites are most likely derived by higher degrees of partial melting than the anatectites with minimum-melt compositions, but that a certain amount of residual mafic material may also be caught up in the former.

Summarizing, it would appear that the first group of anatectites described, which have cotectic or near cotectic compositions, formed by relatively small degrees of fusion such that the melt was in equilibrium with quartz + plagioclase solid solution + orthoclase solid solution, for the most part of its anatectic history. The second group of anatectites, the majority of which come from the Batavia section, plot in the Or-depleted portion of the granite tetrahedron and may represent similar degrees of partial melt, but which contain a significant restite proportion. It is more likely,

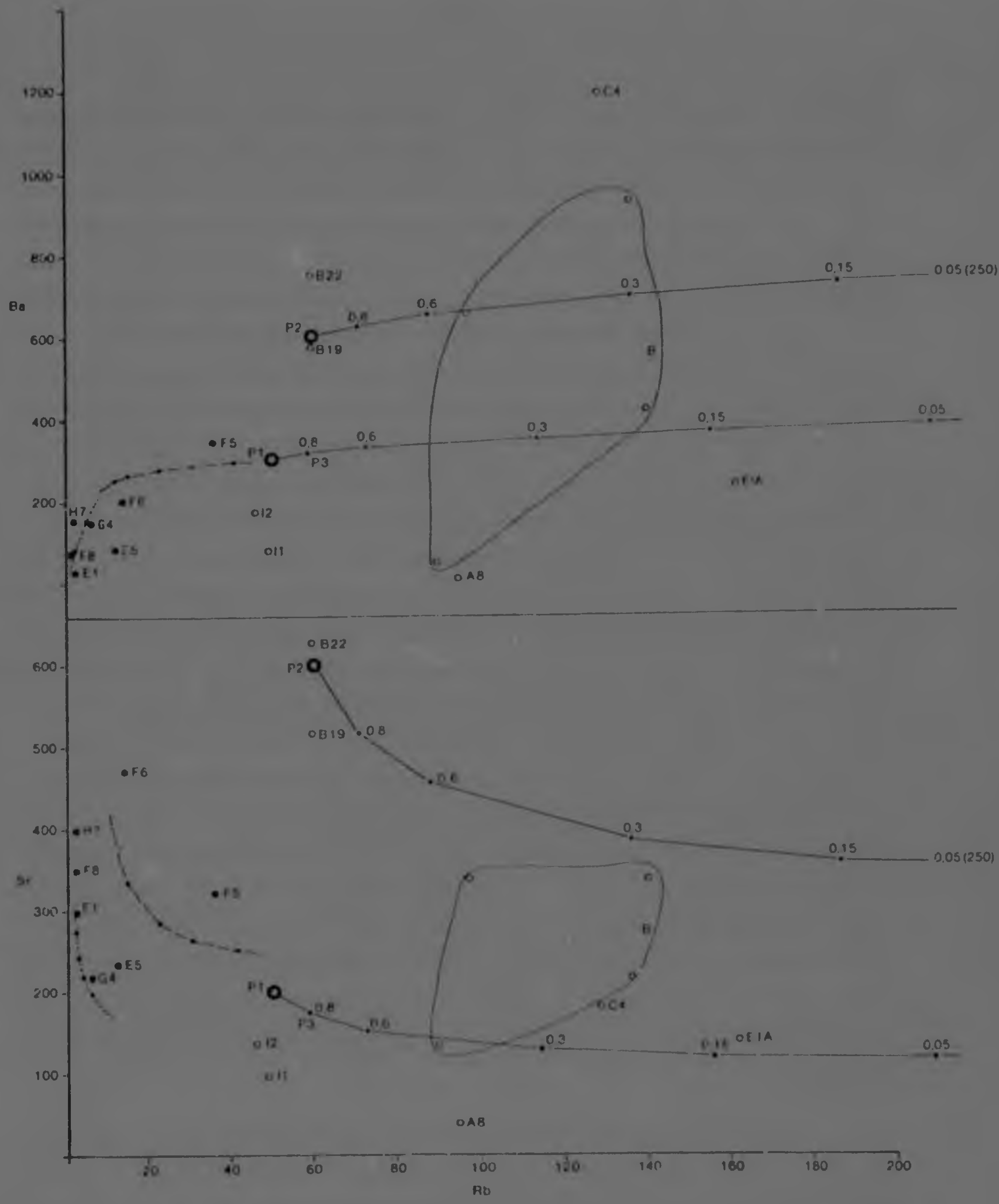


Figure 25 : *Plots of Rb v Sr and Rb v Ba for anatectites from the various migmatite outcrops described in Chapter 2. The individual points are pl..ted from data in Tables 1-10; open circles are cotectic anatectites, dots are orthoclase-depleted anatectites. The solid curves represent predicted model concentrations for successive degrees of partial melt derived from a parent at P1 a. l P2 respectively (encircled stars). The longer dashed curve represents the compositions of residual solids remaining during the melting of successive increments from P1 (see Table 12). The shorter dashed curve represents the crystallization of a quartz + plagioclase dominated assemblage from a melt composition at P3, which is equivalent to an 80% melt of P1. The data for this curve is presented in Table 13.*

however, in view of the presence of garnets both in the anatectites and surrounding trondhjemites, that these anatectites represent a more significant melt proportion generated at temperatures (and pressures) significantly higher than those applicable in the first instance. In both cases, therefore, the generation of the anatectites can be considered in terms of a quartz + plagioclase + K-felspar bearing precursor. The fact that certain of the anatectites have a melt composition that has evolved away from the Or apex of the granite tetrahedron, is consistent with the notion that K-felspar was probably a relatively minor constituent in the parent. As such, it is highly feasible that the tonalite-trondhjemite gneisses that form a ubiquitous component of the migmatite terrane, constitute the parental material for both types of anatectite. This suggestion is tested in terms of the trace and rare-earth element characteristics of these rocks, in the following sections.

