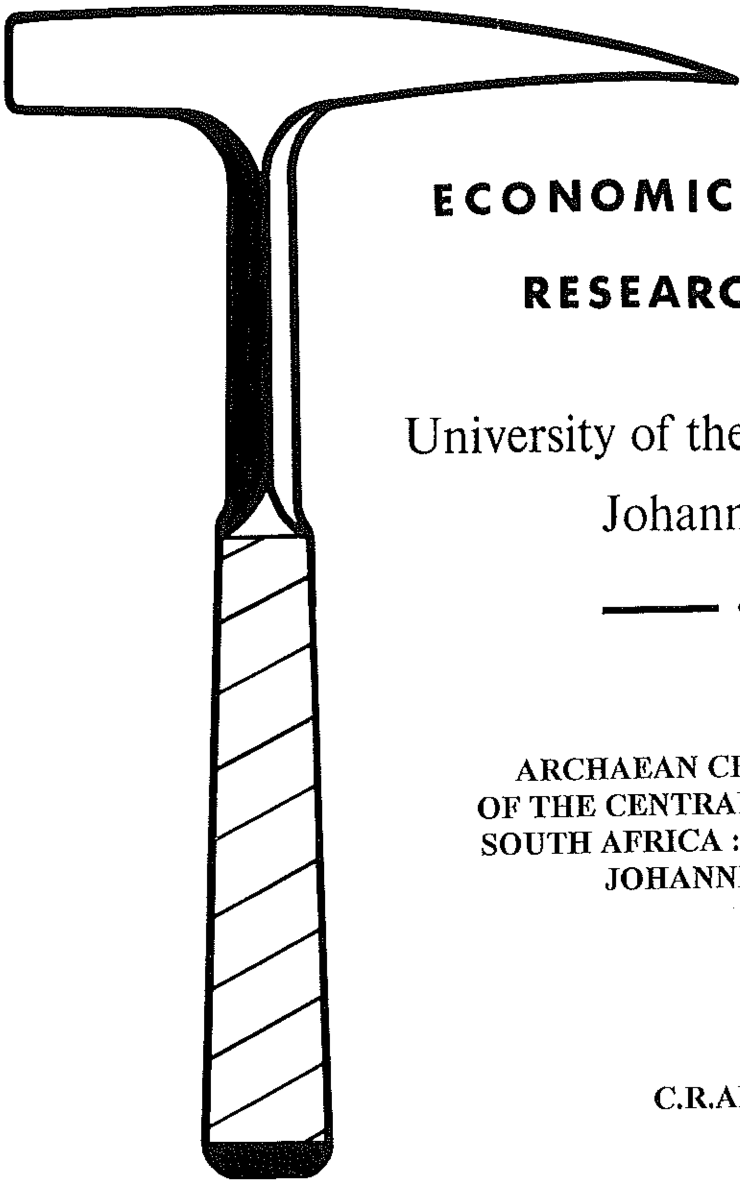

ECONOMIC GEOLOGY

RESEARCH UNIT

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ARCHAEAN CRUSTAL EVOLUTION OF THE CENTRAL KAAPVAAL CRATON, SOUTH AFRICA : EVIDENCE FROM THE JOHANNESBURG DOME

C.R.ANHAEUSSER

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UNIVERSITY OF THE WITWATERSRAND
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by

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ABSTRACT

An exceptional river platform exposure on the farm Nooitgedacht, located on the northern half of the Johannesburg Dome, has been mapped and studied with the view to obtaining information that might assist in understanding the Archaean crustal evolution of the central Kaapvaal Craton. The investigation complements previous studies that provided a regional assessment of the geology of the Johannesburg Dome and which resulted in the recognition of several stages of granite-greenstone development. Successive events led to the emplacement of : (1) mafic and ultramafic volcanic rocks comprising komatiites, basaltic komatiites, high-magnesian basalts and tholeiites, as well as their plutonic equivalents consisting of serpentinized dunites, harzburgites, pyroxenites and gabbros; and (2) a suite of tonalite-trondhjemite-granodiorite (TTG) granitoid rocks that were intruded into the greenstones, thereby resulting in their fragmentation, metamorphism, assimilation and migmatization. The Nooitgedacht platform provides a glimpse of these latter processes that are believed to have ensued following the TTG emplacement.

Characterization of the exposure is achieved with the aid of a detailed outcrop map and carefully selected sampling of the various lithological components on display. Petrological analysis and major and trace element geochemical data, including rare earth element (REE) abundances obtained from a range of rock type that include early-stage amphibolitic greenstones, trondhjemitic-tonalitic-dioritic gneisses, and amphibolitic dykes, together with later-stage homogeneous trondhjemitic-granodioritic-pegmatitic granitoids, are employed to support the view that processes of metamorphism, assimilation and metasomatism have been variously responsible for generating the mixed assemblages seen in outcrop. The chondrite-normalized REE data suggests that the Nooitgedacht amphibolites, with their moderately flat to slightly depleted HREE patterns are similar to those reported elsewhere for Archaean and oceanic-island volcanic rocks. REE patterns for the range of dioritic-tonalitic granitoids are generally similar to those of the amphibolites and show moderate LREE enrichment and flattish to slight HREE depletion suggestive of some genetic link with the mafic rocks. Two mafic dyke varieties that post-date the trondhjemitic gneisses were identified on the basis of distinctive REE signatures and their outcropping structural disposition. The Nooitgedacht trondhjemitic granitoids consist of a low- and a high-Al_2O_3 variety and display steep REE patterns with strong LREE enrichment and moderate to strong HREE depletion, similar to granitoids described from Archaean terranes elsewhere in the world.

Plots of the Nooitgedacht geochemical data in various discrimination diagrams suggest that the Archaean events displayed on the Johannesburg Dome probably occurred in a tectono-magmatic setting analogous to that found in modern-day, plate-tectonic-related, volcanic-arc environments.

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ARCHAEAN CRUSTAL EVOLUTION OF THE CENTRAL KAAPVAAL CRATON, SOUTH AFRICA : EVIDENCE FROM THE JOHANNESBURG DOME

INTRODUCTION

The earliest reference to the Kaapvaal Craton as a geological entity on the African subcontinent appears to have been made by Pretorius (1965) who defined the craton as being "bounded on the east by the lineament now occupied by the Lebombo Volcanic Belt, on the south by the present Tugela Fault Zone, and on the west by the Doringberg Fault Zone. The northern limit," he wrote, "still remains to be determined - it might be the Limpopo Trough, or it might be some structural feature lying still further north in Rhodesia (Zimbabwe)." This somewhat prophetic recognition of a fundamental geological feature that is today unquestioningly referred to as the Kaapvaal Craton came about as a direct result of attempts to define the bounding lineaments to the gold-bearing formations in South Africa, none of which appear to be younger than 2000 million years.

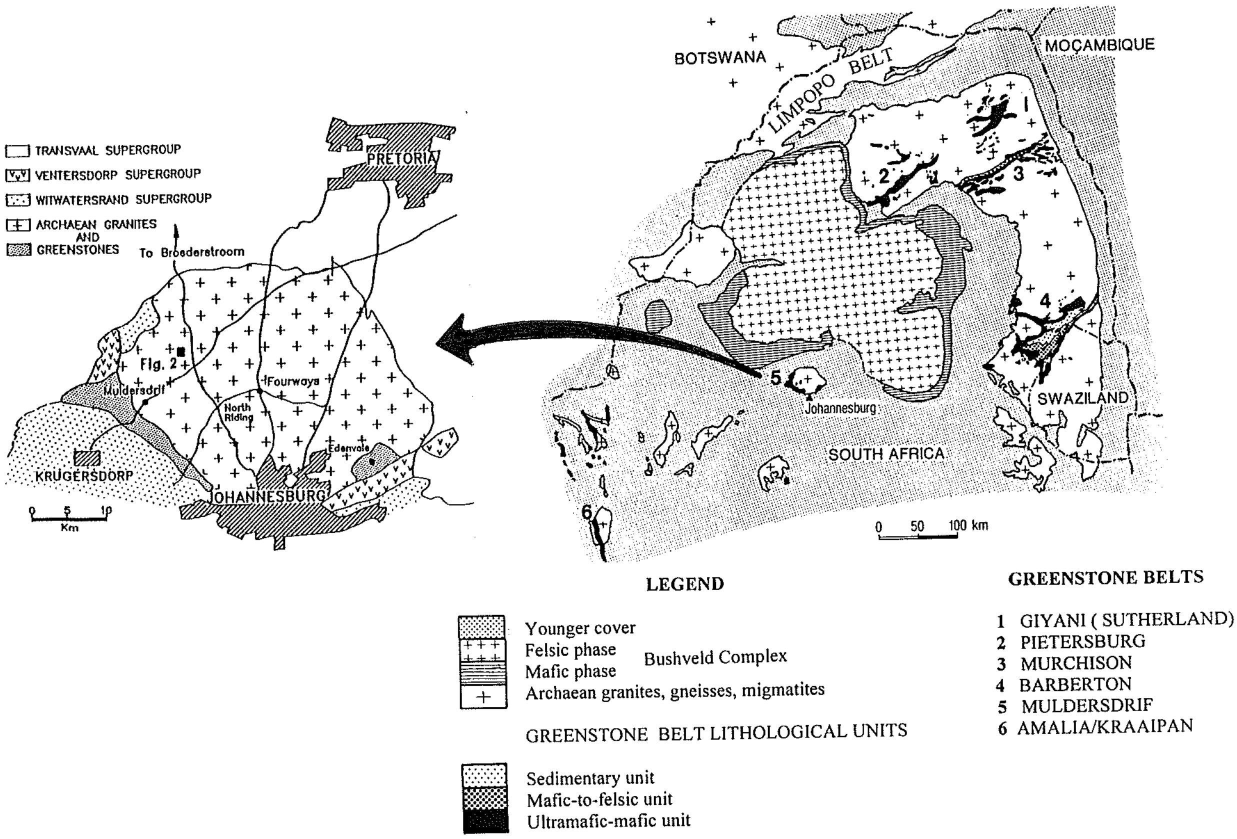


Figure 1: Map showing the main exposures of Archaean basement rocks on the Kaapvaal Craton and the locality of the study area on the Johannesburg Dome (inset map).

The recognition of the Kaapvaal Craton, which formed and stabilized between 3.7 and 2.7 Gyr ago, as one of the oldest microcontinental fragments on Earth, has resulted from protracted studies aimed at deciphering the evolution of the continental crust of southern Africa. Advances made in a number of localities where Archaean granite-greenstone basement rocks are exposed on the Kaapvaal Craton (Fig.1) have led to the suggestion that Archaean cratonic development may have closely followed modern-day plate tectonic processes presently operating on Earth (De Wit et al., 1992). These authors drew attention to the definition of a craton as being that portion of a continent which has attained stability and which has been little deformed for a prolonged period. By contrast, the inner portion of a craton is referred to as a shield. The shields themselves are defined as being initially unstable and subjected to extensive deformation and internal chemical differentiation before cratonic rigidity is attained. The Kaapvaal Craton, they maintained, owed its origin to an initial period of continental lithospheric growth and development from the mantle, followed by a period of continental growth involving processes of collisional tectonic accretion of crustal fragments and subduction-related igneous activity. De Wit et al. (1992) envisaged the shield-forming stage to have occupied the time span ~3.7 to 3.1 Gyr ago, followed by a stage of cratonic assembly and stabilization extending from 3.1 to 2.6 Gyr ago. This latter stage was seen as having been responsible for the welding together of a mosaic of continental fragments or subdomains that collectively constitute the present-day Kaapvaal Craton.

