THE GEOLOGY
OF THE WATERBERG GROUP
IN THE SOUTHERN PORTION OF THE WATERBERG BASIN

by

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To my mother,

Myrtle Violet Callaghan

'Give her credit for all she does.

She deserves the respect of everyone.'

(Proverbs 31:31)

with love.

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1 INTRODUCTION

1.1 AIMS AND OBJECTIVES

The initial aim of this study was to examine the potential of the Waterberg Group sedimentary rocks for significant palaeoplacer cassiterite concentrations. This was achieved in two ways:

1. the rocks were extensively sampled, chiefly at the site of thorium anomalies, where the probability of finding cassiterite is higher (Callaghan, 1983a);
2. sedimentological data were collected to gain a better understanding of the depositional setting of the host sedimentary rocks.

The study later evolved into a synthesis of the mineralogy, sedimentology, tectonics and economic geology of the Waterberg Group. Although sedimentary rocks in the entire basin were studied, work was concentrated in the area bounded to the north by the 24th parallel, in the south by the Murchison-Thabazimbi lineament, and between the international border with Botswana in the west and the area covered with Waterberg sedimentary rocks up to 29° east (Fig. 1.1)

1.2 GENERAL GEOLOGY AND STRATIGRAPHY

The South African Committee for Stratigraphy (SACS) (1980) divides the Waterberg Group into thirteen formations. One of these, the Blouberg Formation, is widely considered to be pre-Waterberg (G. Brandl, pers. comm., 1987) and is not included in this investigation. The remaining twelve formations occur in different areas; some of these formations grade

ABSTRACT

The Waterberg Group consists chiefly of a succession of coarse clastic sedimentary rocks which shows two upward-fining sequences. The sedimentary rocks belong to the Mokolian erathem and they are 1700-1900 Ma old.

The depository evolved as a continental, fault-bounded basin in the northern part of the Kaapvaal craton. The basin is bounded in the south by the Murchison lineament and in the north by the southern part of the Palala shear zone. The Murchison lineament is interpreted to be a long-lived, fundamental strike-slip fault system. Deformation lamellae in quartz in the Alma Formation near Thabazimbi, are thought to have resulted from transpressive strain along this fault zone.

The Swaershoek and lower Sterkrivier Formations are interpreted to have been deposited as fan deltas and were possibly reworked in a littoral palaeo-environment. The Alma and upper Sterkrivier Formations are interpreted as a series of alluvial fans forming a bajada along the scarp caused by the uplifted block on the southern side of the Murchison strike-slip fault zone. The Skilpadkop and Setlaole Formations are considered to have been deposited on narrow braidplains. The Makgabeng Formation was deposited during the more stable period that followed and it is interpreted to be the result of a large dune field, which may have been coastal in nature towards the south. Problematic trace-like structures occur in the southeastern part of the basin in a littoral intercalation in the Makgabeng Formation. The upward-coarsening Aasvoëlkop Formation is thought to have been deposited in a shallow through-flow lake, although fluvial deposition was probably more important towards the top of the formation.

The Mogalakwena and Sandriviersberg Formations are interpreted as having been deposited by large braided rivers, forming an extensive braidplain which probably continued to the southwest, through Botswana into the northern Cape Province, where it may be represented by the Fuller Member

of the Volop Group. As sediment input from the north decreased, the sea transgressed over the braidplain and deposited the Cleremont Formation, which is interpreted as a littoral deposit or, possibly, a tidally influenced shelf deposit. The Vaalwater Formation, which ended the Waterberg period, formed within a littoral or a shallow siliciclastic sea palaeo-environment.

The Swaershoek Formation and the rest of the Waterberg Group probably formed in different tectonostratigraphic milieus, and the exclusion of this Formation from the Waterberg Group is recommended. The Mogalakwena and Sandriviersberg Formations are shown to have a very similar sedimentary character and it is proposed that they represent a single formation which shows gradational facies changes.

Placer, epigenetic hydrothermal, authigenic and possible syngenetic hydrothermal (stratabound) mineralization occur in the Waterberg Group. The association of thorium and tin at Gatkop is due to thorium-bearing minerals such as monazite and thorite occurring with cassiterite in placer accumulations. Uranium mineralization at Gatkop is of an epigenetic hydrothermal nature and it appears to have been localized by chalcopyrite.

Small placers of iron rich and titanium rich minerals are common throughout the group. One such occurrence has undergone authigenic enrichment and ilmenites display wide anatase rims; in places the rock is cemented by anatase. Copper occurrences appear to be genetically related to dolerite intrusions.

UITTREKSEL

Die Groep Waterberg bestaan hoofsaaklik uit growwe, klastiese sedimentêre gesteentes wat twee opwaarts fynerwordende opeenvolgings vorm. Die sedimentêre gesteentes behoort tot die Eratem Mokolium, en is by benadering 1700-1900 Ma oud.

Die afsettingsgebied het ontwikkel as 'n kontinentale verskuiwingsbegrensde kom in die noordelike deel van die Kaapvaalkraton. Hierdie kom is begrens deur die Murchisonlineament in die suide en deur die Palalaskuifskeursone in the noorde. Die Murchisonlineament word as 'n baie ou, gevestigde, strekkingsverskuiwingsisteem beskou. Vervormingslamelle in kwarts naby Thabazimbi in die Formasie Alma mag die gevolg van transpressiewe vervorming langs hierdie verskuiwingsone wees.

Die Formasie Swaershoek en die onderste deel van die Formasie Sterkrivier is waarskynlik as waaierdeltas afgeset, en die sedimente is moontlik in 'n littorale omgewing herwerk. Die Formasie Alma en die boonste gedeelte van die Formasie Sterkrivier word as 'n reeks alluviale waaiers wat 'n bajada langs die eskarp gevorm het, verklaar. Die eskarp het ontstaan as gevolg van die opwaartse verskuiwing van die blok aan die suidekant van die Murchisonverskuiwingsone. Die Formasies Skilpadkop en Setlaole is waarskynlik op smal vlegvlaktes afgeset. Die Formasie Makgabeng is tydens die daaropvolgende stabieler periode moontlik as 'n groot duinveld, wat na die suide littoraal was, afgeset. Problematiese spooragtige strukture kom in die suidoostelike deel van die formasie voor. Die opwaarts growwerwordende Formasie Aasvoëlkop is moontlik in 'n vlak binnelandse deurvloeimeer afgeset, alhoewel fluviale afsetting waarskynlik belangriker word na die bokant van die formasie.

Die Formasies Mogalakwena en Sandriviersberg word as afsettings

van groot vlegstrome op 'n uitgebreide vlegvlakte verklaar, wat moontlik verder suidwes gestrek het, deur Botswana tot in die Kaapprovinsie waar dit waarskynlik deur die Lid Fuller van die Groep Volop verteenwoordig word. Na gelang sedimenttoevoer vanuit die noorde afgeneem het, het die see oor die vlegvlakte getransgresseer en aanleiding gegee tot die ontstaan van die Formasie Cleremont, wat as 'n littorale afsetting of moontlik 'n gety-oorheerste platafsetting geinterpreteer kan word. Die Formasie Vaalwater, wat die Waterberg periode afsluit, is in 'n littorale of vlak silisiklastiese see gevorm.

Die Formasie Swaershoek vorm waarskynlik deel van 'n ander tektonostratigrafiese milieu as die van die oorliggende formasies. Dit word aanbeveel dat hierdie formasie nie by die Groep Waterberg ingesluit word nie. Die Formasies Mogalakwena en Sandriviersberg kom sedimentologies baie ooreen en dit word voorgestel dat hulle as 'n enkele formasie met 'n oorgangsfasies beskou word.

Plaser, asook epigeneties hidrotermale, outigene en moontlike singeneties hidrotermale (laaggebonde) mineralisasie kom in die Groep Waterberg voor. Die tin-toriumassosiasie by Gatkop is toe te skryf aan toriumdraende minerale soos monasiet en toriet wat saam met kassiteriet in plaserakkumulasies voorkom. Uraanmineralisasie by Gatkop is van 'n epigeneties-hidrotermale aard en deur chalkopiriet gelokaliseer.

Klein plaserafsettings bevattende yster- en titaanryke minerale kom algemeen deur die groep voor. Een voorkoms het outigeniese verryking ondergaan, met ilmeniete wat wye anataasrande toon. Plek-plek is die rots deur anataas gesementeer. Kopervoorkomste mag geneties verwant aan doleriet intrusies wees.

1 INTRODUCTION

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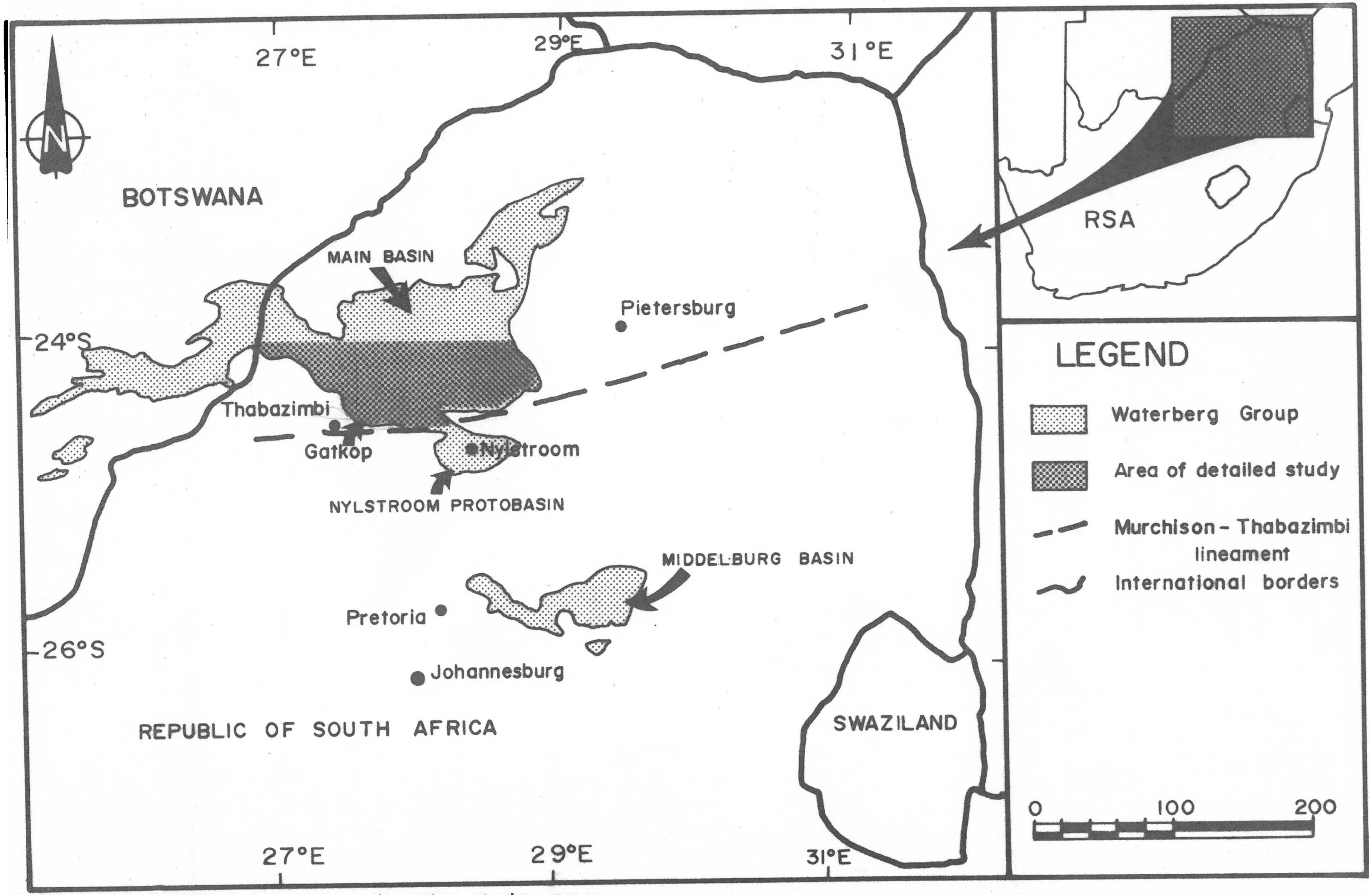


Figure I.1: Locality map showing the study area.

laterally into others (Figs. 1.2 and 1.3). These sedimentary rocks belong to the Mokolian Erathem and have been estimated to be 1900 - 1700 Ma. old (SACS, 1980, p.336; Jansen, 1982; Tankard *et al.*, 1982, p.203). The latter authors state that the Waterberg Group occurs in two basins, the Warmbaths Basin and the Middelburg Basin, and that the sedimentary rocks are up to 5000m thick. Jansen (1982) refers to the Middelburg Basin as the Cullinan-Witbank Basin or the Cullinan-Middelburg Basin, and he divides the larger northern basin into the Nylstroom Protobasin and the Main Basin (Fig.1.1). In this study only the Main Basin is considered; neither the Nylstroom Protobasin nor the Middelburg Basin have been studied by the writer. The Waterberg Group rests unconformably on rocks belonging to the Soutpansberg Group, Transvaal Sequence, granites and mafic rocks of the Bushveld Complex, and Archaean gneisses and granites of the Kaapvaal craton. Karoo Sequence rocks overlie the Waterberg Group to the north.

The Waterberg Group consists chiefly of coarse clastic, red (5R to 10R hue, The Rock Color Chart Committee, 1970) sedimentary rocks which generally fine upwards throughout the succession, from basal rudites, through arenites, to uppermost lutaceous arenites. Rare lavas also occur, mostly near the base of the group, in the Swaershoek Formation. Lutites are relatively uncommon and constitute less than 10 percent of the group (De Vries, 1969; Vos and Eriksson, 1977).

Coarse, thickly-bedded rudites occur mainly in the Swaershoek, Alma, Skilpadkop, Setlaole and Mogalakwena Formations. The rudites are generally clast-supported, with clasts commonly up to 300mm in diameter, but rarely over 1m in diameter. Clasts vary from very angular to well rounded, but are mostly subangular to subrounded; sorting is poor. Clast lithologies include quartzite, vein quartz, rhyolite, jaspillite, iron-formation, rudite, granite, granophyre and rare mica schist. Imbrication is poorly developed, largely because the shape of the clasts is near-equant.

Arenites occurring in the lower to middle formations of the group consist of immature to submature arkose, lithic arkose, and litharenite.

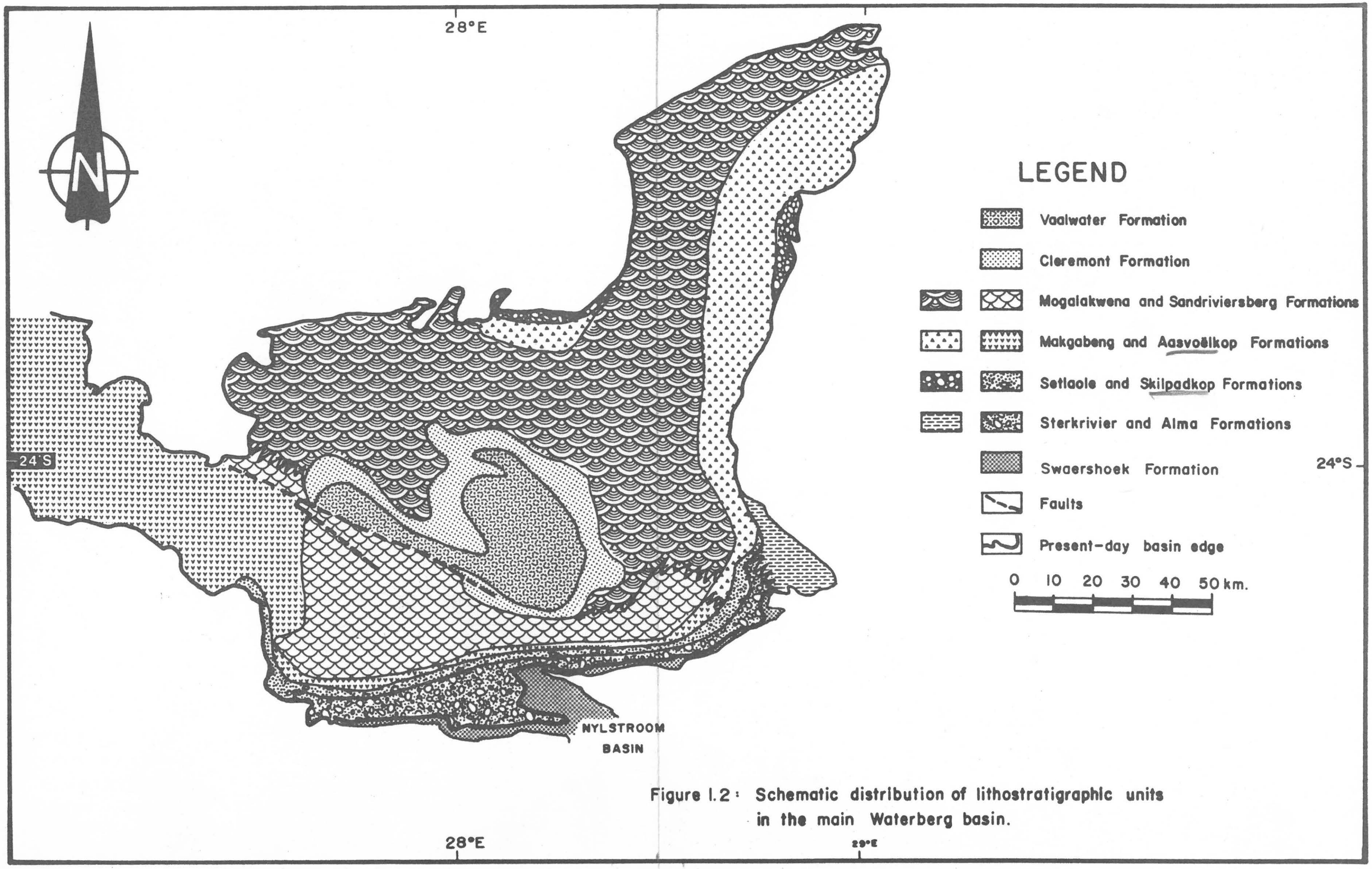


Figure I.2: Schematic distribution of lithostratigraphic units in the main Waterberg basin.

GROUP	SUBGROUP	South/Southwest & Central parts	Southeast and & Central parts	North/Northeast & Central parts	Nylstroom area	Middelburg area
WATERBERG GROUP	KRANSBERG	Vaalwater Formation (475 m)				
		Cleremont Formation (125 m)				
		Sandriviersberg Formation (1250m)	Sandriviersberg/ Mogalakwena Formations	Mogalakwena Formation (1250 - 1500m)		
	MATLABAS	Aasvoëlkop Formation (300-600m)	Aasvoëlkop/ Makgabeng Formations	Makgabeng Formation (380-1000m)		
		Skilpadkop Formation (450-600m)	Skilpadkop Formation (450-600m)	Setlaole Formation (450 m)		
	NYLSTROOM	Alma Formation (3000m)	Sterkrivier Formation (500-1500m)		Alma Formation	
		Swaershoek Formation			Swaershoek Formation (2500m)	Wilgerivier Formation

Figure 1.3 Stratigraphic subdivision of the Waterberg Group (modified after SACS, 1980, p. 344-345)

Higher in the sequence quartz arenites occur together with feldspathic litharenites and litharenites. The Aasvoëlkop and Vaalwater Formations contain a considerable amount of lutite.

Trough and planar cross-bedding are present in certain formations and the characteristic palaeocurrent direction for the Waterberg Group is from the northeast, although the lower formations also show a considerable component from the south.

1.3 PREVIOUS WORK

First mention of rocks which are now included in the Waterberg Group was probably by Cohen, quoted in a paper by Götz (1885). Moodie (1872), however, had already been in the area and had indicated a copper/lead occurrence on the Palala plateau, on his map of the economic geology of the Transvaal (Fig. 1.4).

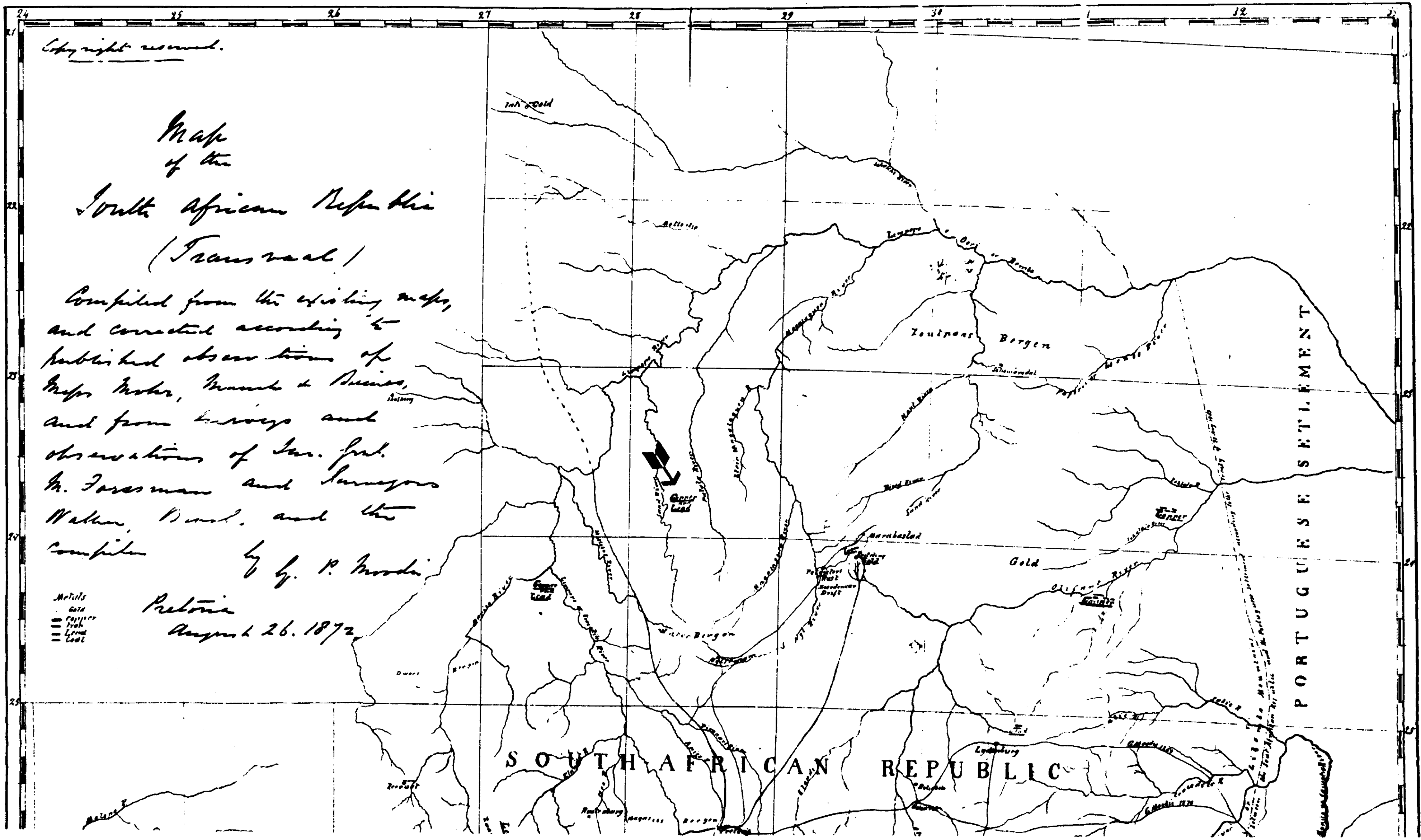
Harger (1897) noted the occurrence of red- to chocolate-coloured sandstone in the Pretoria district (Middelburg Basin). He mentioned that these strata lie unconformably on the Transvaal Sequence and are, in turn, unconformably overlain by rocks of the Karoo Sequence.

Harger's paper was followed by a large number of publications at the turn of the century (Molengraaff, 1898a, 1898b, 1901, 1904; Mellor, 1904, 1905a, 1905b, 1907, 1908, 1909a, 1909b, 1910; Holmes, 1904; Jorrisen, 1904; Hatch and Corstorphine, 1905; Anderson, 1910; Merensky, 1908; Kynaston and Mellor, 1912). Molengraaff (1898 to 1904) named these rocks the "Waterberg Sandstone Formation", and later the "Waterberg Series", after the Waterberg district of the northern Transvaal. Mellor's (1909b) paper on the Hoekbergen is of particular interest. He described the basal Alma Formation and its contact relationships with the underlying granite, which he believed to be intrusive.

A period of fifty years, in which relatively few papers were

His Honor T. F. Burgers
with the compiler's compts.

Figure 1.4 Map of the economic geology of the 'South African Republic' compiled by Moodie in 1872.



written on the Waterberg Group, ensued (Daly and Molengraaff, 1924; Hall, 1932; Le Roex, 1942; Strauss, 1942, 1948; Du Preez, 1944; Glatthaar, 1956; Cullen, 1960). Daly and Molengraaff (1924) described the findings of the Shaler Memorial Expedition and refuted previous claims that Bushveld granites intruded the Waterberg rocks around Gatkop, east of Thabazimbi. They explained the features seen in this area as being due to a series of overthrusts. Hall (1932) gave estimates of the thickness of the Waterberg sedimentary rocks of about 1 400m over the Palala plateau and up to 2 700m north of Warmbaths.

In the mid-sixties a comprehensive study of the Waterberg Group was initiated. The chief contributors to this study were Wilke (1963), De Villiers (1963, 1966, 1967), De Vries (1969, 1970, 1973), Frick (1970, 1971, 1972a, 1972b, 1972c), Meinster (1969, 1970a, 1970b, 1971, 1972, 1975, and with Tickell, 1975), Tickell (1973, 1974, 1975), De Bruiyn (1971a, 1971b, 1972a, 1972b, and with Andrew, 1972), Du Plessis (1972a, 1972b) and Jansen (1969, 1970a, 1970b, 1975a, 1975b, 1976, 1982, Jansen *et al.*, 1970, 1972). During this period understanding of the Waterberg sedimentary rocks was much improved. The stratigraphic subdivision of De Vries (op. cit.) was followed by all the other workers and later formed the basis of the present system of stratigraphic nomenclature applied to the Waterberg Group. Frick (op. cit.) undertook sedimentological and economic studies; he concluded (Frick, 1971) that the sedimentary rocks in the southeastern part of the basin were deposited in a littoral, possibly tidal, palaeoenvironment. Frick (1972b) also postulated that the tin-bearing granites were possibly intruded after the sedimentation in that part of the basin.

Meinster's (1975) paper on the Gatkop area near Thabazimbi is of particular interest. He pointed out that the Swaershoek Formation is preserved only as a few scattered erosion remnants, which are sheared. He found that pebble sizes increase towards the 'Buffelshoek thrust' in the south of the basin. Meinster (1975, p. 61) interprets the boulder beds of the Alma Formation as a littoral deposit. Meinster (1969) and Meinster and

Tickell (1975) recognized aeolian deposits in the Waterberg Group. Tickell mapped the northern part of the basin and was the first to suggest a braided river depositional environment for the Mogalakwena Formation. De Bruiyn (1971 to 1972) mapped in the central and the eastern parts of the basin and identified syn-Waterberg volcanism in the Rust de Winter area (De Bruiyn and Andrew, 1972). Jansen, who coordinated the entire study in the 1960's and 1970's and who mapped in the Nylstroom area, provided tectonic syntheses (Jansen 1969, 1975a, 1975b, 1976, Jansen *et.al.*, 1972) and reviewed available data in a memoir which terminated that period of study (Jansen, 1982).

Vos and Eriksson (1977) contributed a paper on the sedimentology of the Waterberg sedimentary rocks in the Middelburg area. They proposed a fluvial fan model for the Waterberg Group and suggested that the colour of the sedimentary rocks was due to authigenic-diagenetic alteration of iron-bearing detrital silicates.

More recently, the writer conducted a short literature study on placer deposits of cassiterite (Callaghan, 1979), with the view to identifying such deposits in the Waterberg Group. A strong correlation between tin and thorium was shown to exist in the sedimentary rocks in the Gatkop area (Callaghan, 1983a). The study was extended to the rest of the basin (Callaghan, 1982) but the focus of the study remained at Gatkop (Fig 1.1), the only area where sedimentary rocks with significant concentrations of cassiterite were found. A brief overview of the tectono-sedimentary history of the basin is presented in Callaghan (1986).

1.4 METHODOLOGY

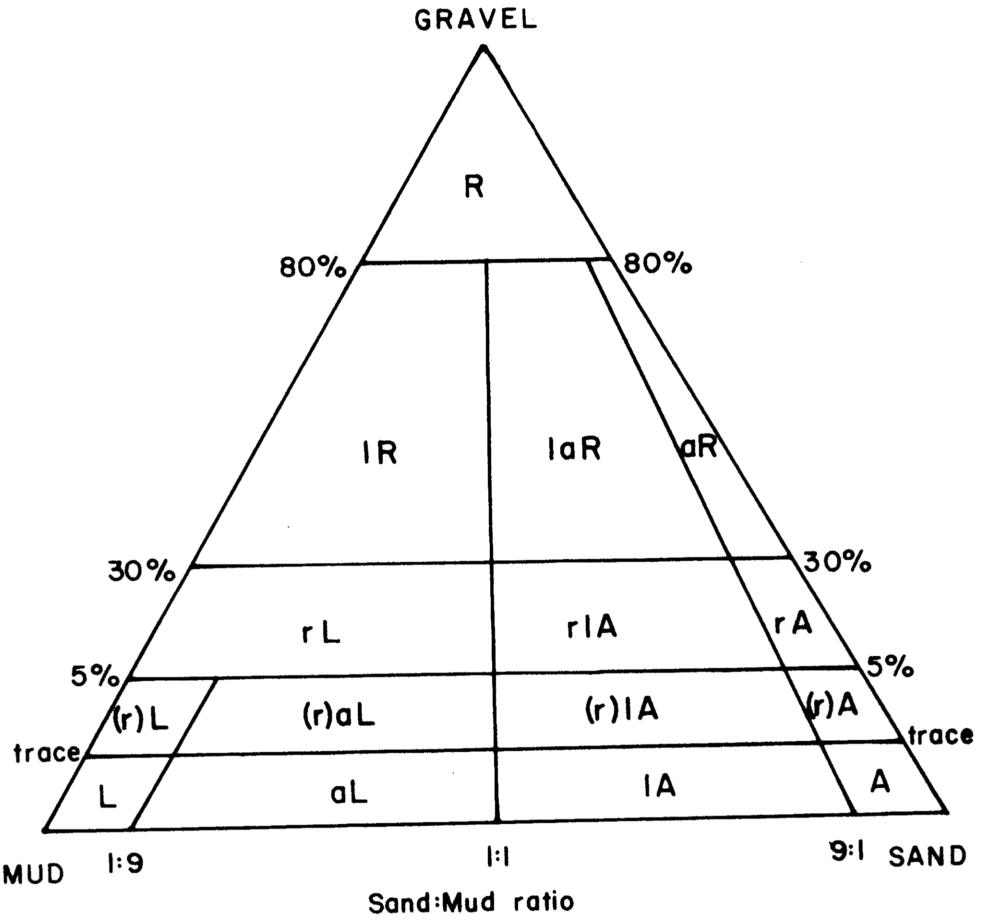
The rocks of the Waterberg Group have been studied in field outcrop, through thin section petrographic studies and by geochemical analyses. The grain size names, lutite, arenite, and rudite, were chosen for practical reasons to describe rocks in the field. 'Sandstone' and 'conglomerate' have textural connotations and are therefore not used, whilst quartzites are utilized by various authors for silica-cemented rocks, or alternatively, for metamorphosed rocks. In addition, 'conglomerate' implies a certain degree of rounding (Bates and Jackson, 1980) and therefore the term breccia would also need to be introduced for angular rudites. The terms chosen, lutite, arenite and rudite, are purely descriptive and do not reflect the geological history of the rocks.

Rocks studied in thin section have been given specific names, based largely on the classification and usage of Folk (1968). The grain size terminology, modified for the lutite/arenite/rudite system, and the compositional diagrams of Folk (1968) are presented in Figures 1.5 and 1.6. Thin sections were studied on a petrographic microscope on a flat stage, and were fully described using the scheme of Folk (1968). Selected slides were further investigated on a universal stage and/or on a scanning electron microscope (SEM). Qualitative compositional analyses were obtained on the SEM using an energy dispersive spectrometer.

Geochemical samples were crushed and analysed on a routine basis at the Geological Survey laboratory. Trace element analysis was by simultaneous X-ray fluorescence. Major element analysis was performed by sequential wavelength dispersive X-ray fluorescence.

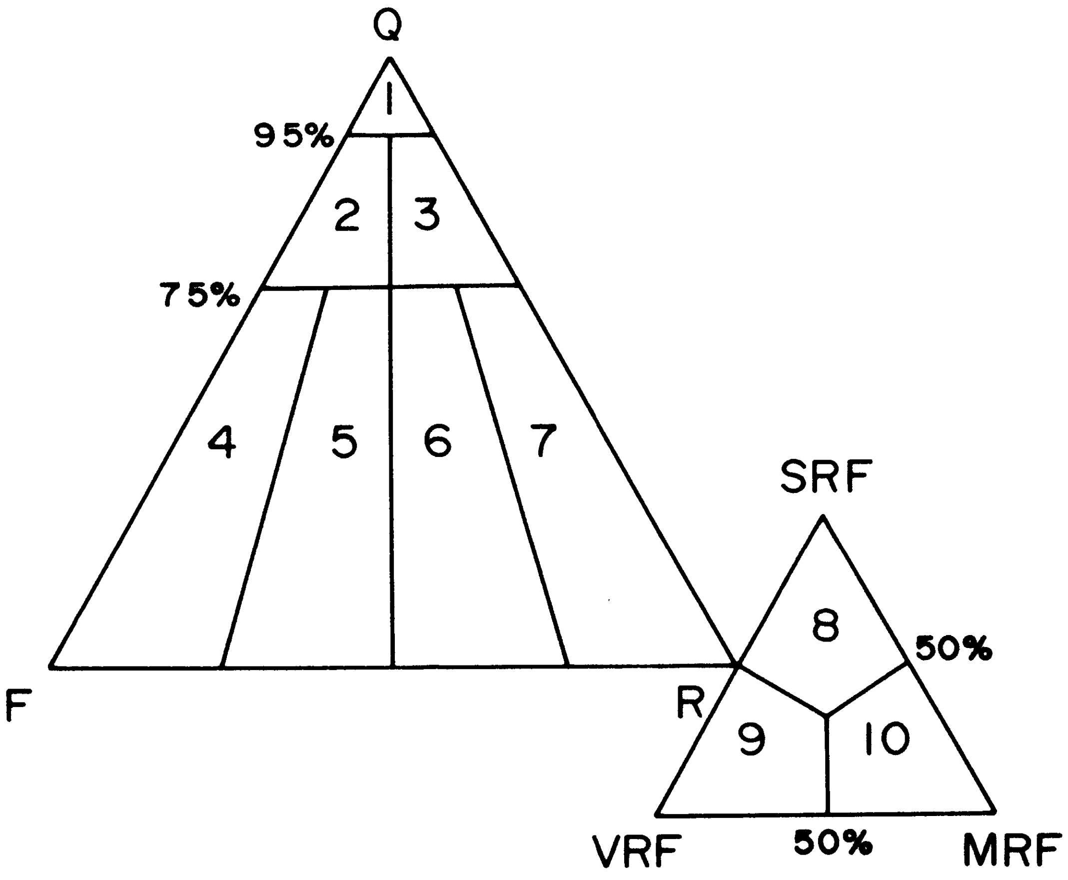
Thorium anomalies were selected from aerial radiometric survey maps, published by the Geological Survey of South Africa. Most maps showed total count, potassium, uranium as well as thorium, and anomalies were selected on their thorium peak. Where channel results were not available anomalies were chosen on total count. Each survey sheet includes the date of survey as well as an instrumentation summary.

A portable gamma-ray scintillometer was used to determine the position, extent and peaks of selected anomalies on the ground. Count rates were converted to eU_3O_8(max) or $eThO_2$(max), using constants which were determined after calibration at the Atomic Energy Corporation's facility at



R	Rudite
r	Rudaceous
(r)	Slightly Rudaceous
A	Arenite
a	Arenaceous
L	Lutite
l	Lutaceous

Figure 1.5 Grain size terminology diagram, modified after Folk (1968).



Q	All quartz, excluding chert.
F	All feldspars plus granite and gneiss fragments.
R	All other rock fragments.
SRF	Sedimentary rock fragments.
VRF	Volcanic rock fragments.
MRF	Metamorphic rock fragments

1	Quartzarenite
2	Subarkose
3	Sublitharenite
4	Arkose
5	Lithic arkose
6	Feldspathic litharenite
7	Litharenite
8	Sedarenite
9	Volcanic arenite
10	Phyllarenite

Figure 1.6 Compositional terminology diagrams, modified after Folk (1968)

Pelindaba near Pretoria. A portable four channel gamma-ray spectrometer was also used at times, notably at Gatkop, and these count rates were converted to K_2O (percent), eU_3O_8 (ppm) and ThO_2 (ppm). The energy windows of the spectrometer were aligned frequently during the investigation to correct for instrumental drift caused by temperature variation. The alignment was carried out away from any obvious magnetic sources since magnetism may have a considerable effect on these instruments (Callaghan, 1983b).

2 PETROLOGY AND GEOCHEMISTRY

2.1 PETROLOGY

2.1.1 Introduction

More than seventy thin sections of Waterberg samples have been studied according to the methods outlined by Folk (1968, p. 144-152). Only selected samples are described here, but short descriptions of all slides studied are given in Table 2.1. Summaries of the composition, grain size and interpreted provenance of the sedimentary rocks are presented in figures 2.1a, b and c. Figures 2.1a and b are adapted from Folk (1968); base diagrams showing the names of the specific size and compositional fields are shown in Figures 1.5 and 1.6. Folk (1968) used a system of naming sedimentary rocks by first stating their grain size name (eg. for sample CC-145, medium arenite with granules) followed by the sample's compositional name (eg. ferruginous submature micaceous arkose). Besides samples of Waterberg Group sedimentary rocks, thin sections of related intrusives were also studied, so that their relationship with the rocks of the Waterberg Group could be better understood. Twenty polished/thin sections were studied under the scanning electron microscope (SEM) in order to identify small particles. SEM analyses were made to confirm microscopic mineral determinations of certain transparent minerals; opaque minerals were also named from these analyses. In some cases the identity of opaque minerals was checked under a reflected light microscope. In a few cases X-ray diffraction analysis was carried out to identify minerals.

2.1.2 Thin Section Study

A brief summary of the thin section data derived from this study

TABLE 2.1

PETROGRAPHIC DATA FOR SAMPLES STUDIED IN THIN AND POLISHED SECTION

NUMBER	FORMATION	MODAL ANALYSIS	SORTING	ROUNDNESS	SPHERICITY	COMMENT/SOURCE
018	Alma	60% quartz, 30% feldspar, 3% aegerine-augite, 3% epidote, 2% metamorphic rock fragments, 2% calcite cement, trace zircon	Poor	-	-	Na-rich igneous or K-rich metamorphic
096	Alma	50% quartz, 25% feldspar, 8% enstatite, 4% clay matrix, 13% sericite, chlorite and heamatite cement	moderate	angular-subangular	50%	Na-rich igneous
100	Alma	35% quartz, 38% sericitized feldspar, 10% mica, 5% clay matrix, 13% iron oxides.	moderate to good	angular-subangular	46%	chiefly granitic,
106	Bushveld Granite	40% plagioclase, 30% quartz, 15% orthoclase, 5% opaques, traces of topaz	-	-	-	granite boulder in Alma Formation
132	Makgabeng	70% quartz, 10% feldspars, 8% mud, 10% rock fragments, 1% muscovite	moderate	subrounded	65%	acid plutonic
133	Mogalakwena	65% quartz, 20% cordierite, 8% epidote, 5% andalusite, 1% silliminite, 1% plagioclase	-	-	-	-
136	Mogalakwena	70% quartz, 15% orthoclase, 1% plagioclase, 2% mica, 2% rhyolite fragments	moderate	rounded	81%	acid intrusives and extrusives
139	Alma	50% quartz, 30% feldspar, 1% zircon, 8% clay, 3% haematite, 10% rock fragments	poor	angular - subangular	67%	granophyric granite
143	Bushveld Granite	20%quartz, 10% plagioclase, 60% orthoclase, 5% hornblende, 2% biotite	-	-	-	-

TABLE 2.1 continued

NUMBER	FORMATION	MODAL ANALYSIS	SORTING	ROUNDNESS	SPHERICITY	COMMENT/SOURCE
145	Alma	40% quartz, 2% chert, 45% feldspar, 2% enstatite, 2% mica, 3% rock fragments, 5% ferruginous cement, 5% clay matrix	poor	angular-subangular	60%	granophyre, quartz veins, metamorphosed limestones and quartzites
146	Alma	40% quartz, 30% orthoclase, 10% plagioclase, 8% enstatite, 3% mica, 3% clay, 6% haematite cement	moderate	angular-subangular	52%	plutonic persilicic to subsilicic
148	Alma	50% quartz, 35% K-feldspars, 8% opaques, 2% rutile, zircon, tourmaline, muscovite, cassiterite, trace auerlite? (a thorium silico-phosphate, with iron)	poor	subangular-subrounded	-	granophyre
156	Alma	45% quartz, 15% fluorite, 1% fluocerite, clay (faratsihite) matrix, traces of wollastonite, zircon, beckelite? (RE-calcium silicate).	-	angular-subrounded	70%	hydrothermal mineralization
157	Bushveld	Chiefly granophyric intergrowths, beta-quartz paramorphs, also biotite, zircon, opaques	-	-	-	granophyric granite porphyry
159	Alma	50% quartz, 15% feldspar, 20% rock fragments, 10% haematite cement, traces of mica and zircon	poor	angular - subrounded	64%	acid plutonic
160	Alma	Quartz breccia in iron oxide matrix, some chert veining quartz contains blue tourmaline inclusions	-	-	-	hydrothermal channelway?
188	Alma	Brecciated arkose with chalcopyrite, barite, pitchblende and kasolite.	-	-	-	uranium/copper vein in arkose

TABLE 2.1 continued

NUMBER	FORMATION	MODAL ANALYSIS	SORTING	ROUNDNESS	SPHERICITY	COMMENT/SOURCE
557	Mogalakwena	15% metamorphic rock fragments, 65% quartz, 3% mica, 4% clay, matrix, 6% opaques, 3% chert, 2% quartz cement, trace zircon, 2% iron oxide cement	poor	subangular-subrounded	70%	metamorphic, plutonic, sedimentary
560	Sand-riviersberg	70% quartz, 15% metamorphic rock fragments, 5% rhyolite rock fragments, 2% mica, 3% opaques, 1% clay matrix, 1% iron oxide cement	poor	subangular	64%	meta-quartzites
562	Skilpadkop	55% quartz, 10% rhyolite rock fragments, 10% calcite grains, 7% clay matrix, 5% mica, 5% metamorphic rock fragments, 2% Fe-oxide cement, 5% sericite, traces of zircon, tourmaline, opaques.	poor	angular-subangular	59%	rhyolite, meta-quartzites and limestone
585	Vaalwater	15% silt in clay matrix	-	-	-	-
588 588a	Cleremont	92% quartz, 5% rhyolite and lutite rock fragments, 2% mica and 1% opaques.	good	rounded to well rounded	-	abundant quartz overgrowths
620	Mogalakwena	97% quartz, 3% opaques in metaquartzite	-	-	-	Sample of clast
624	Swaershoek	65% quartz, 15% silica cement, 17% rock fragments, 2% clay matrix, trace of orthoclase and opaques.	good	rounded	76%	metamorphic rocks, rhyolite, sediments.
638	Mogalakwena	70% quartz, 8% metamorphic rock fragments, 8% mica, 8% clay matrix, 4% silica cement, 2% opaques, 1%iron oxide cement and a trace of zircon	poor	subangular-subrounded	71%	metamorphic terrain
646 and 647	Cleremont	10% quartz, 60% titanomagnetite, 2% rutile, 8% zircon, 2% monazite, 1% thorite, traces of zirkelite, gorceixite and uranothorite, 15% anatase cement. No clay seen.	good	well rounded	-	probably formed as beach placer.
833	Bushveld Granite	brecciated granophyric granite	-	-	-	-

TABLE 2.1 continued

NUMBER	FORMATION	MODAL ANALYSIS	SORTING	ROUNDNESS	SPHERICITY	COMMENT/SOURCE
857	Alma	Granophyric granite porhyry, 1,5% mica, 3% opaques	-	-	-	clast in Alma
888	Alma	Composite cassiterite grains, inter-grown with quartz and manganocalcite	-	-	-	separated grains of cassiterite
1003 1005 1006	Alma	65-70% quartz, 25% rock fragments, 3% silica cement, 1% iron oxide cement, 3% clay matrix, traces of mica, cassiterite, zircon and opaques	moderate	subangular	70%	rhyolite, chert, metaquartzite and granophyre
1018	Alma	45% quartz, 12% granite and granophyre rock fragments, 15% altered feldspar, 25% clay matrix, 3% iron oxide cement.	poor	subangular-angular	68%	granite and granophyre
1047	Alma	25% quartz, 30% feldspar, 1% mica, 15% granite, granophyre and rhyolite rock fragments, 14% opaques (chiefly titanomagnetite and ilmenite), 5% iron oxide cement, 3% zircon, 3% thorite, 2% witherite, 1% monazite,1% cassiterite, traces of topaz, andalusite, barite, apatite and thorotungstite.	poor	subangular	61%	granite and rhyolite
1048	Alma	25% quartz, 30% feldspar, 40% granite rock fragments, 2% mica, 2% opaques, 1% iron oxide cement.	poor	subangular-angular	60%	granite
1050	Sterkrivier	70% rock fragments, 10% quartz, 1% clay matrix, 8% iron oxide cement, 1% prehnite cement, trace of zircon, rutile, titanomagnetite and anatase	poor	subrounded	68%	metaquartzite, rhyolite, iron ore.
1056	Aasvoelkop	40% quartz, 30% feldspar, 3% granophyre and chert rock fragments, 2% opaques, 15% epidote and 10% calcite cement.	moderate	subangular-angular	62%	acid plutonic

TABLE 2.1 continued

NUMBER	FORMATION	MODAL ANALYSIS	SORTING	ROUNDNESS	SPHERICITY	COMMENT/SOURCE
1057	Aasvoelkop	50% quartz, 28% altered feldspar, 2% granophyre fragments 7% clay, 10% epidote, 3% quartz cement	moderate	rounded-subangular	67%	acid plutonic
1059	Aasvoelkop	65% quartz, 15% mica, 15% clay, trace rutile, 3% iron oxide cement, 2% quartz overgrowths.	poor	subangular	64%	mica secondary
1060	Aasvoelkop	55% quartz, 10% volcanic rock fragments, 5% shard-like grains, trace zircon, 30% clay matrix.	moderate	subangular-subrounded	45-61%	Volcanic
1065	Aasvoelkop	30% quartz, 20% rock fragments, 50% clay matrix, trace epidote	poor	subangular	60%	Volcanic
1066	Aasvoelkop	Some quartz and rock fragments in clay matrix.	-	-	-	Volcanic
1067	Aasvoelkop	quartz in clay/silt matrix. 20% epidote, 5% chlorite	-	-	-	-
1069	Dolerite	micrographic quartz/feldspar intergrowths, epidote, chlorite and calcite.	-	-	-	-
1126	Alma	55% quartz, 30% orthoclase, 7% rock fragment, 3% iron oxide cement, 3% clay matrix, .5% silica cement	moderate	subangular	67%	acid plutonic
1129	Alma	40% quartz, 15% feldspar, 35% granite, granophyre and rhyolite rock fragments, 1% opaques, trace zircon, 3% clay matrix, 6% iron oxide cement	poor	subangular	65%	granite/granophyre, rhyolite
1153	Alma	15% quartz, 5% feldspar, 65% granite and granophyre clasts, 5% chert, arenite and lutite fragments, 10% clay matrix	poor	angular-subangular	-	granite and granophyre.