3.3 Rb, Sr and Ba concentrations in the anatectites in terms of their suggested derivation by the partial melting of a tonalite-trondhjemite precursor

Another approach that can be used to place constraints on the melt origin of rocks is a consideration of trace element distributions between the various components of a melt-restite system. An assessment of the partitioning of Rb, Sr and Ba into the different liquidus phases of the two anatectite types described above, will undoubtedly place constraints on suggestions made on the basis of mesonormative compositions.

Plots of Rb v Sr and Rb v Ba (Figure 25) represent, in both cases, an illustration of the relative concentrations of an incompatible element (i.e. Rb) with respect to a compatible element (i.e. Sr and Ba) in terms of the anatectite assemblages. As Hanson (1978) has pointed out the relative behaviour and distribution of two such elements is particularly instructive in terms of granite petrogenesis and the following discussion considers the origin of the anatectites in this light.

In Figure 25, plots of the anatectites exhibit a broad scatter with the single discernible feature being that the cotectic, orthoclase-enriched anatectites (i.e. those representing small degrees of anatexis) are enriched in Rb with respect to those anatectites representing more advanced degrees of fusion. This pattern can be used to test the suggestion made previously that the anatectites are derived by partial melting of a tonalitic or trondhjemitic parent. The suggested parental composition is difficult to asses, particularly in view of the large variation in Sr contents that is evident in tonalites and trondhjemites with broadly similar major element compositions (Figure 85, Chapter 6). Assessment of the extensive compilation of data in Chapter 6, indicates the following ranges in the trace element characteristics of these rocks :-

(i) Sr varies between 150-850 ppm,
(ii) Rb remains relatively constant at about 55 ppm, and
(iii) Ba fluctuates somewhat randomly, but averages approximately 450 ppm.

The modelling procedure, therefore, is best considered in terms of two parental compositions which represent extremes in these ranges, i.e. :-

Trondhjemite Parent 1	Trondhjemite Parent 2
Rb - 50 ppm	Rb - 60 ppm
Sr - 200 ppm	Sr - 600 ppm
Ba - 300 ppm	Ba - 600 ppm

In the melt models, equilibrium *batch* melting is considered using the equations of Shaw (1970); modal melting equations are considered unsuitable as the bulk partition coefficients (K_D's) for melt and parent are slightly different. The K_D values and the actual equations, as well as an explanation of the modelling procedure used in the considerations that follow, are presented in Appendix 2.

The following set of parameters applies to this particular case :-

K_D (Trondhjemite)	Rb - 0,2 Sr - 1,8 Ba - 0,8	for a trondhjemitic assemblage comprising 55% plagioclase; 35% quartz; 5% biotite, 5% K-felspar.
K_D (Anatectites)	Rb - 0,2 Sr - 2,2 Ba - 1,9	for an anatectic assemblage comprising 35% plagioclase; 35% quartz; 30% K-felspar.

Melt compositions for a variety of anatectic products ranging from 5-80% melting are presented below in Table 12.

TABLE 12

TRACE ELEMENT MODEL CONSIDERATIONS FOR THE GENERATION OF ORTHOCLASE-ENRICHED (COTECTIC) ANATECTITES

F	0,05		0,15		0,30		0,60		0,80	
	P1	P2	P1	P2	P1	P2	P1	P2	P1	P2
Cl_{Rb}	208	250	156	187	114	136	73	88	59	71
Cl_{Sr}	114	341	119	357	128	385	151	454	172	517
Cl_{Ba}	370	741	361	722	348	697	326	652	312	625
Cs_{Rb}	41		31		23		15		12	
Cs_{Sr}	251		262		282		332		378	
Cs_{Ba}	296		289		278		261		250	

where : Cl,Cs are the concentrations of trace elements in liquid and solid phases respectively

F is the degree of melting

P1,P2 are the trace element concentrations calculated for each of the two envisaged trondhjemitic parents

These values are plotted in Figure 25, where it is seen that the range of Rb, Sr and Ba concentrations exhibited by the cotectic anatectites are broadly consistent with model melt compositions derived from the two trondhjemitic parents under consideration. It is also clear, however, that the models do not allow a realistic prediction of the degree of partial melting to be made as this is entirely dependent on the original parental composition. The model merely confirms the fact that the anatectites have trace element contents that are consistent with a derivation by partial melting of a trondhjemitic parent.

It is important to stress that the above model implies that the cotectic anatectites have a *liquid* composition; this may well be a realistic tenet as these rocks are represented by *cotectic* compositions so that the three liquidus phases that subsequently crystallize out (i.e. quartz - plagioclase solid solution - orthoclase solid solution) will all do so simultaneously and in equilibrium with each other (Plate 6A). Thus, the final solids will, in all likelihood, have the same composition as the original liquid.

