REACTION PHENOMENA BETWEEN KARROO DOLERITE AND CAVE SANDSTONE XENOLITHS IN THE BIRD'S RIVER COMPLEX

BY

A. K. KENYON

(Submitted as an M.Sc. Thesis to the Department of Geology, Rhodes University, Grahamstown).

DEPARTMENT OF GEOLOGY RHODES UNIVERSITY

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CONTENTS

ABSTRACT

Mapping of the north-eastern portion of the Bird's River Complex revealed that two large xenoliths composed of pyroclastic rocks and sandstone of the Cave Sandstone Stage have reacted with the dolerite. All the reaction phenomena normally associated with Karroo Dolerite are encountered. These are :

(a) Metasomatism during the stage of iron enrichment of the dolerite with the production of a pyroxene-plagioclase metasomatic granophyre

(b) Metasomatism during the stage of alkali enrichment of the dolerite with the production of a potassium feldspar adinole

(c) Assimilation with the production of contaminated dolerites

(d) Fusion with the production of glassy rocks including buchites

(e) The production of rheomorphic veins

CHAPTER ONE.

INTRODUCTION.

General statement.

This project represents an investigation into the reactions that took place between dolerite magma and the associated sediments in the Bird's River Complex, near the village of Dordrecht in the North-Eastern Cape Province. The investigation has been limited to the north-eastern corner of the Complex with the area mapped covering parts of the farms Lemoenfontein and Thysfontein in the north and Romance and Murrelfontein in the south. Here xenoliths of mainly pyroclastic origin have reacted with the dolerite and almost all the reaction phenomena characteristic of Karroo dolerite magma towards associated sediments have been encountered. These include fusion and vitrification, metasomatism, rheomorphism and assimilation of the sediments. A feature of these effects has been the development of quartz paramorphs after tridymite in the bulk of the altered sediments.

In this chapter a review of previous and other related work is given, and this is followed by a description of the scope of the present investigation, a list of definitions of some important terms and an outline of field procedures employed.

A. PREVIOUS AND OTHER RELATED WORK.

Investigations into the effects of Karroo dolerite magma on associated sediments have been carried out by Mountain (1935, 1958) at Coedmore Quarries, Durban, where acidification of dolerite has occurred by incorporation of Table Mountain sandstone. Walker and Poldervaart (1941) described reaction between the Hangnest dolerite sill and Beaufort siltstones near Calvinia in the Cape Province, where rheomorphic injection of the sediments and metasomatism of a large xenolith of siltstone have occurred. Further mention of reaction of the Hangnest dolerite with the Beaufort sediments was made in an account of metasomatism of Karroo sediments by dolerite (Walker and Poldervaart, 1942). This latter account contains descriptions of metasomatism of sediments at three localities, namely Hangnest, Rietkop (near Middelpost, Cape Province), and Alewyn's Gat on the Beaufort West - Loxton road, Cape Province. In all three cases Walker and Poldervaart described reaction between dolerite sills and Beaufort sediments resulting in the conversion of siltstone to granophyre by a metasomatic process. Poldervaart (1944) described metasomatism of Burghersdorp Sandstone by the New Amalfi Dolerite Sheet with the formation of "granophyric rocks of igneous appearance". The associated Elephant's Head Dike has likewise converted Molteno sediments into granophyres.

Mountain (1944) described syntexis by Karroo dolerite in three examples in the Eastern Cape and Transkei where it appears as though intrusive dolerite has brought about the mobilization and metasomatism of the sediments with which it has come into contact. Further investigations of these phenomena in the dolerites of the Eastern Cape were carried out by Mountain (1960) and he reported on various types of felsic material in Karroo dolerite.

Frankel (1950) and Ackermann and Walker (1960) have given accounts of vitrification of sediments by Karroo dolerite. The latter authors described the production of a buchite by vitrification of coarse quartzo-feldspathic sediments by a fifty-foot sill of Karroo dolerite.

Walker and Poldervaart (1949, pp.674-684) summarized the reaction phenomena between Karroo dolerite and the sediments into which it has been intruded. They classified the processes involved into four categories, namely:

a) Fusion and vitrification.

b) Assimilation.

c) Transfusion or metasomatism.

d) Rheomorphism.

The latter two processes are regarded as relatively common and examination of these resulted in the recognition of three stages of emanations from the dolerite affecting the associated sediments. The three stages of emanations are:

a) An early <u>iron-rich</u> stage resulting in the addition of Ti, Fe, Mg and Ca to the affected sediments and a concomitant loss of Si, Al and K to the metasomatizing fluids.

b) A sodium-rich stage, this being one of albitization, resulting chiefly in the addition of Na and Al which were removed previously by the iron-rich emanations.

c) A potassium-rich stage where sodium previously added is now lost and Si is added with the overall effect being one resembling granitization. These two authors consider that the major changes during metasomatism and rheomorphism were produced by a fluid medium comprising both magmatic emanations and sedimentary pore fluid.

