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TRACE AND RARE EARTH ELEMENT GEOCHEMISTRY AND ORIGIN OF ARCHEAN ACID IGNEOUS SERIES, BARBERTON MOUNTAIN LAND, TRANSVAAL

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Trace and rare earth element geochemistry and origin of Archaean acid igneous series, Barberton Mountain Land, Transvaal.

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Abstract

Seventeen Archaean acid volcanic and granitic rock samples from the Barberton Mountain Land, Eastern Transvaal, were analysed for major elements, Co, Ni, Cr, V, Sc, Cu, Zn, Li, Cs, Rb, Ba, Sr, Zr, Hf, Nb, Th, U, Y, and REE. The data indicate extreme depletion of alkali and high-valency cations in both Na-rich porphyries of the ultramafic - mafic volcanic Onverwacht Group, and in the 'ancient tonalites' which intruded this sequence about 3.4 - 3.2 b.y. ago. Some porphyries display highly fractionated REE patterns, indicating equilibration with and separation of garnet. Fractional crystallization of basic magmas at pressures exceeding 9 kb is thus indicated. The tonalites have pronounced positive Eu anomalies and are thought to have formed by partial melting of basic rocks under high-pressure conditions. The chemical data are consistent with the interpretation of the Dalmein and the Bosmanskop plutons as late and progressively differentiated members of the 'ancient tonalite' suite. The origin of the Nelshoogte tonalite, Theespruit trondhjemite, Dalmein trondhjemite, and Bosmanskop granite is interpreted in terms of decreasing degrees of partial melting of mafic rocks with time. The Nelspruit migmatite shows a pronounced negative Eu anomaly, and was probably formed by anatexis of both the 'ancient tonalites' and Onverwacht

Group mafic rocks about 3 b.y. ago, within the depth range of 20 - 45 km. No Eu anomaly is shown by the Hood granite, which occurs above the migmatite. The chemistry of greywackes from the Fig Tree Group is consistent with derivation from a terrain composed of both Onverwacht Group and the 'ancient tonalites', including late K-rich members of this suite. The data lend support to models advocating secular transformation from simatic to a sialic crustal environment, but suggest fundamental differences between the mode of genesis of the Archaean granite-greenstone terrains and modern island-arc systems.

INTRODUCTION

Inherent in the problem of the origin of Precambrian shields is the question of the evolution of their earliest granites, and possibly related acid volcanic rocks - i.e., were these rocks formed by anatexis of still older sialic crust (e.g. Macgregor, 1951; Fyfe, 1973), or by partial melting of mafic crust (Viljoen & Viljoen, 1969e; Glikson, 1970, 1972; Glikson & Sheraton, 1972; Arth & Hanson, 1972; Anhaeusser, 1973; Jakes & Taylor, 1974). Central to this question are the geochemical and isotopic characteristics of the earliest acid igneous members of Archaean granite-greenstone terrains. However, because of generally poor outcrop in granite terrains in Canada, Brazil, India, and Australia, interpretation of the chemical and isotopic data is complicated by difficulties arising from limited understanding of the field relations. Furthermore, differential weathering of the different granite types - for example, more rapid weathering of plagioclase relative to K-feldspar, and thus poorer outcrop of tonalitic and trondhjemitic plutons - has resulted in extensive sampling bias in Archaean cratons (Glikson & Sheraton, 1972).

Granites associated with the Barberton greenstone belt of the Swaziland System within the Kaapvaal Shield are an exception to the above observation in that they include a large variety of well exposed intrusions, most of which fall within the time span 3.4 - 2.6 b.y. (de Gasparis, 1967; Allsopp et al., 1968; 1969; Van Niekerk & Burger, 1969; Oosthuyzen, 1970; Hurley et al., 1972). Regional mapping of this terrain was carried out by the Geological Survey of South Africa (Visser et al., 1956). Viljoen & Viljoen (1969 a, b, c, d, e) conducted a major element composition study of the granites, and demonstrated secular chemical variations which they classified in terms of two distinct plutonic series. Hunter (1970) investigated the ancient gneiss complex of Swaziland, and reviewed the geochemistry of granites in the Kaapvaal craton (Hunter, 1973). Anhaeusser (1971) studied the granites of the Pretoria-Johannesburg dome, and pointed out their similarities to the granites of the Barberton area. Goles (1968) conducted REE analyses of some of these rocks

Because of their well exposed contacts with the greenstones of the Swaziland system and of the availability of isotopic age data, detailed geochemical studies of the granites should be meaningful in connection with the early evolution of Archaean cratons. In this paper we present data for major, trace, and rare earth element concentrations in seventeen samples. These include samples of acid tuff from the Theespruit Formation, porphyries from the Lower Onverwacht Group and the Middle Marker , granites from the Nelshoogte, Theespruit, and Dalmein plutons, the Nelspruit migmatite, Hood granite and Bosmanskop pluton. The new data and earlier published data are discussed in terms of the following problems: (1) genesis of the acid magmas; (2) possible relations between the acid rocks and the greenstones; (3) the role of the granites as provenance rocks for the Fig Tree Group sediments; (4) comparisons with Archaean acid igneous rocks elsewhere, and comparisons with younger acid igneous series, with reference to the tectonic environment in which the acid rocks evolved.

SUMMARY OF GEOLOGY

The Swaziland System of the Barberton Mountain Land comprises the following major stratigraphic divisions (from top to bottom): (1) Moodies Group - an arenaceous sequence 3140 m thick, comprising at least four sedimentary cycles; (2) Fig Tree Group - argillites and turbidites 2150 m thick, divided into three formations; (3) Onverwacht Group (upper part) - bimodal mafic to felsic volcanic cycles 7680 m thick, divided into the Swartkoppie, Kromberg, and Hooggenoeg Formations; (4) Onverwacht Group (lower part) - ultramafic and mafic volcanic and hypabyssal rocks 7530 m thick, divided into the Komati, Theespruit, and Sandspruit Formations (Anhaeusser et al., 1969; Viljoen and Viljoen, 1969 a, c.; Anhaeusser, 1973).

The upper and lower parts of the Onverwacht Group are separated from each other by the Middle Marker - a thin unit of acid volcanics, chert, and carbonate rocks. Rb-Sr age determinations on the carbonate rocks yielded an age of 3375 ± 20 m.y. ($Sr_i^{87/86} = 0.7016 \pm 0.0005$) (Hurley et al., 1972). A quartz porphyry from the upper Onverwacht Group yielded a U-Pb age of 3360 ± 100 m.y. (Van Niekerk and Burger, 1969). The Onverwacht Group is intruded by the 'ancient tonalites', a group of oval diapiric tonalitic to trondhjemitic plutons, including the Kaap Valley, Nelshoogte, and Theespruit plutons, dated at 3310 ± 40 m.y., 3320 ± 40 m.y. and 3250 ± 40 m.y., respectively (U-Pb ages, Oosthuyzen, 1970). The 'ancient tonalites' are not known to intrude units younger than the Middle Marker, and could possibly antedate the upper Onverwacht Group. Another possible member of this group is the Dalmein pluton, with sphene and apatite U-Pb ages of 3190 and 3290 m.y. respectively (Oosthuyzen, 1970). Younger, more differentiated intrusions include the Nelspruit migmatite (3160 ± 50 m.y., Oosthuyzen, 1970; 2992 ± 70 m.y., de Gasparis, 1967) and the Hood granite (3075 ± 100 m.y., Oosthuyzen, 1970). The older age of the Nelspruit migmatite could be related to the inclusion of partly reworked parts of the 'ancient tonalites' (see below).

Specimen localities are plotted in Fig. 1. The petrography and mode of occurrence of the analyzed specimens are summarized in Table 1. Mineral identifications were carried out by polarising microscope and X-ray diffraction using a Philips PW1010 diffractometer (analyst: G.W.R. Barnes, B.M.R.).

ANALYTICAL METHODS

Major elements and Rb and Sr were determined by X-Ray fluorescence following the methods of Norrish and Chappell (1967), Na and K by flame photometry (Cooper,1963) and FeO and loss on ignition by conventional chemical methods. Determinations of Ba, Cs, Zr, Hf, Nb, U, Th and REE were made by spark source mass spectrography using the methods of Taylor (1965, 1971), the precision being about ± 5% expressed as relative deviation, and Co, Cr, Cu, Li, Mn, Ni, and Zn were determined by atomic absorption (analyst: B.I. Cruikshank) using a Varian-Techtron AA-4 model, and using analytical lines as follows: Co - 240.7; Cr - 357.9; Cu- 324.8; Li - 670.8; Ni - 232.0; Zn - 213.9. V and Sc were determined by optical emission spectrography, using a Hilger and Watts direct-reading 3 metre polychromator (analyst: T.I. Slezak).

RESULTS

The major and minor element data, CIPW norms, and various ratios are presented in Table 2. Element enrichment patterns relative to an analyzed metadolerite from the Theespruit Formation, which is similar to oceanic tholeiite, are portrayed in Figure 4; this enables comparisons to be made of various chemical ratios within and between the acid igneous rocks. The features shown by the data are summarized under (a) major elements, (b) ferromagnesian elements, (c) alkali elements, (d) large high-valency cations, and (e) rare earth elements.

(a) Major elements and petrochemical indices

The tuffaceous porphyritic albite-mica-quartz schist (29)* is lower in Si and K, and higher Fe , Mg, and Na than the non-porphyritic mica schists 34, 37, which may represent reworked sedimentary derivatives of the tuff (Viljoen and Viljoen, 1969a). These differences could be caused by leaching of Fe, Mg, and Na during sedimentary transport, whereas the enrichment in Si and K may be due to colloidal co-precipitation and absorption. If this interpretation is correct, only sample 29 should be considered with respect to primary igneous affinities, and the An-Ab-Or ternaries (Figs. 2, 3) suggest that the tuff can be classified as quartz keratophyre. The high solidification index reflects the high chlorite content.

The quartz keratophyres (78, 90, 98, 100) fall close to the Ab apex of the An-Ab-Or and Q-Ab-Or diagrams, and include (a) porphyries associated with the lower part of the Onverwacht Group (78, 90), and (b) porphyries associated with the Middle Marker (98, 100). Group (a) abounds in phenocrysts of partly to completely chloritized amphibole, and is higher in Ti, Al, Fe, Ca, and P, and lower in Si and Na than group (b). Ab is higher in group (a), whereas Or varies considerably. Normative quartz amounts to about 25 percent.

The three samples of 'ancient tonalites' (106, 117, 118) display solidification, differentiation, and peralkalinity indices similar to those of the quartz keratophyres, although they have higher Ca . The similarity could support cogenetic relations between the 'ancient tonalites' and the Middle Marker porphyries. Two samples plot in the tonalite field and one in the trondhjemite field of the An-Ab-Or triangle. The Q-Ab-Or diagram shows that the tonalites have higher Q/Ab ratios than in the quartz keratophyres.

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* Sample number

Compared to the Nelshoogte rocks, the two Dalmein pluton samples (104, 105) have high K and low Ca levels, higher differentiation and peralkalinity indices, and lower solidification indices - the latter reflecting the slightly higher Fe/(Fe + Mg) ratios. The decrease in Na/K ratio is accompanied by an increase in P. The analyses plot within and on the boundary of the trondhjemite field on the An-Ab-Or ternary diagram.

The Bosmanskop pluton specimen analyzed (115) is low in Si, and somewhat high in Na, K, Ti, Fe, Mg, Ca, and P, as compared to the other samples. The Na/K ratio is about 1. Normative quartz is low. The rock plots in the granite field of the An-Ab-Or ternary diagram, but owing to its low silica content may be more appropriately termed adamellite.

Field observations show that remnant bodies of tonalite, trondhjemite, and granodiorite abound in the Nelspruit migmatite and the data presented by Viljoen and Viljoen (1969a) indicate that the migmatites are compositionally intermediate between the 'ancient tonalites' and the Hood granite. Because of the banded nature of the rocks, however, the single sample analyzed (108) is not regarded as representative. The rock has high Si, low Al, Fe, Mg, and Ca, a Na/K ratio of 1.2, high normative quartz, and a Fe/(Fe + Mg) ratio higher than those in the groups discussed above.

The two Hood granite samples (109, 114) have high Al and alkalis relative to the sample from the Nelspruit migmatite. The analyses plot in the granite field of the An-Ab-Or diagram, and close to the eutectic point corresponding to 5 kb H_2O pressure on the Q-Ab-Or diagram (Fig. 3). Normative Q is about 25 percent of the norms. However, the two rocks differ markedly with respect to Fe, Mg, Ca, and Ti, which are higher in sample 114, reflecting its epidote, sphene, and amphibole contents.

(b) Ferromagnesian elements

The new analyses and the data of Viljoen and Viljoen (1969a) indicate a general increase in the average Fe/(Fe + Mg) from the tuffaceous sericite schists (0.54) and porphyries associated with the lower Onverwacht Group (0.55) to porphyries of the Middle Marker and the upper Onverwacht Group (0.64). Likewise, a general increase in this ratio is shown from hornblende tonalites of the 'ancient tonalites' (0.64, averaged data from Viljoen and Viljoen, 1969e), biotite tonalites (0.64, based on the 3 'ancient tonalite' samples and on data from Viljoen and Viljoen 1969e), to the Dalmein pluton (0.69), to the Nelspruit migmatite (0.75) and to the Hood granite and Lochiel granite (0.80). There may also be a weak negative correlation between the Fe/(Fe + Mg) and the Fe + Mg values (Fig. 5).

Relative to average granites, absolute abundances of Cu, Sc and especially Li are commonly low, and Co levels are somewhat high. Ni/Mg and Cr/Mg values are generally high (Fig. 6). Cr/V values are high, V/Ni ratios are low, and Li/Mg values are very low. High Ni/Mg and Cr/Mg values and low Li contents were also recorded in Archaean quartz albite porphyries of the Kalgoorlie System, Western Australia (O'Beirne, 1968).

There is a general sympathetic relation between Mn, Cr, Ni, Co, Cu, V, Zn, and Fe (Fig. 7). A general decrease in Ni/Mg and Cr/Mg values with time occurs in the 'ancient tonalites, Dalmein pluton, and Bosmanskop pluton in that order. The secular increase in the siderophile element abundances and decrease in magnesium-related trace elements is reflected by a parallel decrease in the Ni/Co ratio and an increase in the V/Ni ratios in the plutonic series. A decrease in Cr/V values and an increase in Fe, Mn, V, Sc, and Cu takes place in the Nelshoogte, Dalmein, and Bosmanskop plutons in that order.

Relative to the Theespruit dolerite, the general order of increasing depletion in forromagnesian elements follows (with some exceptions): Mn (least depleted), Fe, Co, V and Sc, Cu, Ni, and Cr (most depleted). The pairs Fe-Mn, V-Sc, and Ni-Cr retain, on average, internal ratios similar to those of the Theespruit dolerite, and thus little fractionation of these elements relative to one another is indicated. Ni/Co values are consistently higher, and V/Ni values consistently lower, than in calcalkaline island-arc type volcanics (Taylor et al., 1969b), mainly owing to the lower Ni contents of the latter (de Long, 1974).

(c) Alkali elements

The susceptibility of the alkali elements to secondary redistribution renders them less reliable indicators of primary composition, especially in the metamorphosed volcanics. K, Rb, Ba, and Cs levels are very low in the Theespruit porphyritic tuff (29), and higher in its reworked sedimentary derivatives. The latter also display increases in K/Rb, K/Th, and K/U - perhaps due to absorption of K relative to Rb, Th, and U from sea water. A parallel decrease in Sr/Ba and an increase in Rb/Sr partly reflect absorption of Ba and Rb from sea water and partial leaching of Sr along with Ca and Na.

The quartz keratophyres of the lower part of the Onverwacht Group and the Middle Marker porphyries display marked differences, notably higher Sr and Ba levels in the latter. The Rb content of one of the lower Onverwacht Group porphyries (78) is as low as 4.5 ppm ($K_2O = 0.2\%$), and K/Rb value for another sample (90) is anomalously high (802). Sr is particularly enriched in one of the Middle Marker rocks (100) (707 ppm), as it is in similar quartz keratophyres of the Kalgoorlie System in Western Australia, where Sr values of 600 - 800 ppm are common (O'Beirne, 1968; Glikson and Sheraton, 1972). The Sr concentrations show no obvious relation to Ca or K levels.

The Nelshoogte biotite tonalites, Theespruit trondhjemite, and Kaap Valley hornblende tonalite (Goles, 1968) have low Rb, Ba, and Cs, and high Sr levels, reflected in very low Rb/Sr values and high Sr/Ba values. The K/Rb ratios are moderate; K/Cs ratios are low and Rb/Cs ratios are also somewhat low as compared to average granites. In the Dalmein pluton samples, K, Rb, Ba, and Cs are higher, and Sr is lower than in the tonalites. This trend is accentuated in the Bosmanskop pluton sample with respect to K, Rb, Ba, and Cs, whose increase in this intrusion is accompanied by anomalous enrichments in Sr and Ba which are higher than in the Dalmein rocks by a factor of more than 2. The very low Rb/Sr value of the Bosmanskop sample suggests that fractional crystallization was not important, as this would have depleted the magma in plagioclase and therefore in Sr. This is also indicated by the lack of a negative Eu anomaly.

The Nelspruit migmatite, Hood granite, and Lochiel granite show broadly similar K, Rb, and Cs levels, and similar K/Rb values (and in sample 5108 also similar K/Cs, K/Th, and K/U values) to those of the Bosmanskop pluton sample; however, the latter is considerably higher in Sr, Ba, Zr, and REE. There are marked variations in Rb and Sr between the Hood granite and Lochiel granite samples.

K, Rb, and Ba show a secular average enrichment from the 'ancient tonalites' to the Dalmein pluton and the Bosmanskop pluton. There is an increase in enrichment relative to the Theespruit metadolerite from Sr (least enriched) to K, Ba, and Rb (Cs was not detected in the dolerite, and thus its enrichment factor cannot be calculated). The same order of enrichment applies in the Nelspruit-Hood-Lochiel group. Discordant trends occur, and the order of average enrichment of K and Ba is reversed in five of nine instances.

(d) Large high-valency cations

The Nelshoogte, Dalmein, and Bosmanskop samples reflect a secular increase in Th and U, and Th/U values in many of the samples are closely similar to those in the Theespruit metadolerite - indicating the close coherence of these elements during partial melting and magmatic fractionation. U is low in the quartz keratophyres and very low in the 'ancient tonalites'. Th levels in the sericite schists are comparable to those of Taylor's (1965) average granite, but are depleted in the quartz keratophyres, and in the 'ancient tonalites' they are low by factors of 3 to 15 relative to average granites. K/U and K/Th values of the tonalites are very high, while those of the other rocks they are closer to average granites, except for the reworked sericite schists (34, 37) and the Bosmanskop and Nelspruit samples which are enriched in Th relative to K, and in the two latter cases also enriched in U relative to K.

Th/U values are high in the sericite schists, possibly indicating oxidation and leaching of uranium. However, we consider the low concentration of both U and Th in the quartz keratophyres of the lower Onverwacht and the Middle Marker and in the Nelshoogte tonalites and trondhjemite as original igneous features, because they are consistent with the very low K, Rb, Cs, Ba, Zr, Hf, Nb, Y, and REE abundances in these rocks.

Zr abundances have a considerable range in the sericite schists and are very low in two samples of the 'ancient tonalites' and one sample of the Dalmein rocks. The Bosmanskop pluton sample has very high Zr. Hf abundances mostly correspond to the range of average granites and average granodiorite, but are high in the Nelspruit migmatite, one of the Hood granite samples, and in the Bosmanskop pluton sample. Zr/Hf values are high in the sericite schists and very low in two samples of the Nelshoogte pluton and one sample of the Dalmein pluton.

Relative to the Theespruit metadolerite, average Zr and Hf show a remarkable covariance (Fig. 4), suggesting near-retention in the acid rocks of their primary ratios. The sub-parallel (though not coincident) trends of REE, Nb, U, and Th in relation to Zr (Fig. 4) may reflect the controlling role of zircon in concentrating these elements. The increasing order of enrichment relative to the Theespruit dolerite is: Y (commonly depleted), Zr and Hf, REE, Nb, Th, and U (most enriched). Whereas in some instances the large-radius high valency elements vary sympathetically with the alkali elements, in other cases they vary in the opposite sense (Fig. 4), suggesting that no correlation exists between zircon concentrations and alkali enrichment. There are few differences between the 'ancient tonalites' -Dalmein-Bosmanskop series and the Nelspruit-Hood series with regard to element enrichment orders. If, as postulated below, the Nelspruit-Hood series formed by partial melting of the tonalites, no major reversals in the enrichment order of the high-valency elements took place, suggesting that little alteration of zircon occurred during the process.

(e) Rare earths

Chondrite-normalized data are portrayed in Fig. 8. The sericite schists of the Nelspruit formation display highly variable REE patterns. The albite-phyric tuff (29) has high total REE and a fractionated pattern ($La_N/Yb_N = 30$)*. A well pronounced negative Eu anomaly is present ($Eu/Eu^* = 0.54$)**, which can be interpreted in terms of extensive plagioclase fractionation, as supported by the very low Sr level (221 ppm). The sericite schist samples (34, 37) are progressively depleted in, as well as less fractionated with

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* N - normalized to average chondrite composition.

** Eu* - calculated Eu for an anomaly-free REE curve.

with regard to the rare earth elements. This is consistent with the major-element evidence, suggesting leaching of the light REE during sedimentary transport.

Quartz keratophyres associated with the lower Onverwacht Group (78, 90) have low total REE, display smooth, moderately fractionated REE curves, with La_N/Yb_N ratios of 25, 20, and light REE over chondrite enrichment factors of about 60. A higher light REE enrichment (over 100) and greater fractionation ($La_N/Yb_N = 100$) are shown by the amphibole-bearing porphyries of the (98,100) Middle Marker. The heavy REE concentrations (Yb = 0.15 ppm, 0.19 ppm) compare with those of an Archaean dacite porphyry from Minnesota (Yb = 0.164 ppm, Arth and Hanson, 1972), and with one of the Amitsoq gneiss samples (Yb = 0.162 ppm, O'Nions and Pankhurst, 1974). The REE fractionation pattern is analogous to that of the North Light gneiss of Arth and Hanson (1972).

The 'ancient tonalite' samples have very low REE levels (30-50 ppm) and portray almost identical REE patterns. They show moderate fractionation ($La_N/Yb_N = 23$-44), moderate light REE enrichment (20-40), chondritic heavy REE abundances, and very pronounced positive Eu anomalies (Eu/Eu* = 1.35, 1.46, 1.85). These patterns are remarkably similar to those of the Saganaga tonalite (Haskin _et al_., 1968; Arth and Hanson, 1972).

The REE patterns of the trondhjemite sample and trondhjemite-granite sample of the Dalmein pluton closely coincide. Both samples show moderately high total REE abundances, very high light REE enrichment ($La_N = 180$), lower heavy REE enrichment ($Yb_N = 4.4, 5.4$), and thus REE fractionation factors of between 30 and 40.

The Nelspruit migmatite sample is enriched in light REE ($La_N = 140$) as well as in heavy REE ($Yb_N = 15$), and shows a pronounced negative Eu anomaly ($Eu/Eu^* = 0.54$) placed between a flat heavy REE segment ($Gd/Yb = 1.5$) and a steep light REE ($La/Sm = 8$) segment.

The two samples from the Hood Granite differ in total REE by a factor of about 10. Specimen 114 has a highly fractionated pattern, the light REE enrichment factor relative to chondrites being over 200 ($La_N/Yb_N = 402$). Specimen 109, however, has a less fractionated REE pattern ($La_N/Yb_N = 8$).

The Bosmanskop pluton sample displays a very high total REE abundance and a highly fractionated REE pattern. The light REE enrichment factor exceeds 400, whereas Ytterbium enrichment is less than 5-fold, resulting in a La_N/Yb_N ratio of over 80.

Total REE vary sympathetically with Zr, Hf, Nb, U, and Th, and to a lesser extent with K, Ba, and Rb. There is no positive correlation between Eu and Sr.

Yttrium varies sympathetically with Zr and total REE, but shows no clear relation to Ca or P, which suggests its presence in zircon rather than in apatite. Both absolute Y abundances and Y/Ca valves are notably low relative to those in average granites, and Y is especially depleted in the 'ancient tonalites', 10^3Y/Ca ratios being as low as 0.15, 0.22, and 0.30. Y levels of the quartz keratophyres, the 'ancient tonalites', and the Dalmein pluton are lower than in the Theespruit metadolerite, in agreement with their depletion in heavy REE. The depletion in Y is in line with observations on Archaean gneisses from Scotland and Canada (Lambert and Holland, 1974) and on Western Australia granites and porphyries (Glikson and Sheraton, 1972).

PETROGENESIS

(a) Acid Volcanics of the Onverwacht Group

The tuff intercalations and porphyries of the ultramafic-mafic Theespruit formation, the volcanic porphyries of the Middle Marker, and the volcanics and breccias of the mafic to felsic upper Onverwacht Group (Viljoen and Viljoen, 1969c, Allsopp et al., 1973), all form dacitic to rhyolitic end members of a bimodal volcanic suite, intermediate lavas being rare in this sequence. Considerations on the origin of bimodal suites of Archaean high-grade terrains (Barker and Petermann, 1974) are thus also pertinent to the greenstone belt assemblages. The acid volcanics could have formed through one of the following processes: (1) anatexis of earlier sialic rocks; (2) crystal fractionation of mafic and/or ultramafic magma; (3) partial melting of mafic and/or ultramafic rocks at crustal or upper mantle levels. The initial $Sr^{87}/_{86}$ ratios of felsic volcanics of the upper Onverwacht Group (2540 + 50 m.y., Ri = 0.719 ± 0.006; 2620 ± 20 m.y., Ri = 0.711 ± 0.007, Allsopp et al., 1968; 1973) are not consistent with mantle derivation of the felsic volcanics. However, these ratios and the stated ages must reflect a younger metamorphism, and the true volcanic ages must antedate the approximate 3.3 b.y. age of the 'ancient tonalites' intruded into them. Partial melting of acid rocks would be expected to generate near-eutectic melts and result in enrichment in the alkali and large-radius lithophile elements. However, fractionated K-rich volcanics have not been observed to date in the Onverwacht Group. Thus the porphyries analyzed by us have low K, Rb, Cs, Ba, U, Th, Zr, Y, Nb, and Rb/Sr, and high Na/K, Ba/Rb, and in some instances high K/Rb and K/Cs. Nor can total melting of sialic crust be invoked with respect to the acid volcanics, in view of the high liquidus temperature of tonalite (over 900°C, pH_2O = pLoad (Piwinskii and Wyllie, 1968; Lambert and Wyllie, 1974). Such temperatures can only have been attained at crustal levels if a geothermal gradient of at least 25°C/km is assumed.

The highly fractionated REE patterns of some of the porphyries suggest that garnet was a residual phase since it is the only common mineral preferentially highly enriched in heavy REE. Insofar as the phenocryst-matrix partition coefficients of Schnetzler and Philipotts (1970) may be applicable to the origin of the acid volcanics, estimates of partial melting or fractional crystallization required to give rise to the observed REE patterns can be made, assuming equilibrium crystal-melt relations. It must be borne in mind, however, that whereas the partition coefficients themselves vary considerably in relation to pressure and temperature of crystallization, the ratio between light and heavy REE enrichments (relative to chondrites) is significant (see O'Nions and Pankhurst, 1974), and can be used for estimates of the degree of partial melting involved in producing these rocks.

For the original composition of the parent rocks or bulk magma composition we assume the composition of a metadolerite from the Theespruit formation (sample 6), showing a flat REE pattern ($Ce_N = 10$; $Yb_N = 10$) (Table 2; Fig. 8). Enrichment values for Ce and Yb, assuming both eclogite and amphibolite source-rock assemblages, were calculated and are presented in Table 3. On this basis the Ce_N/Yb_N ratios of the quartz keratophyres (16, 20) (Table 2) can be produced by over 40 percent of partial melting of eclogite of Theespruit dolerite composition ($Ce_N = 5$, $Yb_N = 10$), but extremely low degrees of partial melting of eclogite are required to give rise to the more fractionated REE patterns of the Middle Marker porphyries ($Ce_N/Yb_N = 76, 84$) (Table 2). Progressive melting of mafic rocks is probably unlikely, as it would have resulted in <u>early</u> eruption of acid melts, which is contrary to the mafic to felsic volcanic cycles observed in the upper Onverwacht Group. However, the melts could have been produced by magmatic segregation and filter pressing during the waning of the igneous episode. The high U, Th, Ba, Zr, Hf, Nb, and REE of the volcanic porphyries relative to the 'ancient tonalites' (Table 2) may also argue in favour of further concentration of these elements upon fractional crystallization of the ascending volcanic magmas. In contrast, the tonalites may represent little-differentiated products of partial melting (see below).

Green (1972) suggested that garnet is stable at pressures of 9 - 13.5 kb (with 10% H_2O present) down to subsolidus temperatures, thus setting a minimum depth limit of about 27 km for the equilibration of the acid volcanic magma, whose fractionated REE pattern implies presence of garnet. Even greater depths of magma derivation are suggested by the abundance of partly resorbed quartz phenocrysts, which may signify pressures of about or over 18 kb ($pH_2O <$ pLoad) at which quartz replaces plagioclase on the liquidus (Green and Ringwood, 1968).

If the acid volcanics resulted from late-stage differentiation of the ultramafic-mafic magma, they could have inherited certain trace element characteristics from the latter. On the other hand, if the ultramafic-mafic magma and the acid melts ensued from partial melting in the mantle and of mafic crust, respectively, fewer similarities could be expected. The latter conclusion was reached in connection with the bimodal suite of the Kalgoorlie System, Western Australia, where the acid volcanics have anomalously high Sr levels (600-800 ppm), but the associated metabasalts are low in Sr (about 100 ppm) (O'Beirne, 1968; Hallberg, 1972). In the Onverwacht Group such comparisons must await further trace element data for the ultramafic-mafic volcanics. We tentatively consider that the overall secular increase in Fe/(Fe + Mg) in the acid volcanics, which parallels the transition from the Mg-rich ultramafic-mafic lower Onverwacht Group to the more Fe -rich mafic upper Onverwacht Group, favours fractional crystallization of increasingly Fe -rich basic magmas, rather than partial melting. From the REE evidence and the presence of quartz phenocrysts, however, it follows that such fractional crystallization must have occurred at subcrustal or mantle depths. The paucity of andesites may be explained if consistent gravitative separation of garnet at deep crustal or upper mantle levels is assumed.

(b) Origin of the 'ancient tonalites'.

The low concentration in the 'ancient tonalites' of Th, U, Rb, Cs, Zr, Nb, and total REE, as well as their low initial $Sr^{87}/_{86}$ (Davies, 1971), sets constraints on models for their evolution. As argued in connection with the acid volcanics, total melting of sialic crust depleted in lithophile elements is unlikely. As noted above, to effect total melting of a tonalitic crust, temperatures of over 900°C are required, and granulite facies metamorphism should have reached higher crustal levels than is suggested by the generally low metamorphic grade in the greenstone belts. Furthermore, partial melting of granitic rocks should have yielded highly fractionated liquids, but no such rocks are known to antedate the 'ancient tonalites'. On the other hand, younger more fractionated intrusions are represented by the Dalmein and Bosmanskop plutons.

The high Ca and Al, low Si, high $Sr/_{Ba}$, low $Rb/_{Sr}$, and pronounced positive Eu anomalies shown by the analyses of the 'ancient tonalites' all point to strong enrichment of the magma in plagioclase. Partial melting or crystal fractionation must therefore have occurred under pressures at which plagioclase is unstable. Lambert and Wyllie (1974) showed that plagioclase is unstable at the tonalite solidus at a pressure of 15 kb (pH_2O = pload) and temperature of 650°C (and at lower pressures at higher temperatures). Green (1972) concluded that garnet, which on the basis of heavy REE depletion was probably present in the source, is stable on the liquidus in the 9-13.5 kb range (with 10% H_2O) at temperatures below 900°C. Thus, crystal-liquid equilibration at crustal levels deeper than about 27 km and possibly as deep as 45 km could account for both the enrichment of the tonalites in plagioclase and depletion in heavy REE. The fractionated REE patterns (Ce_N/Yb_N = 13 to 21) are consistent with over 40 percent melting of eclogite or garnet granulite similar in bulk composition to the Theespruit metadolerite, using the partition coefficients of Schnetzler and Philipotts (1970), but are not consistent with partial melting of amphibolite (Table 3).

To test the partial melting model further, K, Rb, Ba, and Sr enrichments in melts resulting from various degrees of eclogite and amphibolite fusion were calculated, using the appropriate Kd values of Philipotts and Schnetzler (1970). From Table 3 and Fig. 4 it is apparent that the calculated order of increasing enrichments for the alkali and alkaline earth elements - i.e. enrichment in Sr, Ba, K, and Rb in this order corresponds to the observed enrichments in the analyzed tonalites relative to the Theespruit metadolerite analysis. However, the percentages of partial melting of eclogite or amphibolite required to give rise to the observed concentrations vary for each element. Whereas the Ce_N/Yb_N ratios of the tonalites indicate over 40 per cent melting of eclogite of Theespruit metadolerite composition (Table 3), smaller degrees of partial melting are required for the observed enrichments in alkalis relative to the Theespruit metadolerite. Thus, observed Rb enrichment factors (15.2, 31.9, 38.2) imply less than 5 per cent melting; observed K enrichment factors (8.8, 16.4, 22.1) imply between 2 and 10 per cent melting; observed Ba enrichment factors (8.1, 9.4, 16) imply between 5 and 10 per cent melting, and observed Sr enrichment factors (5.3, 5.4, 5.9) imply about 10 per cent melting. This discordance may imply higher alkali levels of the source rocks relative to the Theespruit metadolerite, or alternatively a source composition more depleted in the light REE, by analogy with modern oceanic tholeiites.

The chemical features of the Kaap Valley granite, in particular a REE pattern intermediate between that of the Nelshoogte tonalite and the Theespruit metadolerite (Fig. 8), and the high Ca, Fe and Mg, and low Fe/(Fe + Mg) are consistent with a high degree of assimilation of mafic and ultramafic rocks, as suggested by Viljoen and Viljoen (1969a). However, the Ba and Rb abundances of a single Kaap Valley granite sample (Goles, 1968) exceed those of the 'ancient tonalites', and no fractionation of the biotite tonalite (Nelshoogte pluton) relative to the hornblende tonalite (Kaap Valley pluton) is thus indicated by the available data.

The Dalmein pluton was previously assigned to a "younger granites" series, corresponding to the 2.9 - 2.8 b.y. range (Viljoen and Viljoen, 1969d, e). However, more recent U-Pb work by Oosthuyzen (1970) indicated isotopic ages of 3190 ± 70 m.y. (sphene) and 3290 ± 80 m.y. (apatite). The Dalmein pluton intrudes synclinally folded rocks of the lower Onverwacht Group, and thus is structurally distinct from the adjacent 'ancient tonalites' (Theespruit and Stolzburg plutons) which are emplaced in anticlinal position. The two Dalmain pluton samples have higher lithophile element enrichment levels, higher Fe, Mn, Cu and Fe/(Fe + Mg), and lower Ca, Mg, Ni, Cr, and Co compared to the 'ancient tonalites'. Also, the lower K/Rb and Sr/Ba ratios, higher Rb/Sr, and lack of positive Eu anomalies in the Dalmein pluton rocks are explicable in terms of separation of plagioclase from tonalite magmas. Alternatively, partial melting of ecologite (about 30 percent) of Theespruit metadolerite composition can be invoked to explain the REE data (Table 3), but further crystal fractionation is indicated by the observed enrichment of K, Rb, and Ba far above levels calculated for this extent of partial melting (Fig. 4). The higher REE, U, Th, Nb, Hf, and Zr levels in the Dalmein pluton samples are attributable to higher zircon content. It is likely that the Dalmein trondhjemite represents a late, relatively fractionated member of the 'ancient tonalite' series.

The Bosmankop pluton (3130 ± 30 m.y.) is intruded into the Stolzburg pluton which is a member of the 'ancient tonalite' suite, samples of which from Lekkerloopspruit were dated at as 3170 ± 20 m.y. (Oosthuyzen, 1970). The chemical data indicate very high enrichment of light REE ($Ce_N/Yb_N = 64.5$) and very high U, Th, Zr, Hf, Nb, Y, Rb, and Ba, suggesting either low degrees (about 10 per cent) of partial melting (Table 3) or extreme magmatic fractionation. However the mechanism of segregation and extraction of very small proportions of liquid from the source rocks is difficult to envisage.

Nor is strong magmatic fractionation consistent with the K/Rb value (197), the Sr/Ba value (0.84), the high Sr level, and the lack of a negative Eu anomaly in the Bosmankop pluton sample. It must be tentatively assumed that migration of liquids resulting from incipient fusion was possible under the prevailing conditions. The apparent lack of plagioclase fractionation and the extensive equilibration with garnet suggested by the REE data imply that pressures exceeded 9 kb, and thus derivation from levels deeper than 27 km (see Green and Ringwood, 1968).

(c) Origin of the Nelspruit migmatite and Hood granite.

Viljoen and Viljoen (1969e) considered the Nelspruit migmatites to be anatectic and/or metasomatic derivatives of the 'ancient tonalites', and presented field evidence for a transition upwards from the tonalites into the migmatite, which in turn grades upwards into the homogeneous Hood granite. Both the migmatite and the granite yield isotopic ages of about 3 b.y. (3075 ± 100 m.y., U-Pb age, Oosthuyzen, 1970; 2992 ± 70 m.y., $Sr_i^{87/86} = 0.7052 \pm 0.0019$, de Gasparis, 1967), but older ages were also recorded (3160 ± 50 m.y., U-Pb age, Oosthuyzen, 1970), possibly corresponding to components of the 'ancient tonalites' incorporated in the migmatite. The initial $Sr^{87}/_{86}$ ratios of the Nelspruit migmatite, Hood granite, and Lochiel granite (0.7054, Davies, 1971) are not inconsistent with a mode of origin involving partial melting of the 'ancient tonalites', bearing in mind the low Rb/Sr ratios in the latter. Major element data

(Viljoen and Viljoen, 1969e) show that the average Na/K values for the Nelspruit migmatite (Na_2O = 4.37%; K_2O = 3.57%) fall between the averages of the 'ancient tonalites' (Na_2O = 5.38%; K_2O = 1.92%) and the Hood granite (Na_2O = 3.76%; K_2O = 4.97%). Likewise the average Rb level (105 ppm) and Sr level (278 ppm) of the Nelspruit migmatite are intermediate between the averages of the 'ancient tonalites' (Rb = 52 ppm; Sr = 498 ppm) and the Hood granite (Rb = 189 ppm; Sr = 134 ppm).

Notwithstanding the above considerations, REE data do not permit a derivation of the Nelspruit migmatite sample solely by partial melting of the 'ancient tonalites', because of the marked depletion of the latter in the heavy REE - a characteristic not inherited by the migmatite. It would be difficult to explain this feature, except if partial melting of mafic source rocks with almost flat REE curves and not in equilibrium with garnet has also contributed significantly to the migmatite. For this reason, Nelspruit migmatites probably represent the product of combined melting of the 'ancient tonalites' and of mafic rocks of the Onverwacht Group, which abound as inclusions in the tonalites. As suggested by the negative Eu anomaly in the migmatite, the partial melting was accompanied by marked precipitation of plagioclase. On the other hand, as shown by the highly fractionated REE curves of one of the two Hood granite samples (114), in other instances the 'ancient tonalites' could be almost the sole contributors of partial melt at that stage. Further trace element studies of the Nelspruit migmatite and Hood granite are necessary to document and elucidate the significance of their chemical heterogeneity.

A comparison between the chemistry of the 'ancient tonalites' and the Nelspruit-Hood suite (Fig. 4) indicates a general increase in the abundance of alkali and high-valency cations (Fig. 4). There are some variations in the orders of enrichment in lithophile elements relative to the Theespruit metadolerite, which are as follows (in order of increasing enrichment):

(1) Nelshoogte tonalite (average of 3): Y, REE, Zr, Nb, Hf, Li, Sr, U, Th, Ba, K, Rb.

(2) Nelspruit migmatite: Y, Sr, Li, Hf, Zr, REE, Nb, Th, K, U, Ba, Rb.

(3) Hood granite (average of 2): Y, Zr, Hf, Sr, Li, REE, Nb, Th, U, Ba, K, Rb.

Thus, there is an increase in the ratio between total REE and Zr; a general decrease in Th/U ratio, and a general decrease in the relative importance of Sr upon anatexis.

The Nelspruit migmatite sample (108) has higher Si and lower Al in comparison to analyses presented by Viljoen and Viljoen (1969e), and as shown by the high Ba, Rb, Cs, Zr and Hf, and low K/Cs and Sr, represents a relatively differentiated end-member of the migmatite complex. This conclusion is corroborated by the pronounced negative Eu anomaly, and low Ca and Al, all pointing to fractionation of platioclase (Table 2, Fig. 8).

It is pertinent to compare the chemistry of the Nelspruit migmatite-Hood granite series with that of the Bosmanskop pluton. The Nelspruit-Hood analyses show lesser enrichment in total REE, Sr, Ba, Th, and U, and greater enrichment in Li. Fe/(Fe + Mg) and the order of depletion in ferromagnesian elements are similar in both groups, as follows (in order of increasing depletion) : Mn, Fe, Co and Sc, Mg, Cu, Ni. The high contents of large-radius high-valency elements, REE (553 ppm), Sr (1263 ppm), and Ba (1500 ppm) in the Bosmanskop pluton suggest that phases enriched in these elements were selectively melted at crustal levels at which the magma has equilibrated. It is difficult, however, to envisage a process by which partial melting of the 'ancient tonalites' could result in the observed two-fold increase in Sr, considering the low plagioclase content of the Bosmanskop sample. No such problem exists with respect to the Nelspruit-Hood series, which are depleted in Sr relative to the Nelshoogte tonalite, thus being consistently with partial melting of the latter. The latter process must have therefore taken place at depths at which plagioclase is stable, i.e. at less than 15 kb (Lambert and Wyllie, 1974).

Hunter (1974) pointed out that the Lochiel granite analyses plot near the eutectic minimum which corresponds to the 7 kb (pH_2O = pload) on the Q-Ab-Or ternary. Thus, minimum and maximum limits of approximately 20 km and 45 km, respectively, can be placed on the depth at which anatexis of the 'ancient tonalites' has taken place.

The high Fe/(Fe + Mg) values for the Nelspruit-Hood series relative to those of the 'ancient tonalites' can be understood in terms of separation of residual Mg-rich phase. Formation of basic upper-amphibolite to granulite facies assemblages can thus be expected to occur upon granite formation. It is pertinent in this regard to note the occurrence of plagioclase-diopside granulites reported from the 'ancient gneiss complex' in Swaziland by Hunter (1970), some of which could conceivably represent residues of partial melting processes.

(d) The Barberton granite-greenstone system, the 'ancient gneiss complex', and the source of the Fig Tree Group.

Hunter (1970) and Barker and Peterman (1974) suggested that the amphibolite-facies 'ancient gneiss complex' of Swaziland antedates the granite-greenstone system of the Barberton Mountain Land, and formed a source terrain for the sediments of the Fig Tree Group. Condie et al. (1970) supported this conclusion, citing the occurrence of K-feldspar in, and the high K and Rb levels of, greywackes of the Fig Tree Group, as compared to the low K and Rb in the 'ancient tonalites' (Rb/Sr = 0.08, 0.10).

A comparison between the average 'ancient tonalite', the Theespruit metadolerite and two average greywackes from the Fig Tree Group (cited from Condie et al., 1970, and Wildeman and Condie, 1973)(Table 4), indicates that the greywackes have Si, Ti, Fe, Mg, Sr, and heavy REE abundances intermediate between those of the 'ancient tonalites' and the Theespruit metadolerite. The K, Rb, Ba, Zr, light REE, Rb/Sr, and Ni values in the greywackes are higher, and Al, Na, K/Rb, and Sr/Ba values are lower than in the tonalites and the dolerite. These relations can be interpreted in terms of sediment derivation from a tonalite-mafic-ultramafic provenance, if it is considered that the occurrence of detrital K-feldspar in the greywackes and the excess alkalis result from (1) denudation of late members of the 'ancient tonalite' plutonic suite, such as the Dalmein and Bosmanskop plutons, and (2) adsorption of K and Rb from sea water onto clay minerals. The low Na and Sr in the greywackes may have resulted from leaching, whereas the high Zr and light REE contents may be attributed to mechanical concentration of heavy minerals during sedimentation. The high Ni contents probably represent contribution from ultramafic rocks (Condie et al., 1970). Thus, although derivation of the Fig Tree Group sediments from the 'ancient gneiss complex' is a possibility, the chemical data are not inconsistent with derivation from 'ancient tonalites' and Onverwacht Group rocks. It has been suggested that the 'ancient gneiss complex' represents the deeply eroded coeval high-grade roots of the granite-greenstone terrain. (Anhaeusser, 1973; Glikson and Lambert, 1975). If this is correct, the chemical differences between the tonalites of the 'ancient gneiss complex' and the tonalites of the Barberton region could be due to large-scale metamorphic differentiation processes resulting in a vertically zoned crust (Glikson, 1975) rather than being attributed to chemical differences between rocks of different ages.

(e) On the tectonic significance of Archaean acid magmatism

The preceding considerations suggest that the acid volcanic rocks of the Onverwacht Group and the 'ancient tonalites' (both pre- 3.2 b.y. old) can both be regarded as products of partial melting and fractional crystallization of mafic to ultramafic source rocks or magmas. In contrast, the Nelspruit migmatite-Hood granite series (ca 3 b.y. old) is interpreted in terms of intra-crustal anatexis of sialic rocks, including the 'ancient tonalites'. Thus a secular transformation from ensimatic to ensialic igneous activity is reflected by the data, in agreement with the Archaean models of Anhaeusser (1973) and Glikson (1968, 1970, 1972).

The bimodal volcanic suite of the upper Onverwacht Group can be compared to ocean-crust type assemblages such as the spilite-keratophyre association of Alpine geosynclines (Steinmann, 1927). Na-rich dacitic to rhyolitic volcanic rocks showing considerable depletion in K, Rb, Cs, U, and Th abound in island arcs of the southwest Pacific (e.g. Gill, 1970; Taylor et al., 1969a). However, these examples consitute members of a high-Al andesite-rich calcalkaline association distinct from the Onverwacht Group. Furthermore, with few exceptions (Gale, 1973), no peridotitic and high-Mg volcanics analogous to the lower Onverwacht Group are known from post-Archaean systems.

Andesitic volcanics, which are scarce in both the Onverwacht Group and the Kalgoorlie System of Western Australia (Hallberg, 1972), are apparently more common in Canadian greenstone belts (Baragar and Goodwin, 1969). This difference has been interpreted in terms of different H_2O partial pressure in a mafic source by Barker and Peterman (1974), who suggested that low degrees of partial melting of a wet subducted lithospheric slab were succeeded by total melting, accounting for the bimodal volcanic suite. However, and andesite gap does not necessarily follow from the experimental work of Green (1972). Also, progressive partial melting should result in acid to basic volcanic cycles, in contrast to field observations. One possible interpretation of bimodal suites is that mantle melting episodes were followed by low degrees of partial melting of subsiding mafic crust. Such a dual origin would imply near-concomitant mantle and crustal melting episodes, which could perhaps be explained by rising thermal gradients associated with mentle fusion events. Little crustal melting of acid material is suggested, because of the depleted composition of the acid volcanics with respect to incompatible lithophile elements. An alternative explanation resides in fractional crystallization at depths at which garnet is stable, i.e. deeper than 27 km (Green, 1972). Thus, extensive and consistent gravity settling of the dense garnet from intermediate melts could have produced predominantly acid magmas - a conclusion supported by the REE data. Further detailed trace element studies of the Onverwacht Group are required to assess the various models.

The large volumes of intermediate to acid magma represented in the 'ancient tonalites' are not likely to have formed through fractional crystallization of basic magma, as no genetically related basic intrusions are known to have developed at that stage. As suggested by the chemical data, it is highly unlikely that the tonalites are the products of ensialic anatexis, nor do recent observations from experimental petrology permit direct derivation of intermediate or acid liquids from the mantle, except at very shallow levels (Nicholls and Ringwood, 1972). Thus the two-stage melting model of Ringwood and Green (1966) implying active crustal circulation and partial melting of mafic crust, appears to be the most likely mechanism for the genesis of the 'ancient tonalites'. Decreasing degrees of melting of mafic crust with time may account for the increasing differentiation shown by the Nelshoogte-Dalmein-Bosmanskop plutonic series. It is thus reasonable to compare the Archaean acid igneous rocks with possible analogues in island arcs, where acid rocks depleted in alkali and large-radius high-valency cations have been described by several workers (Taylor _et al_., 1969a; Gill, 1970; DeLong 1974). However, island arc volcanics do not as a rule display strong REE fractionation (Jakeš and Gill, 1970; Taylor _et al_., 1969a). Furthermore, island arc calcalkaline suites are typically very depleted in Ni, Cr, and Co (Taylor _et al_., 1969b; DeLong, 1974; Gill, 1970), in contrast to the Archaean rocks. Because of the high alumina contents of orogenic calcalkaline volcanics (Al_2O_3 = 16-18%), as contrasted to Archaean volcanics (Al_2O_3 = 13-15%), the latter must have equilibrated either under low pressures, at which plagioclase is stable on the liquidus, or under high pressures at which alumina-rich pyroxene is formed. The fractionation of garnet, suggested by the REE data, supports the latter alternative. The lower limit of the stability field of aluminous pyroxene will depend on H_2O pressure. The high Ni, Cr, and Co of the Archaean volcanics militate against crystal fractionation of olivine under hydrous conditions, and relatively dry conditions are therefore implied. If this is correct, Green and Ringwood's (1967) stability range for plagioclase (0 - 15 km) and aluminous pyroxene (over 30 km) in dry mafic magmas may be significant for explaining the low-Al contents of the Archaean volcanics. We tentatively conclude that Archaean acid magmas equilibrated under deep crustal and upper mantle pressures and low H_2O pressures ($pH_2O < pload$). Under such conditions extensive fractionation of garnet and quartz would have taken place, whereby garnet settled gravitatively and quartz phenocrysts were carried upward and were partly resorbed.

The major anatectic event about 3 b.y. ago which gave rise to the Nelspruit migmatite has apparently involved an upward migration of eutectic melts enriched in lithophile elements (Viljoen and Viljoen, 1969e). Accumulation of these melts at higher crustal levels and in the roof zones of the plutonic complexes gave rise to the Hood and Lochiel granites. The chemical data are consistent with this interpretation; the negative Eu anomaly of the Nelspruit migmatite sample signifies the onset of more differentiated acid plutonism, akin to that characteristic of the Proterozoic. A younger igneous phase dated as about 2.6 b.y. is represented by the Mpageni granite (2550 ± 90 m.y., $Sr_i^{87/86} = 0.7065 \pm 0.0016$; de Gasparis, 1967) and Mbabane granite (2550 ± 70 m.y.; Allsopp et al., 1962), and it will be interesting to see how analyses of these rocks compare with those in the present study.

CONCLUSIONS

Reconnaissance analyses of acid igneous rocks reported in this study show that each volcanic and plutonic suite in the Barberton Mountain Land displays a unique set of trace element characteristics which afford both its chemical classification and an insight into its likely mode of origin, as follows:

(1) Acid volcanic rocks associated with the Onverwacht Group may have formed by partial melting of basic source rocks, but more likely by fractional crystallization of basic magma under high pressures at which garnet was stable (over 27 km) and at waning stages of basic-ultrabasic volcanic cycles.

(2) Tonalitic plutons emplaced into the lower Onverwacht Group formed by partial melting of basic and ultrabasic volcanics, under high pressures at which plagioclase was unstable (over 40 km).

(3) The Dalmein and Bosmanskop plutons, as late members of the 'ancient tonalite' suite, probably formed by decreasing degrees of partial melting of basic source rocks.

(4) The Nelspruit migmatite and Hood granite probably formed by partial melting of 'ancient tonalites' and included basic-ultrabasic xenoliths at intermediate crustal levels (20-45 km).

(5) The chemical data do not lend support to uniformitarian correlations between Archaean granite-greenstone systems and modern arc-trench systems, except in very broad terms, but reflect a general evolutionary trend from simatic crust to sialic crust in the Archaean.

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Table 1. Petrographic summary

Specimen No.	Geological unit	Petrographic definition	Texture	Mineralogy*	Notes .
A. Volcanic and hypabyssal rocks					
73325007	Theespruit Formation	metadolerite	Subophitic	Albite, Actinolite, Epidote, chlorite sphene leucoxene, opaques, quartz	Epidote is younger than amphibole
73325028	Intercalations in Theespruit Formation	Metaporphyry Sericite-quartz-albite schist	Blastoporphyritic Altered phenocrysts of albite and rarely of quartz	Albite (zoned), Quartz, White mica Chlorite, tourmaline, zircon, opaques, carbonate	Sheared metamorphosed acid porphyry or tuff
73325034	Intercalation in Theespruit Formation	Sericite-quartz microcrystalline schist	foliated, micro-crystalline	Sericite, Quartz, albite, tourmaline, opaques	No primary texture retained
73325037	Intercalation in Theespruit Formation	Sericite-quartz schist	foliated, micro-crystalline to fine grained	Sericite, Quartz, albite zircon	No primary texture retained. More recrystallized than 73325034
73325078	lens in Theespruit Formation	Albite porphyry	Porphyritic. microcrystalline groundmass	Albite, Quartz, Chlorite, carbonate zircon, opaques	carbonate alteration
73325090	lens in Komati Formation	Albite porphyry	Porphyritic groundmass of albite microlaths	Albite, Quartz, Chlorite, apatite, opaques, zircon	Orthoclase identified by XRD, but not seen in thin section
73325098	Part of the Middle Marker	Albite meta-amphibole acid porphyry	Porphyritic	Albite, Quartz, Sericite, Chlorite, Zircon, apatite, opaques, carbonate	Pseudomorphs of chlorite after porphyritic amphibole. The albite is heavily sericitized
73325100	Part of the Middle Marker	Albite-amphibole porphyry	Porphyritic. zoned plagioclase phenocrysts. Amphibole phenocrysts partly altered by chlorite	Plagioclase (clouded centres and clear zoned albite rims), Quartz, amphibole, chlorite (ferruginous), sericite, sphene, zircon, apatite, epidote, biotite, opaques, carbonate	minor microcline by XRD
B. Plutonic rocks					
73325106	Theespruit pluton	Trondhjemite	Hypidiomorphic unequi-granular, weakly gneissose	Oligoclase, Albite, Quartz, Microcline, amphibole, biotite, chlorite, epidote, zircon, sphene, apatite, sericite, opaques	XRD detected orthoclase, and suggests the amphibole is a hastingsite
73325117	Nelshoogte pluton	Tonalite	Hypidiomorphic granular to slightly porphyritic	Oligoclase, Albite, Quartz, microcline sericite, chlorite, epidote, sphene, apatite, allanite, zircon, biotite, accicular amphibole	Allanite is rimmed by epidote. Epidote replaces chlorite. Biotite relics occur within chlorite
73325118	Nelshoogte pluton	Tonalite	Hypidiomorphic granular	Oligoclase, Quartz, microcline biotite chlorite, epidote, sphene, zircon, apatite, allanite	Chlorite alters biotite, and is commonly interleaved with it. K-feldspar forms granular rims around plagioclase
73325104	Dalmein pluton	Trondhjemite	Hypidiomorphic granular	Albite, Quartz, Microcline, sericite, chlorite, epidote, sphene, apatite, zircon, opaques, amphibole, rutile (inclusions in chlorite)	Plagioclase is clouded and zoned, biotite is interleaved with and altered by chlorite. The chlorite includes both aluminous and ferruginous varieties
73325105	Dalmein pluton	Trondhjemite	Hypidiomorphic granular	Albite, Quartz, Microcline, chlorite (both aluminous and ferroan), sericite, biotite, sphene, apatite, allanite, opaques, rutile (inclusions in chlorite)	Ferroan chlorite is rimmed by aluminous chlorite. Rutile needles in chlorite, exsolved upon alterations of biotite
73325108	Nelspruit migmatite	Migmatitic granite	Xenomorphic granular	Albite, Quartz, Microcline, Orthoclase, chlorite, biotite, chlorite, muscovite, biotite, chlorite, epidote, zircon, opaques, rutile (inclusions in chlorite)	Chlorite as alteration product of biotite
73325109	Need granite	Granite	Xenomorphic granular	Albite, Quartz, Microcline, chlorite (ferroan), sericite, epidote, sphene, opaques, rutile (inclusions in chlorite)	Chlorite as alteration product of biotite, Epidote replaces chlorite
73325114	Need granite	Granite	hypidiomorphic granular	Albite, Quartz, Microcline, sericite, amphibole sphene, chlorite, epidote, biotite, opaques, allanite, rutile	Chlorite as alteration product of biotite, pidote replaces chlorite
73325115	Bosmanskop pluton	Granite	hypidiomorphic granular	Albite, Microcline, biotite, chlorite hastingsite, sphene, epidote, apatite, sericite, zircon, carbonate, opaques allanite	Amphibole replaces chlorite, and is in turn replaced by epidote. Chlorite-muscovite intergrowths.

Table 2.

Major element, trace element and rare earth element data and ratios for volcanic and granitic rocks from the Barberton Mountain Land, and average granites.

					Volcanic and hypabyssal rocks						
					Theespruit fm. tuff	Theespruit fm Sericite schists		Lower Onverwacht quartz keratophyre		Middle Marker: quartz keratophyres	
	Average granite (Nockolds 1954, Taylor 1966)	Average low-Ca granite (Turekian and Wedepohl 1961)	Average high-Ca granite	Theespruit meta-dolerite	5029	5034	5037	5078	5090	5098	5100
Major elements											
SiO_2	72.08	74.25	67.19	50.74	74.34	79.28	80.33	73.40	71.35	67.79	67.49
TiO_2	0.37	0.20	0.56	0.75	0.12	0.20	0.12	0.21	0.31	0.50	0.50
Al_2O_3	13.86	13.53	15.41	15.20	11.73	12.60	12.14	14.02	15.02	16.02	15.99
Fe_2O_3	0.86			3.32	0.40	0.18	0.46	0.47	0.24	0.97	0.86
FeO	1.87	1.82*	3.79*	7.78	2.92	0.19	0.26	1.26	1.72	2.19	2.44
MnO	0.06	0.05	0.07	0.16	0.03	-	0.01	0.03	0.02	0.03	0.05
MgO	0.52	0.26	1.56	7.21	3.06	0.85	0.54	1.23	1.11	1.59	1.18
CaO	1.33	0.71	3.54	8.13	0.13	0.11	0.01	0.55	0.26	0.78	3.03
Na_2O	3.08	3.48	3.83	3.88	3.27	0.11	0.21	7.09	6.48	5.70	5.39
K_2O	5.46	5.04	3.02	0.07	0.55	4.01	3.90	0.20	2.37	1.40	1.56
P_2O_5	-	-	-	0.06	0.08	0.03	-	0.05	0.08	0.19	0.19
CO_2	-	-	-	-	-	-	-	-	-	-	-
SO_3				0.02	-	0.01	-	0.01	-	0.07	-
Loss				3.41	2.81	1.98	1.80	1.62	1.11	2.13	1.26
Total	99.49	99.34	98.97	100.73	99.44	99.53	99.79	100.14	100.07	99.35	99.94
*total iron as FeO											
CIPW Norm											
Q				-	48.01	64.3	64.7	28.23	21.72	25.40	21.38
Or				0.43	3.36	24.3	23.5	1.20	14.15	8.51	9.34
Ab				33.7	28.6	0.95	1.81	60.87	55.38	49.62	46.20
An				24.5	0.13	0.36	0.05	2.44	0.78	2.71	13.97
C				-	5.91	8.15	7.71	1.28	1.53	4.29	0.39
Hy				17.4	12.9	2.2	1.37	4.77	5.30	6.60	6.05
Ol				13.4	-	-	-	-	-	-	-
Mt				4.9	0.6	0.03	0.53	0.69	0.35	1.45	1.26
Hm				-	-	0.16	0.10	-	-	-	-
Il				1.4	0.24	0.39	0.23	0.40	0.59	0.98	0.96
Ap				0.15	0.20	0.07	-	0.12	0.19	0.46	0.46
				01 - 3.9							
differentiation index:				3.4	80	88.6	90	90.3	91.2	83.5	76.9
Solidification index:				32	30	15.9	10.1	12	9.3	13.4	10.3
Peralkalinity:				0.42	0.51	0.36	0.38	0.85	0.88	0.68	0.66
Plag. An				42	0.4	27.3	2.7	3.8	1.8	5.2	13.2

Ferromagnesian elements											
FeO*/FeO* + MgO	0.82	0.87	0.71	0.59	0.52	0.29	0.55	0.58	0.63	0.66	0.73
Cu	10	10	30	114	108	3	2	5	24	5	10
Sc	5	7	14	39	7	6	5	5	5	5	7
V	20	44	88	240	14	13	12	20	25	41	52
Co	1	1	7	47	13	3	5	8	18	12	11
Ni	0.5	4.5	1.5	129	39	4	13	19	16	6	7
Li	30	40	24	5	15	9	12	4	3	6	4
Cr	4	4.1	22	200	11	14	6	13	20	10	10
Zn	40	39	60	81	62	13	12	40	40	70	100
Ni/Co	0.5	4.5	2.1	2.7	3.0	1.3	2.6	2.4	2.0	0.5	0.6
Cu/Ni	0.50	0.22	0.34	0.47	7.71	0.28	0.17	0.25	0.26	0.12	0.19
V/Ni	40	9.8	5.9	1.9	0.4	3.2	0.9	1.0	1.6	6.8	7.4
Cr/V	0.2	0.09	0.25	0.83	0.78	1.00	1.07	0.65	0.80	0.24	0.19
Ni/Cr	0.125	1.1	0.68	0.64	3.54	0.28	2.16	1.46	0.83	0.6	0.7
0^3/Li/Mg	960	1280	250	00.1	80	170	370	50	60	50	50
Alkali elements and large-radius high-valency elements											
Cs	5	4	2	-	0.19	0.46	1.6	-	0.11	2.1	0.66
Rb	150	170	110	1.1	23.6	141.4	101	4.5	24.5	43.2	26.6
Ba	600	840	420	18	170	1300	460	69	290	1300	540
Sr	285	100	440	106.5	22.1	12.2	7.1	128.7	92.6	399.5	706.8
Th	17	17	8.5	0.31	14	18	17	5.0	6.2	4.1	4.1
U	4.8	3	3	0.08	3.2	1.5	2.6	1.5	1.4	1.2	1.0
Zr	180	175	140	53	280	170	120	170	125	150	170
Hf	4	3.9	2.3	1.2	5.3	4.4	1.6	3	3.7	3.2	3.2
Nb	3	21	20	2.5	23	26	20	8.7	12	9.7	9.3

[redacted]kali [redacted]ements and [redacted]rge-[redacted]dius highly charged [redacted]ements											
K/Rb	302	246	228	528	193	235	320	369	802	268	486
[redacted]Cs	9063	10458	12533	-	24026	72354	20231	-	178827	5533	19618
K/Th	2655	2460	2949	1874	326	1849	1904	332	3172	2834	3158
[redacted]U	9441	13944	8355	7262	1426	22188	12450	1106	14050	9683	12948
[redacted]/Sr	0.52	1.7	0.25	0.01	1.07	11.59	14.22	0.03	0.26	0.11	0.04
Rb/Cs	30	42	55	-	124	307	63	-	223	20	40
[redacted]/Rb	4	4.9	3.8	16.3	7.2	0.9	4.5	15.3	11.8	30.1	20.3
Sr/Ba	0.47	0.12	1.04	5.9	0.13	0.09	0.015	1.85	3.2	0.3	1.3
[redacted]/U	3.5	5.6	2.8	3.9	4.4	12	6.5	3.3	4.4	3.4	4.1
Zr/Hf	45	45	61	44	53	37	75	57	34	47	53
[redacted]											
[redacted]re [redacted]rth elements											
[redacted]	25	55	45	3.3	88	12	2.0	18	18	34	36
Ce	46	92	81	8.3	97	29	12	31	33	71	63
[redacted]	4.6	8.8	7.7	1.2	16	2.6	0.51	2.9	3.6	7.4	7.4
[redacted]Nd	18	37	33	5.0	44	7.0	1.5	9.2	11	23	24
[redacted]	3	10	8.8	1.7	6.4	1.7	0.51	1.7	2.21	4.3	4.1
[redacted]	1.6	1.8	1.4	0.7	0.84	0.49	0.25	0.42	0.54	1.2	1.2
Gd	2	10	8.8	2.1	3.5	1.8	0.88	1.2	1.6	2.9	3.5
[redacted]	0.05	1.6	1.4	0.43	0.55	0.27	0.18	0.17	0.27	0.41	0.33
Dy	0.5	7.2	6.3	2.9	3.5	1.8	1.3	0.83	1.6	1.5	1.6
[redacted]o	0.07	2.0	1.8	0.67	0.73	0.37	0.31	0.20	0.33	0.23	0.25
Er	0.2	4.0	3.5	2.0	2.0	1.1	1.2	0.52	0.87	0.46	0.49
[redacted]	0.06	4.0	3.5	2.0	1.9	1.2	1.5	0.44	0.82	0.15	0.19
REE	99.5	233.2	202.2	30	264	60	22	67	74	147	142
[redacted]	40	40	35	21	27	11	6.7	12	9.9	8.8	8.8
Ce_N/Yb_N				1	12.1	5.8	2.0	15.6	20.0	84	76
[redacted]LREE/ HREE				1.9	21	7.8	3.0	19	12	25	21
[redacted]/Yb	417	13.7	12.8	1.7	46	10	1.3	41	22	227	189
Gd/Yb	33	2.5	2.5	1.1	1.8	1.5	1.3	2.7	2.0	19	18
[redacted]/Eu*				1.25	0.54	0.94	1.39	0.94	0.92	1.08	1.04

[redacted]

[redacted]

Plutonic rocks

	'Ancient tonalites'				Dalmein pluton		Bosman-kop pluton	Nel-spruit migma-tite	Hood Granite		
	Kamp Valley granite	Theespruit pluton 5106	Nelshoogte pluton 5117	5118	5104	5105	5115	5108	5109	5114	Lochial granite
ajor elements											
iO_2	64.84	70.63	68.93	70.63	69.72	70.57	65.75	75.99	72.35	68.89	71.32
TiO_2	0.49	0.24	0.30	0.31	0.32	0.35	0.69	0.21	0.11	0.64	0.32
l_2O_3	15.44	14.98	16.21	15.29	15.02	14.52	14.92	12.40	15.22	14.57	14.34
e_2O_3	1.80	0.39	0.76	0.73	1.21	1.45	2.33	0.36	0.33	0.80	0.59
FeO	2.44	1.26	1.58	1.52	1.09	1.00	1.61	1.66	0.64	2.12	1.73
nO	0.04	0.03	0.03	0.03	0.05	0.06	0.08	0.05	0.02	0.05	0.08
MgO	2.60	1.06	1.22	1.06	0.95	0.97	1.14	0.64	0.39	0.62	0.57
aO	4.25	2.37	3.69	3.34	1.72	2.04	2.29	1.18	0.98	2.39	1.33
Na_2O	4.93	5.37	5.16	4.95	4.72	4.74	4.75	3.61	5.21	4.05	3.92
$_2O$	1.53	1.55	0.62	1.15	3.46	2.93	4.67	2.96	3.68	3.85	4.95
P_2O_5	0.18	0.06	0.09	0.09	0.18	0.18	0.37	0.02	0.03	0.23	0.31
$_2$		-	-	-	-	-	-	-	-	-	-
O_3		0.01	0.01	-	-	-	0.01	-	-	0.01	-
Loss	1.10	0.79	1.29	0.84	1.08	1.00	0.85	1.01	0.77	1.15	0.69
otal		98.76	99.87	99.95	99.51	99.83	99.46	100.08	99.72	99.38	
CIPW orm											
Q		26.80	26.63	28.44	24.58	26.74	15.63	39.48	25.31	24.66	
		9.35	3.72	6.86	20.77	17.52	27.98	17.65	21.97	23.16	
b		46.37	44.27	42.25	40.55	40.57	40.74	30.82	44.53	34.88	
An		11.60	17.97	16.12	7.47	9.05	5.69	5.78	4.71	10.40	
		0.31	0.57	0.05	0.83	0.28	-	1.17	0.97	-	
Hy		4.38	4.94	4.41	2.98	2.62	1.69	4.13	1.75	3.82	
		-	-	-	-	-	-	-	-	-	
Mt		0.58	1.12	1.07	1.78	2.13	3.43	0.53	0.48	1.18	
		-	-	-	-	-	-	-	-	-	
Il		0.47	0.58	0.59	0.62	0.67	1.33	0.40	0.21	1.24	
p		0.15	0.22	0.22	0.43	0.43	0.89	0.05	0.07	0.65	
ifferentiation index:		82.52	74.62	77.54	85.90	84.83	84.36	87.95	91.80	82.70	
olidification index:		11.0	13.1	11.6	8.31	8.7	7.9	6.9	3.8	5.4	
eralkalinity:		0.70	0.56	0.61	0.77	0.76	0.86	0.74	0.82	0.74	
Plag. An		20	28.9	37.6	15.5	18.2	12.2	15.8	9.6	23.0	

[redacted]erromag- nesian [redacted]lements											
[redacted]eO*/FeO* + MgO	0.61	0.60	0.65	0.67	0.69	0.70	0.76	0.75	0.70	0.82	0.80
[redacted]u		5	8	12	8	10	17	4	3	15	
[redacted]c	1.8	5	5	5	5	5	8	5	10	5	
[redacted]		24	36	31	30	30	49	10	10	34	
[redacted]o		9	8	9	6	9	10	5	6	10	
Ni		21	13	11	8	6	6	3	3	11	
[redacted]i	23	12	10	14	11	18	7	22	13	31	44
Cr		15	24	21	10	10	8	-	3	25	
[redacted]n		47	46	45	48	70	101	64	31	87	
Ni/Co		2.3	1.6	1.2	1.3	0.7	0.6	0.6	0.5	1.1	
[redacted]u/Ni		0.20	0.22	0.39	0.26	0.33	0.34	-	-	0.44	
V/Ni		1.1	2.8	2.8	3.7	5.0	8.2	-	-	3.1	
[redacted]r/V		0.62	0.66	0.67	0.33	0.33	0.16	-	0.3	0.73	
[redacted]i/Cr		1.4	0.54	0.52	0.8	0.6	0.75	-	1	1.6	
10^3/Li/Mg		180	130	220	190	310	100	570	550	830	
[redacted]		0.62	0.66	0.67	0.33	0.33	0.33	0.16	-	-	0.73
[redacted]lkali elements and [redacted]arge- radius high- [redacted]alency [redacted]lements											
Cs		1.7	1.0	1.7	2.2	2.9	4.4	4.5	3.0	6.7	
[redacted]b	44	42.1	16.8	35.1	120.8	103.1	196.2	118.8	141.6	168.1	226
Ba	422	290	146	170	700	540	1500	890	360	910	500
[redacted]r	530	573.3	626.5	563.5	483.2	523.1	1263.4	171.7	488.4	447.1	122
Th		3.6	1.1	0.77	7.3	12	21	14	2.4	12	
[redacted]		0.56	0.33	0.42	2.8	2.1	5	3.7	1.5	2.8	
[redacted]r	100	55	55	120	77	190	350	310	64	130	
Hf		3.1	2.5	2.1	4.2	2.6	9.1	6.2	1.8	7.5	
[redacted]b		6	2	3.9	15	15	22	32	20	21	

[redacted]

[redacted]

[redacted]

[redacted]

Alkali elements and large-radius highly charged elements											
K/Rb	288	306	306	271	238	236	197	207	216	190	168
K/Cs		7587	5148	5614	13053	8385	8809	5459	10181	4769	
K/Th		3572	4678	12396	3933	2026	1845	1754	12726	2663	
K/U		22937	15593	22726	10256	11580	7752	6640	16075	1142	
Rb/Sr	0.08	0.07	0.03	0.06	0.25	0.20	0.16	0.69	0.29	0.38	1.85
Rb/Cs		25	17	21	55	35	44	26	47	25	
Ba/Rb	9.6	6.9	8.7	4.8	5.8	5.2	7.6	7.5	2.5	5.4	2.5
Sr/Ba	1.25	1.97	4.29	3.31	0.69	0.96	0.84	0.19	1.35	0.49	0.24
Th/U		8.4	3.3	1.8	2.6	5.7	4.2	3.8	1.3	4.3	
Zr/Hf		18	22	57	18	73	38	50	36	21	
Rare earth elements											
La	15	13	17	9.9	52	52	128	42	6.2	65	
Ce	330	25	15	22	98	58	270	80	16	160	
Pr		2.5	1.4	2.1	11	12	27	9.8	1.4	16	
Nd	101	7.4	5.5	6.3	34	36	87	27	4.1	49	
Sm	2.7	1.3	1.3	1.0	6.4	6.7	14	5.2	1.0	8.1	
Eu	0.8	0.54	0.51	0.48	1.7	1.6	3.9	0.81	0.33	1.6	
Gd		1.2	1.2	0.67	4.4	4.5	9.9	4.7	0.89	4.4	
Tb	0.41	0.16	0.16	0.08	0.54	0.52	1.2	0.69	0.17	0.56	
y		0.77	0.77	0.49	2.9	2.9	5.7	3.8	0.90	2.8	
Ho		0.15	0.15	0.12	0.49	0.59	0.94	1.1	0.19	0.64	
r		0.39	0.38	0.24	1.2	1.4	2.0	3.1	0.58	1.3	
Yb	1.2	0.28	0.25	0.24	0.98	1.1	0.95	3.2	0.65	0.80	
REE	151.11	53	34	44	214	187	553	181	32	310	
Y		5.1	4.0	5.2	18	22	32	26	6.7	16	
Ce_N/Yb_N		21.4	12.8	20.0	26.7	14.9	54.5	6.3	7.1	37.0	
LREE/ HREE		17	10	22	17	16	22	9.9	8.5	28	
La/Yb		46	28	41	57	47	135	13	9.5	8.81	
d/Yb		4.3	4.8	2.8	6	4.1	14	1.5	1.4	5.5	
Eu/Eu*		1.43	1.35	1.85	0.94	0.92	0.95	0.54	1.15	0.81	

Table 3: Enrichment in Ce, Yb, K, Rb, Ba, and Sr upon partial melting of eclogite and amphibolite, and resulting Ce_N/Yb_N (N - chondrite normalized) ratios assuming Theespruit dolerite composition and oceanic tholeiite composition*. Partition coefficients are from Schnetzler and Phillipots (1970) and Phillipots and Schnetzler (1970). The calculations are described in the appendix.

Table 3 p. 1

Percent partial melting	Ce enrichment	Yb enrichment	Ce_N/Yb_N (Theespruit dolerite)	Ce_N/Yb_N (oceanic tholeiite)	Rb	K	Ba	Sr
					enrichment			
(1) Eclogite**								
1%	3.36	0.039	43	86	37.8	35.9	28.7	10.3
2%	3.28	0.039	41	83	27.5	26.5	22.4	9.5
5%	3.07	0.041	38	76	17.9	17.5	13.5	7.5
10%	2.77	0.043	32	64	8.7	8.6	8.2	5.6
20%	2.31	0.048	34	48	4.7	4.7	4.5	3.7
30%	1.99	0.054	18	36	3.2	3.2	3.1	2.8
40%	1.74	0.062	14	28	2.4	2.4	2.4	2.2
(2) Amphibolite***								
1%	11.2	4.4	1.27	2.54	7.24	2.06	3.25	0.56
5%	7.9	3.8	1.04	2.08	5.78	1.97	2.98	0.57
10%	5.8	3.3	0.87	1.75	4.61	1.88	2.70	0.58
20%	3.8	2.6	0.73	1.46	3.28	1.71	2.27	0.61
30%	2.8	2.2	0.63	1.27	2.53	1.57	1.96	0.64

---

* Theespreuit dolerite: Ce_N=10; Yb_N=10. Oceanic tholeiite: Ce_N=5; Yb_N=10

** Assuming a 1:1 ratio between melted garnet and melted clinopyroxene.

*** Assuming a 1:3 ratio between melted amphibole and melted plagioclase.

Table 4: Comparisons between average greywacke of the Fig Tree Group (Condie et al., 1970) and possible source compositions.

Table 4 p. 1

	Theespruit metadolerite	Average of 3 Nelshoogte tonalites	Average Sheba formation greywacke	Average Belvue Rd. formation greywacke
SiO_2	50.4	69.1	66.2	58.5
TiO_2	0.5	0.28	0.52	0.55
Al_2O_3	15.20	15.5	10.02	12.9
FeO (total)	10.0	2.01	7.01	6.56
MgO	7.21	1.11	4.50	4.44
CaO	8.13	3.13	1.97	3.18
Na_2O	3.88	5.16	1.80	2.83
K_2O	0.07	1.10	1.58	2.23
FeO/FeO + MgO	0.59	0.64	0.61	0.60
Ni	129	15	290	160
Rb	1.1	31.3	54	90
Ba	18	202	319	826
Sr	106.5	587	98	354
Zr	53	76.6	134	184
La	3.3	10	20	26
Ce	8.3	20	46	55
Nd	5	6.4	18	22
Sm	1.7	1.2	3.2	4.1
Eu	0.7	0.52	0.81	1.04
Gd	2.1	1.02	3.1	3.7
Tb	0.43	0.13	0.45	0.52
Dy	2.9	0.67	2.9	3.0
Ho	0.67	0.14	0.60	0.62
Er	2.0	0.34	1.85	1.58
Yb	2.0	0.26	1.63	1.60
REE	30	43	98	119
Rb/Sr	0.01	0.05	0.64	0.27
K/Rb	528	294	216	204
Sr/Ba	5.9	3.19	0.33	0.56

Figure captions

Fig. 1 - (a) Geological sketch map of the Barberton Mountain Land (after Anhaeusser et al., 1969; Anhaeusser, 1973), showing location of granite samples studied. (b) Sample locality map for volcanic rocks studied. Location of the area is marked by the black rectangle in Fig. 1(a).

Fig. 2 - An-Ab-Or data plots. Open circles - sericite schists; solid circles - quartz keratophyres; crosses - ancient tonalites; oblique crosses - Dalmein pluton; quartered circle - Bosmanskop pluton; circled oblique cross - Nelspruit migmatite; half-solid circles - Hood granite. The petrochemical classification is after O'Connor (1965).

Fig. 3 - Q-Ab-Or data plots. Symbols as for Fig. 2.

Fig. 4 - Enrichment and depletion relations in average and individual Archaean acid igneous rocks relative to the Theespruit dolerite composition (see Table 2). SS - sericite schists; QK - quartz keratophyres; KT - Kaap Valley tonalite; AT - ancient tonalites (Nelshoogte and Theespruit plutons); DT - Dalmein trondhjemite; BG - Bosmanskop granite; NM - Nelspruit migmatite; HG - Hood granite; LG - Lochiel granite.

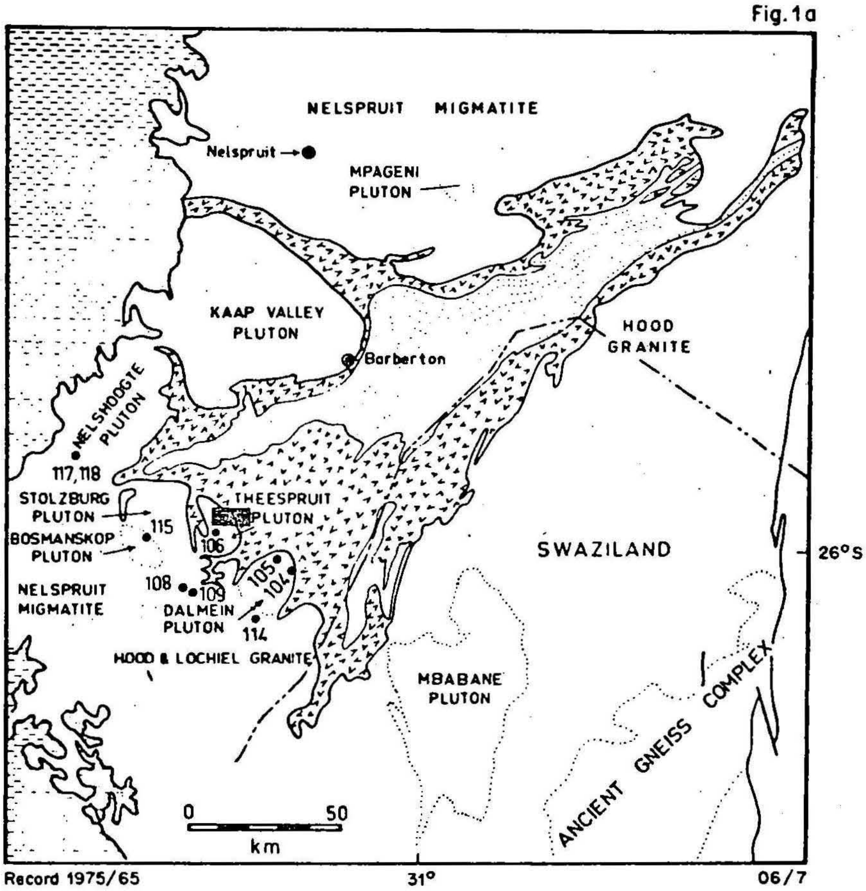
Fig. 5 - Relations between FeO+MgO and FeO/(FeO+MgO) (total iron as FeO) in acid igneous rocks of the Barberton Mountain Land area (data from this paper and from Viljoen and Viljoen, 1969 a,c,e). Solid circles- quartz keratophyres; crosses - hornblende tonalites (Kaap Valley pluton); biotite tonalites (including Nelshoogte pluton) - circled crosses; oblique crosses - Dalmein pluton; quartered circle - Bosmanskop pluton; circled oblique crosses - Nelspruit migmatite; semi-solid circles - Hood granite.

Fig. 6 - Ni-Mg and Cr-Mg relations in the analyzed samples, compared with variation curves for calcalkaline suites of high Ni/Mg and Cr/Mg ratios from Crater Lake (curve 1) and the Scottish Highlands (curve 2) (Nockolds and Allen, 1953).

Fig. 7 - Relations between ferromagnesian trace elements, FeO and MgO in the analyzed samples

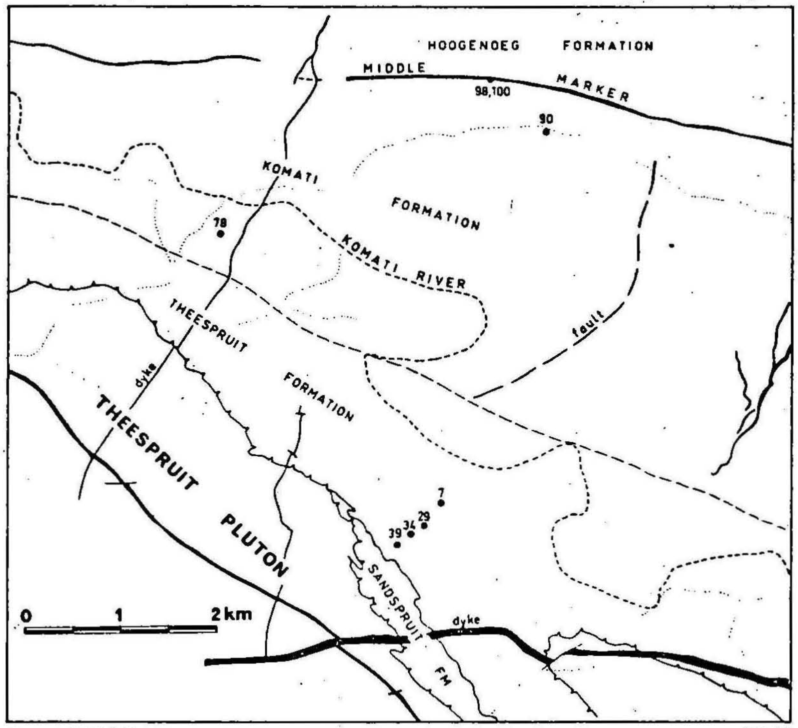
Fig. 8 - Chondrite-normalized rare earth element data for acid igneous rocks of the Barberton Mountain Land area.

Fig. 1a



Record 1975/65 06/7

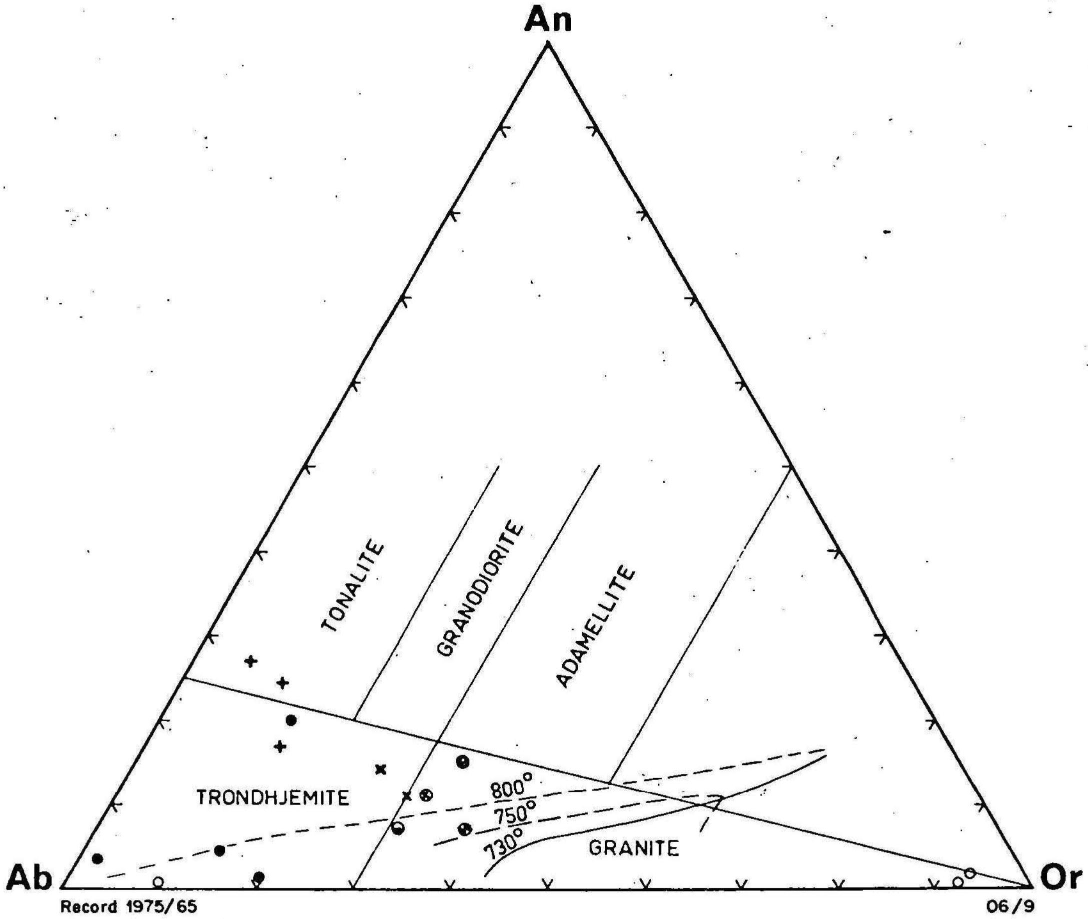
Fig. 1b



Record 1975/65

06/8

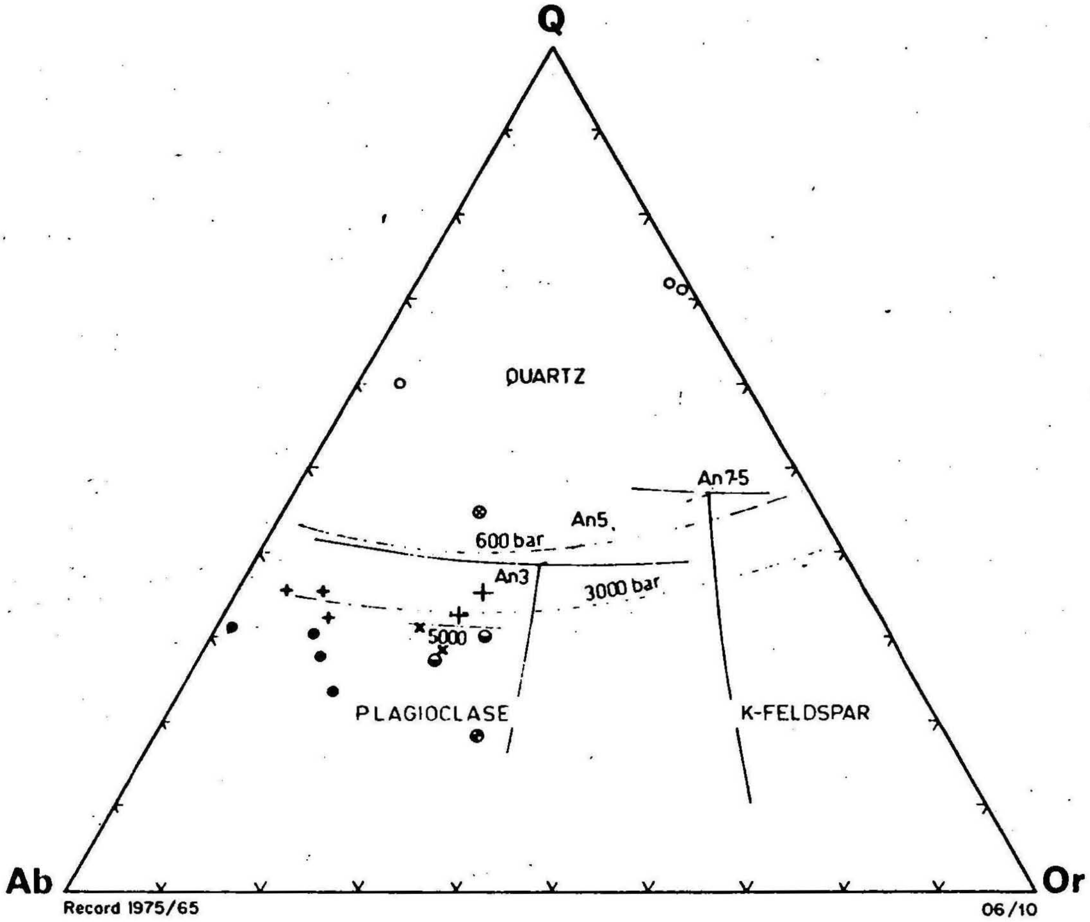
Fig. 2



Record 1975/65

06/9

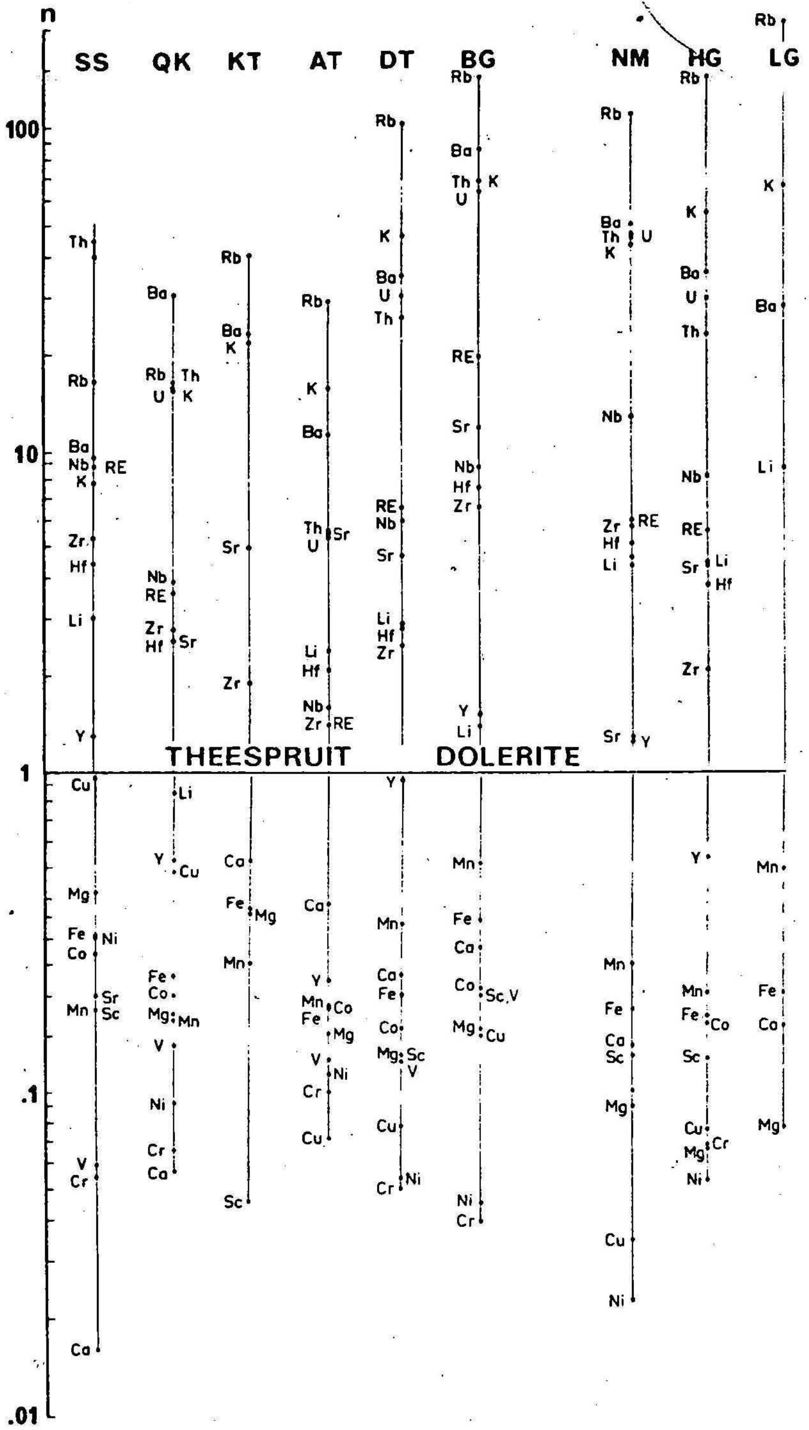
Fig. 3



Record 1975/65

06/10

Fig. 4


n
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10
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.1
.01
SS
QK
KT
AT
DT
BG
NM
HG
LG
THEESPRUIT
DOLERITE
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QK: Ba, Rb, Th, U, K, Nb, RE, Zr, Hf, Sr, Li, Y, Cu, Fe, Co, Mg, Mn, V, Ni, Cr, Ca
KT: Rb, Ba, K, Sr, Zr, Ca, Fe, Mg, Mn, Sc
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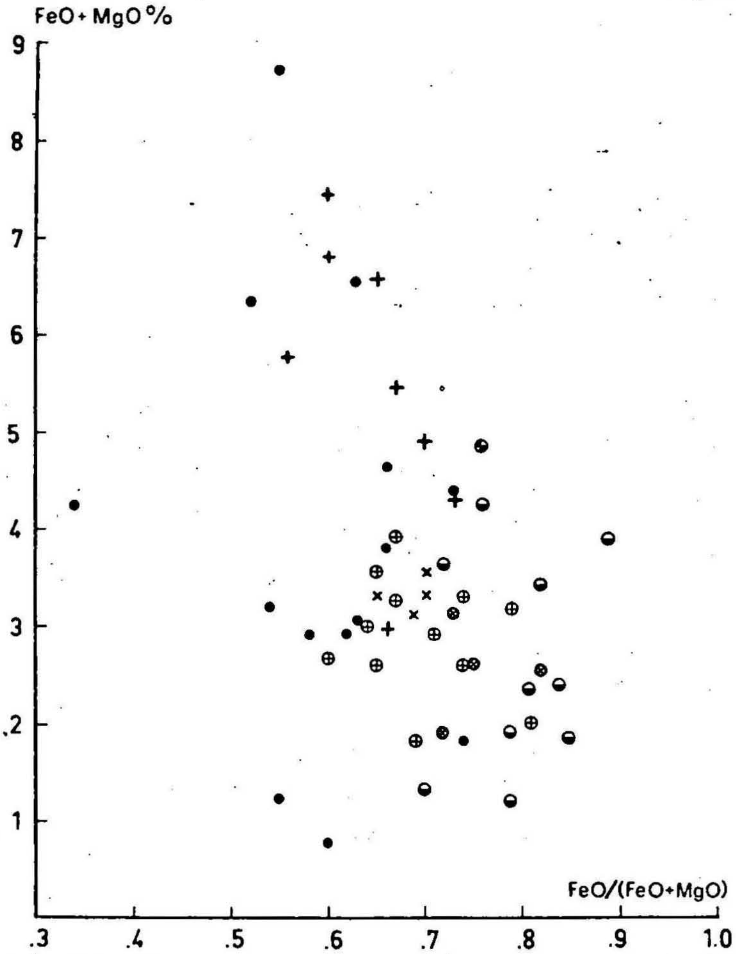
DT: Rb, K, Ba, U, Th, RE, Nb, Sr, Li, Hf, Zr, Y, Mn, Ca, Fe, Co, Mg, Sc, V, Cu, Cr, Ni
BG: Rb, Ba, Th, K, U, RE, Sr, Nb, Hf, Zr, Y, Li, Mn, Fe, Ca, Co, Sc,V, Mg, Cu, Ni, Cr
NM: Rb, Ba, Th, U, K, Nb, Zr, RE, Hf, Li, Sr, Y, Mn, Fe, Ca, Sc, Mg, Cu, Ni
HG: Rb, K, Ba, U, Th, Nb, RE, Sr, Li, Hf, Zr, Y, Mn, Fe, Co, Sc, Cu, Cr, Mg, Ni
LG: Rb, K, Ba, Li, Mn, Fe, Ca, Mg

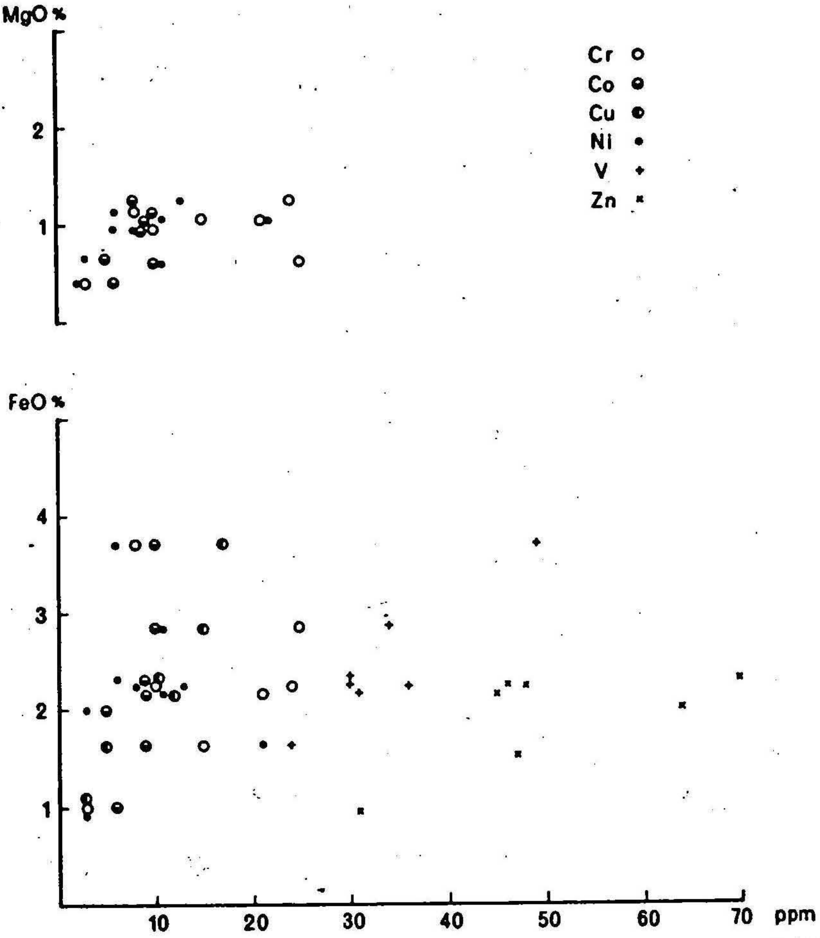
Fig. 5



Record 1975/65

06/12

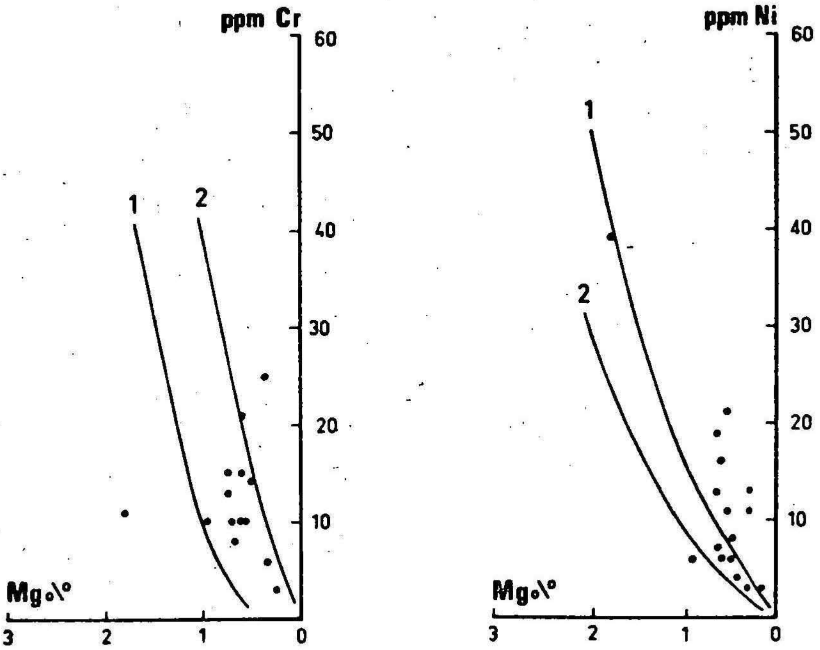
Fig. 6



Record 1975/65

06/13

Fig. 7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50
40
30
20
10
1
2
MgO%
3
2
1
0
ppm Ni
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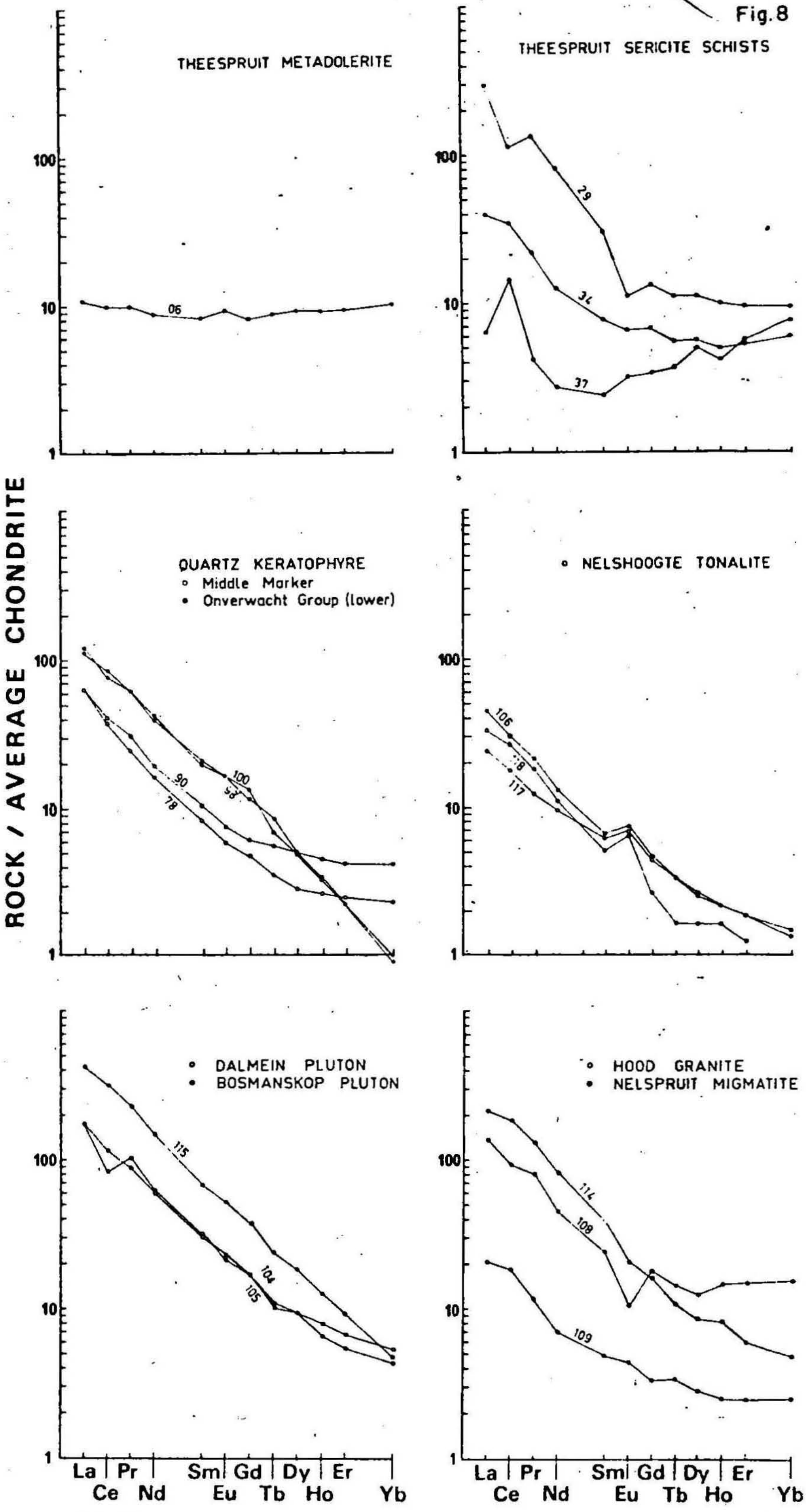
30
20
10
1
2
MgO%
3
2
1
0

Fig. 8


ROCK / AVERAGE CHONDRITE
THEESPRUIT METADOLERITE
06
THEESPRUIT SERICITE SCHISTS
29
34
37
QUARTZ KERATOPHYRE
○ Middle Marker
● Onverwacht Group (lower)
100
98
90
78
○ NELSHOOGTE TONALITE
106
8
117
○ DALMEIN PLUTON
● BOSMANSKOP PLUTON
115
104
105
○ HOOD GRANITE
● NELSPRUIT MIGMATITE
114
108
109
1
10
100
La
Ce
Pr
Nd
Sm
Eu
Gd
Tb
Dy
Ho
Er
Yb