Support for the idea of separate crustal fragments, each with their own evolutionary histories, stems from recent isotopic age data that has emerged from different sectors of the craton. These data constrain the interpretations that have been placed on the development of Archaean greenstones and granitoids found in the respective areas shown in Figure 1. The available isotopic data for areas such as the Barberton, Murchison and Kraaipan granite-greenstone terranes (Kamo, 1992; Kamo and Davis, 1994; Kohler, 1994; Lowe, 1994; Kröner et al., 1996; Poujol et al., 1996; Anhaeusser and Walraven, 1997) suggests that different sectors or domains on the craton represent a complex of diachronous tectono-stratigraphic blocks that formed during multiple periods of extension and magmatic and tectonic accretion.

The Johannesburg Dome, representing a basement inlier approximately 700km^2 in areal extent, and located in the central part of the Kaapvaal Craton (Fig.1), provides additional scope for testing the accretionary hypothesis. This dome, together with a few poorly exposed areas of granitic basement to the south (Vredefort Dome; Reimold, 1993) and southwest (Rand Anticline; Robb and Meyer, 1987) provide the only exposures available for study apart from scattered boreholes drilled by mining companies in their search for extensions to the gold-bearing formations of the Witwatersrand Basin.

Some of the earliest investigations on the Johannesburg Dome were undertaken between 1906 and 1933 (references in Anhaeusser,1973b), but no attempt was made during this period to provide a map of the granitic terrane or the contained Archaean greenstone remnants. The first comprehensive geological map of the Johannesburg Dome was prepared by Anhaeusser (1971,1973b) and the results of some of this mapping were subsequently incorporated into the 1:50 000 Geological Series maps (2527 DD Broederstroom and 2528 CC Lyttelton) of the Geological Survey of South Africa in 1973. Later, detailed geological maps and descriptions were provided of a number of areas underlain by greenstone remnants comprising metamorphosed mafic and ultramafic plutonic and volcanic rocks with komatiite affinities in the Roodekrans, Muldersdrif and Zandspruit areas on the western half of the dome (Anhaeusser, 1977,1978,1992).

Anhaeusser (1971,1973b) identified a number of granitoid varieties, each displaying distinctive field characteristics and possessing significantly variable geochemical, mineralogical and textural properties. A chronology of granitoid emplacement was established solely on the basis of field relationships, the only other clues to the age of the granite dome being the 3200±65 Ma Rb-Sr whole rock isochron age of granodiorite reported by Allsopp (1961). This age was subsequently revised to 3132±64 Ma (2σ) (age data recalculated for a decay constant for ^{87}Rb of $1.42\times10^{-11}a^{-1}$, with an initial $^{87}Sr/^{86}Sr$ ratio of 0.706±0.003 (2σ), Allsopp (1964).

The oldest rocks exposed on the Johannesburg Dome were considered by Anhaeusser (1971,1973b) to be the metamorphosed greenstones (mainly serpentinised dunites, harzburgites, pyroxenites, metagabbros, amphibolites and talc-chlorite schists). These were intruded by an older succession of granitoids, including hornblende-biotite tonalitic gneisses developed mainly on the southern margin of the dome and by leuco-biotite trondhjemitic gneisses and accompanying migmatites occupying most of the northern half of the dome. A younger succession of granitoids, consisting essentially of homogeneous and, in places, porphyritic, medium-to-fine-grained granodiorites and adamellites, occupies much of the southern half of the dome.

Anhaeusser and Burger (1982) attempted to date the various granitic events on the Johannesburg Dome, but were only successful with the tonalitic gneisses found along the southern margin where an U-Pb multiple zircon age of 3170±34 Ma was obtained. The remaining granitoids yielded insufficient zircon concentrates for the dating technique employed at the time and hence no reliable ages could be determined. Currently, a geochronological study using the U-Pb single zircon abrasion method is being undertaken in an attempt to date the main granitoid events (Poujol and Anhaeusser, in prep.).

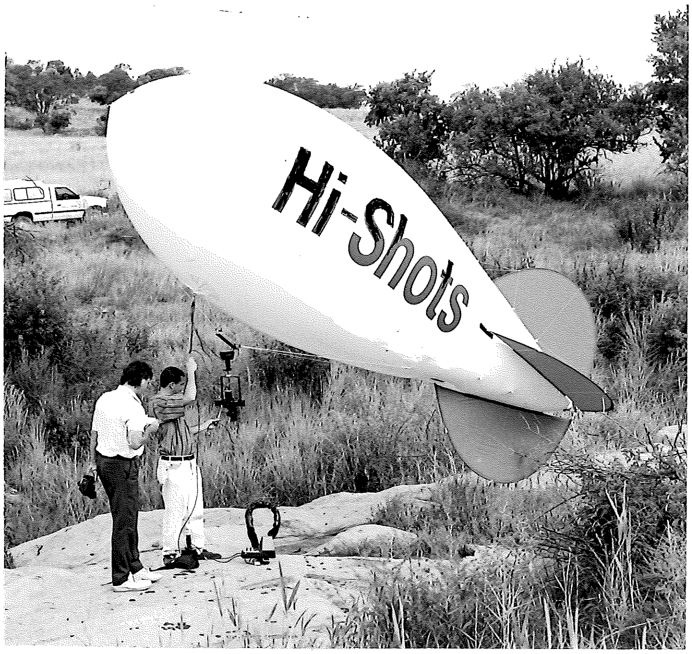


Figure 2: Photograph of the "Hi-Shots" 6m-long helium-filled blimp used in this study to photograph the Nooitgedacht migmatite platform from the air. The self-levelling carriage system suitable for suspending 35mm or other camera attachments, including a video camera, hangs beneath the blimp. The harness and remote control panel used by the operator is on the ground below the blimp.

The aim of the present study is to describe a single outcrop located on the farm Nooitgedacht 534 JQ, situated northwest of Johannesburg and approximately 10km northeast of Muldersdrif (see inset map, Fig.1). The exposure, consisting of a river platform displays a complex history of granite-greenstone evolution, and provides an overview of features seen regionally on the Johannesburg Dome. Because of outcrop complexity and the need to produce a very detailed map, a novel technique of mapping, developed in Canada, was employed (courtesy of Hi-Shots cc) using a 6m helium-filled blimp possessing a self-levelling carriage system suitable for suspending various cameras, including a video camera (Fig.2). A ground monitor, control

Figure 3: Aerial view of the Nooitgedacht migmatite platform seen from the camera of the "Hi-Shots" blimp as it hovers 50m above the outcrop. The operator and the author can be seen standing on the western side of the outcrop (arrow). Scale of photograph : 12mm = 4.66m on the ground.

panel and tether line enables the operator, by remote control, to see the image to be photographed through the camera lens. Photographs of the outcrop were taken from a height of 50m, enlarged, and used in the field to record the finest detail necessary for the purpose of the study. A photograph taken from the blimp and showing the full extent of the Nooitgedacht river platform, which measures 45×21m, is shown in Figure 3.

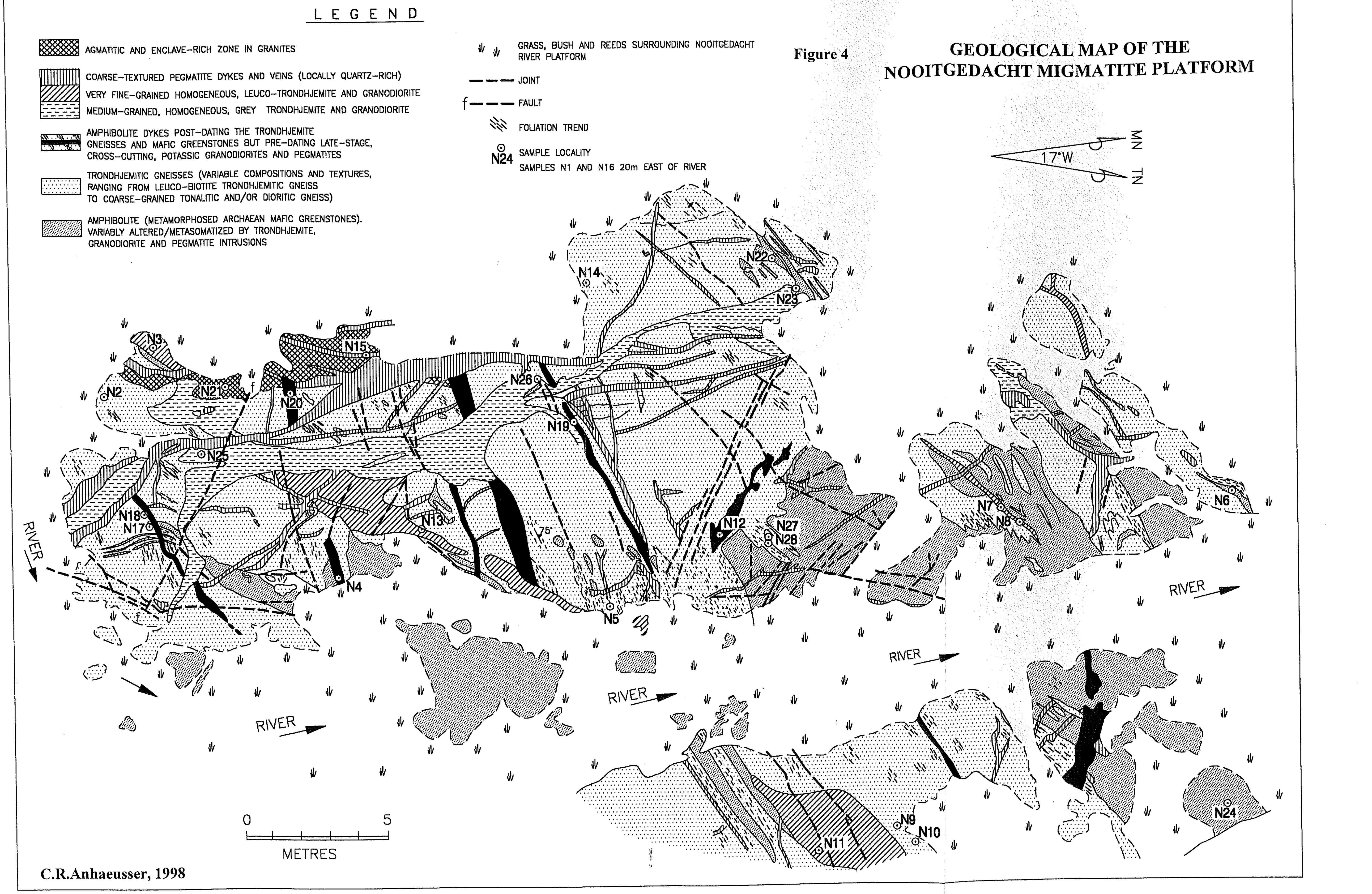
GEOLOGY OF THE NOOITGEDACHT RIVER PLATFORM

The Nooitgedacht river platform is located in the northwestern quadrant of the Johannesburg Dome, which is mainly underlain by scattered greenstone remnants intruded by grey, leuco-biotite trondhjemitic gneisses. These gneisses have, in places, reacted with the greenstones (mainly amphibolites) producing a variety of migmatite-gneiss exposures. On the farm Nooitgedacht 534 JQ several hectares of hornblende amphibolite crops out east and west of the northward-flowing river in which the migmatite-gneiss platform described in this paper is exposed. A major, north-south-trending, white, vein-quartz-filled shear zone occurs approximately 200m east of the river exposure, but has not structurally influenced the platform rocks.