First mention of the Bird's River Complex was made by du Toit (1905, pp.130-132) where he states that "A most curious complex of igneous and sedimentary rocks occurs on the farm Stafelberg's Vley, a few miles north-west of Bird's River Siding, and appears to mark a centre of volcanic activity." He very briefly described the metamorphic effects of the dolerite in this area, noting the formation of a hornstone from fine-grained sediments, and a cordierite glass.

Further report on this area was made by du Toit in 1911 where he records that pebbly sandstones of the Molteno stage are about 1000 feet above their normal position. He (1911, p.134) observed a "strip of indurated sandstone accompanied by a thick and extensive bed of volcanic ash" occurring on the farm Wagen Pads Kloof (subsequently renamed Romance). He regarded this as a xenolith of Cave Sandstone. A short note (p.134) is also made of the existence of a fine-grained quartz-dolerite overlying thin strips of highly altered ashes.

This area, du Toit states, is at the north-easterly beacon of the farm and it may be possible that he mistook some of the metasomatized pyroclastic rocks found in this area for fine-grained dolerites as in the field some of the more highly metasomatized material can easily be misidentified as light-coloured dolerite.

Du Toit (1920, pp.10-11) used the Bird's River Complex to illustrate the mechanism of emplacement of a bell-jar intrusion. Reference is again made here to the high degree of alteration of the sediments and to local fusion of these, producing a cordierite glass.

A more thorough investigation of the Bird's River Complex was carried out by Booth (1971). Booth mapped the area and produced two maps. His first map (scale; 1:28 600) shows the Bird's River Dolerite Complex and surrounding geology and his second (scale; 1:14 300) is a more detailed map of the bell-jar intrusion itself. Fig. 1 of the present work is taken from Booth (loc. cit.) and is on the scale of 1:200 000. The rectangular area marked represents the area mapped by the author.

In a later paper, Eales and Booth (1974) give a summary of Booth's original thesis plus subsequent analytical data by Eales.
Eales (1974) has used examples of the contact-metamorphic rocks of the Bird's River Complex to examine the significance of quartz paramorphs after tridymite in the North-Eastern Cape.

It is worthwhile to examine data from other igneous provinces concerning reaction between dolerite and associated sediments. Reynolds (1940) cites an example of felsitic material developed in Triassic pebble beds at their contact with an olivine dolerite dyke of Tertiary age. Potash metasomatism occurred here at a temperature high enough to facilitate the formation of tridymite. Butler (1961) describes alkali metasomatism and vitrification of Moine arkoses and pelites in contact with a dolerite plug at Glenmore, Ardnamurchan. Smith (1969) illustrates in great detail progressive thermal metamorphism and formation of granophyres in the Dalradian arkoses and phyllites adjacent to a Tertiary dolerite plug. Quartz paramorphs after tridymite have developed in the sediment in this example.

B. SCOPE OF THE PRESENT INVESTIGATION.

This project entails a field, petrological and chemical study of metamorphism and metasomatism of sediments of pyroclastic origin occurring as xenoliths in the Bird's River Dolerite Complex. Professor H.V. Eales introduced the author to this area and it was on his suggestion that this investigation was carried out.

A detailed map of the area investigated was produced with the aid of aerial photographs and field work. Petrological work was carried out on the samples collected. Twenty chemical analyses were completed by the author and one by T.J. Broderick and S.H. Finnemore under the supervision of the author. These analyses and others extracted from the literature will be examined in order to interpret the processes involved in the reaction between the dolerite and the adjacent sediments.

C. DEFINITIONS OF TERMS.

For the purposes of clarity a few terms which will be used in the chapters ahead will be defined at this point.

1) Metasomatism is "an essentially simultaneous molecular process of solution and deposition by which, in the presence of a fluid phase, one mineral is changed to another of differing chemical composition" (Lindgren, 1925). This definition is similar to that used by Walker and Poldervaart (1949, p.675). The adjective metasomatic will be used only when referring to rocks believed to have undergone extreme metasomatism.

2) Granophyre is a "rock having in its composition fine-grained intergrowths of quartz and alkali feldspar" (Barker, 1970). A suggestion is made by Barker that the words "micrographic" and "micropegmatitic" be avoided as they intimate greater structural regularity than is commonly found. In the Bird's River rocks under investigation the texture normally reveals a fine intergrowth of needle-like quartz paramorphs after tridymite, and sanidine, to which the word "graphic" would not apply. A suggested term for this intergrowth found in the Bird's River area would be "tridymite granophyre".