The trace element compositions of the residual solids (Cs) that remain after melting various proportions of the P1 trondhjemitic parent are also plotted on Figure 25. It is seen that this trend plots in the vicinity of the Or-depleted non-cotectic anatectites and, thus, supports the suggestion made earlier that these rocks may have incorporated with them a significant restite component. The trace element contents of the Or-depleted anatectites are not, therefore, compatible with the composition of a liquid partial melt as it is clearly seen in Figure 25 that their Rb contents are lower than those of the envisaged parental rocks. As these anatectites are unlikely to consist entirely of restite, it appears that their present trace element contents reflect the composition of solids that crystallized during the cooling of the anatectic melt. Because the Or-depleted anatectites do not have compositions that lie on the isobaric cotectic in the granite tetrahedron (i.e. P2-E5, Figure 21), but rather that fall on, or near, the plagioclase-quartz cotectic surface (i.e. E5-E2-E1-P2, Figure 21), they will undergo a step-wise crystallization sequence on cooling. This situation is unlike that envisaged for the cotectic anatectites where it was argued that the crystallized solids will entirely reflect their liquid compositions. It is likely, therefore, that the Or-depleted anatectites will crystallize either plagioclase or quartz first, or plagioclase and quartz together, before the liquid line-of-descent reaches the eutectic (or minimum melt composition) and K-felspar crystallizes. If it is assumed that this plagioclase + quartz dominated assemblage did not completely equilibrate with the magma from which it was derived (due to a filter pressing process, for example), then it is possible that little, or no, K-felspar will crystallize at all and this phase is unlikely, therefore, to significantly contribute to the partitioning of trace elements in the resultant solids. Thus, solidified Or-depleted anatectites may not necessarily reflect the trace element contents of the liquids from which they were derived and the former are only likely to be realistically modelled in terms of crystallization processes.

In a consideration of the solidification of the Or-depleted anatectites the parental melt is assumed to correspond with the composition of an 80% melt from the P1 trondhjemite percursor;

PLATE 6

A. *Typical microscopic textures existing in a cotectic anatectite from the Theeboom outcrop. The sample (B15) consists of approximately equal proportions of equigranular quartz (qtz), microcline (ksp) and plagioclase (pl). The photomicrograph was taken under crossed-polars; the bar is approximately 0,5 mm long. The same optical conditions and scale apply to all the other photomicrographs in Plate 6.*

B. *Photomicrograph showing the texture of an Or-depleted anatectite (sample F8) from the Batavia section. The sample is characterised by a "matrix" of fine-grained quartz and plagioclase (fg) enveloping coarser plagioclase and quartz grains.*

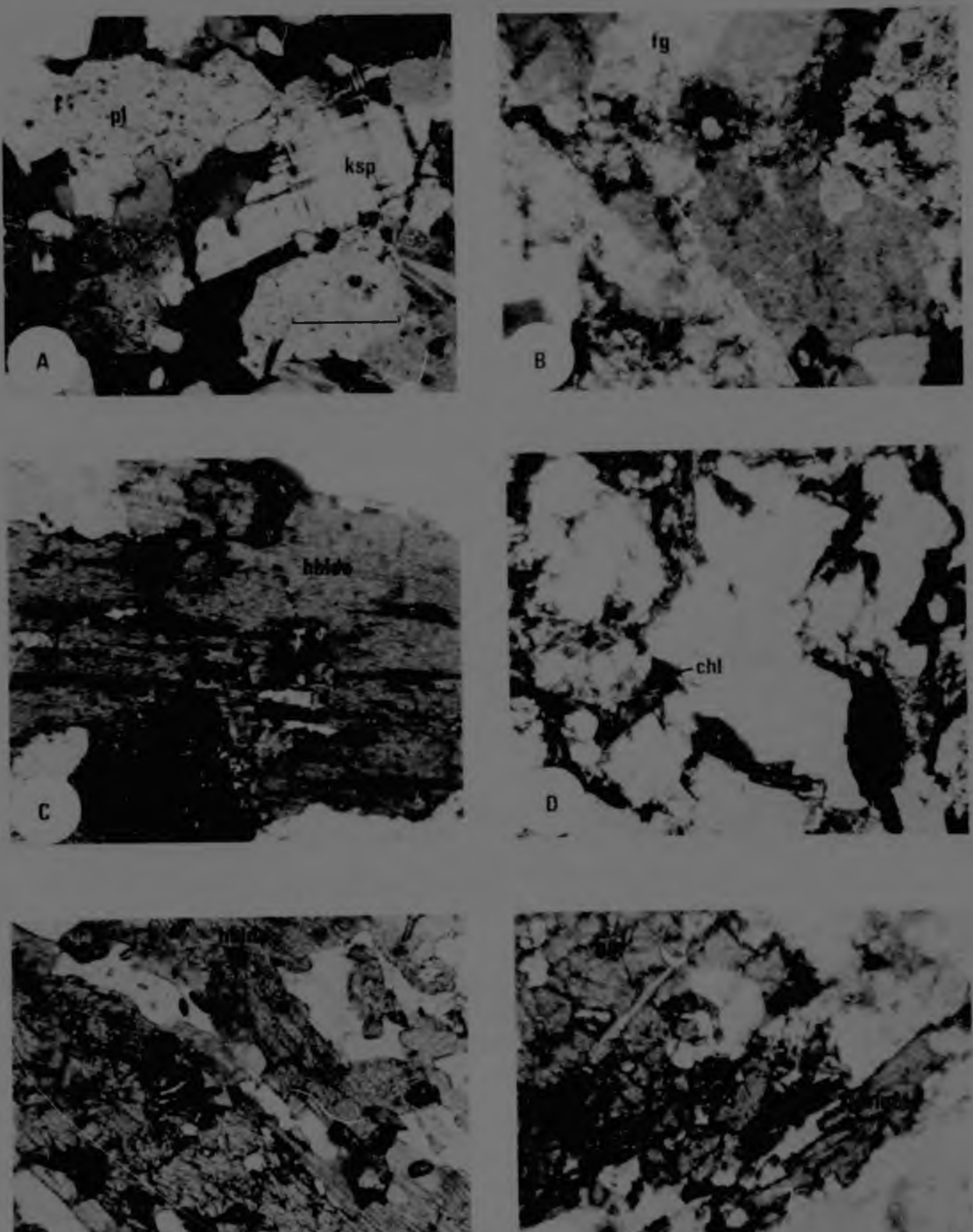
C. *Typical appearance of hornblende (hblde) in an assimilated amphibolite from sample B2. The anhedral grain has been partially dismembered by micro-intrusions of quartz and felspar parallel to the hornblende cleavage planes.*

