4. The Geology and Geochemistry of the Lower Ultramafic Unit of the Onverwacht Group and a Proposed New Class of Igneous Rocks

by

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I. INTRODUCTION

As noted in an accompanying paper, tholeiitic successions of the calc-alkaline type constitute the main rock types of the lowermost volcanic assemblages of most early Precambrian greenstone belts. In the Barberton belt, however, a substantial succession of highly distinctive and as yet undescribed or undefined rock types has been encountered below a normal tholeiitic succession of the calc-alkaline type. The tholeiitic succession constitutes the upper three formations of the Onver-

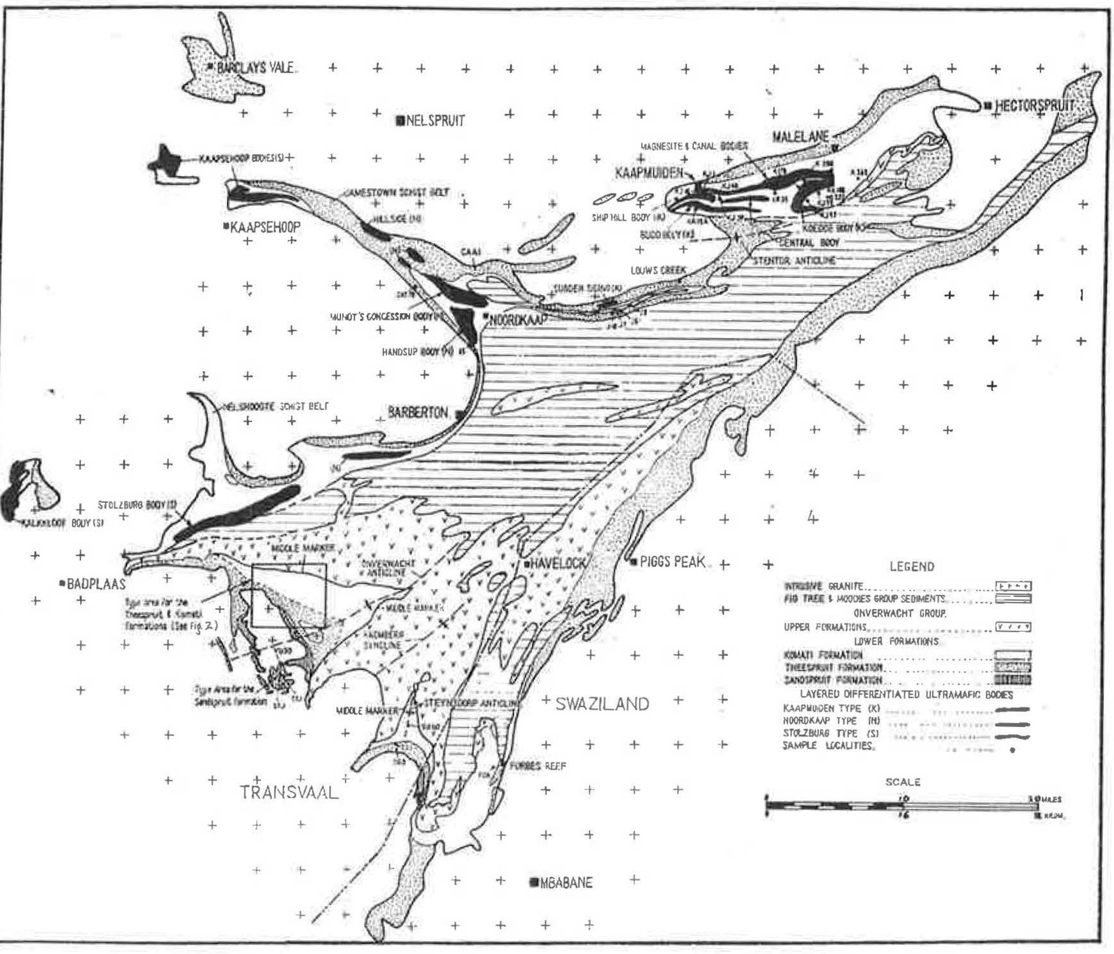

Fig. 1. Distribution of the three lower formations of the Onverwacht Group around the Barberton Mountain Land showing the type area and localities of the chemical analyses quoted.

wacht Group and is described in a following paper (No. 6). The lower formations of the Onverwacht Group together constitute a distinctive succession of what has been termed the Lower Ultramafic Unit, and are described in detail in this paper.

These formations, known from the base to the top as the Sandspruit, Theespruit and Komati formations, attain their maximum development and are best preserved in the southern part of the Barberton Belt which has consequently been chosen as the type locality. In general the rocks are steeply dipping in this area and occupy the cores of two major anticlinal structures, viz. the Onverwacht and Steynsdorp anticlines. Intrusion of granitic rocks has detached these two anticlines and eliminated the median syncline (now occupied only by rocks of the upper formations) which must have existed previously (Fig. 1).

The Onverwacht anticline is an asymmetrical ENE-trending structure with a somewhat reduced and flattened eastern limb but with a well-developed and well-exposed east-west trending western limb which has consequently been established as the type column for the upper two formations of the Lower Ultramafic Unit (Fig. 1). In this area only a narrow sliver of rocks belonging to the lowermost Sandspruit formation is present so that the type section for the latter has been established some several kilometres to the south-east in a large, well-preserved but detached xenolithic mass within the intrusive tonalitic gneisses (Fig. 1).

II. THE SANDSPRUIT FORMATION

The Sandspruit formation constitutes the lowermost recognisable unit of the Onverwacht Group and has an approximate thickness of 2,134 metres (7,000 ft.), an unknown amount of the stratigraphy, together with possible lower formations, having apparently been eliminated by intrusive tonalitic granites. Most of the rocks constituting the formation occur as xenoliths and stringers largely detached from the main contact of the Mountain Land and almost completely enveloped by granite (Fig. 1). The best developed and preserved of these xenoliths, which is partly traversed by the Sandspruit stream, has been taken as the type area of the formation (Fig. 1).

The rocks consist mainly of ultramafites in the form of bands, lenses and pods, interlayered and closely associated with minor mafic bands and lenses (Figs. 2 and 3). The ultramafics generally have a micaceous and dark green to khaki-green appearance and range petrologically from almost pure serpentinites consisting largely of antigorite with minor amounts of chlorite and magnetite, through antigorite-chlorite-tremolite varieties, to tremolite-chlorite rocks. Well crystallized chlorite, often as large green flakes, is ubiquitous in these rocks and accounts for their distinctive micaceous appearance. It is possible, as suggested by Hess (verbal communication), that much of this chlorite formed from original magnetite and antigorite as a result of the fairly high-grade contact metamorphism to which these rocks have been subjected. Such a reaction could explain the generally minor amounts of magnetite compared to similar rocks in the Komati formation, as well as the distinctive greenish colour of the rocks under consideration. The ultramafics constitute about 60% to 70% of the succession and the meta-basalts, in the form of dark green to black, hornblende or actinolitic-hornblende amphibolites with minor amounts of soda plagioclase, the remainder. Occasional narrow, and not very extensive, sedimentary interlayers are present and are composed of quartz and diopside with minor amounts of spinel (pleonaste) and sphene.

Although present, pillow and other volcanic structures are rare in the generally rather massive amphibolites. The ultramafics are usually also massive and structureless, but from their close similarity and analogous setting to the extrusive ultramafics of the Komati formation it is inferred that they represent either lavas or very early contemporaneous near-surface sills.

Selected chemical analyses of ultramafic rocks from the formation are presented in columns 1 to 3 of Table I, and their localities shown in Figs. 1 and 3. These will be discussed later.

The Sandspruit formation has only a limited distribution away from the type area, occurring as isolated xenoliths in the ancient tonalitic gneisses and as a small sliver flanking the eastern side of the Steynsdorp granite in the south-eastern portion of the Mountain Land (Fig. 1). As far as can be ascertained from a reconnaissance investigation the formation does not appear to be developed in other parts of the Mountain Land.

III. THE THEESPRUIT FORMATION

The Theespruit formation is well developed in both the Onverwacht and Steynsdorp anticlines and, as will be shown later, is widespread right around the Mountain Land (Fig. 1). In the type area the formation attains a thickness of 1,890 metres (6,200 ft.) and comprises a succession of metamorphosed mafic lavas characterized by persistent interlayered felsic and minor mafic tuffs. Serpentinized ultramafics, often in the form of conformable and persistent bands, but also occurring as pods and lenses, are fairly well represented, together with talc, chlorite-talc and carbonate schists (Figs. 2 and 3).

The main distinguishing feature of the formation is the occurrence of the felsic tuffs which grade from white fine-grained siliceous often friable rocks consisting almost exclusively of a quartz mosaic with minor amounts of sericite and pyrophyllite to bedded re-worked fine- and coarse-grained felsic tuffs and agglomerates (Plates Ia and Ib). The latter are often aluminous, containing, in addition to quartz and sericite, conspicuous amounts of pyrophyllite together in places with andalusite, chloritoid and staurolite.

In certain instances very siliceous varieties have been completely recrystallized and resemble quartzites. In such cases the sericite has been reconstituted into fairly large muscovite crystals, often with small amounts of staurolite together at times with apatite. Occasional garnets were also noted. The felsic tuffs are frequently associated with and in places apparently gradational into chlorite and talc-chlorite schists.

Analyses of two varieties of felsic tuffs are presented in columns 5 and 6 of Table IV and their localities shown in Fig 2. The former analysis is of the widespread variety of fine-grained friable siliceous quartz-sericite rock of the type shown in Plate IIa, and the latter of the aluminous well-bedded pyrophyllite tuff depicted in Plate Ia. A feature of many of these tuffaceous rocks and particularly the more siliceous varieties is their strongly sheared and lineated nature. This generally increases in intensity towards the granite contact with the lineation taking the form of a steeply plunging "stretch" or "a" variety (Plate IIa). Minute "crinkle" or crenulation folds are often associated with this type of lineation and are widespread in similar rocks around the whole Mountain Land.

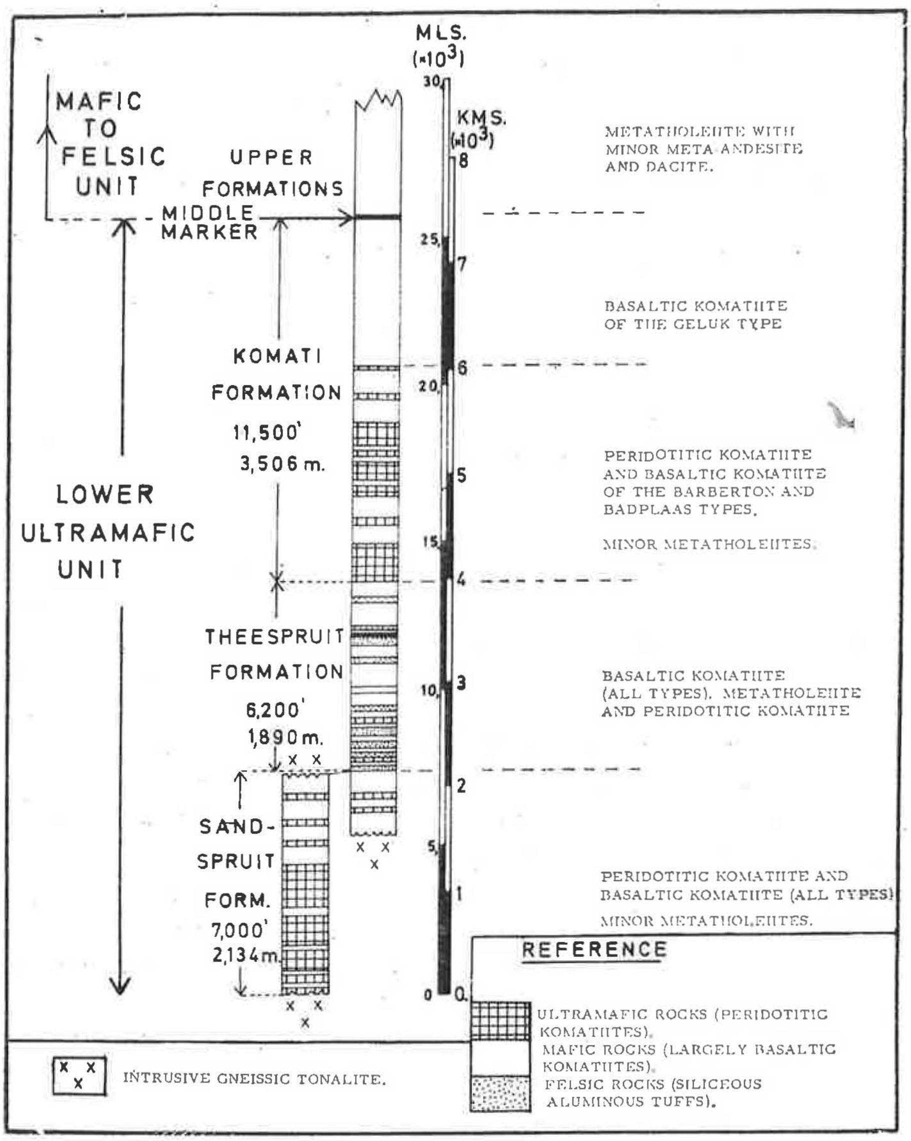

Fig. 3. Stratigraphic column of the three lower formations of the Onverwacht Group.

The felsic horizons are often immediately overlain by, or closely associated with, narrow generally impersistent bands and lenses of black siliceous cherty sediments (Plate Ib). These do not have the fine-grained porcellanous nature of typical chert but are often somewhat coarser grained and duller. They consist dominantly of a fine-grained quartz mosaic with abundant black carbonaceous matter generally scattered throughout, but in places becoming somewhat concentrated into layers. Cherty bands and lenses of this nature often sporadically overlie cycles of tuffaceous material both on a small and a large scale (Plate 1b). This suggests that their origin was closely related to the end phases of felsic pyroclastic activity and is probably to be ascribed to precipitation from silica-charged waters developed as a result of the explosive acid magmatism. A closely analogous situation exists within the upper formations of the Onverwacht Group where acid volcanics are frequently overlain by substantial chert horizons. Although most of the cherts appear to have formed by silica precipitation in the manner outlined above, certain cherty rocks with sedimentary structure such as cross-bedding have been found (Plate IIb). It is suggested that these could have represented fine-grained siliceous tuffs which were deposited by normal sedimentary means and then perhaps further silicified by the silica-charged environment. Similar phenomena have been described by van den Berg (1969) and the authors in some of the sediments from upper formations (Paper No. 6).

Primitive fossil forms have recently been reported in certain carbonaceous cherty rocks from the base of the Theespruit formation, making these the oldest known life forms yet found on earth (Engel *et al.*, 1968). Very recent biogeochemical studies at the National Aeronautics and Space Administration biological laboratories at Moffet Field, Paulo Alto, have revealed evidence for the existence of porphyrins in these cherts (Kvenvolden, 1969), thereby supporting the presence of the primitive fossil morphologies referred to above.

The mafic rocks of the Theespruit formation consist of a varied assemblage of lavas and tuffs. Pillow structures, spherulites and variolites, although not plentiful, are encountered in places, but the lavas are more generally massive. Near the granite contacts these rocks have suffered upper greenschist and more rarely amphibolite facies metamorphism and are generally dark green to almost black in colour. Away from the granite contact the metamorphic grade drops off rapidly to a greenschist assemblage manifested generally by lighter coloured rocks.

At the granite contacts the amphibolitized basalts consist essentially of hornblende or actinolitic hornblende with variable amounts of sodic plagioclase and some quartz. An analysis of a rock of this type is given in Table IIA, column 9, and its locality shown in Fig. 2. Locally the metabasalts are composed almost exclusively of amphibole. Other minerals encountered include pyroxene of a diopsidic composition, as well as epidote occupying fine fractures or as irregular patches resulting from the saussuritization of plagioclase. Accessory minerals include magnetite, sphene, ilmenite and leucoxene. Away from the granite aureole the metabasalts are generally green or grey-green, this colouration often being an indication of the presence of substantial amounts of carbonate and chlorite. The main minerals encountered include actinolite, tremolite, chlorite, epidote, plagioclase and carbonate, all of which vary considerably in their proportions. Some of the carbonated and somewhat schistose rocks have a distinctly pitted appearance due to the weathering-out of carbonate blebs. Petrologically these varieties are composed of a fine-grained felted mass of tremolite-actinolite and chlorite crystals broken every now and then by roughly spherical masses of almost pure carbonate with invariable iron staining. Strongly carbonated layers and bands with commonly associated chlorite and quartz, together with almost pure carbonate lenses, are frequently present in the lava. Similar material is characteristic of the interstices between pillow structures and could in part represent an original impure carbonate-rich oceanic ooze, into which the lavas were extruded. It is also possible that some of the carbonate was "sweated" out of the lavas during metamorphism to form bands and lenses by a process of lateral secretion. The question of carbonitization in general, and particularly its effect on the original chemistry of the Onverwacht volcanic rocks is discussed elsewhere (Paper No. 3).

A variety of layered to finely layered and often sheared mafic schists occur interlayered with the more massive metabasalts described above. On the east limb of the Onverwacht anticline, in the vicinity of the Doornhoek pluton, these schists are closely associated with the felsic schists or tuffs and are considered by the authors to represent sheared mafic tuffs. They consist largely of chlorite and tremolite-actinolite, often with fine bands or layers of carbonate. As noted previously the felsic tuffs are also closely associated with sheared talc-chlorite and talc-chlorite-carbonate schists, also probably representing mafic or ultramafic tuffs.

Ultramafic rocks although fairly well represented in the Theespruit formation are not nearly as widely developed as in the underlying Sandspruit or overlying Komati formations (Figs. 2 and 3). They occur generally as resistant bands, lenses and pods which are largely conformable to the stratigraphy of the formation. Where best preserved they are usually fine-grained dense rocks of a dark blue-green colour and resemble more the ultramafics of the Komati formation. They are, like similar varieties in the latter formation, comprised largely of antigorite and contain variable but generally lesser amounts of tremolite, chlorite and magnetite. They often grade into talcose and talc-chlorite-carbonate rocks.

IV. THE KOMATI FORMATION

The Komati formation attains a thickness of 3,506 metres (11,500 ft.) in the type area in the southern portion of the Mountain Land (Figs. 2 and 3) and consists of an alternating sequence of amphibolitized, pillowed and massive basalt and ultramafic bands. An important feature is the absence of interlayered sediments or acid rocks, although intrusive bodies of felspar and quartz porphyry are plentiful and rather typical. The ultramafics predominate in the lower half of the formation where a striking feature is the sympathetic thinning of individual ultramafic and pillow basalt horizons (Figs. 2 and 3). This, together with other features of the ultramafics described in an accompanying paper, have been employed to prove the extrusive origin of most of these rocks.

A. Ultramafic rocks

The ultramafic rocks will be described in detail in Paper No. 5. To summarize, they are in places remarkably fresh-looking, fine-grained dense rocks with a dark blue-black colour. Microscopic examination, however, reveals extensive alteration and serpentinization with only rarely preserved kernels of olivine in a groundmass of antigorite, tremolite, chlorite and magnetite.

All of these peridotitic rocks have a distinctive and unusual chemical composition. They are unlike any class of peridotitic or picritic rock known and a new name, peridotitic komatiite, after the Komati formation where they are best developed and preserved, has been proposed. An average analysis of peridotitic komatiite from the Komati formation is given in column 5 of Table I.

B. Mafic rocks

Detailed geochemical investigations of the mafic rocks of the lower three formations have been carried out mainly on the Komati formation. Closely similar mafic varieties are present in the lower two formations as is indicated by field and petrological investigations, but only limited geochemical studies were carried out on these because of their generally more highly metamorphosed state. The mafic rocks of the Komati formation (derived almost exclusively from basalts) are generally green to grey-green amphibolites composed of variable amounts of tremolite-actinolite, cummingtonite, anthophyllite, zoisite, chlorite, talc, oligoclase, quartz and carbonate. Detailed field, petrological and geochemical investigations have led to the identification of four general types although it is probable that gradations exist between these. One class, which is of limited extent, is comparable to a known class of basaltic rock, viz. tholeiites. The three remaining and most widespread types, however, are chemically distinctive and unlike any known class of basaltic rocks yet described. Together they constitute a distinctive "primitive" group for which the term Basaltic Komatiite is proposed. The composition of these rocks has generally rendered them very susceptible to shearing and many outcrops take the form of generally low, jagged ridges of the type illustrated in Plate IIIa.

1. Basaltic Komatiite

This class constitutes the bulk of the mafic rocks of the Komati formation and has been divided into three varieties, viz:

(i) The Barberton type,
(ii) The Badplaas type,
(iii) The Geluk type.

(i) *Barberton type*

In the type area basaltic komatiites of the Barberton type are always intimately associated with the ultramafics (peridotitic komatiites) of the lower portion of the Komati formation (Fig. 3). Several pillowed flows associated with massive phases or early, near contemporaneous sills constitute individual mafic horizons which alternate with the ultramafics (peridotitic komatiites).

The pillow structures are of variable shape and size, usually well formed, and often have conspicuous darker and finer, somewhat "crackled"-looking chilled selvedges, generally up to several centimetres wide. A typical group of pillows is illustrated in Plate IIIb. Variolitic and/or spherulitic textures are diagnostic features, being particularly plentiful in the pillowed zones, where they take the form of light-coloured orbicular patches (Plate IVa) often with a clear zonal arrangement within the pillows. The average diameter of these variolites is of the order of a few centimetres, but they may be as large as 10 cm. or more in certain instances. In many cases adjoining variolites merge to form very large irregular light-coloured variolitic patches (e.g. the upper and lower parts of Plate IVa). The etching of the variolites often produces a surface of small craters, rimmed by more resistant ridges, or else the variolites are uniformly resistant to weathering, producing small light-coloured domical features. Both of these modes of weathering are illustrated in Plate IVb. Amygdales are rare, but white vein-quartz frequently occurs in the voids between pillows and is often found occupying large horizontal gas cavities within individual pillows (Plate Va). These invariably occur towards the upper part of the pillows and are therefore useful indicators of the direction of younging.

Microscopically, basaltic komatiites of the Barberton type are composed mainly of amphibole in the tremolite-actinolite range, occurring as stubby laths in the massive varieties and as long slender randomly orientated needles in the pillowed varieties. This mineral represents the alteration of diopsidic pyroxene, remnants of which are occasionally encountered. Varying amounts of soda-plagioclase (generally oligoclase), chlorite, zoisite, epidote, carbonate and quartz are also frequently observed, generally as finer-grained crystals or fibrous aggregates between the amphiboles (Plate Vb). In many places these rocks take the form of massive, tough and resistant, coarsely crystalline amphibolites characterized by huge actinolite needles attaining lengths of up to 10 cm. and more (Plate VIa). Such zones which vary in width from a few metres to about 20 metres always appear to lie parallel to the general layering of the Komati formation. In some instances the large amphibole needles are randomly orientated but frequently they display a very strong parallel alignment, generally giving a marked, near vertical, lineation (Plate VIa). A horizontal or near horizontal growth of parallel actinolite needles was also noted in some places. The material interstitial to the dark green actinolite needles has a light grey-green colour and is comprised largely of finely intergrown chlorite, epidote, clinozoisite and quartz derived mainly from felspathic material. The origin of these coarsely crystalline amphibolites is problematical and two main possibilities exist. In the first instance they could have formed during the period of regional greenschist metamorphism which affected the whole area, in zones of shearing and greater volatile activity under conditions which allowed for large crystal growth. Another possibility is that they formed at the time of subaqueous extrusion of the lava as a result of access of water and rapid cooling or quenching. They could perhaps therefore be closely analogous to the "crystalline quench" structures developed in the associated meta-peridotites (peridotitic komatiites) described in an accompanying paper (No. 5).

Selected chemical analyses of both the pillowed and the massive varieties of basaltic komatiites of the Barberton type from the type area are given in Table IIA columns 1, 2, 3, 7 and 10, and their localities shown in Fig. 2. These analyses will be discussed later.

The lighter-coloured spherules or variolites consist largely of a quartzo-felspathic mosaic often including numerous scattered, partly altered pyroxene crystals and frequently containing scattered carbonate replacement bodies. An analysis of a large spherule of the type shown in Plate IVa is given in Table IIA, column 11.

In some areas the lavas are extensively carbonated and assume a rusty brown appearance. In such instances carbonate, often with minor quartz and chlorite, generally occurs to the near exclusion of all other minerals. The question of carbonization, its cause and the drastic effect it has on the chemistry of the mafic rocks of the Onverwacht Group is discussed in an accompanying paper (No. 2).

(ii) *Badplaas type*

Basaltic komatiites of the Badplaas type are, like the variety discussed above, closely associated with the peridotitic komatiites of the lower part of the Komati formation and can usually be recognised in the field by their generally more coarsely crystalline but even-granular texture, massive pyroxenitic appearance and lighter, somewhat olive green, colour. Although pillow structures have been found, most of the material appears to take the form of massive possible near contemporaneous sills. Rocks of this type are perhaps better termed metapyroxenites as they are composed almost entirely of tremolite-actinolite derived from a diopsidic pyroxene, remnants of which are sometimes encountered. Typical analyses of the Badplaas type are given in columns 1 and 2, Table IIB. The genetic significance and probable origin of these rocks is discussed elsewhere (Paper No. 11).

(iii) *Geluk type*

In the southern portion of the Barberton Mountain Land basaltic rocks of this type appear to be confined to the upper portion of Komati formation in the region which lacks the abundant interlayered ultramafic material encountered lower down (Fig. 3).

Pillow structures are well developed in places but lack the conspicuous spherulitic textures and gas cavities encountered in the two other varieties of basaltic komatiite (Plate VIb). Varying proportions of chlorite, magnesium and calcium amphiboles, talc, epidote, carbonate and very minor plagioclase constitute the main minerals, this assemblage having given rise to incompetent rocks which are strongly sheared in numerous instances. An analysis of the Geluk type from the type area is given in Table IIC, column 9.

In many instances, long amphibole needles of a similar nature to those described from the Barberton type basaltic rocks are also present and have undoubtedly developed in the same manner as the amphiboles in the latter. In the upper part of the Komati formation in both the Onverwacht and Steynsdorp anticlines lenses and blebs of carbonate become conspicuous in the Geluk-type metabasalts, becoming more numerous towards the top and eventually grading into well-banded tuffaceous shales or palagonitic tuffs. These comprise narrow bands of dark green chloritic and carbonaceous material alternating with bands of almost pure carbonate and constitute part of the banded chert and carbonate sediment known as the Middle Marker. This important marker separates the distinctive lower formations of the Onverwacht Group from the upper formations and has been described in detail elsewhere (Viljoen *et al.*, 1969, and accompanying Paper No. 6).

2. Meta-Tholeiite

This group is not widespread in the Komati formation and only appears to be sporadically developed at a few localities, mainly in the vicinity of the basaltic komatiites of the Barberton type. Massive and pillowed varieties are present.

The meta-tholeiites are recognised by a relatively high content of soda plagioclase together with conspicuous green chlorite and minor actinolite. Sulphides and opaque oxides are generally conspicuous and quartz is sometimes encountered. An analysis of a meta-tholeiite from the Komati formation type area is given in column 1 of Table III.

C. Porphyries

Besides the distinctive mafic and ultramafic rocks described above, the Komati formation is characterized by the abundant development of scattered felspar and quartz porphyry bodies. They vary in length from a few metres to about 2,000 metres and generally occur as elongate but somewhat irregular masses largely conformable to the overall layering of the Komati formation. They are readily recognised by their slightly greater resistance to erosion than the surrounding mafic and ultramafic rocks, as well as their distinctive light yellow or yellowish green to yellowish brown colour on weathered surfaces.

Hall (1918) was of the opinion that these rocks formed an integral part of the Onverwacht stratigraphy possibly representing contemporaneous felsic volcanics. In this respect it is of interest to note that the elongated but detached porphyry lenses often tend to remain in one stratigraphic position for long distances. Definite intrusive relationships have however been found so that although it is probable that they are virtually contemporaneous with the mafic and ultramafic vulcanicity they do not represent extrusives. The porphyry bodies appear to have no strong preference for the rock type into which they intrude although to the east of the type region where they are of a much larger size and more extensively developed they appear to be largely confined to the ultramafic rocks.

Felspar-bearing porphyries are the most common variety although quartz phenocrysts are often conspicuous as well. The phenocrysts which average several millimetres in diameter are clearly seen on both fresh and weathered surfaces, the felspars generally taking the form of euhedral to subhedral white patches and the quartz occurring as angular to rounded transparent to translucent blebs. Most of the felspar phenocrysts are albitic in composition, often zoned and generally strongly sericitized, whereas many of the quartz phenocrysts show signs of corrosion. The phenocrysts occur in a matrix comprised largely of fine-grained quartz and sericite. Carbonate is widely present in most instances occurring as disseminated patches which pervade the whole rocks. An analysis of a typical porphyry from the Komati formation is given in Table IV, column 7, and the average of three additional partial analyses for Na_2O and K_2O in column 8. An analysis of a well-preserved, very soda-rich porphyry is given in Table IV, column 9.

V. CORRELATION OF THE LOWER ULTRAMAFIC UNIT

A. Introduction

The description of the stratigraphy of the lower part of the Onverwacht Group as presented above applies specifically to the southern portion of the Barberton belt and more particularly to a well-developed and well-preserved section on the west limb of the Onverwacht anticline where the type section has been established. Previously, as noted in an accompanying paper (No. 2), the well-preserved area of Onverwacht volcanics in the southern portion of the belt was considered to be the only region where this important group was extensively developed (Visser, compiler, 1956). The variety of basic, ultrabasic and associated schistose rocks surrounding the remainder of the belt, and lying conformably below the Fig Tree Group, were all considered to represent part of the basic assemblage of the supposed post-Moodies, called Jamestown Intrusive Igneous Complex (Visse *et al.*, 1956). As has been shown elsewhere (Viljoen and Viljoen, 1967, and accompanying Paper No. 2) the large majority of these rocks actually represent the more highly altered equivalents of the lower formations of the Onverwacht Group and the Jamestown Igneous Complex as previously defined no longer exists (Ferguson, 1967).

Based on a preliminary stratigraphic column for the Onverwacht Group (Viljoen and Viljoen, 1967) a correlation of the pre-Fig Tree rocks in the northern and southern parts of the Mountain Land was suggested (Anhaeusser *et al.*, 1966). With further detailed work by the authors in the southern part of the Mountain Land, the earlier threefold division of the Onverwacht Group has been amended so that the present stratigraphic column contains six formations (see Paper No. 2). Recent investigations, both detailed and reconnaissance by both the authors and Anhaeusser (1969) in other parts of the Barberton Belt, have resulted in a considerable amount of new geological, petrological and particularly geochemical data. In the present section all available data are synthesized and a new correlation of the Onverwacht Group around the entire Mountain Land, based largely on lithological and geochemical grounds, is proposed.

A striking feature is the fact that, almost without exception, the rocks of the Onverwacht Group away from the type area in the south belong almost exclusively to the Lower Ultramafic Unit, and more particularly to the Theespruit and Komati formations of the latter. In the discussion on the lithostratigraphic correlation, given below, in which each formation is discussed in turn, it should be pointed out that, as would be expected, local as well as lateral regional variations and facies changes occur within each of the formations. These are never great enough, however, to alter the identity of each distinctive formation.

B. Sandspruit formation

The only area where the Sandspruit formation appears to be well preserved is in the type area in the southern part of the Mountain Land. Here, as noted previously, it occurs largely in the form of a series of xenoliths almost encircling the Theespruit pluton in the core of the Onverwacht anticline (Fig. 1). A small occurrence is also situated along the Swaziland border on the eastern side of the Steynsdorp tonalitic gneiss pluton in the core of the Steynsdorp anticline (Fig. 1). These are the only two areas where the formation has been positively identified, although it is the authors' contention that many of the mafic and ultramafic bodies within the ancient tonalitic gneiss terrain are probably remnants of the Sandspruit formation.

C. Theespruit formation

The Theespruit formation is one of the most widely developed and most easily recognisable of the entire Onverwacht Group due to the presence of the distinctive siliceous and often aluminous felsic schists. In the southern portion of the belt this formation attains its best development in the core of the Onverwacht anticline where the type area has been established (see previously).

The formation is also well developed, although strongly sheared, in the core of the Steynsdorp anticline where it occurs in the form of a broad arc draped around the Steynsdorp tonalitic gneiss body (Fig. 1).

In most other areas around the entire periphery of the Mountain Land, rock types and assemblages correlated with the Theespruit formation occur in contact with the various granite types which envelop the area. Assemblages which bear a striking similarity to the Theespruit formation in the type area occur along the north-western flank of the Mountain Land. Here the formation constitutes much of the tightly folded Jamestown synclinal belt, is well developed on the northern limbs of the Lily and Eureka synclines in the area between the Consort Mine and Louw's Creek, and flanks the Kaap Valley Granite as a narrow sliver on the eastern margin of the latter (Anhaeusser *et al.*, 1966; Annhaeusser, 1969). In all these areas a narrow zone comprising a variety of dark hornblende or actinolitic hornblende amphibolites, mineralogically identical to similar rocks in the type area of the Onverwacht Group, occur along the immediate granite contacts. Away from the contacts these rocks become greenish in colour, reflecting an increase in the amount of actinolite or chlorite concomitant with a decrease in the grade of metamorphism of the amphibolites. Analyses (quoted in columns 2, 8 and 10 of Table III) clearly indicate the derivation of these amphibolites from original basaltic rocks, confirmed also by the occasional occurrence of well-developed pillow structures as well as variolites (N. Harte, verbal communication, 1967; Anhaeusser, 1969). Forming an integral part of the amphibolite assemblage described above are numerous resistant serpentinite pods and lenses generally associated with, and gradational into, less resistant zones of talcose chlorite, tremolite and carbonate schists (Anhaeusser, 1969). Mineralogically these serpentinitic bodies are identical to similar rocks (komatiites) in the Theespruit and Komati formations of the Onverwacht type area. Associated with the above-mentioned rock types are a variety of highly distinctive quartz-sericite rocks and associated aluminous schists, cherty siliceous sediments and minor shales. These rocks are remarkably similar to the diagnostic siliceous and aluminous felsic tuffs that occur in the Theespruit formation in the Onverwacht type area and it is largely on the basis of this distinctive rock type that a correlation has been effected. Apart from the almost pure quartz-sericite varieties which are the most widely developed, fuchsite-bearing varieties and aluminous schists containing andalusite, pyrophyllite, and more rarely sillimanite, as in the granite contact region to the north of the Consort Mine, are also well represented. Other minerals found in these rocks include chloritoid, staurolite, almandine garnet, plagioclase, muscovite, clinozoisite, leucoxene, magnetite and ilmenite (Anhaeusser and Viljoen, 1965; Anhaeusser, 1969). As in the Onverwacht type area many of these rocks are capped by siliceous cherts or cherty quartzites which often terminate particular depositional cycles and are hence useful indicators of the younging direction of the sequence. Apart from the strong foliation or schistosity generally present in these schists, they frequently also contain a conspicuous near-vertical "stretch" lineation. Numerous minor and accordion folds with near horizontal axial planes are widespread in these rocks and often deform the above-mentioned lineation. Two total silicate analyses of typical aluminous siliceous schists from the eastern portion of the Jamestown schist belt, as well as the average of five partial analyses of similar varieties from the same area, are listed in columns 1 to 3 of Table IV and will be discussed later.

A number of sedimentary horizons not altogether typical of the type area also occur in the Jamestown schist belt. These include black carbonaceous cherts with intercalated slaty shales, ferruginous slates, grits and in places conglomerates or more probably volcanic agglomerates. None of these horizons is very thick or well developed however, and they in no way mask the fundamental identity of the Theespruit formation in this area.

East of Louw's Creek in the Stentor anticlinal structure, mafic rocks, with the exception of the local development of chloritic schists, as well as ultramafic rocks, are only poorly represented. A broad succession of white to grey siliceous and aluminous felsic schists probably derived largely from original tuffs is virtually the only component of the Theespruit formation developed. The main minerals in the latter rocks are quartz, forming a mosaic of small grains, pyrophyllite and sericite. Other minerals include chlorite and soda plagioclase. The latter mineral, together with larger quartz masses, often occurs as conspicuous "knots" around which the schistosity is draped. An interesting feature is the occurrence at the contact between the felsic and mafic schists of barite which is described in an accompanying paper (No. 9).

Assemblages which, although having certain similarities with the Theespruit formation, are not as readily correlated with the latter are encountered in the extreme north-eastern part of the Mountain Land and along its eastern flank in north-west Swaziland.

In a broad strip along the granite contact in the area between Kaapmuiden and Hectorspruit occurs a succession consisting largely of massive and pillowed meta-tholeiitic lavas. Siliceous felsic schist horizons, as well as magnesian-rich basalts and schists, characteristic of the Theespruit formation in the type area, although present are not, however, widely developed in this area. In addition, narrow intercalated layers of banded chert and ironstone, not typical of the Theespruit formation in the type area, are also developed in places.

A variety of actinolite-tremolite-chlorite as well as talc-chlorite schists with narrow intercalated quartzitic, sericitic, and associated cherty and shaly interlayers occurs along the eastern margin of the Mountain Land, adjacent to the granite, in Swaziland and adjoining portions of the Transvaal. Some of the quartz-sericite schists contain andalusite (Jones, personal communication) and serpentinite lenses and bands are sometimes also encountered. The assemblage thus appears to contain most of the components of the Theespruit formation and is therefore correlated with the latter.

In the Forbes Reef area of Swaziland and farther south towards the south-eastern termination of the Barberton belt, much of what has been termed the Metasedimentary Group (Urie and Jones, 1965) has been correlated with the Theespruit formation by the authors. This Group, which occurs at the base of the sequence in this area and in contact with the granite, consists essentially of dark greenish-grey amphibolites constituted largely of actinolite or hornblende with smaller amounts of plagioclase, quartz, chlorite, biotite and diopside (Urie and Jones, 1965). Interlayered siliceous horizons including recrystallised banded cherts, quartzites and quartz-sericite schists also occur within the succession. The main mineral is quartz with varying amounts of sericite, andalusite, biotite, and muscovite with amphibole, felspar, chlorite, epidote and sphene occurring less frequently. The association of andalusite-bearing quartz-sericite schist horizons within actinolitic schists is considered strong evidence for correlating the so-called meta-sedimentary groups with the Theespruit formation.

It is the authors' contention that many of the xenoliths occurring within the granitic terrain surrounding the Mountain Land can be correlated with the Theespruit formation. This applies particularly to the xenoliths containing narrow quartzitic, sericitic or shaly zones in association with mafic and ultramafic rocks. Examples include the xenoliths within the tonalitic gneiss terrain to the south-west of the Mountain Land, especially in the vicinity of Bosmanskop, numerous xenoliths within similar terrain in Swaziland, the large xenolithic body at Barclay Vale, as well as part of a xenolithic mass to the north-west of Badplaas in which the Kalkloof body occurs (Fig. 1).

D. Komati formation

The Komati formation attains its best development and is best preserved in the core of the Onverwacht anticline where it is immediately overlain by the Middle Marker which separates the three lower from the three upper formations of the Onverwacht Group. After being eliminated by intrusive granites in the

Kromberg syncline the marker appears again in the Steynsdorp Valley where it defines the Steynsdorp anticline (Fig. 1) (Viljoen *et al.*, 1969). In this area much of the tight anticlinal structure is comprised of basaltic komatiite of the Geluk type as defined previously with only a reduced amount of ultramafic material in the form of serpentinites and talc-carbonate rocks forming the lower ultramafic part of the Komati formation in this area. Away from the southern area, the Middle Marker has not as yet been identified, although assemblages correlated with the Komati formation are widespread around the Mountain Land (Fig. 1).

It is convenient, because of certain strong similarities, to discuss the correlatives of the Komati formation along the whole western flank of the Mountain Land together. In this region assemblages correlated with the Komati formation generally occur between the Theespruit formation in immediate contact with the intrusive granites and the overlying sedimentary succession of the Fig Tree Group. Rocks of the Komati formation comprise the synclinal Nelshoogte schist belt (Fig. 1), as well as the core of the synclinal Jamestown schist belt at the eastern end of the latter. In addition the formation is extensively developed in the area between Kaapmuiden and Malelane along the northern flank of the Mountain Land. Smaller slivers of Komati formation assemblages partly connect the abovementioned areas of best development. Other assemblages which have been correlated with the Komati formation also occur at the western extremity of the Jamestown schist belt, in the vicinity of Kaapsehoop, as well as farther west as an inlier, exposed by the erosion of the Transvaal System, in the Elands River valley (Fig. 1). In all these occurrences, the main features are the almost complete absence of interlayered sediments or felsic volcanics and an abundance of ultramafic and magnesian-rich basaltic rocks. The ultramafics take the form of extrusives or near-surface sill-like bodies and occur typically as resistant bands and lenses of green serpentinite or partly serpentinized and metamorphosed green to dark blue-black peridotites, generally lying parallel to the overall stratigraphy. In the more strongly deformed areas such as in the Jamestown schist belt, these serpentinites gives way to zones of tremolite, talc, or talc-carbonate-chlorite rocks. The magnesium-rich schists (meta-basalts), with which the serpentinites are interlayered, include tremolite-actinolite schists, chlorite-talc schists, tremolite-chlorite-talc schists as well as a variety of dolomitic and carbonated rocks, the latter often occurring in zones of strong structural disturbance.

Mineralogically and chemically all of these rocks are closely similar to the variety of so-called komatiites, both of the peridotitic and basaltic types, as defined in the type area of the Komati formation. Although, because of their more highly sheared state, diagnostic volcanic structures such as pillows and variolites are rare, these have been encountered in the less sheared basaltic rocks of the western and eastern ends of the Jamestown schist belt (N. Harte, verbal communication, and Anhaeusser, 1969). No unequivocal evidence supporting an extrusive origin for the ultramafic rocks has been obtained in this region, although the presence of two unequivocal peridotitic dykes in the Jamestown schist belt, well exposed in a gorge cut by the Noordkaap River, supports the existence of a peridotitic magma as adduced also from evidence in the type area of the Komati formation (see accompanying Paper No. 5). These dykes are shown in Plates VII (a) and (b). The largest individual, which averages about 15 cm. in width (Plate VII (a)), could be traced for several tens of metres along an exposure on the river bank. Both dykes have sharply defined contacts and display a slightly darker and finer-textured chill margin clearly seen in Plate VII (b). Both dykes are unfortunately serpentinized and are composed of conspicuous antigorite and lesser amounts of tremolite, chlorite and magnetite. They are intrusive into a large peridotite mass of similar composition. A partial chemical analysis of the largest dyke shown in Plate VII (a) is presented in Table I, column 7. The high water content renders the analysis unsuitable for comparison with the better-preserved specimens from the Komati formation type section. Bearing these limitations in mind, however, and comparing the chemistry of the dyke with the more highly serpentinized peridotites from the Komati formation type area (columns 3 and 4, Table I, of Paper No. 3) it is clear that strong similarities exist. These support the authors' contention of the existence of an early widespread peridotitic magma of distinctive chemistry (Papers No. 3 and 11).

Analyses of basaltic komatiites of all three varieties mainly from the area between Kaapmuiden and Malelane (see Fig. 2) are given in Table II, A, B and C. A description of the basaltic and ultramafic rocks of the latter area has been given elsewhere (Viljoen and Viljoen, 1969).

Except for a small patch at the south-eastern extremity of the Mountain Land, it would appear from available evidence that along the whole eastern edge of the belt correlatives of the Komati formation are poorly if at all developed. To the south in the Forbes Reef area, however, the so-called Magnesian Series of Urie and Jones (1965) is correlated with the Komati formation. The magnesium-rich schists of this area are represented by a wide variety of serpentinous, amphibolitic and talcose rocks which appear to be largely, if not entirely, derived from original ultrabasic rocks. Siliceous horizons are virtually absent, although a few very narrow and not very extensive chert bands have been recorded. An analysis of a magnesium-rich schist from this area is given in column 6, Table I. The similarity with the peridotitic komatiites from the type area is clear and it is contended that the dominant original component of the Komati formation in this area was peridotitic komatiite which occurred to the near exclusion of basaltic varieties.

As with the Sandspruit and Theespruit formations, it is contended that certain of the xenoliths within the granite terrain surrounding the area, and particularly some of the ultramafic and mafic varieties, could represent fragments of the Komati formation. To resolve the question of which of the lower formations a particular xenolith should be ascribed to, however, a detailed consideration of the rock types within the xenolith, their associations, petrology and probably also their chemistry would be necessary.

E. Layered, Differentiated Ultramafic Bodies

Intimately associated with the variety of dominantly extrusive mafic and ultramafic rocks described above and forming an integral part of the Lower Ultramafic Unit are a number of well-layered intrusive, sill or pod-like ultramafic bodies. On the basis of their products of differentiation, three main types have been recognized (Viljoen and Viljoen, 1969). These are:—

(1) The Kaapmuiden type.
(2) The Noordkaap type.
(3) The Stolzburg type.

1. *The Kaapmuiden Type*

This variety is confined to the Komati formation between the towns of Kaapmuiden and Malelane, and has been described in detail elsewhere (Viljoen and Viljoen, 1969). To summarise, three well-layered ultramafic sills, attaining thicknesses of over 610 metres (2,000 ft.) have been emplaced into a broad belt of volcanic rocks with minor interlayered sediments. They are all characterized by broad lower dunitic and peridotitic zones which pass upwards abruptly into rather narrow zones of bronzitite and websterite, followed by very narrow anorthositic gabbro/norite zones. The latter are followed in turn by another broad sequence of dunites and peridotites. Secondary alteration of the dunitic and peridotitic zones has given rise to the extensive development of magnesite and talc which are typical of the Kaapmuiden as well as related types of ultramafic bodies in this area (Paper No. 9). Asbestos mineralization, although present, is generally not well developed.

The bulk chemical composition of these bodies, computed by combining the chemistry of each major rock type in the correct proportions, has been shown to be virtually identical to the average composition of the peridotitic komatiite flows of the Komati formation in the southern portion of the Mountain Land (Paper No. 11).

Two other sill-like dunitic bodies of an identical nature to the dunite or dunite-peridotite assemblages of the Kaapmuiden-type bodies, but without any sign of pyroxenitic or gabbroic rocks, are also present in the area. These, termed the Magnesite and Central Bodies, are generally highly altered and contain most of the important magnesite and talc deposits of the area (see Paper No. 9). Also present in the region is a layered and differentiated mafic body, the Canal Body. All of the layered and differentiated bodies of the area are closely associated with and generally intrusive into an assemblage of magnesium-rich basic rocks (basaltic komatiites) (Fig. 1). The significance of these bodies with respect to an understanding of the genesis of most of the mafic and ultramafic rocks of the lower formations of the Onverwacht Group is discussed in the concluding Paper No. 11 and will not be elaborated upon here.

2. *The Noordkaap Type*

A number of distinctive layered ultramafic bodies termed the Noordkaap type (Viljoen and Viljoen, in press) occur in the eastern portion of the Jamestown schist belt, immediately to the west of the town of Noordkaap. Two main masses, viz. the Handsup and Mundt's Concession bodies, as well as a few smaller disconnected occurrences in the same general area have been recognised (Anhaeusser, 1969). Although the bulk chemical composition of these bodies is closely similar to the bulk chemical composition of the Kaapmuiden type ultramafic bodies (see accompanying Paper No. 11), the style and products of differentiation are somewhat different. The bodies consist of a number of cyclic differentiated units comprising a minimum of four differentiation cycles (Anhaeusser, 1969). Most cycles commence with olivine peridotites, pyroxenites and finally fairly extensive gabbros with small patches of anorthositic gabbros in places (Anhaeusser, 1969). Certain of the rock units mentioned above may be missing in individual cycles. All of these rocks have suffered alteration and now consist essentially of serpentinites and amphibolites with only occasional remnants of primary mineral phases still being present. The bodies are of interest in that they contain small scattered deposits of the rare semi-precious serpentinous rocks verdite and budstone, in addition to small asbestos and magnesite deposits. The significance of the Noordkaap type ultramafic bodies with respect to theories on the genesis and processes of magmatic diversification of the rocks of the lower three formations of the Onverwacht Group has been discussed in an accompanying paper (No. 11) and the mineral deposits associated with them in Paper No. 8.

3. *The Stolzburg Type*

Differentiated ultramafic bodies of the Stolzburg type have been recognised at four localities in the Barberton Mountain Land (Viljoen and Viljoen, 1969, and in press). These include the Stolzburg body itself at the south-western extremity of the Mountain Land, established as the type occurrence, the Kalkloof body within a large xenolith of the lower Onverwacht assemblage in the tonalitic gneisses to the north-west of Badplaas, and several bodies in the Kaapsehoop area at the western extremity of the Jamestown schist belt. All of these bodies are typified by alternating layers of resistant orthopyroxenite (often altered to talc or bastite) and serpentinized dunites. They are thus distinguished from the two other varieties of ultramafic bodies described above by the near total absence of clinopyroxene and felspar-bearing rocks.

Asbestos mineralization is well developed in all of the occurrences and has been economically exploited in numerous places. The mineralization is discussed in more detail in an accompanying paper (No. 9) and the genetic significance of these bodies is considered in Paper No. 11.

All the ultramafic bodies described above as far as can be ascertained from present knowledge have been emplaced into the Komati formation more or less contemporaneously with the mafic and ultramafic vulcanicity typical of the latter.

VI. GEOCHEMISTRY OF THE LOWER ULTRAMAFIC UNIT

A. Introduction

Owing to the fact that the primary mineral assemblages of almost every rock type within the lower formations have suffered varying degrees of metamorphism from the amphibolite or epidote amphibolite facies near granite contacts to the greenschist facies farther away, the chemistry, rather than the mineralogy, has been important in classifying them. All available analyses of ultramafic, mafic and felsic rocks from the lower formations are listed in Tables I to IV. These data indicate that most of the rock classes recognized are totally unlike any widespread and generally accepted rock type yet described, and it is proposed in the present session to discuss their distinctive and unusual chemical features. The reasons for the introduction of a new class of igneous rock (with a number of sub-classes) for which the general name komatiite is proposed are given. The broad chemical characteristics of the mafic and felsic rocks will be discussed in turn, followed by a detailed consideration of the chemistry of the mafic and ultramafic rocks in relation to well-established rock classes.

B. Chemical Characteristics of the Rocks of the Lower Ultramafic Unit

1. *Ultramafic Rocks* (see Figures 1 and 2 for localities and Table I for chemical composition)

A full description of the geology and geochemistry of the relatively well-preserved assemblage of peridotitic rocks from the type area of the Komati formation has been given in an accompanying paper (No. 5). Evidence presented in that paper shows that these peridotitic rocks crystallized mainly subaqueously from a peridotitic magma with a distinctive and unusual chemical composition. The unique chemical character of this magma, the composition of which is presented in column 5 of Table I, led the authors to propose a new class of peridotitic rock, viz. peridotitic komatiite. The main features of this peridotitic rock are a high Ca/Al and Fe/Mg ratio and a low alkali content.

TABLE I

Selected Chemical Analyses of Ultramafic Rocks from the Three Lower Formations of the Onverwacht Group. (Excluding the Layered Differentiated Ultramafic Bodies.)

Column No.	1*	2*	3*	4	5	6	7*
Sample No.	87J	88J	VU33	Average	Average	FOR	UDI
SiO_2	46.29	44.85	43.11	44.72	41.61	43.60	36.84
TiO_2	0.68	0.51	1.35	0.52	0.31	0.08	
Al_2O_3	3.75	2.66	3.41	3.25	2.70	4.60	4.58
Fe_2O_3	6.96	6.90	4.10	6.02	5.63	1.53	3.96
FeO	5.18	4.91	6.46	5.52	4.35	4.14	6.40
MnO	0.19	0.20	0.19	0.19	0.17	0.10	
MgO	21.99	24.96	29.17	25.35	30.58	31.68	31.24
CaO	9.09	7.01	4.84	6.97	4.29	4.82	0.14
Na_2O	0.53	0.41	0.53	0.49	0.15	0.10	0.03
K_2O	0.06	0.05	0.05	0.05	0.03	0.11	0.03
P_2O_5	n.d.	n.d.	n.d.	n.d.	0.02	0.03	
H_2O^+	4.31	6.10	6.31	5.58	8.81	7.19	11.20
H_2O^-	0.10	0.34	0.16	0.21	0.22	0.18	0.24
CO_2	0.07	0.20	0.50	0.26		1.72	
Cr_2O_3	0.36	n.d.	0.36	0.36	0.32	0.37	
NiO	0.09	n.d.	0.19	0.14	0.18	0.10	
TOTAL	99.65	99.10	99.77			100.38	94.66

Analysts and Methods Used.

* National Institute for Metallurgy, Johannesburg. (Standard gravimetric, volumetric, colorimetric and flame photometric.)
Alkali determinations (flame photometric) as well as chromium and nickel determinations (X-ray fluorescence) by the authors.

Columns 1 to 4 Metaperidotites (peridotitic komatiites) from the Sandspruit Formation.
2 Tremolite, chlorite, antigorite and magnetite variety.
3 Tremolite, chlorite, antigorite and magnetite variety with numerous remnants of clinopyroxene.
4 Average chemical composition of 3 metaperidotites (peridotite komatiites) Sandspruit Formation.
5 Average chemical composition of peridotitic komatiites from the Komati Formation (Average of 8 analyses - see Paper No. 5).
6 Olivine-bearing amphibolite from the Magnesian Series (Komati formation) in the Forbes Reef Area of Swaziland (Urie & Jones, 1965).
7 Partly serpentinized peridotite dyke (peridotitic komatiite), Jamestown schist belt.

As has been shown elsewhere (Paper No. 11) the average bulk chemical composition of the layered differentiated ultramafic bodies of the Kaapmuiden and Noordkaap types is closely similar to the average chemistry of the peridotitic komatiite flows of the Komati formation and it is clear, as suggested in Paper No. 11, that they formed from the same peridotitic magma. The bulk composition of the Stolzburg type ultramafic bodies, however, differs considerably from the chemistry of the peridotitic komatiite magma. This is due to the fact that these bodies represent largely the accumulation of the high-melting refractory residues (olivine and orthopyroxene) from a parent peridotitic komatiite magma.

The chemistry of a typical magnesium-rich schist (Table I, column 6) from the Magnesian Series of Swaziland also has close similarities with the chemistry of the peridotitic komatiites of the type area (column 5, Table I) and confirms the geological and petrological conclusion that this series consists essentially of a huge pile of peridotitic komatiites.

As noted earlier, the peridotitic rocks from the Sandspruit formation occur in a similar geological setting to those in the Komati formation. Although they also bear a close mineralogical and chemical similarity to the peridotitic komatiites, they are not as ultrabasic as the latter (see column 4, Table I). They have higher silica, calcium, iron and alkali contents and lower magnesium contents than the peridotites of the Komati formation. Their alumina content is about the same, which means that they have an even higher Ca/Al ratio than the peridotites of the Komati formation. These chemical differences are indicative of an originally higher pyroxene (diopside) content and a substantially lower olivine content of the rock, and could reflect a fundamental evolutionary trend. The unusually high Ca/Al ratio of all classes of peridotitic komatiite in general is due largely to significant amounts of diopsidic pyroxene together with negligible amounts of plagioclase. Chemical data are not available from the peridotitic rocks of the Theespruit formation but their mineralogical composition suggests they are also of the peridotitic komatiite type, bearing a closer similarity to the peridotites of the Komati formation than to those of the Sandspruit formation.

2. *Mafic Rocks*

Although the chemistry of the mafic rocks is far more variable and erratic than the chemistry of the associated ultramafics, it was found, by a consideration of the geological setting, petrology and chemistry, that they could be grouped into four main classes. One of these represents the class of metatholeiites whereas the other three represent the varieties of basaltic komatiite, the geological setting and petrology of which have been described previously. The main chemical characteristics of the group of basaltic komatiites in general are a high magnesium content with fairly high silica and calcium contents and very low aluminium and alkali abundances. The chemical characteristics of each of the main classes of basaltic rock occurring in the area are discussed in turn.

(i) Basaltic Komatiites

The Barberton Type

Analyses of all rocks considered to be representative of the basaltic komatiites of the Barberton type are presented in Table IIA. The average chemical composition of three of the best preserved specimens, yielding the most consistent chemical

TABLE II A

Chemical Analyses of Basaltic Komatiites from the lower three formations of the Onverwacht Group. Basaltic Komatiite of the Barberton Type.

	1*	2*	3*	4	5†	6	7*	8	9*	10‡	11*
	AB9	VB4	AB4	Ave	KJ55	J6	P1		AB21	14J	RV14
SiO_2	52.42	52.78	53.00	52.73	53.35	56.28	51.06	50.74	46.48	46.28	57.92
TiO_2	0.72	0.91	0.92	0.85	0.46	0.73	0.90	0.70	1.43	0.67	0.62
Al_2O_3	8.64	9.43	11.43	9.83	10.13	8.38	8.71	10.97	9.02	10.59	7.77
Fe_2O_3	1.79	1.18	0.73	1.23	10.94	10.77	2.11	1.55	2.50	2.82	0.49
FeO	9.19	9.88	10.03	9.70	0.16	n.d.	8.80	9.65	13.21	9.72	6.20
MnO	0.23	0.22	0.22	0.22	n.d.	0.15	0.26	0.22	0.27	0.22	0.19
MgO	11.42	9.63	9.27	10.10	11.73	9.47	10.70	9.34	10.81	10.50	11.23
CaO	10.63	10.52	8.83	9.99	7.35	8.64	11.49	11.07	10.76	13.49	8.80
Na_2O	2.88§	2.18§	2.91§	2.65	1.46	3.30	0.72	2.66	1.67§	0.96§	2.30
K_2O	0.06§	0.92§	0.40§	0.46	0.10	0.29	0.17	0.34	0.11§	0.11§	0.18
P_2O_5	0.07	0.05	0.05	0.06	0.06	0.07	0.05	0.05	0.10	n.d.	0.04
H_2O^+	1.69	2.00	1.91		L.O.I.	1.00	3.41	1.45	2.35	3.51	2.60
H_2O^-	0.25	0.15	0.07		3.19	0.23	0.12	0.05	0.23	0.34	0.14
CO_2	0.14	0.12	0.16			0.11	1.44	0.92	0.25	0.38	1.60
TOTAL	100.13	99.97	99.93		98.93	99.46	99.94	99.71	99.19	99.59	100.08
Sr ppm	34.4	89.8	200.0				345.0			355.3	
Rb ppm	0.0	9.5	9.6				2.1			0.0	

Analysts and Methods used.
* National Institute for Metallurgy, Johannesburg. (Standard gravimetric, volumetric, colorimetric and flame photometric).
† Dr. J. Gurney, Dept. Geochemistry, University of Cape Town (X-ray fluorescence).
‡ Mr. I. Wright, Dept. Geology, University of the Witwatersrand, Johannesburg (X-ray flueorscence).
§ Alkali determinations by the authors (flame photometric).
L.O.I. Loss on ignition. Rb and Sr determinations by the authors (X-ray fluorescence).

Columns 1-3 Best available analyses of massive felspar-bearing metabasalts from the Komati Formation in the type area.
4 Average of above.
5 Amphibolitized metabasalt - Kaapmuiden-Malelane area.
6 Tremolite-actinolite schist, northern flank of Mountain Land (Anhaeusser 1969).
7 Pillowed and somewhat carbonated metabasalt from the Komati formation in type area.
8 Banded amphibole gneiss ("metasediment") Forbes Reef area Swaziland (Urie and Jones, 1965).
9 Massive amphibolite from the Theespruit formation in the type area (sample from close to granite contact).
10 Pillowed metabasalt from the Komati formation in type area.
11 Spherule from spherulitic pillowed metabasalts.

data (columns 1–3), is presented in column 4. One of the most distinctive chemical features of this type of basaltic rock is that calcium, aluminium and magnesium occur in more or less equal amounts (about 10% for each oxide). In addition, the silica and alkali contents of these rocks are also relatively high.

These chemical pecularities are ascribed to several main mineralogical features including a relatively high original diopside content together with a reasonably high plagioclase and sometimes quartz content. An analysis of a typical spherule from this type of basalt is given in Table IIA, column 11. The main feature is a higher silica content indicating essentially only an enrichment in quartz.

A number of analyses show possible anomalies with respect to one or more of the major element oxides (columns 5–10 of Table IIA) compared to the average of the class given in column 4. The significance of these variations is not fully understood, but it is probable from microscopic evidence that some of these are due to metamorphism, secondary silicification, carbonation and hydration. It is possible that the average chemical composition of this class (column 4) is not entirely representative and further analytical data are probably necessary to define the komatiites of the Barberton type more rigorously.

The Badplaas Type

TABLE II B

Basaltic Komatiites of the Badplaas Type

	1*	2*	3†	4*	5*	6	7
	VB1	VB2	KR35	K262	K188	Average	J9
SiO_2	52.80	50.20	53.02	52.57	52.80	52.22	55.11
TiO_2	0.73	0.66	0.36	0.40	0.66	0.56	0.39
Al_2O_3	5.68	5.20	4.84	5.31	6.05	5.42	4.25
Fe_2O_3	0.32	1.81	9.56	0.74	1.05	0.98	8.14
FeO	9.09	9.12	n.d.	8.05	9.28	8.88	n.d.
MnO	0.20	0.28	0.18	0.22	0.23	0.22	0.15
MgO	15.12	15.40	16.01	15.71	13.99	15.25	16.51
CaO	11.89	13.04	13.78	13.53	11.92	12.83	12.28
Na_2O	1.84	1.58	0.61	1.02	1.02	1.21	0.90
K_2O	0.12	0.06	0.05	0.09	0.13	0.09	0.02
P_2O_5	0.02	0.07	0.08	0.03	n.d.	0.05	0.06
H_2O^+	2.16	1.78	L.O.I.	2.11	2.17	2.05	1.41
H_2O^-	0.05	0.09	1.59	0.12	0.09	0.09	0.14
CO_2	0.16	0.23	0.08	0.24	0.04	0.17	0.11
TOTAL	100.18	99.52	100.16	100.14	99.63		99.52
Sr		51.3					
Rb		1.4					

Analysts and Methods Used.

* National Institute for Metallurgy, Johannesburg. (Standard gravimetric, volumetric, colorimetric and flame photometric.)

† Dr. J. Gurney, Dept. of Geochemistry, University of Cape Town (X-ray fluorescence.)

L.O.I. Loss on ignition.

Columns 1 to 2 Massive tremolite-actinolite metabasalts (metapyroxenites) with occasional diopsidic pyroxene remnants and very minor amounts of felspathic material. Komati formation type area.

Columns 3 to 5 Similar to above, from Kaapmuiden-Malelane area.

6 Average chemical composition of basaltic komatiite of the Badplaas type from best available data (columns 1 to 5).

7 Tremolite-actinolite schist from northern flank of the Mountain Land (Anhaeusser 1969).

Analyses of basaltic komatiites of the Badplaas type from both the northern and southern portions of the Mountain Land are presented in Table IIB, columns 1–5 and their average chemistry in column 6.

The main features are the high silica, magnesium and calcium contents and low aluminium and alkali contents. These rocks have the highest calcium content and the highest Ca/Al ratio of all three classes of basaltic komatiite, chemical features ascribed to an abundance of original diopsidic pyroxene, absence of original olivine and very small amounts of original plagioclase. An analysis of a schist from the northern contact of the Mountain Land which probably belongs to the Badplaas type (Table IIB, column 7) was not used in the computation of the average chemistry of the class because of its somewhat higher than normal silica and magnesium contents. The chemical data from the Badplaas type indicates that these rocks have the most consistent chemistry of all the basaltic rocks from the lower formations.

The Geluk Type

TABLE II C

Basaltic Komatiites of the Geluk Type

	1*	2†	3*	4*	5	6†	7	8	9‡	10†
	AB12	SG3	SG80	KJ39	Ave.	K178	J10	Ave.	42J	KJ40
SiO_2	47.84	46.32	46.85	48.45	47.37	50.02	48.36	49.19	50.61	50.12
TiO_2	0.55	0.38	0.56	0.36	0.46	0.32	0.54	0.43	0.36	0.48
Al_2O_3	7.32	6.82	6.90	6.15	6.79	3.77	3.75	3.76	7.78	8.77
Fe_2O_3	1.22	12.78	1.25	1.09	1.18	9.02	13 97	11.00	1.06	11.43
FeO	8.08	n.d.	8.90	7.26	8.08	n.d.	n.d.	n.d.	5.96	n.d.
MnO	0.18	0.25	0.16	0.17	0.19	0.15	0.19	0.17	0.13	0.22
MgO	19.28	19.61	20.97	21.72	20.39	20.80	19.26	20.03	19.20	15.93
CaO	8.52	8.61	7.43	8.69	8.31	9.92	9.11	9.51	6.30	9.14
Na_2O	0.71	0.27	0.09	0.50	0.39	0.04	0.16	0.10	2.12	1.07
K_2O	0.09	0.03	0.04	0.10	0.06	0.01	0.03	0.02	0.04	0.03
P_2O_5	0.03	0.07	n.d.	n.d.	0.05	0.06	0.04	0.05	n.d.	0.08
H_2O^+	5.08	LOI	5.89	4.86	5.26	3.74	3.55		4.96	LOI
H_2O^-	0.34	3.80	0.29	0.12	0.25	0.56	0.58		0.14	2.77
CO_2	0.90		0.02	0.07			0.03		0.10	
Cr_2O_3			0.30						0.41	
NiO			0.06				0.18		0.12	
Total	100.14	99.28	99.67	99.54		98.43	99.75		99.29	100.04

Analysts and methods used.

* National Institute for Metallurgy, Johannesburg (Standard gravimetric, volumetric, colorimetric and flame photometric).

† Dr. J. Gurney, Dept. Geochemistry University of Cape Town (X-ray fluorescence).

‡ Mr. I. Wright, Dept. Geology, University of the Witwatersrand (X-ray fluorescence).

L.O.I. Loss on ignition.

Column 1 Pillowed metabasalt, Komati formation type area.
2 and 3 Amphibolitized metabasalts, Steynsdorp Valley.
4 Amphibolitized metabasalts, Kaapmuiden-Malelane area.
5 Average chemical composition of the Geluk type (high alumina variety).
6 Amphibolite, Kaapmuiden-Malelane area.
7 Amphibole—talc schist, northern flank of Mountain Land (Anhaeusser, 1969).
8 Average chemical composition of the Geluk type (low alumina variety).
9 Amphibolitized metabasalt, Komati formation type area.
10 Magnesium-rich amphibolite, Kaapmuiden-Malelane area.

Analyses of the most representative specimens of basaltic komatiites of the Geluk type are presented in columns 1–4 of Table IIC and the average chemistry of the class given in column 5 of the same table. As in the case of basaltic komatiites of the Badplaas type, the chemistry is remarkably consistent with distinctive features including a silica content which is considerably lower than for the above-mentioned classes but still relatively high, a very high magnesium content and a very low alkali content. Calcium and aluminium are also fairly low and the majority of these rocks, therefore, have a high Ca/Al ratio. The analyses presented in columns 6 and 7 (average in column 8) are of a variety with a very low aluminium and alkali content and somewhat higher silica and calcium contents compared to the first variety of the Geluk type. The magnesium content is approximately the same as in the first variety. As alumina is the element that shows the greatest change, this variety has been termed the low alumina type to distinguish it from the first group, or what has been termed the high alumina variety. The chemical peculiarities of basaltic komatiites of the Geluk type are ascribed to the presence of significant amounts of original orthopyroxene as well as some olivine in certain instances, and to the originally small amounts of plagioclase, particularly in the low alumina variety. Varying amounts of original diopsidic pyroxene were probably also present.

Analyses of two metabasalts which probably also belong to this group but which contain one or more of the major element oxides in anomalous quantities are given in columns 9 and 10. The excessively high sodium content of the analysis presented in column 9 and the higher than normal aluminium, calcium and sodium, together with lower magnesium of that in column 10, necessitated the exclusion of these analyses from the computation of the class average.

(ii) Metatholeiites

The average chemical composition of meta-tholeiitic basalts from the lower formations of the Onverwacht Group calculated from the most consistent analyses available (columns 1–4 of Table III) are given in column 5 of the same table. The main distinguishing features of these rocks are their higher alumina and alkali contents and lower magnesium contents (compared to the basaltic komatiites) reflecting essentially an increase in the plagioclase content and a decrease in the pyroxene content. The analyses presented in columns 6–11, although clearly tholeiitic, have certain anomalous features due to unknown factors and were therefore excluded from the calculation of the average chemical composition. Microscopic evidence seems to suggest that these anomalous features could be due largely to metamorphism and attendant processes such as silicification rather than to significant primary differences in the basaltic magma. The chemistry of the metatholeiites of the lower formations is comparable to the chemistry of the tholeiites of the upper formations.

TABLE III

Selected chemical Analyses of Meta-tholeiites from the Lower Formations of the Onverwacht Group:

	1*	2	3*	4*	5	6†	7*	8	9†	10	11
	V11	CAA1	KJ1	KJ57	Ave	K206	KJ16	65	TS1	CAT 79	J7
SiO_2	52.98	52.30	49.19	54.04	52.13	52.68	54.74	54.11	53.76	49.00	49.64
TiO_2	1.08	0.95	1.59	0.75	1.09	1.07	0.75	0.82	0.74	0.70	1.32
Al_2O_3	13.20	14.15	12.99	12.97	13.33	10.50	15.89	14.42	11.82	14.25	12.63
Fe_2O_3	1.61	1.48	3.60	2.26	2.24	0.88	0.73	10.34	10.33	2.12	16.92
FeO	10.07	9.44	12.39	7.86	9.94	11.59	4.70	n.d.	n.d.	8.04	n.d.
MnO	0.18	0.24	0.28	0.14	0.21	0.21	0.08	0.15	0.17	0.18	
MgO	6.25	6.06	6.53	6.55	6.35	6.58	7.16	5.73	8.98	8.33	5.63
CaO	8.30	10.66	8.58	8.27	8.98	8.46	8.94	9.64	9.28	9.88	9.77
Na_2O	3.35	2.15	2.50	3.87	2.97	3.50	4.93	1.93	3.24	1.75	2.69
K_2O	0.48	0.21	0.23	0.17	0.26	0.20	0.13	0.14	0.15	1.63	0.37
P_2O_5	0.09	0.06			0.07	0.13		0.12	0.12	0.05	0.15
H_2O^+	1.96	1.89	1.79	2.25	1.97	LOI	1.44	2.42	LOI	2.60	1.06
H_2O^-	0.10	0.09	0.13	0.12	0.11	1.45	0.10	0.07	1.19	0.17	0.08
CO_2		0.11	0.06	0.05	0.07		0.11	0.53		0.61	0.15
Cr_2O_3				0.03							
NiO								0.11			0.06
TOTAL	99.65	99.79	99.87	99.33		97.25	99.71	100.53	99.78	99.31	100.85

Analysts and Methods Used

* National Institute for Metallurgy, Johannesburg (Standard gravimetric, volumetric, colorimetric and flame photometric).

† Dr. J. Gurney, Dept. Geochemistry, University of Cape Town (X-ray flourescence).

LOI. Loss on ignition.

Column 1. Massive variety, Komati formation type area.
2. Dark contact amphibolite, eastern end of Jamestown schist belt (Anhaeusser 1969).
3. Fine grained massive amphibolite, Kaapmuiden.
4. Massive amphibolite, core of Koedoe fold structure, Malelane area.
5. Average of best analyses (Columns 1 to 4).
6. Massive amphibolite, core of Koedoe fold structure, Melalane area.
7. Coarse grained amphibolitic xenolith in Ship Hill body, Kaapmuiden area.
8. Tremolite-actinolite schist, eastern end of Jamestown belt (Anhaeusser, 1969).
9. Amphibolite from Theespruit formation, Steynsdorp anticline.
10. Dark contact amphibolite, Jamestown Schist belt, Kaap Valley granite contact (Anhaeusser 1969).
11. Contact amphibolite, northern flank of Mountain Land (Anhaeusser 1969).

3. *Felsic Rocks*

(i) Siliceous aluminous tuffs

Chemical analyses of a variety of felsic tuffs occurring in the Theespruit formation are given in columns 1 to 6 of Table IV. The three main varieties recognised, viz. an extremely siliceous type, a very aluminous type lower in silica, and a variety intermediate between these two extremes, are presented in columns 5, 6 and 4 respectively of Table IV.

The most distinctive chemical characteristics of all of these rocks is their high alumina content. It is considered unlikely that a primary tuff would have been so aluminous and it seems probable that the primary felsic pyroclasts were somewhat modified after deposition. This could have been accomplished by processes of weathering similar to those which give rise on surface weathering to aluminous clays from felsic rocks. From the environment of these rocks, however, it is considered more feasible that alteration took place subaqueously, probably

TABLE IV

Chemical analyses of Felsic Rocks from the lower formations of the Onverwacht Group

	1	2	3	4	5*	6†	7†	8	9†
	J13	J14		Ave.	2	AT2	VP5		R17
SiO_2	79.53	78.28	77.50	78.44	90.04	59.93	68.84		71.26
TiO_2	0.53	0.55		0.54	0.05	0.45	0.30		0.21
Al_2O_3	12.76	17.52	16.27	15.52	6.71	26.26	14.60		14.40
Fe_2O_3	0.11	0.39	0.74	0.41	0.23	0.29	0.26		0.73
FeO	0.36	1.01		0.68	0.00	1.64	1.51		1.15
MnO	tr	0.01		0.01	0.01	0.02	0.05		0.03
MgO	0.30	0.46		0.38	0.00	1.26	1.45		1.10
CaO	0.28	0.30		0.29	0.01	0.42	2.80		0.55
Na_2O	0.27	0.53	0.69	0.49	0.12	3.75	5.12	5.46	8.22
K_2O	3.86	1.48	1.65	2.33	2.31	1.63	1.61	1.74	0.27
P_2O_5	0.18	0.11		0.14	n.d.	0.05	0.11		0.10
H_2O^+	1.74	0.88		1.31	1.06	3.72	1.02		0.95
H_2O^-	0.23	0.20		0.21	0.06	0.32	0.11		0.06
CO_2	n.d.				0.00	0.12	2.60		0.31
Total	100.15	101.72			100.60	99.86	100.38		99.24

Analysts and Methods Used.

† National Institute for Metallurgy, Johannesburg (Standard gravimetric, volumetric, colorimetric and flame photometric).

* Mr. I. Wright, Dept. of Geology, University of the Witwatersrand (X-ray fluorescence.)

COLUMNS 1 to 6: Variety of aluminous and siliceous felsic tuffs.
1 Quartz-sericite schist, eastern portion of Jamestown schist belt (Anhaeusser, 1969).
2 Andalusite and chloritoid-bearing quartz-sericite schist from same locality as above (Anhaeusser, 1969).
3 Average partial composition of 5 andalusite- bearing quartz-sericite schists from the eastern part of the Jamestown schist belt (Anhaeusser, 1969).
4 Average chemical composition of siliceous aluminous schists from the eastern part of the Jamestown schist belt.
5 Siliceous, sericite-bearing tuffaceous sediment (Theespruit formation type area.)
6 Water worked, aluminous (pyrophyllitic) felsic tuff (Theespruit formation type area.)

COLUMNS 7 to 9: Intrusive porphyry bodies.
7 Typical widespread type of felspar porphyry intrusive into the Komati formation in the type area.
8 Average alkali values for three porphyry bodies similar to the one above.
9 Variety of soda-rich felspar porphyry intrusive into the Komati formation in the type area.

aided by a process such as hot spring and late volcanic activity of a similar nature to that which in Puerto Rico has given rise to aluminium potassium silicates from andesitic volcanics (Hess, H. H., verbal communication). The large amounts of silica in the environment were probably also generated by late-stage felsic pyroclastic activity. A number of these tuffs are characterized by concentrations of barium (see Paper No. 9).

(ii) Porphyries

The abundant intrusive felspar and quartz porphyries which attain their best development in the Komati formation have a very consistent chemical composition (columns 7 and 9 of Table IV). A distinctive feature is the high soda content of the rocks and, except for a somewhat lower iron and magnesium content, they are similar in composition to the leuco-biotite-quartz tonalties intrusive into the Onverwacht Group in the southern portion of the Mountain Land (Paper No. 7).

C. Chemical Comparison of the Mafic and Ultramafic Rocks of the Lower Ultramafic Unit with other Well-established Classes of Mafic and Ultramafic Rock

1. Introduction

In an accompanying paper the unique chemical characteristics of the extrusive peridotitic magma of the Komati formation (peridotitic komatiite) are illustrated by a comparison with well-established classes of peridotitic and picritic rocks. In the present section the chemistry of all the ultramafic and mafic rocks of the lower formations of the Onverwacht Group are also compared with the chemistry of well-established classes of peridotitic and picritic rocks in addition to basaltic and extra-terrestrial rocks. The classes of peridotitic and picritic rocks used are the same as those employed in the comparison of the peridotitic komatiites of the Komati formation (Paper No. 5). They include the class of so-called high temperature peridotite intrusions (Green, 1967) and the average of the peridotite inclusions in kimberlite pipes and in alkali basalts. The classes of picrite used can be divided into two groups, viz. basaltic picrites and picrites of the picritic minor intrusions (see Paper No. 5). Other classes of igneous rock employed for comparative purposes are limburgites. In addition to the above classes which were all used in the accompanying paper (No. 5) several other additional rock classes have been employed for comparative purposes in the present paper. These include the well-known basalt classes, viz. oceanic tholeiites, continental tholeiites, alkali basalts and olivine basalts (Table V). In addition, the average chemistry of the meta-tholeiites from the upper formations of the Onverwacht Group as well as of Archean metatholeiites from the Superior Province of the Canadian Shield have also been included for comparison. Of the extra-terrestrial material the average chondrite and achondrite as well as the average lunar sample from the Apollo 11 landing site on the Sea of Tranquillity (recalculated to 100% after subtracting 8.3% TiO_2 and 8.3% FeO to eliminate excessive ilmenite) have been included (see Table V).

2. Presentation of Results by Means of Variation Diagrams

(1) CaO vs Al_2O_3

Two of the most distinctive components of both the peridotitic and basaltic komatiites, viz. calcium and aluminium, have been plotted against each other in Fig. 4a. This plot serves to distinguish komatiites of both the peridotitic and basaltic varieties from most well-established classes of basaltic, picritic and peridotitic rocks. The ankaramite picrites of Madagascar and Hawaii have Ca/Al ratios approaching those of the mafic rocks under consideration, with those from Madagascar plotting close to the field of the Badplaas type and those from Hawaii close to the field of the Barberton type (Fig. 4a). The higher alkali and lower silica content of the ankaramites, however, readily distinguishes them from the basaltic komatiites. The calcium-rich (omphacite) eclogites from kimberlite pipes also have a high Ca/Al ratio but are distinguished from basaltic komatiites by their higher alkali (particularly Na_2O) content which is ascribed to the jadeite molecule in the pyroxene. Recent chemical data from the Apollo 11 lunar sample (L.S.P.E.T., 1969) indicates that this material has a Ca/Al ratio approaching that of the basaltic komatiites of the Barberton type. The high iron and titanium content of the lunar material, however, renders it unlike the Barberton or any other earth rocks.

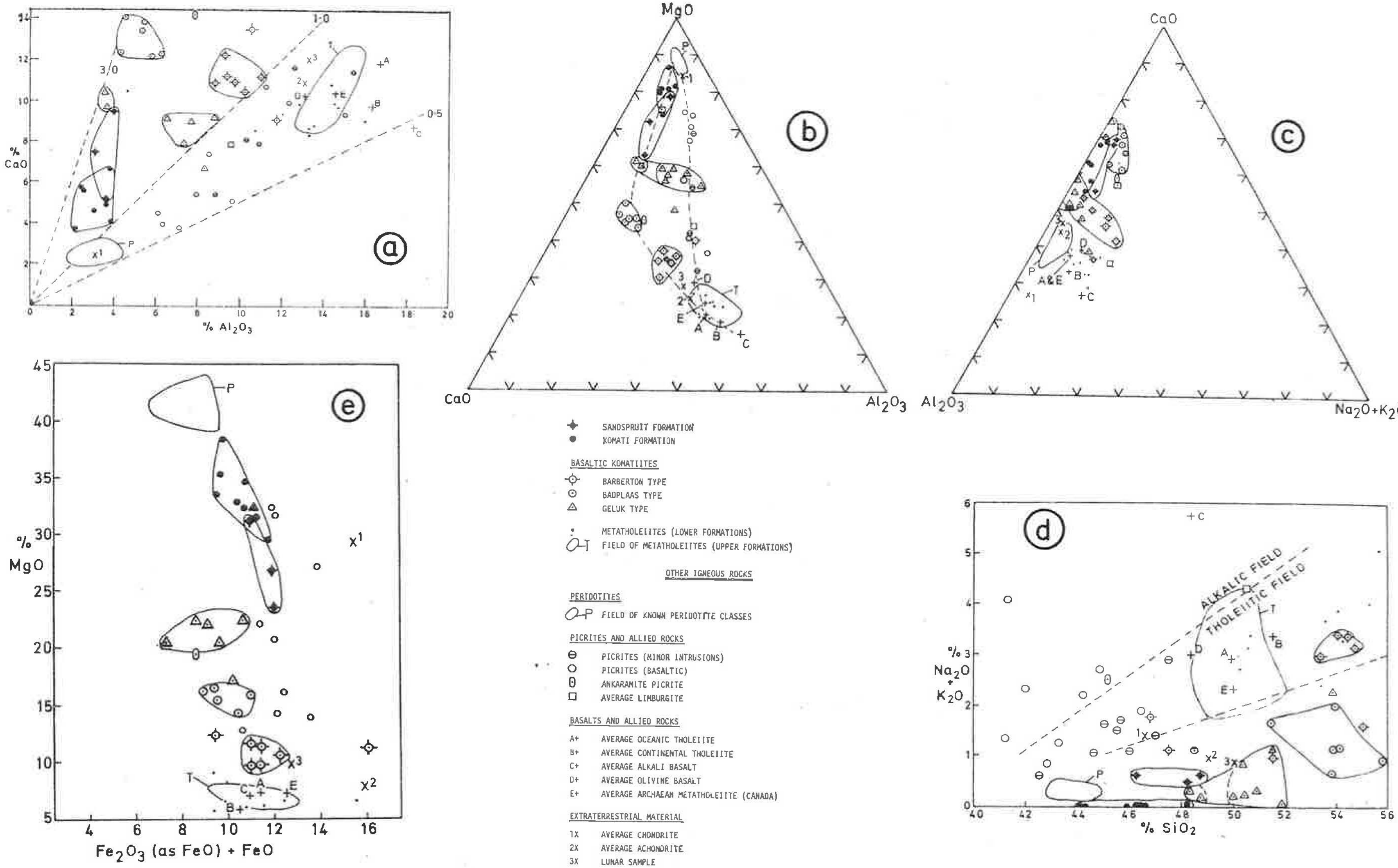

Fig. 4. Chemical comparison of the mafic and ultramafic rocks of the lower formations of the Onverwacht Group with established classes of peridotites, picrites, basalts and allied rocks, as well as extra-terrestrial materials.

The meta-tholeiites of the lower formations of the Onverwacht Group have normal Ca/Al ratios (± 0.70) and are comparable to most classes of tholeiite, including those from the upper formations of the Onverwacht Group, as well as the Archaean meta-tholeiites from the Canadian Shield. Two additional variation diagrams, making use of the other diagnostic variables of the distinctive mafic and ultramafic rocks of the lower formations, viz. magnesium and the alkalies, are depicted in Figs. 4b and 4c.

(ii) MgO—CaO—Al_2O_3

In this plot the peridotitic rocks of the Onverwacht Group fall in a field towards the magnesium corner of the diagram close to the fields of known peridotite classes and olivine-rich picrites (Fig. 4b). They are removed from these fields, however, as a result of their higher Ca/Al ratio, and form an elongate field starting with the peridotites of the Komati formation and extending through the field of peridotites from the Sandspruit formation towards the calcium corner of the diagram (Fig. 4b). Beyond this cluster a trend through the fields of the basaltic komatiites of the Geluk (low-alumina variety) and Badplaas types (at which point it swings towards the aluminium corner of the diagram) towards the field of the basaltic komatiites of the Barberton type and eventually into the field of tholeiitic basalts can be followed (Fig. 4b). A complementary trend joining most of the well-known rock classes employed in this comparison starts at the field of known peridotite classes and the average chondrite at the magnesium corner of the diagram and passes through various types of picrites to the field of basalts. The separation of this and the above trend is mainly a function of calcium and aluminium abundances. When the tholeiite field is reached both trends converge and all the basalt classes mentioned above (except for alkali basalts) cluster in a small, fairly well-defined area (Fig. 4b). The field of one class of rock, viz. basaltic komatiites of the Geluk type, is spread between and partly overlaps the two trends mentioned above, occurring towards the magnesium corner of the diagram (Fig. 4b).

The only rock types falling on or close to the komatiite trend are basaltic kimberlites (discussed in Paper No. 5), ankaramites from Madagascar, certain high calcium (omphacite-rich) eclogites (not plotted) and the average lunar sample. Some genetic connection could exist between the ankaramites and omphacite-rich eclogites and the basaltic komatiites of the Barberton and Badplaas types but, as pointed out previously, other differences clearly separate them. The lunar sample plots on the komatiite trend between the field of the Barberton type and the tholeiite field.

(iii) K_2O+Na_2O—CaO—Al_2O_3

The plot shows a clear separation between the peridotitic and basaltic komatiites and almost all other rock types used in the comparison, including the meta-tholeiites from the lower formations. The peridotitic komatiites from the Komati formation, as well as a number of basaltic komatiites of the Geluk type, lie close to the aluminium-calcium tie line towards the calcium side of the diagram. The peridotitic komatiites from the Sandspruit formation, as well as all of the remaining basaltic komatiites, occur in the same region, but are farther removed from the tie line due to their higher alkali abundances (Fig. 4c). The average ankaramite picrite, basaltic kimberlite and omphacite-rich eclogites plot in the same region with respect to calcium and aluminium, but are generally distinguished by a considerably higher alkali content. The remaining rock types plot on the aluminium side of the tie line but are substantially removed from the latter owing to their higher alkali contents.

(iv) Na_2O+K_2O—SiO_2

In Fig. 4d the alkali abundances have been plotted against the silica abundances following a scheme of classification for the Hawaiian basalts proposed by Macdonald and Katsura (1964). Using this plot the latter authors were able to separate clearly the tholeiitic and alkalic basalts (indicated by means of a diagonal dashed line in Fig. 4d) on the basis of chemical composition. None of the Hawaiian basalts plot below the lowermost dashed line indicated in Fig. 4d. All classes of komatiite, except for the basaltic komatiites of the Barberton type, plot below and well out of the field of all known Hawaiian tholeiites given by Macdonald and Katsura (1964). The only other rocks that plot in this region are the varieties of peridotites quoted, the average achondrite, and the lunar sample. The basaltic komatiites of the Barberton type plot in the lower portion of the tholeiitic field as do the meta-tholeiites from the lower formations, which overlap the field of the basaltic komatiites of the Barberton type (Fig. 4d).

(v) Mgo—$FeO+Fe_2O_3$ (as FeO)

In the final plot (magnesium against total iron) a clear separation is again evident between the different types of komatiite, as well as between the latter and the majority of other rock classes quoted (Fig. 4e). Certain picritic rocks plot close to some of the komatiite fields and the lunar sample plots close to the field of the basaltic komatiite of the Barberton type.

VII. KOMATIITE — A PROPOSED NEW CLASS OF IGNEOUS ROCKS

From the above geochemical comparisons it is clear that the majority of mafic and ultramafic rocks of the lower formations of the Onverwacht Group are not chemically comparable to any well-established class of igneous rock.

In certain respects they bear some similarities to a variety of rocks including basaltic kimberlites, omphacite-rich eclogites, ankaramites, picrites, basaltic achondrites, and the lunar sample. Although some of these similarities may indicate some underlying genetic connection, the bulk chemical composition of the Barberton rocks is clearly different from all of these classes.

Based largely on geochemical data therefore, but also taking into account the petrology, geological setting, development, age and remarkable state of preservation and exposure of the Barberton rocks, it is considered that the main parameters of these are well enough defined to propose the presence of what we consider to be a new and hitherto unrecognised group of igneous rock. The name "komatiite" which has been used throughout this paper and which takes its name from the Komati river which traverses the Southern part of the Barberton Mountain Land, including the Komati formation where these distinctive rocks are best developed, is proposed. It is further suggested that the prefix peridotitic or basaltic be used, depending on the particular rock being described. Two varieties of peridotitic komatiite appear to be present, viz. those from the Sandspruit formation and those from the Komati and Theespruit formations (which are more ultrabasic). Three main types of basaltic komatiite, viz. the Barberton, Badplaas and Geluk types have been recognised and although there might be some overlap between their chemistry they appear for the most part to represent well-defined classes.

VIII. THE GEOLOGICAL SIGNIFICANCE OF THE LOWER FORMATIONS OF THE ONVERWACHT GROUP

It will be shown elsewhere (Paper No. 10) that the distinctive formations of the Lower Ultramafic Unit of the Onverwacht Group can be correlated very closely on lithostratigraphic grounds with the lowermost assemblages of many of the Southern African greenstone belts. It is further contended that certain areas within every shield area might well contain similar assemblages, including the widespread development of the distinctive peridotitic and basaltic komatiites. Stronger dynamic and thermal metamorphism, however, coupled probably with extensive elimination of the succession has, it is suggested, resulted in this lowermost unit not having been recognised or appreciated. Examples of this are given in an accompanying paper (No. 10) where it is proposed that the stratigraphy of the Onverwacht Group might well be used as a model which could be of tremendous value as an aid to the elucidation of the geology of the greenstone belts of the shields.

Not only is the Lower Ultramafic Unit well developed within most of the individual greenstone belts of the Southern African shield, but it would appear that it was previously widespread in the areas between discrete greenstone depositories. The granitic rocks, and more particularly the ancient tonalitic varieties, of not only the Barberton region but of the whole of the Kaapvaal craton and certainly the south-eastern sector of the Rhodesia craton, contain rafts and xenoliths which appear to belong almost exclusively to the Lower Ultramafic Unit. This suggests that before its invasion by the early tonalitic magma, the Lower Ultramafic Unit, which probably existed as a succession of reduced thickness in the areas between the large accumulations in the greenstone depositories, covered much of the ancient Rhodesian and Kaapvaal cratons. As the granitic rocks are younger than the rocks of the Lower Ultramafic Unit, the question remains as to what the base of the latter might have been. This has been discussed at length in an accompanying paper (No. 8), where it is concluded that no vestiges of a pre-Onverwacht basement exist and that the whole Lower Ultramafic Unit might well have represented a primitive and primordial earth crust which was more or less transitional into the primitive mantle. It is likely that little or no sialic material existed and in many respects this original earth crust could have been somewhat similar to the present-day oceanic crust. In the areas of the mid-oceanic ridge the oceanic crust consists of a complex assemblage of serpentinized peridotite, pillowed lava, together with numerous sill and dyke swarms, as well as sediments (cherts) and possible tuffs (Hess, 1965, and verbal communication). The emplacement of the widepread ancient tonalitic granites at 3.4 to 3.2 $\times 10^9$ years could well be a manifestation of the single-cell convective overturn, suggested by Vening Meinesz (1952) and favoured by Hess (1965). This catastrophic event in the earth's early history is regarded by these authors as having resulted in the formation of the nickel-iron core, concomitant with the rising of the low-melting silicates to form a primordial single continent (Hess, 1965).

Data from the Barberton region might well add support to this theory. Assuming a major early convective overturn as outlined above, it is thought that only after or perhaps in part during this catastrophic event did the normal tholeiite basalts of the upper formations develop in abundance and to the near exclusion of the distinctive earlier komatiites. Tholeiitic calc-alkaline assemblages of this type appear to have been confined to much smaller depositories largely within well-defined greenstone successions and could in fact represent the true initial magmatic phase of the greenstone belts developed only locally on a much more extensive crust of the Lower Ultramafic Unit. If the above suggestions are correct, then the geological significance of the Lower Ultramafic Unit is tremendous. It could represent part of the earth's primitive crust developed before the establishment of a substantial sialic plate and nickel-iron core. The lower formations in this case would have developed at a stage when the budget of elements between the crust, mantle, and core was significantly different. Total or near total melting of the uppermost mantle at this stage could well have been expected to produce rock types of a kind not found in later geological times and, it is suggested, afford an explanation as to the unusual and distinctive chemistry of the komatiites which form the bulk of the Lower Ultramafic Unit (Paper No. 11).

The composition of these could clearly assume tremendous importance in providing an insight into such problems as the composition of the earth's primitive mantle as well as the bulk composition of the earth prior to significant differentiation. With respect to the latter a major problem concerns the low alkali abundances of both the basaltic and peridotitic komatiites. If they were derived from a mantle which had not as yet differentiated to form an alkali-enriched crust, then the material derived from this primitive mantle by partial or near total melting might be expected to have had a high alkali content. The authors have no explanation for the observed low alkali characteristic of komatiites except to comment on the fact that there does seem to be a complementary relationship between the widespread mafic and ultramafic komatiites, singularly depleted in lithophile elements, and the immediately preceding generation of the vast alkali (and lithophile) enriched granite event which formed the earliest known continental sial.

Plate I (a). Alternating layers of fine- and coarse-grained (agglomerate) water-laid felsic, aluminous tuff—Theespruit formation—type area. Analysis of this rock given in column 6, Table IV, and locality shown in Fig. 2.

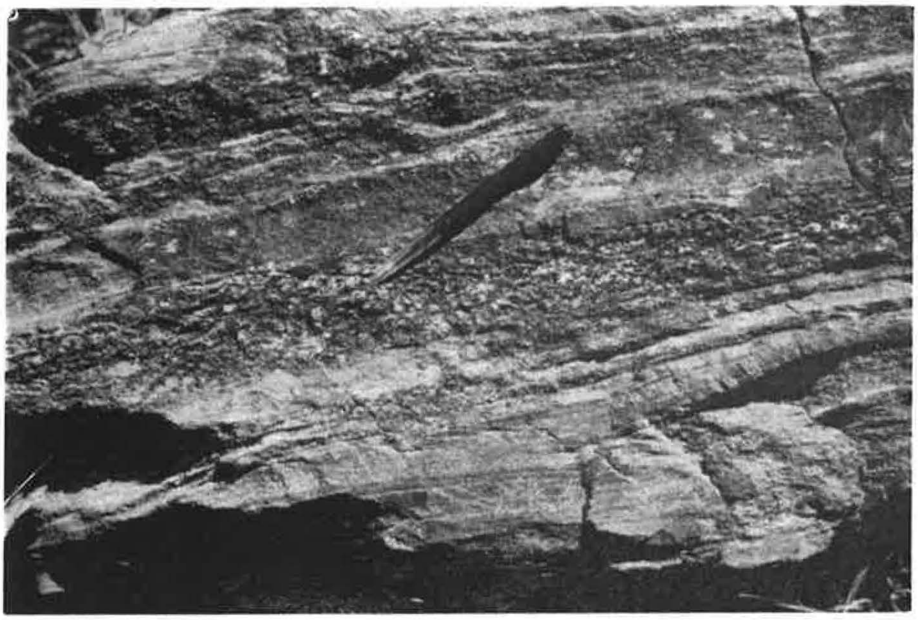

Plate I (b). Similar to (a) above, but showing the development of fine-grained, siliceous cherty interlayers. Succession younging towards the bottom of photograph and showing individual cycles of coarse- to fine-grained tuff overlain by chert.

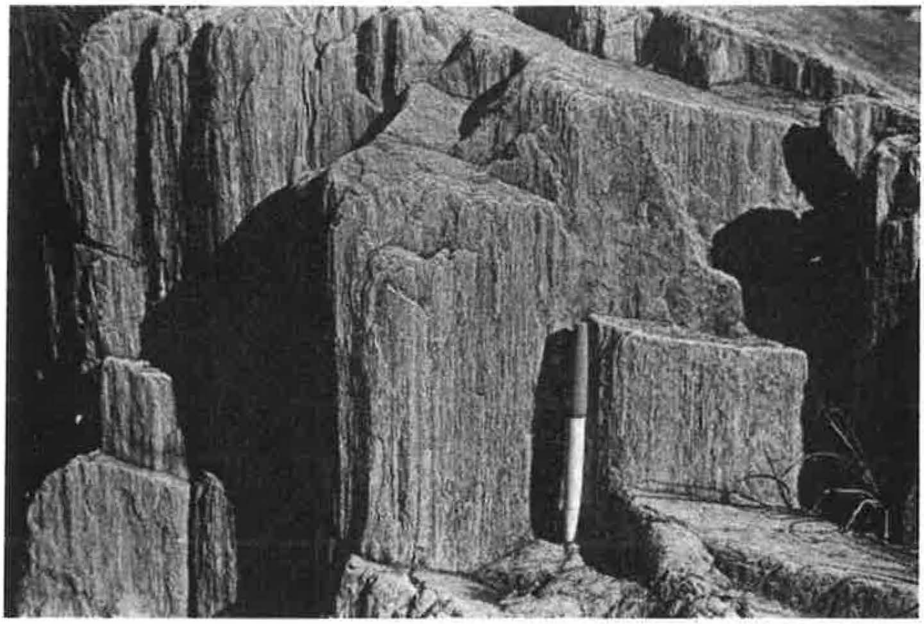

Plate II (a). Typical steeply plunging "stretch" or "a" lineation developed in a siliceous (quartz-sericite) tuff of the Theespruit formation close to the granite contact.

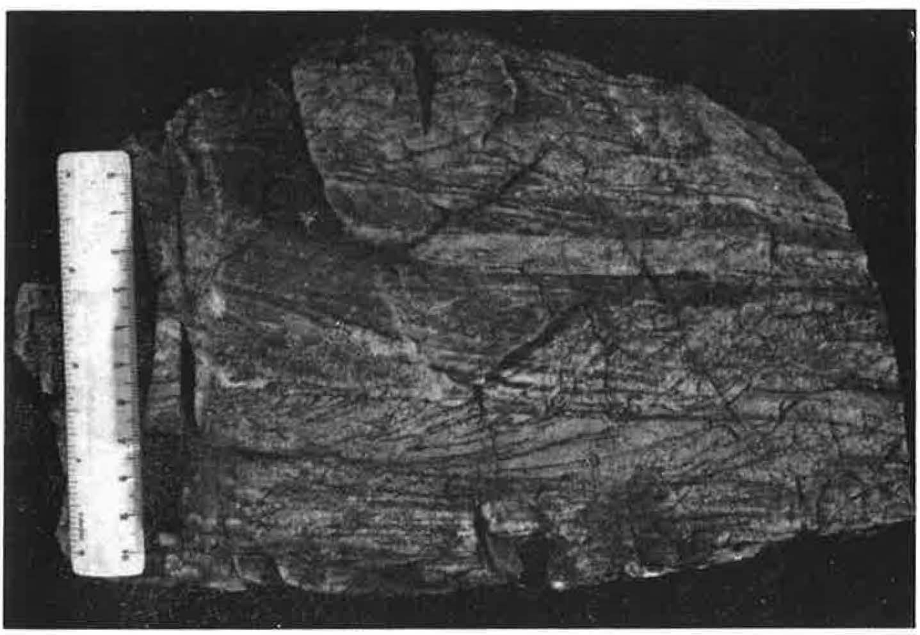

Plate II (b). Cross bedded siliceous cherty sediment from the Theespruit formation representing a silicified fine-grained water-worked siliceous tuff.

Plate III (a). Typical jagged outcrop of sheared basaltic komatiite. Komati formation in the type area.

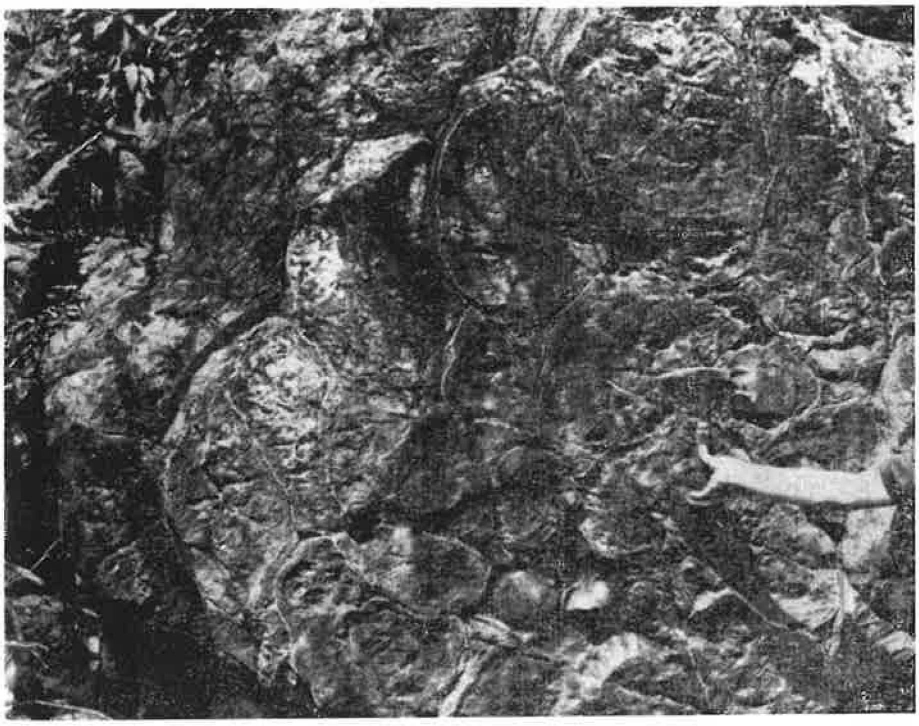

Plate III (b). Group of pillows developed in basaltic komatiite of the Barberton type showing great variation in shape and size. Komati formation—type area.

Plate IV (a). Typical rounded, light-coloured spherulites or variolites developed in a pillowed basaltic komatiite of the Barberton type. Note the merging of the spherules in the upper and lower parts of the photograph. Komati formation—type area.

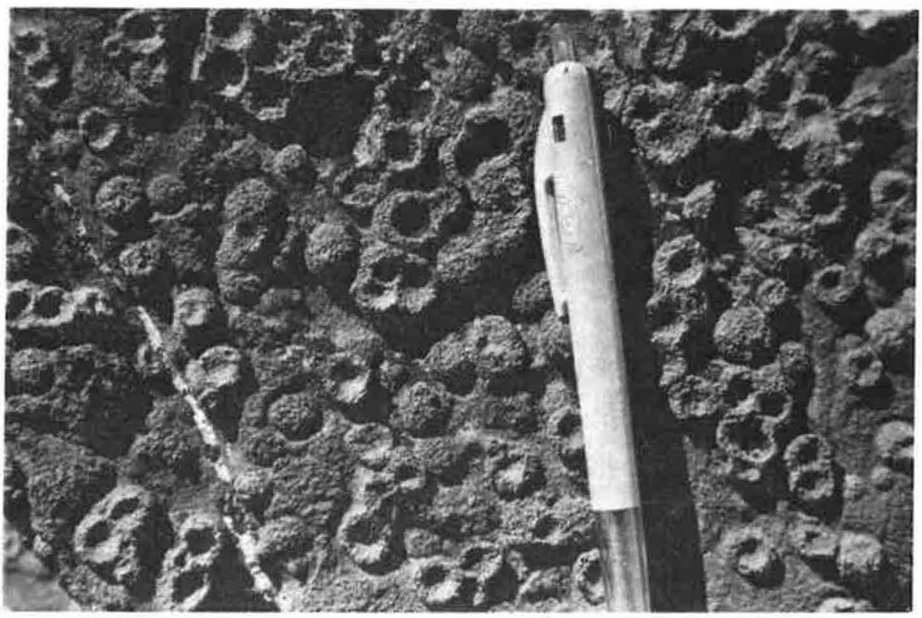

Plate IV (b). Etching of variolitic structures produced by surface weathering giving rise to domical features, or craters rimmed by resistant ridges. Basaltic komatiite of the Barberton type, Komati formation—type area.

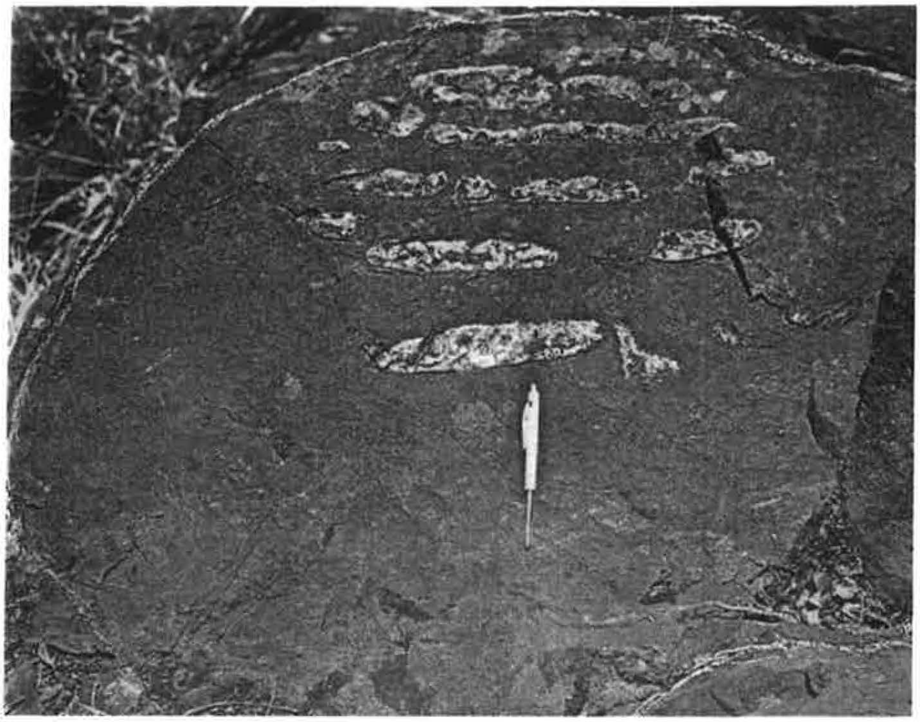

Plate V (a). White vein-quartz occupying large horizontal gas cavities in the upper portion of a pillow structure and therefore indicating the direction of younging. Basaltic komatiite of the Barberton type, Komati formation—type area.

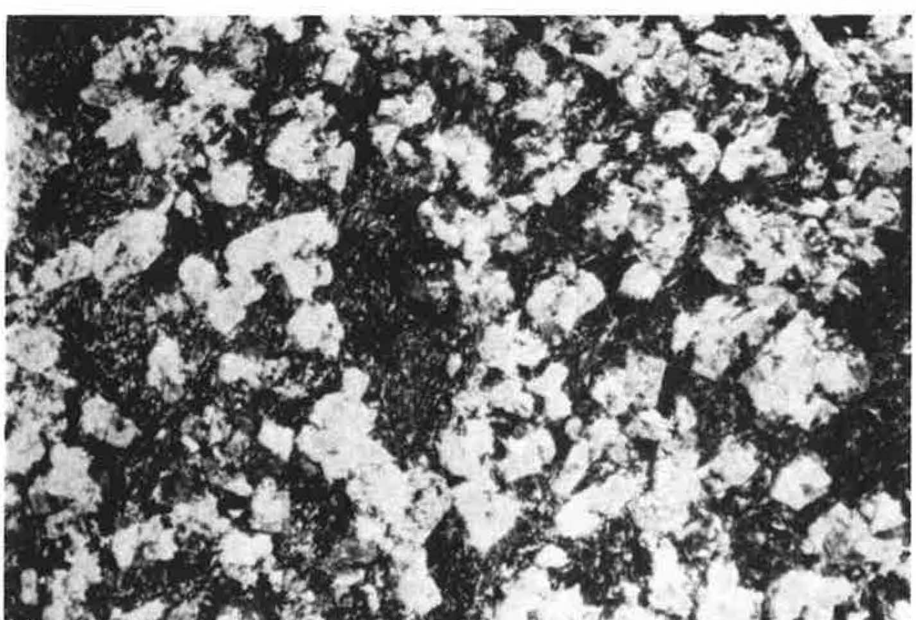

Plate V (b) Tremolite-actinolite crystals derived from original diopside (white), occurring in a fibrous aggregate of plagioclase, zoisite, amphiboles and chlorite (grey and black). Massive basaltic komatiite of the Barberton type from the Komati formation in the Onverwacht type area. Crossed nicols × 20. Analysis of this rock given in column 1, Table IIA and locality shown in Figure 2.

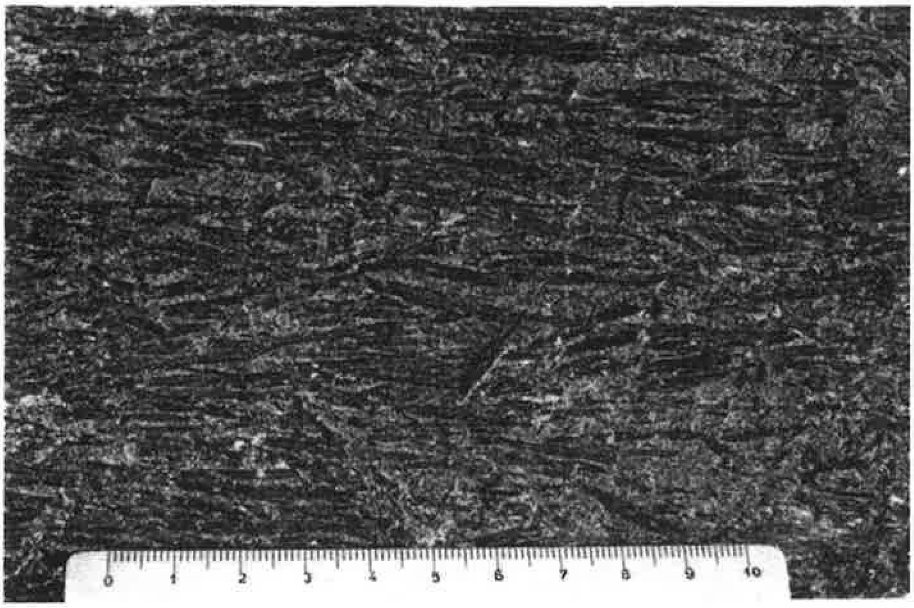

Plate VI (a). Elongated and well aligned actinolite needles (dark grey) in a matrix consisting of a fine-grained intergrowth of epidote, chlorite, clinozosite and quartz. Represents either a primary crystalline quench structure or a greenschist metamorphic phenomenon. Basaltic komatiite of the Barberton type—Komati formation—type area.

Plate VI (b). Well developed pillow structures in basaltic komatiite of the Geluk type. Note interstitial material developed in the voids created between three or more adjoining pillows. Hammer head in the direction of younging. Komati formation—type area.

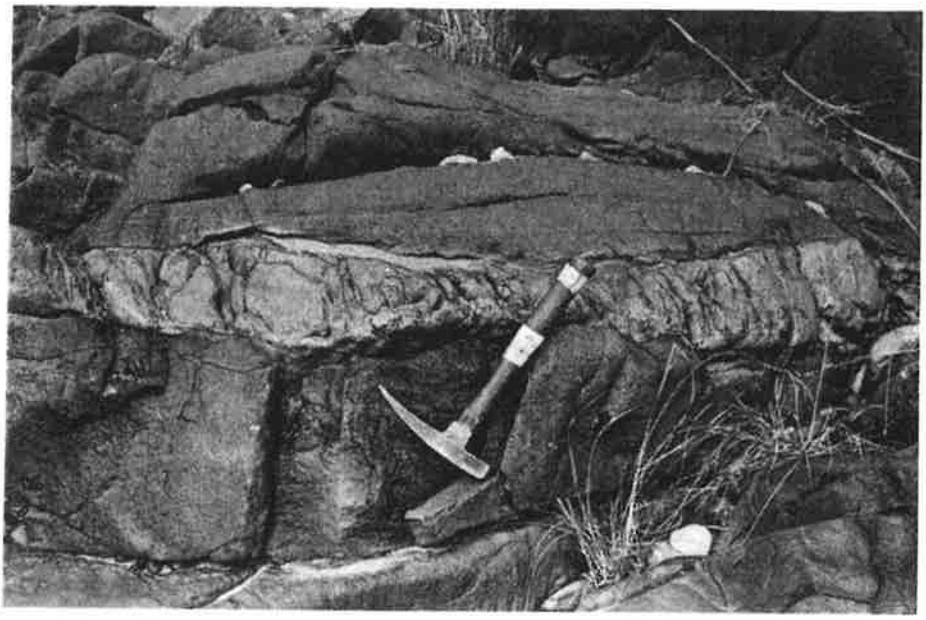

Plate VII (a). Serpentinized peridotite dyke intrusive into a large serpentinized peridotite mass of similar composition. Exposure in Noordkaap river, central part of Jamestown schist belt. Analysis of this dyke given in Table I, column 7.

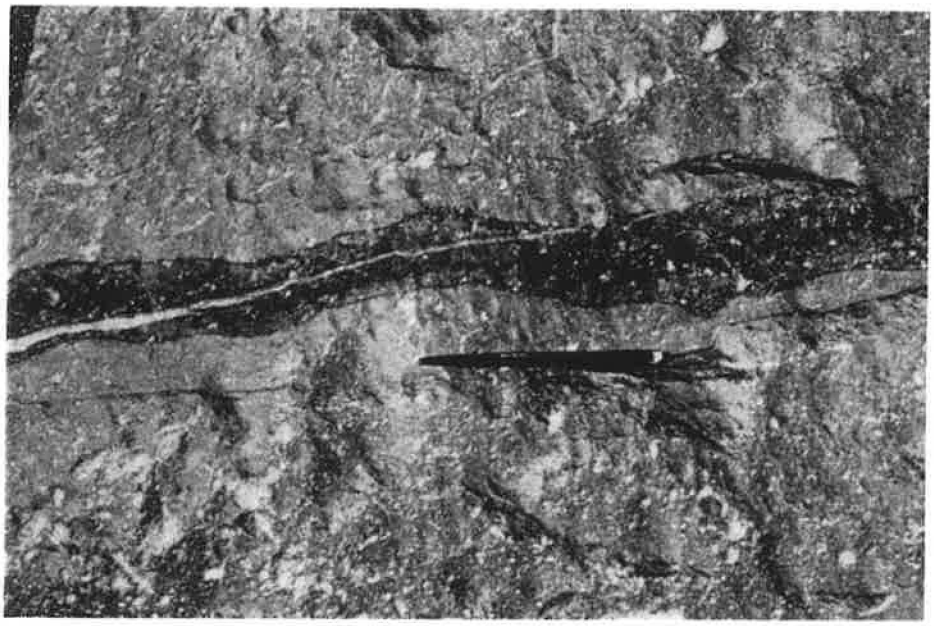

Plate VII (b). Serpentinized peridotite dyke from same locality as the one illustrated in Plate 7 (a), but showing a narrow, fine-grained, darker chilled selvedge.

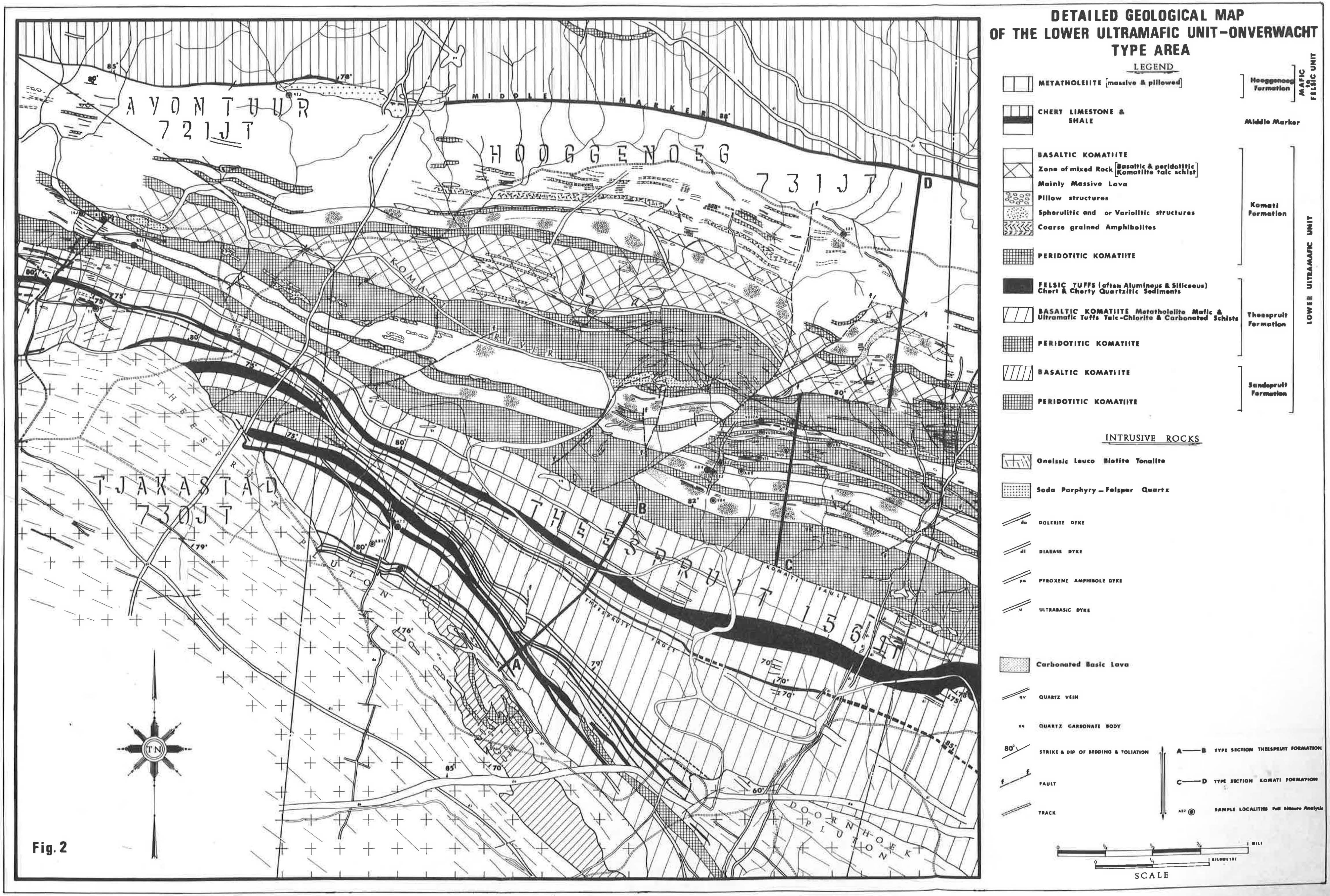
DETAILED GEOLOGICAL MAP
OF THE LOWER ULTRAMAFIC UNIT–ONVERWACHT
TYPE AREA
LEGEND
METATHOLEIITE [massive & pillowed]
Hooggenoeg Formation
MAFIC to FELSIC UNIT
CHERT LIMESTONE & SHALE
Middle Marker
BASALTIC KOMATIITE
Zone of mixed Rock [Basaltic & peridotitic Komatiite talc schist]
Mainly Massive Lava
Pillow structures
Spherulitic and or Variolitic structures
Coarse grained Amphibolites
PERIDOTITIC KOMATIITE
Komati Formation
FELSIC TUFFS (often Aluminous & Siliceous) Chert & Cherty Quartzitic Sediments
BASALTIC KOMATIITE Metatholeiite Mafic & Ultramafic Tuffs Talc-Chlorite & Carbonated Schists
PERIDOTITIC KOMATIITE
Theespruit Formation
BASALTIC KOMATIITE
PERIDOTITIC KOMATIITE
Sandspruit Formation
LOWER ULTRAMAFIC UNIT
INTRUSIVE ROCKS
Gneissic Leuco Biotite Tonalite
Soda Porphyry – Felspar Quartz
do DOLERITE DYKE
di DIABASE DYKE
pa PYROXENE AMPHIBOLE DYKE
u ULTRABASIC DYKE
Carbonated Basic Lava
qv QUARTZ VEIN
cq QUARTZ CARBONATE BODY
80° STRIKE & DIP OF BEDDING & FOLIATION
FAULT
TRACK
A—B TYPE SECTION THEESPRUIT FORMATION
C—D TYPE SECTION KOMATI FORMATION
SAMPLE LOCALITIES Full Silicate Analysis
0 ¼ ½ ¾ 1 MILE
0 ½ 1 KILOMETRE
SCALE
AVONTUUR 721JT
HOOGGENOEG 731JT
TJAKASTAD 730JT
THEESPRUIT 156
MIDDLE MARKER
KOMATI RIVER
THEESPRUIT PLUTON
DOORNHOEK PLUTON
KOMATI FAULT
THEESPRUIT FAULT
TN

Fig. 2

TABLE V

	Komatiites						Ave. perid-otite	Picrites						Lim-burg-ites	Basalts								Extraterrestrial Material		
	Peridotitic		Basaltic																						
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
SiO_2	47.49	45.94	53.75	53.29	50.02	51.78	44.52	46.00	42.60	46.41	41.26	44.10	45.07	50.23	46.25	45.36	50.24	48.35	49.94	51.50	48.16	49.83	46.86	48.51	49.96
TiO_2	0.55	0.34	0.87	0.57	0.49	0.45	0.15	0.61	0.29	1.98	2.66	2.74	1.30	3.25	0.47	0.75	0.16	2.77	1.51	1.20	2.91	0.94	0.13	0.48	2.46
Al_2O_3	3.45	2.98	10.02	5.50	7.17	3.95	2.75	10.86	8.98	8.53	10.31	11.60	7.85	9.60	15.79	7.49	7.71	13.18	16.69	16.30	18.31	14.64	3.08	13.04	13.17
Fe_2O_3	6.39	6.23	1.25	1.00	1.25	11.58	1.74	3.98	1.50	2.47	5.58	2.84	2.42	2.54	1.06	5.20	1.02	2.35	2.01	2.80	4.24	3.03		1.11	
FeO	5.86	4.80	9.90	9.06	8.53	n.d.	6.74	6.86	8.25	9.82	8.62	9.91	6.44	8.24	9.60	9.72	4.64	9.08	6.90	7.90	5.89	8.77	15.34	15.90	12.79
MnO	0.20	0.18	0.22	0.72	0.23	0.18	0.04	0.14	0.14	0.15	0.14	0.16	–	0.15	–	0.31	0.11	0.14	0.17	0.17	0.16	0.21	0.30		
MgO	26.92	33.79	10.30	15.56	21.53	21.08	40.98	22.15	32.12	20.81	14.00	15.13	18.39	12.97	14.36	15.55	17.79	9.72	7.28	5.90	4.87	7.36	29.37	7.87	9.84
CaO	7.40	4.73	10.18	13.09	8.78	10.01	2.26	7.88	5.48	7.38	11.65	10.69	14.29	7.79	9.12	10.92	16.66	10.34	11.86	9.80	8.79	10.46	2.40	11.00	12.15
Na_2O	0.52	0.15	2.70	1.23	0.41	0.10	0.24	1.07	0.56	1.58	3.19	1.66	1.31	2.40	2.10	2.66	0.97	2.42	2.76	2.50	4.05	2.02	1.21	0.68	0.66
K_2O	0.05	0.03	0.47	0.09	0.06	0.02	0.70	0.04	0.04	0.32	0.88	0.54	1.19	1.92	0.30	0.00	0.11	0.58	0.16	0.86	1.69	0.23	0.21	0.25	0.17

N.B. All analyses re-calculated anhydrous

1 *Peridotitic komatiite* (average of Sandspruit formation).
2 *Peroditiitic komatiite* (average of Komati formation).
3 *Basaltic komatiite* (average of Barberton type).
4 *Basaltic komatiite* (average of Badplaas type).
5 *Basaltic komatiite* (average of Geluk type).
6 *Basaltic komatiite* (average of Geluk type–low alumina variety).
7 *Peridotite* (average of high temperature intrusions and nodules in basalt and kimberlite, see accompanying Paper No. 5).
8 *Picritic minor intrusion*-chilled margin of dyke – Skye (Drever and Johnson, 1961. p. 81).
9 *Picritic minor intrusion* – centre of sill – Skye (Drever and Johnson, 1967, p. 81).
10 *Oceanite* type of picrite basalt – Hawaii (Mac Donald and Katsura, 1964, p. 19).
11 *Mimosite* type of picrite basalt – Hawaii (Mac Donald, 1949, p. 1571).
12 *Ankaramite* type of picrite basalt – Hawaii (Mac Donald and Katsura, 1964).
13 *Ankaramite* type of picrite basalt – Ankaramy, Madagascar (Johannsen, 1937).
14 *Limburgite* – average from Naunetsi Igneous Province, Rhodesia (Cox et al., 1965, p. 145).
15 *Eclogite* nodule – typical kimberlitic ecolgite from Roberts Victor Mine (new analysis, analysts – N.I.M. = Johannesburg).
16 *Eclogite* nodule with abundant omphacite relative to garnet – Roberts Victor Mine (Williams, 1932).
17 *Eclogite*, Roberts Victor Mine (Wagner, 1928).
18 *Olivine basalt*-average Hawaiian (Mac Donald, 1949).
19 *Oceanic tholeiite* – average given by Engel et al. (1965).
20 *Continental tholeiite*-average given by Mansen (1967).
21 *Alkali Basalt* – average from East Pacific rise (Engel et al., 1965).
22 *Archaean Metabasalt* of Superior Province of Canadian Shield – average given by Wilson et al. (1965).
23 *Chondrite* – average of superior analyses given by Urey and Craig, 1953; recalculated without Fe and FeS.
24 *Basaltic Achondrite* – average given by Urey and Craig, (1953), quoted in Engel et al. (1965).
25 *Lunar Sample* minus excessive ilmenite (8.31% TiO_2 and 8.31% FeO) from Apollo 11 landing site on the Sea of Tranquillity (L.S.P.E.T., 1969).