3) Definitions relating to the pyroclastic rocks. The terminology to be used in the description of the pyroclastic rocks will be based on the definitions and classification of Wentworth and Williams (1932) and updated by Fisher (1961).

(a) Pyroclastic Rocks are produced by explosive or aerial ejection of material from a volcanic vent (Wentworth and Williams, 1932 p.50). Fisher (1961, p.1412) regards tuffs as consisting of pyroclastic fragments less than 2mm.

(b) Blocks are "fragments of accessory or accidental material, usually angular and larger than 32mm in diameter, erupted in a solid state" (Wentworth and Williams, 1932, p.46). Fisher (1961, p.1411) improved upon this by limiting the size of "fine blocks" to the range 64 - 256 mm and "coarse blocks" to those exceeding 256 mm.

(c) Lapilli are "essential, accessory and accidental ejecta ranging mostly from 32mm to 4mm in diameter" (Wentworth and Williams, 1932, p.47). Fisher (1961, pp.1410-11) has broadened the range of these fragments to include the diameters 2mm to 64mm. Fisher classifies fragments less than 2mm as ash. It is worth noting that the size classifications of Fisher correspond to boulder, cobble and pebble sizes of sediments.

(d) Agglomerate and pyroclastic breccia. Wentworth and Williams (1932, p.45) defined an agglomerate as "a pyroclastic rock containing a predominance of rounded or subangular fragments greater than 32mm in diameter, lying in an ash or tuff matrix". Fisher (1961, p.1412) redefined an agglomerate as a "rock aggregate composed mainly of large (greater than 64mm) pyroclastic fragments rounded by volcanic processes. Where the fragments are angular Fisher proposes the use of the term pyroclastic breccia.

The adjectives accessory, accidental and essential are defined as follows:

Accessory refers to "pyroclastic materials derived from previously solidified volcanic rocks of consanguineous origin". This is debris of earlier formed lavas or pyroclastic rocks that have been ejected from the same cone.

Accidental means "pyroclastic materials derived from volcanic rocks, non-consanguineous with the magma involved during an eruption, or from other igneous, metamorphic or sedimentary rocks through which the vent was developed" (Wentworth and Williams, 1932, p.45).

Essential means "pyroclastic debris, whether loose or indurated, which is of immediate, juvenile, magmatic origin" (Wentworth and Williams, 1932 p.17).

From the above, the term lapilli-tuff would mean "an indurated deposit essentially made up of lapilli in a fine tuff matrix" (Wentworth and Williams, 1932 p.47). The range in the size of the lapilli would be as laid down by Fisher (1961, p.1412). However, he proposes the use of the word lapillistone for these rocks whereas a pyroclastic tuff would contain fragments less than 2mm in size.

4) Adinole is an argillaceous sediment which has undergone abilitization

as a result of contact metamorphism along the margins of a sodium-rich mafic intrusion. (Gary et al., 1972). The term "potassium adinole" has been coined by the author to define a similar rock where potassium metasomatism been dominant.

5) Spilosite is a spotted metamorphic rock representing the early stage of formation of an adinole. (Gary et al., 1972). The spots are composed of an assortment of minerals, generally feldspar.

6) Dolerite-pegmatites are coarse-grained segregations occurring as veins or schlieren in dolerite intrusions. Augite, ferroaugite, and pigeonite may occur, while orthopyroxene is absent (Walker and Poldervaart, 1949, p.617).

7) Buchite is a vitrified hornfels produced by fusion of an argillaceous rock by intense, local thermal metamorphism. (Gary et al., 1972).

D. FIELD PROCEDURES EMPLOYED.

1) Collection of data in the field.

Initial sampling was carried out to determine the limits of the area of interest. Samples for chemical analysis were collected along traverses and localities sampled were permanently marked in the field with painted numbers.

The area was subsequently mapped on a scale of 1:5 000 using 1:30 000 aerial photographs of the area enlarged 6 times. These enlargements were purchased from the South African Trigonometrical Survey Offices. The geological data were initially plotted on transparent overlays placed over the photographs. However, this method proved tedious as constant alignment of the overlays was difficult in the field. The overlays also obscured further the poor detail produced in the photographs as a result of the excessive enlargement. Subsequent use of photographic paper having a matt finish enabled data to be plotted directly onto the photograph, thus making the process much easier. Dips and strikes were measured using a magnetic compass and clinometer.

Most of the Samples were collected along the dolerite-sediment contact, however, a few sets of samples were collected along traverses at right angles to the contact with the sediments.