TABLE 2.1 continued

NUMBER	FORMATION	MODAL ANALYSIS	SORTING	ROUNDNESS	SPHERICITY	COMMENT/SOURCE
1169	Alma	40% quartz, 8% feldspar, 35% rhyolite and granophyre rock fragments 5% opaques, 1% mica, trace zircon, 10% clay matrix	poor	angular	63%	granophyres and acid volcanics.
1184a	Alma	40% quartz, 40% feldspar 5% heavy minerals, 3% mica, trace zircon 5% clay matrix, 3% iron oxide cement.	poor	angular-subangular	53%	acid plutonic
1184b	Alma	40% quartz, 10% feldspar, 10% mica, 6% opaque heavy minerals, trace of zircon and enstatite, 33% clay matrix.	poor	angular-subrounded	71%	acid plutonic
1193	Alma	25% quartz, 8% mica, 65% feldspar, 1% opaques, 0,5% zircon				granitoid clast
1197	Alma	Quartz and zircon in muddy matrix	poor	angular-subrounded	-	clast in Alma
1200	Alma	40% quartz, 15% feldspar, 10% opaque minerals, 5% mica, 1% zircon, 30% clay matrix	poor	angular-subangular	49%	plutonic
1204	Alma	30% quartz, 20% mica, 20% clay, 20% iron oxide cement, 10% opaques	-	angular-subangular	-	interfan lake?
1211	Alma	Muscovite/quartz schist with 10% opaques				metamorphic clast
1215	Alma	50% quartz, 20% weathered feldspar, 10% clay, 10% opaques, 2% zircon		angular-subrounded		proximal debris flow.
1223	Alma	Quartz, mica and opaque minerals in clay matrix	-	angular-subangular	-	lutite intraclast (mud flake)

TABLE 2.1 continued

NUMBER	FORMATION	MODAL ANALYSIS	SORTING	ROUNDNESS	SPHERICITY	COMMENT/SOURCE
1235	Alma	48% quartz, 20% plagioclase, 10% orthoclase, 5% granophyre fragments, 3% mica, 2% chert1% lutite, traces of tourmaline and opaque minerals, 5% clay matrix, 5% iron oxide cement.	moderate	angular-subrounded	58%	acid plutonic
1236	Alma	40% quartz, 25% feldspar, 10% mica, 4% enstatite, trace zircon, lutite and thorite, 7% clay matrix, 10% Fe-oxide cement	poor	angular-subrounded	56%	acid plutonic
1246	Alma	38% quartz, 19% orthoclase, 10% andesine, 3% enstatite, 3% mica, 7% opaque minerals, 1% zircon, traces of monazite and rutile, 10% clay matrix, 1% iron oxide cement.	poor	angular-subrounded	56%	acid plutonic
1250	Alma	Similar to 1246, but 25% opaques	poor	subangular	-	acid plutonic
1261	Alma	50% quartz, 25% feldspar, 10% mica, 5% enstatite 5% clay matrix and 5% iron oxide cement	good	angular-subrounded	60%	acid plutonic
1285	Alma	55% rock fragments, 20% quartz, 7% feldspar, 5% opaques, 1% mica, traces of tourmaline, garnet, axinite, pyroxene, thorite, zircon, 7% clay matrix, 2% Fe-oxide cement, 1% calcite cement	poor	subangular	-	plutonic
1355	Alma	40% quartz, 40% feldspar, 5% opaques, 7% iron oxide cement, 5% clay matrix, 0,5% sphene, traces of zircon, monazite, uranothorite, tourmaline, barite, diopside, garnet, topaz, celsian	moderate	angular-rounded	67%	acid plutonic
1380	Dolerite	Consists chiefly of chlorite, trace zircon, clusters of twinned calcite, polycrystalline bertrandite and sphene	-	-	-	
1417	Alma	Granophyre with calcite/chlorite vein, also present is barite, chlorite and prehnite (with bow-tie structures)	-	-	-	granophyric granite clast in Alma

TABLE 2.1 continued

NUMBER	FORMATION	MODAL ANALYSIS	SORTING	ROUNDNESS	SPHERICITY	COMMENT/SOURCE
1426	Alma	Contact zone consists chiefly of calcite and epidote, dolerite is mass of felted chlorite needles, also barite, celsian, sphene, prehnite, zircon, nagatelite	-	-	-	intrusive contact of dolerite and arenite
1442	Intrusive	Consists chiefly of Na-feldspar	-	-	-	Porhyritic bostonite
1524	Bushveld Complex	Granophyre with some mica and trace zircon shows 'mortar texture' in places	-	-	-	highly fractured from Bh 020
1552	Bushveld Complex	Quartz and microperthite with a trace of zircon	-	-	-	Highly fractured from Bh020
1563	Vaalwater	80% clay (K-rich), 20% silt, iron oxide cement. Grains prolate to equant	-	angular-rounded	-	-
1564	Vaalwater	97% clay, 3% silt and sand, iron oxide cement.	good	-	-	-
1577	Vaalwater	89% quartz, 10% plagioclase feldspar, 1% chert extensive quartz overgrowths.	-	-	-	acid igneous.and volcanic rocks
1587	Dolerite	40% anorthite, 33% enstatite, 15% hornblende, 8% biotite 2% granophyre, 2% opaques. Much sericite and chlorite	-	-	-	altered dolerite
1597	Alma	55% quartz, 2% mica, trace zircon, 22% sericitized grains, 10% granophyre rock fragments, 4% clay matrix, 6% Fe-oxide cement	moderate	subangular	60,5%	Acid plutonics
1598	Alma	30% rock fragments, 22% feldspars, 10% opaque grains, 20% quartz, 1% muscovite, 10% clay matrix, 7% iron oxide cement	poor	-	-	acid plutonics and sediments
1601	Bushveld Complex	Micographic quartz/feldspar intergrowths, 7% chlorite, 2% opaques, trace of sphene.	-	-	-	shallowly intruded late stage granite
1603	Dolerite	50% plagioclase, 10% quartz, 5% feldspar, 15% augite, 15% hornblende, 4% opaques	-	-	-	tungsten = 25ppm

TABLE 2.1 continued

NUMBER	FORMATION	MODAL ANALYSIS	SORTING	ROUNDNESS	SPHERICITY	COMMENT/SOURCE
1612	Skilpadkop	35% quartz, 5% rock fragments, 10% chert, 15% metaquartzite, 5% schist, 15% opaques, 1% zircon and rutile, 2% granophyre fragments, 1% mica, 1% microline, 6% clay matrix, 4% Fe-oxide cement.	poor	w. rounded- v. angular	57%	metamorphic source
1613	Skilpadkop	30% quartz, 20% chert, 17% metaquartzite, 5% opaques, trace tourmaline, 25% clay, 3% iron oxide cement	poor			metaquartzite and chert
1614	Skilpadkop	65% quartz, 7% mica, 8% chert, 2% opaques, trace of tourmaline, 10% clay, 6% iron oxide cement	poor	angular- subangular	49%	chemical sediments and metaquartzites
1620	Dolerite	60% granophyre, 5% augite, 8% hornblende, 20% plagioclase feldspar, 2% opaques, 5% quartz	-	-	-	-
1623	Mogalakwena	72% quartz, 15% opaques, 2% rock fragments, 2% mica, 1% zircon trace rutile and chlorite, 3% clay matrix, 5% quartz cement	-	subrounded- rounded	69%	igneous/metamorphic
1628	Cleremont	99% quartz, traces of chert, zircon, tourmaline and mica	good	rounded	73%	littoral environment
1643	Cleremont	87% quartz, 10% quartz cement, 1% rhyolite rock fragments, 1% clay, traces of chert, opaques and zircon.	good	rounded- subrounded	71%	acid plutonic and volcanic
1665	Aasvoelkop	60% quartz, 20% quartz overgrowths, 6% clay matrix, 6% opaques, 3% mica, 5% andesine.	poor	-	-	-
1667	Aasvoelkop	95% quartz, 2% mica, 1% titanomagnetite, trace of plagioclase, 2% clay. Coating on outcrop identified as coquimbite (XRD).	-	-	-	-
1668	Aasvoelkop	'Vesicles' filled with calcite, barite and minor cordierite	moderate	angular	50%	ash fall?
1669	Dolerite	Completely altered to chlorite and sericite, malachite occurs in blebs and in veins.	-	-	-	hydrothermally altered dolerite

is given in Table 2.1. Several general trends which were noticed during the field investigation were confirmed in this study. In general the sediments become finer, better sorted and rounded and more mature overall from the bottom of the sequence upwards. In contrast, quartz grain sphericity shows few specific trends although it does appear to be generally higher in the Mogalakwena Formation. The overall fining of the rocks, from the base up to the Aasvoëlkop and Makgabeng Formations, and again from the Mogalakwena Formation up to the Vaalwater Formation is apparent in Figure 2.1b which shows the grain sizes of samples studied in thin section. Trends in the composition of the rocks are more complex as they are the result of provenance, sedimentary processes and the durability of constituent grains. Samples from different individual formations do, however, group quite well (Fig.2.1a) and a vague upward trend is seen from feldspar rich rocks, via mixed quartz/rock fragment rich types to quartzarenite. The interpreted provenance of the rocks is shown in Figure 2.1c; it is clear from this diagram that most of the samples show at least a partial contribution from igneous rocks. In the case of the Alma Formation this igneous contribution is due mainly to acid plutonic rocks (granite and granophyre). In contrast, most of the other formations show a partial input from volcanic rocks (chiefly rhyolite). Most of the higher formations also show the influence of sedimentary and metamorphic rocks.

Of the 38 thin sections from the Alma Formation twenty are classified as submature to immature arkoses, four as lithic arkoses, three as feldspathic litharenites, three as subarkoses and two as volcanic litharenites (Fig. 2.1a, b). The rest of the thin sections were either clasts or samples which could not be classified according to Folk's (1968) system, such as thin section 156 which is highly altered and mineralized.

The sedimentary rocks of the Alma Formation are typically sericitized, to a greater or lesser extent. They often contain a considerable quantity of mica, especially bleached biotite (Fig. 2.2). Some of the finer-grained varieties contain quartz 'slivers' (Fig. 2.3).

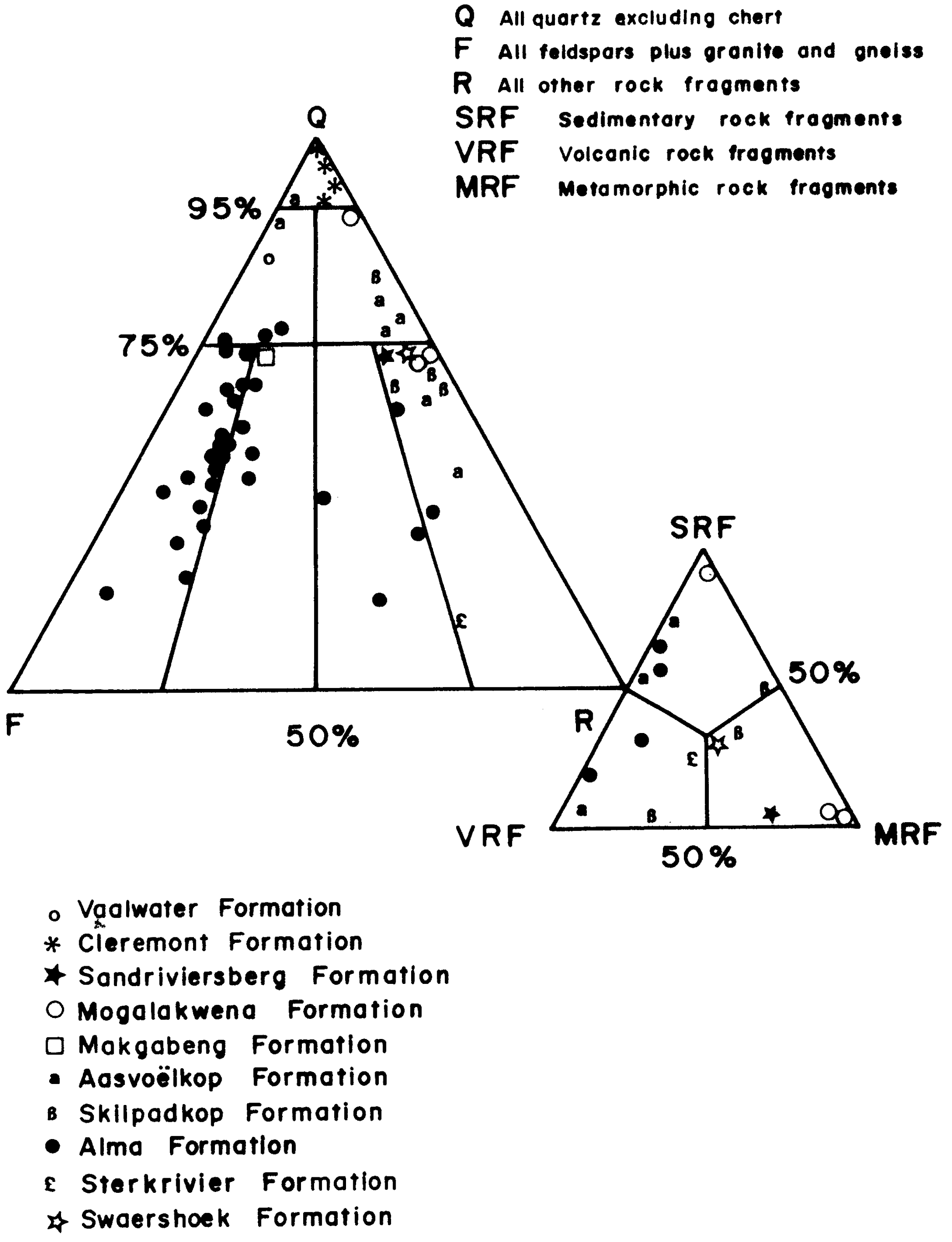


Figure 2.1a: Composition of rocks studied in thin section.

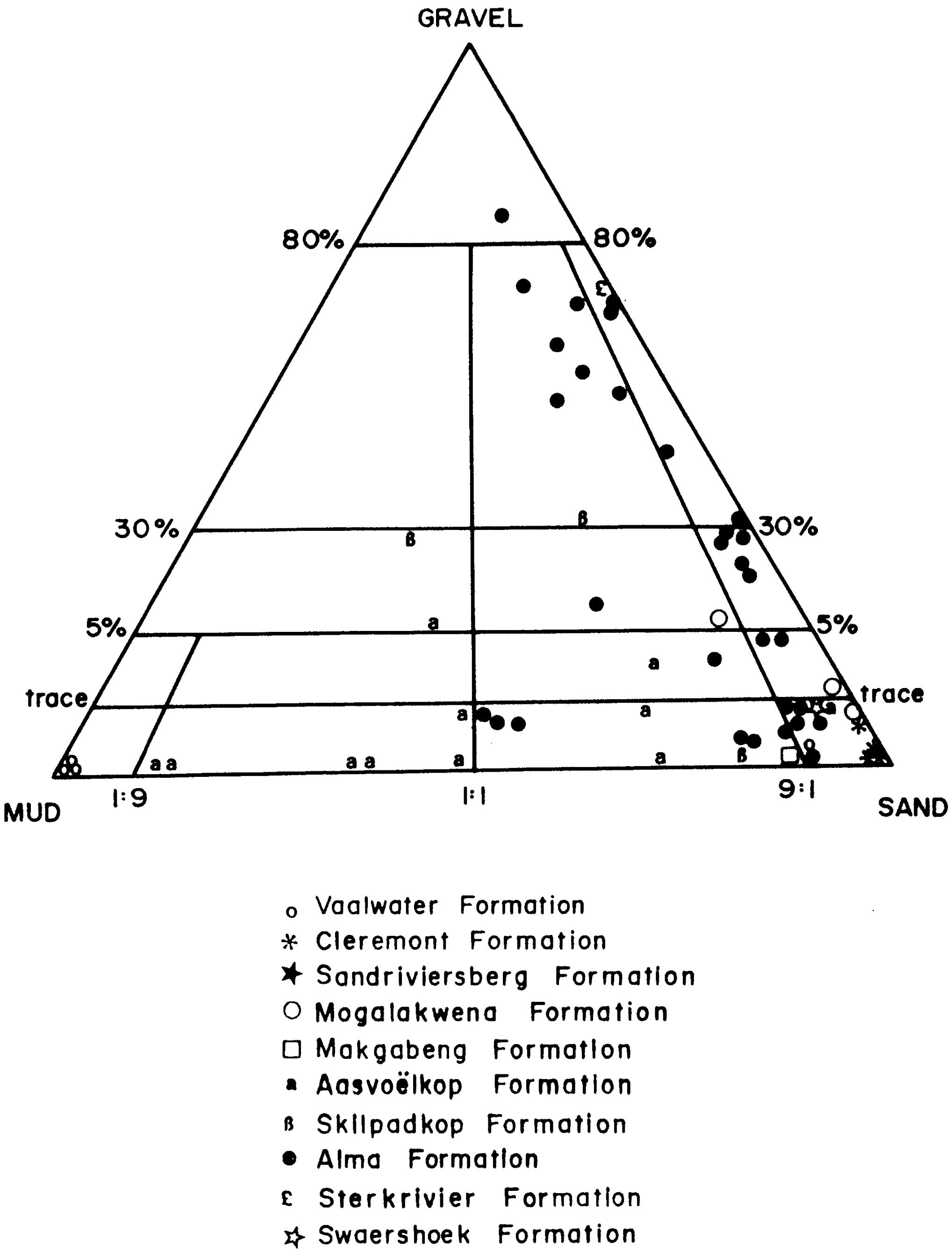


Figure 2.1b: Grain size of samples studied in thin section.

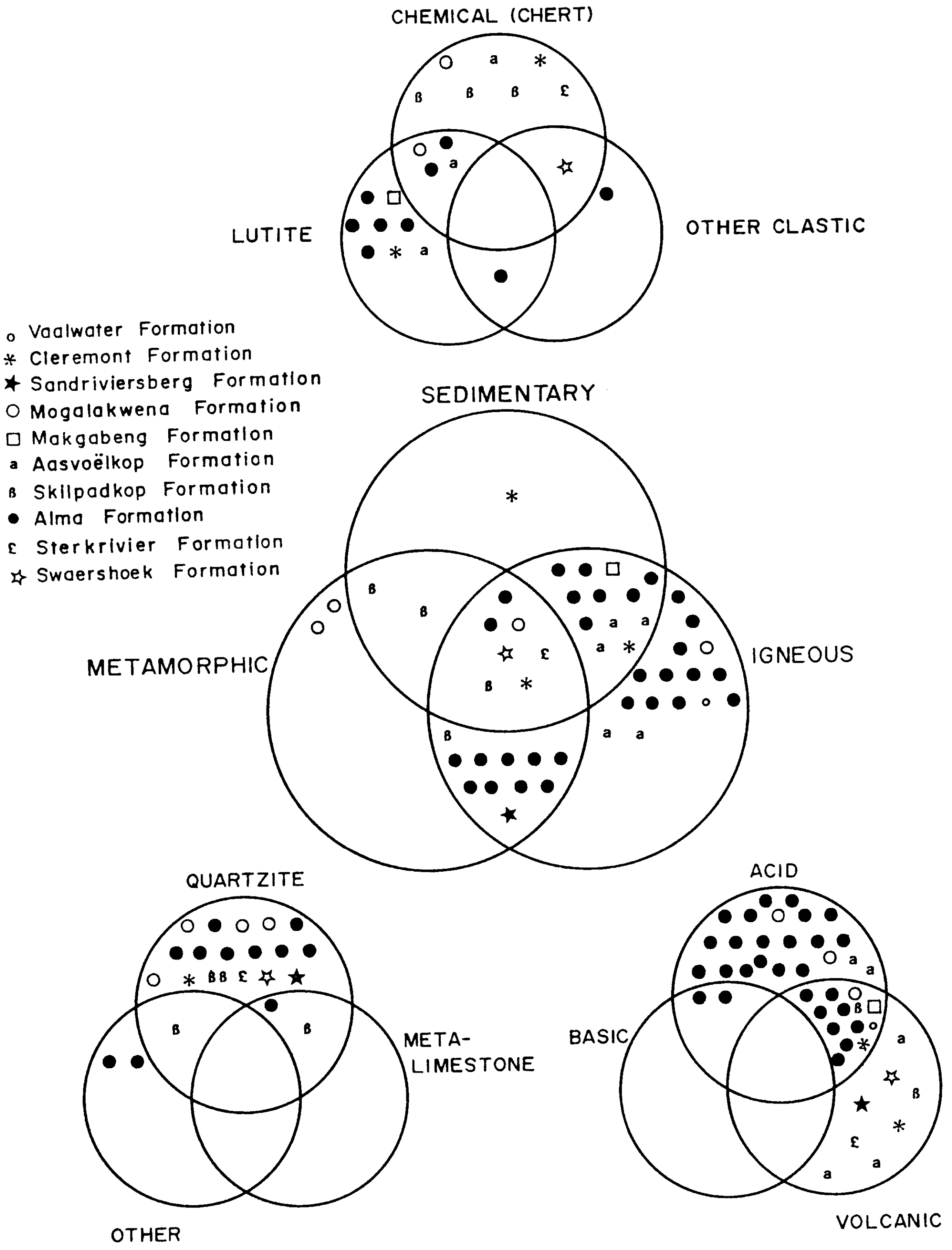


Figure. 2.1.c Showing interpreted provenance for rocks studied in thin sections.

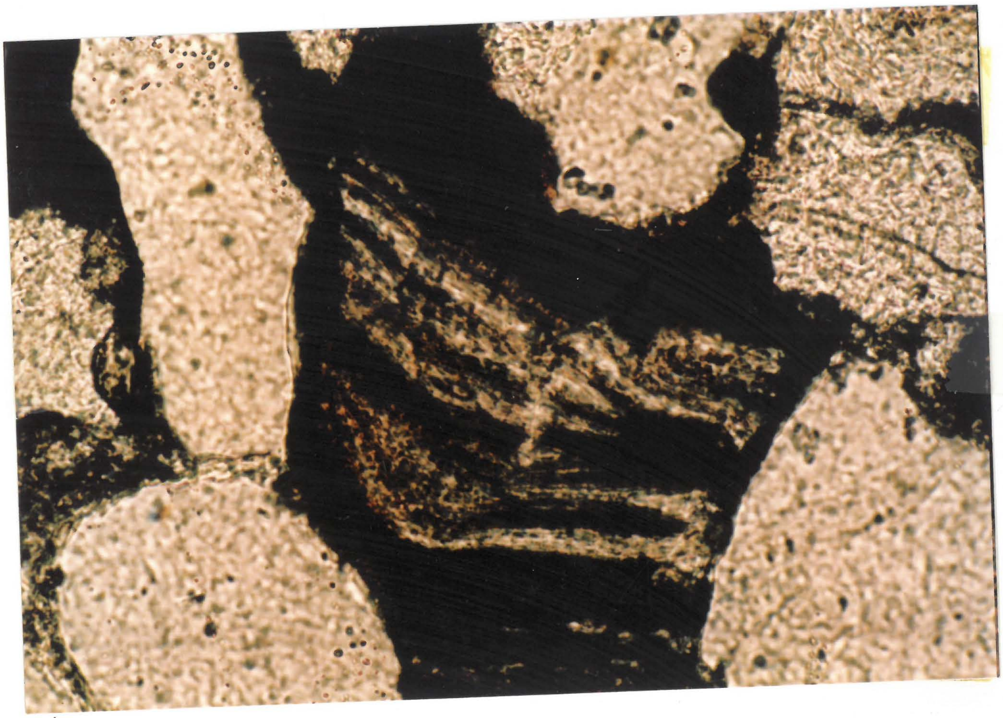


FIGURE 2.2 Fine arenite: ferruginous, sericitized, submature micaceous arkose. From the Alma Formation on Groenfontein 458KQ. This rock contains 10% bleached biotite. (Thin section 100: Base of photo = 0,45mm)

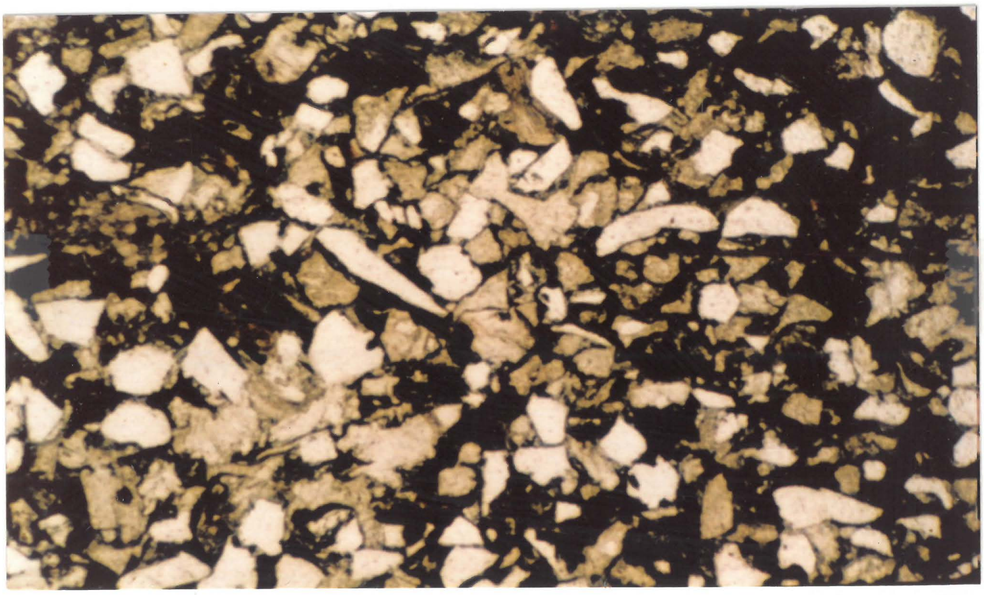


FIGURE 2.3: A medium-grained arenite which is classified as a haematitic submature arkose. Notice extreme angularity of particles (quartz slivers). (Thin section 146: Base of photo = 1,4mm)

Deformation lamellae are relatively common, both in the quartz grains as well as in quartz crystals in granite clasts (Fig. 2.4). The fact that only some quartz grains show deformation lamellae indicates that the strain which caused them affected the source rocks rather than the sedimentary rocks in which they now occur. Sorting in the Alma Formation is in general poor although it may be locally moderate to good. Roundness is in the range of angular to subrounded and most grains are subangular. Average sphericity is moderate (61%).

Granitoid clasts in the Alma Formation have a granophyric and sometimes a porphyritic texture. Quartz usually occurs as individual xenomorphic or idiomorphic grains as well as in intergrowths, whereas the feldspars commonly occur only in granophyric intergrowths. Other clast types which occur are quartzite and schist rock fragments as well as mudflakes. Rutile and zircon are common accessory minerals. Other heavy minerals seen are tourmaline, cassiterite, opaque iron/titanium oxides, thorite, topaz, andalusite, barite and apatite. Haematite cement is common.

Waterval 443KQ provided many interesting specimens of which CC-148 is one. This arenaceous rudite is a submature, heavy mineral-rich arkose. It is vaguely layered and it contains a few beta-quartz crystal paramorphs (Fig. 2.5). The rock comprises 50% quartz, 35% K-feldspar, 8% opaques (titanomagnetite and minor ilmenite), and 2% of rutile, zircon, tourmaline, muscovite, and cassiterite. Quartz grains sometimes show deformation lamellae. These lamellae, which are similar to those described by Ingersol and Tuttle (1945) and Christie and Raleigh (1959), are also common in granite clasts in the Alma Formation. These structures display closely spaced, planar to spindle shaped, parallel lamellae which do not transgress grain boundaries. In plane polarized light the lamellae look like thin fractures; those lamellae that are seen most clearly lie at a large angle (more than 60°) to the plane of the thin section. On close inspection they appear to show light edges with a dark centre; when the microscope is carefully focussed the lamellae virtually disappear. Under crossed nicols

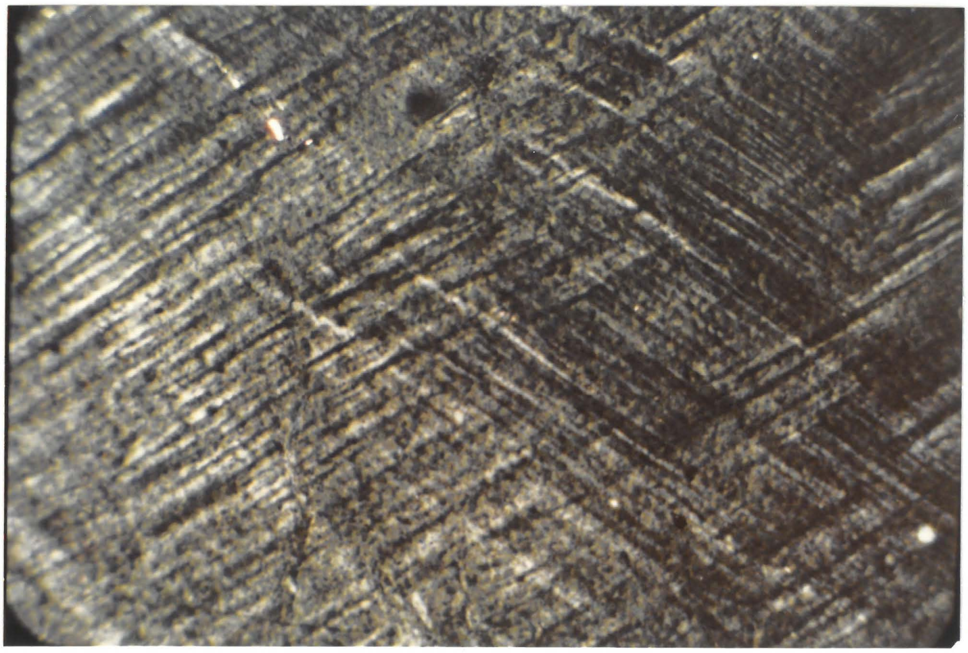


FIGURE 2.4: Deformation lamellae in two directions in quartz in a coarse-grained granophyric granite clast from the Alma Formation at Waterval 443KQ. (Base of photo = 1,4mm)

FIGURE 2.5 Euhedral paramorphs after beta-quartz seen in sample CC-148, which is a submature, heavy mineral-rich arkose. (Base of Photo = 1.1mm)

the lamellae are usually very apparent near the extinction position for the crystal (Fig 2.4). The lamellae are far more apparent in phase contrast illumination, having a character similar to that described by Carter and Friedman (1965, p. 762). The lamellae do not show any inclusions along the 'fractures'; this is significant since the first described natural varieties consisted essentially of lines of tiny inclusions (Böhm, 1883). Studies on the universal stage microscope showed that the lamellae are at a moderate angle to the basal (0001) plane; this indicates that they must be classified into the subbasal I category (Carter, 1975).

Another sample from Waterval which proved to be very interesting is sample CC-156, which is an altered and mineralized, fluorite- and fluocerite-bearing arenite. This sample is extensively altered and mineralized. Fluorite replaces quartz in places and there are virtually no other signs of the original detrital material left.

A pebbly, granule-rich, very coarse arenite (sample CC-1047), from Buffelshoek 446KQ, is classified as a ferruginous, submature heavy mineral-rich arkose. It is very poorly sorted, with a width/length ratio for quartz of 61%. The quartz and zircon grains are angular to subangular, whilst the rest are subangular to subrounded. Quartz grains are commonly fractured and they often show deformation lamellae. The rock contains 25% quartz, 30% weathered feldspar (orthoclase), 1% mica, 15% granite, granophyre and rhyolite rock fragments, 14% opaques (chiefly titanomagnetite and some ilmenite), 5% haematite cement, 3% zircon, 3% thorite, 2% witherite, 1% monazite, 1% cassiterite, and traces of topaz, andalusite, barite, apatite, and thorotungstite.

A medium to coarse arenite from Buffelshoek 446KQ provides further interest. It comprises a ferruginous submature arkose and besides its heavy mineral composition (0,5% sphene, traces of zircon, monazite, uranothorite, tourmaline, barite, diopside, garnet and topaz), it is interesting because of a possible fossil it contains. This tiny fragment may represent a chitonozoan or perhaps a deformed complex algae (C. S. Macrae, 1986 - pers.

comm.).

The effect of the dolerite intrusions on the Waterberg sediments is seen in sample CC-1426 of a dolerite/Alma Formation contact from Buffelshoek 446KQ. It can be seen that pieces of sediment were assimilated by the flowing magma. A contact zone, about 3mm thick, consists of calcite and epidote. A vein of igneous material intruding the sediment consists of calcite, chlorite and epidote, as well as large crystals (>7mm across) of barite and celsian. The dolerite groundmass consists of a felted mass of chlorite needles with scattered epidote and a few much altered feldspar laths. Traces of sphene, nagatelite?, epidote, prehnite and zircon occur.

A rather interesting intrusion was intersected, at 345,4 to 345,5m, by borehole 19 (Fig. 3.8, 3.9) through the Alma Formation. It is a porphyritic bostonite and it consists essentially of extremely finely crystallized feldspar. Oligoclase-andesine and orthoclase occur as phenocrysts; a few pods and veins of orthoclase, epidote, sphene and schorlomite? can also be seen.

A single thin section from the Sterkrivier Formation was studied (Thin Section 1050). This rock was identified as a litharenite (Fig. 2.1a, b). Rock fragments present are haematized rhyolite, stretched metaquartzite, vein quartz, haematite and chert. The rock contains 10% quartz, much of which shows well-developed deformation lamellae. Besides quartz and rock fragments the thin section contains traces of zircon, titanomagnetite, rutile and anatase. Iron oxide and prehnite cement occur. This rock is an arenaceous granule rudite which comprises 70% gravel, 27% sand and 3% mud. The width:length ratio of rock fragments is 50% and of quartz grains is 68%.

The four samples of the Skilpadkop Formation which were studied, comprise two phyllarenites (Fig. 2.6), one sublitharenite and a volcanic arenite. This coincides with Jansen's (1982) description of this formation as being generally low in feldspar. Chert, metaquartzite, volcanic fragments and schist make up the lithic portion of the rocks. Quartz, calcite, mica and opaques may also be present in quantity. Traces of zircon, tourmaline and microcline occur. Sorting is poor and roundness is variable with a mode of subangular. Sphericity is low, ranging from 49% to 59%. The chief postulated source for these rocks is metaquartzites, minor sources include rhyolite and chert.

Nine thin sections from the Aasvoëlkop Formation were studied. This formation shows a wide range of rock types (Fig. 2.1a, b), including arkose, quartzarenite, volcanic sublitharenite, volcanic sedarenite, subarenite, subarkose and lutite. The bulk of the rocks are made up of quartz, plagioclase (commonly sericitized), mica, volcanic rock fragments, mudflakes and opaque minerals. Traces of rutile, zircon and possible devitrified glass shards may occur. Cement is common, comprising epidote, calcite, iron oxides (haematite), quartz or chlorite. A clay matrix is usually present. Sorting ranges from poor to moderate and sand-sized grains are generally subangular; sphericity ranges from forty-five to sixty-seven percent. The provenance usually comprises volcanic rocks, and possible shards occur in rocks of the Aasvoëlkop Formation. Jansen (1982) described the vesicular rocks as 'lahar' deposits.

An arenaceous lutite from Haarlem Oost 51KQ (sample CC-1060) is an immature volcanic sublitharenite (Fig. 2.1a). It is inhomogeneous and consists of mud with about 20% sand (Fig. 2.1b); the coarsest grain in the slide is only 1mm in length. The sphericity of sand-sized quartz is W/L=61% (range: 37-93%) and of the silt-sized quartz is only 45% (range: 19-68%). The larger grains are subrounded and the smaller ones are subangular. The rock is composed of 55% quartz, 10% volcanic rock fragments, 5% clay replacing original needle-shaped grains, a trace of xenomorphic zircon and thirty percent very fine matrix which appears glassy in places. Another interesting sample from the Aasvoëlkop Formation is CC-1668 from the farm Klipdrift 231KQ. This is an arenaceous, submature lutite which displays apparent 'vesicles' filled with calcite, barite and a small amount of a magnesium aluminium silicate which has been interpreted as cordierite. Dana (1932, p. 583) points out that cordierite does have a wide range of

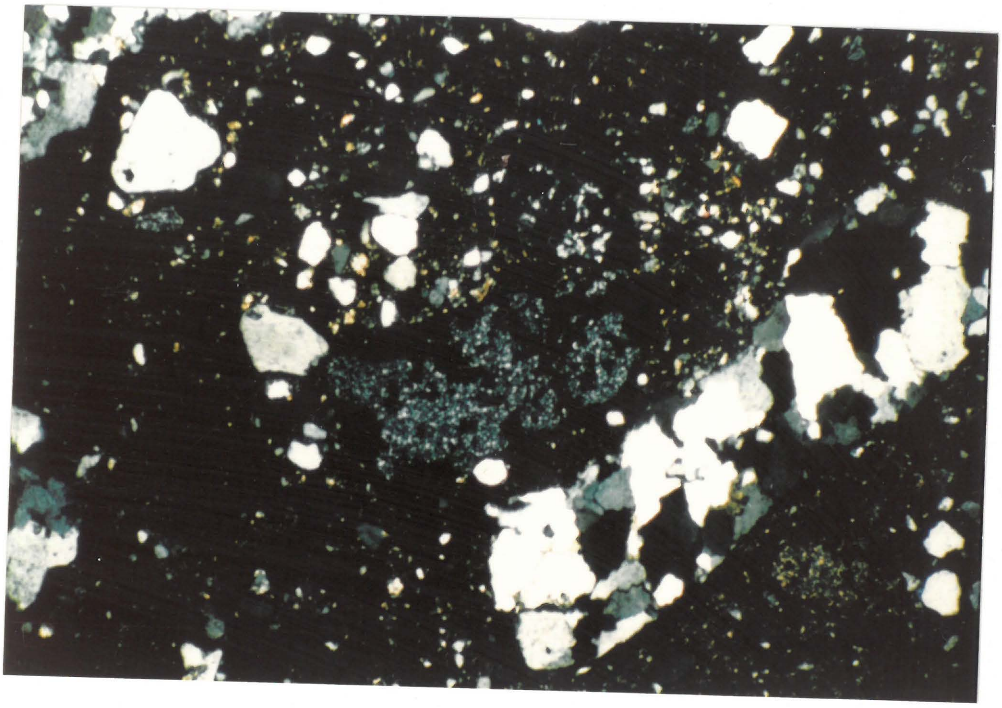


FIGURE 2.6: Rudaceous lutite from the Skilpadkop Formation on Groothoek 278KQ comprised of immature phyll/sedarenite. (Thin Section 1613: Base of photo = 7,0mm)

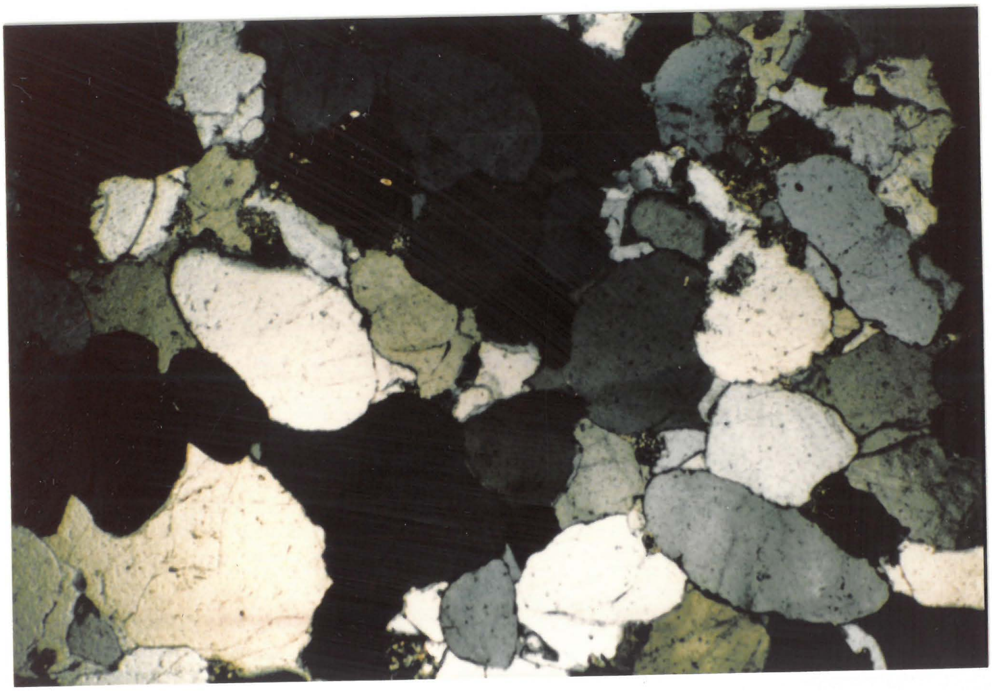


FIGURE 2.7: Coarse arenite from the Cleremont Formation on Voorstandfontein 622LQ which has been classified as a mature quartzarenite. (Thin section 1643: Base of photo = 7,0mm)

stability and that it may form in various environments. The sediment has angular to very angular grains which have a sphericity of 49,7% (ranging from 17-83%). Quartz is the most common mineral present and mica is the second most common; although the rock is very fine-grained, it contains only about 5% clay-sized material.

Two samples of material from the 'vesicles' in the Aasvoëlkop Formation on the farm Groothoek 278KQ were submitted to XRD analysis. In one of these analyses a greenish infilling consists of epidote, sericite and quartz; in the other a white infilling comprises smectite, sericite, kaolinite, chlorite and epidote.

The lutaceous medium arenite from the Makgabeng Formation (Fig. 2.1b), is probably atypical of the formation as a whole, since it contains 8% lutite and the grains are subrounded. Both of these features are abnormal for an aeolian environment and this sample is thought to represent a fluvial intercalation in the generally aeolian Makgabeng Formation. This thin section was classified as a submature lithic arkose (Fig 2.1a); the sediment grains are subrounded and the width:length ratio for quartz grains is 65%. The maximum grain size is coarse sand and the rock displays moderate sorting. The rock consists of 70% quartz, 10% feldspars, 10% rock fragments (rhyolite, lutite and chert), 8% mud, 1% muscovite and traces of tourmaline and of opaque minerals.

One rudaceous arenite from the Sandriviersberg Formation was studied. This rock is classified as a submature micaceous phyllarenite. Grain size layering is present and opaque minerals show preferential concentration in the arenaceous layers. Some quartz grains are contact welded, due to pressure solution. The quartz grain sphericity is 64% and the grains are generally subangular. The rock is composed of 70% quartz, 15% metamorphic rock fragments, 5% rhyolite rock fragments, 2% muscovite, 3% opaque minerals, 1% clay matrix and 1% iron oxide cement.

Five thin sections from the Mogalakwena Formation were studied.

One of these is a quartz cordierite hornfels with a granoblastic hornfelsic texture. It consists of 65% quartz, 20% cordierite, 8% epidote, 5% andalusite, 1% sillimanite and 1% plagioclase. Dykes and sills occur in the area, and this specimen is probably a thermally altered impure arenite. Of the rest, two are phyllarenites, one is an arkose and one is a subsedarenite (Fig. 2.1a). These rocks are submature to mature and contain quartz, orthoclase (sericitized), metamorphic rock fragments, mica, opaque minerals and chert, as well as minor quantities of plagioclase, zircon, lutite clasts and rutile. Iron oxide and silica cements occur. They are generally poorly to moderately sorted, and the grains are subangular to rounded. Sphericity is high, ranging from 69% to 81%. The provenance is mixed (Table 2.1).

The Cleremont Formation sedimentary rocks were studied in six samples, four of which are quartzarenites (Figures 2.1a and 2.7) and two are natural heavy mineral concentrates. The quartzarenites consist of 87% to 99% quartz and they also contain small amounts of rhyolite rock fragments, chert, heavy minerals and mica. Sorting is good and grains are subrounded to well rounded, sphericity of quartz grains ranges from 71% to 73% (Table 2.1). The source area contained volcanic rocks.

Coarse arenite from the Cleremont Formation was studied in thin sections 588 and 588a. Compositionally, the rock is classified as mature, micaceous, volcanite-bearing quartzarenite. It is homogeneous and shows abundant quartz overgrowths and welding of quartz grains. Many grains show ghost outlines of original well rounded grains. The rock is well sorted and the grains are rounded to well rounded. Samples 646 and 647 are fine to very fine arenaceous, supermature heavy mineral concentrates. Modal grain sizes in these samples are: quartz - 0,18mm; opaque minerals - 0,10mm; zircon - 0,10mm. Sorting is very good and rounding is variable; some grains are exceptionally well rounded whilst others (chiefly zircon) are almost totally unrounded (and euhedral). The rock is composed of 10% quartz and 75% heavy mineral grains. It also has 15% anatase cement; no clay-sized material was seen. The two arenite specimens from Paulskloof 636LQ and Voorstandfontein

622LQ are similar to sample 588 but they are more mature and have a greater percentage of quartz.

Three samples from the Vaalwater Formation yielded a fissile lutite, a massive lutite and a subarkose (Fig.2.1a). The shale is very fine-grained, consisting of 15% silt in a mottled clayey matrix. The lutite is perhaps the most representative sample of the Vaalwater Formation; it is dark grey in colour and is very fine-grained with 20% silt and 80% clay. Grains vary from angular and prolate to rounded and equant, and the rock is well sorted (Table 2.1)

Five Bushveld Complex granite samples were studied to establish their relationship with Waterberg rocks. They yielded two granophyric granites, a granophyric granite porphyry, a granite and a micropegmatitic granophyric granite. Orthoclase tends to be the chief rock-forming mineral, together with quartz, plagioclase, hornblende and some mica. Zircon occurs as an accessory. The granophyric granite porphyry contains some beta-quartz crystals (Fig. 2.8).

Dolerites intruded into the Waterberg Group are often differentiated. They consist of plagioclase, enstatite or augite and hornblende. Most thin sections studied showed advanced alteration with epidote and chlorite being the chief alteration products. Accessory minerals include calcite, quartz, sphene, prehnite, zircon, biotite and polycrystalline bertrandite (biaxial negative, 2V=0-15°, birefringence=.025, two good cleavages at ±90°, SEM analysis gives Si, theoretical composition of bertrandite is $H_2Be_4Si_2O_9$ - Dana, 1932, p. 632; Be is too light to be detected on the SEM). Copper occurrences in the Waterberg basin are generally associated with these dolerites.

2.1.3 Scanning Electron Microscope study

The scanning electron microscope (SEM) was used both as a tool to assist in identification of mineral species as well as an aid in resolving particularly small grains and fine structures. Most of the sections studied

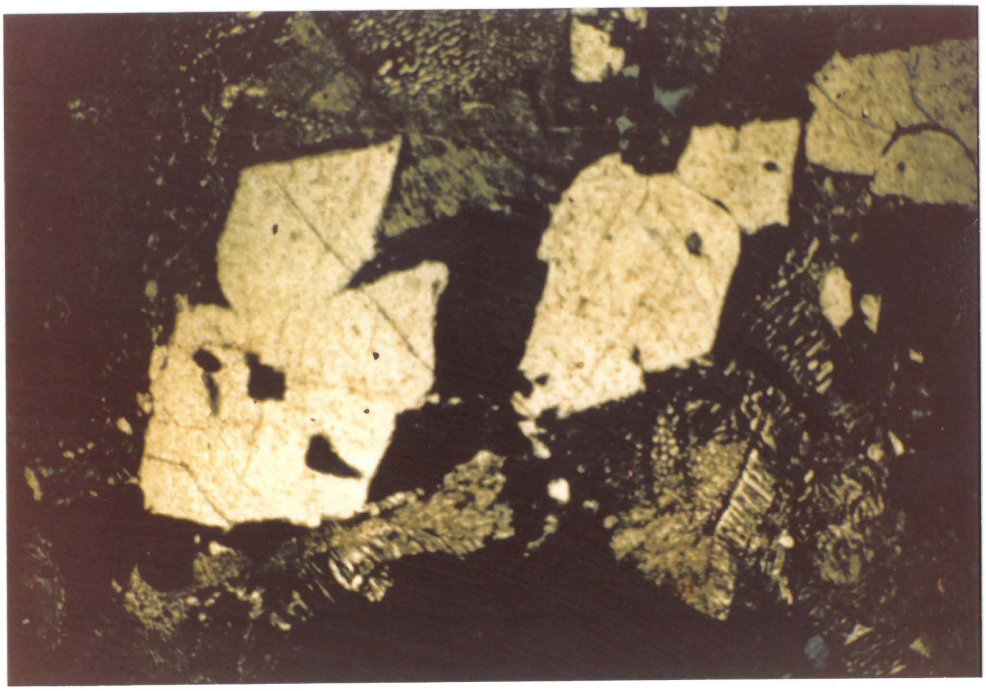


FIGURE 2.8: Granophyric granite porphyry from the Bushveld Complex granites on Waterval 443KQ. Notice the euhedral paramorphs after beta-quartz. (Thin section 157; base of photo = 4,5mm).

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were from the Alma Formation.

Sample 146 of the Alma Formation from Buffelshoek 446KR contains traces of thorite (which has a spongy texture and contains some inclusions which analyse as silver), zircon and cassiterite. The cassiterite was unexpected since no tin had been detected in the X-ray fluorescence analysis; it is very pure and contains only a few inclusions of iron oxide. An unidentified grain from Waterval 443KQ (sample 148) was tentatively identified as auerlite (approximately $Th(SiO_4.PO_4)$) from a qualitative analysis which showed it to be a thorium silico-phosphate with some iron.

X-ray fluorescence analysis of sample 156 from Waterval 443KQ showed a content of 3562 ppm zinc, and this led the author to believe that the resinous-coloured grains in the specimen were sphalerite. Scanning electron microscope work, however, revealed several facts which resulted in a different interpretation. The grains showed an excellent cleavage which had not been visible under the optical microscope and a qualitative analysis showed only cerium, lanthanum, neodymium and praseodymium. The mineral was identified as fluocerite, which has a composition of (Ce,La,Di)F_3, is yellowish to reddish brown in colour and has one perfect cleavage. The clayey groundmass in this sample was tentatively identified as faratsihite (a variety of kaolinite) on its composition (iron aluminium silicate) and colour. The rock also contains a niobium- and yttrium- rich iron titanium silicate, and a rare earth-rich calcium silicate.

Sample 188 consists essentially of a mineralized vein in a brecciated arkose. Chalcopyrite is the most common mineral in the vein, whilst some bornite also occurs. The chalcopyrite contains tiny inclusions of silver. Barite is common and contains inclusions of chalcopyrite and galena. The uranium mineral present is rather variable in composition and it is possibly pitchblende. In a second section studied the uranium mineral was found to be kasolite, a lead uranium silicate.

Sample CC-888 from the Alma Formation on Waterval 443KQ is a heavy mineral-rich arkosic rudite. The heavy minerals occurring in this sample were separated on a laboratory model Wilfley table, and the cassiterite was hand picked under a binocular microscope. The grains were subsequently studied on a scanning electron microscope. The grains are composite, intergrown with quartz and manganocalcite. The identity of several species in sample CC-1047 from Buffelshoek 446KQ were confirmed with the use of the SEM. Heavy minerals contained in this sample are 14% titanomagnetite and ilmenite, 3% zircon, 3% thorite, 2% witherite, 1% monazite, 1% cassiterite as well as traces of topaz, andalusite, barite, apatite and thorotungstite. Cassiterite crystals are exceptionally homogeneous and pure, with only very rare inclusions of a potassium aluminium silicate (potassium feldspar?). The single thorotungstite grain seen is homogeneous and contains apatite inclusions. In contrast the thorite grains are notably inhomogeneous, with a highly variable iron content. The titanomagnetite and ilmenite show exsolution structures. The monazite has a highly variable composition but is essentially a cerium lanthanum phosphate with minor Nd, Cu, Zn and Th.

Sample CC-1355 from the Alma Formation on Buffelshoek 446KQ was taken from the core of Borehole 019 (Fig. 3.8) at 246,1m depth. Heavy minerals present in this thin section are 5% ilmenite (and some titanomagnetite) with well-developed exsolution laminae, 0,5% sphene (with quartz inclusions) and traces of zircon, monazite, uranothorite, tourmaline, barite, diopside, garnet, topaz and celsian. The sphene occurs both as primary grains and as an alteration of ilmenite. The monazite has tiny inclusions of thorite.

Several minerals were identified from the heavy mineral placers of the Cleremont Formation on Modderspruit 150KR. Besides some 60% titanomagnetite, ilmenite and ulvöspinel, the identification of rutile, zircon and monazite was confirmed. Other minerals identified from, or confirmed by their chemistry were thorite, uranothorite, possible zirkelite (SEM analysis gives Ca, Fe, Zr, Ti and Th as constituents) and gorceixite (Ba-Al phosphate) as well as about 15% anatase cement. Qualitative analysis of the gorceixite gives Al, P, Ba and Fe as major constituents and Ca as a minor constituent. Gorceixite is a member of the crandallite group. Fleisher (1980) shows that Fe can replace Al and that calcium can replace Ba in this group.

Sample CC-1563 is from the Vaalwater Formation on the farm Hermanusdorings. The rock is a fine-grained lutite consisting of 75% clay, 20% silt and 5% opaque material; the clay is a potassium silicate. The opaque material which presumably gives the rock its dark grey colour is iron oxide.

2.2 GEOCHEMISTRY

2.2.1 Trace Element Analyses

Since the potential of the Waterberg Group for tin concentrations is a primary aim of this study, the majority of the samples taken were submitted for trace element analysis, to test for Sn, Th and other elements which would be expected to occur in heavy mineral placer deposits. Initially it was hoped that these analyses could also serve as a distinquishing feature between the various formations, or at least show trends related to the mineralization encountered. Unfortunately, batch variation for several elements was high and since standards were not submitted with each batch this could not be controlled.

Listed in Appendix I are the data regarding the number of samples analysed in eleven Waterberg Formations as well as the mean, minimum and maximum value and the standard deviation of each trace element, except vanadium. Vanadium has not been included, since in the standards which were submitted from time to time, it proved to have a poor reproducibility. Values are also given for clasts sampled as well as for some dolerite and granite samples which were taken. The dolerite samples were analyzed since copper mineralization in the Waterberg is commonly associated with dolerites, and the granite samples were taken primarily for comparison with clasts from the Waterberg sedimentary rocks. In Appendix II the values for trace elements in the 17 boreholes drilled at Gatkop (all of which are in the Alma Formation - Fig. 3.8) are given.

Many of the average values shown in these appendices are anomalous when compared to world average values for sandstones (Beus and Grigorian, 1977); these are also given in Appendix II, together with world average values for granites obtained from Levinson (1980). In many cases the anomalously high average values in Appendix II are due to one or two particularly high values which have a strong influence on the average. These cases are obvious from their high maximum values and standard deviations. It should be noted that although actual values obtained were used for statistical purposes the detection limit for the majority of the traces is 10ppm.

In the Alma Formation elements of particular interest are zinc, tin, thorium and uranium. The high rubidium content may be directly related to the arkosic nature of the sediment (compare with granite analyses). The Skilpadkop Formation is the unit richest in manganese, total iron, cobalt, nickel, copper, zinc, barium and tungsten. The manganese and iron values are due to mineralization related to fracture zones along the southern boundary of the basin. The high strontium values in the Aasvoëlkop Formation are interesting. The average value falls within the range to be expected for greywackes and arkoses (Wedepohl, 1969). However the maximum value of 2589 ppm is certainly highly anomalous and is probably due to alteration associated with alkaline intrusive activity. An alkaline intrusive has been discovered in borehole 019 and strontium is often associated with alkaline intrusives. Wedepohl (1969) gives the range in strontium in 22 samples of syenite from Africa as 90 to 1536 ppm, with an average of 499 ppm.

The Cleremont Formation shows the highest concentrations for titanium, zirconium, molybdenum, antimony and thorium. Standard deviations are high. The high concentrations of these elements in the mature Cleremont arenites may be due to the fact that they tend to occur in resistate minerals (ilmenite - titanium, niobium; rutile - titanium, niobium; xenotime - molybdenum, thorium; zircon - thorium, zirconium, titanium, niobium; monazite - thorium, titanium,; magnetite - titanium; thorite - thorium; anatase - titanium; tourmaline - niobium). All of these minerals, except xenotime, have been identified in Cleremont sedimentary rocks. In the Vaalwater Formation the Mo is high in most samples.

The high tungsten values in the dolerite are surprising since the average content given by Wedepohl (1969), quoting Jeffery (1959), is 6,3 ppm with a range from 0,9ppm to 14,5 ppm.

The tin:thorium relationship in the Alma Formation, referred to by Callaghan (1983a), remained significantly high when data from other Formations were included. Tin:thorium values outside of the Gatkop area are, however, low and they have not been shown here for the sake of clarity (Figs. 2.9a and 2.9b). The correlation coefficient of 0,89 is significant at the ninety-five percent level. This relationship as well as the mineralogical relationship of cassiterite- and thorium-bearing minerals at Gatkop, compares well with 204 reported cassiterite-bearing mineral assemblages from more than 100 published papers (Callaghan, 1983a).

2.2.2 Major Elements

A limited number of major element analyses were made, chiefly on arkosic rudites from the Alma Formation. Füchtbauer (1964), as quoted in Pettijohn *et al.* (1973), showed that a coarse-grained sand may be petrographically classified into a different group to a fine-grained sand from the same stratigraphic unit, merely because of the differential size distribution of minerals. Rudites may suffer even more severely from these problems. Except in the case of borehole samples, rudites with coarse clasts (greater than fine pebble size) were not utilized for major element analysis. The argument that the clasts have a too large influence on the analysis is to some extent true and for this reason large samples, of about 5 to 10 Kilograms, were taken.

Four plots have been made in an attempt to compare the major element chemistry of Waterberg sediments to other clastic sediments. Figure 2.10 shows the logarithm of SiO_2/Al_2O_3 plotted against the logarithm of $(CaO+Na_2O)/K_2O$ for the sedimentary rocks of the Waterberg Group. The field marked A appears, from field observation and thin section study, to be the arkose - arkosic rudite field. Notice that it stretches well to the left of the arkose point of Garrels and Mackenzie (1971), which is shown in Figure 2.10a. This may be due to a source which is less sodic than the norm. It may also, however, be due to a weathering pattern that destroyed the sodium

Figure 2.9a: Plot of thorium vs tin for thorium values <500ppm (to be read with figure 2.9b)

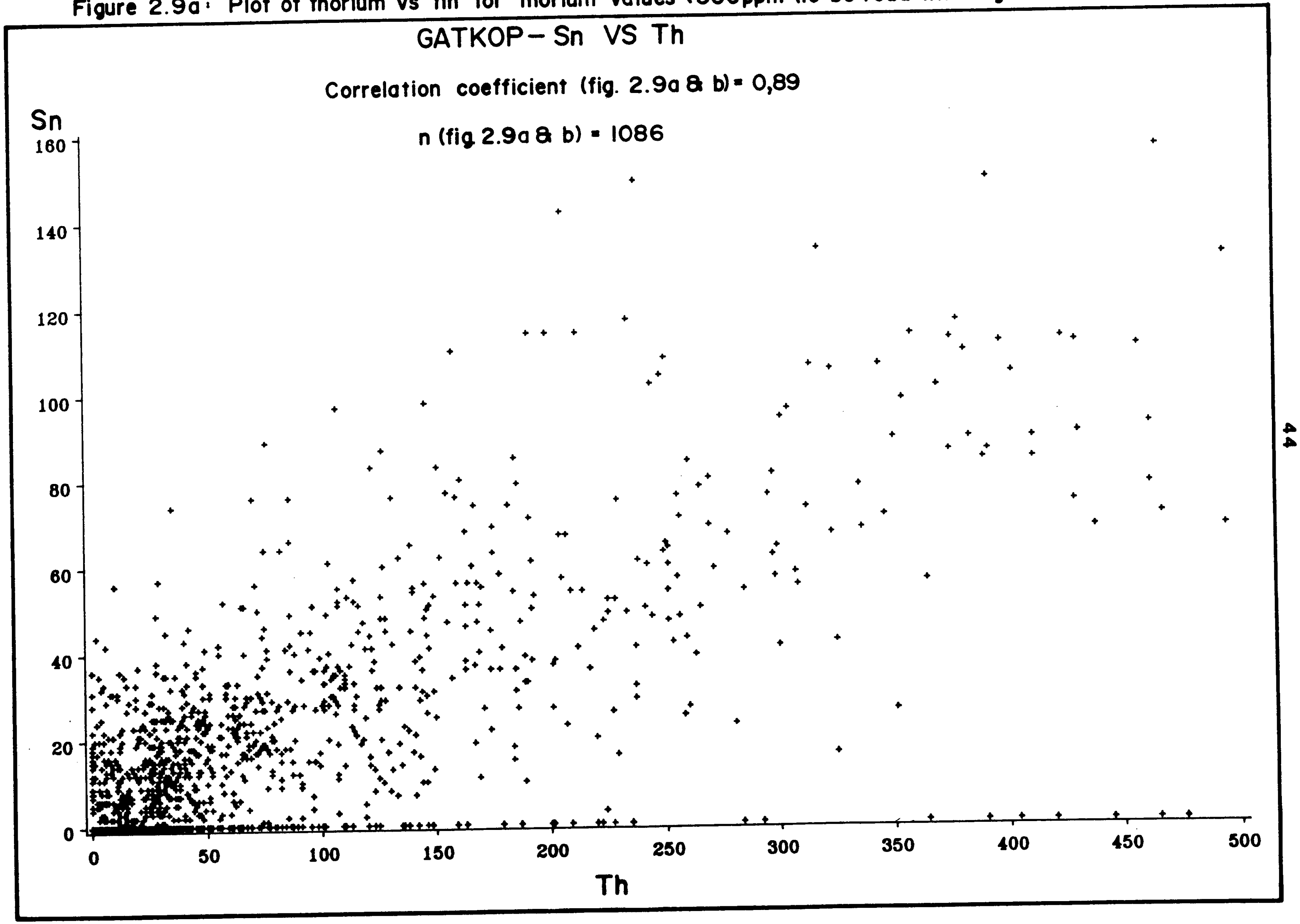
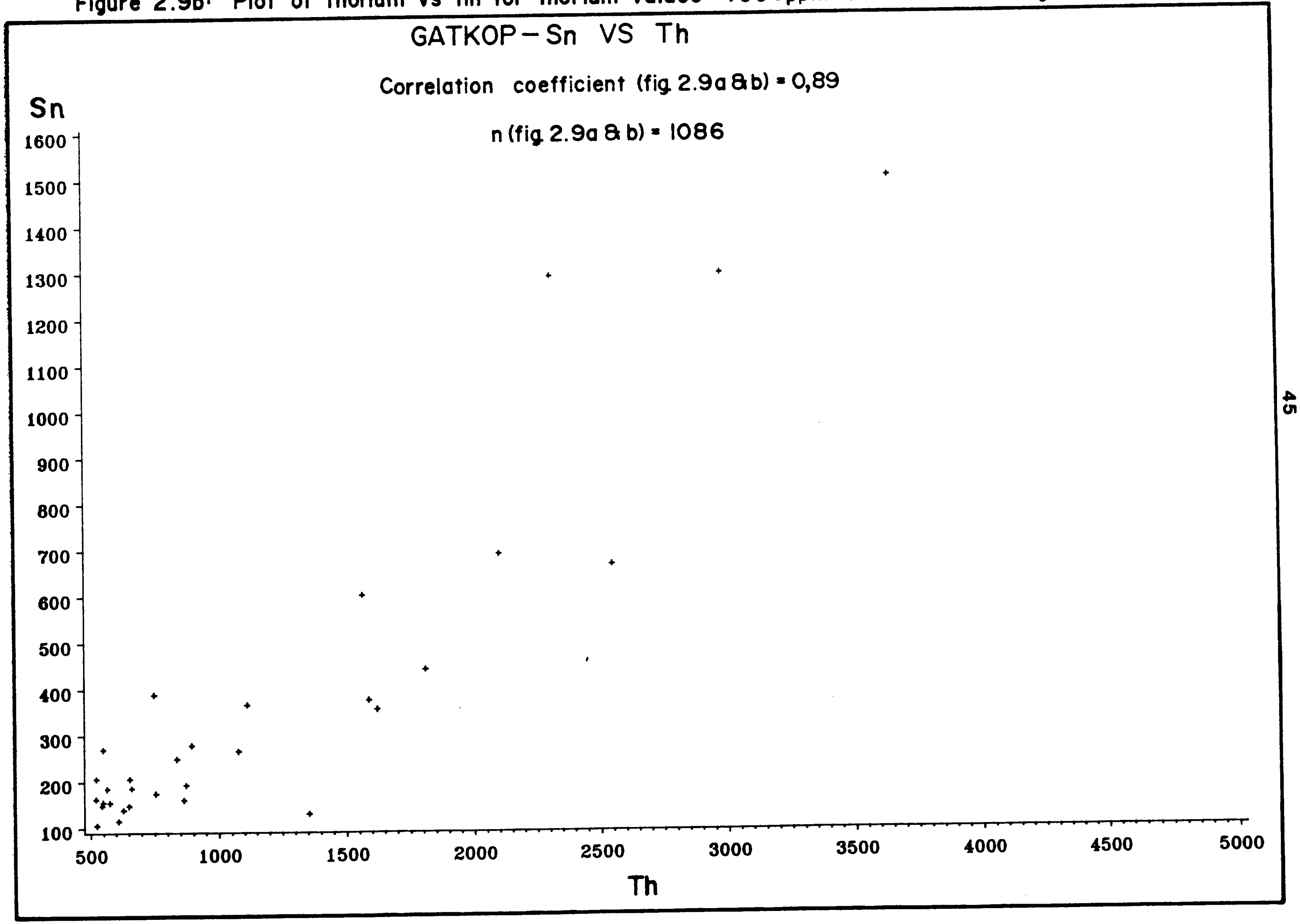


Figure 2.9b: Plot of thorium vs tin for thorium values >500ppm (to be read with figure 2.9a)



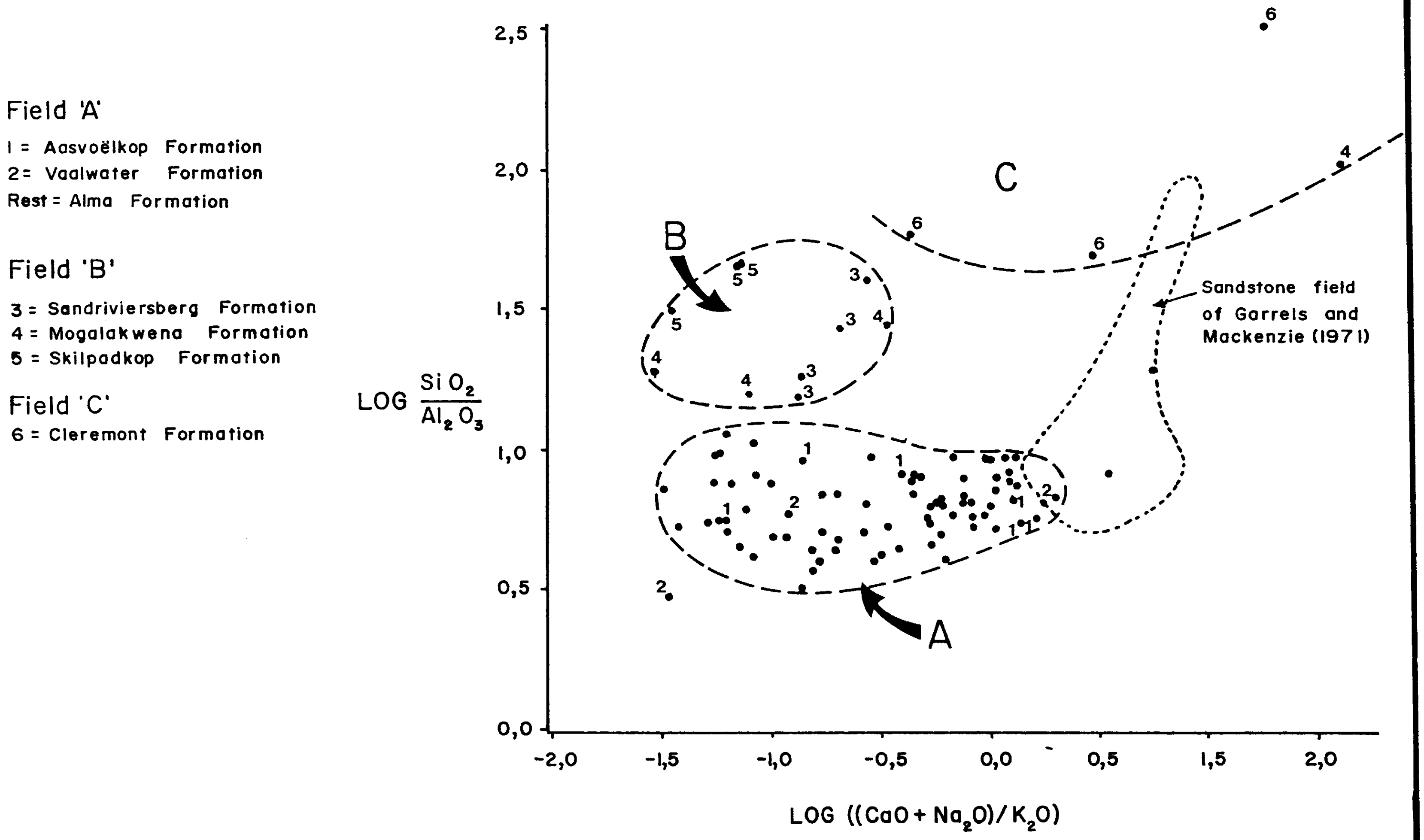


Figure 2.10 Plots of major element ratios of rocks from the Waterberg Group.

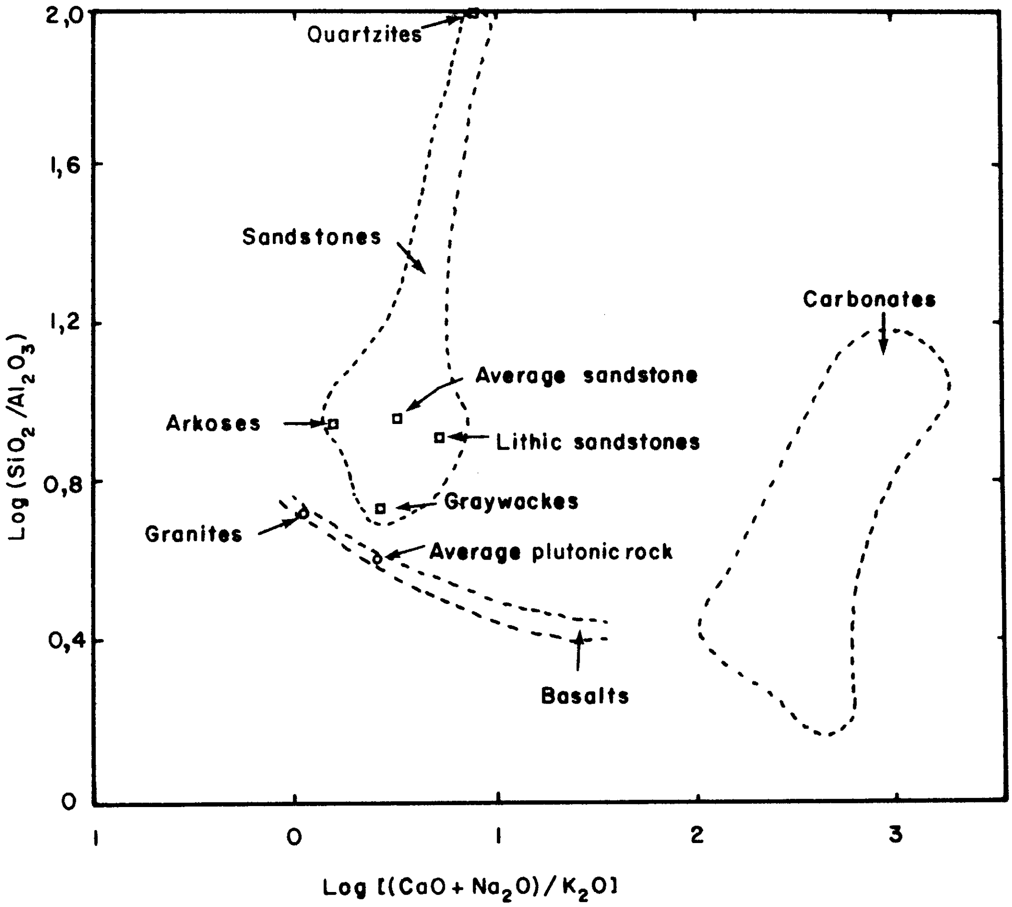


Figure 2.10a Relation between igneous and sedimentary rocks.

(After Garrels and Mackenzie, 1971).

feldspars, whilst preserving the potassium feldspars. The high mobility of the sodium cation, together with the quick response of sodium feldspar to weathering, may lead to a rapid removal of sodium under certain weathering conditions (Botha, 1986).

Plots marked '1' in area A (Fig. 2.10) all belong to the Aasvoëlkop Formation, and plots marked '2' belong to the Vaalwater Formation. The plot which falls outside of area A is a silty, very fine-grained (tuffaceous) arenite. The unmarked plots are all from the Alma Formation. Thin section studies show that several of the samples in the field marked B are lithic arkoses and feldspathic litharenites; this field remains one of uncertainty since the nature of the lithic clasts is so variable. Field classification indicates that plots in the area marked B are probably subarkosic in nature. Here Sandriviersberg (3), Mogalakwena (4) and Skilpadkop (5) Formations are represented. Area C is well defined and makes up the quartzarenite field. Three of the points in this field (6) represent the Cleremont Formation, whilst the fourth (4) represents a very mature heavy mineral concentrate from the Mogalakwena Formation.

Figure 2.11 shows a plot of FeO vs Fe_2O_3 for the sedimentary rocks of the Waterberg Group. Points A and B represent the mean arkose and mean greywacke as plotted by Blatt, Middleton and Murray (1972, p. 320). The dashed line is a suggested dividing line between the arkose and greywacke fields based on both the present data as well as that of Blatt *et al.* (1972). Notice that the Fe_2O_3 does not appear to be critical in this plot or that of Blatt *et al.* (1972). The FeO content of the rocks does, however, appear to be significant and most of the samples fall into a narrow belt of FeO values. Only four samples plot in the area above the dashed line; they are:

1. medium-grained feldspathic arenite with ferruginous intraclasts from the Alma Formation (Thin Section 1223).
2. coarse-grained arkosic arenite from the Alma Formation. This sample occurred between two small dolerite intrusions

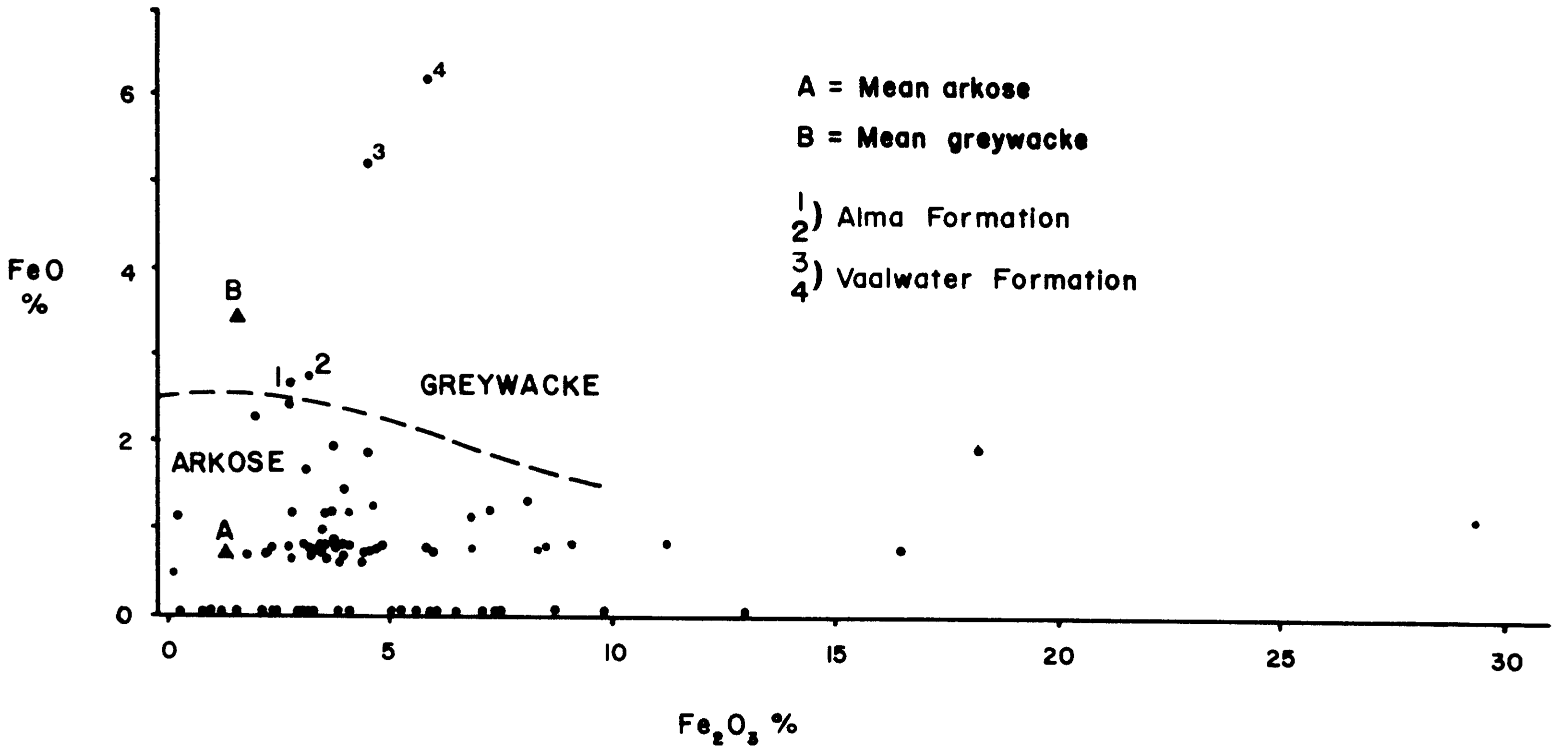


Figure 2.11 Plots of FeO versus Fe_2O_3 for rocks from the Waterberg Group.

and showed signs of pyrite and chalcopyrite mineralization.

3 and 4. these are both from the Vaalwater Formation, and are silty very fine-grained arenites, which may be tuffaceous. These samples plot into the arkose field in the other plot (Fig.2.10). Their dark grey colour and relative lack of Fe_2O_3 suggests that the iron may have been reduced during diagenesis.

Figure 2.12 shows a plot of Na_2O to K_2O. The only rocks which plot in the greywacke field on this graph are: 1. a quartzarenite of the Cleremont Formation, 2. an Aasvoëlkop Formation 'laharite', 3. a heavy mineral rich 'quartzarenite' (field term) of the Mogalakwena Formation, and 4. quartzarenite of the Cleremont Formation. Notice numbers 5 and 6 which are the above two samples from the Vaalwater Formation and which fall well into the arkose field.

In Figure 2.13 $\log(Na_2O/K_2O)$ is plotted against $\log(SiO_2/Al_2O_3)$. This plot is similar to that of Figure 2.10 except that the influence of CaO is not taken into account here. The rock class fields in Figure 2.13 have been extended towards higher and lower log (Na_2O/K_2O) values than those given by Pettijohn, Potter and Siever (1973) and Pettijohn (1963) (Fig 2.13a). Most plots fall well into the arkose or subarkose fields. A few plots occur in the lithic arenite field, and of these only one was identified under the microscope (Thin Section 1285) as a feldspathic sedarenite, which is acceptable for this field. Of the two samples that fall into the greywacke field one has been microscopically identifed as a lithic arkose (Thin Section 1236) and the other is a spotted lutite (laharite?) of the Aasvoëlkop Formation

2.3 INTERPRETATION

The two general upward-fining sequences in the Waterberg Group

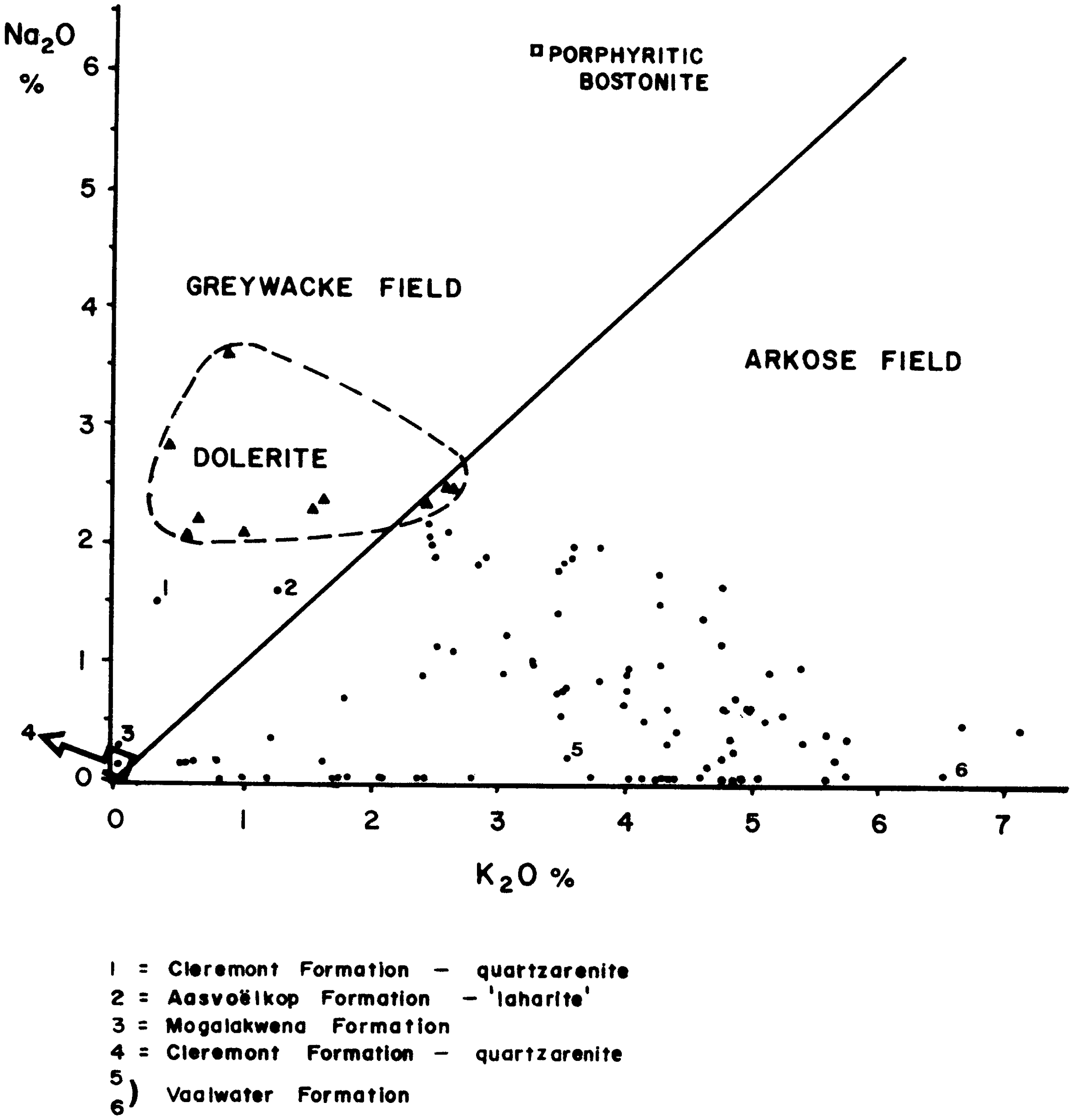


Figure 2.12: Plots of Na_2O versus K_2O for rocks encountered in this study. After Pettijohn et al. (1973).

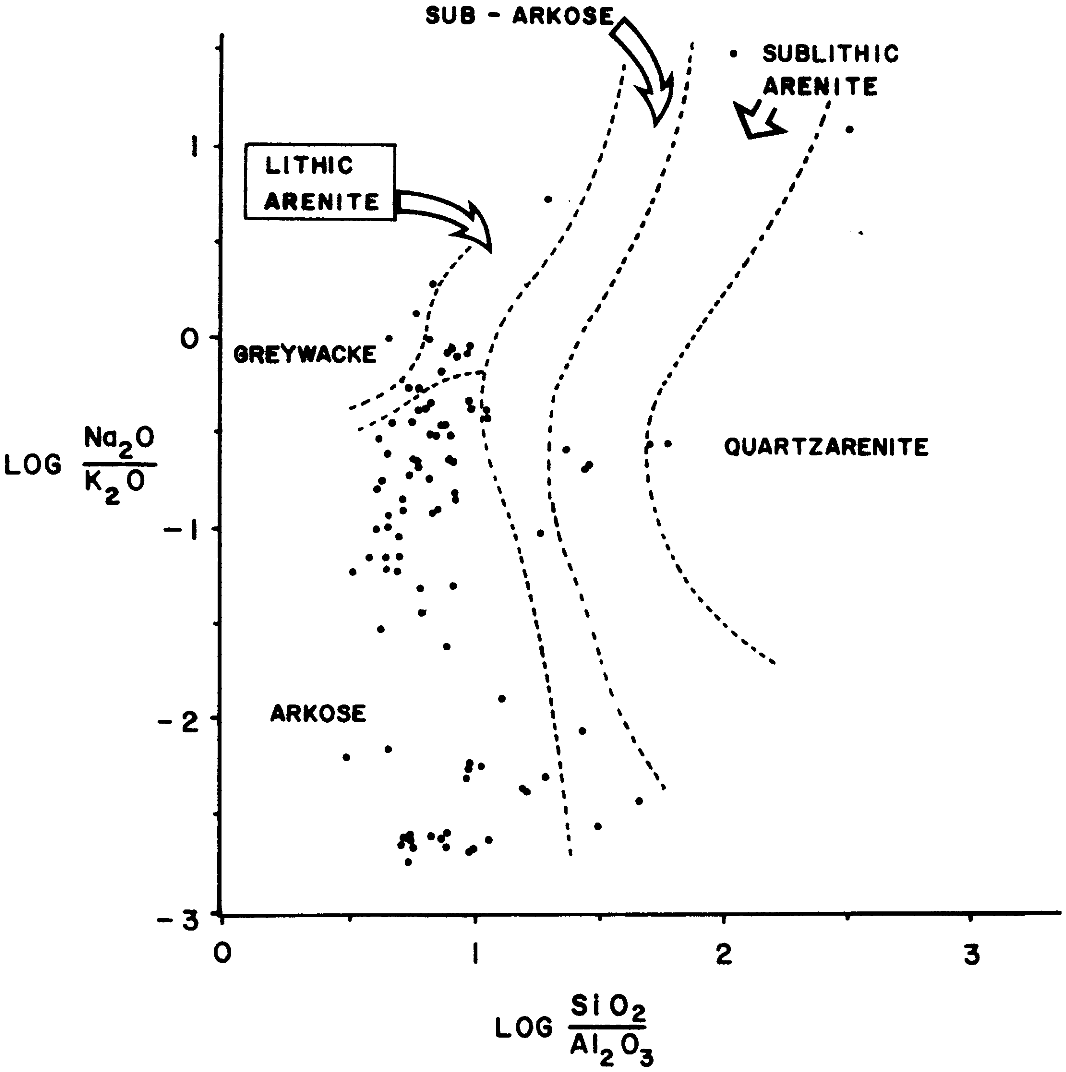


Figure 2.13 Plots of major element ratios of rocks from the Waterberg Group.

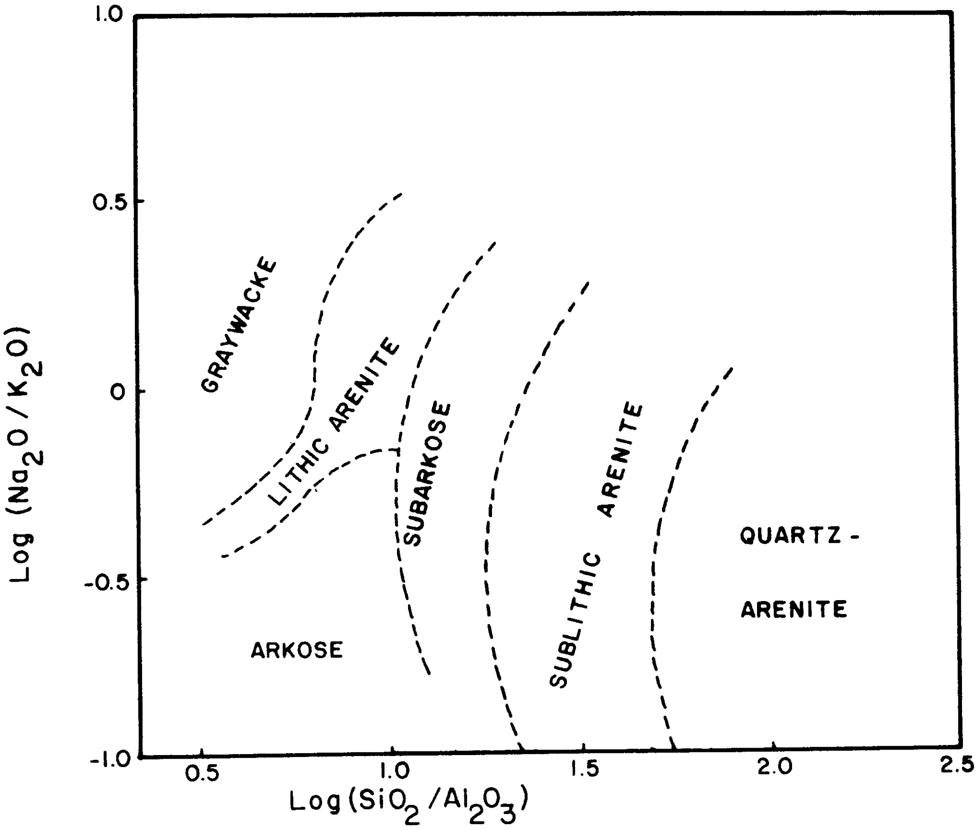


Figure 2.13a Classification of sedimentary rock types by major element ratios. (After Pettijohn et al., 1973.)

sedimentary rocks (Table 2.1, Figure 2.1b) are interpreted to be due to two major phases of basin deepening related to marginal faulting (see Chapter Three).

The composition of the provenance as interpreted from thin section studies (Figure 2.1c) shows that a shift occurred in the source area from the Alma Formation (chiefly acid plutonic) upwards. In the higher formations the provenance was mixed, generally incorporating sedimentary and metamorphic material. The large acid plutonic input into the Alma Formation and its resultant arkosic nature may indicate that it had a completely different source to that of the sedimentary rocks in the rest of the basin, which are largely lithic in character (Figure 2.1a). The presence of euhedral beta-quartz paramorphs in the Alma Formation (Figure 2.3) indicates very little transport from the source which was most likely Bushveld granite, which contains similar crystals (Figure 2.8, Table 2.1-thin section 157). Topaz in the Alma Formation is probably also derived from this source, since topaz has been seen in a granite clast (Table 2.1-thin section 106).

The genesis of the quartz 'slivers' shown in Figure 2.4 are problematical. Two possible modes of origin present themselves; the slivers could have been produced by high energy impacts of clasts during the deposition of the coarse sediments which now form the Alma Formation, or perhaps a more feasible mode of origin is formation of the quartz slivers by high energy aeolian collisions, as described by Smalley and Vita-Finzi (1968) and Eriksson (1985).

Deformation lamellae similar to those found here have been well studied in the past quarter of a century (Christie and Raleigh, 1959; Hansen and Borg, 1962; Short, 1970; Christie and Ardell, 1974). They are now considered to be due to relatively rapid, low temperature deformation. The lamellae in this study were found to be at a moderate angle to the basal (0001) plane which places them into the basal I category of Carter (1965, 1971). A formation temperature of 900° or less is indicated at 10Kb pressure. If a temperature of 200°C and a pressure of 10Kb is assumed, the strain must have taken place over a period of at least 300 years. Heard and Carter (1968) state, however, that the 'subbasal mechanism' is favoured in moderate to shallow crustal conditions and at inferred tectonic strain rates. In these conditions basal lamellae do not occur.

The high correlations between trace elements in the Waterberg Group sedimentary rocks may be related to two possible causes. Firstly, the elements may occur in related heavy minerals, for example Sn/Th in cassiterite/monazite and thorite. Secondly, the elements may have behaved similarly within the geochemical environment, as suggested by Wolf and Chilingarian (IN Chilingarian and Wolf, 1976, p. 287-288).

Rock type is reflected in both major and trace element analyses; for example, the high rubidium, low cobalt/nickel values of the Alma Formation reflect the arkosic nature of these rocks. It is interesting to note the similarity in the values of these three elements for the Bushveld granites sampled (Appendix I). The differences between the Alma Formation and other formations of the Waterberg Group are also shown clearly by the Rb as well as the Co and Ni values; this reinforces the trend seen in the mineralogy and the major element analyses. It is also shown that the heavy mineral composition of the Cleremont Formation is clearly reflected in XRF analyses.

The high tungsten values in the dolerites are of great interest. Most high tungsten results obtained throughout this study are from the southermost part of the Waterberg basin. This includes high tungsten in the matrix and clasts of the Alma Formation, high tungsten in the manganese occurrences of the Skilpadkop Formation and high tungsten in the dolerites. It appears that there is a source of tungsten in the southern part of the Waterberg basin, possibly with the major fault lines in the south acting as a channel for distribution of traces. Since tungsten is not very mobile this may indicate a relatively large deposit somewhere in this region.

The close grouping of Alma Formation plots in the arkose field in figures 2.10 and 2.13 fits very well with the dominance of arkose in thin sections of this unit. Similarly, the Cleremont Formation samples fit into the quartz arenite field in both of these figures. Plots of the other formations are more random, but indicate a more lithic character in figure 2.13, which agrees with the compositional plots in figure 2.1a. If the varied and complex source material (shown in figure 2.1c) of these formations is considered, a more random plot might be expected.

3. SEDIMENTOLOGY

3.1 INTRODUCTION

3.1.1 Stratigraphy

The sediments of the Waterberg Group constitute an upward-fining sequence of red beds, showing characteristics of rapid deposition in the lower part of the succession.

The Swaershoek Formation is considered to form the basal unit of the Waterberg Group (Jansen, 1982). The Alma Formation conformably to unconformably overlies the Swaershoek Formation. The Sterkrivier Formation appears to grade laterally into the Alma Formation as well as the upper Swaershoek Formation (Figures 1.2 and 1.3). The Skilpadkop Formation overlies the previously mentioned units and is laterally gradational into the Setlaole Formation in the north and northeast. These are in turn succeeded by the Makgabeng Formation in the north and northeast and by the Aasvoëlkop Formation in the south and southwest (Figures 1.2 and 1.3). These formations are overlain by the Mogalakwena Formation in the northeast and by the Sandrivierberg Formation in the southwest. These in turn grade upwards into the Cleremont Formation. The Waterberg Group is terminated by the Vaalwater Formation which gradationally overlies the Cleremont Formation.

3.1.2 Structure

The geological map of South Africa (Visser, 1984) shows two prominent lineaments, which are of particular importance to the development of the Waterberg basin, as well as to other sedimentary and igneous events on the Kaapvaal craton. These are the Murchison lineament in the south and the Palala shear zone in the north (Fig. 3.1).

The Murchison lineament can be traced from the Murchison greenstone belt, along the Strydpoort mountains and the southern edge of the

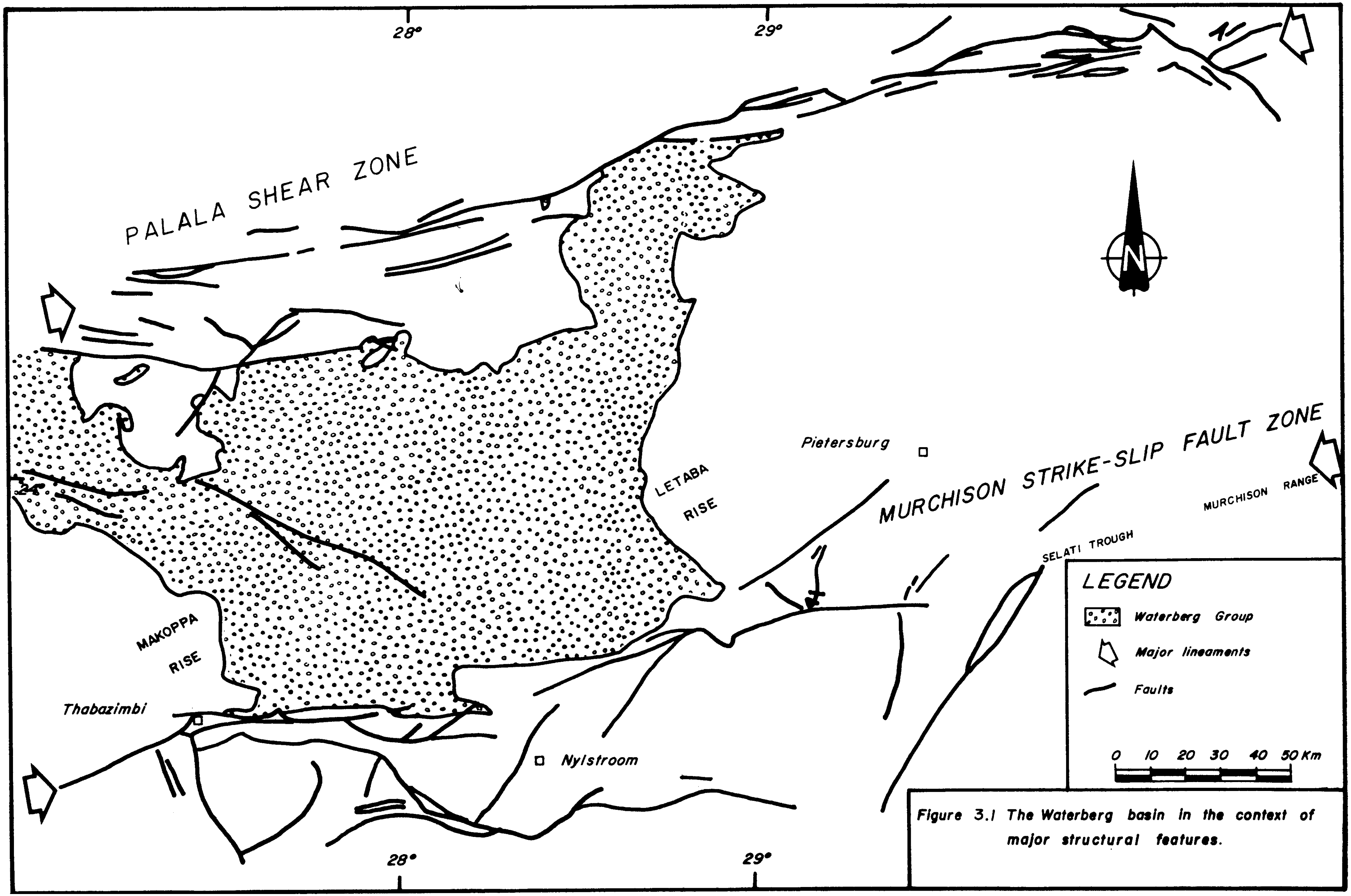


Figure 3.1 The Waterberg basin in the context of major structural features.

Waterberg Group and past Thabazimbi before it enters Botswana. In Botswana it continues past Dikgomo di Koe; a southern branch tends towards Lobatse (Crockett and Jones, 1975, Fig. 9). Previous authors have hinted at the presence of a deep-seated structure along the Murchison lineament, and have shown that sedimentation occurred in deep troughs along the lineament at various stages in geological history (Crockett, 1971; Button, 1972; Crockett and Jones, 1975; Tyler, 1979; Jansen, 1982). The lineament may have been the approximate northern edge of the 2300Ma old Transvaal Sequence basin during certain periods of its development. Palaeocurrent directions in the Transvaal Sequence show transport from the north into the Selati trough, the northern flank of which is very steep and is in line with the Murchison lineament (Button, 1972). Button further postulates that a linear crustal weakness affected the Murchison schist belt as well as the Wolkberg Group, Black Reef Formation and Chuniespoort Group, acting as a zone of maximum accumulation of sediment. Visser (1970, Fig. 9) shows two topographic highs north of the lineament; he called these the Makoppa rise and the Letaba rise. Towards the west the Buffelsfontein Group displays a sudden thickening to the immediate south of Thabazimbi and a relatively gentle thinning further southwards (Tyler, 1979). A transcurrent fault was described by Truter (1947) to the southeast of Potgietersrust; this faulting may be related to the Murchison lineament.

Jansen (1975a, 1975b) recognized that the development of the Waterberg/Soutpansberg basins could not be adequately described with conventional tectonic terminology and he classified the Waterberg basin as an intracratonic basin. Jansen points out that the Murchison line probably represents an old line of weakness. The block between the Murchison lineament and the Palala Shear Zone was once again a highland in Karoo times. Rust (1975) points out that an epeirogenically elevated Transvaal craton was a major source for sediments which now constitute the Karoo Sequence. Van Biljon (1976, Fig. 15) shows the control of these linear features on the coal beds in the Karoo sediments; he also points out that their continued importance is shown by the distribution of modern sediments and hot springs.

3.1.3 Colour

All the colour descriptions in this work refer to the Rock-Color Chart (The Rock-Color Chart Committee, 1970). Figure 3.2 shows the yellow-red to red segment of the colour sphere used in constructing the Rock-Color Chart.

The most common hue in the Waterberg Group is 5R - mid red (n=303 of 528, occurring in 10 formations). The hues 5R (mid red), 10R (orange-red), 5YR (mid orange) and 10YR (yellowish orange) make up 88 percent of colour measurements in the group. The two most common colours are greyish red 5R4/2 (ninety-one occurrences in seven formations) and dusky red 5R3/4 (eighty-eight occurrences in three formations).

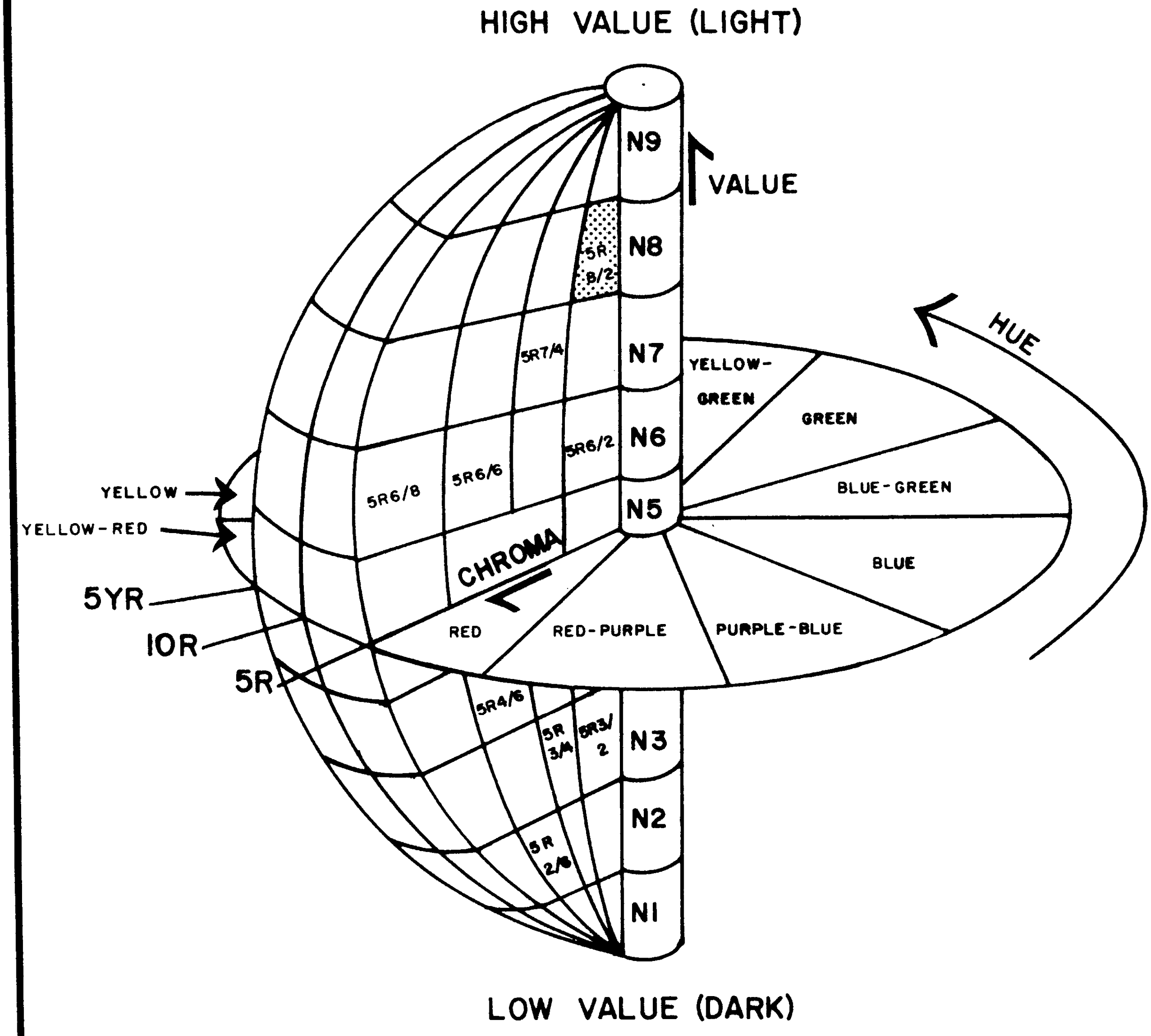
The colour of the Waterberg sediments as a whole can best be described as being of a 5R hue (mid red), of medium to low value (relatively dark) and of a low to moderate chroma (poorly to moderately saturated).

"Red beds" are coloured by haematite and have hues of 5R and 10R (Turner, 1980, p.1). In the Waterberg sedimentary rocks these hues make up 67 percent of the colours recorded.

Formation of the haematite coatings on grains, which gives the typical red colours, appears to have taken place soon after the deposition of the Waterberg sediments, or at least early in their diagenetic history. Evidence for this is seen in the deformation of the coatings, visible in thin sections, which must have taken place during compaction and in the quartz overgrowths which incorporate the coatings (Eriksson and Vos, 1979)

3.2 SWAERSHOEK FORMATION

Since the Swaershoek Formation shows a very limited distribution in the Main Waterberg basin and has minimal potential for tin mineralization



Example: ▨

The colour 5R8/2 (greyish pink) has a hue of 5R (mid-red), a value of 8 (light) and a chroma of 2 (low saturation).

Figure 3.2 Diagrammatic presentation of the colour sphere, showing the mid yellow-red to mid red segment (modified after The Rock-color Chart Committee, 1970).

it was not studied in any detail during this investigation. It is described here largely from the literature.

The geographical distribution of this formation differs considerably from the overlying formations in the group. An isopach map for the rocks of the Swaershoek and Alma Formations is shown in figure 3.3.

The Swaershoek Sandstone Formation has been informally divided into an upper and lower part by several authors. The lower portion has a much smaller areal extent, includes a quartz porphyry and has no Bushveld Granite clasts; the upper portion has a thick trachytic lava at its base and contains several other trachytic lava flows (Jansen, 1982, Fig.3.2). Meinster (1971) describes the lower part as usually being moderately to intensely sheared and jointed. The Swaershoek Formation consists largely of arenite and it is distinguished from underlying rocks by its siliciclastic nature. Until quite recently the lower Swaershoek Formation was thought to be part of the Rooiberg Group (Coetzee, 1969, p. 318). The similar geographical distribution of the Swaershoek Formation, and its correlate the Wilgerivier Formation, to rocks of the Rooiberg Group has been commented on by van Biljon (1976, p. 165) and by Coertze *et al.* (1977, p. 155). Du Plessis (1972a) shows that the lower Swaershoek Formation is conformable with the Rooiberg rhyolites and the Bushveld granites in the Nylstroom area. Since there is no faulting of the granite core of the Zwartkloof anticline, du Plessis argues that the granite was still pliable during this deformational phase, and that the lower Swaershoek is thus penecontemporaneous with the Bushveld granite. In the southwestern part of the basin the upper Swaershoek Formation unconformably overlies Rooiberg Group rhyolite, but where the rhyolite has been completely eroded away prior to the deposition of the Swaershoek, it unconformably overlies Bushveld granite (Meinster, 1975).

The Swaershoek Formation is distinquished from the overlying Alma Formation by the presence of lava flows and by its generally non-arkosic composition, as well as the higher degree of deformation which it shows in

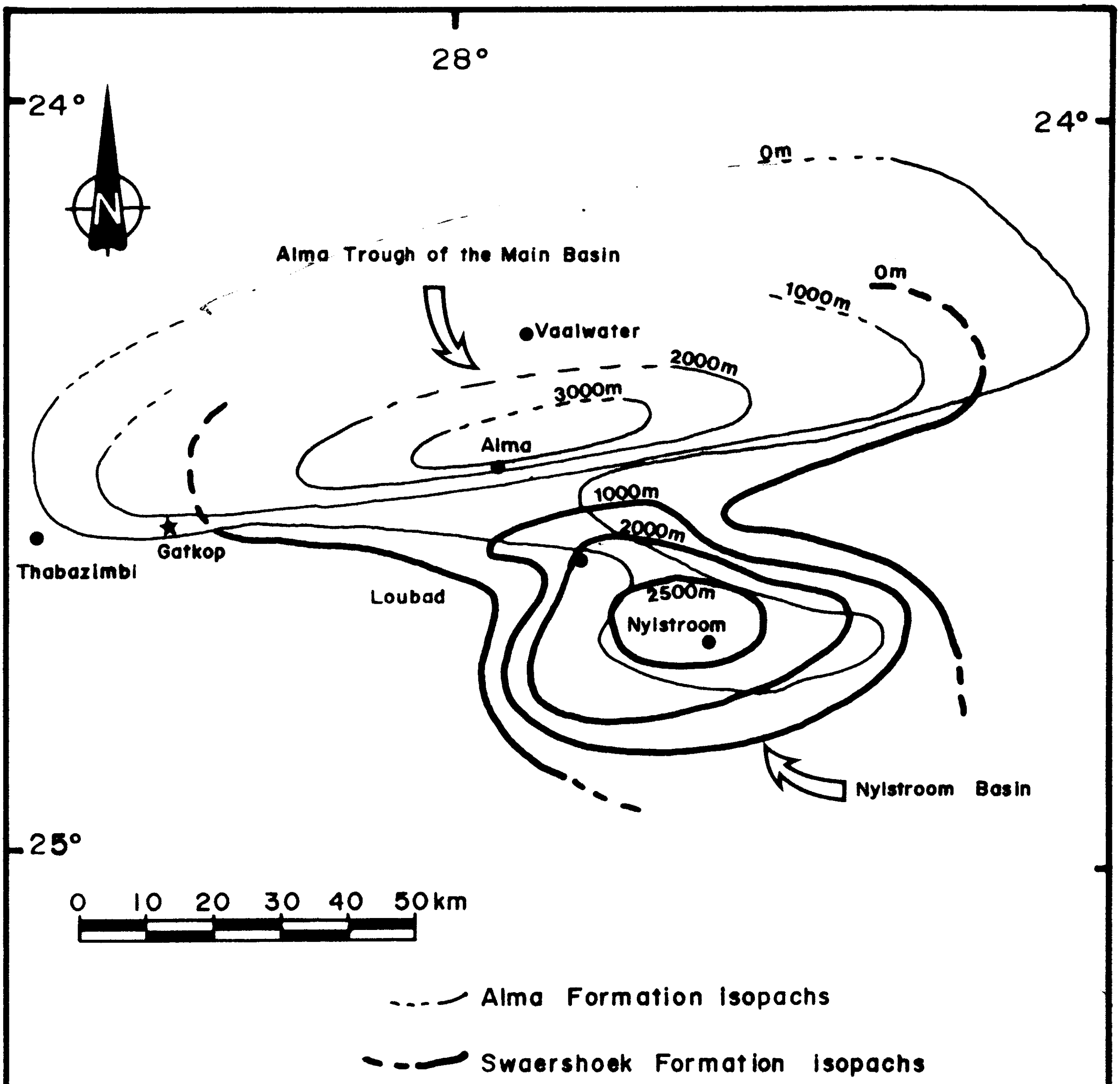


Figure 3.3: Isopach map of the Swaershoek and Alma Formations (modified from Jansen, 1982).

places. Meinster (1975, p. 59) points out that in the Gatkop area the Swaershoek Formation is represented by sheared rudite; he further states that most of the minor faults intersecting the Swaershoek Formation do not continue into the Alma beds. This latter relationship also occurs in the southeastern part of the basin (Meinster, 1971, p. 27).

The Swaershoek Formation is lenticular on a regional scale, showing a rapid thickness variation from 2500m in the central portion of the Nylstroom basin (De Vries, 1970) (Fig. 3.3) to a few hundred metres or less at the present day edges of the basin. The lenticular nature of these sediments is well illustrated by an example given by De Vries (1970), where he mentions a lava flow which lies at the basal contact of the formation on Boekenhoutskloof 187KR. Towards the southeast this lava band is underlain by 1350m of sediments which lie between it and the felsite on the farms Elandsbosch 372KR and Doornfontein 374KR. Towards the north a thin succession of Swaershoek Formation rocks extends into the southernmost part of the Main Basin (Figs. 1.1 and 3.3); at Gatkop they are less than 100m thick (Meinster, 1975, Table I).

The characteristic arenite of the Swaershoek Formation is coarse- to medium-grained, with common granule and pebble layers. Colours are of the hue 5R and composition ranges from litharenite to quartz-arenite. About 15% of the arenites consist of rock fragments of which some 50% are rhyolite; also present are arenite, lutite, chert and iron-formation clasts, as well as quartz cement (De Vries, 1970). The rudites consist of small pebbles to boulders of rhyolite, arenite, vein quartz, chert, iron-formation, jasper, rudite and lutite. The rudites are coarsely bedded with beds ranging from 3-6m in thickness (Tankard *et al.*, 1982), with an average of 5m (De Vries, 1970). Ripple marks and small scale trough cross-beds are common in the arenites (De Vries, 1970). Cross-beds may show intraformational deformation (Meinster, 1970a). The rudites are generally massive. The top of the Swaershoek Formation is defined by a five metre thick pebble rudite which is persistent over a large area (De Vries, 1970).

Lutites may attain a thickness of 250m in places, and they appear to be genetically related to the lavas and may even be volcanic in origin. The lavas are developed throughout the succession except in the lowermost beds. They have been intensely altered, but a trachytic composition is indicated (Jansen, 1982). The lavas are typically amygdaloidal and occur in flows of 10-30m in thickness. Lenticular quartz porphyry lava flows are exposed in the lowermost beds of the Swaershoek Formation.

3.3 ALMA FORMATION

The Alma Graywacke Formation is largely confined in its distribution to the Alma trough (Fig.3.3), where it overlies the Swaershoek Formation and, in places, the Lebowa Granite Suite. In the east it grades laterally into the upper Sterkrivier Formation; the division between the two formations is arbitrary and is taken on the boundary of the farms Roodepoort 314KR and Buffelsdoorns 315KR where the rocks grade from feldspathic to non-feldspathic (Jansen, 1982). It is overlain by the Skilpadkop Formation. A maximum thickness of 3000m is recorded around Alma and it decreases in thickness in all directions from this point (Fig. 3.3)

The Alma Formation comprises a succession of medium- to coarse-grained arkoses, lithic arkoses, feldspathic arenites, subarkoses and litharenites (Fig. 2.1a). Arkosic rudites are common whilst lutites are relatively rare, although an arenaceous lutite to the east of Gatkop has been given member status (Donkerpoort Siltstone Member). Around Gatkop the Alma Formation is especially coarse-grained and contains boulder beds; the arkosic boulder rudites on the farm Buffelshoek 446KQ have been given member status (Buffelshoek Boulder Conglomerate Member). To the west of Gatkop the Alma Formation consists mainly of lithic arenites and rudites. In the zone from the northeastern border of the farm Waterval 443KQ to the Sondags River these rocks consist of volcanic arenites and rudites whilst on the western

TABLE 3.1

DESCRIPTIONS OF LITHOFACIES CODES

CODE	DESCRIPTION
Gs	matrix-supported granite boulder rudite
Gsc	poorly sorted, unrounded, chaotic clast-supported rudite
Gms	matrix-supported rudite: commonly massive
Gm	clast-supported rudite: commonly massive
Gh	horizontally stratified rudite
Gt	trough cross-bedded rudite
Gxt	very large-scale cross-bedded rudite
Gp	planar cross-bedded granule rudite
Sm	massive arenite
Sh	horizontally laminated arenite
Shhm	horizontally laminated heavy mineral-rich arenite
Si	arenite with resedimented intraformational clasts
Slic	granule-rich arenite with isolated cobbles
St	trough cross-bedded arenite
Sxt	very large-scale cross-bedded arenite
Sp	planar cross-bedded arenite
Sxp	very large-scale cross-bedded arenite
Sr	ripple laminated arenite
Spe	very large-scale planar wedge-shaped cross-bedded arenites
Smc	massive arenite in channel-shaped masses within Spe
Sl	arenites with ripples, interference ripples, adhesion warts, problematic traces and desiccation cracks
Sme	tabular bodies of massive arenite associated with Spe
Sre	large assymetrical ripples associated with Spe
Fm	massive lutite
Fsc	massive to horizontally laminated lutite with quartz slivers
Fmt	massive to horizontally laminated tuffaceous lutite
Fmv	massive to horizontally laminated lutite with 'vesicles'
Fh	horizontally laminated lutite

side of the river they are sedarenites and rudites, with white quartzite clasts predominating.

Coarse-grained arkoses, lithic arkoses and feldspathic litharenites make up the bulk of the Alma Formation in the Gatkop area (Fig. 1.1). The most common colours seen during this study are in the range 5R3-4/2-6, moderate greyish to dusky red; De Vries (1970) describes the characteristic colour as greenish grey in the areas in which he worked.

Although commonly not clearly defined, bedding is from 0,15 to 3,0m thick in the arenaceous rocks. In places planar laminations of 10 to 15 mm occur in pebbly beds; individual laminations can usually be traced laterally for about 1m. These horizontally laminated rocks constitute facies Sh and Gh in the Alma Formation (Table 3.1). Bedding is often defined by upward-fining cycles in which only the coarse material becomes finer, whilst the modal grain size remains approximately constant. Trough cross-bedding occurs in places and may be more common than it at first appears, since it is often not visible on weathered surfaces. A good example of this is seen on Donkerpoort 448KQ where a recently exfoliated surface shows trough cross-bedding in steeply dipping granule rich arenites, whereas no trace of the structures can be seen on the more weathered surfaces. These trough cross-beds have a set thickness of 30-35cm and are generally more than a metre across. To the south of this occurrence large scale trough cross-beds in coarse-grained pebbly arenites have a set thickness of 1-2m and are more than 4m wide. Facies St and Gt refer to the trough cross-bedded arenites and rudites. On Doornhoek 318KQ plane laminated beds are seen in angular to subangular, poorly sorted coarse granule-rich arenite, which shows isolate clasts and isolate 'nests' of clasts which usually occur more than a metre apart; these rocks are assigned to lithofacies Slic (Fig. 3.4). Associated very large-scale cross-beds which show only slight curvature of laminae, and low angles of inclination are classified as facies Sxt. These structures are more than 10m across and more than 1m thick. Trough cross-beds with set thicknesses of about 30cm are also developed here.

Although the outcrop is too poor for accurate measurement of the cross-beds on Donkerpoort 448KQ, the sense of direction of palaeoflow is towards the northeast. Only 12 paleaocurrent measurements were made in the Alma Formation (Fig.3.5). Since neither of the Ajne statistics is significant these data are not representative and the average direction obtained is not significant.

FIGURE 3.4: Planar bedded granule-rich arenite with isolate pebbles (facies Slic) of the Alma Formation on Doornhoek 318KQ.

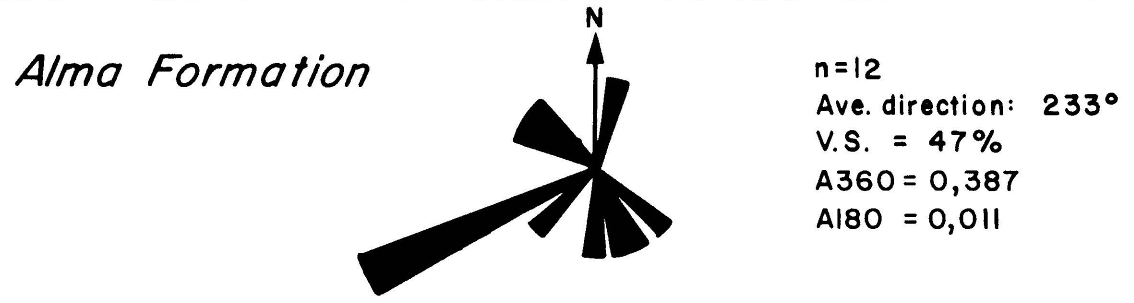


Figure 3.5: Rose diagram of palaeocurrent indicators – Alma Formation

In a thin section of medium to coarse arenite from borehole 019 a possibly biogenic particle occurs (Figure 3.6). The walls of this particle now consist of fine chert. C. S. MacRae (pers. comm., 1986) suggests that it may be a deformed complex algae or a chitonozoan; the particle is not well enough preserved for positive identification.

The coarse rudites in the Alma Formation are commonly massive, although a poorly developed parallelism of clast length to strike occurs locally. These rudites may be matrix-supported or clast-supported and are assigned to facies Gms and Gm respectively. Granules are considered as matrix in these coarse rudites. Imbrication is poorly developed at some localities. Clasts are predominantly subangular and pebble-sized and they range from rounded to very angular; cobble and boulder beds are locally developed. On Buffelshoek 446KQ a basal boulder bed containing very large (> 1m across) rounded granite boulders occurs; the matrix shows concentric banding around the boulders and is highly feldspathic. Lithofacies Gs refers to these sedimentary rocks. To the west of the Sondags River, on Waterval 443KQ, boulders up to 2m in length were measured in a coarse, chaotic, clast-supported boulder rudite, described as facies Gsc. Basinward of these coarse, bimodal clast- to matrix-supported subangular rudites, facies Gm-Gms are developed (Fig 3.7). In the Gatkop area there is a tendency for grain size of clasts to increase in size southwards towards the faulted basin edge, which is in agreement with the findings of Meinster (1972, 1975). The average grain size of the ten largest clasts measured at various localities in the Alma Formation ranges from 61 to 718mm (n=22) which indicates peak current velocities of up to 7,62m/s. The peak current velocities in this study are determined from the formula provided by Baker (1973).

Modal analyses in the Gatkop area show rudite clast composition to vary quite dramatically from one locality to the next, with quartzite, felsite and granophyre predominating at various localities; other clast types include lutite, iron-formation and rudite.

FIGURE 3.6 Deformed algae? from borehole 019 (Alma Formation) on the farm Buffelshoek 446KQ, as seen in ordinary light. The base of the photograph is 0,88mm across.

FIGURE 3.7 Bimodal, clast-supported, subangular rudite (facies Gm) of the Alma Formation on Waterval 443KQ

Clast to matrix ratios are variable but the clasts only rarely represent more than 60% of the rock, granules being considered as part of the matrix in the coarse beds. West of the Sondags River the sorting of rudites becomes noticeably poorer upwards in the sequence, and on Buffelshoek 446KQ, in borehole CC-019, the rock becomes coarser upwards in the sequence (Figures 3.8 and 3.9). Clast contact types were measured, indicating that tangential contacts are the most common. Longitudinal contacts are the next most abundant whilst concavo-convex contacts are rare and sutured contacts were not seen. Clasts are usually equant in shape. In the area between the Sondags River and Thabazimbi some wedge-shaped beds occur, which thicken basinward.

The lutite in the Alma Formation is commonly of a dusky red to very dark red colour (5R3/4-5R2/6). Thin lutite drapes, however, are often greyish pink (5R8/2) in colour. The main occurrence of lutite in the Alma Formation is the Donkerpoort Member which is well exposed on Donkerpoort 448KQ. The rock is usually well sorted and consists of silt-sized quartz particles. The quartz grains are often extremely angular with quartz 'slivers' being common (facies Fsc).

In order to facilitate economic studies of the Waterberg Group, a number of boreholes were drilled in the Alma Formation at Gatkop (Figs. 1.1, 3.8 and 3.9). Lithofacies defined from the boreholes correlated well with those already described from field outcrops:

facies Gm, clast-supported massive rudite, occurs in all the boreholes and constitutes the major portion of boreholes 004, 005, 008-018 and 020;

facies Gms, matrix-supported massive rudite, occurs in all boreholes but nowhere forms the dominant facies;

facies Sh, horizontally stratified arenite, occurs in boreholes 006, 007 and 019;

facies St, trough cross-bedded arenite, occurs in boreholes 006 and 019

facies Gt, trough cross-bedded rudite, only occurs in borehole 019 as does facies Sp, planar cross-bedded arenite. Dessication cracks were also noted

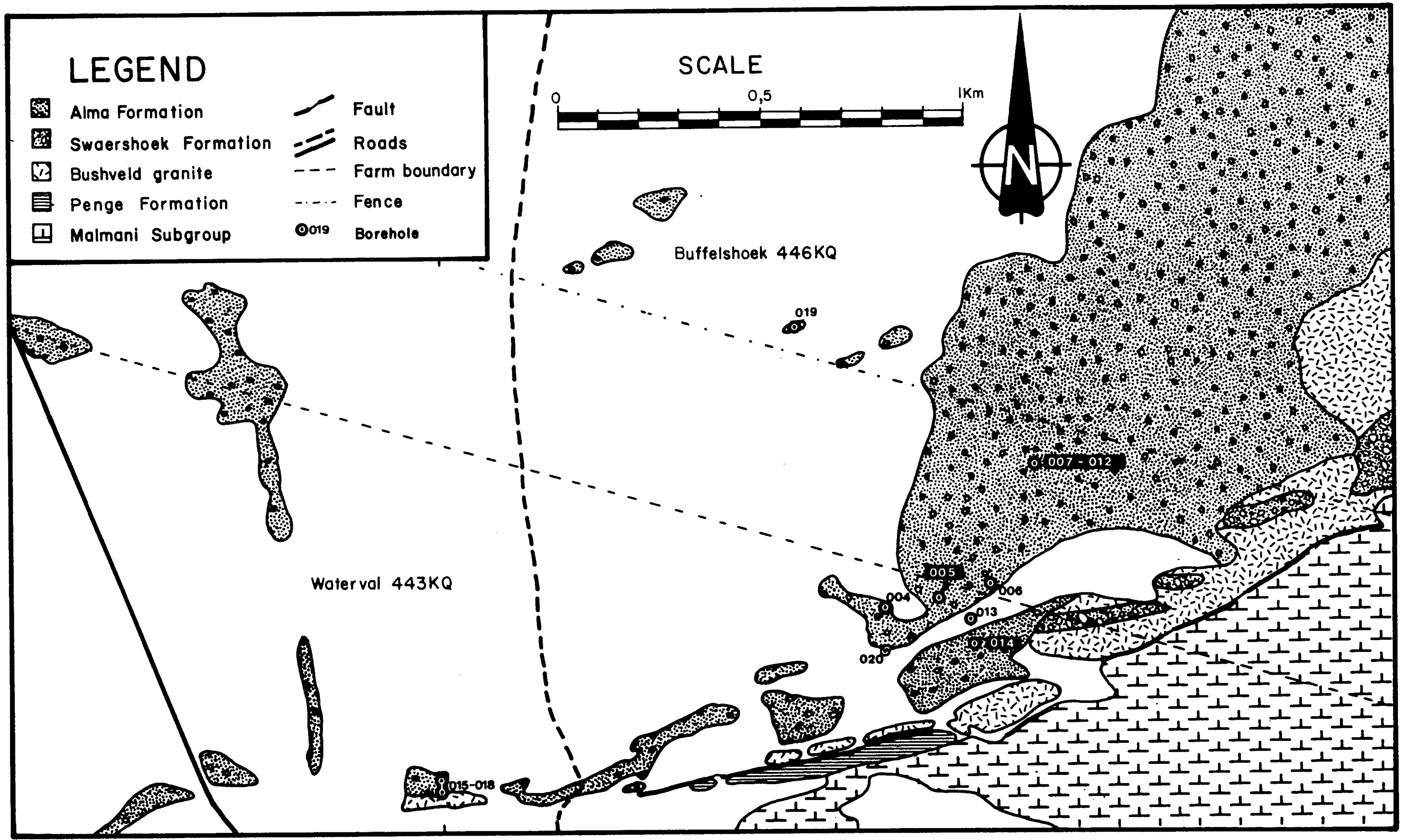


Figure 3.8: Geology of the Gatkop area (modified after Meinster, 1975), also showing borehole sites.

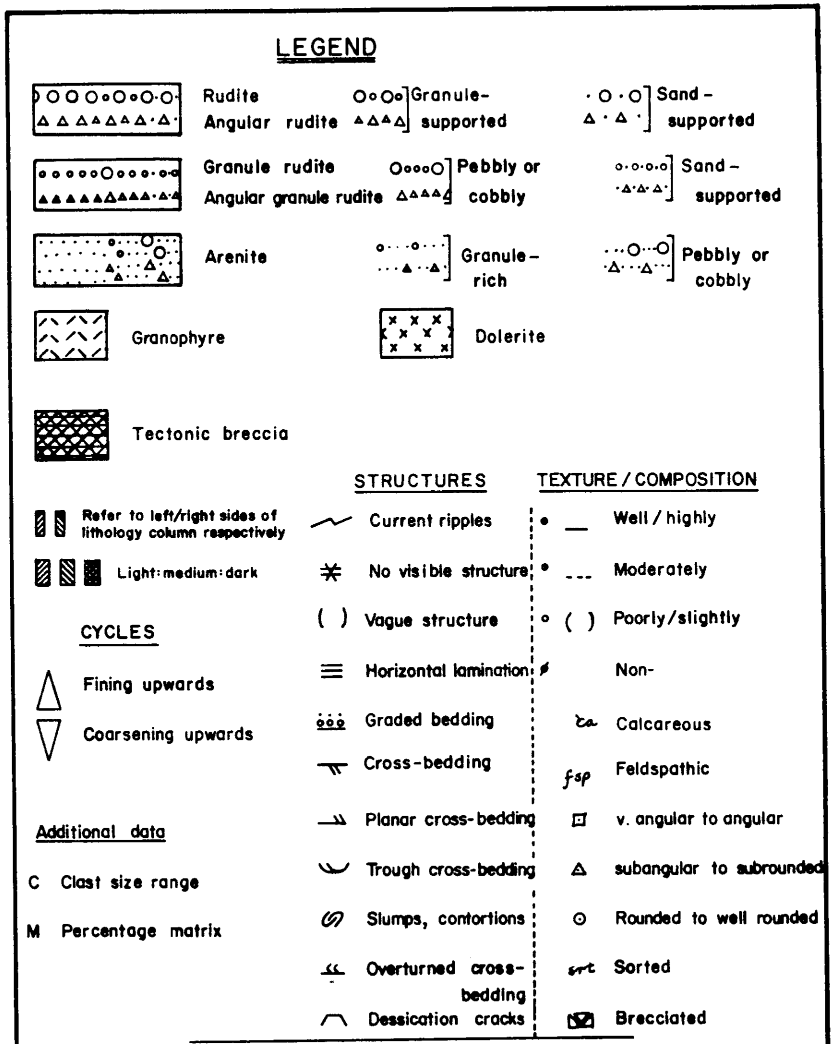


Figure 3.9 a-l Legend and logs of boreholes drilled on the farms Waterval 443KQ and Buffelshoek 446KQ, east of Thabazimbi.

Fig. 3.9b

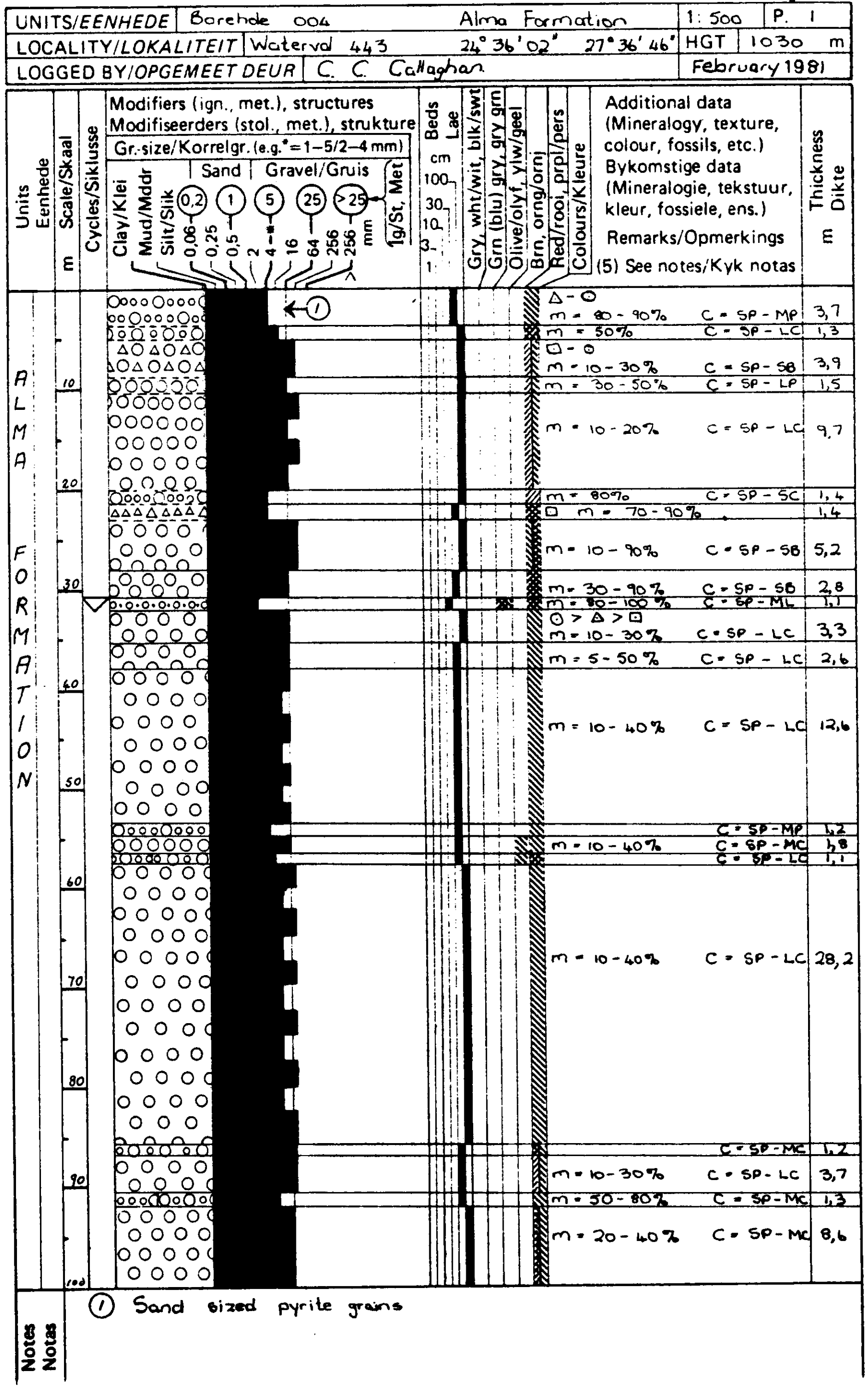


Fig. 3.9c

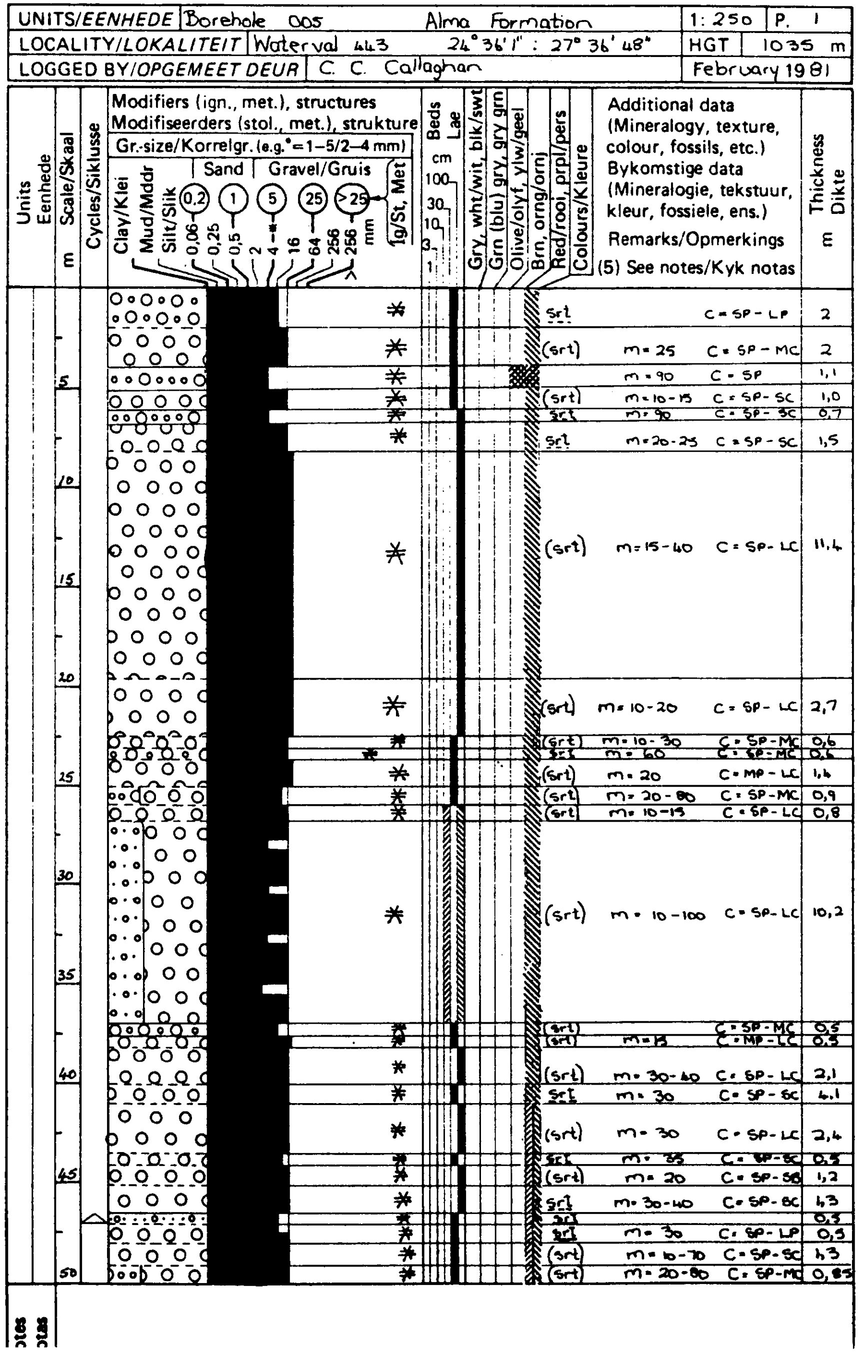


Fig. 3.9d

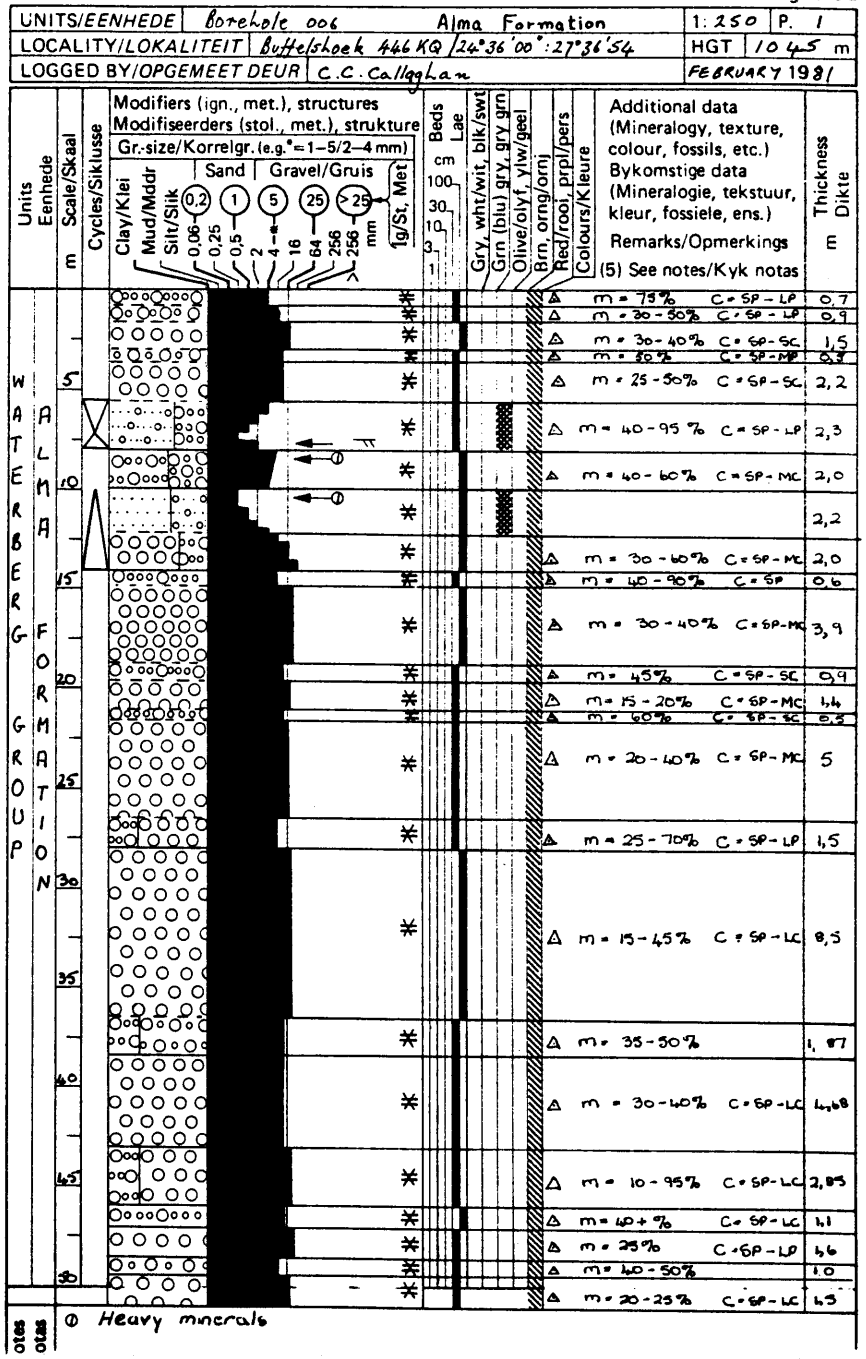
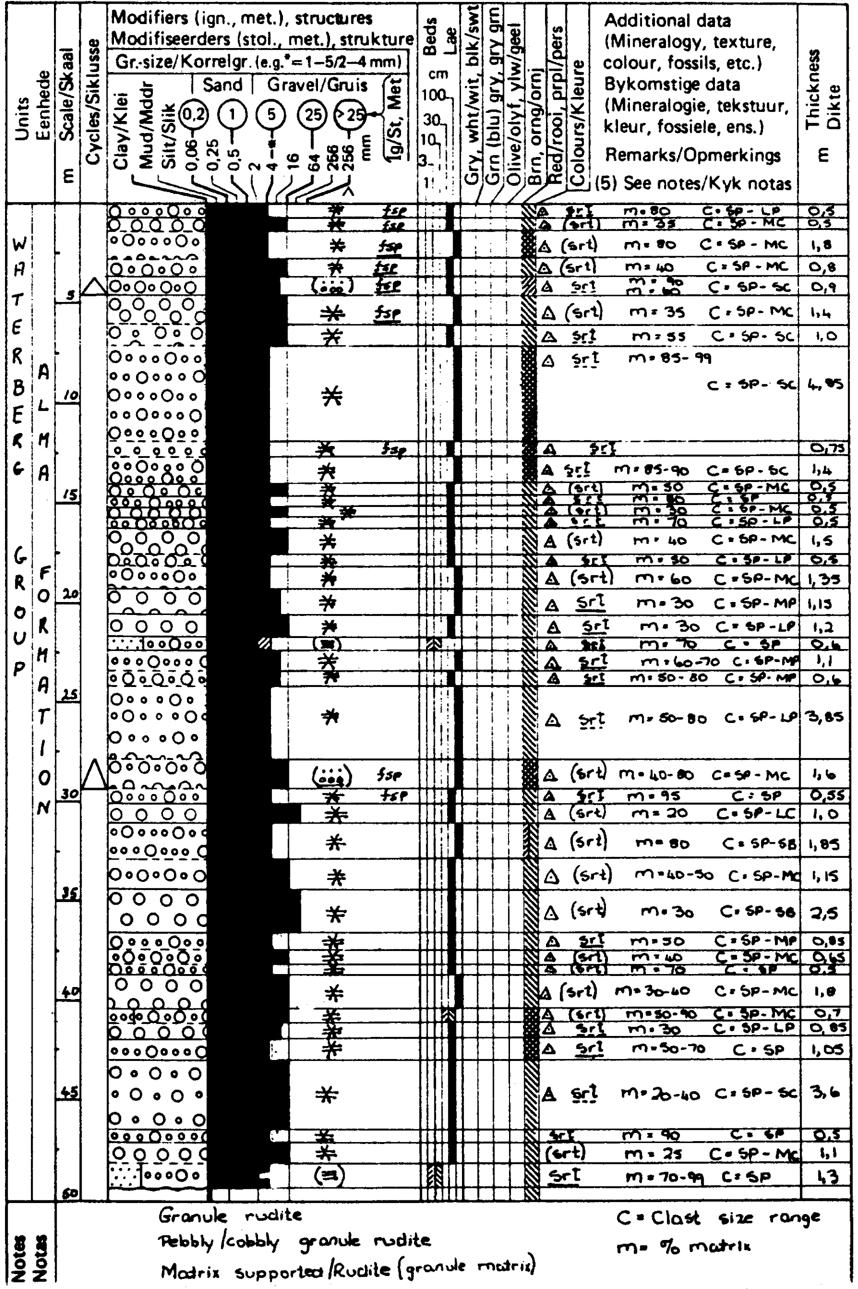


Fig. 3.9e

UNITS/*EENHEDE* Borehole 007 Alma Formation 1:250 P. 1
LOCALITY/*LOKALITEIT* Buffelshoek 446 KQ 24° 35' 49" : 27° 36' 51" HGT 1070 m
LOGGED BY/*OPGEMEET DEUR* C. C. Callaghan February 1981



Granule rudite
Pebbly/cobbly granule rudite
Matrix supported Rudite (granule matrix)

C = Clast size range
m = % matrix

Fig. 3.9f

UNITS/*EENHEDE* Boreholes 008-013 Alma Formation 1:250 P.
LOCALITY/*LOKALITEIT* Buffelshoek 446 KQ 24° 35' 47" : 27° 36' 57" HGT 1060 m
LOGGED BY/*OPGEMEET DEUR* C. C. Callaghan January 1982

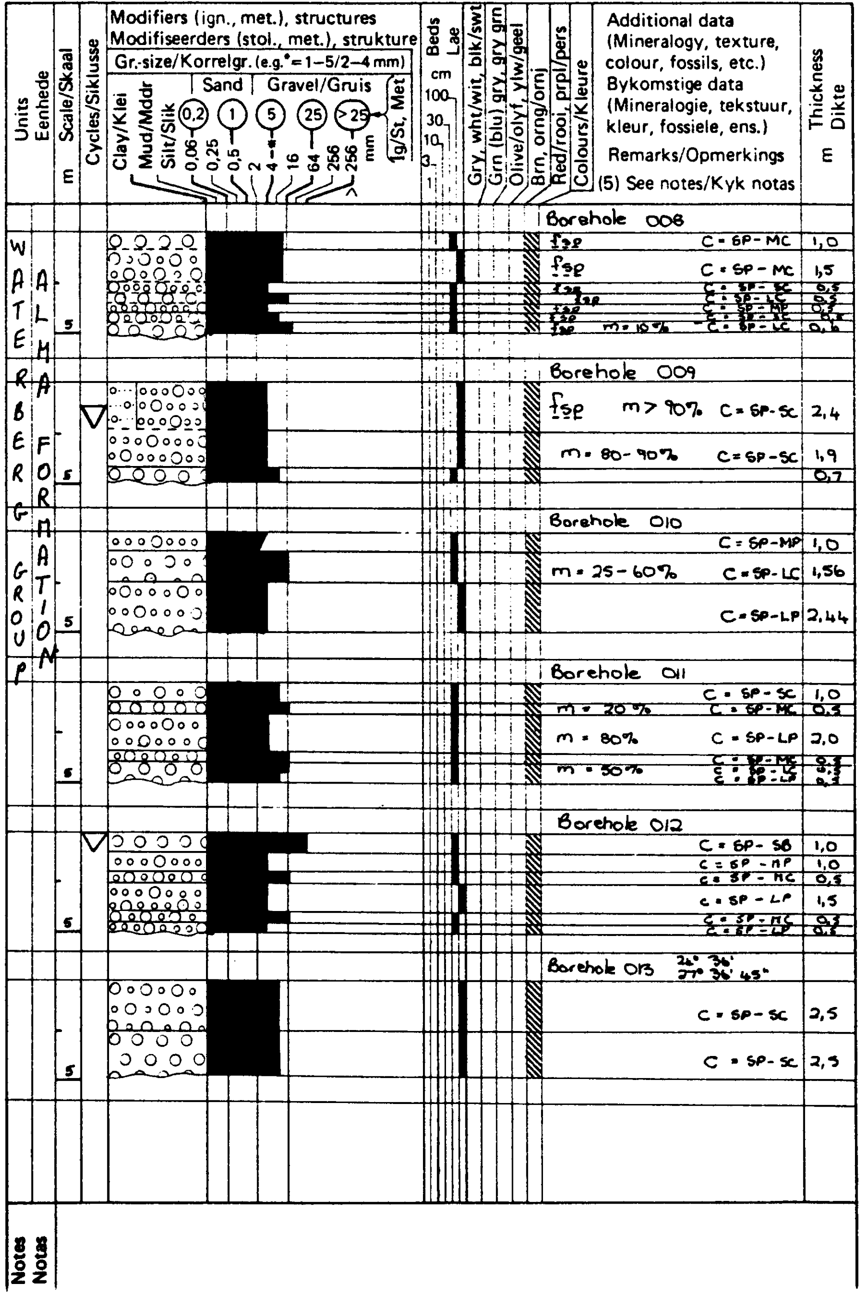


Fig. 3.9g

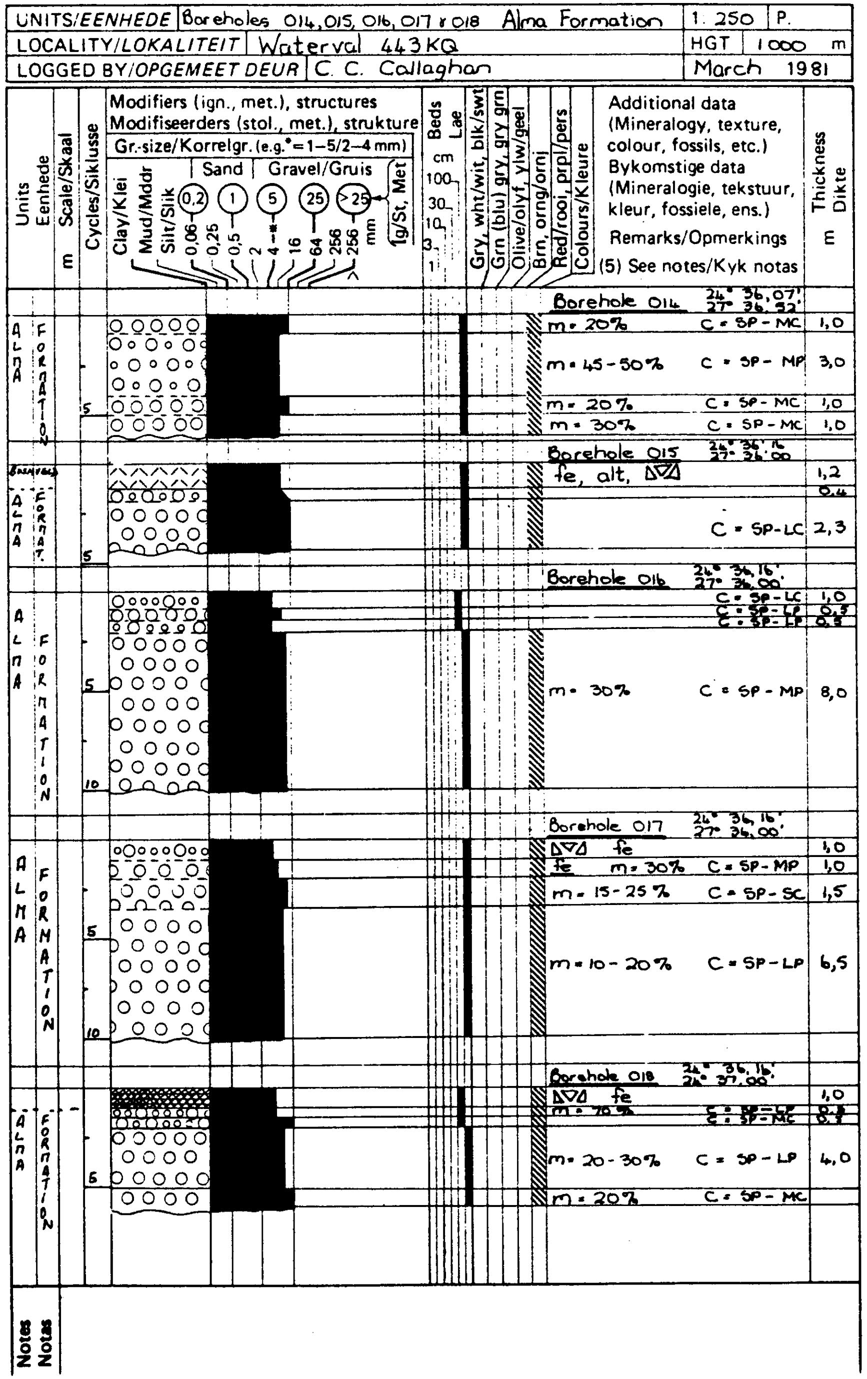
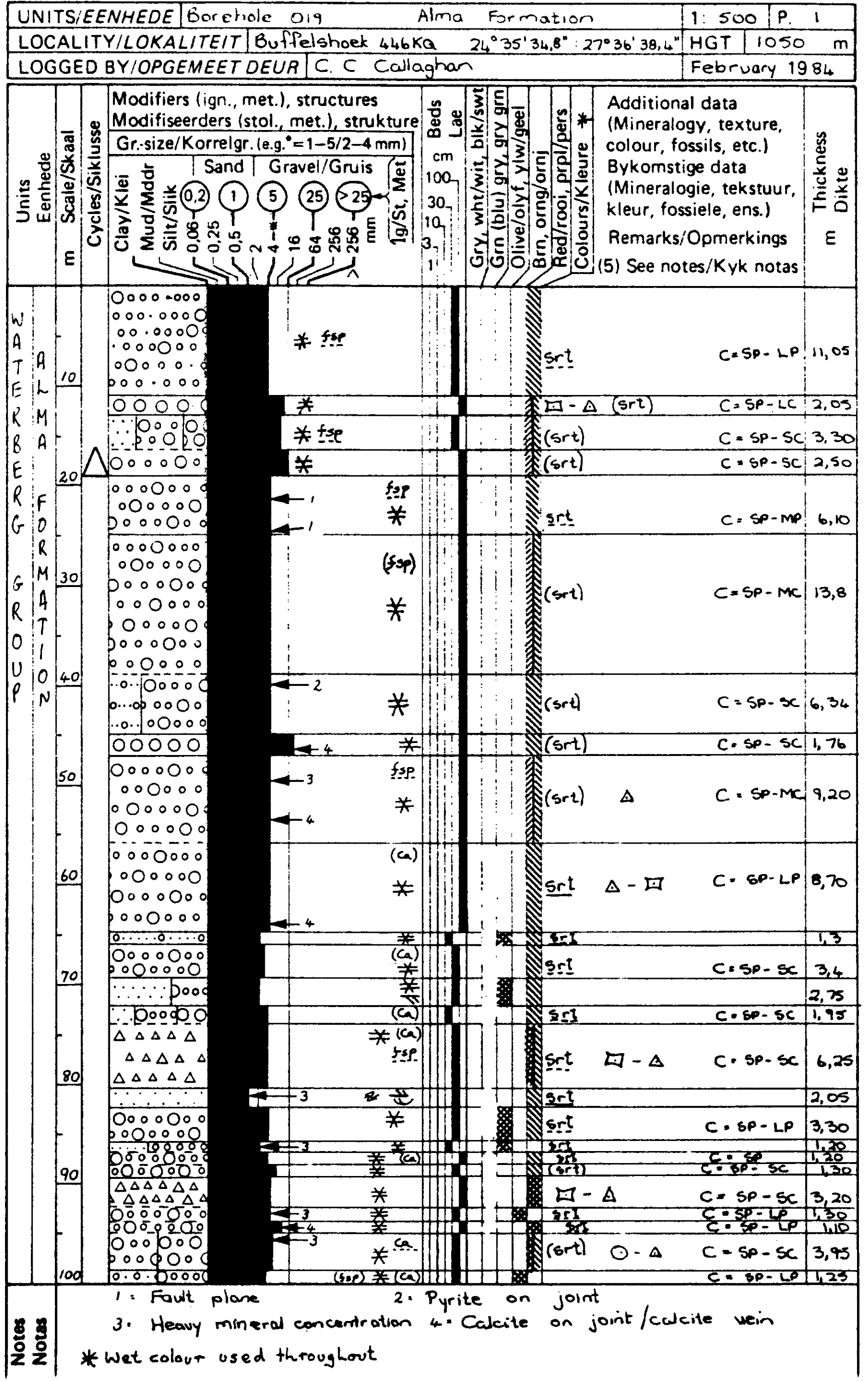


Fig. 3.9h



1 = Fault plane 2 = Pyrite on joint
3 = Heavy mineral concentration 4 = Calcite on joint / calcite vein
* Wet colour used throughout

Fig. 3.9i

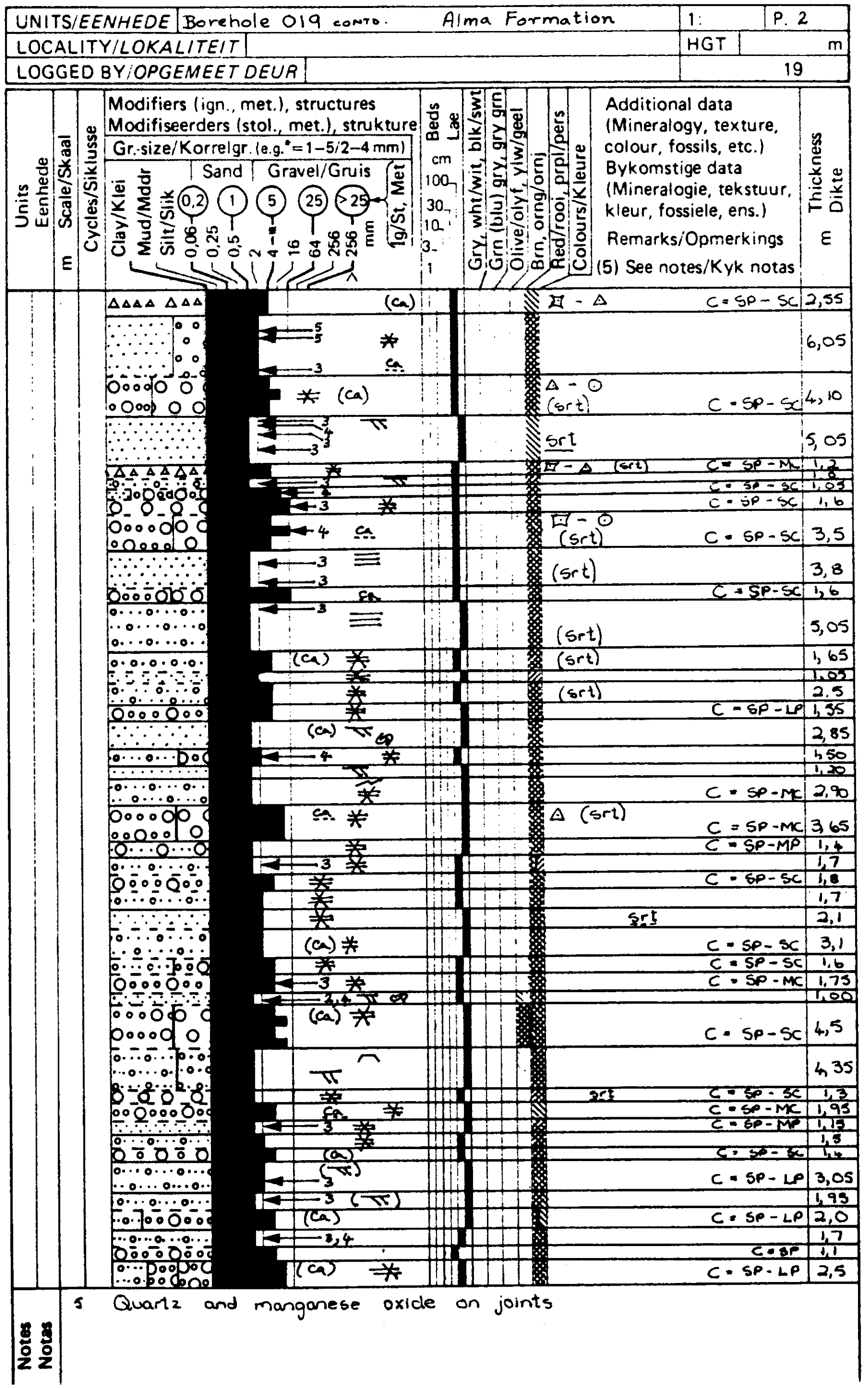


Fig. 3.9j

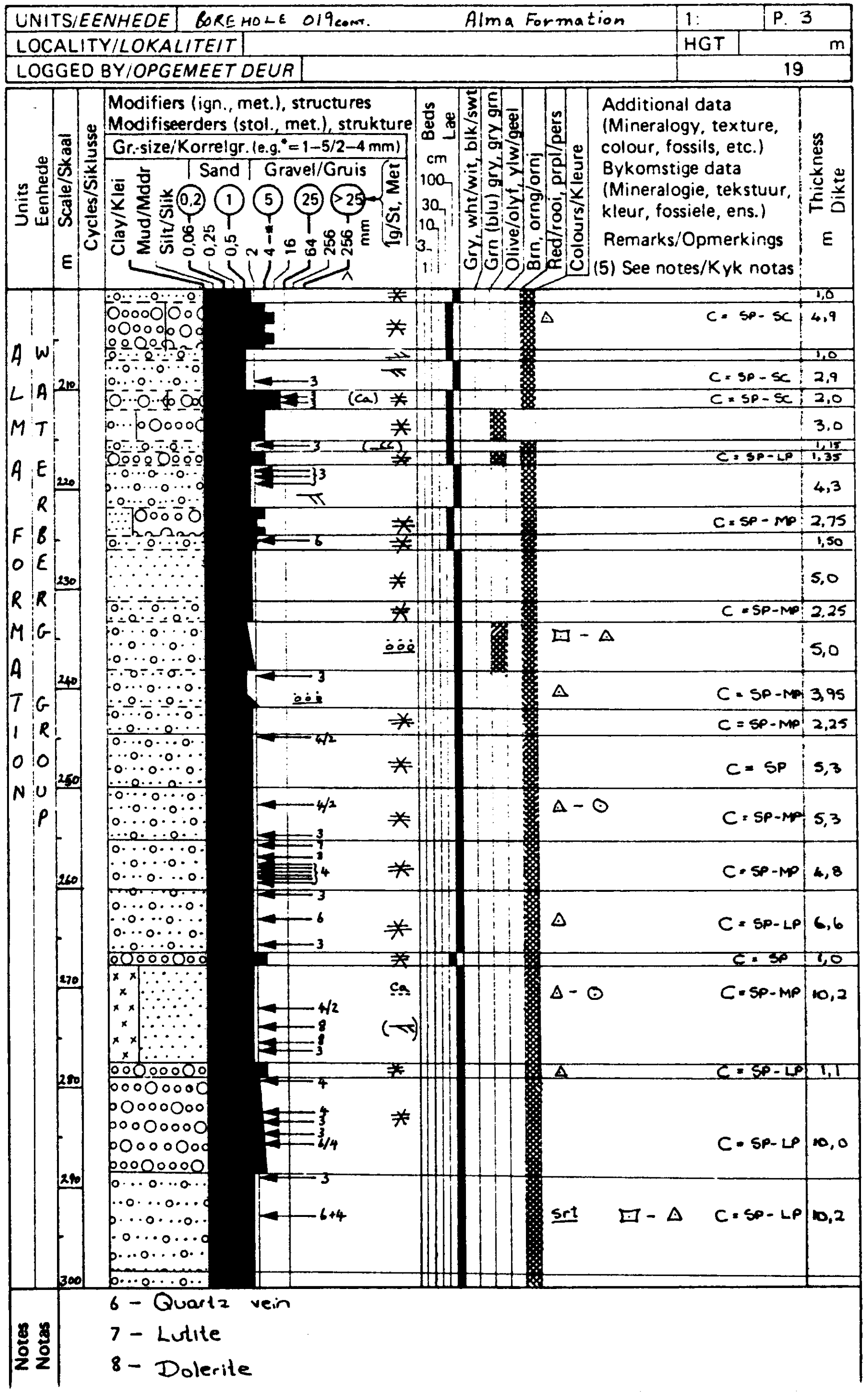
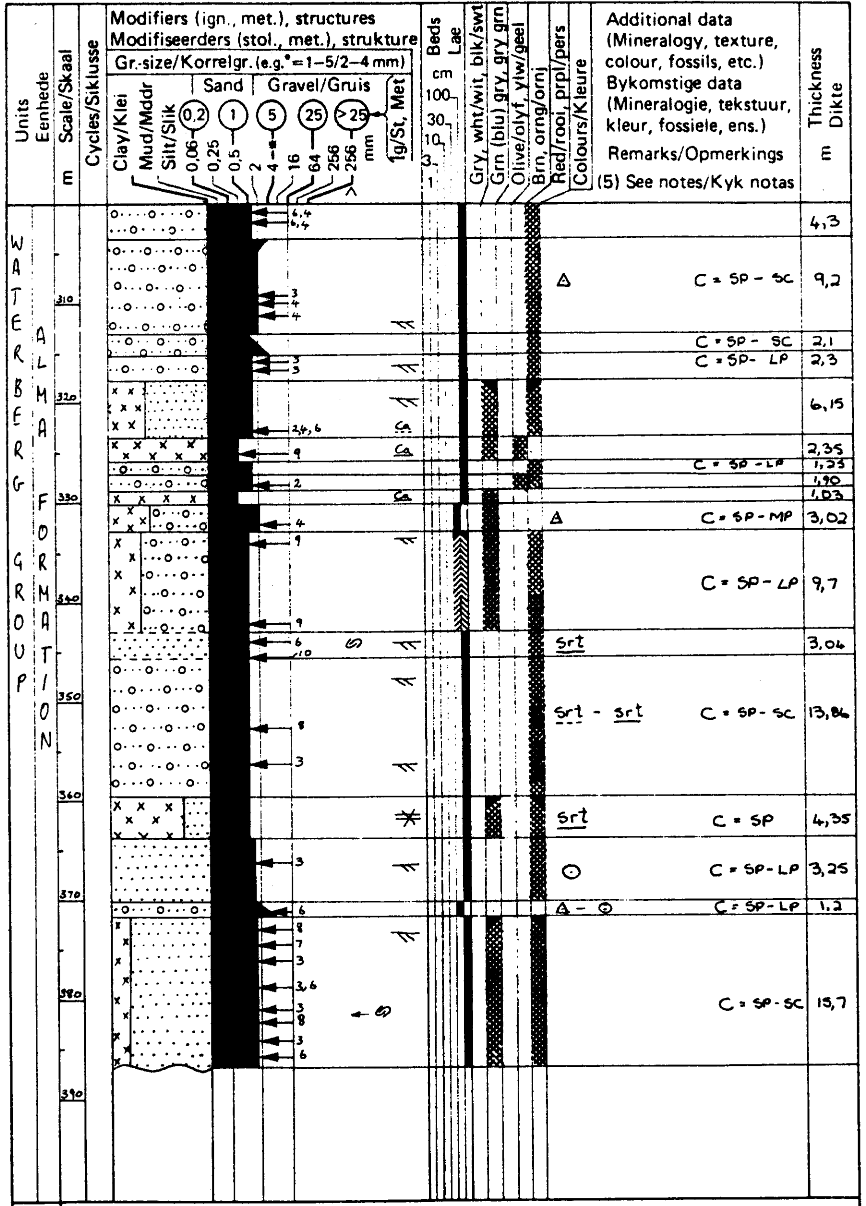


Fig. 3.9k

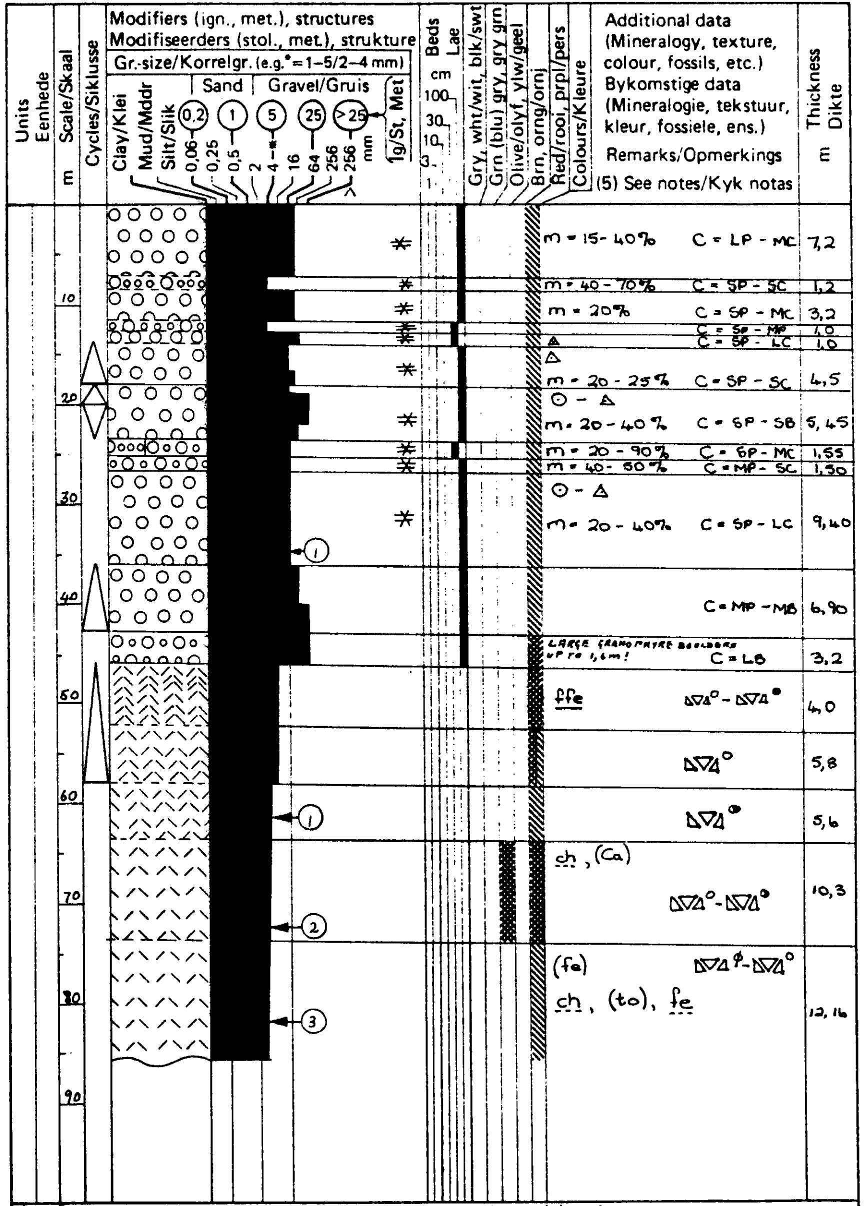
UNITS/*EENHEDE*	Borehole 019 contd. Alma Formation	1:500	P. 4
LOCALITY/*LOKALITEIT*		HGT	1050 m
LOGGED BY/*OPGEMEET DEUR*		February 1984	



Notes Notas
9 · Disseminated Sulphides
10 = Porphyritic bostonite

Fig. 3.91

UNITS/*EENHEDE*	Borehole 020 Alma Formation/Bushveld	1: 500	P. 1
LOCALITY/*LOKALITEIT*	Waterval 443KQ 24° 36' 5,68": 27° 36' 48,53"	HGT	1030 m
LOGGED BY/*OPGEMEET DEUR*	C C Callaghan	March 1984	



Notes Notas
m = matrix
① = pyrite in vein
② = quartz/specularite vein
③ = haematite vein
ch = chloritic
ca = calcareous
fe = ferruginous
to = tourmaline bearing

from borehole 019.

Lithofacies in outcrop and from the boreholes in the Gatkop area exhibit a characteristic arrangement from the southern edge of the Alma trough towards the centre. The most common facies exposed in the Gatkop area, near the basin edge, are Gsc, Gs, Gm, Fsc; a little further into the basin, Gm, Sh, Gh, Gms, Gxt, Sxt, Gt, Sp; still further into the basin, Gm, Sh, Gms, St, Sp; and at some distance (>1 kilometre) from the basin edge, facies St, Gt, Sxt, Gxt and Slic. This trend is also reflected in the boreholes (Figures 3.8 and 3.9), where those closest to the basin edge show only facies Gm and Gms (Boreholes 004, 005, 008-018 and 020). Borehole 006 shows facies Gm, Gms, St and Sh. Borehole 007 shows the facies Gm, Gms, and Sh. Borehole 019 which is the furthest from the basin edge shows facies Gm, Gms, Sh, St, Sp and Gt. An indication of the vertical facies relationships is seen in borehole 019, where facies Gms and Gm are dominant in the top 100m. In the next 100m facies Sh, St and Sp are interspersed with facies Gm and Gms. Facies Gm and Gms become rarer down the section and in the last 100m facies St and Sp are dominant.

3.4 STERKRIVIER FORMATION

The Sterkrivier Sandstone Formation occurs in the extreme eastern part of the Alma trough. To the west it grades laterally into the Swaershoek and Alma Formations. It is about 1500m thick in the west, but thins rapidly to about 500m towards the northeast (Jansen, 1982). The Sterkrivier Formation unconformably overlies the Rooiberg Group and the Bushveld Complex and conformably underlies the Skilpadkop Formation in the south. Further north it unconformably underlies the Makgabeng Formation (Jansen, 1982). The Sterkrivier Formation consists chiefly of red arenite, as well as rudite, lutite and lava.

The arenites occur in beds of 0,3m to more than one metre thick and may display rhythmically and chaotically deformed cross-bedding

(Meinster, 1970a). The most common sedimentary rocks represented in this formation are lithic arenites which contain rhyolite, metaquartzite, vein quartz, banded iron-formation and chert fragments. The rocks may be cemented with iron oxide. Clay content is low and rutile, zircon, titanomagnetite and anatase occur as accessory minerals.

The rudites are typically pebbly with subrounded to angular clasts. They consist of rhyolite, vein quartz, metaquartzite, banded iron-formation and chert. Lutites are poorly developed but where the formation overlies Bushveld Granite on Baviaanskloof 290KR and Waterval 297KR a basal shale of up to 20m thick occurs (Jansen, 1982). Thin, highly altered trachytic lava flows, which Jansen (1982, p. 28) correlates with those of the Swaershoek Formation, occur in the lower part of the Sterkrivier Formation. Frick (1970) measured long axes of pebbles in the Sterkrivier Formation and he concludes that several current directions were effective. Frick states that two directions are usually present. Jansen (1982, p. 29 to 31) gives directions of long axes as NW and NNE in the northeast and as E in the southwest. No sedimentary structures were observed during the present study due to limited outcrop accessibility and low economic potential.

3.5 SKILPADKOP FORMATION

The Skilpadkop Grit Formation occurs in the southern and southwestern portions of the Main Waterberg Basin where it conformably to unconformably overlies the Alma Formation. Jansen (1982) mentions that it unconformably overlies pre-Waterberg rocks west of Matlabas. The Skilpadkop Formation conformably underlies the Aasvoëlkop Formation. In its northeastern part the Skilpadkop Formation is unconformably overlain by the Makgabeng Formation. Jansen (1982) points out that the Skilpadkop Formation is in fact identical to its northerly correlate, the Setlaole Formation. The Skilpadkop Formation reaches 600m in thickness in the type area at

Skilpadkop, but it is as little as 30m thick in the east where it wedges out (Jansen, 1982).

The formation typically consists of thickly bedded immature lithic arenites and rudites. The rudites are usually pebbly, but may be very coarse-grained with cobbles and boulders; only minor lutite occurs. The Skilpadkop Formation is distinquished from the underlying Alma Formation by its generally non-arkosic character.

The arenites and rudaceous arenites are thickly bedded, with beds of 0,6 to 2m thick predominating. They are immature, containing 6-20% lutite as well as containing several percent granules (Fig. 2.1b). Thin sections from this formation have a high lithic content and are classified as sublitharenite and litharenite (Fig. 2.1a). Lithic particles consist of chert, metaquartzite, schist, granophyre and rhyolite. Arkoses are developed in the west near the Botswana border. The arenites are red of a 5R hue; in places (eg. Klipspruit) golf ball-sized reduction spots occur. Jansen (1982) mentions a whitish arenite which is developed at the top of the formation. The arenites and rudaceous arenites are typically massive or trough cross-bedded (lithofacies Sm and St-Gt). These trough cross-beds are deformed in places. Trough cross-beds on Groothoek 278KQ show palaeocurrent directions towards the northeast, but in the eastern part of the basin cross-beds show palaeocurrents towards the west. Well exposed current ripples with an amplitude of 4mm and a wavelength of 20-30mm on Rhenosterpoort 283KQ show a current direction towards the west-southwest (facies Sr). This arenaceous facies is rare, but when developed usually overlies a trough cross-bedded facies. Palaeocurrent measurements on structures in the Skilpadkop Formation (Fig. 3.10) show a significant A_{360} value at the 0.001 level of significance (Dale and Ballantyne, 1980). The data are thus meaningfully grouped into a single semi-circle, but are multimodal.

The rudites generally contain a higher percentage of matrix than do those of the underlying Alma Formation. Beds are commonly 1,5 m or more

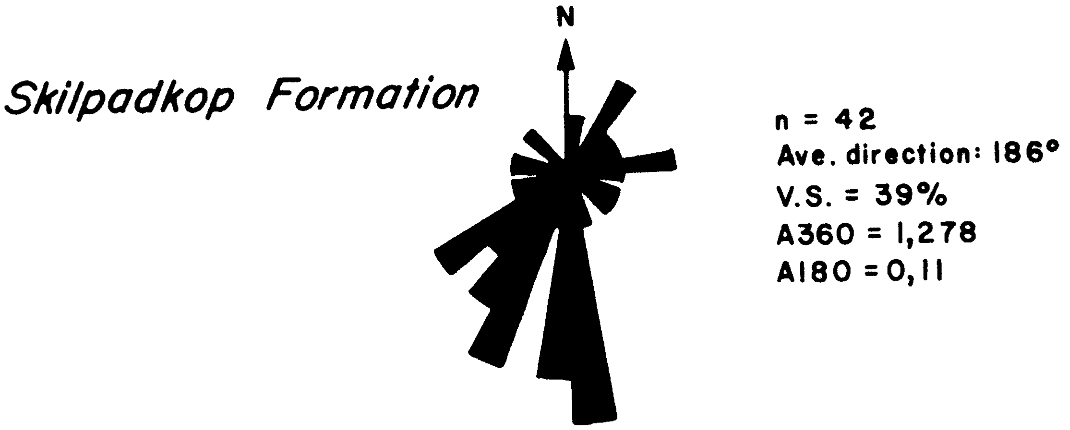


Figure 3.10: **Rose diagram of palaeocurrent indicators – Skilpadkop Formation**

in thickness. The average size of the ten largest clasts at various localities in the Skilpadkop Formation varies from 37,1 to 523,5 mm which indicates peak current velocities of up to 6,5 m/s. Clasts are typically equant to oblate in shape and are subrounded to subangular, although well rounded clasts do occur. They are commonly composed of quartzite, vein quartz, and rhyolite, while less abundant clast types include chert, jasper, banded iron-formation, lutite and rudite. Poorly developed imbrication is found locally, although the rudites usually show no structure (facies Gm, Gms). On Klipspruit 457KQ imbrication indicates a southerly palaeocurrent direction.

The most common facies types in this formation are immature lutite- and granule rudite-bearing massive arenite (facies Sm) or trough cross-bedded arenite (facies St-Gt) and arenaceous pebble/cobble rudite which is typically massive (facies Gm-Gms).

3.6 SETLAOLE FORMATION

The Setlaole Grit Formation occurs in the northern and northeastern parts of the Main Waterberg Basin, where it forms the base of the Waterberg Group. It has an unconformable lower contact with rocks of the Limpopo Metamorphic Province, the Rustenberg Layered Suite, the Lebowa

Granite Suite and the Rooiberg Group. The basal contact is generally poorly exposed, but a well defined contact with rocks of the Limpopo Metamorphic Province is reported by Jansen (1982), in the area north-northwest of Setlaole. A weathered contact with Bushveld Complex Granite was seen by the writer on Gotha 517LR. The basal beds of the Setlaole Formation at this locality show a poorly defined contact with the granites; they also show concentric colour patterns. Pebbles and cobbles are found scattered throughout this exposure and podlike masses of rudite also occur. The Setlaole Formation is gradationally overlain by rocks of the Makgabeng Formation. The formation reaches its maximum thickness of 450m near Setlaole in the northeast of the basin (Jansen, 1982).

The Setlaole Formation consists predominantly of granule-rich arenites and rudites with lesser tuffs and tuffaceous mudstones (Ngwepe Tuff Member) which are sporadically developed near the base of the unit (Jansen, 1982). The arenites and rudaceous arenites are coarse-grained, arkosic to subarkosic and locally micaceous (Jansen, 1982). Beds vary from 0,2-1m thick and trough cross-bedding occurs (facies St-Gt). About one metre above the basal contact on Gotha 517LR, a thin layer of well indurated blackish pebbly arenite occurs, which contains 19% iron oxides, 3,9% TiO_2, 3631 ppm zirconium as well as 562 ppm thorium and 59 ppm uranium.

The rudites are red (5R hue) and commonly highly arkosic. In the east they are massive with a feldspar-rich matrix and may sometimes consist totally of granite clasts (facies Gm). The pebbles are generally angular to rounded; at Zwartkop 742LR the occurrence of angular fragments of previously rounded clasts was noted. The rudites are typically pebbly although cobbles do occur. The only occurrence of boulders observed is at Gotha 517LR where small, matrix-supported boulders of up to 300mm were measured (facies Gms). In general the clasts are matrix-supported; where they are clast-supported, pressure brecciation is found. On Gotha 517LR clasts consist of quartzite and vein quartz. Poorly exposed trough cross-bedding is seen in light brownish grey (5YR6/1) granule rudites on Helderdaagsfontein 442LR (facies

Gt). There are five to six sets in a coset and the cosets are about two metres thick. They show an approximate palaeocurrent direction towards the northeast.

Massive lutites (facies Fm) and tuffaceous lutites (facies Ft) occur, particularly towards the east. The Ngwepe Tuff Member is a very fine-grained black facies developed at the base of the formation near Setlaole. It can only be followed for less than three kilometres and attains a thickness of seven metres (Jansen, 1982). An exposure of tuffaceous lutite on Goedgedacht 461LR contains 118ppm copper.

3.7 AASVOËLKOP FORMATION

The Aasvoëlkop Formation occurs in the southern and eastern parts of the basin and stretches westwards into Botswana. It overlies the Skilpadkop Formation in the south as well as various older rocks in the west where the Skilpadkop Formation is only sporadically developed. The Aasvoëlkop Formation is conformably overlain by the Sandriviersberg Formation. Jansen (1982) describes the Aasvoëlkop Formation as grading laterally into the Makgabeng Formation in the east. The Aasvoëlkop Formatiom reaches a maximum thickness of 600m (SACS, 1980), but is usually considerably thinner.

The formation coarsens upwards from arenaceous lutites at the base (Groothoek Mudstone Member) to arenites and rudaceous arenites higher up in the sequence. A rudite bed of 1,5m thick occurs near the type locality, approximately 150m from the base of the formation (Jansen, 1982, p. 36). The rocks generally have a high lithic content and most samples studied in thin section are classified as sublitharenite and subarenite (Fig. 2.1a).

The most common colour throughout the formation is mid-red although some of the fine lutites are orange or even greenish in colour. A feature of the lutite near the base of the succession in the southwestern part of the basin is mottling, and in places the lutite appears to be 'vesicular' (facies Fmv). Jansen (1970a, 1982, p. 38) records the following suite of minerals in these cavities: sericite, chlorite, iron oxides, quartz, epidote and zoisite. The present writer recorded barite, cordierite, calcite, sericite, quartz, smectite, kaolinite, chlorite and epidote in the cavities (XRD and SEM analyses). The lutites usually contain a small percentage of fine arenite. Common clastic particles are rhyolite, lutite, chert, devitrified glass and shard-like needle-shaped grains which have been replaced by clay. Epidote is almost universally present in the southwestern part of the study area and other cements which are common include calcite, haematite and chlorite. Symmetrical ripples with crests striking 092° occur on Groothoek 278KQ. De Vries (1969) also reports mudcracks and raindrop imprints.

The arenites are also usually of a mid-red colour and are typically fine-grained and immature. Textural inversions (Folk, 1968) occur where well rounded arenites contain more than 5% clay matrix. The arenites are sometimes horizontally laminated (facies Sh). Trough cross-beds of 20 to 120 mm thick occur in cosets of four to seven sets; the sets tend to increase in thickness upwards in the bed (facies St). The cross-beds give a palaeocurrent direction of west-southwest. Planar cross-beds occur in cosets of one to four sets, 0,1 to 0,3m thick (facies Sp). On Groothoek 278KQ, planar cross-beds towards the top of the sequence show contortions, especially in the upper part of the sets. In places these are simply overturned, but more commonly they show random contortions and in places cross-beds are almost totally destroyed. De Vries (1973) reports linguoid and cuspate ripple marks. The ten largest clasts measured in the rudaceous arenites at Hartebeestdrift 189KQ range from 17 to 23mm (peak current velocity: 1,3m/s). The clasts seen in this formation are mainly of quartz or quartzite, although granophyre, rhyolite, chert and lutite fragments have been identified. On Welgevonden 16KQ laminated and cross-bedded arenite contains disseminated pyrite. It is not clear whether the pyrite is syngenetic or diagenetic. Only 15 palaeocurrent measurements were made in the Aasvoëlkop Formation; they show random orientations (Fig. 3.11)

Lutites near the base of the formation fall into four facies: a massive lutite facies (Fm), a massive to laminated facies with 'vesicles' (Fmv), a laminated facies (Fh) and a massive facies with lutite intraclasts (Fmi). The arenites comprise facies St, Sp and Sh. Observed facies associations from the base of the formation upwards are: Fm, Fmv, followed by Fm, Fmv, Fl, Fmi, Gm, and higher in the sequence Fl, Fmi, Sh, Sp and St.

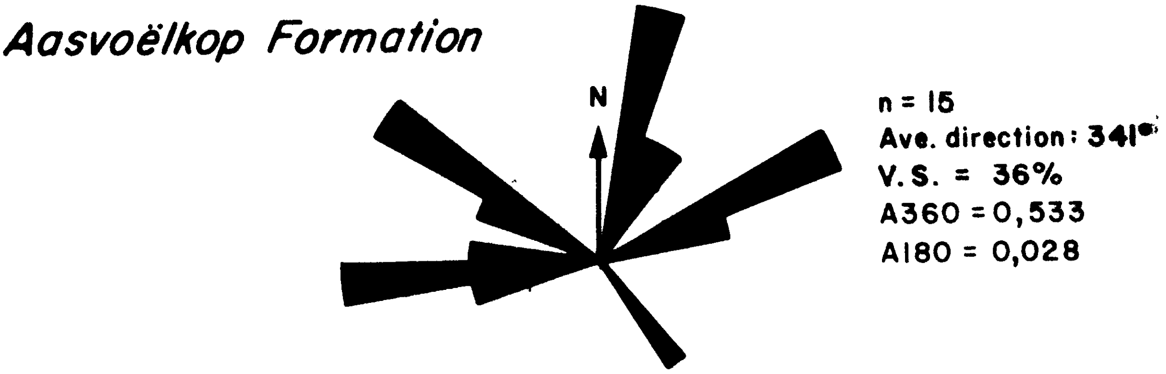


Figure 3.11: Rose diagram of palaeocurrent indicators – Aasvoëlkop Formation.

3.8 MAKGABENG FORMATION

The Makgabeng Sandstone Formation occurs in the eastern and northern areas of the Main Waterberg Basin. It has a conformable lower contact with the Setlaole and Skilpadkop Formations, where they are present. In the area of the Letaba rise it unconformably overlies granites of the Bushveld Complex. The Makgabeng Formation is conformably overlain by the Mogalakwena Formation; towards the north, however, it wedges out and is unconformably succeeded by the Mogalakwena Formation (Jansen, 1982). SACS (1980) gives a maximum thickness of 1000m for this formation, compared with Jansen's (1982) maximum of 1200m; he gives a thickness of only 380m for the type area. Towards the south and west the Makgabeng Formation grades into or interfingers with the Aasvoëlkop Formation.

The Makgabeng Formation consists of fine- to medium-grained arenites which display very large scale planar cross-bedding. Outcrops are uncommon except on the Makgabeng Plateau, which forms the type area. Jansen (1982) mentions occurrences of rudite and lutite; the latter have not been found in the present study. Only one sample was studied in thin section, being classified as a lithic arkose (Fig. 2.1a).

Arenites of the Makgabeng Formation are usually pale greyish red (5R5/2) in colour to very pale red (5R7/2) and they consist of subrounded to well rounded grains of quartz, feldspar (locally abundant) and rock fragments (rhyolite, lutite, chert, metaquartzite, jasper, quartzite). Minor muscovite and heavy minerals also occur. The arenites are moderately to well sorted and usually have a modal grain size of medium sand. The arenites are usually devoid of matrix and have either small voids or intergranular silica cement (Meinster and Tickell, 1975). The most common sedimentary structure seen is very large scale cross-bedding. The cross-beds are planar wedge-shaped, and from a distance many of them exhibit curved transverse sections (facies Spe). The individual cross-beds are 150-500mm thick and are internally laminated with 10-15mm thick laminae; cross-bed sets are usually 8m or more in height. Sets may be overlain by further cross-beds, or more rarely, by a massive arenite of about 1m thick (facies Sme).

FIGURE 3.12 Very large scale cross-bedding in the Makgabeng Formation, on Mont Blanc 328LR on the Makgabeng Plateau. Marked tree is ±5m tall.

These cross-beds are best seen on the Makgabeng Plateau (Fig. 3.12), but this area is not easily accessible and they are also well exposed on Morgenzon 138LR and the adjoining farms. At Morgenzon the northernmost of the two best exposures has been tilted to vertical by the Melinda Fault and it presents an excellent cross-section. Because of their size these structures are not easily seen in the other exposures that occur in the northwestern part of the basin. Other structures seen, chiefly in the more southern areas, are symmetrical and assymmetrical ripples, interference ripples, channels (facies Smc), adhesion warts caused by wind blowing dry sand over a wet surface (Reineck and Singh, 1975, p. 56), current lineation, desiccation cracks and problematic traces. Asymmetrical ripples on Bonne Esperance 356LR in the type area, have a wavelength of 8-9cm and an amplitude of 2mm. The crest to trough lengths are about 3 and 6cm. The current direction forming the ripples was towards 265°, which coincides approximately with local foreset dip azimuths. In places (eg. Goedgelegen 194LR) reduction spots occur; these are often formed around a dark central spot. A detailed description of bedforms occurring in the type area is given in Meinster and Tickell (1975).

The rose diagram shown in figure 3.13 shows the rather random palaeocurrent data obtained from the Makgabeng Formation. Even locally this formation displays multimodal palaeocurrent directions, which probably reflect its depositional mode.

The problematic traces mentioned above occur on a small exposure of ripple-marked arenite, on the northeastern side of the main road from Potgietersrust to Marken, as it traverses the farm Verdoornsdraai 808LR. Structures present at this exposure include ripples, interference ripples, desiccation cracks and adhesion warts (this assemblage of structures has been classified as facies Sl). Mudcracks were reported from Makgabeng by De Bruiyn (1971a, p. 6).

The traces are generally sinuous, rarely branching and sometimes

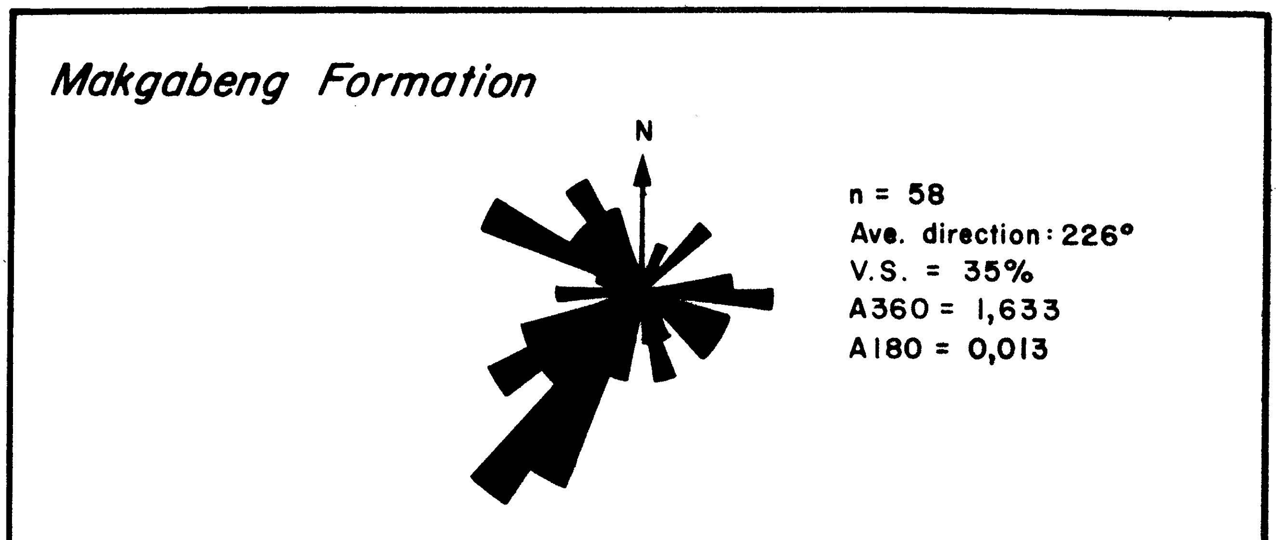


Figure 2.6. Rose diagram of palaeocurrent indicators – Makgabeng Formation.

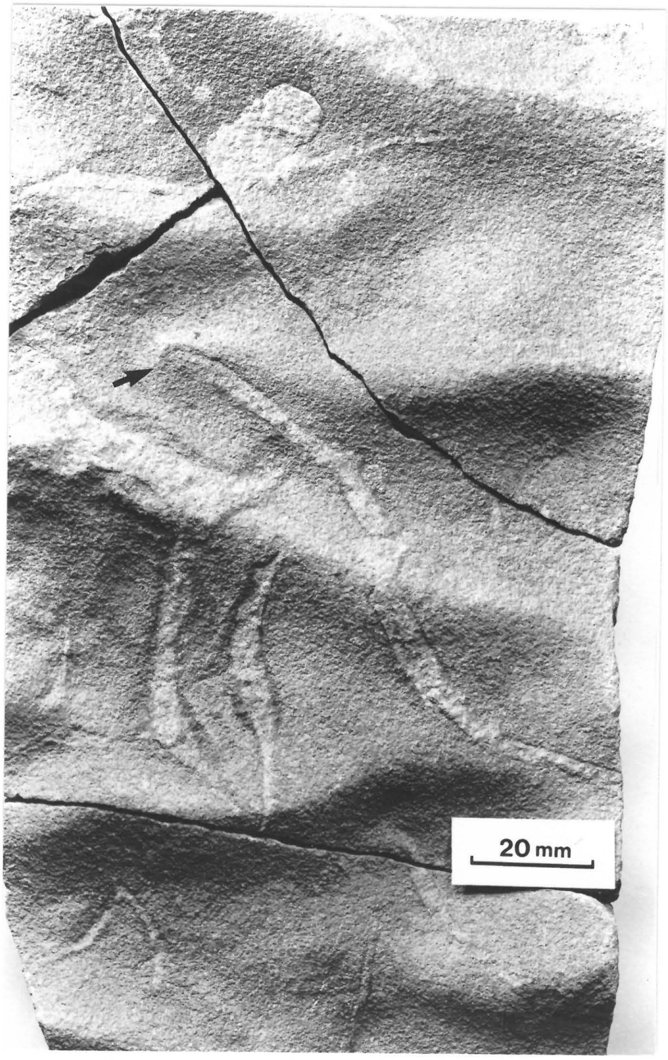


Figure 3.14 Showing a trace which can be followed over a ripple crest. Notice the 'nudge' at the end of the trace.

have dark coloured levee-like ridges along their edges, similar to Glaessner's (1969) Form B. Although these traces appear at first glance to belong to the *Manchuriophycus* (Hantzschel, 1975) or *Rhysonetron* type (Hoffman, 1971), there are certain distinct differences. The traces at the Verdoornsdraai occurrence are not confined to the troughs of the ripple marks, but may extend from one trough to the next at an oblique angle to the crest (Fig. 3.14). One such trace also shows a nudge-like mark at its abrupt end. This is distinctly different to some other traces in this occurrence, as well as to the *Manchuriophycus* and *Rhysonetron* types, which seem to show tapering ends more reminiscent of cracks. In some cases traces are seen to intersect at angles close to 90°.

There is a gradation of these traces into mudcrack-like structures which appear on a flat surface a few metres to the northwest of the ripple-marked surface. A similar feature is described from the Beltian Quartzite in Montana by Wheeler and Quinlan (1951, Fig.2).

Thin section study reveals that some of the narrower traces may be described as similar to the 'epichnial grooves' of Martinsson (1970). The wider traces show a morphology similar to that described by Wheeler and Quinlan (1951, Fig.5), as being due to cracking of the sediment (Fig. 3.15).

Facies associations encountered in this formation are: very large scale planar cross-bedded arenites (facies Spe) together with minor massive arenite beds (facies Sme) and arenite with large assymmetrical ripples (facies Sre); facies Spe together with arenite exhibiting channels (facies Smc) and interference ripple marks; and in the Verdoornsdraai area, facies Sl - no facies Spe was seen in close relationship with these rocks, although it does occur a few kilometers away in exposures in the Mokamolo River.

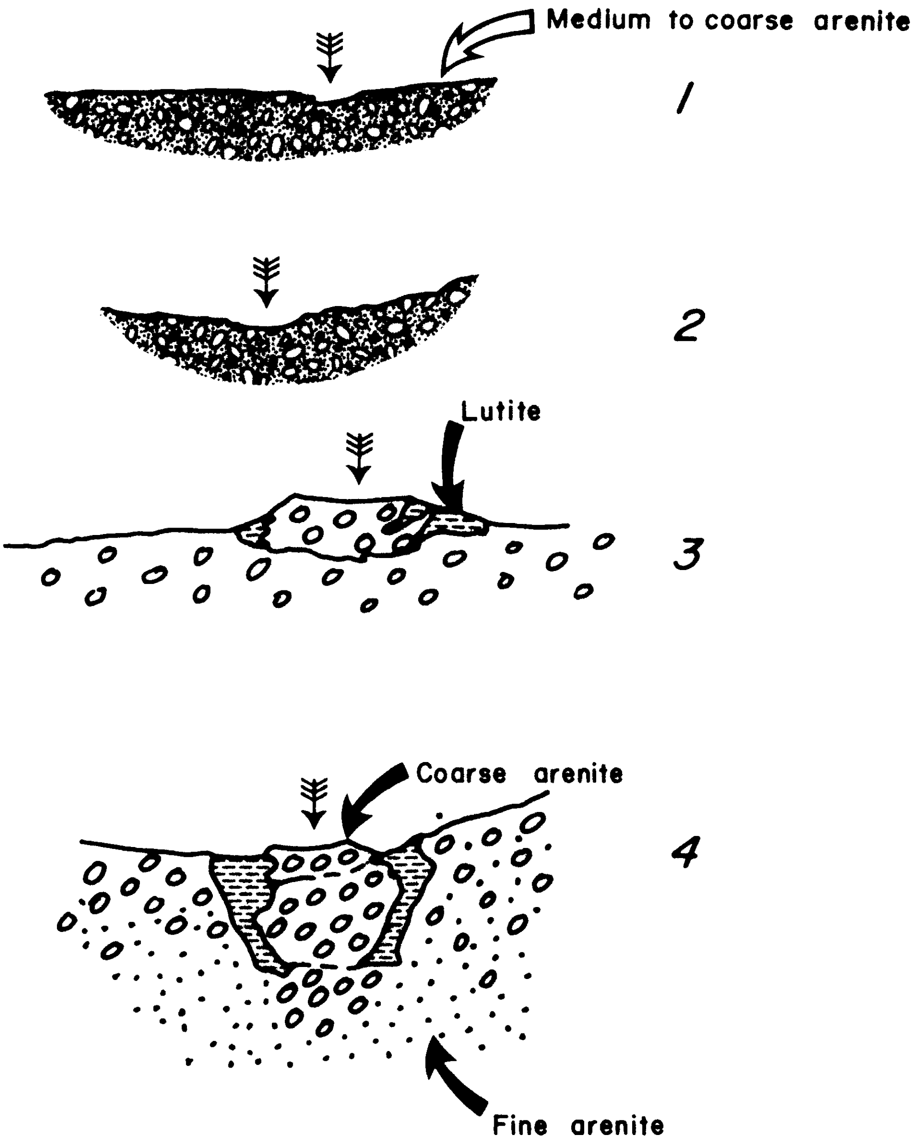


Figure 3.15: Showing cross-sections of trace-like structures (1&2) and wider crack-like structures (3&4). There appears to be a gradation between these two types.
Scale: approx. 2X

3.9 SANDRIVIERSBERG FORMATION

The Sandriviersberg Formation is confined to the southern and southwestern parts of the Main Waterberg Basin where it is transitional into the underlying Aasvoëlkop Formation. The upper contact is gradational into the overlying Cleremont Formation. De Bruiyn (1971a), however, reported a small fault which intersects the Sandriviersberg Formation but does not displace the Cleremont Formation. Towards the northeast the Sandriviersberg Formation grades laterally into the Mogalakwena Formation. The division between the Mogalakwena and Sandriviersberg Formations is an abritary one (Jansen, 1982, p. 43), taken along a line in the southeastern and northwestern parts of the basin (Fig. 1.2). SACS (1980) gives the thickness of the Sandriviersberg Formation as 1250m; Jansen (1982) supports this and further points out that this thickness is more or less constant throughout the present-day exposure of the formation.

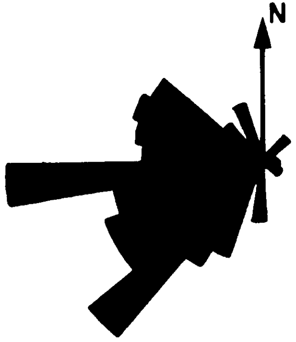
The Sandriviersberg Formation consists of medium- to coarse-grained arenite, granule-rich arenite and granule rudite, with interbedded pebble rudites; the formation becomes progressively coarser towards the northeast where it grades into the Mogalakwena Formation. The rudaceous arenites and arenites show well developed trough and planar cross-bedding.

The arenites and rudaceous arenites of the Sandriviersberg Formation can usually be described as sublitharenites or litharenites. The specimen studied in thin section proved to be a litharenite (Fig. 2.1a). Common lithic fragments are metaquartzite and rhyolite. Where this unit grades into the Cleremont Formation, the rock becomes quartzarenite. The typical hue is mid yellow-red, with light brown being the most characteristic single colour. Cross-bedding is universal with trough cross-bedding being the most plentiful (facies St), although planar cross-bedding (facies Sp) is locally more abundant (Fig. 3.16). Individual cross-laminae thicknesses range from 2 to 30mm and trough cross-bed set thickness average 135mm (standard deviation=104, n=125). Planar cross-beds have a mean set thickness of 113mm (standard deviation=89, n=17) and large scale trough cross-beds have sets in the order of 500mm in thickness (facies Sxt). Straight crested asymmetrical ripples are poorly exposed at a few localities; ripple cross-lamination is sometimes seen in the upper parts of beds, mostly overlying tabular planar cross-bed sets.

The Sandriviersberg Formation shows a far better grouping of palaeocurrent indicators than any other formation in the Waterberg Group (Fig. 3.17, 3.18). The A_{360} value for trough cross-bedding in figure 3.18 is highly significant at the 0,001 level of significance, indicating a meaningful grouping of the data into a single hemisphere, whilst the A_{180} value shows that there is only one chance in ten that this sample is from a population which has a multiple mode. This indicates that the average palaeocurrent reading is a reasonable estimate of the palaeoslope at the time of deposition. The vector strength is high. Figure 3.19 shows directions indicated by planar cross-beds and reveals a weakly developed multimodal grouping.

FIGURE 3.16 Planar cross-bedded, granule-rich arenite from the Sandriviersberg Formation at Bulsfontein 139 KQ.

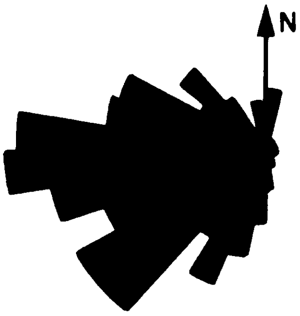
Sandriviersberg Formation



n = 211
Ave. direction: 255°
V.S. = 72%
A360 = 21,804
A180 = 0,557

Figure 3.17. Rose diagram of palaeocurrent indicators - Sandriviersberg Formation.

Sandriviersberg Formation — Trough cross-beds

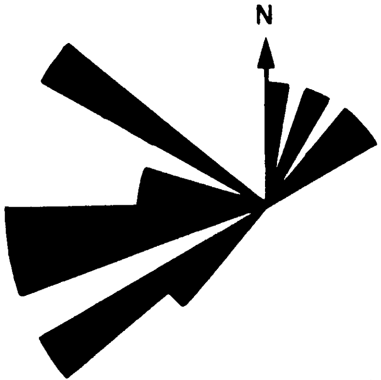


n = 194
Ave. direction: 253°

V.S. = 74%
A360 = 21,625
A180 = 0,499

Figure 3.18. Palaeocurrent directions indicated by trough crossbeds - Sandriviersberg Formation.

Sandriviersberg Formation - Planar cross-beds



n = 15
Ave. direction: 287°

V. S. = 54%
A360 = 0,813
A180 = 0,073

Figure 3.19. Palaeocurrent directions indicated by planar crossbeds - Sandriviersberg Formation.

Local lenses and washes of small to large pebbles are common, especially towards the northeast where the Sandriviersberg Formation grades into the Mogalakwena Formation. The most common hues in the rudaceous beds are browns and reds of the segment 5YR to 5R of the colour sphere. Clasts are equant and sub-rounded to well rounded. Imbrication and length orientation are poorly developed, probably because of the equant nature of the clasts (facies Gm). Average grain size for the ten largest clasts at each of fifteen localities ranges from 7,0 to 48,2mm; this results in a calculated peak palaeocurrent velocity (Baker, 1973) of 1,97m/s. The geographical distribution of these pebble beds with their respective average sizes can be seen in figure 3.20. They do not show any distinct areal trend and are similar to the average sizes recorded in adjacent parts of the Mogalakwena Formation. A plot of the sphericity versus coefficient of flatness for clasts from this formation as well as from the correlated Mogalakwena Formation is presented in Figure 3.20a. Stratten (1975) shows that the mean value of samples from fluvial deposits should always plot above the coefficient of 45 for flatness and above a value of .65 for sphericity. He further shows that only very few plots below a sphericity of .55 should occur in fluvial deposits. Clast types include vein quartz, metaquartzite, jasper, chert, iron-formation and rhyolite.

Lutites are rare in this formation, occurring chiefly as drapes of a few millimetres in thickness (facies Fm). The lutite content increases towards the northeast where the Sandriviersberg Formation grades into the Mogalakwena Formation.

The most common facies associations in the Sandriviersberg Formation are: St occurring by itself; St with lesser Sp and minor Sxt; Sp with subsidiary Sxt and St; and especially in the areas close to the Mogalakena Formation, but also rarely elsewhere, facies St together with Sxt and Gm. Facies St commonly overlies facies Sxt or Sp where they are present.

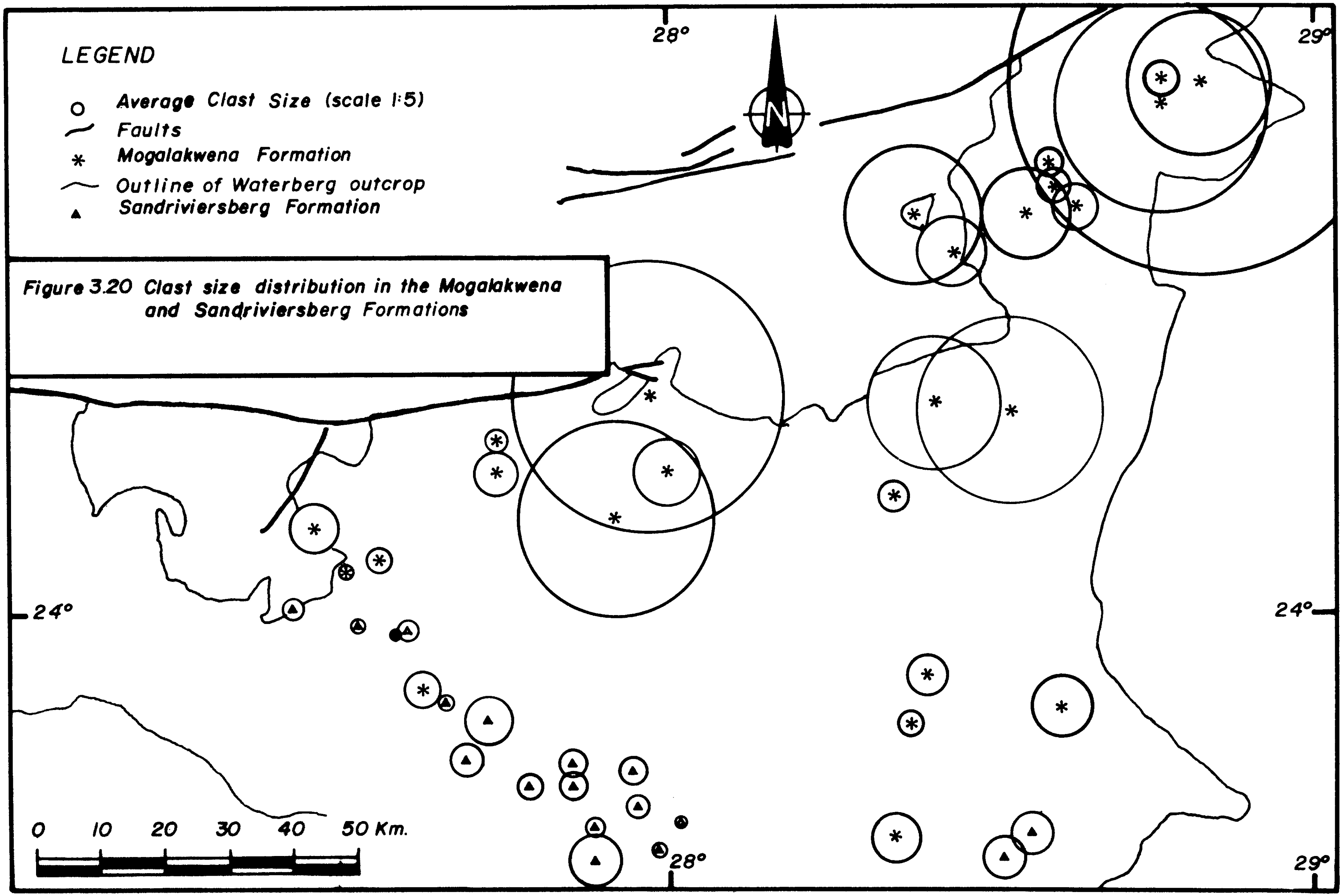


Figure 3.20 Clast size distribution in the Mogalakwena and Sandriviersberg Formations

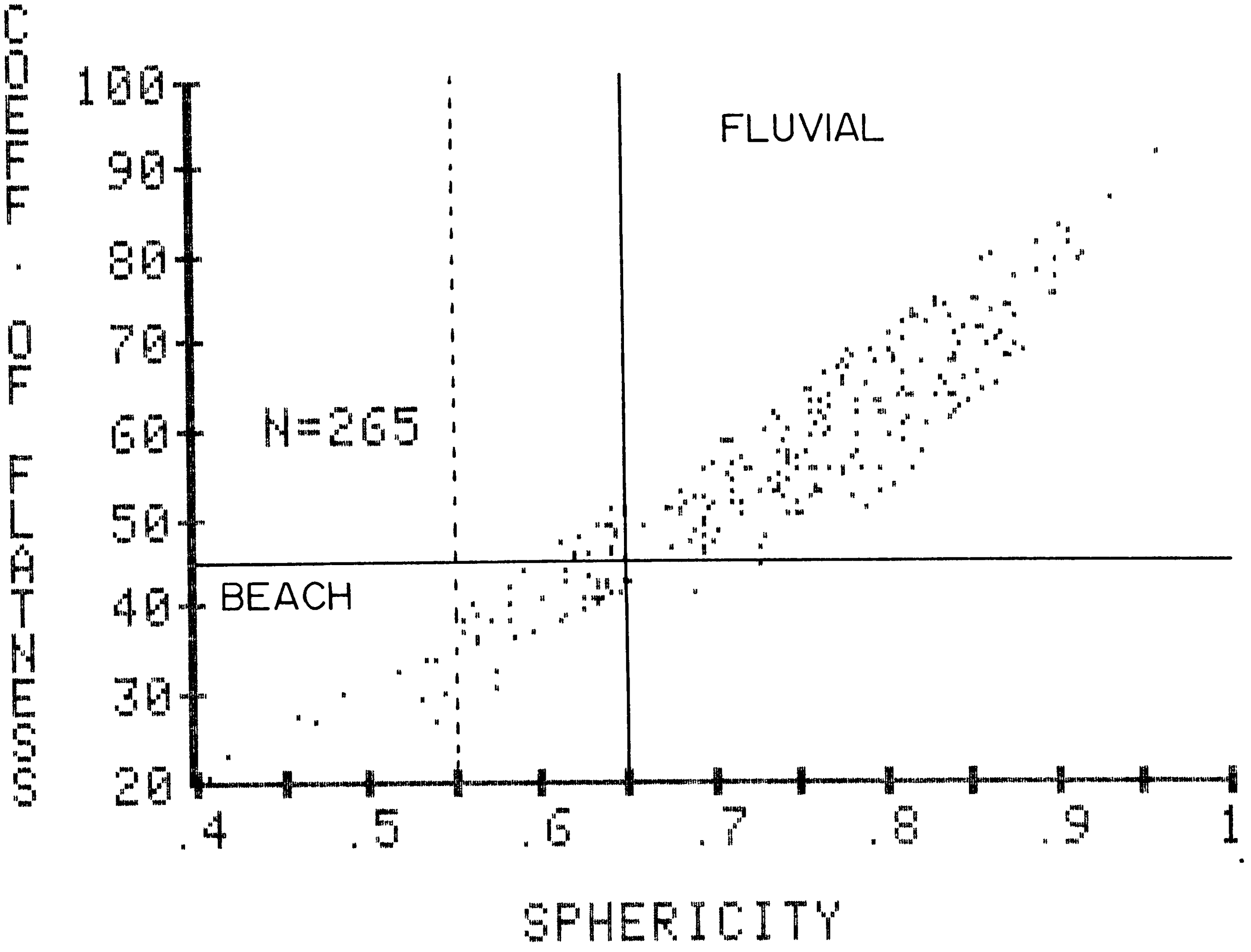


FIGURE 3.20a Plot of coefficient of flatness versus sphericity for clasts from the Mogalakwena and Sandriviersberg Formations.

3.10 MOGALAKWENA FORMATION

The Mogalakwena Conglomerate Formation is situated in the northeastern and northern reaches of the Main Waterberg Basin. It has a conformable, transitional lower boundary with the Makgabeng Formation. Where the Makgabeng Formation wedges out, the Mogalakwena Formation unconformably overlies pre-Waterberg rocks. The upper boundary is a conformable, transitional contact with the overlying Cleremont Formation (Tickell, 1975). Towards the south and southwest the formation grades laterally into the Sandriviersberg Formation, but the boundary is poorly defined (Tickell, 1975). The Mogalakwena Formation is 1250 to 1500m thick, but in the Steilloopbrug area only 120m is preserved (Tickell, 1975).

The Mogalakwena Formation consists of granule-rich arenites and granule rudite with pebble washes and interbedded pebble rudites. The rudites are subordinate in volume to the arenites (Tickell, 1975). Coarse rudites are common, especially towards the north. Three of these rudite zones are named members, the Tafelkop Conglomerate Member, the Marken Conglomerate Member and the Sessalong Conglomerate Member.

Arenites, granule-rich arenites and pebbly granule arenites, which can usually be described as litharenites or sublitharenites (Fig. 2.1a), make up the bulk of the Mogalakwena Formation. They commonly have a red or yellow-red hue (with a high to low value and a low to medium chroma). The arenites are generally granule-rich and poorly sorted, with a high percentage of lutaceous matrix. The grains are usually subangular to subrounded and equant. Cross-bedding is universally present with trough cross-bedding (facies St, Gt - Fig. 3.21) being the most plentiful, although planar cross-bedding may be locally more abundant (facies Sp, Gp). Individual cross-stratum thicknesses range from 2 to 34mm and trough cross-bed set thicknesses have a mean value of 124mm (standard deviation 67mm, n=101). Trough cross-beds occur in cosets of 2 to 6 sets.

FIGURE 3.21 Large scale trough cross-bedding in pebbly granule rudite of the Mogalakwena Formation, on Rhenosterhoek 582LR

Large-scale trough cross-beds with a mean set thickness of 476mm (standard deviation=244mm, n=10) also occur. The trough cross-beds typically occur within spoon shaped scours with lengths of 1,5 to 5m and widths of 1 to 2m. The average palaeocurrent direction derived from all structures for the Mogalakwena Formation is 244° (Fig. 3.22). The average direction for trough cross-beds is 254° (Fig. 3.23) and that derived from very large trough cross-beds is 253° (Fig. 3.24). The vector strength is high (69% to 80%) showing them to be consistent palaeocurrent indicators, whilst the A_{360} value indicates that there is less than one chance in a thousand that the population from which these samples was drawn has a uniform distribution around a circle (Dale and Ballantyne, 1980). Planar cross-beds show a more random pattern of palaeocurrent directions (Fig. 3.25), as do imbrication and long axes measurements (Figures, 3.26 and 3.27). Planar cross-beds have been shown to have a greater dispersion than trough cross-beds (High and Picard, 1974; Cant and Walker, 1976; Miall, 1977; Vos and Eriksson, 1977). Although only a few planar cross-beds were measured in this study, the trend seen is in agreement with the results of these previous workers.

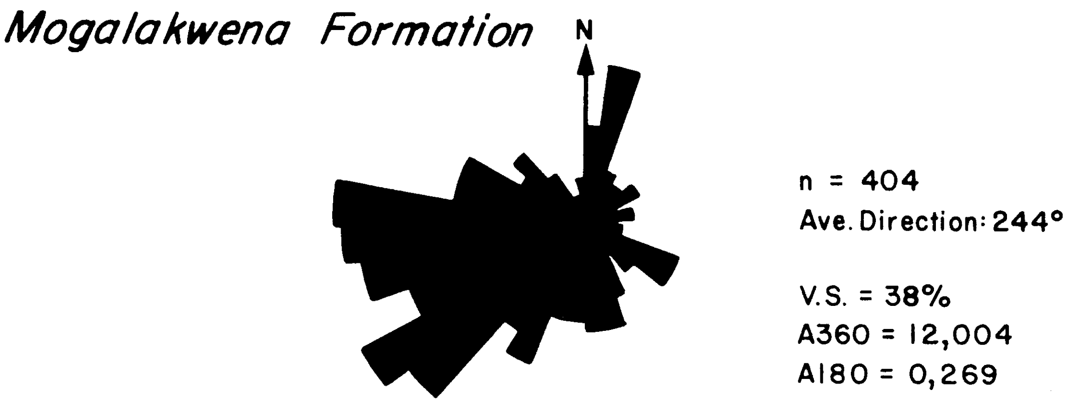


Figure 3.22 Rose diagram of palaeocurrent indicators - Mogalakwena Formation.

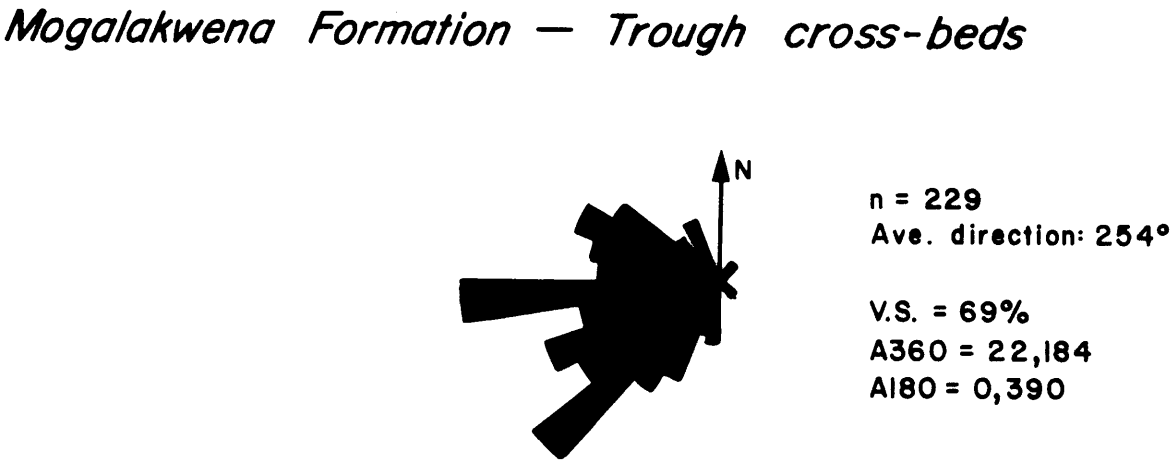


Figure 3.23 Palaeocurrent directions indicated by trough cross-bedding Mogalakwena Formation.

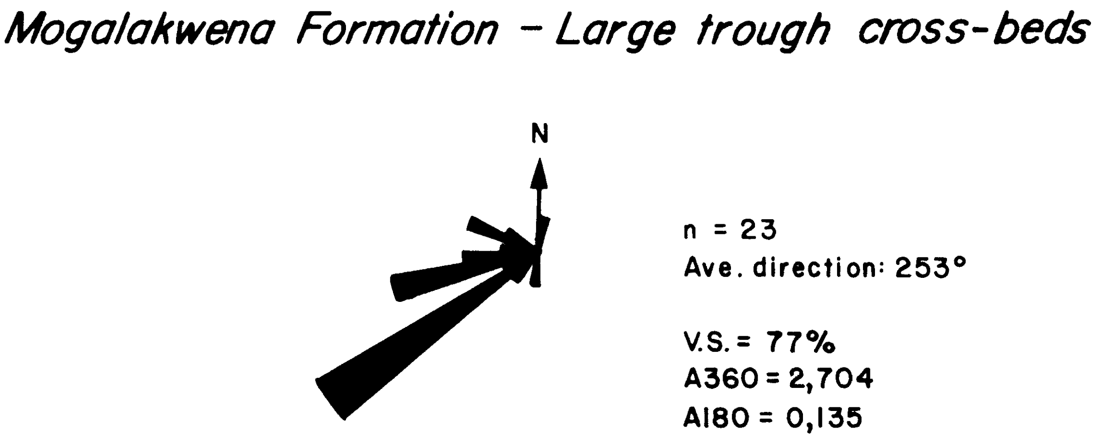


Figure 3.24 Palaeocurrent directions indicated by large-scale trough cross-bedding Mogalakwena Formation.

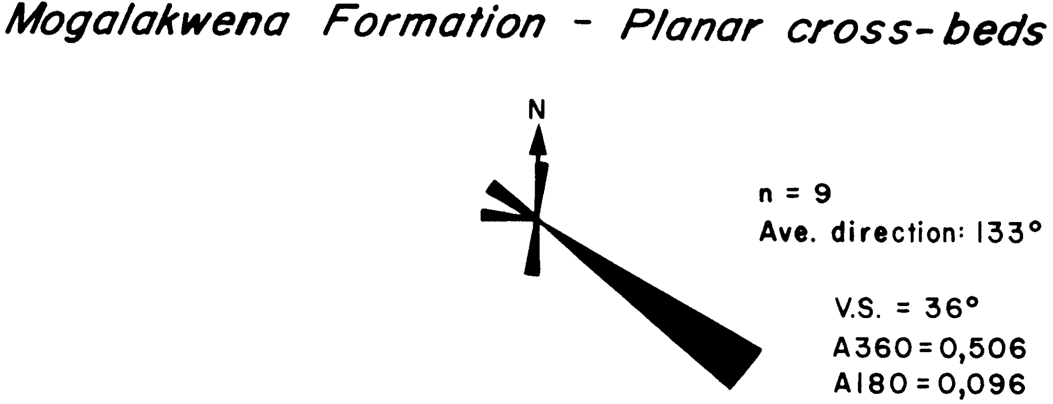


Figure 3.25 Palaeocurrent directions indicated by planar cross-bedding Mogalakwena Formation.

In an exposure of the Mogalakwena Formation on Riebeek West 539LR, planar cross-beds (Fig. 3.28) can be seen on two sides of a paleaochannel, dipping towards each other and oriented at about 90° to immediately adjacent trough cross-beds outside the channel. Heavy minerals occur in the channelway.

Local washes and lenses of small to large pebbles are a common phenomenon in this formation. More extensive rudite beds also occur and are on average 3m thick (Tickell, 1975). Figure 3.20 shows the average size of the clasts at various localities for the Mogalakwena and Sandriviersberg Formations. There appears to be an increase in the average size of clasts in the Mogalakwena Formation towards the northern basin edge. In the transition zone with the Sandriviersberg Formation there is, however, no apparent difference in average clast size between the two Formations. On a more local scale, Tickell (1975, p. 85) points out that the Sessalong Conglomerate Member in the northeast shows a gradation over some 10 to 30km from boulder rudites in the extreme north to cobble rudites towards the southwest. De Bruiyn (1971b, p. 7) points out that there is a general increase in coarseness of the sediments towards the north. Clasts are equant and subrounded to well rounded; in places they show pressure marks due to pressure solution and possible grain restructuring within clasts caused by the very high pressures developed on clast-clast contacts during burial.

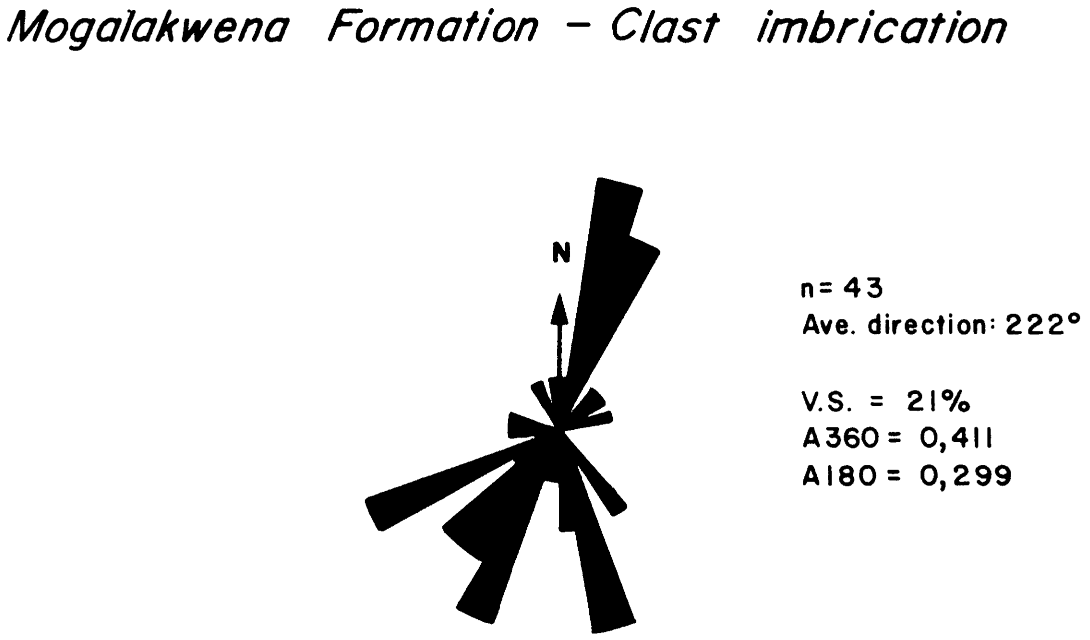


Figure 3.26 Palaeocurrent directions indicated by imbrication - Mogalakwena Formation.

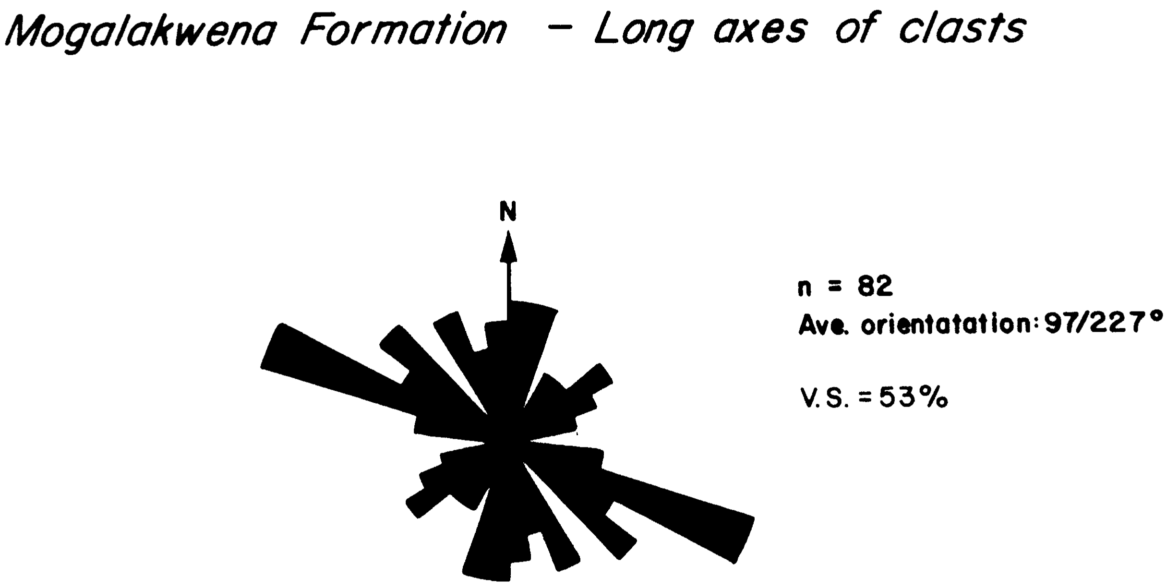


Figure 3.27 Palaeocurrent directions indicated by clast long axes - Mogalakwena Formation.

FIGURE 3.28 Large-scale planar cross-bedding dipping into palaeochannel (upper right) in the Mogalakwena Formation. Diagonal distance from top left to bottom right of photograph is about 8m.

Imbrication and length orientation are not well developed and this is very probably the result of the equant shape of the clasts. Figures 3.26 and 3.27 show that, on average, the imbrication direction is at approximately right angles to the clast long axes directions measured. This indicates the existence of a-transverse, b-imbricate (a(t):b(i)) type cross-bedding, characteristic of normal fluvial processes (Harms *et al.*, 1975). Figure 3.20a shows the plot of sphericity vs. the coefficient of flatness for clasts from the Mogalakwena and the Sandriviersberg Formations. Stratten (1975) shows that the mean value of samples from fluvial deposits should always plot above the coefficient of 45 for flatness and above a value of .65 for sphericity. He further shows that only very few plots below a sphericity of .55 should occur in fluvial deposits.

The rudites may be clast-supported or matrix-supported (facies Gm, Gms). Clast types include vein quartz, metaquartzite, fuchsitic quartzite, arenite, rudite, schist, quartzite, chert, jasper and iron-formation. The average grain size of the 10 largest clasts measured at forty localities throughout the formation ranges from 13,5mm to 352,0mm, which indicates peak current velocites of up to 5,33m/s (Baker, 1973).

Lutites as such are restricted to clay drapes at the tops of beds; these are quite common in the Mogalakwena Formation, and are usually very thin, being less than 5mm in thickness (facies Fm). The lutite layers are typically pale pink in colour. The best exposures showing lutite drapes at bed tops are to be seen in the cutting south of Ellisras on the Vaalwater to Ellisras road. Besides these layers, lutite is a common matrix constituent of the other rock types.

The most common facies associations seen in this formation are Gms, Gm, Gt, St, Gp, Fm in the northeast, St, Gt, Sp, Gms, Fm further south and finally St, Gt, Sp, Gm as it grades into the Sandriviersberg Formation to the southwest.

3.11 CLEREMONT FORMATION

The Cleremont Sandstone Formation is developed in the central portion of the Main Waterberg Basin where it overlies the Sandriviersberg and Mogalakwena Formations with a conformable and gradational contact. The upper contact is likewise a conformable, transitional one with the Vaalwater Formation. Both boundaries are poorly exposed as is most of this formation. The Cleremont Formation is consistently 125m thick (Jansen, 1982).

The Cleremont Formation typically consists of medium-grained, rounded to well rounded quartzarenites. The most common colours in this formation are light to dark greyish mid red (5R2-8/2). Uncommon layers of rounded pebbles occur, as well as rare isolate pebbles. Predominant bedforms are small to large scale planar cross-beds (facies Sp, Sxp, Fig. 3.29), small to large scale trough cross-beds (facies St, Sxt) and horizontally laminated beds (facies Sh). The cross-beds are often deformed due to soft sediment slumping.

Deformation of cross-beds in the Cleremont Formation varies from mild oversteepening of cross-beds to total destruction of the internal

FIGURE 3.29 Very large scale planar cross-beds in the Cleremont Formation on Voorstandfontein 622LQ.

laminae. De Bruiyn (1971a, p. 9) interpreted these structures as being due to shock movements during basin subsidence. The very large scale planar cross-beds (facies Sxt) have inclination angles of 15-31° and an average set thickness of 481mm (standard deviation 205, n=9). Trough cross-beds (facies St) have a set thickness of 66mm (standard deviation 59mm, n=22). Individual laminae in the trough cross-beds are typically 2 to 30mm thick and those of the very large planar cross-beds are 10 to 30mm thick. The trough cross-beds are grouped in cosets of three to four sets and the small scale planar cross-beds are grouped in cosets of five to twenty sets. Reactivation surfaces are seen at several localities. Heavy minerals occur on the farm Kaffershoek 23KR in a fine-grained laminated arenite (facies Shhm).

Combined cross-bedding readings show a multimodal palaeocurrent pattern (Fig. 3.30) in the Cleremont Formation. Trough cross-beds exhibit palaeocurrents towards the southwest, west and northwest (Fig. 3.31). In both cases the A_{360} value is significant at the 95% level which shows that the readings are meaningfully confined to a semi-circle, but there are clearly several modes within that semi-circle. Planar cross-beds show two

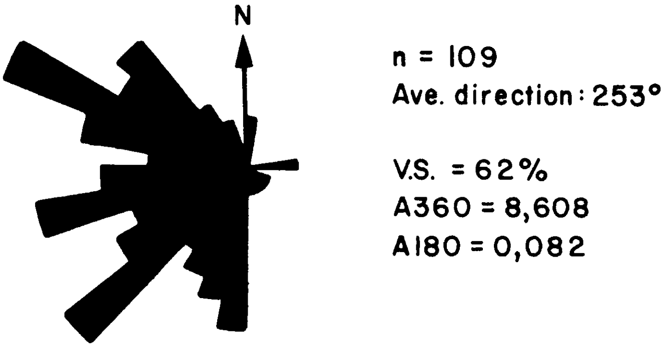


Figure 3.30 Rose diagram of palaeocurrent indicators - Cleremont Formation

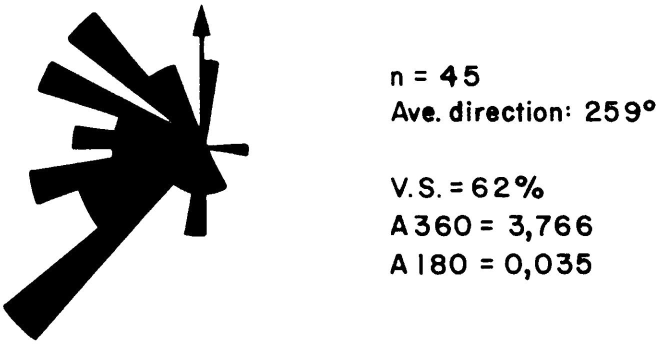


Figure 3.31 Palaeocurrent directions indicated by trough cross-bedding - Cleremont Formation.

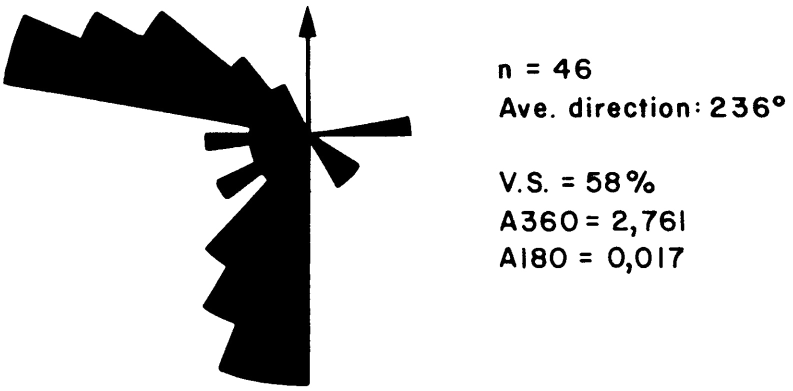


Figure 3.32 Palaeocurrent directions indicated by planar and large-scale planar cross-beds — Cleremont Formation.

distinct modes towards the south-southwest, and towards the west-northwest (Fig. 3.32). Because of their rarity, pebble sizes were only measured at one locality, where the average size of the ten largest clasts is 17,1mm. Pebbles are associated with both trough and planar cross-beds, often occurring in concentrations on specific cross-laminae.

Resedimented mud clasts and, in places, phosphate clasts also occur in the arenites (facies Si). The phosphate clasts consist chiefly of fluorapatite (XRD); they contain copper and lead as well as rare earth elements (SEM analysis).

Lithofacies defined in this formation are: well sorted, well rounded trough cross-bedded to large trough cross-bedded quartzarenites (St, Sxt), and a planar cross-bedded (Sp) and very large-scale planar cross-bedded quartzarenite (facies Sxp) which commonly show soft sediment slumping. Cross-bed sets are sometimes topped with small scale cross-lamination. A minor occurrence of a horizontally laminated, fine-grained, well-sorted heavy mineral placer (facies Shhm) may have environmental significance. Facies Si occurs chiefly toward the southern part of the present day outcrop.

3.12 VAALWATER FORMATION

The Vaalwater Formation is developed in the central part of the Main Waterberg Basin where it overlies the Cleremont Formation with a conformable, gradational contact. The formation attains its maximum thickness of 475m near Visgat and Dorset north of Vaalwater (Jansen, 1982). The Vaalwater Formation is the uppermost formation in the Waterberg Group, and consists of feldspathic arenites and lutites. A sample studied in thin section proved to be a subarkose (Fig. 2.1a). Rocks of the Vaalwater Formation are generally greyish red to greyish in colour with the most common range being 5R2-7/2-4.

FIGURE 3.33 Typical exposure of the massive lutaceous to fine-grained arenaceous facies (Fsc) seen in the Vaalwater Formation. From Middelboomfontein 60KR.

The feldspathic arenites are fine- to medium-grained, rounded to well rounded and well sorted, although less mature lutaceous arenites also occur locally. The feldspars consist chiefly of plagioclase and orthoclase, with lesser perthite and microcline (De Bruiyn, 1971a). Most of the Vaalwater outcrop encountered in this study consists of poorly exposed, jointed, lutaceous arenite and lutite, which commonly display horizontal lamination with laminae of 10 to 50mm thick (facies Fsc - Fig. 3.33). Trough cross-bedding, ripple marks and overturned cross-bedding are reported by De Vries (1969, 1973). Jansen (1982, p. 50) as well as De Vries (1969, 1973) report convolute lamination in the Vaalwater Formation.

3.13 INTERPRETATION AND PALAEOENVIRONMENTAL ANALYSIS

3.13.1 General

Intrusion of Bushveld granites was penecontemporaneous with the earliest Swaershoek sedimentation (Du Plessis, 1972a, p. 86; Coertze *et al.*, 1977, p. 150). The Swaershoek Formation and its correlate, the Wilgerivier Formation, show a greater similarity in geographic distribution with the Rooiberg Group than with overlying Waterberg Group sedimentary rocks (Fig. 3.3; see also Van Biljon, 1976, p. 165 and Coertze *et al.*, 1977 p. 155). The Swaershoek and Wilgerivier Formations are also completely confined within the limits of the Transvaal Basin (Coertze *et al.*, 1977, p. 154). The genesis of the Nylstroom Basin has been interpreted as being due to upper crustal warping, whilst the Alma trough has been interpreted as the result of deep-seated faulting (Jansen, 1975a; Coertze *et al.*, 1977). Together with the difference in distribution of these sedimentary rocks, this tectonic contrast in basinal development leads the writer to believe that the Swaershoek and Wilgerivier Formations may well belong to the terminal phase of sedimentation of the Transvaal Sequence.

The Main Waterberg Basin evolved as a continental, fault-bounded basin in the northern part of the Kaapvaal Craton. The Murchison Lineament, which extends past the southern edge of the basin appears to be important in its evolution. This deep-seated linear structure developed deep basins on the southern side before and during the emplacement of the Bushveld granite (Crockett, 1971; Button, 1972; Crockett and Jones, 1975; Tyler, 1979; Jansen, 1982); it also developed a deep (post-Bushveld granite) trough on the northern side (Coertze *et al.*, 1977; Jansen, 1975a, 1982). The lineament is of great antiquity (Button, 1972; Jansen, 1975a, 1982) and has remained active during Karoo and recent times (Rust, 1975; Van Biljon, 1976). The Murchison lineament can thus be interpreted as a long-lived, fundamental fault system.

Alma sedimentary rocks west of Gatkop show rapidly varying clast composition parallel to the fault; in one area rhyolite clasts are the most abundant, but since rhyolite does not occur in any significant quantity directly across the fault, the question of the provenance of the rhyolite is raised. In the Gatkop area remnants of the Swaershoek Formation lie directly on the Bushveld Granite (Meinster, 1975). The possibility that the rhyolites are not present because they were eroded to provide detritus for the Alma Formation is thus precluded, and another source of rhyolite must be found. Since rhyolite is abundantly present to the east, lateral movement may have taken place on the Murchison lineament. Thus the fault system forming the Murchison lineament is interpreted to be of strike slip character, with an overall left lateral movement since Alma times.

Quartz lamellae described in Chapter 2 are interpreted to be due to transpressive stress along this fault zone, whilst later transtensile forces led to the development of the Alma trough.

"Red beds" are coloured by haematite and have hues of 5R and 10R (Turner, 1980, p. 1). In the Waterberg sedimentary rocks these hues make up 67 percent of the colours recorded. The occurrence of this red pigmentation indicates that the sediments were formed in an oxidizing environment (Berner, 1969; Turner, 1980). It does not, however, give any indication of the palaeoclimate, beyond indicating that the sediments were deposited within 30° of the equator (Berner, 1969; Walker, 1974; Turner, 1980).

Turner (1980) points out that ancient red beds are considered to be almost exclusively diagenetic in origin. The mechanism of formation is postulated as being intrastratal solution of detrital iron silicates, especially in coarse-grained permeable sediments. He further states that much of the colouring matter could be due to alteration of titanomagnetites, which are common in red beds. In the present study of the Waterberg Group, an SEM investigation indicated that titanomagnetite and ilmenite are common constituents of these rocks.

An authigenic-diagenetic origin for the colouration in Waterberg sediments was postulated by Eriksson and Vos (1979), who suggested that iron from detrital orthoclase, pyroxene and lithic rhyolite fragments imparted the colour to the rocks. They state that 'magnetite', derived from the 'Bushveld Mafic Phase , is stable in the Waterberg sediments and as such could not have acted as a source of iron. The writer agrees with their basic authigenic-diagenetic hypothesis. However, the breakdown of titanomagnetite and ilmenite to produce anatase, as well as the bleaching of biotite, as observed in thin sections, probably supplied much of the iron to be converted to haematite, thereby leading to the red colouration of the rocks. More intense colours are commonly observed on cross-beds containing opaque (iron titanium oxide) minerals; these are particularly noticeable in the Sandriviersberg and Mogalakwena Formations (Jansen, 1982).

Jansen (1982, p. 20) describes the Swaershoek Formation as having been formed by the reworking of fluvial deposits under littoral conditions. The present writer agrees in principle with this concept and proposes that the environment of deposition was a fan-delta complex. The Alma and upper Sterkrivier Formations, on the other hand, consist largely of immature arkoses, and rudaceous sedimentary rocks more reminiscent of proximal to medial fanglomerates. These formations form the base of the first upward-fining sequence seen in the Main Waterberg Basin. The overlying sedimentary rocks contain evidence of finer sediments interpreted to have been deposited in succeedingly more distal environments, until a major influx of sediment from the northeast covered the entire basin (and perhaps beyond) with coarser sediments (the Mogalakwena and Sandriviersberg Formations). After this sediment influx the sea transgressed onto previously subaerial areas and the Cleremont and Vaalwater Formations were deposited.

3.13.2 The Swaershoek and lower Sterkrivier Formations

The Swaershoek and its correlate the lower Sterkrivier Formation have been interpreted by Jansen (1982, p. 20 and 31) as having been deposited in shallow water, possibly with tidal influences. Vos and Eriksson

(1977) proposed that the Wilgerivier Formation (also a correlate of the Swaershoek Formation) was deposited in an environment of fan deltas and embayed tidal flats. Several points raised by Jansen would tend to support the fan-delta - tidal flat model for the Swaershoek and lower Sterkrivier Formations. Jansen (1982, p. 20) states that the deposition of the lowermost beds took place under chaotic conditions; he carries on to describe probable sand and mud flows and a very irregular palaeotopography. Jansen (1982, p. 21) describes active block faulting. Thus the Swaershoek Formation is interpreted to have been deposited on fan-deltas by streamflow and debris flow; in places the sediments were reworked on beaches and on inter-fan-delta tidal flats; contemporary volcanism may have caused heavy ash falls and lahars (Jansen, 1982).

3.13.3 The Alma and upper Sterkrivier Formations

The Alma and upper Sterkrivier Formations were deposited in response to the downfaulting of an area to the north of the Murchison Lineament. This trough was steep on its southern side, against the fault zone, and less steep along its northern boundary (see Fig. 3.3). Alma sediments also filled the last vestige of the previously formed Nylstroom Basin, which still remained as a relative lowland. The upper part of the Sterkrivier Formation is correlated with the Alma Formation and it has a similar history. The northern highlands of Swaershoek times were now forming the base of the new basin. In the Gatkop area, on the farm Buffelshoek 446KQ, the interstices between large well rounded granite boulders were filled with arkosic sand being washed into the new basin (facies Gs). These boulders probably represent residual granite boulders which were present on the eroding highland prior to its down-faulting. Borehole 020 penetrated two such boulders before hitting solid granite. The concentric banding around the boulders probably indicates that onion-skin type weathering was taking place - it is not clear where granitic material ends and clastic infill starts, but there is no doubt that the infill exists, since small pebbles are seen in the infill in places. In places scree deposits formed against the fault scarp (facies Gsc). Rivers bringing in detritus from the newly formed highlands formed alluvial fans north of the scarp. Clast-supported rudites were the principle deposits (facies Gm). The indicated peak current velocities of 7,62m/s for the rudite beds, show that unless flow was extraordinarily deep, only antidunes or upper stage plane beds could be produced at velocities of this order (Blatt *et al.*, 1980, Fig. 5-4a). This is probably the reason for the relative scarcity of structures in these rocks. Even if stream velocities of about 1,5 to 2m/s are projected for the deposition of coarse sands, only upper stage plane beds or antidunes would be produced at a depth of 0,4m (Blatt *et al.*, 1980, Fig. 5-4b). Miall (1977, Table IV) reports a facies similar to facies Gm of this study as having been deposited by various streams with velocities varying from 1-6m/s and with flow depths of 0,2-6,6m.

The few palaeocurrent measurements that were made in the Alma Formation give a random pattern, but grain size of the rudites in the Gatkop area decreases away from the fault zone in the south (Meinster, 1972, 1975); also, the lateral sequence of facies indicates that the flow was approximately from south to north. This coincides with the sense of direction shown by trough cross-beds on Donkerpoort 448KQ to the east of Gatkop.

Fines were washed into interfan lakes, or may have been deposited in distal parts of fan-deltas building out into a shallow lake to form the Donkerpoort Siltstone Member. The angularity of the lutite grains may reflect the vigorous conditions under which the larger clasts were transported, with angular fragments being formed due to high velocity interclast collisions (facies Fsc). A second feasible origin of these very angular grains is that they were formed by high energy aeolian collisions (Eriksson, 1985; Smalley and Vita-Finzi, 1968).

As the fans built out into the basin coarse, clast-supported rudites accreted on longitudinal bars (facies Gm). Occasional debris flows occurred producing matrix-supported rudites (facies Gms). Increasing maturity of the fan systems allowed the formation of large scale trough cross-bedded rudites and arenites on linguoid bars in braided channels (facies Gxt and Sxt). Horizontally stratified sand and gravel (facies Sh, Gh) formed on higher areas, possibly the tops of bars, due to reduced water depth and increased velocity (Blatt, Middleton and Murray, 1980, Fig. 5.4). Sandwaves (facies Sp) and megaripples (facies Gt, St) formed in channels, possibly coalescing to form complex bars. Distally, overland flow (sheetflood) produced horizontally laminated sand with isolate oversize clasts (facies Slic), similar to that described by Gloppen and Steel (1981, p. 57-58). They interpret the facies as having developed at the base of fans and they point out that the outsize clasts may have been deposited because of an abrupt drop in competence as flow width increased. They further point out that the facies is always restricted to the outer reaches of the fans. In the present case associated trough cross-bedding (facies St) and large scale trough cross-bedding (Facies Sxt), are interpreted as being produced in localized channels as linguoid bars and megaripples.

The Alma and upper Sterkrivier sediments are thus interpreted to have been deposited as a series of alluvial fans, forming a bajada along the scarp caused ~~by the uplifted~~ block on the southern side of the Murchison strike-slip fault zone (Fig. 3.34).

3.13.4 The Skilpadkop Formation

The Skilpadkop Formation rudites contain a higher percentage of matrix than do those of the Alma Formation. The average size of the ten largest clasts at various localities indicates peak current velocities up to 6,5m/s; in general peak velocities are lower than those estimated for the Alma Formation. At the indicated peak velocities only upper stage plane beds or antidunes would develop in all but extremely deep flows (Blatt *et al.*, 1980, Fig. 5.4). The chief facies are Sm, St, Gt and Gm; facies Gms is more common than it is in the Alma Formation, but it remains of relatively minor

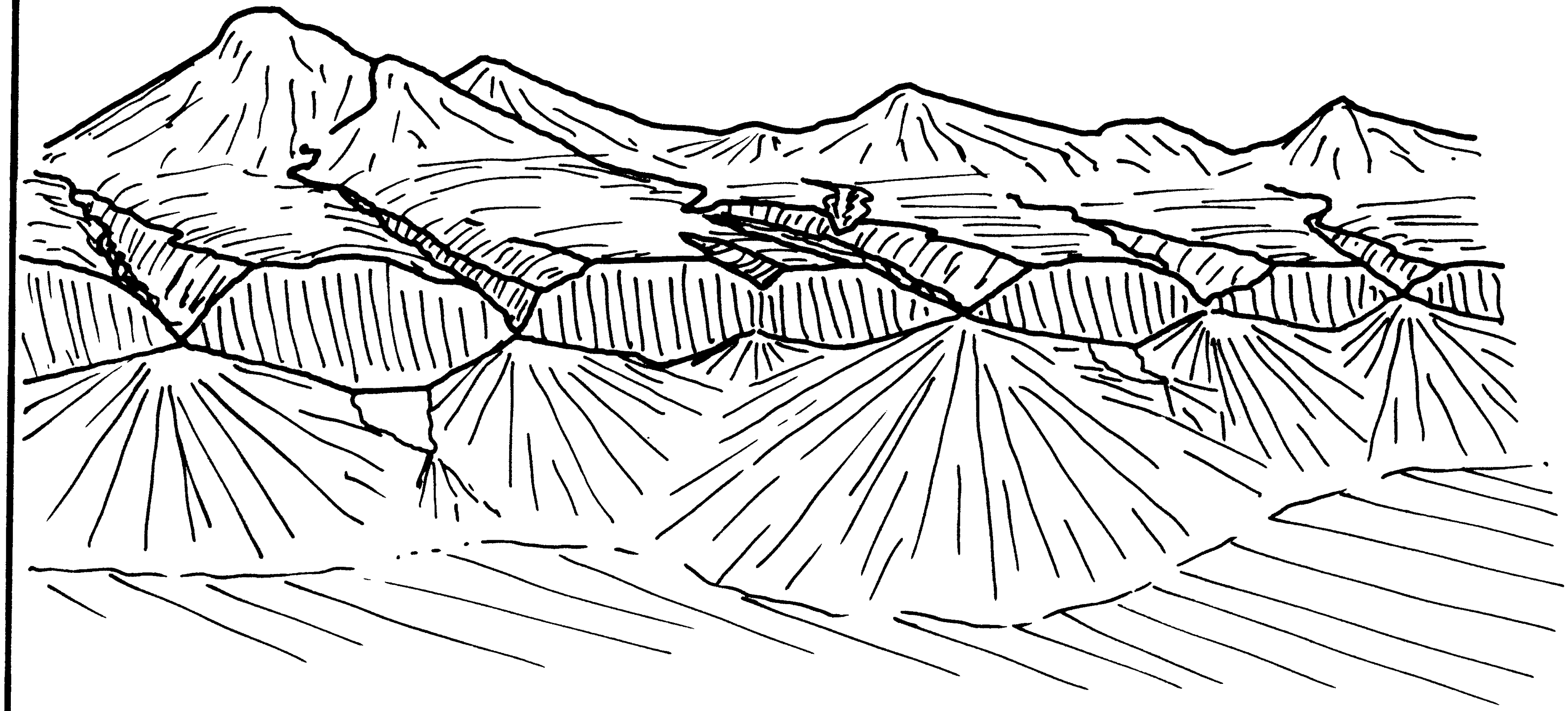


Figure 3.34: Palaeo-environmental interpretation of the Alma Formation.

importance. This formation is interpreted to have been deposited in proximal to distal braided rivers, on longitudinal bars and in deep channels dominated by megaripples. Rust and Koster (1984) point out that massive to horizontally bedded imbricate gravels (similar to facies Gm) dominate proximal braided river environments. They further state that these deposits typically accumulate as longitudinal bars. Trough cross-bedded gravels are more common in medial to distal braided rivers, forming as 'dunes' (megaripples) in deep channels (Rust, 1979, p. 16). The observed overturning and slumping of cross-beds may have been due to drag of heavily laden fast-flowing currents, or to shock caused by movement on the boundary faults. During waning flow, ripples formed on the tops of bars, but were seldom preserved due to erosion during the ensuing high flow period. The massive sand facies may be similar to the apparently massive facies mentioned when discussing the Alma Formation (p. 67), where it in fact represents a trough cross-bedded facies, but where weathering has rendered the structures invisible.

Thus the Skilpadkop Formation is interpreted as the deposit of a braided river which formed a narrow braidplain to the north of the Murchison Strike-slip Fault System (Fig. 3.35). The variability of major palaeocurrent directions may be due to different braid systems being active over a period of time, with palaeoslope being dependent on shifts on the boundary faults.

3.13.5 The Setlaole Formation

The Setlaole Formation consists of immature to submature granule-rich arenites and rudites, as well as minor tuff and tuffaceous mudstone. Although the formation was not studied in detail, the facies present (Gm, Gms, Gt, St, Fm, Fmt) are interpreted as being proximal, and having been deposited on a narrow braidplain. The proximal nature of the deposits is assessed by the occurrence of facies Gm and facies Gms and by the absence of facies Gp and Sp. Proximal braidplain deposits typically consist of facies similar to Gm and Gms with facies analogous to Gt, St and

Figure 3.35: Palaeo-environmental interpretation of the Skilpadkop Formation.

Fm also being present (Miall, 1978, p. 599). This interpretion coincides with that for the laterally equivalent Skilpadkop Formation in the south and southwest of the basin. The general immaturity of the sediments also points towards a deposit of this type. The mottled rocks at Gotha 517LR, which show concentric colour patterns, are interpreted as a palaeosol, whilst the heavy mineral layer about 1m above the contact with granite is seen as a heavy mineral lag formed by selective entrainment of the light minerals. Podlike masses of coarse rudite at this locality may represent cross sections of early (small) channels. Broken, previously rounded clasts from Zwartkop 742LR probably represent clasts which were well rounded outside of the basin. The high energy conditions produced by the uplift of the provenance areas resulted in these (previously rounded) pebbles, possibly from mature extrabasinal sediments, being swept into the basin where high energy collisions caused weaker clasts to break, some splintering into wedge-shaped slivers.

3.13.6 The Aasvoëlkop Formation

The Aasvoëlkop Formation represents an upward-coarsening sequence, which is interpreted as the deposit of a shallow inland lake; dominant suspension deposition is inferred for the base of the succession, but influx from rivers played an ever more important role upwards in the sequence, leading to an upward gradation from finer to coarser facies. The lake is thought to have been of the through-flow type since no chemical sediments have been recorded. The sedimentary rocks are usually reddish in colour although greenish intercalations are common; such interbedded red and green layers have been recorded in other ancient lacustrine deposits (Collinson; IN Reading, 1978, p. 72). The unit is underlain by fluvial deposits of the Skilpadkop Formation and overlain by distal braidplain deposits of the Sandriviersberg Formation; towards the north it is thought to interfinger with deposits which have been interpreted as aeolian (Meinster and Tickell, 1975). The Groothoek Mudstone member at the base, facies Fmv, has been interpreted by Jansen (1970a, 1982) as being the result of deposition by lahars. There certainly appears to be a strong volcanic influence in these sediments, and an alternative origin could involve ash falls producing tuffaceous beds in a distal lacustrine environment. The present author has seen no evidence of lahar flow structures to support Jansen's hypothesis. Oscillation, linguoid and cuspate ripples, mudcracks and raindrop imprints may be indicative of fluctuating water levels in the lake; Collinson (IN, Reading, 1978, p. 67) points out that signs of emergence are common features of lacustrine sediments. Facies similar to lithofacies Fmi of this study are common in rocks interpreted as ancient lake deposits, such as in the Green River Formation of the western USA (flat pebble conglomerate facies) as discussed by Collinson (IN, Reading, 1978, p. 68). The presence of facies Fmi may be indicative of a shallow water lake, although associated evaporites should also be present; a through flow of the water may, however, have kept the mineral concentrations low. Pyrite rich sediments are common in lacustrine sediments (Collinson, IN Reading, 1978, p. 74-76), where they represent anaerobic bottom conditions during deposition. Contorted bedding in the upper part of the sequence, which was probably dominated by fluvial processes, may indicate a very high water table - a feature which would be expected near a temporary base level. The trigger for the contortions was probably movement along the southern fault zone.

3.13.7 The Makgabeng Formation

The maximum thicknesses of 1000m and 1200m given in SACS (1980) and Jansen (1982) for the Makgabeng Formation are probably not reliable. Besides its intersection in borehole P188 where it is about 60m thick, the only area where outcrop is continuous enough for reasonably accurate measurement is in the type area, where it is given as 380m thick by Jansen (1982). After the pervasive mega-cross-bedding, the most characteristic feature of this formation is its uniform medium-sand grain size and the absence of clayey matrix. The relative absence of rudites and lutites is a further important characteristic. The rudites mentioned by Jansen (1982) as belonging to the Makgabeng Formation are regarded by the present writer as probably belonging to the Setlaole Formation. Facies Spe has been interpreted as an aeolian deposit by Meinster and Tickell (1975) and that interpretation is supported by the present writer. The large foresets are postulated as having been produced by slip faces of aeolian dunes of more than 8m in height; Jansen (1982) mentions sets of up to 17,3 m thick occurring in borehole P188. Facies Sme is somewhat of an enigma, but it is thought to be due to interdune deposition; it could feasibly be caused by gusts during storms taking the sand into temporary suspension and then 'dumping' it. Similar features are reported from the aeolian deposits of the Clarens Formation by Eriksson (1983). He considers that they are either only apparently massive, with indiscernible laminae, or that the laminae have been destroyed by post-depositional rainfall (Eriksson, 1983, p. 145). The ripples seen in the type area have a height to wavelength ratio of 0,025 which is within the range of 0,02-0,08 for aeolian ripples given in Turner (1980, p. 74). The ripple index of 40-45 and the ripple symmetry index of 2 indicates that the ripples are probably of aeolian origin, although a swash origin cannot be ruled out (Tanner, 1967, Fig. 1). Facies Smc is most likely the result of surface runoff after sporadic heavy downpours; this facies is rare in the Makgabeng Formation. The multimodal palaeocurrent pattern seen in figure 3.13 can also be related to an aeolian palaeoenvironment, probably being indicative of a longitudinal dunefield. Turner (1980, p. 85) points out that longitudinal dunes produce a bimodal pattern when the foreset attitudes are plotted because of the alternating slip faces. The pattern derived from the Makgabeng Formation is, however, not a simple bimodal one as could be expected from longitudinal dunes; Turner (1980 p. 85) indicates that this sort of pattern is probably due to superposition of dunes. There may also be an influence of seasonal wind directions. Reduction spots are common in some areas and are thought to be due to post-depositional reduction of iron oxides.

The problematic traces on Verdoornsdraai 808LR occur in the more southerly area of the Makgabeng Formation where it shows signs of grading into the probably lacustrine Aasvoëlkop Formation. The small bedforms present in facies Sl are similar to those found in littoral deposits. Hunter (1969) shows that adhesion warts (which he calls aeolian microridges) occur on modern beaches; Callaghan (1978) reports similar features as well as ripples and interference ripples from a modern estuarine/tidal environment. Allen (1982, p. 503) reports superimposed ripples similar to the interference ripples seen at Verdoornsdraai from barred beaches. These features perhaps show the gradation to the subaqueous deposits of the Aasvoëlkop Formation. The possibility that the traces seen at Verdoornsdraai are a form of crack cannot be totally discounted in view of the fact that no undisputed vital traces of this age have yet been described in the literature. The wider traces, especially, are in doubt because of their similarity to those of Wheeler and Quinlan (1951, Fig. 5). The continuation of several of the tracks over the crests of the ripples, without showing any evidence of differing width, however, supports the case against a crack origin.

Baldwin (1974) showed that biogenic structures associated with mudcracks might well be masked by the latter and that subsequent interpretations may be biased in favour of the non-biogenic. The present writer thus proposes that the traces seen in the Makgabeng Formation may be signs of early metazoan evolution and that Precambrian traces which have been discounted as desiccation cracks should be re-examined in the light of Baldwin's findings.

3.13.8 The Sandriviersberg and Mogalakwena Formations

The Sandriviersberg and Mogalakwena Formations are dealt with together because of their lateral stratigraphic equivalence, and their great similarity in sedimentary style. The writer has submitted a proposal to the SACS working group for the Waterberg and Soutpansberg Groups in which these formations are considered to be a single formation. The proposal has been accepted in principle by the working group. Both formations typically consist of trough to planar cross-bedded medium- to coarse-grained arenites and rudaceous arenites. They contain frequent pebble washes and the Mogalakwena Formation includes three rudite members.

The coarser nature of the Mogalakwena Formation, as well as its higher percentage of lutite matrix and clay drapes, suggest that it is less mature than the rocks of the Sandriviersberg Formation. This implies that the Mogalakwena is the more proximal of the two.

Cross-bedding is almost universal in the arenaceous facies of these rocks and trough cross-bedding is the most common type (facies St, Gt). Planar cross-bedding is less common overall but becomes relatively more abundant towards the southeast (facies Sp). Miall (1977, p. 48) shows that, in general, trough cross-bedded arenites tend to be more proximal than planar cross-bedded arenites, and that grain size and bed relief index both become smaller with distance away from the source. Figure 3.20 clearly shows the decrease in the sizes of the ten largest clasts across the basin from the northeast. This supports De Bruiyn's (1971b, p. 7) contention that there is a general increase in grain size as well as an increase in the number of rudite layers towards the north.

Calculated peak current velocites for rocks of the Mogalakwena Formation range up to 5,33 m/s, whereas the maximum current velocities associated with deposition of the Sandriviersberg Formation were in the order of 1,97 m/s. These figures relate very well to 'typical' flood velocities for rivers given by Allen (1982, p. 6). He also gives 'typical' velocities during normal flow as 0,5 to 1,0 m/s. In sediments like those that formed the Sandriviersberg and Mogalakwena Formations, which have a mean grain size in the range of 0,5 to 2,0 mm, such velocities would produce trough and planar cross-beds in flows of 0,4m depth (Blatt *et al.*, 1980, fig. 5.4).

Planar cross-bed azimuths are often at a large angle to associated trough cross-bed azimuths in these sedimentary rocks. Williams (1966) describes similar features from the Torridonian (Precambrian) arenites of northwest Scotland. He suggests that they form from point bars (lateral bars) in shallow, possibly braided streams. Allen (1966, p. 166) suggested that such cross-beds could be formed by avalanching of sediment over lateral bars in low sinuosity channels. High and Picard (1974) showed that planar cross-bedding is generally either unimodal with a wide scatter, or bimodal with subequal modes of 50° and 60° on both sides of the channel direction. In an exposure on Riebeek West 539LR two sets of planar cross-beds are seen on either side of a small channel, dipping towards each other and at a high angle to the azimuths of the associated trough sets. Heavy minerals which occur in the 'channel' as well as the areal distribution of the structures indicates that the planar cross-beds were possibly formed on laterally migrating bars. The heavy minerals were most probably concentrated by a converging flow in a similar way to that described by Smith and Beukes (1983), in modern rivers.

The overall palaeocurrent direction for these two formations (244°-255°) is towards the southwest; this similarity of palaeocurrent directions is a further indication of the close relationship of the two formations. The consistent thickness of the formations (except in the far north-northeast) suggests that they may have had a far greater extent at one time. Their extension in a southwesterly direction, would, by projection, lead to an arenaceous, planar cross-bedded deposit. Jansen (1983) points out that no proximal sediments have as yet been located in the Fuller Member of the Volop Group, Olifantshoek Sequence, in the northern Cape Province, and he suggests that it may be a distal correlate of the Waterberg Group. Since the Fuller Member represents an arenaceous, planar cross-bedded unit, the present writer proposes that it may well be a distal correlate of the Mogalakwena and Sandriviersberg Formations.

The Mogalakwena and Sandriviersberg Formations appear to have been deposited during a period when the basin was deepening at a steady rate and during the rapid development of a mountain mass to the northeast of the basin. Sedimentation appears to have been rapid (coarse-grained and poorly rounded grains), but ordered as indicated by a low occurrence of facies Gms and relatively consistent palaeocurrent directions. The thinning of the Mogalakwena Formation towards the north was probably due to drag from the continued upheaval of the source area to the north-northeast. Sediments from this mountain range built out into the basin as a large braidplain (Fig. 3.36), overtopping the Letaba-Makoppa rise and possibly continuing to a distant ocean. Coarse rudite accumulated in proximal areas as longitudonal bars (facies Gm), whilst much of the sediment was laid down in channels in which megaripples migrated downstream (facies Gt, St). Less common lateral bars and sandwaves deposited planar cross-bedded sediments, especially in the more southerly areas (facies Sp). The Mogalakwena Formation was first attributed to braided river deposition by Tickell (1975).

3.13.9 Cleremont Formation

Even though De Bruiyn (1971a) reported a fault which intersects the Sandriviersberg Formation, but which does not displace the Cleremont Formation, the latter has been described as gradational upwards into the former (Jansen, 1982). Exposures seen by the present writer support the view that the boundary between these formations is transitional. The Cleremont Formation is reported to be 125m thick (Jansen, 1982). It consists of medium- to coarse-grained, rounded to well rounded quartzarenite, with occasional layers of rounded small pebbles. The sediment is very clean and is usually well sorted. The inferred palaeoenvironment is a relatively high energy, distal subaqueous setting. The grain size and maturity of the unit as well as the presence of small, well rounded pebbles, support an origin in a littoral environment. A tidally-influenced palaeoenvironment seems most likely since the trough cross-beds indicate palaeocurrents away from probable land areas and the planar cross-beds are distinctly bimodal.

The common occurrence of trough cross-beds (facies St) supports

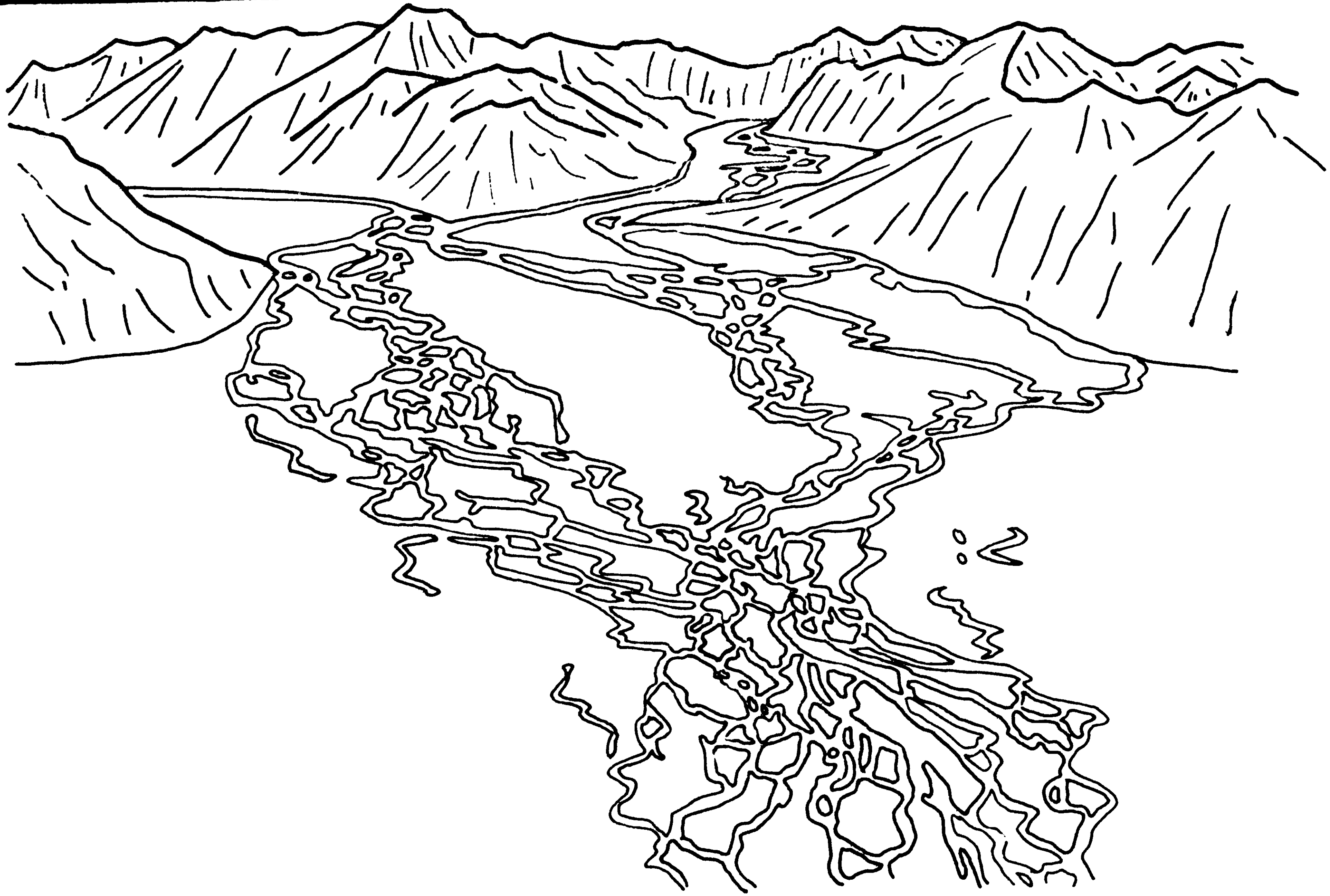


Figure 3.36 Palaeo-environmental interpretation of the Sandriviersberg and Mogalakwena Formations.

this hypothesis since they are abundant in both high energy as well as intermediate to low energy coastal environments (Clifton *et al.*, 1971; Davidson-Arnott and Greenwood, 1976). Planar lamination (facies Sh), which occurs extensively in the Cleremont Formation, is typical of several coastal subenvironments, specifically tidal delta deposits (Reinson, 1984) and tide-dominated shelf deposits (Walker, 1984). The horizontally laminated heavy mineral arenite (facies Shhm) possibly formed due to storm activity levelling a beach (Gadow and Reineck, 1968; IN Reineck and Singh, 1973, p. 311). Such a levelling-off would result in the removal of all the light minerals by selective entrainment. Phosphates occur mainly in shallow marine and pelagic environments (Johnson, 1978, p. 230). The phoshate clasts seen in this study are rather angular and have not suffered much transport; they give additional evidence of the proposed marine influence on this formation.

Large planar tabular cross-beds represent somewhat of a problem in that most of the processes that form them call for distinct tidal or longshore currents. Tidal channel inlets, tidal deltas and tide-dominated shelf deposits commonly contain planar cross-beds of comparable dimensions to those seen in the Cleremont Formation. If these structures are due to tidal processes it would imply that the associated sea was large enough to produce tides capable of transporting sediment. Reinson (1979, p. 62) points out that small to medium scale delta foresets, which produce planar cross-beds, may be caused by washover deposits associated with barrier islands. The planar cross-bedded structures encountered in the Cleremont Formation could also feasibly be due to very large straight-crested megaripples. Straight-crested megaripples, producing planar cross-bed sets, occur in the lunate megaripple (outer rough) marine facies of Clifton *et al.* (1971). However, in both of these cases the foresets are oriented toward the proposed land. Harms *et al.* (1975) describe very similar features from the St. Peter Sandstone which also shows several apparent transport directions; they indicate that these deposits formed on an open shelf. The Cleremont Formation is thus interpreted to have formed due to the deposition of arenaceous sediments along a shoreline, possibly as a shelf deposit.

3.13.10. Vaalwater Formation

The Vaalwater Formation attains its maximum preserved thickness of 475m in the centre of the Main Basin. It consists of fine feldspathic arenites and lutaceous arenites. Much of the exposure encountered by the present writer consists of mature horizontally laminated to massive arenite and arenaceous lutite, although trough cross-bedding and ripple marks have been reported. The depositional environment was probably of relatively low energy, although the maturity of the sediments implies that at some stage they went through an efficient sorting process. Taking into account the proposed environments of deposition of the underlying formations, it seems that the most likely depositional environment for the Vaalwater Formation is that of a shallow siliciclastic sea or littoral environment. It could simply represent a finer facies from a similar environment to the Cleremont Formation. The association of ripples and trough cross-bedding, shown in De Vries (1973), is, however, a feature usually seen in estuarine environments (as de Vries points out) and this may indicate a fluctuating sea level. Some of the 'convolutions' reported by De Vries (1973, Fig. 10) look as if they could be hummocky cross-stratification (Harms *et al.*, 1975, p. 88), which is taken as indicating storm wave conditions. In support of this analysis by the present writer, de Vries does mention that the lamination follows the topographical outlines of the structures and that no disruption is seen. The generally greyish colour of the sediments may be significant; the red colour of the rest of the Waterberg sedimentary rocks has been shown to be due to pre-diagenetic or early diagenetic coating of grains; the implication is that these sediments were in a less-oxidizing environment.

4. ECONOMIC GEOLOGY

4.1 MINERALIZATION AT GATKOP

Mineralization in the Gatkop area on the farms Waterval 443KQ and Buffelshoek 446KQ comprises tin mineralization associated with thorium, uranium associated with copper, and zinc mineralization; minor secondary enrichment of ilmenite occurs. Each of these are discussed below with their specific associations and known distribution.

4.1.1 Tin and associated mineralization

The writer discovered tin in a sample taken on Waterval 443KQ in 1978, while on a reconnaissance trip to sample a thorium anomaly in the Waterberg Group. This thorium anomaly was investigated in response to a literature survey that showed thorium-bearing minerals such as zircon, monazite and xenotime as common components in 204 tin-bearing sediments throughout the world (Callaghan, 1983a). Further sampling was carried out to ascertain the tin/thorium relationship. It was shown that a statistically meaningful relationship exists between tin and thorium values in the Gatkop area (Callaghan, 1983a). Microscope and scanning electron microscope study of samples from the Gatkop area established that the tin is in the form of cassiterite. Thorium-bearing minerals which are common in these sediments are thorite, monazite and zircon. Detailed investigation of exposures has shown that the thorium is generally more abundant in areas of heavy mineral concentration.

Heavy mineral placers are usually formed by the process of selective entrainment of lighter grains during late stage flows; this leaves the heavy minerals as a lag. At Gatkop this process has caused a small degree of concentration of heavy minerals. However, the relatively high concentration in the area as a whole, even in beds that appear to have undergone no sorting, indicates that the sediment moving into the basin at this point must have been enriched in heavy minerals such as zircon, cassiterite, thorite and monazite. The placer minerals of interest occur only in the rhyolite- and the granite/rhyolite-bearing rudites. No tin-thorium mineralization is present in the monomict quartzite-bearing rudites. Where selective entrainment processes have caused concentration of heavy minerals the following minerals may occur: titanomagnetite, ilmenite, zircon, thorite, monazite, cassiterite, witherite, andalusite, topaz, barite, tourmaline, apatite and possible auerlite (SEM qualitative analysis gives major components as thorium, iron, silicon, and phosphorous, the grains are inhomogeneous). A single small grain thought to be thorotungstite (given in Dana (1932) as an oxide of thorium and tungsten) was seen in thin section 1047 during study under the scanning electron microscope; this grain is homogeneous in comparison to the thorite grains and it contains a few small inclusions of apatite. The topaz seen in these heavy mineral placers is probably derived from Bushveld granite - topaz has been identified in sample 106 from a granite boulder in the Alma Formation. No less than eight of the ten minerals most commonly associated with cassiterite in placer deposits, occur with cassiterite at Gatkop (Table 4.1).

At Gatkop the cassiterite is coarse (Figure 4.1) and may occur as large composite grains. The composite cassiterite grains contain 'veins' of manganocalcite and quartz. Inclusions of manganocalcite and iron oxide also occur (Figure 4.2). The fact that such large grains occur and that composite grains are present shows that the cassiterite did not travel far before being deposited in its present position. A distance of hundreds of metres or perhaps as much as a few kilometres is envisaged. The cassiterite only occurs in sediments which contain rhyolite clasts and it appears to be associated with the rhyolite. This is significant since no rhyolite is exposed today across the fault zone to the south. The source rocks of the cassiterite and other heavy minerals are thought to have moved tens of kilometres towards the east since Alma times due to the continued reactivation of the Murchison strike-slip fault. The establishment of the tin as detrital and the recognition of the strike-slip nature of the bounding fault, presents a prospecting target in the rhyolites to the east of Gatkop.

TABLE 4.1

"Typical" mineral assemblages
associated with cassiterite-bearing placer deposits.
Those minerals occurring at Gatkop are marked with an asterisk.
(Adapted from Callaghan, 1983a)

MINERAL	% OCCURRENCE
CASSITERITE *	100
ZIRCON *	88
TOURMALINE *	81
ILMENITE *	80
MONAZITE *	73
TOPAZ *	56
LEUCOXENE	55
ANDALUSITE *	50
GARNET	50
EPIDOTE *	45
FE OXIDES *	42
XENOTIME	42
HYDRO-ILMENITE	29
ALLANITE	24
QUARTZ *	22
STAUROLITE	20
ANATASE	19
PYRITE	19
AMPHIBOLE	18
CORUNDUM	18
SPINEL AND PLEONASTE	17
GOLD	17
LIMONITE	16
MUSCOVITE *	15
CHROMITE	14
KYANITE	13
BIOTITE *	13
BROOKITE	12
URANOTHORITE	11
CHLORITE *	11

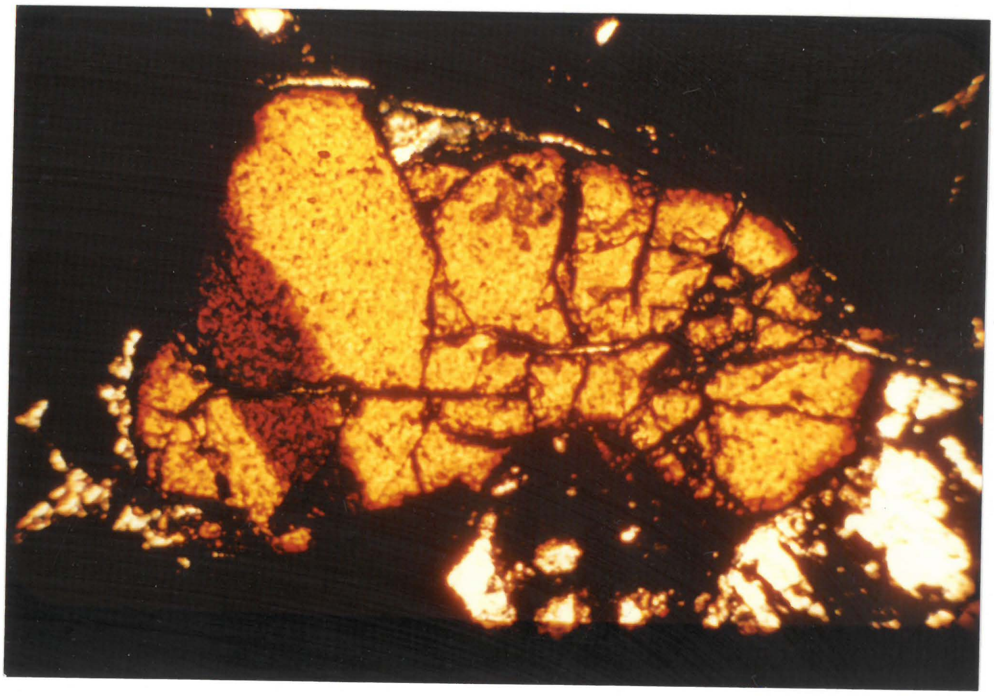


FIGURE 4.1: Twinned cassiterite grain from sample CC-1047 (Alma Formation) on Buffelshoek 446KQ, seen in ordinary light. The base of the photograph is 1,1 mm long.

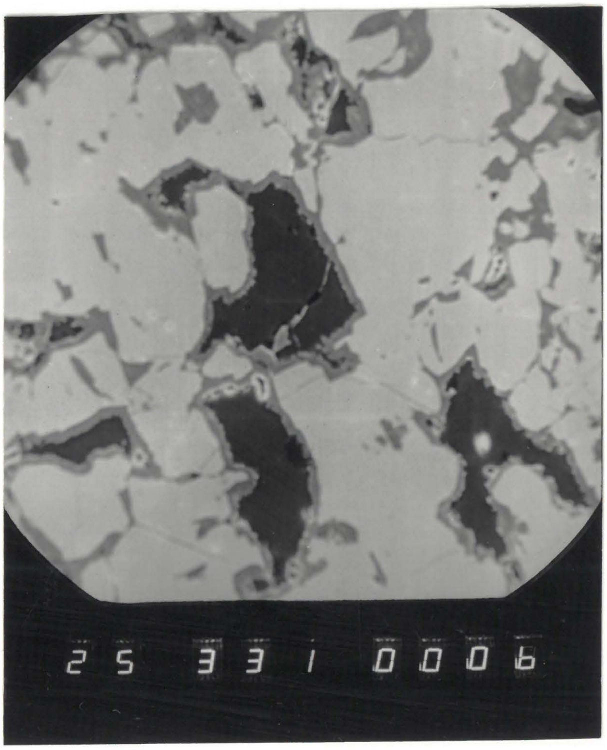


FIGURE 4.2: Scanning electron microscope photograph showing cassiterite (pale grey) with iron oxide inclusions (medium grey) as well as iron oxide lined manganocalcite inclusions (black). From sample CC-888 taken at 57,5 - 58,48 m from borehole 004 on Waterval 443KQ. The area photographed measured 150 microns across.

4.1.2 Uranium and associated Mineralization

This mineral association is found chiefly on the farm Buffelshoek 446KQ. The chief uranium mineral present was identified as pitchblende, after comparison with pitchblende from the Witwatersrand Supergroup. A second uranium mineral present has been identified from a qualitative analysis as kasolite, a lead-uranium silicate. Chalcopyrite is by far the most common mineral in this association; it has a high copper and sulphur content relative to its iron content, tiny inclusions of silver are to be seen in places. Other minerals which occur are bornite, quartz and galena.

Minor amounts of galena are intergrown with the chalcopyrite. Barite contains inclusions of chalcopyrite and galena. Quartz has occasional inclusions of galena and of uranium minerals. The pitchblende is usually intimately associated with chalcopyrite, with the latter tending to form a 'halo' around the uranium mineral. This is well illustrated in figure 4.3. This association is also seen in Figure 4.4 where a chalcopyrite crystal appears to have been embayed and replaced by kasolite. A 'pebble' from Buffelshoek 446KQ was identified in hand specimen as chalcocite, it was coated with micaceous, green uranium oxides.

A large area at Gatkop shows anomalous uranium values. Uranium and copper values of interest, however, only appear infrequently and are confined to very small areas within the mineralized zone. The mineralization is often confined to granite or rhyolite clasts and in one case appears to occur in a vein. The uranium/copper association occurs chiefly in the area of mixed granite/rhyolite clasts.

The uranium/copper mineralization is clearly not of detrital placer origin since it shows no relationship to the detrital cassiterite/heavy mineral association; also, vein material is present. Vein type uranium deposits have been ascribed to continental weathering by Barbier (1974). There are several factors which support a genesis of uranium/copper enrichment due to an allitization/monosiallization weathering

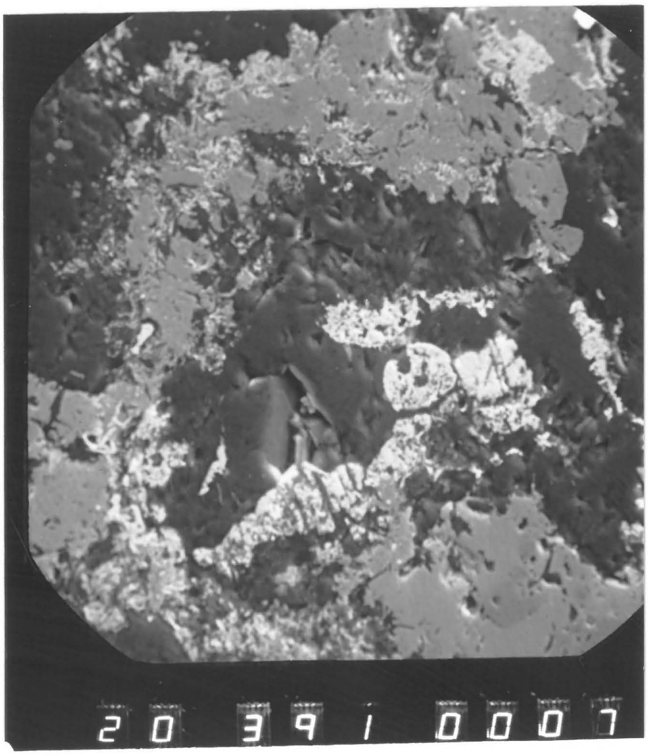


FIGURE 4.3: SEM photograph of pitchblende (white) in quartz (dark grey) surrounded by copper and lead sulphides (light grey). From a mineralized vein in the Alma Formation on Buffelshoek 446KQ. The area photographed is 130 microns across.

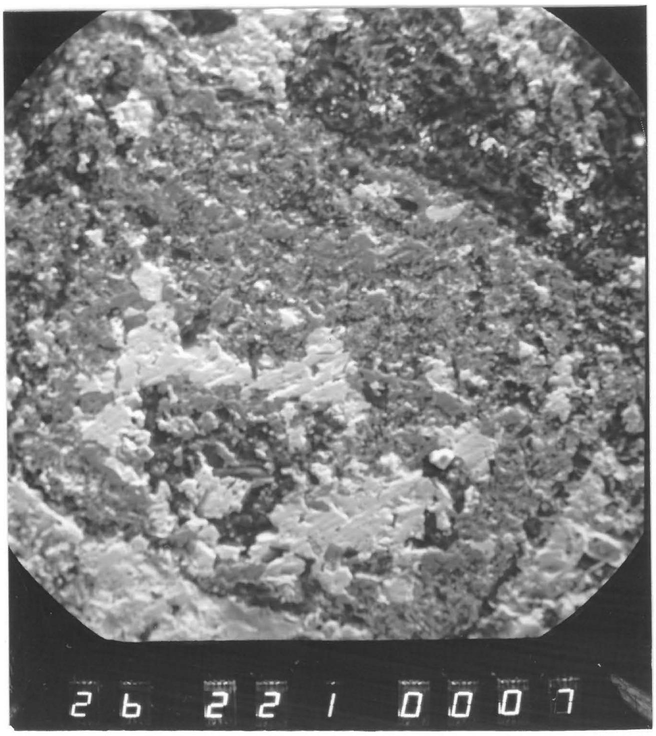


FIGURE 4.4: SEM photograph of kasolite (light grey) replacing chalcopyrite (mottled darkish grey) in a sample from the Alma Formation on Buffelshoek 446KQ. The area photographed is 220 microns across.

regime such as that proposed by Samama (1973). Uranium and copper will be concentrated in the sediments whilst lead and zinc (especially in an allitization regime) will be eliminated and leached away. At the same time reddening (which is prevalent in the Alma Formation) would take place under such conditions. If such a weathering regime was already in action before deposition of these sediments, the parent rocks (Bushveld Complex granite) would already have been enriched in uranium and copper. The weathering process would have continued after deposition of the sediments on proximal alluvial fans leading to further concentration. This process would explain the association of the mineralization with a specific sedimentary facies (which is rich in granite clasts). Two factors support the probability that such uranium concentration would occur preferentially over granite and in sediments with a high percentage of granite clasts rather than over adjacent (at Alma times) rhyolites and quartzites. The granites contain far more uranium than the rhyolite (Twist and Harmer, 1987, p. 20 - 13±7ppm U in granites compared to <6ppm in rhyolites), or the quartzite. At the same time the granite is far more susceptible to weathering than are the rhyolites (I. T. Crocker, 1987, pers.comm.). The quartzites are, of coarse, very resistant to weathering. Thus, besides the initial advantage held by the granitic material due to its inherent uranium content, its susceptibility to weathering under this regime would greatly enhance the uranium/copper content of sediments forming from it.

The uranium and copper could have undergone further enrichment by being taken into solution by connate (meteoric) waters as they became hot, either because of geothermal gradients on burial or because of late granitic intrusion. Magmatic waters may, or may not have mixed with these connate waters before they moved up towards higher (coarser, in a coarsening-upwards sequence) levels, where they deposited dissolved solids as veinlets, or replaced pebbles. Gamma ray spectrometer measurements over the thrust fault on the western part of Waterval 443KQ, where it is well exposed, showed raised uranium values towards the central part of the brecciated zone. This shows that it may have been a conduit for mineralizing fluids. The mechanism for the movement of the mineralizing fluids may have been by seismic pumping (Dixon, 1979, p. 61). This calls for a fault plane with periodic movement such as that postulated in the Gatkop area. Dilation of the rocks surrounding the fault during the building up of stress is seen in modern day situations by the drying up of springs. When stress is released the dilatational fractures collapse and expel the water along the fault plane. Leaching occurs in the zone of dilation (Dixon, 1979), and enriched waters formed in this process may deposit their 'load' where suitable conditions prevail.

4.1.3 Zinc and associated mineralization

Anomalous zinc concentrations in the Gatkop area occur chiefly on the farm Waterval 443KQ especially near the southern boundary fault. This can be seen for example in the average values for zinc in boreholes 004, 005, 006, 013, 014, and 020 (Appendix 2), which were all drilled within about 300m of the fault zone (Fig. 3.8). In contrast boreholes 007 to 012 and borehole 019 show lower zinc values. A sample from a very poorly exposed section of the Alma Formation adjacent to the fault zone on Waterval 443KQ contains more significant zinc mineralization. XRF analysis of this sample (no. 156) showed 3562 ppm zinc. Lamination in the thin section that was studied is shown by variations in the grain size of quartz; no feldspars are to be seen and if they were present they must have been destroyed during the intense alteration and weathering which it has undergone. This weathering has partially destroyed the ore minerals with chalcopyrite and sphalerite occurring only as boxworks (Figure 4.5). The other minerals which occur and which appear to belong to the mineralization phase are fluocerite, fluorite and zircon; these minerals are still fresh. The mineralization is interpreted to be due to hydrothermal processes. Fluorite (which makes up the bulk of the thin section) is colourless to pale yellow and it replaces quartz (Figure 4.6). Both the hydrothermal minerals and the original quartz grains float in a yellowish clay matrix. This matrix material has a low birefringence and in thin section appears to be a yellow kaolinite. SEM analysis shows that it is an iron aluminium silicate, and it was therefore identified as faratsihite ($(\mathrm{Al,Fe})_2\mathrm{Si}_2\mathrm{O}_5(\mathrm{OH})_4$ - Hey, 1975). The fluocerite shows good cleavage and is of a resin-orange colour (Figure 4.7, see p. 146). SEM analysis shows it to consist chiefly of cerium, lanthanum, neodymium and praseodymium (the flourine content has been assumed). The fluocerite is closely associated with the sphalerite. Some idiomorphic zircon crystals which have clearly grown in situ also occur.

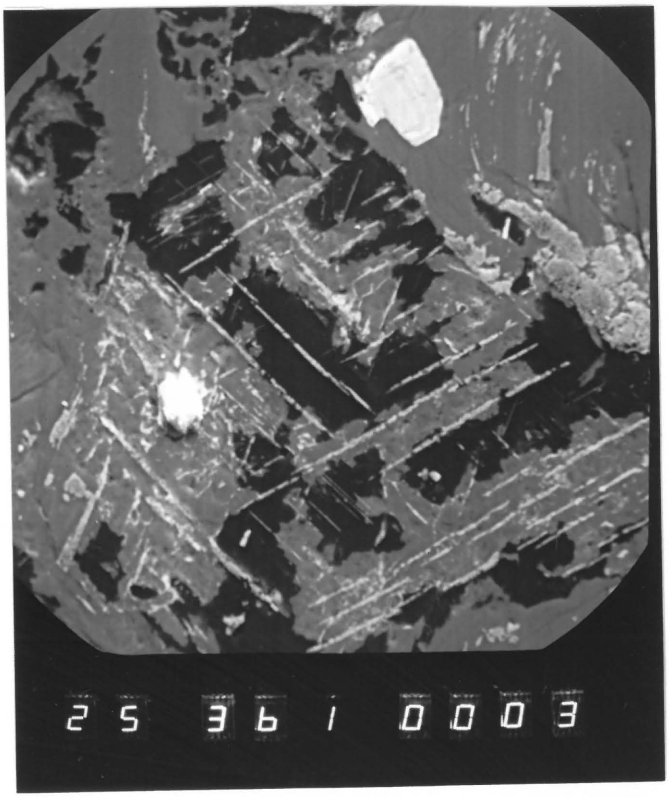


FIGURE 4.5: SEM photo of sphalerite boxwork in sample CC-156, showing the typical diamond shaped pattern due to the (110) cleavage of sphalerite. The darker areas are titanium- and iron-rich whilst the lighter areas consist chiefly of iron; the boxwork lamellae are rich in zinc as well as iron and titanium. From the Alma Formation on Waterval 443KQ. The area photographed is 130 microns across.

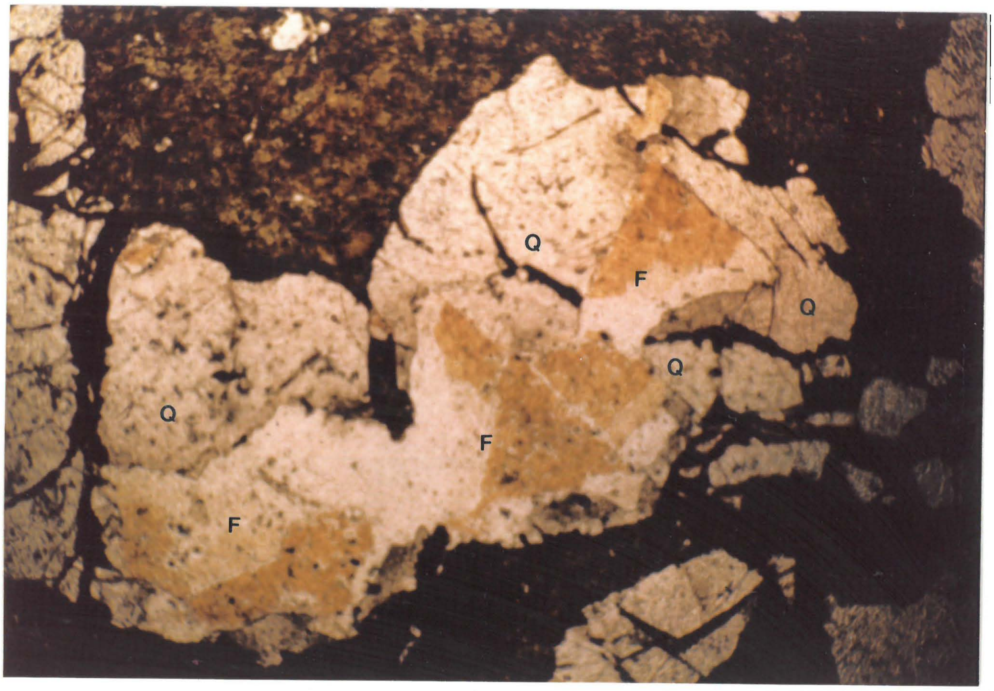


FIGURE 4.6: Fluorite replacing quartz in sample CC-156.The groundmass is faratsihite. From the Alma Formation on Waterval 443KQ. The base of the photograph is 4,5 mm across.

The constant increase of zinc, measured in surface as well as borehole samples, as the fault zone is approached may indicate that this mineralization is also genetically connected to the fault; however, the proximity of dolomite of the Malmani Subgroup on the southern side of the fault zone may also have caused a zinc anomaly in this area, by 'leaking' of zinc into the clastic sediments.

There are several old workings on Waterval 443KQ in the Malmani Subgroup, within the fault zone. Some galena has been found in the walls of one of these workings.

4.1.4 Anatase Mineralization

Anatase rims on ilmenite grains are seen in a few thin sections from the Gatkop area. These rims are attributed to authigenic/diagenetic processes in which iron is lost from the ilmenite.

4.2 MINERALIZATION IN THE REST OF THE BASIN

The mineralization in the rest of the Main Waterberg Basin falls into four categories: small heavy mineral placer occurrences, manganese occurrences, copper and barite occurrences and anatase enrichment.

4.2.1 Heavy Mineral Placer Mineralization

Small, low grade placers of titanomagnetite and ilmenite occur throughout the Waterberg Basin, especially in the Vaalwater, Cleremont and Sandriviersberg/Mogalakwena Formations. Only a few of these are of interest and none of them appear to be of economic significance. On the farm La Rochelle 310LR a large area (probably covering several square kilometres) of the Mogalakwena Formation is slightly enriched in heavy minerals. It contains 15-20 percent of iron-titanium oxides and is also relatively rich in zirconium, thorium and uranium. Analyses for samples from this occurrence as well as those discussed below are given in Table 4.2.

At Duikerfontein 263KR a small exposure in the Mogalakwena Formation was first noted by De Villiers (1966), who reported 49 percent ilmenite and 2 percent zircon in a sample. The values of a sample taken by the writer from this locality show low TiO_2 and Zr concentrations, but high thorium.

De Villiers (1966) also described an occurrence at Kaffershoek 23KR in the Cleremont Formation. Only a small exposure is to be seen and there is no indication as to the total extent of the heavy mineral occurrence. De Villiers noted 64% ilmenite and 10% zircon in a sample from this deposit. The interpretation of the Cleremont Formation as a littoral deposit accounts for the exceptional degree of sorting and for the purity of the concentrate. The heavy mineral placer is a very fine-grained arenite (thin sections 646 and 647), which is associated with medium- to coarse-grained, sugary-textured, mature quartz-arenites. Sixty percent of the rock consists of titanomagnetite (finely exsolved into Ti- and Fe-rich lamellae).

TABLE 4.2

SOME OF THE BETTER HEAVY MINERAL CONCENTRATIONS ENCOUNTERED IN THE WATERBERG GROUP

FARM NAME AND NUMBER	FORMATION	LITHOLOGY AND COMMENTS	NO.	TiO_2 %	Total Fe %	Zr ppm	Mo ppm	Th ppm	U ppm
BOSCHDRAAI 60KR	Vaalwater	Laminated medium-grained arenite	378	0,98	13,86	7271	243	992	151
DIGGERSFONTEIN 15KR	Vaalwater	Mottled fine arenite.	300 301	2,53 3,10	7,68 10,02	1447 1753	48 63	101 138	22 28
DUIKERSFONTEIN 236KR	Mogalakwena	Poorly exposed, heavy mineral rich arenite.	413 414	0,51 1,04	14,40 16,95	1209 1061	5 12	748 852	52 52
GOTHA 517LR	Setloale	Pebbly rudite sampled 1m above underlying granite	610	3,87	19,88	3631	3	526	59
HAAKDOORNBOOM 223KQ	Vaalwater	Very fine-grained arenite	1565	1,83	11,19	4124	60	222	45
HARTEBEESTFONTEIN 116KR	Mogalakwena	Pebble rudite associated with trough crossbedded granite rudite	397	3,88	11,92	1113	11	235	38
HARTEBEESTHOEK 288KQ	Sandriviersberg	Granite rich crossbedded arenite. Heavy minerals concentrating chiefly on cross-laminae	1585 1586	8,09 12,11	21,89 25,88	1938 6206	26 80	227 867	52 58
HOUTBOSCHKLOOF 561LQ	Mogalakwena	Composite sample from trough crossbedded granite rudite	1639	2,34	22,57	979	17	283	51
KAFFERSHOEK 23KR	Cleremont	Horizontally laminated, very fine grained arenite	646 647	10,76 13,16	- -	20633 17794	317 254	637 404	128 108
KLIPSPRUIT 457KQ	Skilpadkop	Pebbly granule rudite	1602 1606	3,55 2,21	15,09 19,78	1578 2215	0 0	148 200	38 38
LA ROCHELLE 310LR	Mogalakwena	Sample 599 is of sand. 600 and 601 are of granule rich crossbedded arenite.	599 600 601	3,44 0,67 0,98	19,39 15,15 16,08	1890 1380 862	3 2 4	95 220 179	43 38 33
MALMANSRIVIER 236KQ	Sandriviersberg	Pebbly granule rudite	1561	7,37	21,77	2035	23	209	42
MIDDELBOOMFONTEIN 68KR	Vaalwater	Fine arenite	298	3,89	15,71	3090	138	465	79
MOOIMEISIESFONTEIN 254KQ	Sandriviersberg	Trough crossbedded arenite	1583	9,37	23,73	4461	53	420	48

TABLE 4.2 Continued...

FARM NAME AND NUMBER	FORMATION	LITHOLOGY AND COMMENTS	NO.	TiO_2 %	Total Fe %	Zr ppm	Mo ppm	Th ppm	U ppm
OLIFANTSHOEK 27KR	Cleremont	Heavy mineral laminae in a large scale planar crossbed set	589	79,02	19,24	20742	103	1600	262
STERKRIVIER-NEDERSETTING 253KR RIETFONTEIN 249KR STERKSTROOM 301KR		Very poorly exposed, a total of five formations occur in the area. Sample 628 from Sterkriviernedersetting. Frick (1972c) gives analyses of up to 16,97% TiO_2 and 0,26% ZrO_2	628	2,57	14,76	215	2	30	21
TOULON 495LR	Mogalakwena	Coarse arenite underlying cobble rudite	1636	2,70	20,08	1156	10	364	35
UITVAL 216KQ	Vaalwater	Lutite	1576	1,42	7,96	2335	35	91	25
VERDOORNDRAAI 803LR	Makgabeng	From ripple-marked arenite which exhibits problematical 'trails'	629	3,24	14,21	276	0	33	21
VRYHEID 537LQ	Mogalakwena	Plane laminated arenite associated with pebbly rudite	1632	5,05	25,77	---	---	---	---
WELGEVONDEN 16KQ	Aasvoelkop	Heavy minerals associated with pebble lag in pebbly granule rudite	1555	2,13	15,92	1016	11	109	26

Some grains show extremely fine exsolution lamellae in two directions; this is probably ulvöspinel. SEM analysis shows that some of this, apparent, ulvöspinel is probably ilmenite ($FeTiO_3$). This may be due to oxidation (Stanton, 1972, p. 380). The rock also contains 10 percent quartz, 8 percent zircon, 2 percent rutile, 2 percent monazite, 1 percent thorite and traces of gorceixite (a barium aluminium phosphate which occurs both as inclusions in zircon and as discrete grains), zirkelite (SEM analysis gives calcium, iron, zirconium, titanium and thorium as constituents) and uranothorite (a uranium thorium silicate). Authigenic/diagenetic alteration is an important process in the enrichment of the titanium content of this rock and is discussed in section 4.2.4.

Frick (1972c) describes three farms where heavy minerals occur. They are Sterkriviersnedersetting 253KR, Sterkstroom 301KR, and Rietfontein 249KR. The deposit on Sterkriviersnedersetting is described as being the largest. These occurrences are poorly exposed and Jansen's (1982) map shows them to be underlain by no less than five formations. Frick gives analyses with up to 16,97 percent TiO_2 and 0,27 percent ZrO_2. He considers titano-haematite and ilmenite to be the most important minerals present.

Four occurrences in the Vaalwater Formation are of interest. On Middelboomfontein 68KR at the site of radiometric anomaly 9-4-12, the radioactivity as measured with a scintillometer is high and a sample of the fine arenite proved to be rich in titanium, zirconium, molybdenum and thorium. Similar sediments at Diggersfontein 15KR indicate that although individual occurrences appear small they may in fact be quite extensive in the Vaalwater Formation. A laminated medium arenite from Boschdraai 60KR (which may have been deposited in a littoral environment) was found to be rich in zirconium, molybdenum, thorium and uranium. Radiometric anomaly 8-4-11 on Vischgat 11KR proved to be rather interesting. No outcrop was seen at the site of the anomaly, but tiny iron-rich pebbles are highly radioactive and rich in zirconium and molybdenum; the genesis of these is not understood.

Besides the Kaffershoek placer one other occurrence in the Cleremont Formation is of interest. On Olifantshoek 27KR the Cleremont Formation is slightly enriched in heavy minerals and individual cross-bed laminae sometimes show particularly high concentrations of more than 50 percent heavy minerals. One such lamina gave the analysis shown in Table 4.2.

There are dozens of samples which show 10 to 15 percent heavy minerals with about 1 percent TiO_2 and/or >1000ppm Zr; but besides the deposit at La Rochelle 310LR, which was included because of its size, only the richer concentrates have been tabulated.

4.2.2 Manganese Mineralization

The Waterberg basin contains many small occurrences of manganese. These have been described by De Villiers (1960) and by Hammerbeck and

Taljaardt (1976). The deposits occur as gash vein fillings and shear zone impregnations as well as localized concentrations in the sediments. One low grade deposit occurring in an outlier of the Waterberg sediments on Bronkhorstfontein 42LR and on Baden 90LR to the north-northeast of Steilloopbrug, was worked in the 1960's.

Some of the occurrences in the southern part of the basin are associated with faults which may form part of the Murchison fault zone, others appear to be small stratabound syngenetic deposits. The deposits have not been studied in detail since this is outside the scope of this project.

A relatively large (previously undescribed) occurrence can be seen at Klipspruit 457KQ; it has been prospected in the past as can be seen from a number of trenches and pits as well as a small quarry. Samples from this occurrence are rich in manganese, barium, tungsten, copper and zinc (Table 4.3). The author found the relatively high tungsten values to be of interest, since anomalous tungsten values also occur elsewhere along the southern edge of the basin. Although the significance of this is not clear, these occurrences may indicate a possible tungsten deposit at depth which is related to the fault zone. The nature of the tungsten content has not been established, but it may be of colloidal form as discussed by Kerr (1940) and by Lindgren (1922) in their papers on tungsten-rich manganese deposits. The chief manganese mineral present at this locality was determined by X-ray diffraction to be cryptomelane. Also present in small amounts are pyrolusite, braunite and hollandite. Very small XRD peaks which could represent chalcocite and wolframite are present.

TABLE 4.3

ANALYSES OF THREE SAMPLES TAKEN AT THE KLIPSPRUIT MANGANESE OCCURRENCE

FARM NAME AND NUMBER	FORMATION	NO.	MnO %	Cu ppm	Zn ppm	W ppm	U ppm	Ba ppm
KLIPSPRUIT 457KQ	Skilpadkop	1604	26,50	2938	796	636	113	3618
		1605	20,31	1866	627	421	103	5233
		1607	8,84	134	1113	44	97	2788

4.2.3 Copper and Barium Mineralization

Several occurrences of mineralization, which are areally related to dolerite intrusions, are to be seen in the Waterberg Basin. The mineralization usually consists of copper, lead or barium minerals, and is often accompanied by brecciation and quartz veining. One of these occurrences at Nooitgedacht 92KR has been mined for a short while.

At Nooitgedacht the orebody occurs in and along a dolerite dyke which dips 50° N20°E. The ore occurs in quartz veins (De Vries, 1970; De Bruiyn, 1972b). Minerals described by De Bruiyn include digenite, chalcopyrite, malachite, azurite and chalcocite. De Bruiyn reports that whilst no galena was present in the specimens which he studied, it did occur in the mine. Samples where taken from the dumps and the analytical results are given in Table 4.4. Nearby on the farms Vogelsfontein 69KR and Rhynosterfontein 96KR samples of lutaceous quartz-arenite are rich in copper and lead. This shows that besides the vein mineralization the rocks have also been pervasively altered.

On Klipdrift 231KQ a shaft and several pits have been excavated on a dolerite dyke and associated quartz veins. There is much malachite to be seen and the dolerite itself is of a malachite green colour. This dolerite contains 1,7 percent copper, whereas the brecciated dolerite-quartz vein material gave only 0,12 percent copper (Table 4.4).

On Schoonwater 14KQ several small occurrences of barite and barite-copper mineralization are to be seen. At 24°2,95'S : 27°27,87'E barite occurs in a pipe-like body in the middle of a ploughed field; the occurrence is about 10m in diameter and the barite is quite pure with about 43 percent barium (Dana, 1932, gives 65,7 percent Ba for pure barite). Although some malachite was seen under a binocular microscope no Cu was detected by the XRF analysis, possibly due to background effects caused by the high barium content. At 24°4,86'S : 27°26,53'E a barite-lutite breccia with copper staining is seen in a trench. At 24°5,59'S : 24°26,74'E several

TABLE 4.4

ANALYSES OF SAMPLES INTERPRETED TO HAVE BEEN ENRICHED BY EPIGENETIC HYDROTHERMAL MINERALIZATION

FARM NAME AND NUMBER	FORMATION	LITHOLOGY AND COMMENTS	NO.	Tot. Fe %	Sr ppm	Ba ppm	Cu ppm	Zn ppm	W ppm	Pb ppm
GROENDRAAI 213KQ		Vein quartz	1648	1,10	14	107	63	38	23	403
		Vein quartz with chalcopyrite and malachite.	1649	0,01	14	53	250	37	92	1073
		Dolerite	1650	15,40	333	849	229	153	7	22
	Cleremont	'Spotted' arenite	1652	0,46	33	205	13	25	118	0
	Cleremont	Brecciated arenite with vein quartz infillings.	1653	0,27	10	94	71	46	0	51
GROOTHOEK 278KQ	Aasvoelkop	Horizontally laminated pebbly granule rudite	1040	14,94	22	325	2325	1378	0	84
	Skilpadkop	Granule rudite at top of Skilpadkop Formation	1613	8,75	16	801	1414	806	267	29
	Aasvoelkop	Arenaceous lutite at base of Aasvoëlkop Formation	1614	5,73	21	1139	260	240	11	26
	Aasvoelkop	Malachite rich arenite. A major differentiated sill intrudes the Aasvoëlkop sediments at this locality	1615	7,96	1528	485	24600	31	0	29
KLIPDRIFT 231KQ	Dolerite	Mineralized dolerite	1669	14,77	192	1169	17680	172	0	30
		Brecciated vein quartz and dolerite	1670	0,79	20	75	1253	177	294	0
MODDERSPRUIT 150KQ	Dolerite	Highly weathered dolerite	644	-	5	0	504	93	81	43
			1571	15,25	5	0	389	76	58	0
			1572	15,96	148	803	580	208	119	0
			1573	15,43	3	133	361	63	54	0
			1574	17,34	46	106	370	79	81	0
MOOIFONTEIN 150KQ	Vaalwater	Medium to coarse-grained arenite	1559	4,27	-	-	348	2	9	0
NOOITGEDACHT 92KR		Samples 304 and 305 are from dumps of crushed material which may have been a concentrate. Sample 306 is a composite sample from the main dump.	304	27,15	57	3689	+	0	0	15749
			305	30,93	89	3538	+	0	0	16390
			306	4,52	15	492	5966	29	52	2959
RHYNOSTERFONTEIN 96KR	Vaalwater	Arenite	299	6,48	113	897	1004	24	9	419
SCHOONWATER 14KR		Barite and lutite breccia with malachite	1662	0,81	1459	43%	+	0	0	0
		Lutite breccia with barite and malachite	1663	5,84	1806	19%	1351	116	196	0
		Lutite and quartz breccia	1666	4,78	58	1238	532	101	91	0
VOGELSFONTEIN 69KR	Vaalwater	Fine-grained arenite	297	7,98	69	1159	351	42	0	483

SYMBOLS:
- not analysed
+analysis unreliable

trenches are cut into a lutite-quartz breccia.

On Groendraai 213KQ a small excavation with several trenches and an adit, dating from the late 1950's, is to be seen. A dolerite dyke passes near the trenches, quartz veins are abundant. Although local farmers say that tin was mined here, the only minerals recognized in situ were chalcopyrite and malachite. Samples 1648 to 1653 were taken here. Sample 1648 contains 31 ppm Sn and sample 1649 contains 37 ppm Sn. In an excavation next to the adit, spotted quartz arenite contains 33ppm Sn and 118ppm W. This working was supposedly mined for more than a year but there is no dump, so that the material taken out must have all been taken elsewhere for beneficiation.

At Groothoek 278 KQ an occurrance of copper (with minor tungsten) is ambiguous in nature and may in fact be of syngenetic origin, being related to the volcanic material in the Aasvoëlkop Formation. It does, however, occur near a major sill which may have been the conduit for epigene mineralizing fluids. On the Skilpadkop/Aasvoëlkop boundary there is some mineralization. The medium to large pebble-rudite at the top of the Skilpadkop Formation has malachite coatings on the granule and coarse sand grains of the matrix. The rock is nevertheless of a greyish red 5R4/2 colour. Immediately above this a dusky red 5R4/2 sandy lutite of the Aasvoëlkop Formation occurs. The Cu, Zn and W content of these rocks is summarized in Table 4.4. Also from this formation are blocks of mineralized lutite at 24°30,31'S : 27°33,4'E. No outcrop of this material was seen since these blocks appear in an area of soil cover. They are probably from the base of the Aasvoëlkop Formation. A prehistoric furnace occurs on this farm and slag-like material from it was sampled; the only metallic element occurring in quantity in this 'slag' is iron.

A weathered dolerite an Modderspruit 150KR shows high Cu and W analyses. The tungsten is thought to have been enriched in the dolerite by percolating groundwaters.

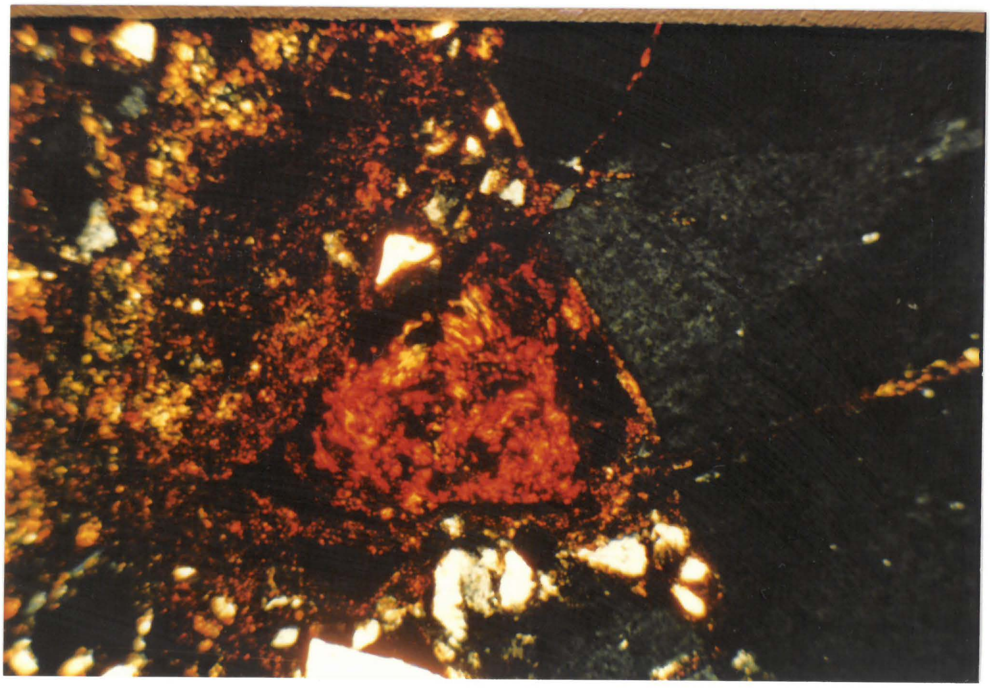


FIGURE 4.7: Fluocerite (bright orange) under crossed nicols, the yellowish mineral is faratsihite. From the Alma Formation (sample CC-156) on Waterval 443KQ. Base of photograph is 1,1mm long.

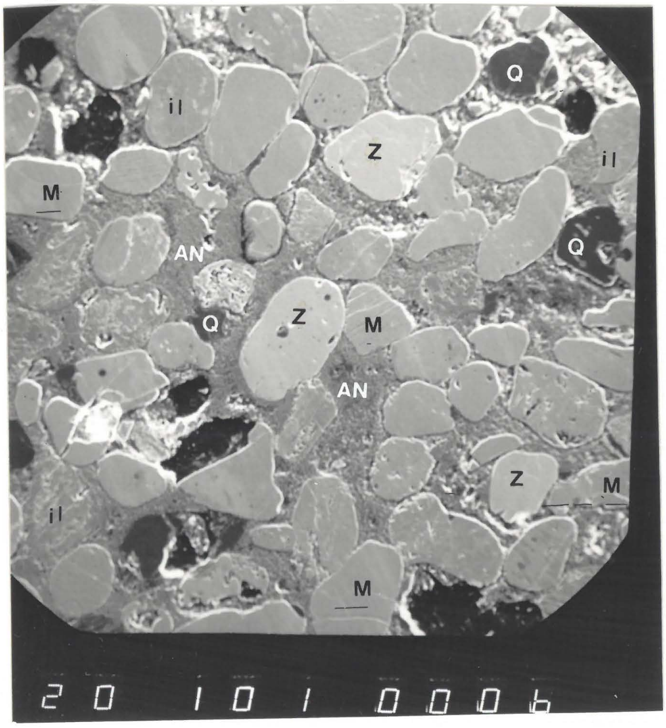


FIGURE 4.8: SEM photograph showing fine sand-sized grains of magnetite (m), ilmenite (il), zircon (z), and quartz (q), cemented by anatase (an). From the Cleremont Formation on Moddersspruit 150 KR. The area photographed is 4,7 mm across.

4.2.4 Secondary Enrichment

Secondary, *in situ* enrichment of titanium has taken place in several heavy mineral occurrences, but it is only on Kaffershoek 23KR where this form of mineralization is of importance. At this locality the iron titanium oxides show extensive alteration with wide rims of anatase being common. In thin section 647 the rock has in fact been cemented by anatase (Figure 4.8). In Figures 4.9 and 4.10 element intensities are shown on X-ray element distribution images. Here the relation of titanium to iron can be seen; this indicates quite clearly the titaniferous nature of the cement. This deposit appears to be of limited extent from the small area of exposure seen, but it may well extend some distance under the thin soil cover.

FIGURE 4.9 An X-ray distribution image of the same area shown in Figure 4.8. This gives an image for iron and shows the titanomagnetite and ilmenite grains.

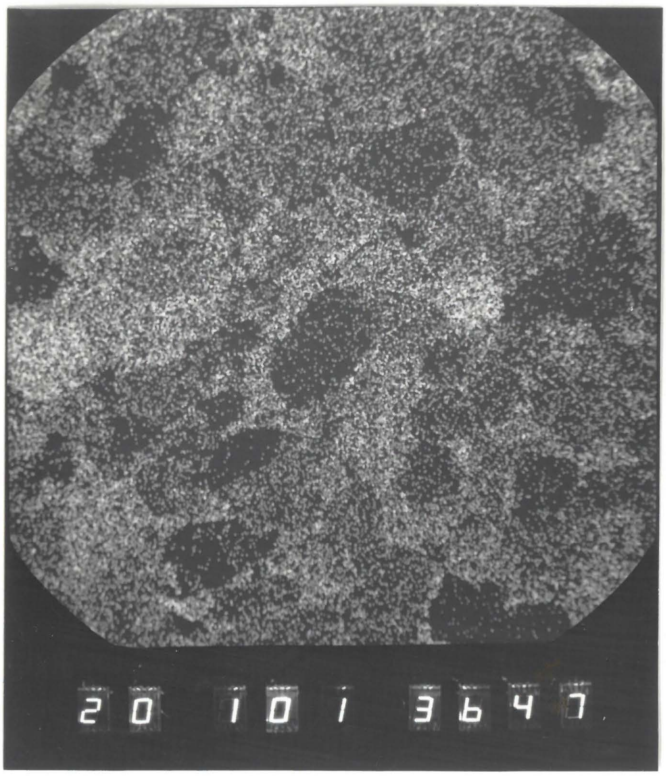


FIGURE 4.10 An X-ray distribution image of the same area shown in Figure 4.8. This gives an image for titanium and shows the anatase matrix very well.

5 SUMMARY AND CONCLUSIONS

5.1 GENERAL GEOLOGY

The Waterberg Group has been divided into a total of thirteen formations (SACS, 1980). The group consists chiefly of coarse clastic sediments which show a general fining upwards throughout the succession from rudites through arenites to lutaceous arenites. Lutites are uncommon and constitute less than ten percent of the group as a whole. Lavas are rare and tuffs are uncommon. The sediments are thought to belong to the Mokolian Erathem and they are approximately 1800my old. The Waterberg Group rests unconformably on rocks belonging to the Soutpansberg Group, the Rooiberg Group, granites and mafic rocks of the Bushveld Complex, the Transvaal Sequence and the Archaean gneisses and granites of the Kaapvaal Craton.

Trough and planar cross-bedding are present in certain formations and the characteristic palaeocurrent direction for the group is from northeast to southwest. The lower formations in the southern part of the Main Basin show a considerable palaeocurrent component from the south. Two broadly upward-fining sequences are evident in the Waterberg Group. The first appears in the lower half of the group, from the base up to the Aasvoëlkop and Makgabeng Formations (which are stratigraphically adjacent). The second is from the Mogalakwena and Sandriviersberg up to the Vaalwater Formation.

The most common colour of Waterberg sediments is of a mid-red (5R) hue, of medium to low value (relatively dark) and of a low to moderate chroma (poorly to moderately saturated).

5.2 STRATIGRAPHY

The areal distribution of the Swaershoek Formation (Fig. 3.3) shows minimal overlap of significant thickness with the rest of the Waterberg sediments. The Swaershoek Formation and its correlate, the Wilgerivier Formation, show a great similarity in geographic distribution with the Rooiberg Group (Van Biljon, 1976; Coertze *et al.*, 1977). The Swaershoek and Wilgerivier Formations are almost completely confined to the limits of the Transvaal Basin. The genesis of the Nylstroom Basin has been interpreted as being due to upper crustal warping, whilst the formation of the Alma trough has been attributed to lower crustal events such as crustal subsidence and deep faulting (Coertze *et al.*, 1977).

The Swaershoek Formation appears to belong in a different tectono-stratigraphic milieu to the overlying sediments of the Waterberg Group. It is suggested that the Swaershoek Formation is therefore removed from Waterberg Group stratigraphy and possibly grouped with the Loskop, Glentig, Rust de Winter and Wilgerivier Formations in the upper part of the Transvaal Sequence. The term Nylstroom Subgroup should be discontinued.

The laterally equivalent Mogalakwena and Sandriviersberg Formations are shown to have a similar sedimentary character. They are considered by the author to constitute one formation which is gradational in character from the north-northeast to the south-southwest. This gradation encompasses grain size, maturity, bedforms and colour, but is in all cases gradual and in context with a facies change from more proximal to more distal sediments. Palaeocurrents are remarkably similar with 194 trough cross-bed measurements in the Sandriviersberg Formation giving an average direction of 253° whilst 229 trough cross-bed measurements in the Mogalakwena Formation give an average direction of 254°. The author has submitted a proposal to the SACS working group for the Waterberg and Soutpansberg Groups in which it is suggested that a single unit called the

Sandriviersberg Formation is accepted into the stratigraphy to replace the present Sandriviersberg and Mogalakwena Formations. The proposal has been accepted in principle by the working group.

5.3 BASIN EVOLUTION AND SEDIMENTATION

The Main Waterberg Basin evolved as a continental, fault-bounded basin, in the northern part of the Kaapvaal Craton. The Murchison lineament, which lies on the southern edge of the basin, is interpreted as a long-lived, fundamental, strike-slip fault system. It shows evidence of predominantly left lateral movement since the deposition of the Alma Formation. The stratigraphic record shows that this line was of considerable importance in delineating basin edges and basin deeps throughout the geological history of the craton. Evidence from the Waterberg Group sediments confirms this trend.

Transpressive strain along the Murchison strike-slip fault zone resulted in the formation of deformation lamellae in quartz in Bushveld granites near Thabazimbi. Later transtensile forces along the fault system led to the development of the Alma Trough. In the Gatkop area east of Thabazimbi this transtensile period resulted in block faulting and the consequent deposition of highly arkosic sediments which can be described as tectonic arkoses.

The sediments of the Waterberg Group constitute an upward-fining sequence of red beds, which show characteristics of rapid deposition in the lower parts of the succession. The Swaershoek and lower Sterkrivier Formations are considered by the present writer to belong to a pre-Waterberg phase of deposition. They are interpreted to have been deposited on fan-deltas by streamflow and debris flow processes. The sediments may have been reworked on beaches and fine-grained sediments were deposited on interfan-delta tidal flats. Contemporary volcanism resulted in tuffaceous beds and lahar deposits.

The Alma and upper Sterkrivier Formations, which are considered by the present writer to form the base of the Waterberg Group, are interpreted to have been deposited as a series of alluvial fans forming a bajada along the scarp caused by the uplifted block on the southern side of the Murchison strike-slip fault zone (Fig. 3.34). Granite, previously subjected to high strain rate deformation, was eroded into the basin and granite clasts as well as individual quartz grains in the Alma Formation show deformation lamellae of the sub-basal type I as described by Carter (1971).

The Murchison strike-slip fault remained active and the Skilpadkop Formation was deposited. At this stage the locus of erosion moved towards the east and northeast, although there was clearly still considerable input from the south. The deposits of the Skilpadkop Formation are considered to have formed a narrow braidplain and the envisaged geomorphical expression of the southern part of the basin at this time is shown in Figure 3.35.

Activity in the southernmost portion of the Palala shear zone meanwhile produced the partly feldspathic arenites and rudites of the Setlaole Formation, which were deposited on a narrow braidplain. Contemporaneous volcanism resulted in minor tuffs and tuffaceous lutites

The Aasvoëlkop Formation represents an upward-coarsening sequence of lutites and arenites which are interpreted to have been deposited in a shallow, through-flow lake. Fluvial sedimentation probably played an increasingy important role towards the top of the sequence.

Sedimentary rocks which today form the Makgabeng Formation are interpreted to have formed a large dune field which may have been coastal towards the south, where the Makgabeng Formation grades into the Aasvoëlkop Formation. Meinster and Tickell (1975) first interpreted this deposit as being due to aeolian processes. Problematical structures discovered in a shallow water intercalation may have a vital origin.

The Mogalakwena and Sandriviersberg Formations are interpreted as having been deposited by large braided rivers flowing from the highlands in the north-northeast towards a distant sea in the southwest. Tickell (1975) first interpreted the Mogalakwena Formation sedimentary rocks as representing the deposits of a braided river system. An extensive braidplain was formed (Fig. 3.36), with a gradation in facies from the northeastern parts towards the southwestern parts. The Fuller Member of the Volop Group may represent a distal correlate of these formations.

As the highlands in the north were eroded and the sediment input decreased, the sea transgressed over the braidplain and the Cleremont Formation was deposited. The Cleremont Formation is interpreted to have formed due to the deposition of arenaceous sediments along a shoreline, possibly as a tidally influenced shelf deposit. The Vaalwater Formation is also interpreted as being representative of a littoral or shallow siliciclastic sea environment.

The Murchison strike-slip fault underwent further periods of activity after the deposition of the Alma beds. This resulted in the tilting and overturning of the Alma Formation sediments. At Gatkop the Malmani Group of the Transvaal Sequence was overthrust, towards the northeast onto the overturned Alma sediments. The Melinda Fault in the southern part of the Palala shear zone tilted the Makgabeng Formation at Morgenzon 138LR into a vertical position.

5.4 PETROLOGY, GEOCHEMISTRY AND ECONOMIC GEOLOGY

Common rock types seen in thin sections of the Waterberg Formation include submature to immature arkose in the Alma Formation and various litharenites in the Sterkrivier, Skilpadkop, Aasvoëlkop, Sandriviersberg and Mogalakwena Formations. The Cleremont Formation consists chiefly of quartzarenites (Fig. 2.1a). There is a vague upward trend through the Waterberg Group from arkosic sediments near the base, via mixed quartz/rock fragment-rich types to quartzarenites.

The sedimentary rocks show two upward-fining trends, the first from the base of the group up to the Aasvoëlkop and Makgabeng Formations and the second from the Mogalakwena and Sandriviersberg Formations up to the Vaalwater Formation (Fig. 2.1b).

The composition of the provenance rocks as interpreted from thin section studies, shows that a shift occurred in the source areas from the Alma Formation (chiefly acid plutonic), upwards. In the overlying formations the provenance appears to have been mixed, with contributions from acid plutonics as well as from sedimentary and/or metamorphic rocks.

Deformation lamellae in quartz crystals in Bushveld Granite and in quartz grains of the Alma Formation were found to be at a moderate angle to the basal (0001) plane, which indicates that they are due to geologically normal strain rather than to impact.

Rock type is reflected in both major and trace element analyses, and in the case of the Alma Formation the similarity of geochemistry with analyses from Bushveld Granites may be indicative of their source-sediment relationship. There appears to be a good relationship between plots of major element ratios and thin section studies, with Alma Formation samples consistently showing their arkosic character, whilst many samples from other formations show a lithic character. The samples from the Cleremont Formation are persistently classified as quartzarenites.

Mineral occurrences in the Waterberg Group have formed by placer, hydrothermal epigenetic-authigenic and possibly hydrothermal stratabound processes. Placer mineralization of interest occurs in the Alma and Cleremont Formations. Epigenetic hydrothermal mineralization occurs in the Alma, Skilpadkop, Aasvoëlkop and Vaalwater Formations.

Minerals occurring in placer deposits in the Cleremont Formation include titanomagnetite, ilmenite, ulvöspinel, zircon, gorceixite, monazite, thorite, zirkelite, rutile and uranothorite. Authigenic/diagenetic alteration of the ilmenite has produced anatase rims and at Kaffershoek 23KR the anatase is a major cement comprising more than 20% of the rock.

The Alma Formation is mineralized in the Gatkop area, where it contains the following suite of detrital heavy minerals: ilmenite, titanomagnetite, thorite, zircon, witherite, monazite, cassiterite, topaz, andalusite, tourmaline, barite, auerlite, apatite, sphene, uranothorite, garnet and thorotungstite. The high tin/thorium correlation at Gatkop has been related to the association of thorium-bearing minerals with cassiterite. This relationship is seen in most other cassiterite placer deposits throughout the world. Authigenic/diagenetic mineralization is seen in places at Gatkop as thin anatase rims on ilmenite. Epigenetic hydrothermal enrichment at Gatkop produced at least two associations: a pitchblende, kasolite, chalcopyrite, barite, bornite association and a sphalerite, fluocerite, chalcopyrite, fluorite association. The uranium and associated mineralization is ascribed to an allitization/monosiallization weathering regime which also resulted in the reddening of the sediments; enrichment due to epigene processes may have resulted in the deposition of some of the uranium and copper in veins and also in the replacement of clasts.

Manganese occurrences have been summarized in previous works (Hammerbeck and Taljaardt, 1976; De Villiers, 1960) only one new occurrence of any significance was discovered during this study; this occurs at Klipspruit 457KQ in the Skilpadkop Formation. The geometry of this body suggests that it may have been syngenetic. The chief manganese mineral present at this locality is cryptomelane. Also present are pyrolusite, braunite and hollandite.

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REFERENCES

ALLEN, J.R.L., 1966. On bedforms and palaeocurrents : Sedimentology, 6, p.153-190

ALLEN, J.R.L., 1982. Sedimentary structures, their character and physical basis : 1, 593p.

ANDERSON, W., 1910. Notes on the general geology of a little known portion of the Waterberg District, between Nylstroom and the Limpopo River to the north west : Trans. geol. Soc. S.Afr., 13, p.17-25.

BALDWIN,C.T., 1974. The control of mudcrack patterns by small gastropod trails : J.Sed. Petrol., 44, no 3, p.695-697.

BAKER, V.R., 1973. Paleohydrology and sedimentology of Lake Missoula flooding in eastern Washington : Geol. Soc. Am. Special Paper, 144, 79p.

BARBIER, M.J., 1974. Continental weathering as a possible origin of vein-type uranium deposits : Mineral. Deposita (Berl.), 9, p.271-288.

BARNES, W.C. and SMITH, A.G., 1964. Some markings associated with ripple-marks from the Proterozoic of North America : Nature, London. 201, p.1018-1019.

BATES, R.L. and JACKSON, J.A. (Eds.), 1980. Glossary of Geology : Second Edition : Am. geol. Inst., Falls Church. Virginia.

BEER, E.J., 1919. Note on a spiral impression on the lower Vindhyan limestone : Records of the Geol. Surv. of India. 50, p.139.

BERNER, R.A., 1969. Goethite stability and the origin of red beds : Geochim. et Cosmochim. Acta. 33, p.267-273.

BEUS, A.A. and GRIGORIAN, S.V., 1977. Geochemical exploration methods for mineral deposits : Applied Publishing Ltd. 287p.

BISHOP, P., 1982. Calculation of the An 360/An 180 orientation statistic using a programmable calculator : J.Sed. Petrol., 52(2), p.668.

BLATT, H., MIDDLETON, G. and MURRAY, R., 1972. Origin of sedimentary rocks : Prentice-Hall Inc., Englewood Cliffs, New Jersey. 634p.

BLATT, H., MIDDLETON, G. and MURRAY, R., 1980. Origin of sedimentary rocks : Prentice-Hall Inc., Englewood Cliffs, New Jersey. 782p.

BöHM, A., 1883. Uber die Gesteine des Wechsels: Tschermak min. u. petr. Mitt., 5, p.197-214.

BOTHA, G.A., 1986. Significance of parent rock type in the development and distribution of soils in the Kruger National Park, south of the Olifants River : Palaeoecology of Africa.

BRAY, J.G., 1966. Shatter cones at Sudbury : J. Geol. 74, p.243-245.

BURGER, A.J. and WALRAVEN, F., 1979. Summary of age determinations carried out during the period April 1977 to March 1978: Ann. geol. Surv. S. Afr., 12, p.209-218.

BUTTON, A., 1972. The depositional history of the Wolkberg proto-basin, Transvaal : Economic geology Research Unit., Inf. Circ. No 71.

CALLAGHAN, C.C., 1978. Bedforms of the Swartkops Estuary. B.Sc.(Hons) Thesis, University of Port Elizabeth, 34p.

CALLAGHAN, C.C., 1979. Tin placer deposits : How and where to find them : Rep. geol. Surv. S.Afr., 1979-0178 (unpublished).

CALLAGHAN, C.C., 1982. The search for tin placer deposits in the Waterberg Group. IN Sedimentology 82: Sedimentology applied to exploration, mining, engineering and environmental studies : p.111-112.

CALLAGHAN, C.C., 1983a. Thorium as a guide to potentially tin-bearing placer deposits : Ann. geol. Surv. S.Afr., 17, p.35-41.

CALLAGHAN, C.C., 1983b. The effect of magnetism on radiometric instruments : Ann. geol. Surv. S.Afr., 17, p.43-68.

CALLAGHAN, C.C., 1986. The Waterberg Basin: Its Evolution, Sedimentation and

Mineralization. IN GEOCONGRESS 86 : Extended abstracts. Geol. Soc. S. Afr. Publ. p.759-762.

CANT, D.J. and WALKER, R.G., 1976. Development of a braided fluvial facies model for the Devonian Battery Point Sandstone, Quebec: Can. J. Earth Sci., 13, p.102-119

CARTER, N.L., 1965. Basal quartz deformation lamellae - a criterion for recognition of impactites : Am. J.Sci., 263, p.786-806.

CARTER, N.L., 1971 Static deformation of silica and silicates: J. Geophys. Res., 76, no.23, p.5514-55

CARTER, N.L. and FRIEDMAN, M., 1965. Dymanic analysis of deformed quartz and calcite from the dry creek ridge anticline, Montana : Am. J.Science, 263, p.747-785.

CHILINGARIAN, G.V. and WOLF, K.H., (Eds.). 1976. Compaction of coarse-grained sediments II: Elsevier, Amsterdam. 808p.

CHRISTIE, J.M. and ARDELL, A.J., 1974. Substructures of deformation lamellae in quartz: Geology, 2, no 8, p.405-408.

CHRISTIE, J.M. and RALEIGH, C.B., 1959. The origin of deformation lamellae in quartz : Am. J.Sci., 257, p.385-407.

CLIFTON, H.E., HUNTER, R.E. AND PHILLIPS, R.L., 1971. Depositional structures and processes in a non-barred high energy nearshore : J. Sedim. Petrol., 41, p.651-670

CLOUD, P. 1976. Beginnings of biospheric evolution and their biogeochemical consequences : Paleobiology. 2. p.351-387.

COERTZE, F.J., JANSEN, H. and WALRAVEN, F., 1977. The transition from the Transvaal Sequence to the Waterberg Group : Trans. geol. Soc. S. Afr., 80, p.145-156.

COETZEE, G.L., 1969. The Rooiberg felsite series north of Nylstroom IN Symposium on the Bushveld Igneous Complex and other layered intrusions. Spec. Publ. geol. Soc. S.Afr., 1, p.312-325.

COLLINSON, J.D., 1978. Lakes IN Reading, H. G., Sedimentary Environments and Facies, Blackwell, Oxford, 557p.

CORNER, B., 1979. Quantitative gamma scintillometry and spectrometry in uranium exploration : IN Training course on radiometric prospecting techniques. Presented by the AEB in collaboration with the South African Geophysical Association and the Geological Soc. of South Africa. Pelindaba 21-23 May 1979.

CROCKETT, R.N., 1971. Some aspects of post Transvaal tectogenesis in south-eastern Botswana : Trans. geol. Soc. S.Afr., 74, p.211-235.

CROCKETT, R.N. and JONES, M.T., 1975. Some aspects of the geology of the Waterberg system in Eastern Botswana : Trans. geol. Soc. S.Afr., 78, part 1, p.1-10.

CROWELL, J.C., 1974. Origin of late cenozoic basins in southern California IN Tectonics and Sedimentation : Ed. by W.R. Dickinson : Spec. Publ. SEPM. Tulsa, 22 p.190-204.

CULLEN, D.J., 1960. A note on the distribution of Waterberg and Loskop Formations in the southern Bechuanaland Protectorate : Trans. geol. Soc. S.Afr., 63, p.161-174.

DALE, M.L. and BALLANTYNE, C.K., 1980. Two statistics for the analysis of orientation data in geography : Professional Geographer, 32(2), p.184-191.

DALY, R.A. and MOLENGRAAFF, G.A.F., 1924. Structural relations of the Bushveld Igneous Complex, Transvaal : J. Geol., 32, no.1, p.1-35.

DANA, E.S., 1932. A textbook of mineralogy : John Wiley and Sons Inc., New York, 851 p.

DAVIDSON-ARNOT, R.G.D. and GREENWOOD, B., 1976. Facies relationships on a barred coast, Kouchibougwac Bay, New Brunswick. Canada : IN Davis, R.A. (Jr) & Ethington, R.L., Beach and nearshore sedimentation SEPM Spec Publ. 24, p.149-168

DE BRUIYN, 1971a. The geology of the central portion of the Waterberg Basin around Vaalwater, northern Transvaal : Rep. geol. Surv. S.Afr., 1971-0044, 11p. (Unpublished).

DE BRUIYN, H., 1971b. The geology of the eastern portion of the Waterberg Basin between Mokamole and the Blouberg (Sheet 2328) : Rep. geol. Surv. S.Afr., 1971-0045, 11p. (Unpublished).

DE BRUIYN, H., 1972a. Folded cross-bedding in the Waterberg system : Ann. geol. Surv. S.Afr., 9, p.91-93.

DE BRUIYN, H., 1972b. Report on the Nooitgedacht lead mine, north east of Vaalwater, northern Transvaal : Rep. geol. Surv. S.Afr., 1972-0041, 5p. (Unpublished).

DE BRUIYN, H. and ANDREW, G.F., 1972. Syn-Waterberg volcanism in the vicinity of Rust der Winter Dam : Ann. geol. Surv. S.Afr., 9, p.89-90.

DE VILLIERS, J., 1960. The manganese deposits of the Union of South Africa : Handbk. geol. Surv. S.Afr., 2.

DE VILLIERS, S.B., 1963. Die geologie van die noordwestelike gedeelte van gebied 2428B : Int. Rep. geol. Surv. S.Afr., 1963-0065, 31p. (Unpublished).

DE VILLIERS, S.B., 1966. Voorkoms van ilmeniet-sirkoonhoudende sandsteen in die distrikte Waterberg en Potgietersrus : Rep. geol. Surv. S.Afr., 1966-0013, (Unpublished)

DE VILLIERS, S.B., 1967. Aanvoerrigtings van sedimente van die sisteme Loskop en Waterberg in noord Transvaal soos weerspieel deur kruisgelaagdheid : Ann. geol. Surv. S.Afr., 6, p.63-68.

DE VRIES, W.C.P., 1969. Stratigraphy of the Waterberg system in the southern Waterberg area, north western Transvaal : Ann. geol. Surv. S.Afr., 7, p.43-56.

DE VRIES, W.C.P., 1970. The geology of the southern portion of the Waterberg area, north eastern Transvaal : Rep. geol. Surv. S.Afr.(Unpublished)., no.1970-0062.

DE VRIES, W,C,P., 1973. Sedimentary structures in the Southern and central portions of the Waterberg area, north-western Transvaal : Ann. geol. Surv. S.Afr., 7, p. 73-56.

DIXON, C.J., 1979. Atlas of economic mineral deposits : Chapman and Hall, London, 143p.

DU PLESSIS, M.D., 1972a. The relationship between the Bushveld Complex and the Waterberg system in the area between Loubad and Warmbad : Ann. geol. Surv. S.Afr., 9, p.85-88.

DU PLESSIS, M.D., 1972b. The geology of the area north west of Warmbaths, Transvaal : Sheet 2428C : Rep. geol. Surv. S.Afr., 1972-0043. (Unpublished).

DU PREEZ, J.W., 1944. The structural geology of the area east of Thabazimbi and the genesis of the associated iron ores : Ann. Univ. Stell., 22A, p.263-360.

DU TOIT, S.R., 1976. Mesozoic geology of the Agulhas Bank : Ph.D. thesis (unpubl.), Univ. Cape Town..

ERIKSSON, P.G., 1984. A palaeoenvironmental study of the Molteno, Elliot and Clarens Formations in the Natal Drakensberg and the northeastern Orange Free State. Ph.D. thesis Univ. Natal, 209p. (unpublished)

ERIKSSON, P.G., 1985. The depositional palaeoenvironments of the Elliot Formation in the Natal Drakensberg and north-eastern Orange Free State : Trans. geol. Soc. S.Afr., 88, p.19-26.

ERIKSSON, K.A. and VOS, R.G., 1979. A fluvial fan depositional model for middle Proterozoic red beds from the Waterberg Group, South Africa : Precambrian Research, 9, p.169-188.

FLEISHER, M., 1980. Glossary of mineral species 1980 : Mineralogical Record Tuscon, Arizona, 1992p.

FOLK, R.L., 1968. Petrology of sedimentary rocks : Hemphill's, Austin. 170p.

FRICK, A., 1970. Sedimentological aspects of a portion of the south eastern Waterberg area : Ann. geol. Surv. S.Afr., 8, p.69-74.

FRICK, A., 1971. Sedimentological aspects of a portion of the south eastern Waterberg area : Rep. geol. Surv. S.Afr., no.1971-0050, 12p.

(Unpublished).

FRICK, A., 1972a. The possibility of heavy mineral deposits in the Waterberg System : Ann. geol. Surv. S.Afr., 9, p.93-95.

FRICK, A., 1972b. Geological and geochemical investigations of a portion of the south eastern Waterberg basin : Rep. geol. Surv. S.Afr., no.1972-0002, 23p. (Unpublished).

FRICK, A., 1972c. Heavy mineral deposits in the sediments of the Waterberg System : Rep. geol. Surv. S.Afr., no.1972-0021, 6p. (Unpublished).

FUCHTBAUER, H., 1964. Sedimentpetrographische Untersuchungen in der alteren Molasse nordlich der Alpen : eclogae geol. helv. 57, p.157-298.

GADOW, S. and REINECK, H.E., 1968. Der Abbau einer Magnetit-Strandseife in Italien. Natur Mus. 98, p.57-63.

GARRELS, R.M. and MACKENZIE, F.T., 1971. Evolution of sedimentary rocks : W.W. Norton and Co., Inc. N.Y. 397p.

GLAESSNER, M.F., 1969. Trace fossils from the Precambrian and basal Cambrian : Lethaia, 2, p.369-393.

GLATTHAAR, C.W., 1965. Die verysterde piroklaste en 'n na-Waterbergse graniet, suid-oos van die dam Rust der Winter : M.Sc. Pret. Univ., 80p.

GLOPPEN, T.G. and STEELE, F.J., 1981. The deposits, internal structure and geometry in six alluvial fan-fan delta bodies (Devonian, Norway) - a study in the significance of bedding sequence in conglomerates IN Ethridge, F.G. and Flores, R.M., eds., Recent and ancient nonmarine depositional environments: models for exploration. Society of Economic Paleontologists and Mineralogists, Special Publication 31, p.64-69.

GöTZ, J., 1885. Untersuchung einer Gesteinsuite aus der Gegeng der Goldfelder von Marabastad in nordlichen Transvaal, Sud-Afrika: Neues Jahrbuch fur Mineralogie, Geologie und Palaeontologie, Beilageband, IV.

HALL, A.L., 1932. The Bushveld Igneous Complex of the central Transvaal : Mem. geol. Surv. S.Afr., 28.

HAMMERBECK, E.C.I. and TALJAARDT, J.J., 1976. Manganese IN Coetzee, C.B. (Ed) : Mineral resources of the Republic of South Africa : 5th Ed., p.167-172.

HANSON, E.C. and BORG, I.Y., 1962. The dynamic significance of deformation lamellae in quartz of a calcite cemented sandstone : Am. J.Sci., 260, p.321-336.

HANTZSCHEL, W., 1975. Part W. Miscellaneous supplement; Trace fossils and problematica IN Moore, R.C., Treatise on invertebrate paleontology.

HARGER, H.S., 1897. On the occurrence of red sandstone in the Pretoria district : Trans. geol. Surv. S.Afr., 3, part 9, p.107-108.

HARMS, J.C., SOUTHARD, J., SPEARING, D.R. and WALKER, R.G., 1975. Depositional Environments as Interpreted from Primary Sedimentary Structures and Stratification Sequences. Lecture Notes: Soc. econ. Paleont. Miner., Short Course 2, Dallas, 161p.

HATCH, F. and CORSTORPHINE, G., 1905. The geology of South Africa. 2nd edition. McMillan and Co., London. 394p.

HAY, M.H., 1975. An index of Mineral Species and Varieties arranged chemically. 2nd Ed. British Museum of Natural History. 758p.

HEARD, H.C. and CARTER, N.L., 1968. Experimentally induced 'natural' intragranular flow in quartz and quartzite : Am. J. Sci., 266, p.1-42.

HIGH, L.R. and PICARD, M.D., 1974. Reliability of cross stratification types as palaeocurrent indicators in the fluvial Rocks: J. Sed. Petrol. 44, p.158-168.

HOFFMAN, H.J., 1971. Precambrian Fossils, Pseudofossils and Problematica in Canada. Bulletin 89. Geological Survey of Canada.

HOLMES, G.G., 1904. Some notes on the geology of the northern Transvaal : Trans. geol. Surv. S.Afr., 7, p.51-56.

HUNTER, R.E., 1969. Eolian microridges on modern beaches and a possible ancient example. J. Sediment. Petrol. 39, p.1573-1578.

INGERSON, E. and TUTTLE, O.F., 1945. Relations of lamellae and crystallography of quartz and fabric directions in some deformed rocks. Am. Geophs. Union Trans., 26, p.95-105.

JANSEN, E., 1983. Die stratigrafie en sedimentologie van die Volop-Groep, Olifantshoekopeenvolging : Unpubl., M.Sc. Thesis, RAU., Dec. 1983.

JANSEN, H., 1969. The structural evolution of the southern part of the Waterberg Basin : Ann. geol. Surv. S.Afr., 7, p.57-62.

JANSEN, H., 1970a. Volcanic rocks and associated sediments in the southern portion of the Waterberg Basin : Ann. geol. Surv. S.Afr., 8, p.53-62.

JANSEN, H., 1970b. The geology of the area around Nylstroom : Rep. geol. Surv. S.Afr., no.1970-0057, 25p. (Unpublished).

JANSEN, H., 1975a. Precambrian basins on the Transvaal craton and their sedimentological and structural features : Trans. geol. Surv. S.Afr., 78, part 1, p.25-33.

JANSEN, H., 1975b. The Soutpansberg trough (northern Transvaal) - An Aulacogen : Trans. geol. Surv. S.Afr., 78, p.129-136.

JANSEN, H., 1976. The Waterberg and Soutpansberg groups in the Blouberg area, northern Transvaal : Trans. geol. Surv. S.Afr., 79, p.281-291.

JANSEN, H., 1982. The geology of the Waterberg Basins in the Transvaal, Republic of South Africa : Mem. geol. Surv. S.Afr., 71, 98p.

JANSEN, H., MEINSTER, B. and DE VRIES, W.C.P., 1970. The geology of the area between Thabazimbi and Rankins pass : Rep. geol. Surv. S.Afr., 1970-0061, 40p. (Unpublished).

JANSEN, H., MEINSTER, B., DE BRUIYN, H. and DU PLESSIS, H., 1972. Modern concepts of Waterberg tectonics and sedimentation : Rep. geol. Surv. S.Afr., 1972-0046, 28p. (Unpublished).

JEFFERY, P.G., 1959. The geochemistry of tungsten with special reference to the rocks of the Uganda Protectorate : Geochim et Cosmochin Acta. 16, 278-295.

JOHNSON, H.D., Shallow Siliciclastic Seas IN READING, H.G., Sedimentary Environments and Facies. Blackwell Scientific Publications. p.207-258.

JORISSEN, E., 1904. On the occurrence of the dolomite and chert series in the north eastern part of the Rustenburg district : Trans. geol. Surv. S.Afr., 7, p.30-38.

KERR, P.F., 1940. Tungsten bearing manganese deposit at Golconda, Nevada : Geol. Soc. Am. Bull., 51, p.1359-1390.

KYNASTON, H and MELLOR, E.T., 1912. Explanation of sheet 10 (Nylstroom). The geology of the country around Warmbaths and including the Rooiberg tin field : Gov. Printer, Pretoria. 52p.

LE ROEX, H.D., 1942. The geology of a portion of the north eastern section of the New Belgium block of farms. Sheet 31, Potgietersrust District : Rep. Geol. Surv., 1942-0052. (Unpublished).

LEVINSON, A.A., 1980. Introduction to exploration geochemistry : Applied Publishing Ltd, 310p.

LINDGREN, W., 1922. A recent deposit of a thermal spring in Bolivia : Econ. Geol., 17, p.201-206.

MARTINSSON, A., 1970. Toponomy of trace fossils. IN T. P. Crimes and J. C. Harper (Eds.), Trace Fossils. Geol. Jour., Spec. Issue 3, p.323-330

MEINSTER, B., 1969. Bedding or crossbedding? : Ann. geol. Surv. S.Afr., 7, p.63-67.

MEINSTER, B., 1970a. Deformed crossbedding in the Swaershoek stage; Waterberg system : Ann. geol. Surv. S.Afr., 2, p.63-68.

MEINSTER, B., 1970b. The geology of the area between Matlabas and

Buffelsdrift, north western Transvaal (Sheet 2326 Ellisras and 2426 Thabazimbi) : Rep. geol. Surv. S. Afr., 1970-0143, 34p (Unpublished).

MEINSTER, B., 1971. The geology of the south-eastern portion of the Waterberg Basin between Heuningfontein and the Makapansberge (Sheet 2428) : Rep. geol. Surv. S.Afr., 1971- , 38p, (Unpublished).

MEINSTER, B., 1972. The geology of the area around Gatkop east of Thabazimbi, Transvaal : Rep. geol. Surv. S. Afr., 1972-0040, 35p. (Unpublished).

MEINSTER, B. 1975. Thrusting and block-faulting around Gatkop east of Thabazimbi, Transvaal : Ann. geol. Surv. S. Afr., 10, p.57-72.

MEINSTER, B. and TICKELL, S.J., 1975. Precambrian aeolian deposits in the Waterberg Supergroup : Trans. geol. Soc. S.Afr., 78, p.191-199.

MELLOR, E.T., 1904. The Waterberg Formation and its relation to other formations in the Transvaal : Trans. geol. Soc. S.Afr., 7, p.39-50.

MELLOR, E.T., 1905a. The geology of a portion of the Springbok flats and the adjacent areas : Ann. Rep. geol. Surv. Tvl. for the year 1904. Transvaal Mines Dept., p.27-36.

MELLOR, E.T., 1905b. The geology of the neighbourhood of Rhenosterkop : Ann. Rep. geol. Surv. Tvl. for the year 1904. Transvaal Mines Dept., p.45-55.

MELLOR, E.T., 1907. The geology of the central portion of the Middelberg district, including the town of Middelberg : Ann. Rep. geol. Surv. Tvl. for the year 1906 Transvaal Mines Dept., p.53-71.

MELLOR, E.T., 1908. Discussion on paper by H. Merensky : The rocks belonging to the area of the Bushveld granite complex : Proc. geol. Soc. S.Afr., 11, p.35-36.

MELLOR, E.T., 1909a. On a portion of the Waterberg district west of Potgietersrust : Ann. Rep. geol. Surv. Transvaal for 1908, p.25-50.

MELLOR, E.T., 1909b. The geology of the Hoekbergen in the Waterberg District including Gatkop : Ann. Rep. geol. Surv. Tvl., for 1908, p.51-60.

MELLOR, E.T., 1910. The geology of a portion of the Waterberg district to the north of Nylstroom, including Zwagershoek : Ann. Rep. geol. Surv. Tvl. for 1909, p.41-51.

MERENSKY, H., 1908. The rocks belonging to the area of the Bushveld Granite Complex in which tin may be expected with descriptions of the deposits actually found : Trans. geol Surv. S.Afr., 11, p.25-42.

MIALL, A.D., 1977. A review of the braided river depositional environment : Earth Science Reviews 13, No. 1, p.1-62.

MIALL, A.D., 1978. Lithofacies types and vertical profile models in braided river deposits : a summary. IN A.D. MIALL (ed), Fluvial Sedimentology, Canad. Soc. Petrol. Geol. Memoir, 5, p.597-604.

MOLENGRAAFF, G.A.F., 1898a. Geological sketch of the Waterberg district : Geol. Surv. of the Tvl. Ann. Rep. 1898, p.18-26.

MOLENGRAAFF, G.A.F., 1898b. Rapport over het jaar 1898 van den Staats-geoloog : Geol. Surv. Tvl. Ann. Rep., 1898, 58 p.

MOLENGRAAFF, G.A.F., 1901. Geologie de la Republique Sud-Africaine du Transvaal : Bulletin Soc. Geol. France, Ser. 4, 1, no. 1, p.13-92.

MOLENGRAAFF, G.A.F., 1904. Geology of the Transvaal : Esson and Perkins, Johannesburg. 90p.

MOODIE, G.P., 1872. Map of the South African Republic (Transvaal). Original in authors posession.

PETTIJOHN, F.J., 1963. Chemical composition of sandstones - excluding carbonate and volcanic rocks : V.S. geol. Surv. Prof. Paper. 440-S, 19p.

PETTIJOHN, F.J., POTTER, P.E. and SIEVER, R. (1973). Sand and sandstone : 618p; 258 figures. Springer-Verlag, New York.

READING, H.G. (ED), 1978. Sedimentary environments and facies : Blackwell Scientific Publications. 557p.

REINECK, H.E. and SINGH, I.B., 1975. Depositional sedimentary environments : Springer-Verlag, New York, 439p.

REINSON, G.E., Barrier Island Systems IN WALKER, R.G., 1979. Facies Models. Geoscience Canada, Reprint Series 1. p.75-90.

RUST, B.R., 1979. Coarse Alluvial Deposits IN WALKER, R.G., 1979. Facies Models. Geoscience Canada, Reprint Series 1. p.9-22.

RUST, B.R. and KOSTER, E.H., 1984. Coarse Alluvial Deposits IN WALKER, R.G. (ed)., Facies Models, 2nd ed. Geoscience Canada, Reprint Series 1. p.53-70.

RUST, I.C. (1975). Tectonic and sedimentary framework of Gondwana basins in Southern Africa : in Campbel, K.S.W., Ed. Gondwana Geology Proc. Papers 3rd Gondwana Symposium, Canberra 1975, p.537-564.

SAMAMA, J.C., 1973. Ore deposits and continental weathering : A contribution to the problem of geochemical inheritance of heavy-metal contents of basement areas and of sedimentary basins IN Amstutz, G.C. and BERNARD, A.J., (Eds). Ores in sediments. Springer, New York, p.247-266.

SHORT, N.M., 1970. Progressive shock metamorphism of quartz ejecta from the Sedan nuclear explosion crater : J.Geol., 78, p.705-732.

SMALLEY, I.J. and VITA-FINZI, C., 1968. The formation of fine particles in sandy deserts and the nature of "desert" loess : J.Sedim. Petrol., 68, p.766-774.

SMITH, N.D. and BEUKES, N.J., 1983. Bar to bank flow convergence zones: a contribution to the origin of alluvial placers : Economic geology, 78, no 7, p.1342-1349.

SOUTH AFRICAN COMMITTEE FOR STRATIGRAPHY (SACS),1980. Stratigraphy of South Africa Part 1 (Comp. L.E. Kent). Lithostratigraphy of the Republic of South Africa, South West Africa/Namibia, and the Republics of Bophuthatswana, Transkei and Venda the Handb. geol. Surv. S. Afr., 8.

STANTON, R.L., 1972. Ore Petrology. McGraw-Hill, New York. 713p.

STRATTEN, T., 1975. Notes on the application of shape parameters to differentiate between beach and river deposits in Southern Africa. Trans. geol. Soc. S.Afr., 77(1), p.59-64

STRAUSS, C.A., 1942. The geology of the north eastern portion of the New Belgium block, Potgietersrust : Rep. geol. Surv. S.Afr., 1942-0052, (Unpublished).

STRAUSS, C.A., 1948. The petrology of a small dolerite and granophyre complex in the New Belgium block, Potgietersrust district : Trans. geol. Soc. S.Afr., 50,p.73-101.

TANKARD, A.J., JACKSON, M.P.A., ERIKSSON, K.A., HOBDAY, K.A., HUNTER, D.R. and MINTER, W.E.L., 1982. Crustal evolution of Southern Africa : 3,8 billion years of earth history : with a contribution by S.C. Eriksson : 523p. 182 figs. Springer-Verlag, New York.

TANNER, W.F., 1967. Ripple Mark Indices and their uses. Sedimentology, Elsevier Publishing Company, Amsterdam, 9, p.89-104.

THE ROCK COLOR CHART COMMITTEE, 1970. The rock color chart. Geol. Soc. Am.

TICKELL, S.J., 1973. The geology of the northern Waterberg area (Sheets: 2328, Pietersberg and 2326, Ellisras) : Rep. geol. Surv. S.Afr., 1973-0054 (Unpublished).

TICKELL, S., 1974. Report on borehole P188 Rhenosterpan 361LQ (Northern area Waterberg).

TICKELL, S., 1975. Braided river deposits in the Waterberg Supergroup : Trans. geol. Soc. S.Afr., 78, part 1, p.83-88

TRUTER, F.C., 1947. A remarkable transcurrent fault near Potgietersrus, Transvaal : Trans. geol. Surv. S.Afr., 50, p.1-15.

TRUTER, F.C., 1950. A review of volcanism in the geological history of South Africa : Proc. Geol. Soc. S.A. pxxix-xci.

TURNER, P., 1980. Continental red beds : Developments in Sedimentology. Elsevier, 562 p.

TYLER, N., 1979. The stratigraphy of the early Proterozoic Buffalo Springs group in the Thabazimbi area, west-central Transvaal : Trans. geol. Soc. S.Afr., 82(2), p.215-226.

TWIST, D. and HARMER, R.E., (in press) Geochemistry of contrasting intra-cratonic siliceous magmatic suites in the Bushveld Complex: genetic aspects and implications for tectonic discrimination diagrams. J. Volc. Geotherm. Res.

VAN BILJON, W.J., 1976. Goud is nie waar dit gevind word nie, 'n Oorsig van die struktuur, gesteentes, en ertsafsettings van die Transvaal : Trans. geol. Soc. S.Afr., 79, p.155-167.

VISSER, D.J.L., 1984. (Compiler). Geological map of the Republics of South Africa, Transkei, Boputhatswana, Venda and Ciskei and the Kingdoms of Lesotho and Swaziland. The Geological Survey of South Africa, 4 sheets.

VISSER, J.N.J., 1970. The Transvaal Basin - a new sedimentary model : Ann. geol. Surv. S.Afr., 8. p.75-86.

VOS, R.G. and ERIKSSON, K.A., 1977. An emboyment model for tidal and wave-swash deposits occurring within a fluvialy dominated Proterozoic sequence in South Africa : Sediment Geol. 18, p.161-173.

WALKER, T.R., 1974. Formation of red beds in moist tropical climates: A hypothesis: Geol. Soc. Am. Bull., 85, p.633-638.

WEDEPOHL, K.H., 1969. Handbook of geochemistry. Vols 1 and 2. Springer-Verlag Berlin, 442p.

WHEELER, H.E. and QUINLAN, J.J., 1951. Precambrian sinuous mud cracks from Idaho and Montana : J Sed. Petrol. 21, p.141-146.

WILKE, D.P., 1963. Die geologie van die suidelike gedeelte van blad 2428B/2 : Int. Rep. G.S. 1963-0066.

WILLIAMS, G.E., 1966. Palaeogeography of the Torridonian Applecross Group. Nature, 209, p.1303-1306.