Detailed mapping of the Nooitgedacht platform (Fig.4) has revealed complex interrelationships between the amphibolites and the various granitoids. The amphibolites are mainly developed on the eastern side of the platform close to the river channel. Scattered amphibolite xenoliths. occur elsewhere on the western half of the outcrop, occurring mainly as mafic slivers and altered remnants intruded by trondhjemite gneisses and granitoid veinlets. Amphibolite boudins, banded gneissic zones and agmatites are also present (Fig. 5A-G). Inclusions of amphibolite, diorite and tonalite occur in trondhjemite in the southwestern part of the exposure (Fig.4 - sample locality N21, and Fig 5H).

Figure 4

GEOLOGICAL MAP OF THE NOOITGEDACHT MIGMATITE PLATFORM



C.R.Anhaeusser, 1998

The amphibolites east of the river platform (samples N1 and N16) occur as massive, black outcrops with sporadic intrusive granitic veins. Thin sections reveal that the amphibolites are made up almost entirely of hornblende, actinolite, and minor epidote, with some epidote veins derived from saussuritized plagioclase feldspar. Large poikilitic amphibole crystals occur as overgrowths enclosing an earlier generation of amphibole. Some amphibole has been altered to biotite and chlorite and relic crystals of clinopyroxene (diopsidic augite) can still be discerned in places. Accessory minerals include magnetite, apatite, sphene, quartz and sericite. Some of the amphibolites have a schistose texture and others have actinolite as the principal amphibole (e.g. sample N8), with lesser amounts of hornblende, plagioclase (altered to sericite and epidote), quartz, sphene, magnetite, biotite, chlorite and apatite.

Trondhjemitic, tonalitic and dioritic gneisses are manifest over much of the platform and represent the earliest granitoids emplaced into the amphibolites. The trondhjemites consist mainly of plagioclase, quartz and biotite, with accessory amounts of zircon, rutile, apatite and muscovite. The plagioclase (albite) is variably altered to epidote and sericite and some of the biotite has been altered to chlorite. The tonalites and diorites have variable amounts of quartz and hornblende together with lesser amounts of biotite and chlorite. The plagioclase (albite) also shows alteration to epidote and sericite and accessory minerals include sphene, magnetite, apatite, zircon and rutile, the latter mineral occurring as needle-like inclusions in the biotite.

The trondhjemitic gneisses predominate, with field relationships suggesting that the tonalites and diorites might represent the hybridized or assimilated products of amphibolites that were intruded by the trondhjemitic magma. Most of the tonalitic and dioritic rocks occur close to or in direct contact with the amphibolites and also occur in places as interlayered or banded gneisses (Fig. 6A-G). Away from the mafic rocks the trondhjemites are even-textured, medium-to-coarse-grained foliated gneisses with occasional leuco-trondhjemitic dykes and veinlets (Fig.7A). Metasomatic replacement of amphibolite to diorite or tonalite can be seen in Figure 7B, which shows thin veins of trondhjemitic material diffusely permeating the amphibolite, causing alteration in and adjacent to the veins.

Two sets of mafic dykes appear to have intruded the trondhjemitic gneisses and the amphibolites prior to a late intrusive granitoid event. One set of mafic dykes strikes 60-90° and the second set 110-130° (Fig.4). The dykes have been metamorphosed to amphibolite grade with hornblende and biotite being responsible for the planar fabric seen in the rocks. Plagioclase, saussuritized and sericitized to epidote and sericite, occurs in the matrix together with minor amounts of magnetite, quartz, apatite and chlorite. Sphene is a particular prominent accessory mineral in all the dykes examined.

The mafic dykes crosscut the foliation seen in the trondhjemitic gneisses as well as in some of the greenstone xenoliths and were, themselves, intruded by later, approximately north-south-trending granitic and pegmatitic dykes and veins (Fig.7C-F). Three textural varieties of this granitoid material have been distinguished (Fig.4), but all three are considered to be approximately coeval and are probably genetically linked to the potassic granodiorites which form a batholith on the southern half of the Johannesburg Dome (Anhaeusser, 1973b).

Of the three late-phase granitoid varieties the very fine-grained, white-to-buff coloured, homogeneous, leuco-trondhjemitic-to-granodioritic dykes trending ~45° across the southern part of the outcrop appear to be the earliest (Fig.4 - sample localities N3, N13, N11). These rocks contain quartz, albitic plagioclase, the latter variably altered to sericite and epidote, and minor biotite and muscovite. Microcline is also present, but unlike the plagioclase does not

Figure 5:

A. *Leuco-biotite trondhjemite gneiss with xenolithic inclusions of amphibolite, and later cross-cutting veins of pegmatite and aplite. In places, close to the xenoliths, the trondhjemites have assimilated parts of the amphibolite resulting in the local development of hornblende-biotite tonalites or diorites.*

B. *Hornblende/actinolite amphibolite bands intruded by lenses of foliated, hornblede-biotite trondhjemitic gneiss and cross-cut by later leuco-trondhjemite dykes and veinlets.*

C. *Partially altered amphibolite lenses intruded by melanocratic hornblende-biotite tonalite or diorite, and cross-cut by leuco-trondhjemite veinlets.*

D. *Amphibolite xenolith surrounded by melanocratic hornblende-biotite tonalite or diorite. Later leuco-trondhjemitic dykes and veins intrude both rock types.*

E. *Massive and dyke-like leuco-biotite trondhjemitic gneiss intruded into amphibolites and associated melanocratic hornblende/actinoliute diorites.*

F. *Homogeneous, medium-textured diorite (feldspathized amphibolite) separated by a lens of foliated hornblende-biotite tonalite (beneath the pen) and intruded by veins of leuco-trondhjemite associated with the trondhjemite gneiss on the left of the photograph.*

G. *Ptygmatic veins of leuco-trondhjemite cross-cutting feldspathized amphibolite (beneath the pen) which is, in turn, enveloped by hornblende tonalite/diorite, the latter also intruded by veins of trondhjemite. Trondhjemite gneiss and pegmatite occurs flanking the melanocratic rocks.*

Fig. 5

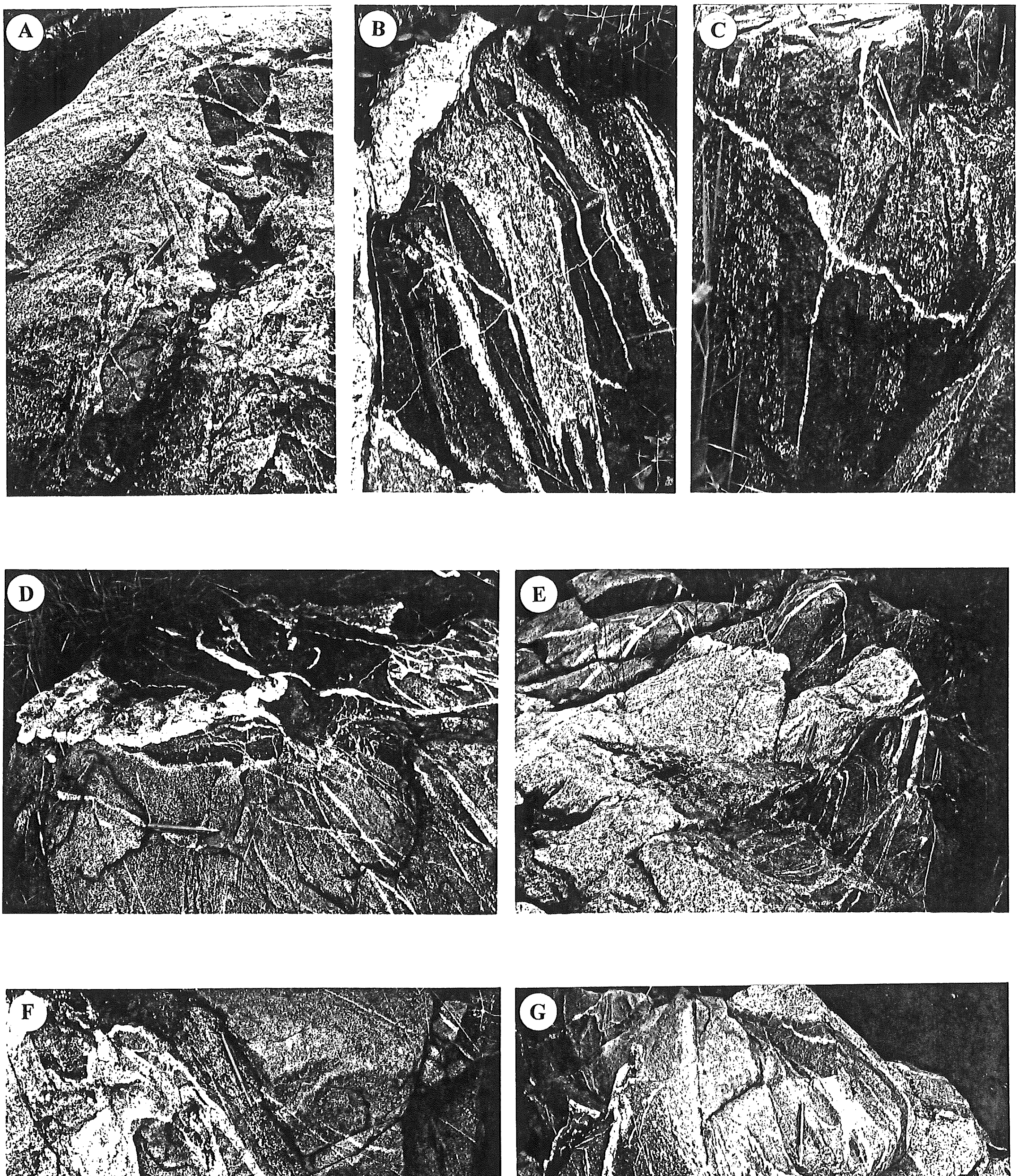


Figure 6:

A. *Hornblende amphibolite (right, sample N8 in Fig.4 and Table 1) associated with foliated hornblende-biotite tonalite (lower left; centre - below pen and to the right). Also present is a boudinaged leuco-trondhjemite gneiss lens (left of pen, sample N7 in Fig.4 and Table 1), as well as a cross-cutting vein of leuco-trondhjemite/granodiorite (beneath pen).*

B. *Amphibolite xenolith (left) enveloped by pegmatitic and tonalitic granitoids occurring adjacent to tonalitic/dioritic gneiss (centre, below pen). More dark feldspathized amphibolite occurs on the right of the photograph. Veins and patches of pegmatite and trondhjemite cross-cut the layering and also occur subparallel to the foliation in the amphibolites and the tonalite/diorite.*

C. *Domical section of the Nooitgedacht platform showing mainly foliated leuco-biotite trondhjemite gneiss (upper part of photograph) and coarse-textured hornblende-tonalite gneiss (lower centre, below hammer). Some xenolithic remnants of amphibolite occur within the tonalites (see also Fig. 5A), the latter having developed as a result of partial assimilation of the amphibolites by the trondhjemite.*

D. *Amphibolite and diorite (sample N22, Fig.4 and Table 1) inclusions in hornblende-biotite tonalite gneiss. Cross-cutting and ptygmatic veins of leuco-trondhjemite intrude all rock types seen in the exposure.*

E. *Boudinaged hornblende-amphibolite remnants enveloped in hornblende-biotite tonalite.*

F. *Leuco-trondhjemite gneiss and associated dykes and veinlets intruding altered (feldspathized) amphibolite/diorite.*

G. *Agmatitic remnants of hornblende amphibolite in a matrix of leuco-trondhjemite (southern part of Nooitgedacht platform near sample N21, Fig.4).*

H. *Variably altered (feldspathized) agmatitic remnants of amphibolite in a host matrix consisting mainly of biotite-trondhjemite gneiss. One of the remnants (sample N21, below pen) shows rounded edges and consists of hornblende-tonalite gneiss (Table 1).*