Two sampling problems arose. The first is that completely fresh unaltered pyroclastic material required for chemical analysis was not found and thus about 10kg. of the freshest material available was taken. The second problem came to light only in the laboratory. None of the contact dolerite samples collected adjacent to the xenoliths was entirely free from small sedimentary fragments. Much of this foreign material is not visible in the hand specimens.

2) Compilation of the geological map.

In the field geological data were plotted on 6 times enlargements of the standard 1:30 000 aerial photographs. These data are reproduced in the 1:10 000 map to be found in the back flap of this book.

E. LABORATORY PROCEDURES.

A description of laboratory procedures is in the appendix.

CHAPTER TWO.

A SUMMARY OF THE GENERAL GEOLOGY OF THE BIRD'S RIVER COMPLEX.

General Statement.

This chapter constitutes a summary of investigations into the Bird's River Complex by Booth (1971) and also Eales and Booth (1974).

A. LOCATION OF THE AREA.

The Bird's River Complex lies about 20 km. south-west of the village of Dordrecht in the North Eastern Cape Province of South Africa. The area covered by Booth's map (see Fig. 1) is approximately 310 sq. km. The actual intrusion and associated ring-dikes occupy about one quarter of the area mapped. The south-western margin of the intrusion forms part of an escarpment which rises steeply to 2080 metres above sea level, from undulating plains at an average elevation of 1500 m.

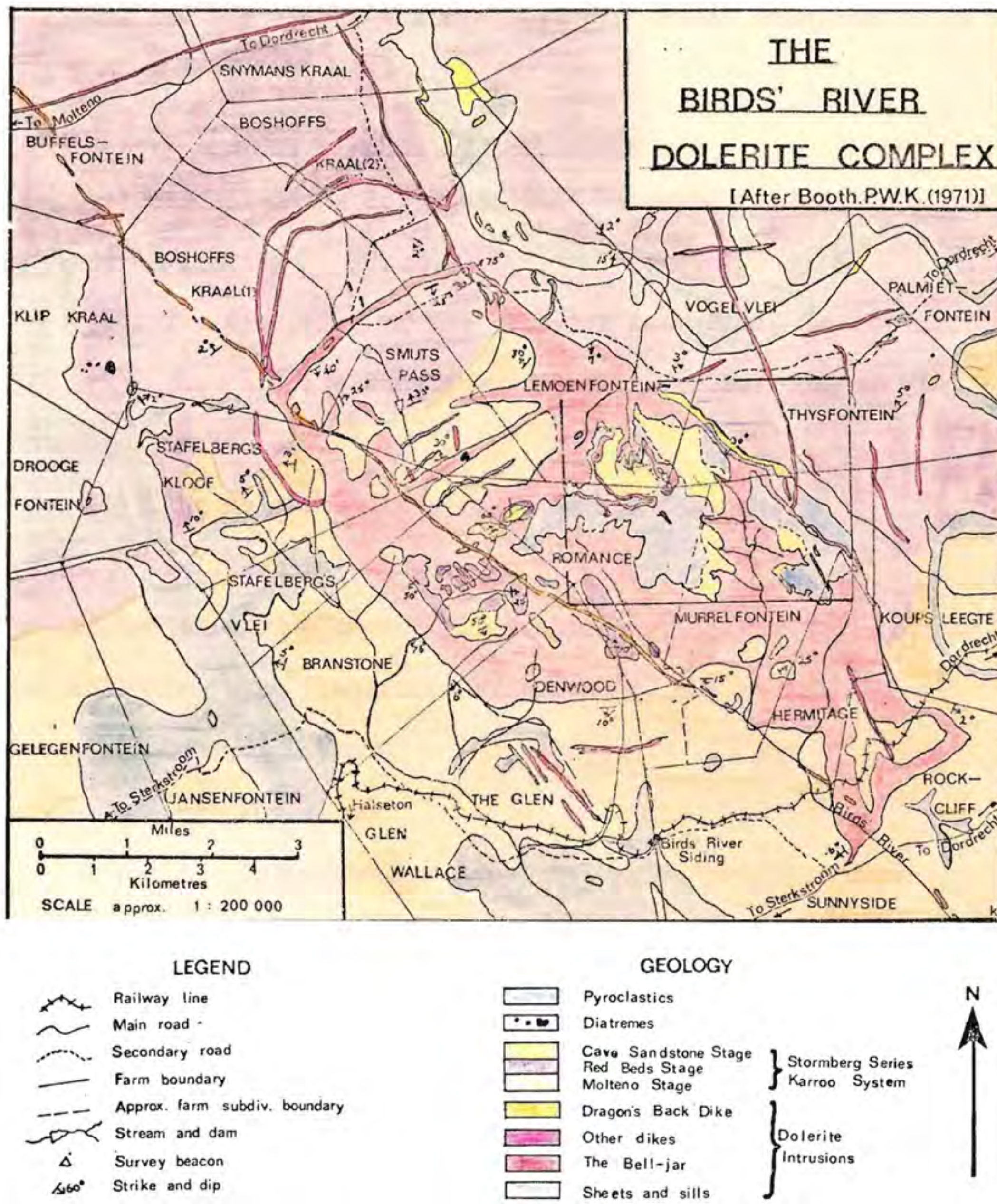
B. STRUCTURE OF THE INTRUSION.