D. *Photomicrograph of the hybridized quartz diorite unit (D4) from the Mara outcrop. Hornblende has totally disintegrated and is altered to chlorite (chl) which coexists with plagioclase, quartz and microcline in the assimilated rock.*

E. *Coexisting hornblende (hblde) and clinopyroxene (cpx) in an amphibolitic meta-basalt (B6) of komatiitic bulk composition from the Theeboom outcrop. The clinopyroxene has a poikiloblastic appearance by comparison to the hornblende crystals.*

F. *Coexisting garnet (gar) and biotite (biot) in a tonalite gneiss (E2) from the Batavia section. Garnet poikiloblastically encloses quartz and plagioclase grains.*

PLATE 6



i.e. Rb = 60 ppm
Sr = 175 ppm
Ba = 300 ppm (from Table 12)

The bulk partition coefficients of an assemblage fractionating plagioclase + quartz in the ratio 60:40, are as follows :-

Rb - 0,03
Sr - 1,68
Ba - 0,24

Using the principles of Rayleigh fractionation and the equations for equilibrium crystallization (see Appendix 2), the trace element contents of a range of crystallized anatectites between 10-70% are presented in Table 13.

TABLE 13

TRACE ELEMENT MODEL CONSIDERATIONS FOR THE CRYSTALLIZATION OF ORTHOCLASE-DEPLETED ANATECTITES

F	0,1	0,3	0,5	0,7
Cs_{Rb}	2	2,5	3,5	5,6
Cs_{Sr}	275	244	219	199
Cs_{Ba}	78	93	116	154

(Symbols used in this table are the same as those in Table 12)

These values are plotted in Figure 25 where it is seen that the trend coincides closely to the empirical data for the non-cotectic anatectites. It is clear, therefore, that these anatectites must have been derived from a fairly high degree of partial melt of a trondhjemitic parent, a factor which is consistent with their mesonormative compositions. However, because of the extremely low Rb contents of these rocks it is argued that their trace element contents do not reflect (as in the case of the cotectic anatectites) the liquids from which they were derived, but rather, a distribution resulting from the crystallization of a quartz + plagioclase dominated assemblage. These suggestions are considered again in terms of the REE contents of the anatectites, in the following section.

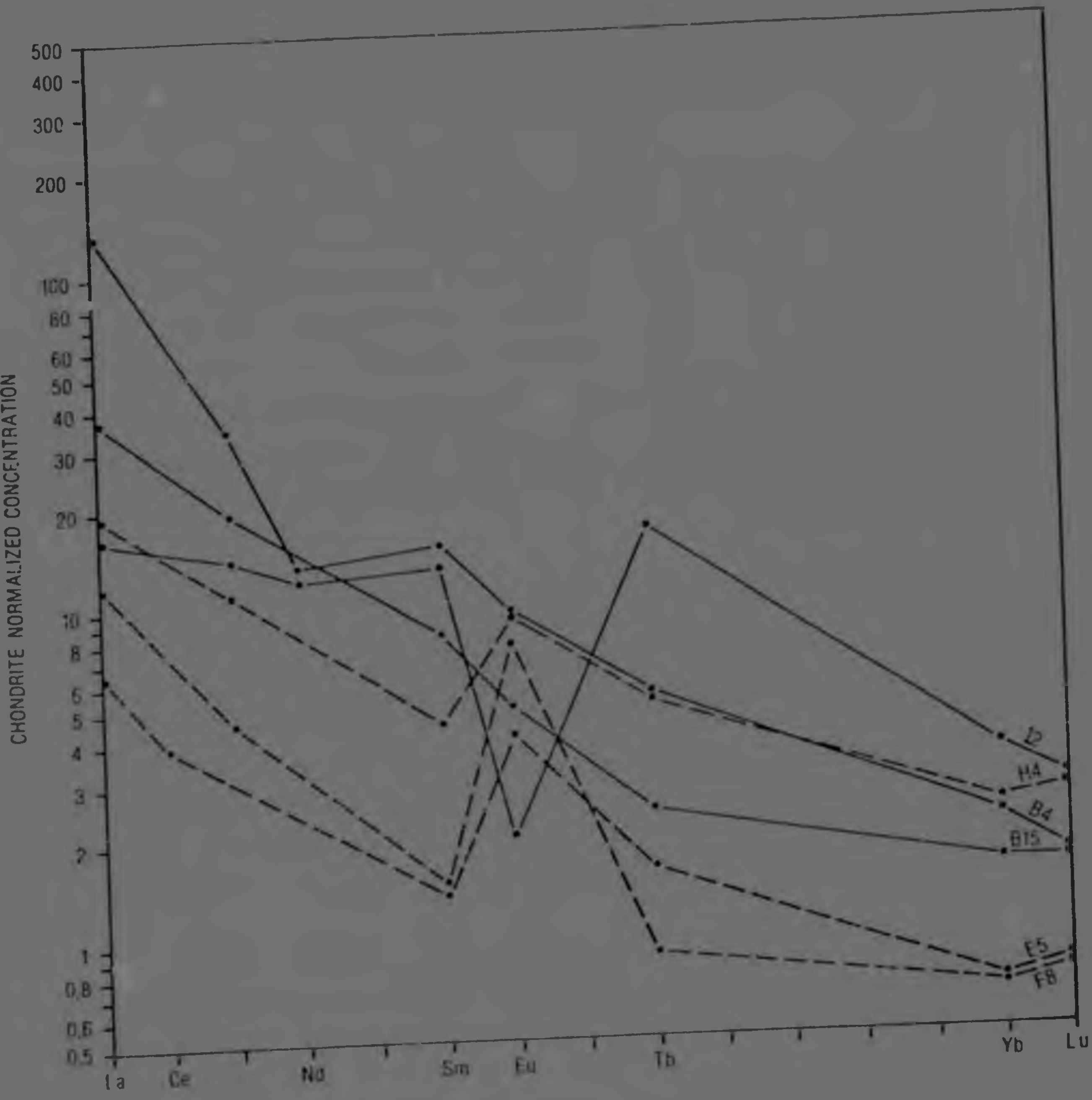


Figure 26 : *Chondrite-normalized rare-earth element plot for anatectites from the various migmatite outcrops described in Chapter 2. Samples I2, B4 and B15 (solid lines) are cotectic anatectites; samples H4, E5 and F8 are Or-depleted anatectites (dashed lines). The data are from Tables 1-10.*

3.4 Rare-earth element concentrations of the anatectites in terms of their suggested derivation by the partial melting of a tonalite-trondhjemite percursor

As seen in Figure 25, the distribution of Rb, Sr and Ba in the anatectites is somewhat random and the variations in these elements do not allow for a rigorous interpretation of their melt origins. It is widely recognized, however, that the REE behave more systematically during petrologic processes and probably reflect, more accurately, the origins of these rocks. The following section considers the suggestions made previously in terms of the chondrite normalized REE concentrations of the anatectites; these model considerations are also presented in the form of a "worked example" in Appendix 2.

The cotectic anatectites are characterized by LREE enrichment, a Ce_N/Yb_N (*) ratio of approximately 20 on average and, either no Eu anomaly (in the case of samples B4 and B15), or a negative Eu anomaly (in the case of sample I2; Figure 26). The Or-depleted anatectites on the other hand, are not as LREE enriched, have smaller Ce_N/Yb_N ratios (~ 6 on average) and in all cases exhibit a positive Eu anomaly (Figure 26). These characteristics can be viewed in terms of the same petrologic models that were considered in the case of the Rb, Sr and Ba concentrations.

The REE composition of a likely trondhjemite parent from which the anatectites are considered to have been derived is taken from averaged data available for the migmatite-related trondhjemite gneisses in section 2 of this Chapter :-

i.e.

	La	Ce	Nd	Sm	Eu	Tb	Yb	La
ppm	13	22	8	1,30	0,40	0,18	0,28	0,03

(*) Footnote : The ratio Ce_N/Yb_N refers to the chondrite normalized ratio of cerium to ytterbium, in contrast to Ce/Yb which is the absolute ratio.

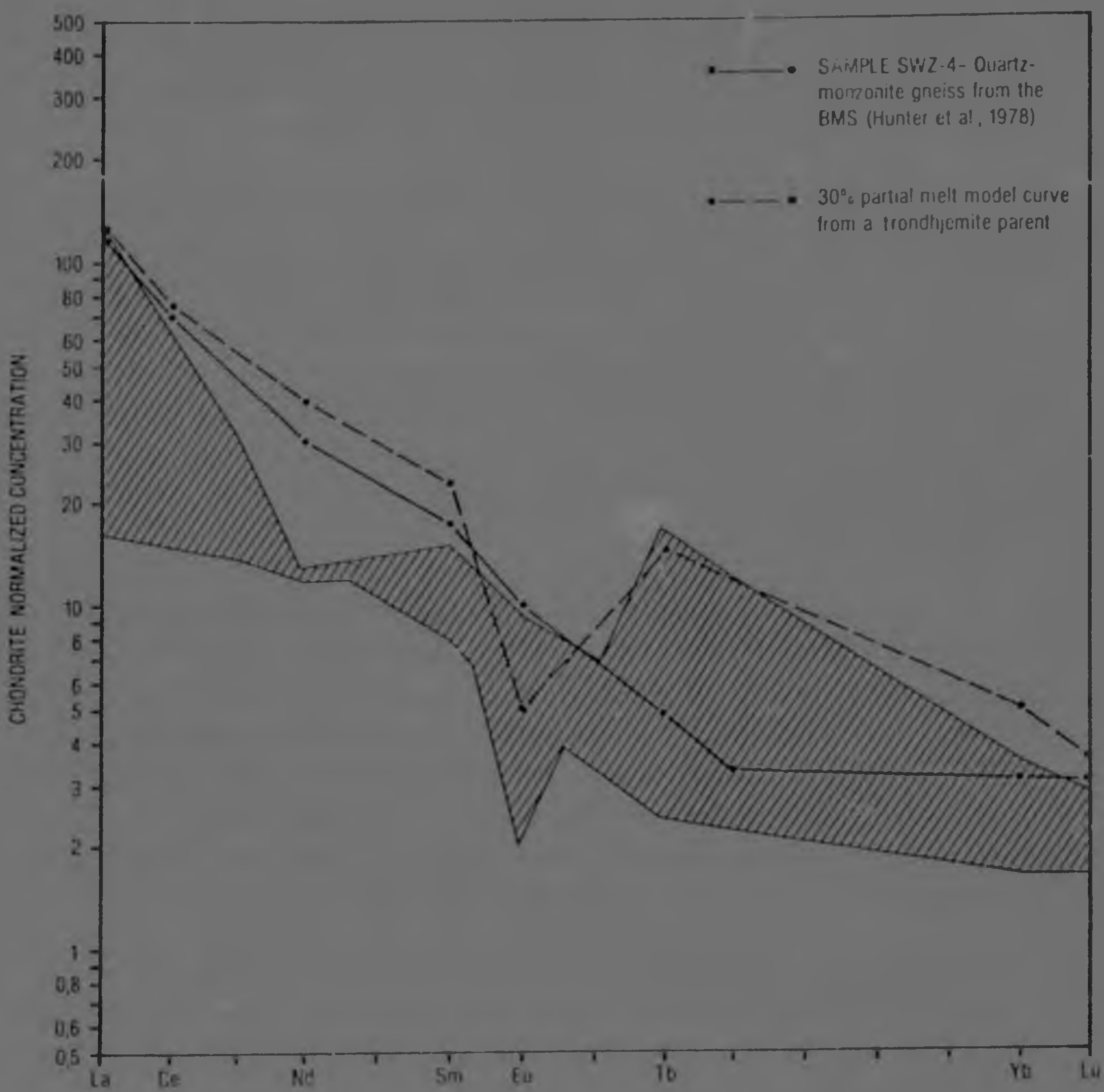


Figure 27 : *Chondrite normalized rare-earth element model plots for the partial melt origin of cotectic anatectites from a trondhjemitic precursor. For comparative purposes, a sample of quartz-monzonite gneiss from the Bimodal Suite (BMS) in Swaziland, is plotted in relation to the envelope of samples of cotectic anatectites from Figure 26 (i.e. hatched area).*

The bulk partition coefficients (K_D's) for a trondhjemitic assemblage similar to that considered in the previous section (i.e. 55% plagioclase; 35% quartz; 5% K-felspar; 5% biotite) are presented below :-

	La	Ce	Nd	Sm	Eu	Tb	Yb	La
ppm	0,18	0,20	0,15	0,09	1,43	0,04	0,06	0,04

Likewise, the K_D's for the cotectic anatectites (i.e. comprising 30% K-felspar; 35% plagioclase; 35% quartz) are :-

	La	Ce	Nd	Sm	Eu	Tb	Yb	La
ppm	0,12	0,14	0,09	0,06	1,21	0,03	0,06	0,02

The bulk partition coefficients for the REE's in the Or-depleted anatectites (i.e. comprising plagioclase + quartz in the ratio 60:40) are very similar to the cotectic anatectites :-

	La	Ce	Nd	Sm	Eu	Tb	Yb	La
ppm	0,18	0,21	0,14	0,09	1,50	0,03	0,04	0,03

As in the case of the Rb, Sr and Ba models, partial melting is considered for equilibrium batch melting as the K_D's for melt and parent are slightly different; the relevant equations are provided in the Appendix 2.

3.4.1 *Cotectic anatectites*

The REE content of the cotectic anatectites can be realistically modelled in terms of a 30% partial melt of a trondhjemitic precursor. The concentrations of the REE in a 30% melt (Cl) are provided below :-

	Cl_{La}	Cl_{Ce}	Cl_{Nd}	Cl_{Sm}	Cl_{Eu}	Cl_{Tb}	Cl_{Yb}	Cl_{Lu}
ppm	30	48	18,9	3,50	0,29	0,54	0,09	0,09

When plotted on a chondrite normalized diagram the above concentrations have a negative Eu anomaly (similar to that of sample I2 in Figure 26) and a Ce_N/Yb_N ratio very similar to that of the envelope of samples representing the Or-rich anatectites (Figure 27). It is clear that in terms of the rare-earth elements, a partial melt origin for the anatectites is consistent with the previous suggestions. In this model, as in the case of the Rb, Sr and Ba considerations, the crystallized cotectic solid is considered to largely reflect the melt compositions calcula ed above.

It is interesting to note that quartz-monzonite gneisses from the Bimodal Suite in Swaziland have very similar major and REE compositions to the cotectic anatectites of the study area. A quartz-monzonitic component of the migmatites of the Bimodal Suite (i.e. one described by Hunter, 1968 as a possible anatectite resulting from the melting of hornblende or garnet-bearing gneisses) is plotted in Figure 27 and has a similar REE trace to the envelope of Or-enriched anatectites from the Badplaas region. These comparisons lend support to the view that a similar suite of rock types occurs in both the migmatites of the Ancient Gneiss Complex and in the migmatite/gneiss terrane of the Badplaas region and that processes of partial melting envisaged in the latter area are equally applicable in Swaziland (Robb and Anhaeusser, 1979).

3.4.2. *Or-depleted anatectites*

In order to model the positive Eu anomaly that characterizes the Or-depleted anatectites on a chondrite normalized plot (Figure 26) it is necessary to consider the fractionation of a dominantly plagioclase + quartz assemblage (i.e. in the ratio 60:40) from an advanced partial melt of a trondhjemitic precursor. The REE content of an 80% partial melt of a trondhjemite (i.e. the same parental melt composition that was considered in the case of the Rb, Sr and Ba model) is calculated using batch melt equations; the results are as follows :-

	La	Ce	Nd	Sm	Eu	Tb	Yb	Lu
ppm	14,7	24,8	9,1	1,50	0,32	0,22	0,34	0,04

If a plagioclase + quartz dominated assemblage is crystallized from this melt, the concentrations of REE in the resultant solid phase (Cs) can be calculated for equilibrium crystallization. The concentrations in the solid phase after 50% of the melt has actually crystallized are given below :-

	Cs_{La}	Cs_{Ce}	Cs_{Nd}	Cs_{Sm}	Cs_{Eu}	Cs_{Tb}	Cs_{Yb}	Cs_{Lu}
ppm	4,5	8,6	2,2	0,25	0,38	0,013	0,030	0,002

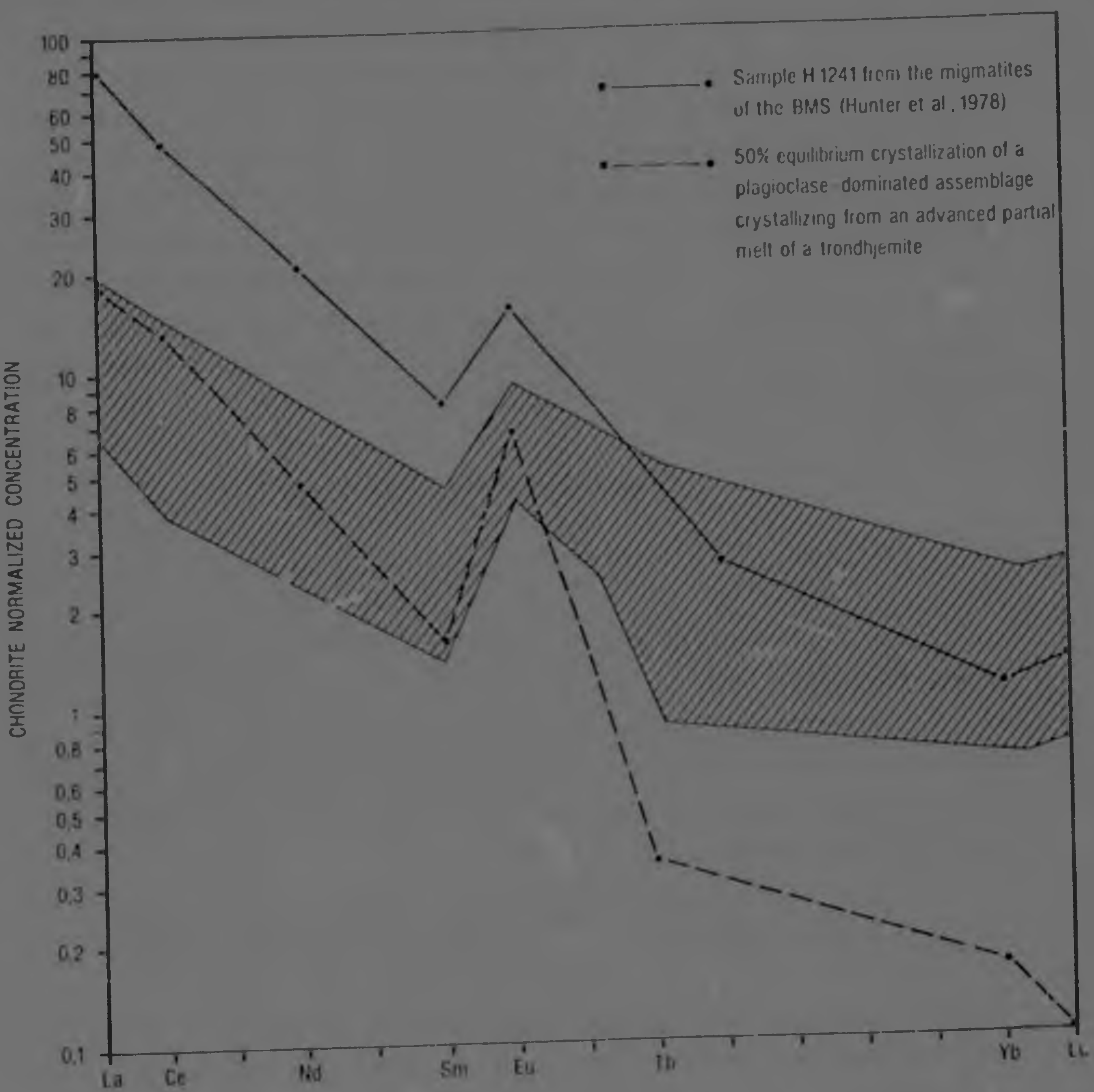


Figure 28 : *Chondrite normalized rare-earth element model plots for a plagioclase + quartz assemblage crystallizing from an advanced partial melt of a trondhjemitic precursor. For comparative purposes, a sample of siliceous migmatite gneiss (H1241) from the Bimodal Suite in Swaziland is plotted in relation to the envelope of samples of non-cotectic, Or-depleted anatectites from Figure 26 (i.e. hatched area).*

When plotted on a chondrite normalized diagram these concentrations have a positive Eu anomaly and a LREE enrichment that is very similar to the envelope of Or-depleted samples (Figure 28). The model HREE are, however, too low by a factor of approximately 2 and this may be due to discrepancies in the partition coefficients for these elements. In spite of this, the model confirms the suggestions made previously that the trace element contents of the Or-depleted anatectites largely reflect those of a solid that formed by the crystallization of plagioclase + quartz. This assemblage could not have equilibrated entirely with the liquid from which it was derived either because solidification was achieved by processes akin to fractional crystallization or residual liquids were removed by a mechanism such as filter-pressing. The dominance of crystallizing plagioclase is the only means whereby a positive Eu anomaly can be generated in rocks of this nature.

It is again of interest to note that components of the Bimodal Suite in Swaziland have REE contents that are similar to those of the Or-depleted anatectites. In Figure 28 a siliceous migmatitic gneiss has a broadly similar REE trace to these anatectites, which supports the view that similar rock-types and processes are found in the migmatitic terranes of both regions.

4. AMPHIBOLITIC XENOLITHS AND DYKES FROM MIGMATITES IN THE BARBERTON MOUNTAIN LAND

The detailed mapping of migmatites in the Barberton Mountain Land resulted in the recognition of numerous amphibolitic phases; as described in Chapter 2, certain of these could be unequivocally interpreted as greenstone xenoliths whereas others are clearly dyke-like features. The relevant samples (from Tables 1-10) that fall into these two categories are listed below, together with a third category where the distinction between dyke and xenolith is uncertain :-

A4, A6
D2, D7
E3, E4
I4
} - Amphibolitic xenoliths/greenstone remnants

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It is again of interest to note that components of the Bimodal Suite in Swaziland have REE contents that are similar to those of the Or-depleted anatectites. In Figure 28 a siliceous migmatitic gneiss has a broadly similar REE trace to these anatectites, which supports the view that similar rock-types and processes are found in the migmatitic terranes of both regions.

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A4, A6
D2, D7
E3, E4
I4

} - Amphibolitic xenoliths/greenstone remnants

B 6, B14, B16 } - Amphibolitic bodies that may either be
J3 } xenoliths or dykes

G1, G2 }
H1, H2, H3 } - Amphibolitic dykes
C5, C7 }

4.1 Petrographic characteristics

All the above rocks characteristically have hornblende as the dominant mineral phase, with the possible exception of samples C5 and C7 where biotite is more prominent; as such these rocks can generally be described as "amphibolites", a term that is consistent with the amphibolitic grade of metamorphism that has greatly affected them. In spite of the dominance of hornblende, samples from the various localities have markedly contrasting attendant mineral phases and exhibit differences in both texture and degree of alteration.

The amphibolitic xenoliths, in particular the B, D and I samples, are more melanocratic than the remainder of the amphibolites. These samples consist dominantly of hornblende but may also contain significant amounts of clinopyroxene (Plate 6E). In sample B6, for example, approximately 30% of the rock is made up by clinopyroxene which, in contrast to the hornblende in the rock, has a poikiloblastic texture. The clinopyroxene usually contains inclusions of plagioclase and quartz as well as minor hornblende. Samples from outcrop A consist dominantly of hornblende with lesser amounts of quartz and plagioclase; these amphibolites, however, have a tholeiitic bulk composition, by comparison with the komatiitic composition that characterizes the previous samples. Samples from outcrop E consist of a hornblende + clinopyroxene assemblage but have been permeated by numerous small anatectite veinlets and are, as a result, less mafic than the samples first described. These samples are also tholeiitic in composition although it is difficult to gauge their original composition prior to contamination.

Samples G and H are amphibolitic dykes which intrude older trondhjemite gneisses. These rocks have hornblende as their dominant mineral phase but contain minor amounts of mica, usually in the form of white-to-pale brown muscovite and biotite. All of the dyke-like samples have been affected by a form of residence contamination which is reflected in an irregular distribution of plagioclase and quartz which may have been introduced into the rock during migmatization. In addition, the hornblende is invariably anhedral and is usually observed in varying stages of alteration and disintegration (see for example, Plate 6c). Grain boundaries are commonly corroded and the rock (particularly in the case of samples H3 and H4) can occasionally be observed in a hybridized condition. Intensive alteration has also taken place with micas being converted to chlorite and plagioclases undergoing sericitization. It is apparent, in certain cases, that a liquid has been physically introduced into the amphibolitic dykes as later plagioclase grains (which are much larger than the primary grains) have grown around both pre-existing plagioclase and hornblende crystals. The amphibolite dyke at outcrop C is somewhat different to those at G and H due to biotite exceeding hornblende and the fact that the rock does not appear to be effected by assimilation and contamination. Both biotite and hornblende are subhedral to euhedral in texture suggesting that the rock may be primary.

4.2. The petrogenesis of Archaean komatiites and tholeiites - current thoughts

This section briefly considers some of the current thoughts that have emerged regarding the petrogenesis of Archaean komatiitic volcanics since they were first identified in the Barberton greenstone belt by Viljoen and Viljoen (1969c). These authors recognized a primitive form of spinifex-textured peridotitic komatiite (STPK) which was regarded as being an extrusive equivalent of an advanced degree of partial melt of mantle peridotite. Related to this primitive magma are a series of evolved basaltic komatiites described, in order of decreasing MgO content, as Geluk-type basaltic komatiites (GBK), Badplaas-type basaltic komatiites (BdBK) and Barberton-type basaltic komatiites (BBK). In addition, basalts of typical tholeiitic composition were also recorded in the Tjakastad Subgroup, within which the komatiitic lavas are best developed. Viljoen and Viljoen (1969c) were the first to realize the relationship between, and the significance of, the komatiitic series in the Barberton greenstone belt. They qualitatively suggested that STPK represented an advanced degree of partial melt of mantle-derived material, whilst regarding the series GBK → BBK as having formed by increasingly smaller degrees of partial melt from the same source. These authors also speculated on the effects of fractionation in the formation of the cumulate-enriched layered ultramafic bodies that are intimately related to these volcanics. In addition, they also considered the effects of crystal fractionation prior to the extrusion of the volcanic komatiites and the possibility that the latter are genetically related by differentiation and not incremental partial melting (Viljoen and Viljoen, 1969j), a factor indicating that this early work was not conclusive in respect of the petrogenesis of the komatiitic rock series.

One of the first detailed studies concerning the petrogenesis of the komatiite series was made by Arndt et al. (1977) who examined the mafic and ultramafic flows at Munro Township in the Abitibi greenstone belt, Ontario. The individual komatiitic flows at Munro Township are layered, with distinctive basal zones that are characterized by well-exposed cumulate assemblages of olivine, clinopyroxene, orthopyroxene and plagioclase, in ascending order. In the light of this textural evidence, therefore, the basaltic komatiite series was considered to be genetically linked by the successive fractionation of these mineral phases and the subsequent generation of differentiated liquids represented by quenched flows of varying compositions.

Arth et al. (1977) further studied the Munro Township lavas from the point of view of trace and rare-earth elements. Modelling procedures suggested that the genesis of the basaltic komatiite series was likely to have been the result of either fractional crystallization or partial melting of a peridotitic source with plagioclase as a significant liquidus phase. Tholeiites and STPK, however, were considered to represent the melt products of garnet peridotite and an unspecified mantle source respectively. These authors also suggested that tholeiites could only be genetically linked to the komatiite series if the former were the first liquids (i.e. the smallest degrees of partial melt) to be removed from the source, with the komatiites forming subsequently, by progressive melting and successive removal of liquid phases (i.e. fractional melting). A follow-up study by Whitford and Arndt (1978) concentrated specifically on a particular layered flow at Munro Township and confirmed the role played by crystal fractionation in causing the compositional variations in individual flow units. On a broader scale, however, the komatiitic basalt series were viewed as probably reflecting different degrees of partial melt rather than fractional crystallization.