Fig. 6

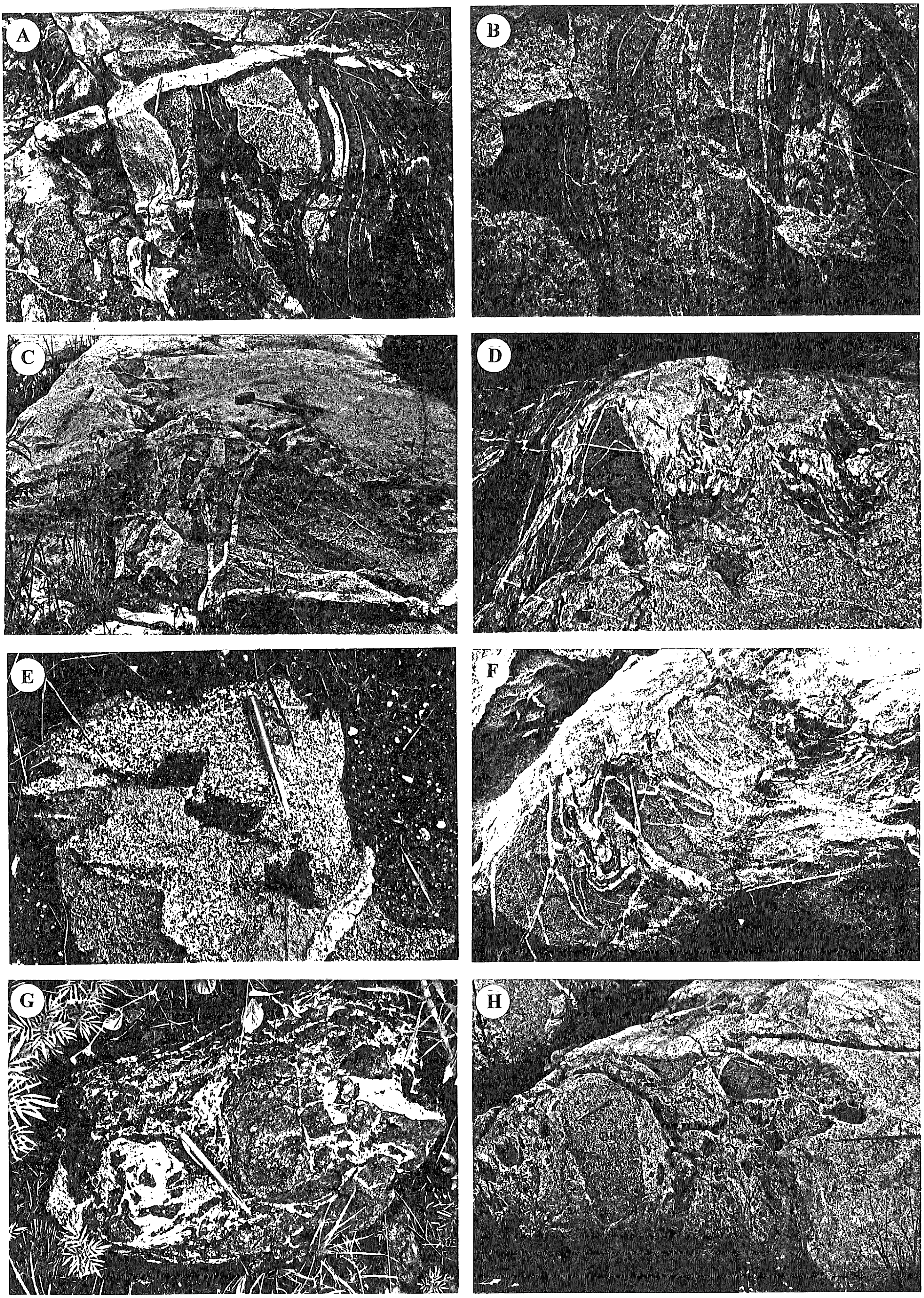


Figure 7:

A. *Foliated leuco-biotite trondhjemite gneiss typical of the earliest granitoid phase developed on the Nooitgedacht platform. Several later stages of leuco-trondjhemite dyke emplacement and veining can be seen in the outcrop between sample sites N12 and N19 (see Fig.4).*

B. *Altered (feldspathized) amphibolite in the vicinity of sample locality N24 (northeastern sector of the outcrop area – Fig.4). Fluids emanating from the leuco-trondhjemite veins cutting through the amphibolite appear to have introduced the metasomatizing elements responsible for transforming parts of the rock into diorite or tonalite.*

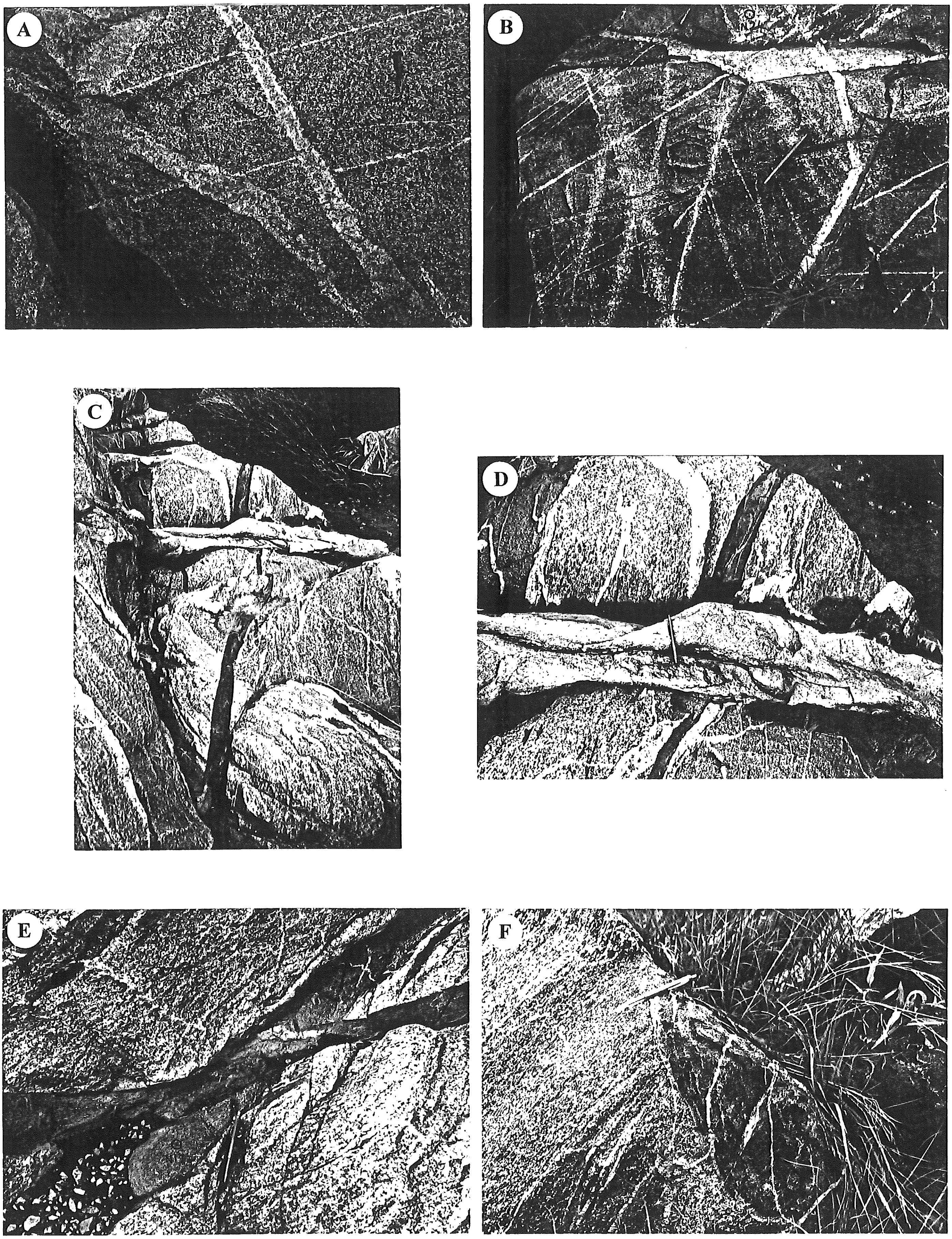
C. *Outcrop on the southern edge of the Nooitgedacht platform, near sample sites N17 and N18 (Fig.4), displaying a number of stages in the development of the Archaean basement on the northern half of the Johannesburg Dome. The earliest event seen comprises xenolithic amphibolite extending from the top left to the bottom centre of the photograph. The amphibolite, which has an aligned mineral fabric, is intruded and surrounded by foliated leuco-biotite trondhjemite gneiss displaying conformable and cross-cutting dykes and veins of leuco-trondhjemite. This was followed by the intrusion of a mafic (amphibolite) dyke seen extending down the centre of the photograph and cutting across the above-mentioned amphibolite xenolith (bottom centre), as well as the layering in the trondhjemitic gneiss. The amphibolite dyke is, in turn, intruded by a later, more potassic, trondhjemitic-to-granodioritic dyke forming part of the body represented by samples N25 and N26 (Fig.4 and Table 1).*

D. *Close-up photograph of the homogeneous, medium-grained, trondhjemitic-to-granodioritic dyke shown in Figure 7C. All the rocks older than this dyke, excluding some of the leuco-trondhjemite veins in the amphibolite as well as in the trondhjemite gneiss, display a mineral foliation. This includes the mafic dyke, which consists of aligned hornblende crystals.*

E. *Close-up photograph of the mafic dyke (N18), shown also in Figures 7C and D, cross-cutting the amphibolite xenolith (N17).*

F. *Foliated hornblende-tonalite gneiss truncated by a NW-trending hornblende-amphibolite dyke (near sample site N24, Fig.4). This dyke has, in turn, been intruded by veinlets of later metasomatizing granitoid material resulting in the localized transformation of the dyke to diorite.*

Fig. 7



show any effects of alteration. Accessory minerals include ilmenite with leucoxene alteration rims, apatite, zircon, sphene and rutile, the latter occurring as needle-like inclusions in the biotite.

A north-south trending homogeneous, medium-grained, pinkish-grey granodioritic dyke cuts across all earlier phases, including the trondhjemitic gneisses, the mafic dykes and the very fine-grained granitic phase described above (Fig.4 – sample localities N26 and N25). The relationship of this granite-type to the earlier greenstones, the trondhjemitic gneisses and the mafic dykes, can be seen near sample localities N17 and N18 (Figs. 4 and 7C-E). The granodiorite consists of quartz, microcline, partially sericitized and saussuritized plagioclase (with alteration products sericite and epidote), and lesser quantities of muscovite, biotite, chlorite, magnetite, sphene, leucoxene and rutile needles in the biotite.

The last granitic phase consists of pegmatitic dykes and veins that also trend in a generally north-south direction across the platform. These pegmatites are very coarse textured in places with pink microcline and quartz interlocked together with minor amounts of muscovite and biotite. Adjacent to sample locality N18 a tongue of medium-grained, pinkish-grey granodiorite displays coarse pegmatitic selvedges indicating that these two granitic phases are coeval.

GEOCHEMISTRY

Sampling and Analytical Methods

Sampling of the Nooitgedacht platform was carried out primarily to determine the geochemical characteristics of the various mafic and granitic rocks exposed at the site. In addition, an investigation of the various products of the perceived metasomatic alteration of the amphibolites by the trondhjemites was deemed necessary. Sampling was, in places, problematical on the relatively flat migmatite-gneiss platform and a portable diamond drill was used to target specific samples.

Whole rock major elements and a number of trace elements were analysed by X-ray fluorescence in the Department of Geology at the University of the Witwatersrand, Johannesburg, using fused glass disks and pressed powder pellets, respectively. Rare earth elements (REE) were analysed using the ICP-MS facility in the Department of Geological Sciences at the University of Cape Town. The major, trace and REE data for 29 samples from the Nooitgedacht site are presented in Table 1. The REE data is quoted in ppm and the relative standard deviations were typically better than 3% for all REE for both within-run statistics and replicate analyses. In terms of accuracy, repeat analyses of the international rock standard JB-2 yielded relative errors, from accepted values, of better than 3.6% for all REE.

CIPW norms, also presented in Table 1, were calculated using a computer program in general use in the Department of Geology at the University of the Witwatersrand written by T.S. McCarthy. The various rock types encountered on the Nooitgedacht platform were grouped together into selected categories on the basis of their mineralogy and geochemistry.

Major Elements

Amphibolites

Chemical analyses of the greenstone remnants, now altered to hornblende-actinolite amphibolites, are shown in Table 1 (columns 1-4). Noteworthy are the high MgO and CaO and the low TiO_2, Al_2O_3, Na_2O, K_2O and P_2O_5 contents of samples N1 and N16, which have komatiitic affinities. The presence of clinopyroxene relics, the massive texture, and the high contents of magnesium and calcium in the rocks, suggest that they may have been part of an igneous body such as a sill or a layered ultramafic complex. Rocks of this type have been described in the Barberton greenstone belt and elsewhere on the Johannesburg Dome by Anhaeusser (1977,1978,1985,1992). Samples N8 and N23, by contrast, appear to be more akin to high-Mg basaltic or tholeiitic volcanic rocks by virtue of their higher contents of Al_2O_3, total iron, Na_2O and K_2O and their lower MgO and CaO contents.

Mafic dykes

Analyses of the mafic dykes described earlier are given in Table 1 (columns 5-9). The most notable major element variations are seen in the MgO (11.75 - 4.93 %), CaO (10.40 - 5.78 %), Al_2O_3 (15.36 - 12.64 %), SiO_2 (53.02 - 48.10 %) and TiO_2 (1.41 - 0.78 %) contents. Although there is little to distinguish the dykes from one another in the field or petrologically, they do, however, show chemical variations suggesting more than one population of dyke may be present. For example, samples N4, N18 and N19 show lower SiO_2, TiO_2, Al_2O_3, K_2O and P_2O_5 and higher $Fe_2O_{3\,Total}$, MgO and CaO than dyke samples N12 and N20. Variations in the same samples, shown later, are also evident in the trace element abundances, including the REE's.

Dioritic and tonalitic gneisses

A wide range of rock types with dioritic and tonalitic geochemical characteritics are listed in Table 1 (columns 10-20). A broad range exists in the contents of SiO_2 (53.43 - 62.95%), Fe_2O_{3Total} (5.24 - 8.5%), CaO (5.12 - 9.21%), Al_2O_3 (13.34 - 16.95%) and Na_2O (3.05 - 4.75%) reflecting the variability in the mineralogy (mainly the relative amounts of amphibole and plagioclase).

Trondhjemitic gneisses

The trondhjemitic gneisses differ from the tonalites by possessing biotite as the main ferromagnesian mineral in place of amphibole and also displaying higher silica contents (SiO_2 in the range 69.38 - 74.41%; Table 1, columns 21-24). Total iron, TiO_2, MgO, CaO, K_2O and Al_2O_3 are depleted relative to the diorite/tonalite, but Na_2O shows a significant increase because of the albitic plagioclase dominant in the trondhjemites.

Barker et al.(1976) and Barker (1979) subdivided trondhjemites into high and low Al_2O_3 types separating the two varieties at 15% Al_2O_3 and 70% SiO_2. Because a continuum of Al_2O_3 compositions exists the separation these authors proposed was done for convenience. It is now furthermore generally accepted that most trondhjemite-tonalite liquids formed from basaltic sources and involved processes of partial melting or fractionation (Arth and Hanson, 1972,1975). A variety of cumulate or residual minerals, including plagioclase, result in liquids being of the low-Al_2O_3 type. Where, however, plagioclase is not considered to be a residual phase the liquids are of the high-Al_2O_3 type.

The variations in Al_2O_3 content, it was claimed by Arth (1979), reflect differences between trondhjemites originating in oceanic environments and those originating in continental environments. Continental trondhjemites, he noted, generally contain more than 14.5 - 15% Al_2O_3, whereas oceanic trondhjemites generally contain less than 14.5 - 15%. Both low and high Al_2O_3 types are, however, now known in every era and even the old gneiss terranes of Swaziland (Hunter et al., 1978), the Barberton Mountain Land (Glikson, 1976; Anhaeusser and Robb, 1983) and the Johannesburg Dome (Anhaeusser, 1973b) contain both types. Also in this study of the relatively limited-scale Nooitgedacht platform both high- and low-Al_2O_3 trondhjemites occur virtually side by side thereby making any inferences as to the geotectonic setting, based on Al_2O_3 alone, somewhat conjectural.

Homogeneous trondhjemites and granodiorites

The trondhjemite-granodiorite samples listed in Table 1 (columns 25-29) include rocks unaffected by tectonic influences and represent the youngest granitoids seen on the Nooitgedacht platform. On average these rocks are somewhat more siliceous (73.27% SiO_2) than the foliated leuco-trondhjemitic gneisses (71.77% SiO_2) and also display increased amounts of K_2O, the latter manifest in the rocks by increased K-feldspar (microcline). The late granitoids show relative depletion in TiO_2, total iron, CaO and MgO. Abundances of Na_2O also show a decrease, particularly in the granodioritic rocks.

Harker variation diagrams

Figure 8 displays Harker-type variation diagrams of SiO_2 plotted against other major elements in the Nooitgedacht rocks. In most cases well-defined linear distribution trends are evident with TiO_2, FeO, MnO and CaO exhibiting inverse correlations with SiO_2. Al_2O_3 remains somewhat constant over a wide range of SiO_2 contents, whereas Na_2O and, to a lesser extent, K_2O show positive correlations with increasing silica contents. Less regular trends are shown by both K_2O and P_2O_5.

Trace Elements

Trace and rare earth element (REE) concentrations in rocks from the Nooitgedacht exposure are also listed in Table 1. The trace element patterns (Fig.9) show trends that are less clearly defined compared to those of the major elements, although Cr, Ni, Zn and V display approximately linear distribution patterns. Rb, Sr, Ba, Zr and, to a lesser extent, Nb show broadly positive correlations with increasing SiO_2, whereas Cr, Ni, Zn and V have negative correlations. The Harker diagrams (Figs. 8 and 9) also emphasize some data point clustering, the latter reflecting the geochemical variability of the different lithological categories or suites defined earlier. Chondrite-normalized REE patterns of some of the mafic and felsic rocks from the Nooitgedacht platform are shown in Figure 10.

Amphibolites

The REE abundances of two high-MgO amphibolites (samples N1 and N16) and one with lower MgO content (N8) are plotted in Figure 10A. The high-MgO amphibolites (also high in Ni, Cu and Cr, and low in Rb, Sr, Zr, Zn, Nb and Ba), which are considered to have komatiitic affinities, are more depleted in light REE than their lower MgO counterpart (the latter also showing enrichment

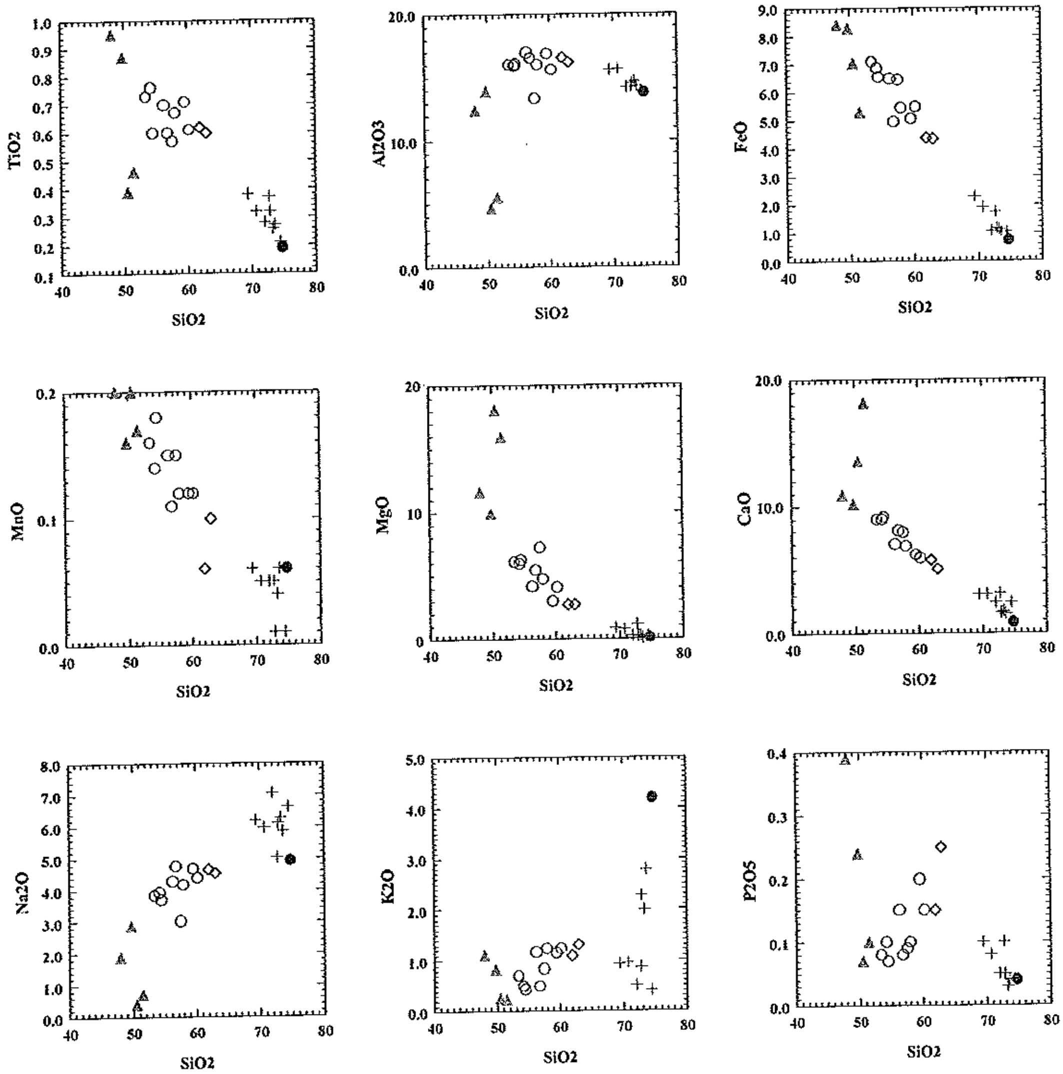


Figure 8: Harker-type major element variation diagrams for the rock types sampled on the Nooitgedacht platform (Fig.4 and Table 1). Symbols depict amphibolites (solid triangles); dioritic and tonalitic gneisses (open circles and diamonds); trondhjemitic gneisses and homogeneous trondhjemites (plus signs) and leucogranodiorite (solid circle).

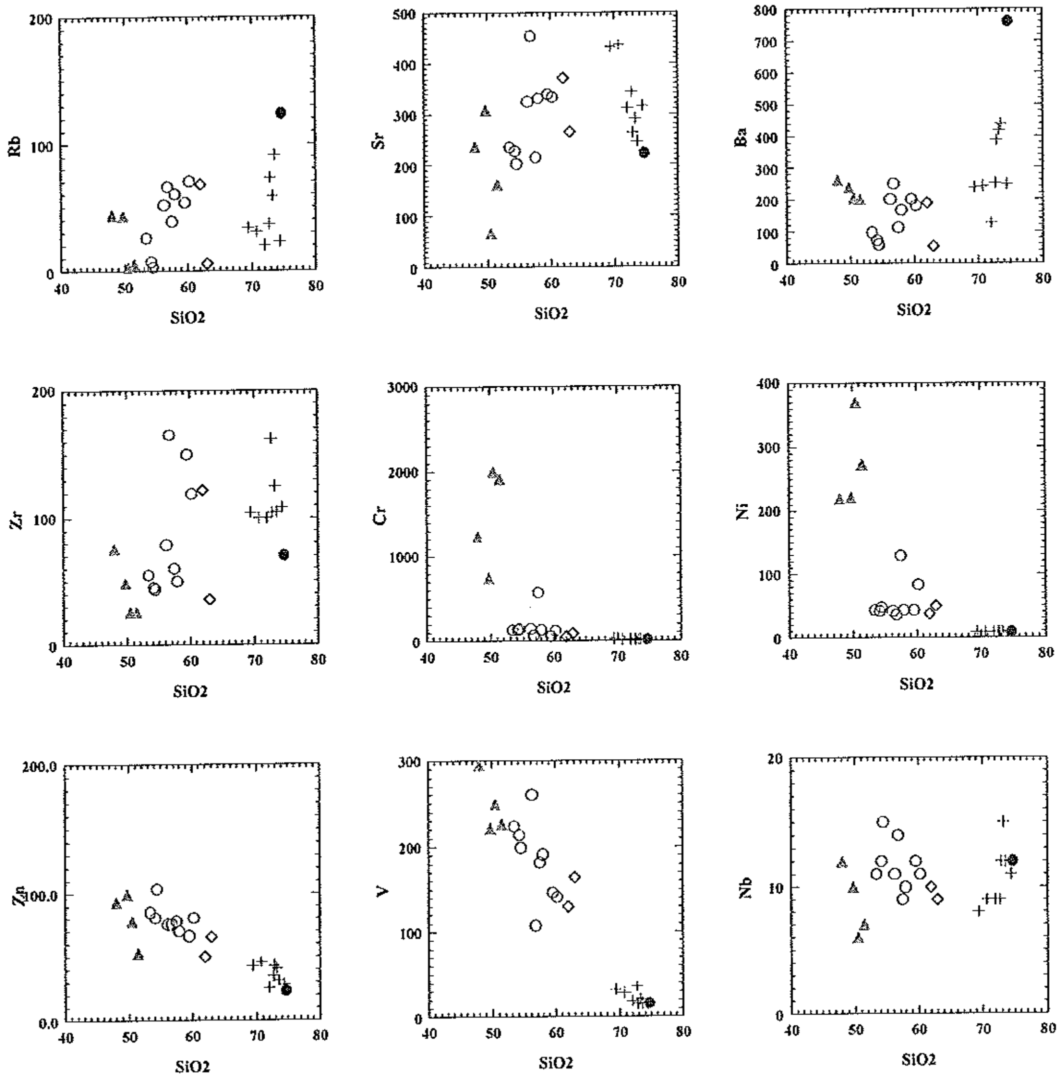


Figure 9: Plots of SiO_2 versus trace elements Rb, Sr, Ba, Zr, Cr, Ni, Zn, V and Nb for the Nooitgedacht granitoids (symbols as in Fig.8).

in Rb, Sr, Zr, Zn, V and Ba), but both varieties show relative enrichment in LREE. This tendency for some igneous rocks to display LREE enrichment has been attributed to the presence of olivine, orthopyroxene and clinopyroxene (Rollinson, 1993; Wilson, 1993). All the Nooitgedacht mafic rocks are metamorphosed to hornblende or actinolite, but the protolith mineralogy most likely consisted of clinopyroxene as this mineral was seen as relics in some thin sections.

According to Sun and Nesbitt (1978) and Humphries (1984) REE patterns, particularly the LREE enriched patterns of some Archaean basalts, can be affected by metamorphism. These authors were of the opinion, however, that the consistency of patterns from high quality REE data were more likely to represent original magmatic patterns. The Nooitgedacht amphibolites appear to identify with a specific group of Archaean basalts with high MgO and characteristic quench clinopyroxene textures. These basalts Sun and Nesbitt (1978) referred to as spinifex-textured basalts (STB) whose REE patterns, particularly their LREE-enriched character and fairly flat to slightly depleted heavy REE patterns, mirror their mantle source. The Nooitgedacht amphibolites show moderately flat to slightly depleted HREE patterns (Fig.10A), similar to those reported for Archaean and oceanic-island mafic volcanics (Hermann et al., 1976; Sun and Nesbitt,1978; Wilson,1993).

Mafic dykes

As mentioned earlier at least two mafic dyke varieties appear to have intruded the gneisses of the Nooitgedacht platform. Mineralogically, all the dykes have been metamorphosed to amphibolites and show little to distinguish them petrologically one from the other. One variety (Table 1, columns 5-7) displays high MgO (~11%) and high CaO (~10%) abundances and lower SiO_2 (~48%) contents than the other variety (columns 8-9) with MgO (~5.5%), CaO (~6.5%) and SiO_2 (~53%). The high-MgO variety also shows enrichment in Co, Ni, V and Cr and depletion in Rb, Zr, Nb, Cu and Zn. Two samples, one from each major element category, as outlined above, yielded REE abundances (Table1, columns 6 and 9) that are plotted in Figure 10B.

Clearly, two chondrite-normalized REE patterns are evident. Both show moderate to substantially enriched LREE abundances and flattish to slight HREE depletion (Fig.10B). A slight Eu anomaly also appears to be present for sample N18. Both REE trends are approximately similar, but sample N12 has consistently higher overall REE abundances relative to sample N18. As discussed previously, the REE patterns, particularly the LREE, can be affected by metamorphism (Sun and Nesbitt, 1978; Humphries,1984) and care has to be taken in interpreting the REE patterns of heavily altered or metamorphosed rocks. Despite this possible constraint Rollinson (1993) argued that even in altered rocks REE patterns can faithfully represent the original composition of the unaltered parent. In addition, a fair degree of confidence can also be placed on the significance of peaks and troughs and the slopes of REE patterns. If metamorphism has been responsible for the extreme fractionation trends shown in Figure 10B it must equally have affected both dyke varieties. It can thus be concluded with some confidence that more than one dyke event preceded the emplacement of the homogeneous trondhjemites and leucogranodiorites, the latter granitoids reflecting the last magmatic event recognized on the Nooitgedacht platform.

Dioritic and tonalitic gneisses

Trace elements for a range of dioritic and tonalitic gneisses from Nooitgedacht are listed in Table 1 (columns 10-20). These generally show some consistency, but without providing any definitive trends in Figure 9. Overall there is enrichment of Sr relative to Rb, a spread of Zr, relative enrichment in Y, Ni, Cr, Zn and V, and some depletion in Ba. The consistency displayed by the trace elements is also manifest in the REE patterns for these rocks shown in Figure 10E.

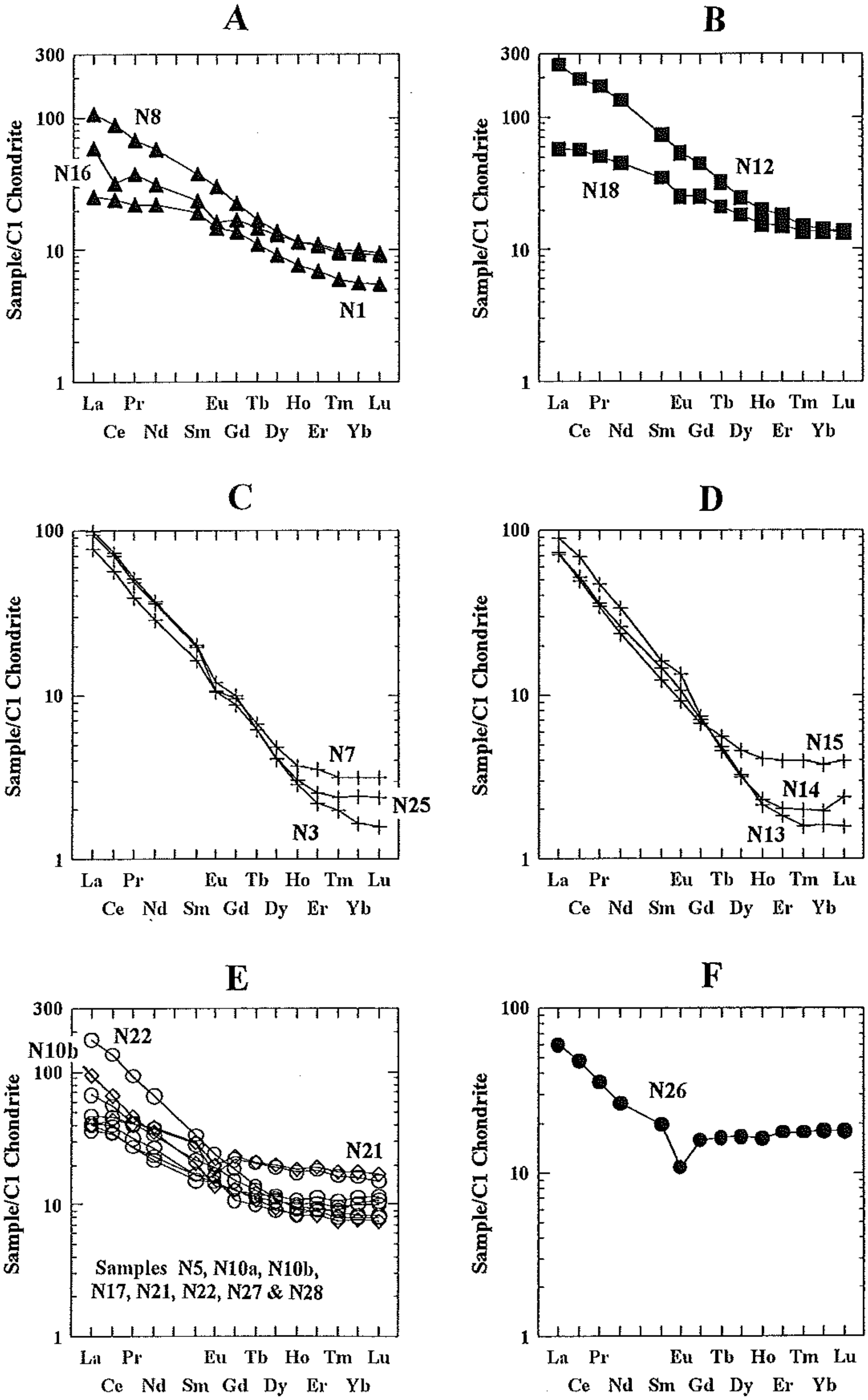


Figure 10: Chondrite-normalized rare earth element plots for rocks of the Nooitgedacht platform (REE data from Table 1; symbols as in Figs. 8 and 9). A. Amphibolites (metakomatiite, high-Mg basalt/metatholeiite); B. Mafic dykes; C and D. Gneissic and homogeneous trondhjemites; E. Dioritic and tonalitic gneisses; F. Leucogranodiorite.

Collectively, the patterns are generally similar to those of the amphibolites (Fig. 10A) and show moderate LREE enrichment and flattish to slight HREE depletion. Sample N22 has the highest LREE abundance and samples N10b and N21, which are tonalites, show slight negative Eu anomalies suggesting a more differentiated character of these rocks relative to the dioritic gneisses.

Trondhjemitic gneisses

Trace element abundances of four trondhjemitic gneiss samples from different parts of the Nooitgedacht platform are listed in Table 1 (columns 21-24). Samples N2 and N14 are representatives of the main mass of trondhjemitic magma that initially intruded the komatiitic and tholeiitic mafic precursor rocks at Nooitgedacht (now represented by various amphibolite and mafic diorite remnants and xenoliths seen on the river platform and in the area to the east of Fig. 4). By contrast samples N7 and N15 are from leucotrondhjemite veinlets that also display a mineral foliation like that seen in the main or representative exposures of the trondhjemitic gneisses. Samples N2 and N14 are also representatives of the high-Al_2O_3 variety of trondhjemite mentioned earlier, whereas the dyke-like veinlets (as well as the later homogeneous trondhjemites, Table 1, columns 25-28) are representatives of the low-Al_2O_3 trondhjemites. In general, consistent trace element abundances are displayed by the trondhjemites. However, there is considerable enrichment in Sr relative to Rb and some spread is evident in values of Rb, Sr, Ba, Zr and Nb (Fig.9).

Rare earth element abundances were determined for six trondhjemitic samples from various parts of the Nooitgedacht exposure. Three of the samples are of trondhjemitic gneiss (Table 1, columns 22-24) and three are of the homogeneous, low-Al_2O_3 trondhjemite variety (Table 1, columns 25, 27 and 28). Plots of chondrite-normalized REE data for the trondhjemites are shown in Figure 10C and D. All the samples display very steep REE patterns with strong LREE enrichment and moderate to strong HREE depletion. These patterns show considerable fractionation between the light and heavy REE's and negligible or very slight negative Eu anomalies (Fig.10C) or slight positive Eu anomalies (e.g. sample N14, Fig.10D). The slightly developed positive Eu anomaly seen in Figure 10D is for sample N14.

The Nooitgedacht REE patterns are similar in shape and abundance levels to REE patterns reported elsewhere in Archaean granitoid terranes (e.g. northern Minnesota, Arth and Hanson, 1972,1975; Barberton, Glikson,1976; southwest Finland, Arth et al., 1978; Scotland and East Greenland, Tarney et al., 1979; Kolar, India, Balakrishnan and Rajamani, 1987; Swaziland and northern KwaZulu-Natal, Hunter et al.,1992; Yilgarn, Western Australia, Witt and Davy,1997). Most noteworthy, and what appears to be a feature of Archaean tonalitic-trondhjemitic gneiss terranes, are the strongly fractionated REE patterns and the moderate to strong HREE depletion characteristics. In some cases a tendency to develop positive Eu anomalies is also a feature, but is not always in evidence.

If Archaean tonalitic-trondhjemitic-granodiorite (TTG) magmas are subduction related, as has been suggested by Barker (1979) and numerous other workers, it is possible to ascribe the above geochemical differences to a component derived by hydrous melting of a downgoing slab. Heavy REE depletion and positive Eu anomalies generally signify that garnet was involved in the petrogenesis and composition of the TTG magmas (Pitcher,1995; Tarney et al.,1979), but hornlende fractionation (Arth et al., 1978) or either hornblende fractionation or partial melting of a garnet amphibolite mafic source at high water pressures could also produce the fractionation paths that are seen (Tarney et al.,1979).

The Nooitgedacht trondhjemites, in summary, are characterized by HREE and Y depletion and strongly fractionated REE patterns, and have either no or small negative or positive Eu anomalies. In this respect they appear analogous to the TTG granitoids in southern Swaziland, southeastern Mpumalanga and northern KwaZulu-Natal described by Hunter et al. (1992). These authors concluded, on geochemical grounds, that the TTG magmatism prevalent in this sector of the Kaapvaal Craton had been generated repeatedly either by partial melting of a garnet-bearing mafic source or by the remelting of an earlier generation of TTG rocks.

As pointed out by Tarney and Saunders (1981) it is apparent from trace element relationships, the nature of which have been described above, that there are many different fractionation paths between basic magmas and granitic rocks. This may imply an equal diversity of P, T, P_{H2O} and P_{O2} conditions controlling magma genesis and subsequent crystal fractionation. This complex issue is not the purpose of this study and will not be pursued further.

Homogeneous trondhjemites and granodiorites

Trace element analyses of five samples belonging to this category of late-stage, homogeneous, granitoid rocks are listed in Table 1 (columns 25-29). In general the abundances of most trace elements appear similar to those of the foliated variety of trondhjemitic gneisses described earlier. However, corresponding with the increases seen in the major element proportions of SiO_2 and K_2O, and the decreases in Na_2O and the ferromagnesian constituents, there are changes in the amounts of some trace elements. Rb and Ba are enriched, particularly in the samples showing increased amounts of potassium feldspar, and Sr shows a decrease as the amount of sodium diminishes coinciding with the progressive replacement of albitic plagioclase feldspar by microcline. Sample N26, which is a granodiorite, shows the greatest variation, particularly in the major elements, but increased amounts of Rb, Y and Ba and lesser quantities of Sr, Zr and Zn are apparent in the trace element abundances.

The behaviour of the REE's, particularly with respect to the low-Al_2O_3 trondhjemites, has been discussed previously, and displayed in Figure10 C and D. The chondrite-normalized REE pattern applicable to granodiorite sample N26 (Fig.10F) shows considerable contrast, with LREE enrichment, flat to slightly positive HREE abundances and a negative Eu anomaly, the latter expected from feldspar fractionation. Surprisingly, sample N25, from the same cross-cutting granitic dyke 12m south of N26 (Fig.4), shows depleted HREE and only a slight negative Eu anomaly (Fig.10C).

GEOCHEMICAL DISCRIMINATION

Any attempts to categorize granitic rocks must, as pointed out by Pitcher (1995), bear in mind the seemingly infinite number of different types which might be generated in response to a variety of generative processes and possible source rock compositions. Geochemical data permits discrimination and comparison of granitic rocks on a wide front and has increasingly come to be regarded as an essential aspect of any granite-related study. Numerous discrimination procedures have been devised to extract genetic information and to determine different tectono-magmatic settings based on the chemical variability displayed by granitic rocks (see Cox et al., 1979; Rollinson, 1993), but caution as to their many shortcomings as petrogenetic or tectonic environment indicators were pointed out by Clarke (1992).

Despite this some consensus has emerged whereby geochemical data is used to classify rocks and to obtain information relating to geological processes. In the case of Nooitgedacht, the data previously discussed has been plotted in a variety of discrimination diagrams (Fig.11), which are

Figure 11 :

A. *QAP classification diagram of the granitoid family after Streckeisen (1976). The earliest Nooitgedacht granitoids plot mainly in the fields of diorite, quartz diorite and tonalite. Trondhjemite (not labelled) was defined by Streckeisen as leucotonalite whose plagioclase is oligoclase or andesine. Barker (1979) suggested, however, that albite- as well as oligoclase-bearing leucotonalite be termed trondhjemite. The later granitoids on the Nooitgedacht platform plot mainly in the leucotonalite - granodiorite fields.*

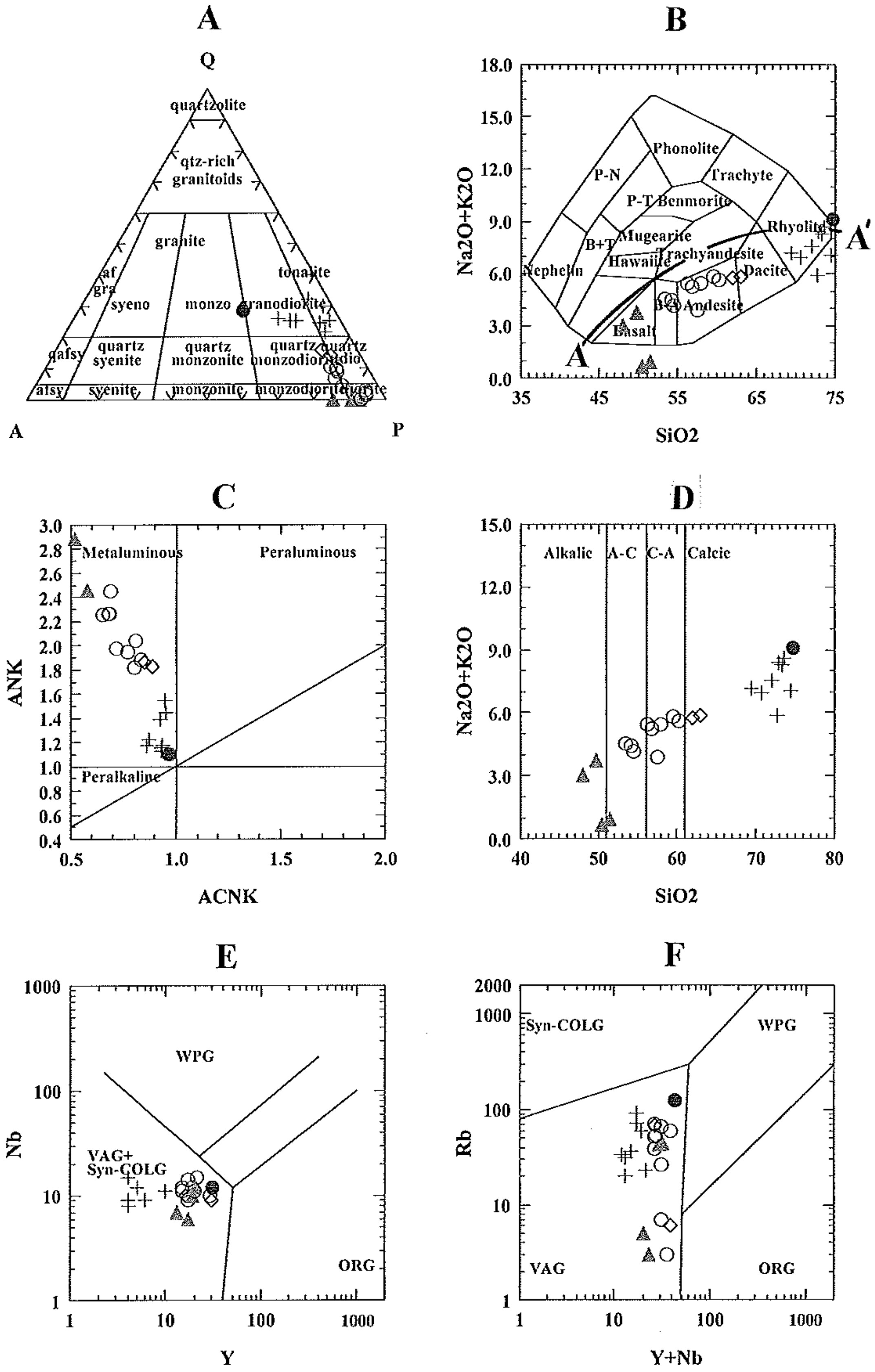
B. *Alkali (Na_2O+K_2O) versus SiO_2 (TAS) discrimination diagram (after Cox et al., 1979,) showing the spread of mafic, intermediate and felsic volcanic rock types. Wilson (1989) adapted the diagram for use in classifying igneous rocks (see text), and line A-A' (after Miyashiro,1978) represents the divide between alkalic rocks (above) and subalkalic rocks (below). The Nooitgedacht data define a typical calc-alkaline series extending from basalt (gabbro) to rhyolite (granite).*

C. *ANK versus ACNK diagram (after Maniar and Piccoli, 1989) showing the Nooitgedacht samples plotting in the metaluminous field. Attempts to link chemical characteristics directly to a tectonic and/or genetic significance have been suggested by Chappell and White (1974) and Barbarin (1990). Metaluminous granitoids generally have I-type characteristics and are considered to have formed in subduction-related continental and island arc geological settings. (A,C,K,N = mol Al_2O_3, CaO, K_2O and Na_2O, respectively).*

D. *Alkali (Na_2O+K_2O) versus SiO_2 diagram (alkali-lime index, after Peacock, 1931) showing the compositional spread of lithologies from the Nooitgedacht granitoid platform.*

E. *Nb - Y discriminant diagram (after Pearce et al., 1984) for syn-collisional granites (syn-COLG), volcanic-arc granites (VAG), within-plate granites (WPG) and ocean-ridge granites (ORG). Discrimination between VAG and syn-COLG granite is achieved by plotting Rb versus Y+Nb (see Fig. 11 F).*

F. *Rb versus Y+ Nb diagram (after Pearce et al., 1984) showing whole-rock compositions of the amphibolites and calc-alkalic granitoids at Nooitgedacht. On the basis of this classification a volcanic arc appears to be the likely tectonic setting for the calc-alkalic granitic rocks on the Johannesburg Dome.*


A
Q
quartzolite
qtz-rich granitoids
granite
tonalite
syeno
monzo
granodiorite
quartz syenite
quartz monzonite
quartz monzodiorite
syenite
monzonite
monzodiorite
A
P
B
Phonolite
P-N
Trachyte
P-T
Benmorite
Rhyolite
Mugearite
B+T
Hawaiite
Trachyandesite
Nephelin
Dacite
Andesite
Basalt
A
A′
Na2O+K2O
SiO2
C
Metaluminous
Peraluminous
Peralkaline
ANK
ACNK
D
Alkalic
A-C
C-A
Calcic
Na2O+K2O
SiO2
E
WPG
VAG+ Syn-COLG
ORG
Nb
Y
F
Syn-COLG
WPG
VAG
ORG
Rb
Y+Nb

presumed to be of petrogenetic significance. In the first of these diagrams (Fig.11A) modal proportions of quartz, alkali feldspar and plagioclase (QAP) have been derived from CIPW normative mineralogy, which in turn, was calculated from the geochemical data (Table1). The QAP classification (after Streckeisen, 1976) shows that most of the Nooitgedacht granitic rocks fall into the fields of diorite, quartz diorite, tonalite and granodiorite. Trondhjemite is not named on the diagram, but is effectively a leucotonalite with albite or oligoclase feldspar and several other distinguishing characteristics (Barker,1979).

A total alkalis-silica diagram (TAS) was devised by Cox et al.(1979) to classify volcanic rocks. The Nooitgedacht data, plotted on such a TAS diagram, is shown in Figure 11B. Wilson(1993) adapted the diagram for use as a preliminary classification of igneous rocks and substituted 'gabbro', 'diorite', 'quartz diorite (granodiorite)' and 'granite' in place of 'basalt', 'andesite', 'dacite' and 'rhyolite' in the TAS diagram. A dividing line between alkalic and subalkalic magma is also shown on the diagram and is after Miyashiro (1978). An early attempt to subdivide alkalic and subalkalic rocks using alkali-silica geochemistry was that of Peacock (1931), shown in Figure 11D. In this diagram the Nooitgedacht data displays a calc-alkaline trend extending from low alkalic to intermediate calcic.

As pointed out by Clarke (1992) there is more to granitoid rocks than just quartz and feldspar and a system using the concept of alumina-saturation in which the ratio A/CNK {i.e. molar [Al_2O_3/(CaO + Na_2O + K_2O)]}can range from >1 to <1 in igneous rocks was devised. In this system granitoid rocks are peraluminous where A/CNK >1, metaluminous (A/CNK <1) and peralkaline where A< NK. Figure 11C shows the Nooitgedacht data plotted on a diagram after Maniar and Piccoli (1989). All samples plot in the metaluminous field and may be regarded as either I- or M-type granitoids. This implies source rocks of mafic to intermediate composition or infrastructural derivation (I-type, Chappell and White,1974: Chappell and Stephens,1988), or rocks derived from mantle sources either directly through partial melting of subducted oceanic crust, or directly by fractional crystallization of basalt (M-type, White,1979; Pitcher, 1982).

A study of the geochemistry of granitic rocks from known tectonic settings was undertaken by Pearce et al.(1984). These authors classified the granitic rocks into ocean-ridge (ORG), volcanic-arc (VAG), within-plate (WPG) and syn-collisional (syn-COLG) types based on the variations these rocks showed with respect to Rb,Y and Nb - elements which were found to be the most efficient discriminants of granites according to their tectonic settings.
Using these diagrams it can be seen that the Nooitgedacht data clusters into the VAG + syn COLG category of the Nb versus Y diagram (Fig.11E) and more selectively into the volcanic-arc-related field in the Rb versus Y+Nb diagram (Fig.11F).

DISCUSSION AND CONCLUSIONS

Field, petrological and geochemical evidence has been presented from a small granite-gneiss-migmatite river platform on the Johannesburg Dome, which shows that a complex geological history prevails for this sector of the Kaapvaal Craton. Follow-up radiogenic isotope studies involving U-Pb zircon dating of the different granite events on the Dome (including material from the Nooitgedacht platform) are to be reported shortly (Poujol and Anhaeusser, in prep.). These studies, together with the foregoing account, should help provide some clarity on the nature of the Archaean crust in the central part of the Craton, including some thoughts and constraints on the geotectonic setting and timing of the various events manifest in the region.

The Nooitgedacht exposure is one of only a very few localities on the Johannesburg Dome known to the writer where the complex relationships described earlier can be seen clearly and the relative timing of events can be determined. These relationships have been displayed and discussed in this paper. The results further complement the relationships determined by the writer for the entire Johannesburg Dome (Anhaeusser, 1971,1973b).

In its most elementary form the evolutionary history envisaged by the writer for the basement rocks exposed on the dome involved the initial deposition or emplacement of volcanic and plutonic rocks of komatiitic, basaltic komatiitic, high-MgO basaltic and tholeiitic compositions. Numerous examples of rocks of this type can be seen at various localities (Anhaeusser,1977,1978, 1992), and are believed to have been emplaced in an Archaean oceanic or volcanic arc-like geotectonic setting in much the same manner as that envisaged for the primitive mafic and ultramafic rocks of the Barberton greenstone belt (Viljoen and Viljoen, 1969; Anhaeusser, 1973a).

An initial period of felsic magmatism led to the emplacement of TTG granitoids, of which the approximately 3.17Ga hornblende-biotite-tonalite gneisses formed a part in the suburban Rooseveldt Park-Linden areas of Johannesburg (Anhaeusser and Burger, 1982). On the northern half of the Johanneburg Dome leuco-biotite trondhjemite gneisses appear to have been the earliest granitoid rocks, as can be demonstrated at the Nooitgedacht exposure. These sodium-rich granitoids intruded into the earlier-formed mafic and ultramafic rocks causing dismemberment of the successions into variably sized greenstone remnants as well as smaller xenolithic relics (Anhaeusser, 1973b, 1992). Metamorphism of the mafic and ultramafic rocks by the TTG magmas led to the development of a variety of amphibolitic and serpentinitic rock types as well as areas of granite-greenstone hybridization. This stage of mixing of the felsic magma with the mafic-ultramafic precursors probably occurred on a variety of scales, but limited exposures prevent confirmation of this possibility. At Nooitgedacht the mixing and mingling of the trondhjemite magma with amphibolites present at the locality produced the range of gabbroic-dioritic-tonalitic rocks seen and described in this paper (Figs. 4-7). These rocks, in the experience of the writer, both at Nooitgedacht as well as elsewhere on the Johannesburg Dome, are developed mainly in close proximity to the granitoid-greenstone contacts and appear to have formed as a result of assimilation, mixing and metasomatism of the mafic-ultramafic rocks by the granitoids.

The chemical and petrological characteristics of the various hybrid products seen in the Nooitgedacht exposure have been documented in this study. In some cases field evidence supports a degree of metasomatic replacement of the mafic rocks by solutions emanating from veins and dykes of trondhjemite (Fig.7B), but most of the hybrid products appear to result from assimilation and mixing. Chemical data plotted in variation diagrams (Figs. 8 and 9) show either positive or negative trends which lend support to the mixing hypothesis. Although Wall et al.(1987) cautioned on the interpretations that are commonly placed on Harker-type variation diagrams they conceded that magma mixing could result from contamination by partial assimilation of xenoliths.

In parts of the Nooitgedacht exposure the interdigitation of felsic and mafic rock material produced localized migmatites (Fig.5B). These migmatites formed as a result of injection or intrusion of felsic magma in much the same way as described many years ago by Sederholm (1934). In some places the migmatites consist of small-scale heterogeneous exposures comprising leucosomes, melanosomes and mesosomes (Johannes,1983). Differing degrees of partial melting probably caused different types and amounts of leucosome and restite material to develop. Some of the heterogeneous amphibole- and biotite-rich diorites and tonalites (Fig.5) may have been formed in this manner.

As can be judged by the variability of the granitoid-greenstone relationships on the Nooitgedacht platform, as well as elsewhere on the northern half of the Johannesburg Dome, the resolution of the genetic history of these rocks probably calls for a number of processes working in tandem. No single model accounts for all the subtle variations on display.

Following the events outlined above, and which were largely linked to the emplacement of early TTG granitoids into the primitive mafic-ultramafic supracrustal sequences, there followed a period of mafic magmatism manifest in the form of the amphibolite dykes seen in Figures 4 and 7C-E. Geochemical evidence, in the form of distinctly differing REE abundances (Fig.10B), supports the view that more than one dyke event took place. If a single stage of dyke emplacement did occur the magmas probably formed from different sources. The crust at the time of their emplacement must have been sufficiently consolidated to experience brittle deformation, thereby causing the dykes to intrude along similarly orientated fractures or joints (Fig.4). That the dykes are metamorphosed to amphibolite grade may have to do with the subsequent heating of the terrane by the late- stage granitoid event described below.

The final stages of Archaean crustal evolution evident on the Johannesburg Dome coincided with the emplacement of an areally extensive homogeneous granodiorite-porphyritic granodiorite batholith, the latter occupying most of the central and southern half of the dome (Anhaeusser,1973b). Manifestations of this essentially potassic-granitoid massif are also seen in places on the northern half of the dome in the form of granodiorite and pegmatite dykes that intrude the earlier-formed greenstones, gneisses and migmatites. At Nooitgedacht the medium-to-fine-grained homogeneous trondhjemite-granodiorite dykes and the coarse-grained pegmatites that crosscut earlier phases on the platform, including the amphibolite dykes (Figs.4 and 7C,D), are believed to be representatives of this event. Whilst some of these late-stage homogeneous-textured granitoids have trondhjemitic affinities, they do, nevertheless, possess potash contents that place them in the granodiorite field of Streckeisen (1976; see Fig.11A). REE data from sample N26, a medium-grained granodiorite, provides further confirmation that these rocks are geochemically distinct (Fig.10F).

Some final thoughts on the tectonic environmental setting of the rocks found on the Johannesburg Dome, must of necessity, be regarded as preliminary at this stage. The source region of rocks of the type described are best characterized by radiogenic isotope compositions because, as explained by Rollinson (1993), isotopic ratios are not modified during partial melting and magma chamber processes. Trace element geochemistry, particularly the REE abundances, is being employed increasingly to finger-print the environments in which various magmas are formed. The REE data acquired during this study has shown, if the variation diagrams are presumed to have petrogenetic significance, that the Nooitgedacht rocks (and hence those of the Johannesburg Dome) probably developed in a volcanic-arc setting (Fig.11E,F). This presupposes that some form of plate tectonics was operative in the Archaean which led to the development of microcontinents. The contention that the Kaapvaal Craton consists of a mosaic of subdomains welded together, as outlined by De Wit et al.(1992), awaits further confirmation. The need for further studies of this type, as well as isotopic age dating where such subdomains might be suspected, appears to signal the way ahead.

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