The Bird's River Complex is a discordant, plug-like intrusion of Karroo dolerite intruded into the generally flat-lying sediments of the Stormberg Series. Molteno sediments occur along the southern contact of the intrusion while the overlying Red Beds are in contact with most of the northern margin of the complex. A narrow band of volcanic breccia belonging to the Cave Sandstone Stage of the Stormberg Series is in contact with the dolerite along the north-eastern margin of the intrusion.

In plan the intrusion is roughly oval in shape with its longest axis trending northwest - southeast. Along the western, northern and southern margins of the intrusion the margin of the dolerite dips vertically or steeply outwards from the centre. At the eastern margin the intrusion becomes sill- or sheet-like in character and the contact dips inwards at a shallow angle. It is assumed that the south-eastern portion of the intrusion (at a point about one kilometer north of the railway line shown in Fig. 1) is an off-shoot of the intrusion in the form of a flat-lying tongue. Eales and Booth (1974 p. 4) adhere to du Toit's (1920, p. 11) original structural classification of this body of dolerite as a bell-jar intrusion. Du Toit did not recognise that on the eastern and south-eastern sides of the intrusion magma broke out and assumed the form of a westerly dipping sheet.

The attitude of the sediments has been little affected by this relatively large dolerite intrusion and the bulk of these sediments dip away from the intrusion at shallow angles. However, in the portion mapped by the writer, along the eastern margin on the farms Thysfontein, Lemoenfontein and Murrelfontein, the sediments dip in towards the intrusion at angles of 30-40 degrees.

Within the intrusion large areas of sediment are found which are regarded as foundered roof fragments. These xenoliths show a wide diversity in size, attitude and lithology. They vary in size from a few metres to that of the Smuts Pass xenolith which is 4.4 km. across. The two xenoliths pertaining to this dissertation occur within the eastern portion of the complex and are composed in the main of


THE
BIRDS' RIVER
DOLERITE COMPLEX
[After Booth. P.W.K. (1971)]
To Dordrecht
SNYMANS KRAAL
To Molteno
BUFFELS-FONTEIN
BOSHOFFS
KRAAL(2)
BOSHOFFS
KRAAL(1)
KLIP KRAAL
SMUTS PASS
VOGEL VLEI
PALMIET-FONTEIN
LEMOENFONTEIN
THYSFONTEIN
DROOGE FONTEIN
STAFELBERGS KLOOF
ROMANCE
STAFELBERGS VLEI
MURRELFONTEIN
KOUPS LEEGTE
BRANSTONE
DENWOOD
HERMITAGE
GELEGENFONTEIN
To Sterkstroom
JANSENFONTEIN
Halseton
THE GLEN
GLEN WALLACE
Birds River Siding
Birds River
ROCK-CLIFF
To Dordrecht
To Sterkstroom
SUNNYSIDE
Miles
0 1 2 3
0 1 2 3 4
Kilometres
SCALE approx. 1 : 200 000
LEGEND
Railway line
Main road
Secondary road
Farm boundary
Approx. farm subdiv. boundary
Stream and dam
Survey beacon
Strike and dip
GEOLOGY
Pyroclastics
Diatremes
Cave Sandstone Stage
Red Beds Stage
Molteno Stage
Stormberg Series
Karroo System
Dragon's Back Dike
Other dikes
The Bell-jar
Sheets and sills
Dolerite Intrusions
N

(Fig. 1)

sediments of pyroclastic origin. Booth estimated the size of the western and larger of the two xenoliths (the Cairn Xenolith) to be 4,2 X 3,5 km. and the almost basin-shaped Grootkloof xenolith to be of 3,0 X 1,0 km.

C. PETROLOGY OF THE DOLERITES.

Booth (p. 59) described the dolerites that he mapped under three broad headings, namely:

(1) The dolerites of the bell-jar intrusion.

(2) The dolerite sheets surrounding the bell-jar intrusion.

(3) The dolerite dikes of later age than the bell-jar intrusion.

Those dolerites belonging to the first category, namely those of the bell-jar intrusion were classified by Booth (p. 60) as follows:

(a) Contact Rocks

- (i) Tholeiite
- (ii) Intergranular type

(b) Coarse-grained rocks

- (i) Poikilophitic olivine dolerite
- (ii) Poikilophitic olivine dolerite with quartz
- (iii) Quartz dolerite
- (iv) Roof zone rocks

A summary of petrographic and mineralogical data relating to some of these rocks are given in Table I.

TABLE I

Petrographic data of some of the igneous rocks of the Bird's River Complex.

Type	Poikilophitic Olivine Gabbro	Poikilophitic Qtz. Olivine Gabbro	Quartz Dolerite	Ferrogabbro	Ferrotholeiite	Dolerite-pegmatite
Grain size	Coarse	Coarse	Coarse	Medium	Medium	Coarse
Texture	Poikilophitic	Poikilophitic	Ophitic	–	Porphyritic	Subophitic to ophitic
Plagioclase Composition	An_{75} to An_{78}	An_{75} to An_{78}	An_{70} to An_{78}	–	–	An_{63}
Augite Composition	$Ca_{41}\ Mg_{50}\ Fe_{9}$*	$Ca_{40}\ Mg_{47}\ Fe_{12}$✶ (core) $Ca_{36}\ Mg_{42}\ Fe_{22}$✶ (margin)	$Ca_{37}\ Mg_{42}\ Fe_{21}$*	$Ca_{34}\ Mg_{34}\ Fe_{32}$✶	From $Ca_{40}\ Mg_{16}\ Fe_{44}$✶ to $Ca_{42}\ Mg_{6}\ Fe_{52}$✶	i) $Ca_{40}\ Mg_{47}\ Fe_{13}$* ii) $Ca_{29}\ Mg_{22}\ Fe_{48}$
Olivine Composition	Atomic % ✶ Mg : 73,6 Fe^{2+}: 26,4	Present	Absent	Fa_{25} to Fa_{55}*	Atomic % ✶ Mg : 11,0 Fe^{2+}: 89,0	Absent
Orthopyroxene (Opx.) Pigeonite (Pig.)	Opx. present Pig. present	Opx. minor Pig. present	Opx. absent Pig. present	Opx. absent Pig. $Ca_{34}Mg_{34}Fe_{32}$✶	Opx. absent Pig. absent	Opx. absent Pig. present
Mesostasis	–	Micropegmatite and quartz	Micropegmatite and quartz	Microcrystalline with quartz	–	Micropegmatite and quartz

* implies optical data and ✶ implies microprobe data. All the above data are from Booth (1971) and Eales and Booth (1974).

Booth (1971, p. 81) and Eales and Booth (1974, p. 5) regard the bell-jar dolerites as being similar to the "Kokstad Type" dolerite of Walker and Poldervaart (1949, p. 616). The latter authors describe this type as a coarse-grained, subophitic dolerite where plagioclase generally constitutes 50 per cent of the rock by volume, augite occurs with orthopyroxene, olivine varies in abundance and interstitial micropegmatite is present.

The quartz dolerites and roof zone rocks of the bell-jar intrusion are the result of differentiation from a parent dolerite magma with associated iron enrichment. The intrusion itself is considered to have evolved by successive injections of magma.
A number of sills and sheet-like bodies of dolerite are found within the sedimentary xenoliths of the intrusion. The largest, Skerprand, is about three kilometers long and is approximately 50 metres thick. As the dolerite of this sill appears to merge into the dolerite of the bell-jar intrusion, Booth (p. 29) believes that this sill is of the same age as the bell-jar dolerite.

The relative ages of the numerous other sills and sheet-like bodies in the xenoliths were not determined by Booth due to lack of field evidence and a tentative interpretation is that these sills could have been intruded into the sediments before these became disrupted by the intrusion. He described the dolerites of these sills noting that they have ophitic to intergranular texture.

D. THE PYROCLASTIC ROCKS.

The pyroclastic rocks associated with the Bird's River area were described by Booth (pp. 100-114) under the following headings:

(1) Pyroclastic rocks containing less than 5 per cent igneous inclusions.

(2) Pyroclastic rocks containing between 5 and 25 per cent igneous inclusions.

(3) Pyroclastic rocks containing between 25 and 50 per cent igneous inclusions.

(4) Pyroclastic rocks containing more than 50 per cent igneous inclusions.

Types (1) to (4) all occur within the Cairn Xenolith and Grootkloof Xenolith. However, types (3) and (4) are the most common.

The classification devised by Gevers relating to fragmental rocks occurring within volcanic vents of the western Stormberg was listed by Booth (p. 102). He attempts to relate this classification to the pyroclastic rocks of the Bird's River area.

Pyroclastic rocks in the Bird's River area are interbedded with Stormberg sediments both within and beyond the periphery of the bell-jar intrusion. In the field they are generally highly weathered. Reference to these pyroclastic rocks based on the present author's observations will be made at a later stage.

Mode of Formation of the Pyroclastic Rocks.

As these pyroclastic rocks constitute the bulk of the rock types that have undergone metamorphism and metasomatism within the Cairn and Grootkloof xenoliths it is pertinent at this point to examine Booth's deductions relating to the origin of the pyroclastic rocks. He (p. 109) considers that the Bird's River area was once a site of intense volcanic activity and as the sedimentary rock types produced by this volcanic action contain abundant quartzitic material he states that "......... gaseous activity in a 'central' type of volcano played the principal role in their formation."

Both Booth and the present writer agree that the main focus of volcanic action is in all probability in the eastern portion of the bell-jar. The two xenoliths that occur in this area, i.e. the Cairn and Grootkloof xenoliths, contain large clasts of volcanic ejecta within the pyroclastic rocks. These clasts included sedimentary material of Molteno, Red Beds and Cave Sandstone Formations and also coarse-grained dolerite, finer grained basalt and glassy fragments. In the Cairn xenolith large fragments of doleritic material, some over a metre in size, occur in the pyroclastic rocks. Also, the largest outcrop of pyroclastic rocks is to be found in this area. The total exposed area of outcrop of pyroclastic rocks including the two previously mentioned xenoliths is at least 20 sq. km.
Booth (pp. 110-112) suggests that after a short phase of gaseous activity which produced diatremes, the vent was widened by build-up and subsequent explosive release of pressure, resulting in the blowing

out of fragmental rock material. A tuffaceous sandstone with a few igneous fragments was produced. Some of these igneous fragments are in the form of large blocks of dolerite, indicating high gaseous pressure in the vent. These doleritic blocks are either from original magma that cooled and crystallized in the vent or they are members of an earlier intrusion that were broken off as the vent forced its way upwards. The large size of the blocks indicates possible deposition of this rock type in or just outside of the vent.

Booth (p. 112) also considers the possibility of some of the pyroclastic material being redeposited some distance from the original volcanic vent as a result of a mudflow. However, the author disagrees with this hypothesis as the glass lapilli present in these agglomerates are not distorted or broken as one would expect as a result of being pushed along in a mudflow.

The proportion of the igneous matter in the Bird's River pyroclastic rocks increased with the increase in volcanic activity in this area. Booth cites the lapillistones on Murrelfontein as an example of this. It is these rocks that exhibit most of the metasomatic effects to be described.

E. METAMORPHISM AND METASOMATISM.

Booth (pp. 124-132) makes brief mention of metamorphism and metasomatism within the Bird's River intrusion and much of his information is based on the author's own preliminary work. However, he made certain observations outside the area examined by the author which are worth noting.

Firstly, Booth noted that the metamorphic aureole in the country rocks surrounding the bell-jar is remarkably small considering the large size of the intrusion. The aureole extends a few metres away from the contact. The rocks produced are quartzites, lydianites and "a rock resembling a porcellanite."

The more intense metamorphism of the xenoliths within the bell-jar intrusion is discussed. Near the western margin of the Smuts Pass xenolith, in the western part of the intrusion, Booth observed signs of a glassy rock having been produced. Mention is made of the "glassy ridge" on Murrelfontein where continual streaming of the dolerite past the xenolith at this point resulted in partial fusion of the pyroclastic rocks.

Eales (1974) examined the melting behaviour of two fused sedimentary rocks and a partly vitrified dolerite - pegmatite clast from the xenoliths on Lemoenfontein and Murrelfontein, and deduced P-T conditions for contact-metamorphosed rocks in the Bird's River Complex. He concluded that the tridymite that occurs in the contact rocks of the xenoliths formed within its stability field.

CHAPTER THREE.

FIELD RELATIONSHIPS.

Preliminary Statement.

The area mapped covers 20,7 sq. km. and occupies the south-eastern and south-western portions of the farms Lemoenfontein and Thysfontein, and the north-eastern and northern portions of the farms Romance and Murrelfontein. There are two large roof fragments of sedimentary material within this area and for the purpose of convenience the western and larger xenolith will be referred to as the Cairn xenolith and the eastern one as the Grootkloof xenolith.

The investigation was carried out in order to examine metamorphic and metasomatic effects resulting from reaction between the dolerite of the bell-jar intrusion and the xenoliths. Most of the field-work entailed examination of the xenoliths with little attention being paid to the outer contact of the intrusion. For the most part this latter contact exhibits baking of the country for a few feet from the dolerite.

A. THE TOPOGRAPHY AND GEOMORPHOLOGY OF THE MAPPED AREA.

The altitude within this area varies from less than 1650 m. above sea level to slightly more than 2000 metres above sea level, an overall variation of about 400 m. Data obtained from the 1 : 50 000 scale map of the Trigonometrical Survey (map 3126 EM 78 BIRD RIVER) shows that the highest ground within the area mapped by the author is a few hundred metres north of the cairn where a spot height is given at 6588 feet above sea level (2007 m. above sea level).

Within the confines of the intrusion the hills are characterized by steep sides and generally rounded outlines, while the high ground at the north-eastern edge of the intrusion forms a sharp ridge having a north-westerly trend.

The steep-sided hills that occupy the western half of the area mapped rise up to a plateau south and south-west of the cairn (grid refs. B4, B5, C4, C5, D5 and D6). This plateau slopes gently to the south and portions of it have been cultivated in the past. It is drained by a number of small, mostly dry streams and gullies that flow in northerly and southerly directions. The set of streams and gullies that flows towards the north joins up with a slightly larger stream in the north-western corner of the area (grid ref. B1). The latter stream appears to contain water for most of the year and flows towards the north-east.

A valley runs adjacent and almost parallel to the ridge that forms the eastern margin of the intrusion. In the south-eastern portion of the map (grid ref. F7) this valley becomes a deep and impressive gorge cut by a narrow, apparently continuously flowing stream. This stream, fed by gullies from the steep valley sides, flows to the south.

A steep dolerite cliff rises above the north-eastern bank of this stream and the gorge has aptly been named Grootkloof by the local farmers (see Plates III and IV). The stream has as its source a series of springs that occur in the central portion of the area mapped.

B. THE CAIRN XENOLITH.

This is the larger of the two xenoliths in this area and occupies the bulk of the western half of the area mapped. Booth (1971) estimated the size of this xenolith and gave its dimensions as 4,2 x 2,2 km.

The xenolith is rather irregular in shape and is primarily composed of pyroclastic rocks and Cave Sandstone. From the evidence (geological section A-B, see back flap) it seems that the sandstones and sandstone-tuffs which underly the pyroclastic rocks, form a quite substantial horizon of sediments. Dolerite in the form of sheets and irregular bodies is found within this xenolith.

1. The pyroclastic rocks.

Fresh, unaltered pyroclastic material not exhibiting the effect of thermal metamorphism was not found in the field. Thus the data presented relating to laboratory observations on these rocks were obtained from samples exhibiting the effects of weathering.

The pyroclastic rocks consist of fragments varying in size from minute ash fragments, less than a millimetre in size, to large blocks of doleritic material measuring over a metre. Most of the fragmental material over 20 cm. in size appears to be dolerite, while the smaller fragments are sedimentary, or are glassy or crystalline igneous fragments.

The groundmass of these pyroclastic rocks is a medium-grained, light-coloured, quartz-rich assemblage. These rocks are characterized by poor sorting and lack of any development of bedding.

The pyroclastic rock containing the largest blocks appears to be centred south and south-west of the cairn. (Grid ref. B5 and C5). In this area fragments of older pyroclastic rocks were found in the sediments (accessory fragments of Wentworth, 1932). These fragments are from deposits of pyroclastic rocks that were broken up by later cycles of volcanism and subsequently redeposited to form part of the present outcrop.

On the opposite side of the valley north of the cairn, (grid ref. E3) pyroclastic rocks are found containing fragments up to 60 cm. in diameter. There is a decrease in the size of the fragmental material downwards towards the underlying sandstones.

The bulk of the pyroclastic material however, is essentially lapilli-stone (Wentworth, 1932, p. 52). The majority of the lapilli are yellow-brown to brown, irregular-shaped, glass fragments occurring with an assortment of sedimentary fragments. The modal analyses presented in

Table II are of three lapillistone samples collected at three places within the xenolith and illustrate the inhomogeneity of these rocks.

On thermal metamorphism these pyroclastic rocks become dark blue or blue-green in colour. They are hard, brittle, break with conchoidal fracture, and in outcrop intense jointing in two directions is often exhibited. Most of the pyroclastic rocks seen in this xenolith have undergone some degree of thermal metasomatism and often at quite substantial distances from any <u>visible</u> outcrops of dolerite, suggesting that the present erosion surface of the xenolith is not very far above the underlying dolerite.

In the extreme cases of metamorphism and metasomatism the assorted lapilli have been almost completely destroyed. Rocks of this nature were found at the cairn and in the high ground slightly further north, (grid ref. C4 and plate II). