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CHEMICAL AND PETROGENETIC CHARACTERISTICS
OF ARCHAEOAN TONALITE-TRONDHJEMITE
GNEISS PLUTONS IN THE
BARBERTON MOUNTAIN LAND

L.J. ROBB and C.R. ANHAEUSSER

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UNIVERSITY OF THE WITWATERSRAND
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BARBERTON MOUNTAIN LAND

by

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ABSTRACT

Tonalite and trondhjemite gneiss plutons are best exposed in the region southwest of the Barberton greenstone belt where thirteen discrete bodies have now been identified. Certain of these are clearly defined in terms of a regular elliptical shape and a prominent greenstone selvedge, whereas others may be irregularly shaped and incorporate sizable greenstone remnants.

Most of the tonalite-trondhjemite bodies are characterized by subtle, yet significant, chemical differences. The compositional ranges within individual plutons indicate typical fractionation trends whilst bulk chemical variations between certain of the plutons are attributed to small differences in the degree of partial melting that occurred in their formation. Distinguishing between the various bodies is best achieved through their Sr signature, which may vary by a factor of five from one body to another. Rare earth element data, where available, also serves to characterize the various tonalite-trondhjemite types.

When considering the data from the Barberton region together with that from the Ancient Gneiss Complex in Swaziland, two broad tonalite-trondhjemite gneiss sub-types emerge; the first, a high Sr (low Rb/Sr) low Σ REE sub-type and the second, a lower Sr (higher Rb/Sr), higher Σ REE sub-type. It is suggested that these differences may be attributable to a melt origin at different crustal levels, where isochemical mineral phase changes in the residual material results in different distributions of trace elements between melt and restite. Hence, the characteristics of the first sub-type are compatible with a melt that equilibrated with a dominantly hornblende-bearing residue (i.e. partial melting at amphibolitic grades) whilst the second sub-type appears to have formed from a melt equilibrating with a residue in which a significant clinopyroxene component existed (i.e. partial melting in an environment tending towards granulite grades). This scheme obviates the need to invoke a polygenetic origin for the tonalites and trondhjemites from the Barberton area and the Ancient Gneiss Complex.

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I. INTRODUCTION

Hornblende tonalites and leucocratic biotite trondhjemites underlie large areas of the Archaean granitic terrane in both the eastern Transvaal and Swaziland. These rock types are considered, collectively, to constitute the oldest cycle of granitic magmatic activity in these areas and are viewed as representing remnants of early sialic nuclei (Anhaeusser and Robb, 1981). The tonalites and trondhjemites generally form discrete bodies which are invariably gneissic (i.e. S > L fabric) but may also be associated with complex migmatitic rocks (Robb, 1982; Hunter, 1970, 1973, 1979). In the eastern Transvaal tonalite-trondhjemite plutons vary in size from 1,5 - 25 km in diameter and may form well-defined elliptical bodies (Fig. 1); compositionally and mineralogically these bodies vary from hornblende-bearing tonalites to more leucocratic biotite-bearing trondhjemites (*). In Swaziland, large well-defined elliptical plutons have not been recorded although intermediate- to small-sized hornblende tonalite plutons have recently been recognized by Jackson (1979). These plutons occur in terrane formerly regarded as consisting of bimodal, leucocratic trondhjemitic gneisses and migmatites associated with amphibolitic paleosomes (Hunter et al., 1978). This paper describes the factors relating to the recognition of a number of discrete tonalite-trondhjemite bodies in the Barberton Mountain Land, these being developed immediately to the west and southwest of the Barberton greenstone belt. Chemical and petrogenetic characteristics of these bodies are compared with similar rock types in Swaziland. These considerations are made in the light of current thoughts regarding the origin of Archaean tonalites and trondhjemites and their significance in terms of early crustal evolution.

II. CURRENT THOUGHTS ON THE PETROGENESIS OF
ARCHAEN TONALITES AND TRONDHJEMITES

Much of the recent work on Archaean tonalites and trondhjemites is characterized by a consensus view that these rocks have been derived by partial melting of a basaltic precursor (Hanson and Goldich, 1972; Arth and Hanson, 1975; Arth and Barker, 1976; Condé and Hunter, 1976; Glikson, 1976; O'Nions and Pankhurst, 1978; Collerson and Bridgwater, 1979; Payne and Strong, 1979; Tarney et al., 1979). This common origin is based on characteristics which include (i) generally low initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios which have been interpreted as evidence precluding a significant crustal pre-history; (ii) a common association between tonalite-trondhjemite gneisses and amphibolitic (basaltic) remnants; (iii) trace and rare earth element characteristics compatible with the partial melting of a mafic precursor and (iv) a geological setting which usually involves intrusion into enveloping, synclinorial greenstone remnants.

The partial melting of mafic precursors to form tonalitic or trondhjemitic magmas is a mechanism which could take place in a number of different geological environments. Early petrogenetic models favoured the partial melting of eclogitic assemblages at deep crustal levels primarily because the depleted heavy rare earth element (HREE) contents of typical Archaean tonalites and trondhjemites could best be accommodated in terms of a garnet-bearing residue (Arth and Hanson, 1975; Condé and Hunter, 1976). This notion suffered, however, from the common lack of eclogitic remnants associated with these rocks in all but high-grade environments, the latter being atypical of granite-greenstone terranes. Later models were facilitated by the calculation of high partition coefficients for the HREE into hornblende (Arth and Barker, 1976). This resulted in a consideration of Archaean tonalites and trondhjemites as partial melts of amphibolitic metabasalts at shallower crustal levels, this idea being compatible with common rock associations in these terranes.

The above ideas, which relate Archaean tonalites and trondhjemites to a mafic precursor, argue in favour of models suggesting a primordial ensimatic crust although it is noted that in some areas (metamorphic belts ?) evidence for older sialic material does exist. These models are compatible with the view that mafic and ultramafic greenstone successions represented once extensive oceanic crust which was progressively transformed into a stable continental platform. Thus, whilst certain models of Archaean crustal evolution invoke a primitive sialic crust, geological relationships (at least within certain Archaean granite-greenstone terranes) as well as current views on the origin of tonalites and trondhjemites, are mutually compatible in terms of the opposite view.

(*) The distinction between tonalite and trondhjemite is viewed in terms of Barker's (1979) definition of a trondhjemite, i.e. a trondhjemite is a leucotonalite. Barker provided the following quantitative major element distinctions between trondhjemites and tonalites :-

<u>Trondhjemite</u>	<u>Tonalite</u>
$\text{SiO}_2 > 68\%$	$\text{SiO}_2 < 68\%$
$\text{Fe}_2\text{O}_3_{\text{Total}} + \text{MgO} < 3,4\%$	$\text{Fe}_2\text{O}_3_{\text{Total}} + \text{MgO} > 3,4\%$
CaO typically 1,5 - 3,0%	CaO typically > 3,0%
Na ₂ O typically 4,0 - 5,5%	
K ₂ O typically < 2,0%	
High alumina trondhjemites	
have > 15% Al_2O_3 at 70% SiO_2	

III. GEOLOGICAL CHARACTERISTICS OF TONALITE-TRONDHJEMITE BODIES
IN THE BARBERTON MOUNTAIN LAND

A. The Recognition of Individual Tonalite-Trondhjemite Bodies
Southwest of the Barberton Greenstone Belt

The best exposed and most extensively developed tonalite and trondhjemite gneisses in the eastern Transvaal occur immediately to the southwest of the Barberton greenstone belt. This region has been mapped on a scale of 1 : 10 000 and extensively sampled for geochemical studies. A total of 139 samples, analysed for major and trace elements as well as a limited number of rare earth elements (see Robb, 1981) are utilized in this investigation. All these data are included in the microfiche appendix of the Barberton Project geodynamics volume (in press, 1982).

Figure 1 shows the study area discussed in this paper. The gneissic terrane has been subdivided into 13 tonalite-trondhjemite bodies, each of which is identified on the map. A number of these bodies had been recognized and named prior to the present study (Viljoen and Viljoen, 1969a). Occurrences such as the

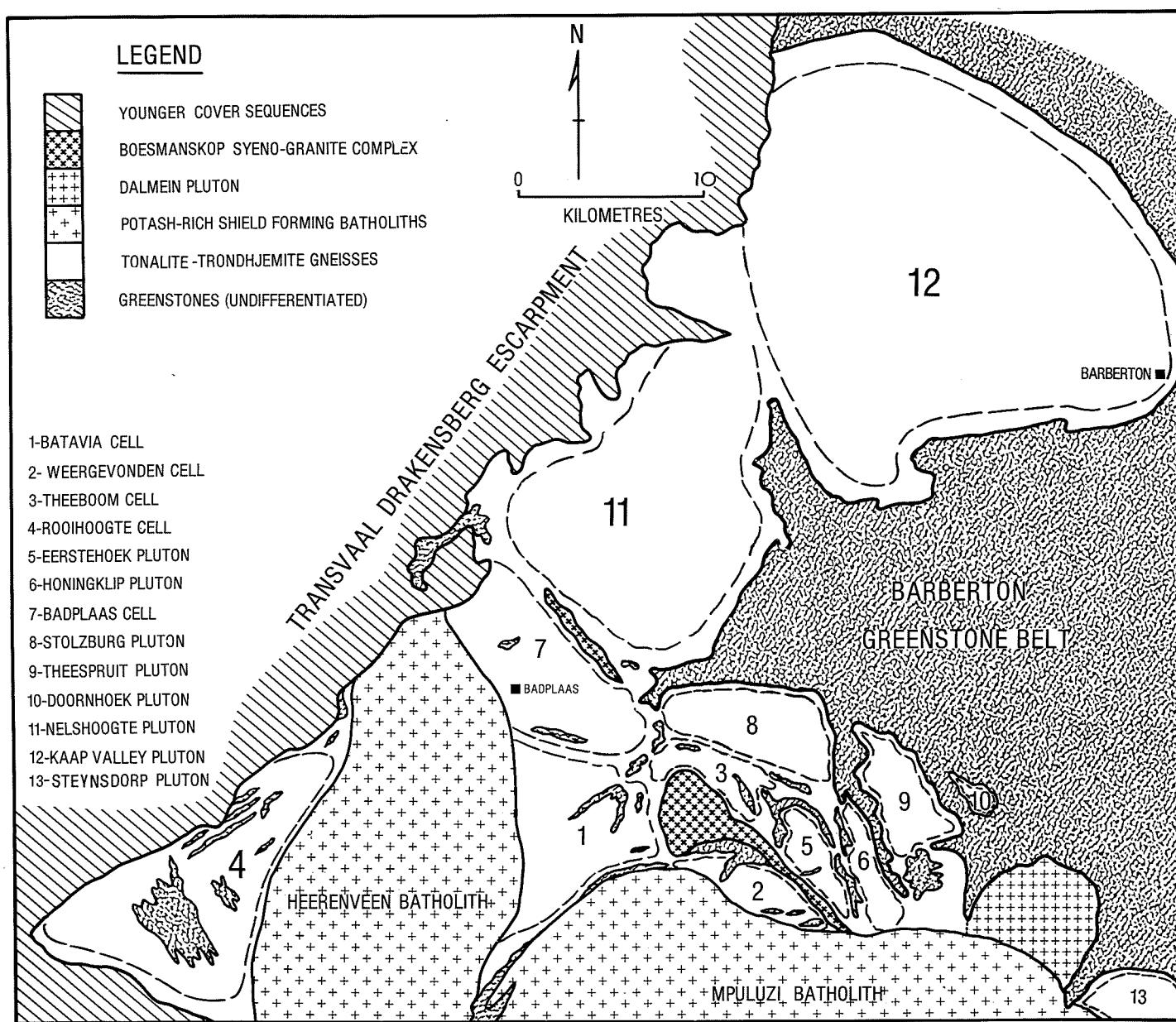


Figure 1 : Simplified geological map showing the names and outlines of the tonalite-trondhjemite plutons and cells in the area southwest of the Barberton greenstone belt.

Kaap Valley, Nelshoogte, Stolzburg, Theespruit, Doornhoek and Steynsdorp plutons, owe their early recognition to well-defined elliptical outlines which define the curvilinear shape of the Barberton greenstone belt itself. However, the more recent geological mapping, which extended for 40 - 50 km southwest of the greenstone belt, was unable to readily outline the shapes of individual tonalite and trondhjemite plutons as had been done previously. The newly defined bodies were recognized principally in terms of their distinctive geochemical (compositional) characteristics and may have shapes which are not necessarily elliptical and whose outlines are not defined by greenstone selvedges. These bodies are referred to as "cells" in Fig. 1 in order to distinguish them from the earlier-defined bodies. Inferred in the definition of the 13 plutons and cells is the implication that each body represents an individual magmatic event that is spatially and perhaps temporally unrelated to other, albeit similar, bodies in the vicinity. The difference between plutons and cells is important as the latter are not easily identifiable field units and are recognized principally on the basis of their compositional characteristics. Although plutons are unequivocally manifest as individual, discrete units (e.g. the Kaap Valley pluton) it is feasible that increased sampling or mapping resolution over the entire area could result in the identification of additional plutons within existing cells. As such, it may be unwarranted to consider the entire study area as having formed in response to only 13 discrete magmatic pulses.

B. Field Characteristics of the Plutons and Cells

The tonalite-trondhjemite plutons and cells vary in diameter by more than an order of magnitude (compare the Kaap Valley pluton with the Doornhoek pluton in Fig. 1). As mentioned earlier, the plutons in the study area are invariably outlined by greenstone septa and although they are generally homogeneous in appearance (e.g. Stolzburg, Nelshoogte), the plutons do contain small greenstone xenoliths (roof-pendants?) as well as possible cognate xenoliths which might reflect the nature of their source environment. The cells, on the other hand, contain and incorporate innumerable, often large, greenstone rafts which may either be xenoliths or structurally infolded remnants (e.g. Rooihoopte and Batavia cells).

The tonalite-trondhjemite gneisses are characterized by an ubiquitous, but variable, mineral fabric. This is generally manifest as a moderate to well-developed foliation which tends to dip subvertically. The foliation in the plutons reflects their elliptical shapes and is always parallel or concordant with the tonalite-greenstone contact. Mineral lineations (or $L > S$ fabrics) are generally not well-developed in the gneiss terrane with the exception of parts of the Theespruit pluton where these structures have sub-vertical plunges. Certain tonalites and trondhjemites have extremely well-developed foliations which often incorporate a distinct compositional banding. In the case of portions of the Batavia cell, the foliation/compositional banding is itself refolded by successive deformational increments which indicate a prolonged dynamo-thermal history for this unit (Figs. 2 and 3). By comparison, extensive portions in the centre of the Doornhoek pluton have a very weakly-developed or non-existent mineral fabric (Fig. 4) in a region which has otherwise been highly deformed. The absence of a mineral fabric is probably indicative of a zone of no finite strain resulting from the diapiric intrusion of a solid, buoyant, mass of tonalite into an overlying, denser, greenstone overburden (Robb, 1981).

Tonalite and trondhjemite gneisses are intimately associated with migmatitic rocks in the area southwest of the Barberton greenstone belt (Anhaeusser and Robb, 1980; Robb, 1982). Migmatitic exposures reveal evidence for the magmatic intrusion of gneiss protoliths into pre-existing greenstone remnants. However, the contacts between the gneissic plutons and the Barberton greenstone belt are generally characterized by few magmatic intrusive features (i.e. tonalitic veins, apophyses, etc.). In the Kaap Valley and Doornhoek plutons, for example, contacts with enveloping greenstones are invariably sheared suggesting, as mentioned above, the structural emplacement of a solid tonalitic or trondhjemitic mass into an overlying greenstone assemblage. The mechanism responsible for this style of emplacement is thought to be related to gravity inversion arising from density contrasts (Dixon, 1975; Gorman et al., 1978; Schwerdtner et al., 1978) and implies that although the gneiss protoliths may originally have been magmatically intrusive into the greenstones, the gneiss plutons were structurally emplaced into their present positions.

Whilst in the majority of cases the above relationships appear to prevail there are, nevertheless, examples where the tonalite-trondhjemites unequivocally intrude and transect the greenstones flanking the plutons. This is particularly clearly demonstrated around the northern margins of the Theespruit pluton where the trondhjemite abruptly truncates various lithological units of the Sandspruit and Theespruit formations of the Barberton greenstone belt (Viljoen and Viljoen, 1969b; Anhaeusser and Robb, in prep.). Likewise, the transgressive nature of the contact between the Nelshoogte pluton and the flanking greenstones of the Nelshoogte schist belt (Anhaeusser, 1972) demonstrates clearly the magmatic nature of the tonalite-trondhjemite gneiss protoliths prior to their structural realignment by subsequent diapirism.

The tonalites and trondhjemites in the study area have a variable mineralogical content which is reflected principally in their mafic constituents. The majority of the gneisses are characterized by approximately equal proportions of quartz and plagioclase (albite-oligoclase) together with 10 - 15% biotite. Minor amounts of microcline and chlorite occur together with accessory sphene and apatite. The notable exception to this assemblage is the Kaap Valley tonalite which is considerably more mafic than the biotite-bearing tonalite-trondhjemites and is characterized by ubiquitous hornblende. The more mafic phases of the Kaap Valley body contains as much as 25% hornblende, generally without any biotite, whereas the more felsic phases have considerably less hornblende which usually coexists with small amounts of biotite (Robb, 1981). It is interesting to note that a body of hornblende tonalite (the Tswela gneiss) also occurs within the Ancient Gneiss Complex in Swaziland.

IV. MAJOR ELEMENT CHARACTERISTICS

The major element characteristics of the 13 tonalite-trondhjemite bodies defined in the area southwest of the Barberton greenstone belt were examined to establish the existence of any systematic compositional differences between them. In Fig. 5, selected Harker plots of the available data clearly indicate subtle, yet significant, chemical differences between certain of the plutons and cells. Plots of SiO_2 v Al_2O_3 and SiO_2 v $\text{Fe}_2\text{O}_3^* + \text{MgO}$ indicate a broad inverse relationship between silica and the alumina and ferromagnesian content of this suite. Within individual plutons and cells a range in composition is observed which is probably attributable to *in situ* crystal fractionation as discussed by McCarthy (1978) and Robb (1981). However, in these two plots it is apparent that systematic differences in the fractionation trends between certain of the bodies is also evident. In the SiO_2 v Al_2O_3 plot, for example, the overall trend for the Weergevonden cell has a marginally higher alumina content than the trend for the Doornhoek pluton. The tonalite-trondhjemite suite all have "high-alumina" characteristics in terms of Barker's (1979) definition (i.e. > 15% Al_2O_3 at 70% SiO_2) suggesting that the magma protoliths of these rocks were derived from a parent-melt system containing insignificant quantities of residual plagioclase. Differences between plutons and cells are even more apparent in the SiO_2 v $\text{Fe}_2\text{O}_3^* + \text{MgO}$ plot where, for example, the averaged data for the Kaap Valley pluton is significantly more ferromagnesian than the remainder of the tonalite-trondhjemite suite. Even the more felsic members of the suite show differences, however, and it is evident that over a similar range in SiO_2 , the Rooihoopte cell is, for example, markedly more ferromagnesian than the Weergevonden cell.

The plot of SiO_2 v Na_2O in Fig. 5 differs from the normal Harker trends in that the soda concentrations are independent of silica. In addition, certain of the tonalite-trondhjemite bodies have distinctive Na_2O



Figure 2 : Foliation and compositional banding in trondhjemite gneiss from the Batavia cell; the fabric illustrated here is characterized by a Z minor-fold geometry.



Figure 3 : Pronounced foliation in trondhjemite gneiss from the Batavia cell; symmetrical (M-type) minor fold structures suggest proximity to a fold-closure.



Figure 4 : Relatively undeformed trondhjemite from the Doornhoek pluton showing evidence for primary igneous layering; portions of this body appear to preserve a zone of neutral strain characteristic of the crestal regions of gravitationally induced diapiric structures (see Robb, 1981).

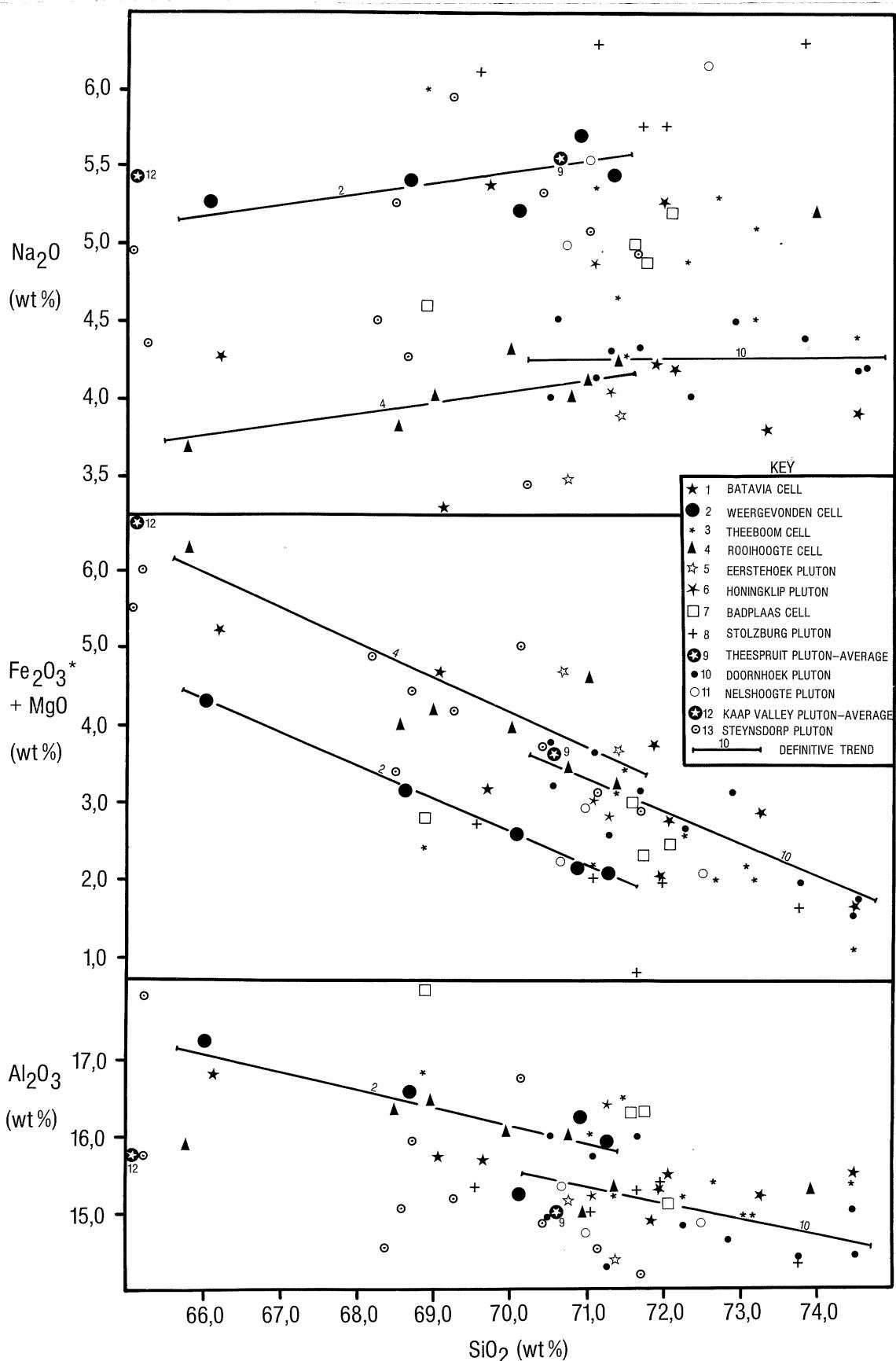


Figure 5 : Selected Harker diagrams showing the chemical variations in the tonalite-trondhjemite plutons and cells from the study area. The diagram and its data sources are referred to in Robb (1981). Chemical analyses are included in the microfiche appendix of the Barberton Project geodynamics volume (in press, 1982). Fe_2O_3^* refers to total iron as Fe_2O_3 .

contents with the Weergvonden cell and Stolzburg pluton being characterized by $\text{Na}_2\text{O} > 5.25\%$, whereas the Doornhoek and Eerstehoek plutons and the Rooihoopte cell all have values of $\text{Na}_2\text{O} \approx 4\%$, for a similar range in SiO_2 . It is also apparent in Fig. 5 that the bodies with relatively high ferromagnesian contents for any value of silica, are distinctive in terms of their markedly lower Na_2O contents (compare trends 2, 3 and 10 in the relevant sections in Fig. 5). This suggests an inverse relationship between Na_2O and $\text{Fe}_2\text{O}_3^* + \text{MgO}$ in the tonalite-trondhjemite suite, a feature which is demonstrated in Fig. 6, where averaged values for each of the 13 bodies are plotted. In this diagram all but one of the bodies produce a trend indicating a broad increase in Na_2O with decreasing ferromagnesian content. These bodies are dominantly trondhjemitic in composition and differ significantly from the tonalitic Kaap Valley pluton with markedly lower SiO_2 (average $\text{SiO}_2 \approx 65\%$) and higher $\text{Fe}_2\text{O}_3^* + \text{MgO}$ contents.

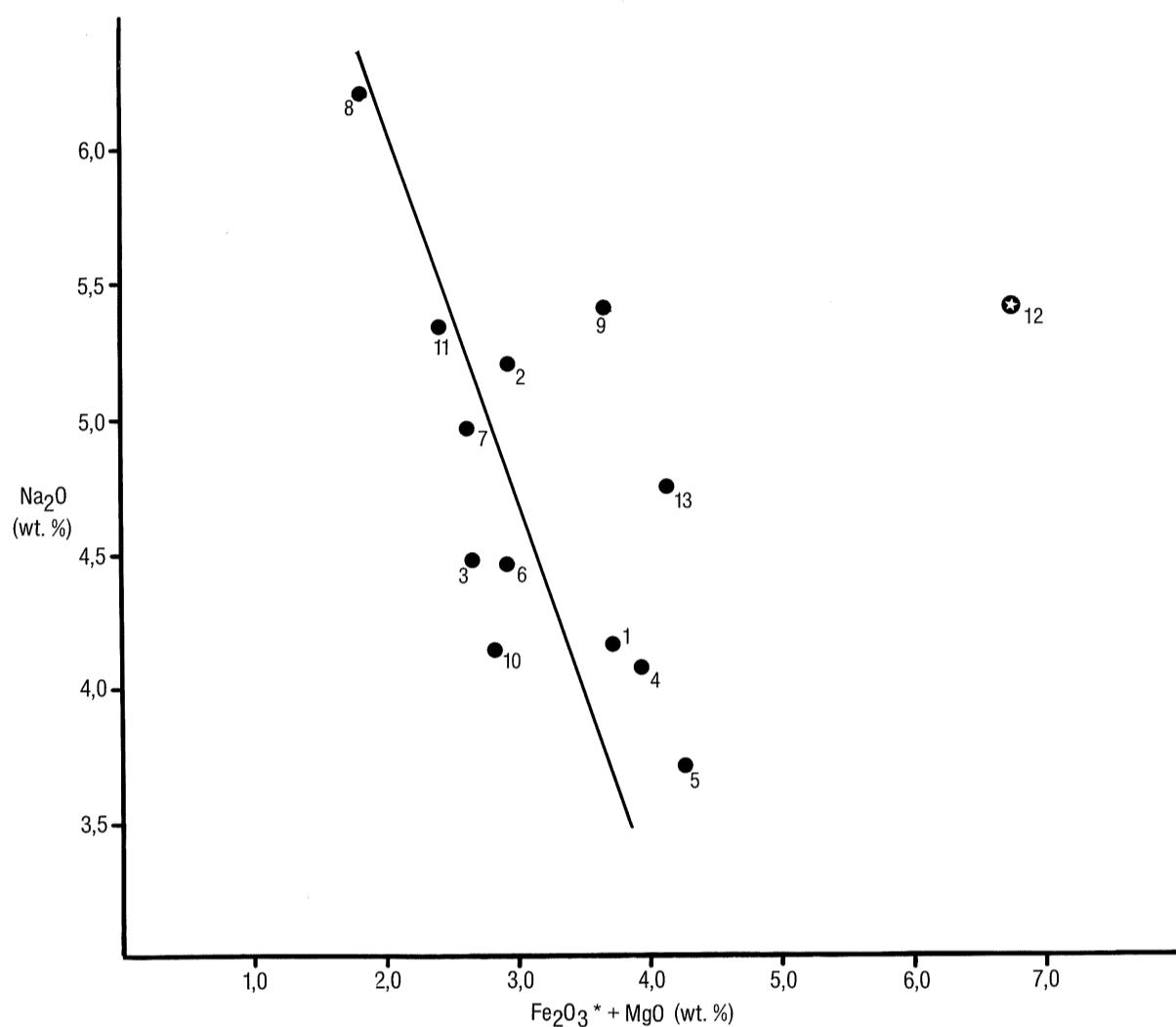


Figure 6 : Plot of the average values of $(\text{Fe}_2\text{O}_3^* + \text{MgO})$ and Na_2O for each of the 13 tonalite-trondhjemite bodies in the study area. The Kaap Valley tonalite (data point 12) lies removed from the trondhjemite field reflecting a higher ferromagnesian content for this pluton.

The compositional trends discussed above indicate that the tonalites and trondhjemites in the study area exhibit variations of two types. Systematic internal variations result in trends which have a general tendency towards trondhjemitic compositions (with the notable exception of the Kaap Valley tonalite pluton) and which are probably related to *in situ* crystal fractionation. In certain cases, however, an individual body as a whole may have a significantly different major element composition from that of another, indicating variations in the original magma composition of the gneiss protoliths. It is logical to assume, in the light of previous discussion, that such variations may be due to small differences in the degree of partial melting that occurred during the formation of this magma, although the effects of subsequent crystal fractionation means that it is difficult to rigidly quantify this aspect. The melting behaviour of hornblende (i.e. in an amphibolitic metabasalt) is broadly compatible with the subtle observed compositional differences in the tonalite-trondhjemite suite and yet allows for these rocks to have all been derived by a common process in a similar pressure-temperature environment. Helz (1976) showed that melt compositions derived from a variety of basaltic precursors do not change significantly over a wide range of melt temperatures until such time as conditions approach the upper stability limit of hornblende. Over a restricted, but critical, temperature range the continued breakdown of hornblende results in a sharp rise in the FeO and MgO contents of the melt. Thus, the differences observed in Fig. 6 between the Kaap Valley pluton and the remainder of the tonalite-trondhjemite bodies may be accounted for by only slightly more advanced breakdown of hornblende in the case of the former. Helz (1976) also showed that the complex incongruent melting behaviour of hornblende results in variations in the composition of successive melt increments. Thus, in any one temperature interval, hornblende may absorb Na and Al from the melt leaving Ca and Al relatively enriched in melts representative of that temperature interval, whilst at slightly higher temperatures, continued breakdown of hornblende will redress the soda and alumina contents in subsequent melts. Considerations such as these, which involve amphibolitic parental material, are consistent, not only with the observed compositional variations, but also with the preferred origins of the tonalite-trondhjemite suite in the study area.

V. TRACE ELEMENT CHARACTERISTICS

The following section examines the trace element characteristics of the tonalite-trondhjemite bodies in the Barberton Mountain Land. In particular the Rb, Sr, and the rare earth elements (REE) are considered as they are most commonly used in petrogenetic considerations regarding granitoids.

In Fig. 7, a plot of SiO_2 v Sr for all available data representing the 13 bodies serves as the means whereby the individual plutons and cells can most easily be "finger-printed". In particular the Sr signature of each body is reasonably definitive and is SiO_2 independent. In terms of this diagram, most of the bodies appear to fall within a discrete compositional field with Sr varying from ≈ 150 ppm in the Doornhoek pluton to ≈ 750 -850 ppm in the Weergevonden and Theeboom cells. Overlaps do occur, however, and the diagram best distinguishes between low-, intermediate-, and high-Sr bodies. The large variation of Sr contents in a suite of rocks that are both geologically similar and spatially related, is problematical and must have an important bearing on the petrogenesis of these rocks. This question is discussed more fully later.

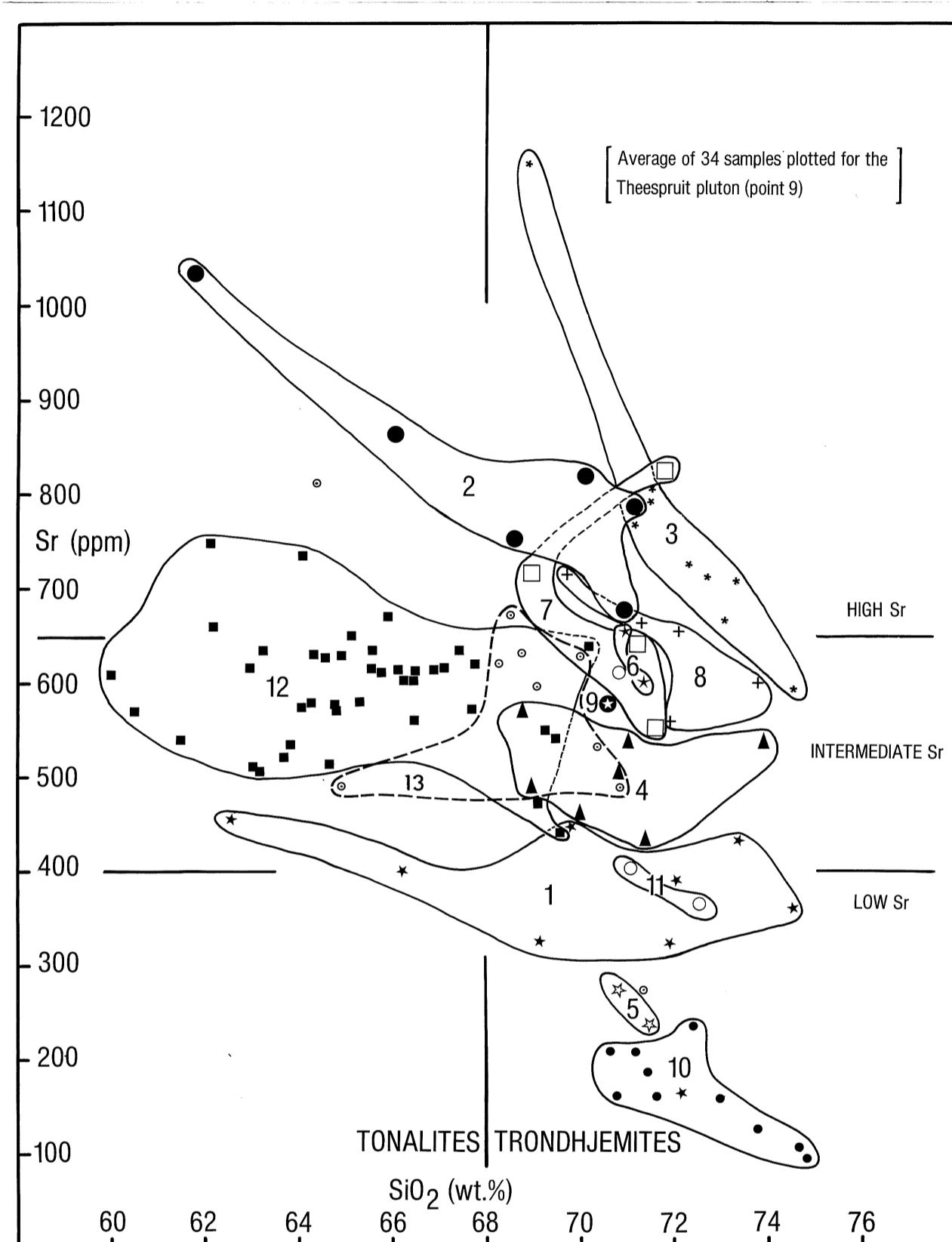


Figure 7 : Plots of SiO_2 against Sr for the 13 tonalite-trondhjemite plutons and cells defined in the study area (see Fig. 1 for key to numbers). The data source is available on microfiche (see caption to Fig. 5).

The average Rb-Sr characteristics of the tonalite-trondhjemite suite in the study area are summarized in Fig. 8. In spite of significant variations in Sr content, the intermediate- and high-Sr bodies are characterized by remarkably constant Rb/Sr ratios that cluster around a value of 0.1. Exceptions of this are two low-Sr bodies (i.e. the Doornhoek and Eerstehoek plutons, Fig. 7) which are characterized by significantly higher Rb/Sr ratios (0.3 - 0.4). It is interesting to note that these last-mentioned bodies have Rb/Sr ratios similar to certain tonalitic and trondhjemitic components of the Ancient Gneiss Complex (AGC) in Swaziland, which generally have major element characteristics identical to those in the study area (Hunter et al., 1978; Robb and Anhaeusser, 1979). Regarded collectively, the two Rb/Sr sub-groups define a distinct duality in rocks of broadly similar age, composition, and geological setting. These Rb/Sr characteristics are quite distinct, both from rocks of later magmatic cycles in the region, as well as from plagiogranites associated with greenstone remnants and migmatites (Fig. 8).

Typical REE patterns for certain of the tonalite-trondhjemite plutons and cells in the study area are shown in Fig. 9. The leucocratic biotite trondhjemites (i.e. Theespruit, Stolzburg and Nelshoogte plutons)

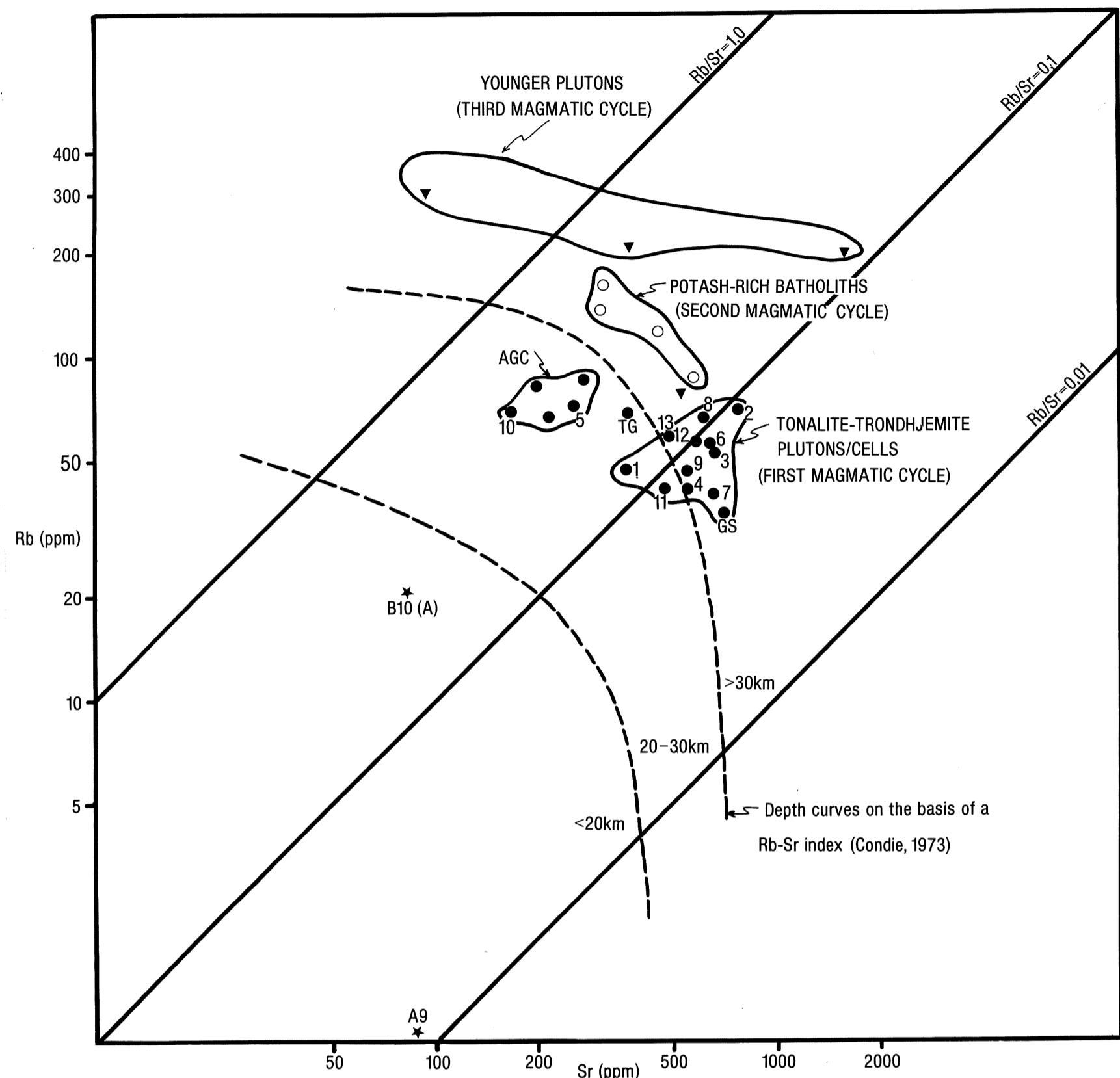


Figure 8 : Plot of averaged values of Rb against Sr for the various tonalite-trondhjemite plutons and cells (i.e. 1-13) in the region southwest of the Barberton greenstone belt. Also plotted for comparative purposes are three averaged values from the Ancient Gneiss Complex in Swaziland, the field of potash-rich batholiths and certain post-tectonic granite plutons. In addition, two plagiogranite samples B10(A) and A9 from migmatites in the study region are included. Data sources for all additional plots are referred to in Robb (1981).

have chondrite normalized traces that are relatively LREE enriched ($50 - 70 \times$ chondrites), are HREE depleted, and have no significant Eu anomaly. The Kaap Valley tonalite pluton has similar characteristics although it has higher HREE contents and greater Σ REE than the more felsic trondhjemites. The overall REE patterns of tonalites and trondhjemites from the study area are typically like those from Archaean terranes the world over (Arth and Hanson, 1975; Hunter et al., 1978; O'Nions and Pankhurst, 1978). However, REE data from certain components of the AGC in Swaziland indicate a significantly different pattern for gneisses of otherwise similar major element composition. An average trace for the AGC is considerably enriched in Σ REE content with higher concentrations of the LREE and significant enrichment in the HREE (Fig. 9). In order to emphasize the relatively higher HREE abundances the diagram also shows a trondhjemite from the AGC (sample SWZ-7) with similar LREE enrichment to the tonalite-trondhjemite plutons yet possessing a noticeably higher HREE content.

The contrasting characteristics shown in the REE patterns confirm the duality noted for the tonalite-trondhjemite kindred on the Rb-Sr diagram. A representative REE trace from the Doornhoek pluton indicates that the two groupings are not restricted to a simple sub-division between AGC and Barberton tonalite-trondhjemite gneisses as the Doornhoek pattern closely resembles that from the AGC. Thus, similar rock types from both regions can be categorized into a high Rb/Sr, high Σ REE sub-type and a low Rb/Sr, low

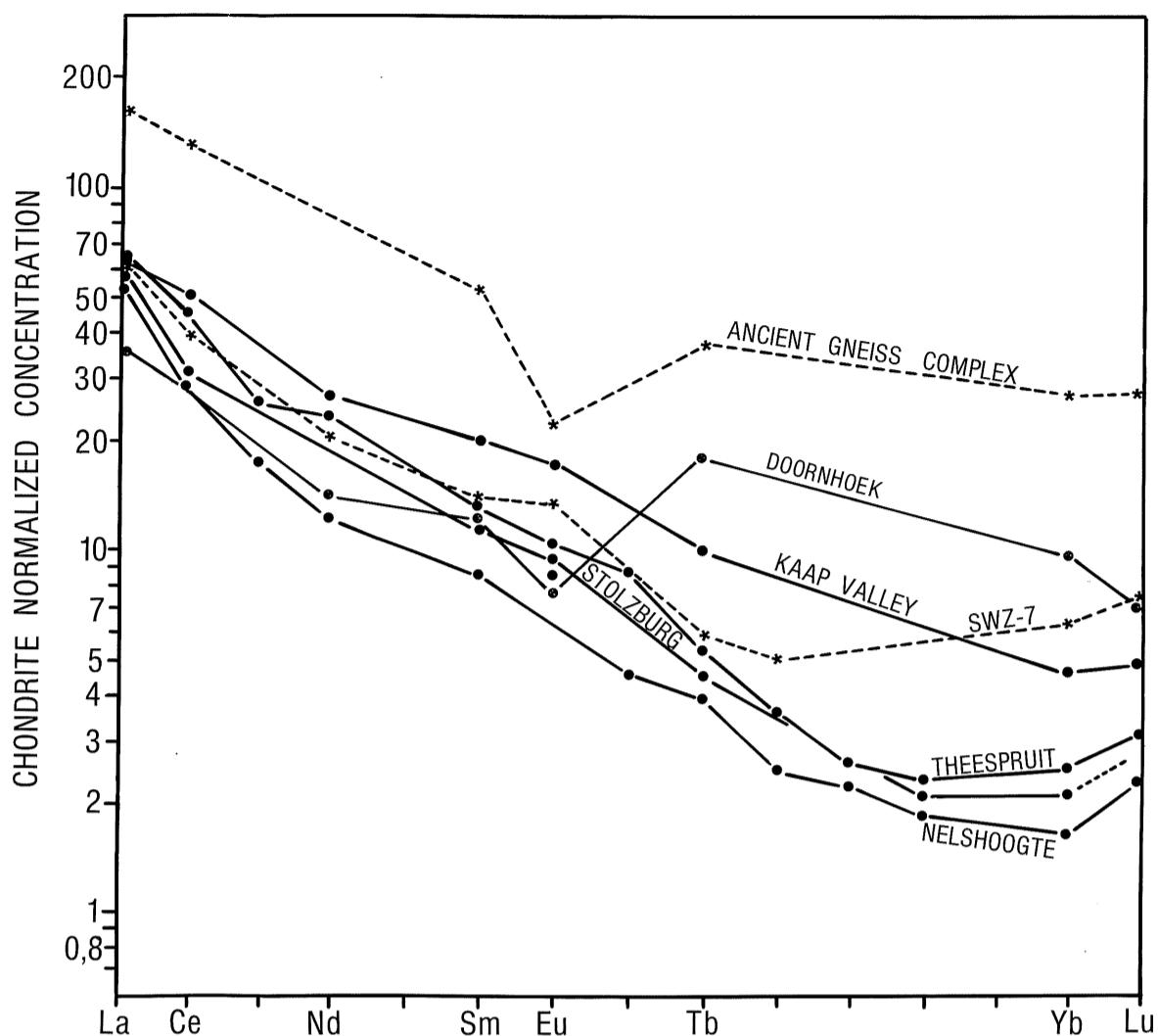


Figure 9 : Average chondrite normalized REE plots for the four largest tonalite-trondhjemite plutons in the Barberton region. Also plotted in dashed lines are an average curve for the Ancient Gneiss Complex in Swaziland (Condie and Hunter, 1976) and a siliceous gneiss (sample SWZ-7) from the bimodal suite of the AGC (Hunter et al., 1978).

Σ REE sub-type, although presently available data indicates a bias in the former towards the AGC, and in the latter towards the plutons and cells immediately southwest of the Barberton greenstone belt. It is noteworthy that O'Nions and Pankhurst (1978) recorded a similar subdivision on the basis of REE patterns in the Amitsôq gneisses of West Greenland. Their Group A gneisses, characterized by low $\text{Ce}_{\text{N}}/\text{Yb}_{\text{N}}$ ratios, coincide with the AGC-type trend in Fig. 9, whereas their Group B gneisses, with significantly higher $\text{Ce}_{\text{N}}/\text{Yb}_{\text{N}}$ ratios, correspond to the more typical Archaean tonalite-trondhjemite pattern.

Significant variations in the trace element contents of Archaean rocks that are otherwise characterized by similarities in bulk composition and geological setting have, on occasion, been attributed to open-system behaviour such as metasomatism or widespread crustal degassing (Bridgwater and Collerson, 1976; Collerson and Fryer, 1978) and the subsequent mobility of certain trace elements. Such conclusions are generally difficult to quantify and, moreover, are unwarranted if trace element patterns reflect predicted concentrations in theoretical modelling of magmatic processes. The remainder of this paper discusses a model suggesting a process whereby the two tonalite-trondhjemite gneiss sub-types identified above may be linked such that a polygenetic approach to their origin is avoided.

VI. PETROGENETIC CONSIDERATIONS

A singular constraint on the origin of tonalite and trondhjemite gneisses from both the AGC of Swaziland and those in the Barberton region is imposed by their similar Sr-isotopic characteristics. Components from both areas have yielded overlapping ages in the range 3,555-3,432 Ga with low initial ${}^{87}\text{Sr}/{}^{86}\text{Sr}$ ratios (R_0) between 0,6999-0,7002 (Barton et al., 1982). Younger, probably re-set, ages in the range 3,350-2,769 Ga (with R_0 's ranging between 0,7011-0,7023) have also been obtained from both areas. Consequently it is unlikely that the tonalite and trondhjemite gneiss suite from the two regions could have been ultimately derived from significantly different source material. The low R_0 values, in particular, indicate an origin for both sub-types by partial melting of primitive basaltic precursors. The marked differences in Sr and REE characteristics of the two sub-types might, therefore, be attributable to processes occurring subsequent to the formation of the magma protoliths. It is possible, for example, that fractionation of plagioclase will result in rocks with divergent Sr contents. However, tonalites enriched in Sr as a result of plagioclase accumulation will also be expected to have positive Eu anomalies, a feature which does not occur in the

observed data. Such considerations are, therefore, not consistent with the observed characteristics of the two tonalite-trondhjemite sub-types.

A possible solution to this discrepancy may lie in a consideration of differences in the P-T environment at which melting of the source rocks occurred. Both granitic and greenstone components in the Barberton Mountain Land show no evidence for ever having been metamorphosed to higher than amphibolite grade (Anhaeusser, 1969). In contrast, the AGC has been described as containing the most highly metamorphosed (possibly granulite grade) portions of the Archaean basement in the region (Hunter et al., 1978), whilst structural arguments have been used to suggest that the greenstone remnants associated with this terrane are preserved at a lower crustal level than time equivalents in the Onverwacht Group (Jackson, 1979). Thus, differences in the trace element characteristics of the tonalite-trondhjemite kindred may be related either to a chemical heterogeneity in their source regions or, to differences in the degree of partial melting required to form the various sub-types. The latter point is however, inconsistent with the relatively constant Rb values in the gneisses, as this element would be likely to record changes in the degree of fusion. A chemically heterogeneous source region is also deemed unlikely as a strong case cannot be made for a heterogeneous distribution of Sr in crustal rocks of progressively higher grades of metamorphism. Considerable chemical evidence indicates that the abundance of elements such as Ba, Sr and Zr in fact *increases* in granulite grade environments representative of deeper crustal levels (Heier, 1964; Tarney, 1976). Hence, the derivation of the tonalites and trondhjemites in the AGC from a deeper crustal level that is Sr-deficient relative to that indicated for the source area of the Barberton equivalents, is also incompatible with empirical observations.

A more viable consideration in terms of a crustal depth approach involves the effects of isochemical phase changes in the prospective source material as the latter is introduced into progressively higher P-T environments. As the bulk distribution coefficient of a trace element into the residue is the more important factor (together with the degree of fusion) affecting the concentration of that element into the melt relative to its parent, this consideration may prove more fruitful than those outlined above. If it is assumed that a likely precursor for the derivation of a tonalitic melt would be a Barberton-type basaltic komatiite (see Table 1), it is pertinent to consider the phase changes involved in the progressive metamorphism of this rock type. In the Barberton Mountain Land remnants of basaltic komatiite are preserved at amphibolite grades as assemblages comprising dominantly hornblende together with minor plagioclase and quartz. In some instances clinopyroxene is also developed together with the hornblende component (Robb, 1981). It has been shown, both for basaltic and tonalitic compositions, that at temperatures in excess of approximately 1 000°C, hornblende is no longer stable even in the presence of excess H₂O (Helz, 1973; Wyllie et al., 1976). The breakdown of hornblende at relatively high pressures may occur according to the following reaction (after Green and Ringwood, 1967) :



This reaction describes the nature of phase changes that occur in the transition from amphibolite to granulite facies or, more specifically, in the isochemical transformation of gabbro to eclogite. If one is to assess the distribution of trace elements between a melt phase and these various source rocks, it is necessary to assess in what proportions the eclogitic phases would occur in a rock of komatiitic affinity. These proportions can be calculated using mass-balance considerations, the results of which are provided in Table 1. It is apparent that the transition from amphibolitic to eclogitic komatiitic basalt involves a phase transformation from an assemblage dominated by hornblende to one dominated by clinopyroxene. The proportion of garnet that forms from a Barberton-type basaltic komatiite is seen to be low (< 15%) because of the Al₂O₃ deficiency in these rocks. This figure becomes even lower (< 7%) if the protolith composition is akin to the higher-Mg Badplaas-type basaltic komatiite.

TABLE 1
PROPORTIONS OF TYPICAL ECLOGITIC MINERAL PHASES LIKELY TO FORM
FROM BASALTIC KOMATIITE COMPOSITIONS

	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃ *	MnO	MgO	CaO	Na ₂ O	K ₂ O	PROPORTIONS (1)	PROPORTIONS (2)
1.	52,70	0,90	9,80	10,90	0,22	10,10	10,00	1,65	0,40		
2.	52,22	0,56	5,42	9,90	0,22	15,25	12,83	1,22	0,10		
3. (CPX)	52,00	0,20	2,00	9,00	0,40	14,00	21,00	0,50	0,10	56,4% } 85,2%	79,0% } 93,1%
4. (JADEITE)	60,00	0,10	25,00	0,50	0,00	0,20	0,10	13,00	0,20	28,8% }	14,1% }
5. (GARNET)	40,50	1,50	22,70	16,60	0,50	12,40	15,80	0,30	0,10	14,8%	6,9%

Fe₂O₃* - Total iron content of rock or mineral presented as Fe₂O₃

- Row : 1. Representative Barberton-type basaltic komatiite } on the basis of data from
 2. Representative Badplaas-type basaltic komatiite } Viljoen and Viljoen (1969b).
 3 - 5. Representative analyses of typical eclogitic mineral phases; clinopyroxene (cpx) is taken from microprobe analyses of amphibolitic meta-basalts from the study area (Robb, 1981); jadeite is from Deer, Howie and Zussman (1971); and garnet is from a coexisting garnet-clinopyroxene pair in equilibrium with a tholeiitic melt at 1100°C and 20 kb (Raheim and Green, 1974).

PROPORTIONS (1) - are the proportions of Rows 3 - 5 that best combine to form the analysis in Row 1.

PROPORTIONS (2) - are the proportions of Rows 3 - 5 that best combine to form the analysis in Row 2.

(NOTE: Sum squares of errors in the above calculations are high because of the arbitrary nature of the three eclogitic phases chosen; in the absence of clinopyroxene and garnet analyses in equilibrium with a komatiitic melt, realistic compositions are not available).

Considering the above it is possible to calculate the comparative effects of a clinopyroxene-dominated (as opposed to a hornblende-dominated) residual assemblage on the distribution of trace elements during the extraction of a tonalitic partial melt. With respect to Rb and Sr the data compiled in Table 2 show that the bulk partition coefficient for Sr into an assemblage comprising a dominantly hornblende-bearing residue will be lower than that for a dominantly clinopyroxene-bearing one. Thus, during the partial melting of a komatiitic basalt at an amphibolitic metamorphic grade, Sr will be more freely liberated from the residue than in the case where the same komatiitic basalt is in an environment approaching granulite grades. Rubidium, on the other hand, has bulk partition coefficients that are so low as to be insignificantly different in either case, and this element will be distributed equally into melt phases derived from the two environments. As a result Rb/Sr ratios in tonalitic melts derived from amphibolitic metabasalts will be lower, for any specific degree of partial melting, than the Rb/Sr ratios derived from eclogitic metabasalts. This is demonstrated in Fig. 10 where the variation in Rb/Sr ratio for between 5-40% melting of amphibolitic and eclogitic metabasalts is calculated using the various parameters compiled in Table 2. The diagram shows that at an arbitrary value of, for example, 25% partial melting, tonalite-trondhjemite melts that equilibrated with dominantly hornblende-bearing residues will have a Rb/Sr ratio of ≈ 0.1 whereas magmas equilibrating with a dominantly clinopyroxenitic residue will have $Rb/Sr > 0.2$. These values are relatively consistent with the observed Rb/Sr ratios in the two tonalite-trondhjemite sub-types described above.

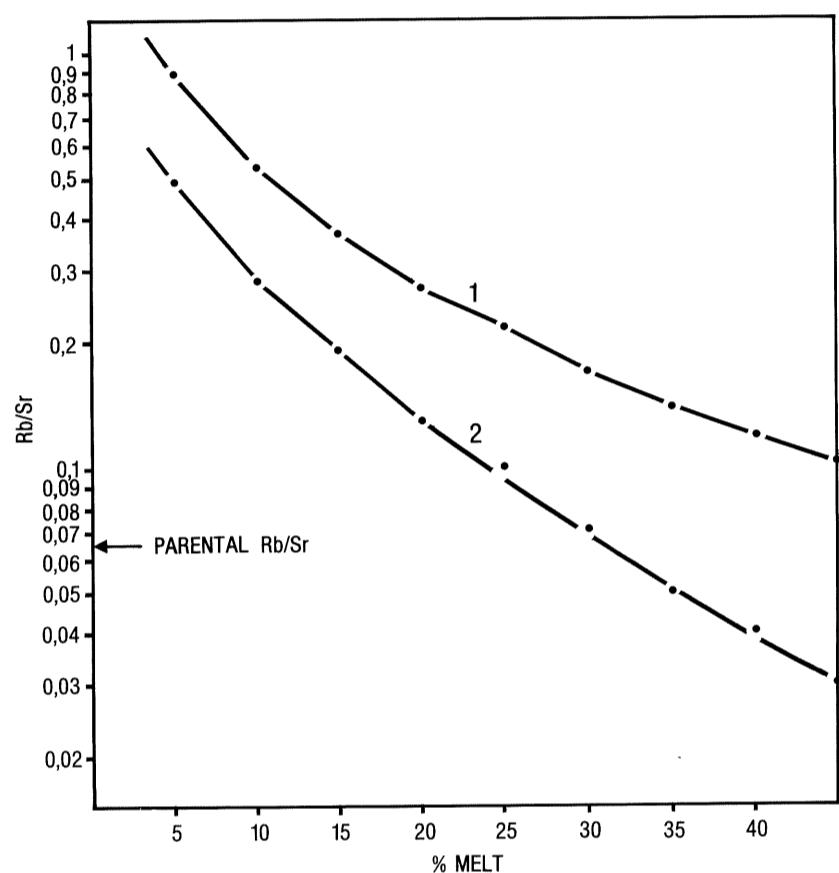


Figure 10 : Model diagram showing the change in the Rb/Sr ratio with successive partial melt increments. Curve 1 represents a melt equilibrating with a dominantly clinopyroxene-bearing residue and Curve 2 a melt equilibrating with a dominantly hornblende-bearing residue. Model parameters are provided in Table 2.

As indicated in Table 2, uncertainty exists in the distribution coefficients for Sr into hornblende and clinopyroxene and quoted values often vary significantly. It is necessary, therefore, to consider the above model in terms of the distribution of REE, where slightly better control over the distribution coefficients is available. As indicated previously, early models for the generation of Archaean tonalites and trondhjemites tended to regard the precursor basaltic material as eclogitic because the depleted HREE patterns commonly observed in the former required equilibration of magma with a phase such as garnet, into which the HREE were strongly partitioned. Later petrogenetic models were based on new REE distribution coefficient data for hornblende which obviated the need for the garnet phase and made it feasible to derive tonalite-trondhjemite melts from amphibolitic metabasalts. Calculation of the distribution of REE between a tonalite-trondhjemite melt and an amphibolite grade metabasalt using the parameters outlined in Table 2 confirm the later petrogenetic model. In Fig. 11, model curve 1 represents a 25% partial melt that equilibrated in the presence of a dominantly hornblende-bearing residue, this curve being relatively consistent with the REE characteristics of the low Rb/Sr, high Ce_N/Yb_N, low Σ REE tonalite-trondhjemite group described above. The important feature of this model involves the replication of a depleted HREE content, this being accomplished by using the partition coefficients between the REE and hornblende obtained by Arth and Barker (1976) (see Table 2).

The distribution of the REE between a melt phase and a residual eclogitic metabasaltic assemblage can be considered along similar lines to those above. Previous considerations involving the partial melting of eclogites have usually considered a significant quantity of residual garnet (e.g. 45% garnet in the case of the petrogenetic models of Condie and Hunter, 1976). Naturally, melts that equilibrated with a residual assemblage of this nature would also be characterized by HREE-depleted patterns and would not, therefore, coincide with the high Rb/Sr, low Ce_N/Yb_N, high Σ REE group described earlier. However, as indicated in Table 1, if a komatiitic basalt precursor is considered, then the low Al₂O₃ contents do not allow for a significant garnet content in isochemically transformed basalts, the quantities of which would probably be reduced even further after 20-30% partial melting. Hence, partial fusion of a clinopyroxene-dominated metabasalt will result in a significantly different distribution of REE between melt and residue. In Fig. 11, model curve 2 represents a 25% partial melt that equilibrated in the presence of a dominantly clinopyroxene-bearing residue. A different set of bulk partition coefficients to the system containing a hornblende residue (see Table 2) produces a curve with greater Σ REE content and lower Ce_N/Yb_N ratios, features which are compatible with the high Rb/Sr tonalite-trondhjemite group. Thus, petrogenetic considerations which involve partial melting of similar rock types but at different crustal depths appear to be broadly compatible in terms of both Rb-Sr and REE characteristics.

TABLE 2
PARAMETERS USED IN THE CONSIDERATIONS OF TONALITE-TRONDHJEMITE PETROGENESIS

MODAL MINERALOGY	BULK PARTITION COEFFICIENTS (1)									
	Rb	Sr	La	Ce	Nd	Sm	Eu	Tb	Yb	Lu
Tonalite /Trondhjemite	Qtz - 35%									
	Plag - 50%									
	Biot - 10%	0,40	1,60	0,18	0,20	0,15	0,10	1,09	0,05	0,07
	K-fels - 5%									0,05
Metabasalt (Amphibolitic)	Hblde - 90%									
	Plag - 10%	0,02	0,40(2)	0,14	0,27	2,20	3,20	2,70	3,30	3,90
Metabasalt (Eclogitic)	Cpx - 95%									
	Gar - 5%	0,02	0,70(2)	0,09	0,09	0,11	0,18	0,19	0,25	0,71
Parent Basaltic Composition (3)	10	150	4,0	10,3	6,5	1,89	0,61	0,39	1,49	0,22
	ppm									

Notes: (1) Partition coefficient data from Arth and Hanson (1975), Condie and Hunter (1976) and Arth and Barker (1976).

(2) Uncertainty exists in the values for the partition coefficient of Sr into hornblende and clinopyroxene. Values of $D_{\text{hblde}}^{\text{Sr}}$ vary in the above sources from 0,02 to 0,40 and in this case the higher value is preferred. Values of $D_{\text{cpx}}^{\text{Sr}}$ also vary and the value used in this instance is one inferred from the experimental data of Sun et al. (1974). Values of $D_{\text{cpx}}^{\text{Sr}} > D_{\text{hblde}}^{\text{Sr}}$ are consistent with the partition coefficients compiled by Condie and Hunter (1976).

(3) Data from Robb (1981) and Herrmann et al. (1976).

The calculations of trace element distribution models in Figs. 10 and 11 were carried out using Shaw's (1970) batch melt equation together with the parameters compiled in the above table.

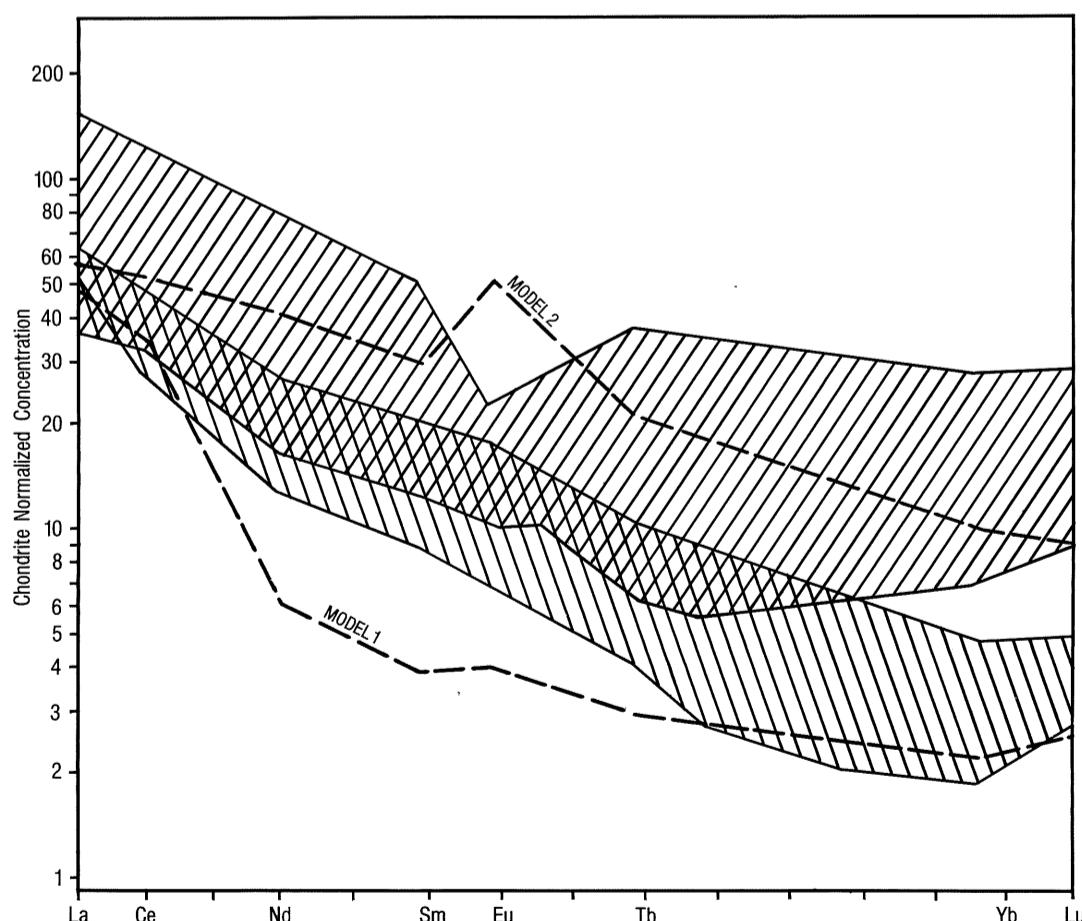


Figure 11 : Chondrite normalized REE model plots for the two tonalite-trondhjemite sub-types described in the text. Hatched fields represent the tonalite-trondhjemite gneisses from the Barberton region (lower envelope) and Swaziland (upper envelope), as represented in Fig. 9. Model 1 is the REE pattern for a 25% partial melt in equilibrium with an amphibolitic residue whereas Model 2 is the pattern for a similar degree of melting in the presence of a dominantly clinopyroxenitic residue. Model parameters are provided in Table 2.

VII. DISCUSSION AND CONCLUSIONS

The model proposed in the preceding section envisages the origin of Archaean tonalitic and trondhjemite magmas in terms, not so much of compositional variations in the parental material but of response differences in P, T, PH_2O and/or crustal depth of specific source regions. The trace element models considered the formation of low Rb/Sr, high Ce_N/Yb_N tonalites and trondhjemites by partial melting of a hornblende-dominated metabasalt, whereas the origin of the high Rb/Sr, low Ce_N/Yb_N melts was viewed in terms of equilibration with an isochemically transformed, clinopyroxene-dominated residual assemblage. A problem that arises from this approach relates to the fact that clinopyroxenes are generally not as silica-depleted as hornblendes, particularly when these two minerals occur as residual phases (Heiz, 1973). Thus, partial fusion of a clinopyroxenitic assemblage in the absence of a garnet phase will tend not to produce melts that are as siliceous as might have been derived from the equivalent melting of a hornblende-dominated assemblage. This is confirmed by some experimental data which suggests that fusion of clinopyroxenes yields significant melt proportions having the composition of mare (lunar) basalts (Huebner et al., 1973).

The resolution of this problem may lie in a consideration of the gradual nature of the phase transition envisaged in the above model. Green and Ringwood (1967) have shown that the gabbro-eclogite transition is essentially temperature independent and occurs over a pressure range of 4-5 kb (Fig. 12).

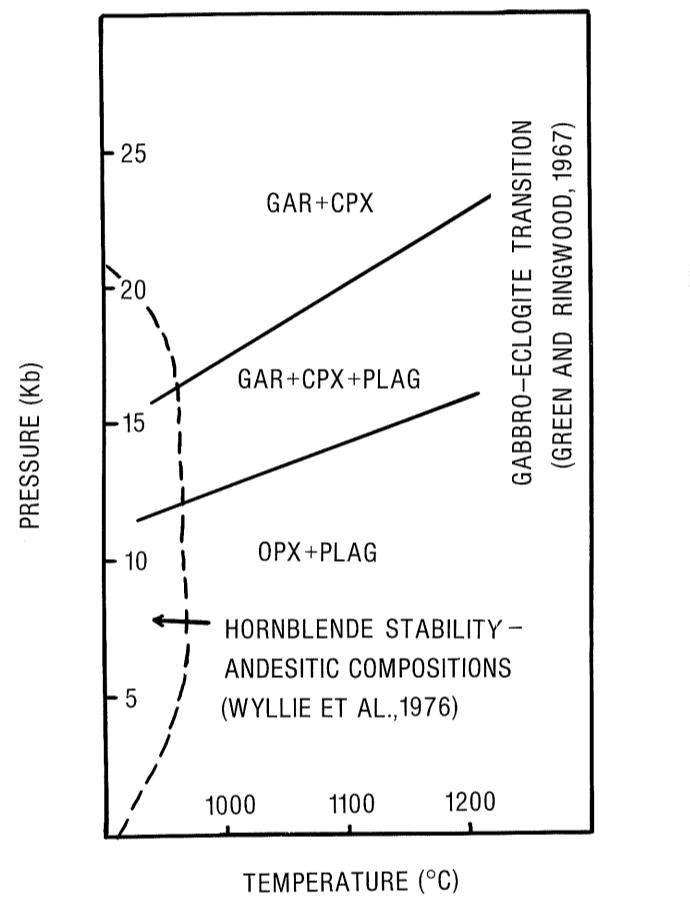


Figure 12 : Diagram showing the approximate pressures and temperatures involved in the gabbro-eclogite transition as well as the upper limit of the hornblende stability field for andesitic compositions.

It is unlikely, therefore, that an amphibolitic metabasalt will suddenly be transformed into an eclogite at a certain critical P-T condition. It has also been shown for olivine tholeiite compositions that hornblende and clinopyroxene may actually co-exist under conditions of excess H_2O (Stern et al., 1975), a fact which accords with observed co-existing hornblende-clinopyroxene assemblages in certain metabasaltic remnants occurring southwest of the Barberton greenstone belt (Robb, 1981). Thus, the transition from a dominantly hornblende-bearing to a dominantly clinopyroxene-bearing metabasaltic assemblage is likely to be a gradual process which, in reality, involves a progressive decrease in the hornblende:clinopyroxene ratio with increasing crustal depth. A progressive change of this nature would probably ensure that a sufficiently silica-depleted residual phase is present such that silica-rich melt phases will continue to form. In terms of trace element distribution, the generation of low Rb/Sr, high Ce_N/Yb_N tonalites and trondhjemites will characterize melt processes at crustal depths concomitant with amphibole metamorphic grades, with a gradual increase in Rb/Sr and decrease in Ce_N/Yb_N ratios occurring as clinopyroxene progressively replaces hornblende in residual assemblages. An important constraint on the formation of Archaean tonalite and trondhjemite magmas will be imposed, therefore, by the inability of rocks of increasing clinopyroxene:hornblende ratio either to melt at all, or to form melts with the required composition.

It is interesting to speculate on the relative proportions of tonalitic or trondhjemitic material in any one Archaean terrane which may have formed either from amphibolitic or eclogitic parentage. In the eastern Transvaal and Swaziland, the Barberton area appears to be dominated by the first type whereas the AGC in Swaziland (more specifically, the bimodal suite component of the AGC) is largely characterized by the second type. However, as mentioned previously, the Doornhoek and Eersteplaats plutons in the Barberton Mountain Land have high Rb/Sr, low Ce_N/Yb_N characteristics whereas the Tsawela gneiss in the AGC has a relatively low Rb/Sr (Fig. 5) and a REE pattern similar to that of the Kaap Valley pluton (Hunter et al., 1978). It is difficult, therefore, to assess the relative proportions of the one type as opposed to the

other, particularly as the density of analysed samples in the Barberton area is now considerably greater than that in the AGC. In West Greenland, where the Amitsôq gneisses also appear to be characterized by two groupings on the basis of their REE contents, an assessment of the relative proportions of each is, likewise, difficult. However, extensive compilations of geochemical data for Archaean tonalite and trondhjemite gneisses indicate that the most notable consistency in this suite is found in their depleted HREE character (Glikson, 1979). This would appear to indicate (at least in terms of the above considerations) that tonalites and trondhjemites derived from metabasaltic precursors of dominantly amphibolitic character form the predominant component in Archaean "grey-gneiss" terranes.

In conclusion, tonalite and trondhjemite bodies in the Barberton Mountain Land are shown to be characterized by significant and systematic compositional variations. These differences can be attributed to subtle variations in the degree of partial melting involved in their derivation and also to *in situ* crystal fractionation processes. Differences in the trace element contents of these bodies may, however, also be attributed to fusion at different crustal depths when residual mineral assemblages change during progressive isochemical transformation of source material. Thus, it appears unnecessary to invoke a polygenetic origin for this tonalite-trondhjemite suite and it is suggested that the observed chemical variations reflect a complex petrogenesis involving combinations of the variables described above. More specifically, these considerations indicate that a sharp genetic distinction between the Ancient Gneiss Complex in Swaziland and the tonalite-trondhjemite gneiss terrane in the Barberton Mountain Land is unwarranted, and that a unified approach would assist in solving common problems applicable to both areas.

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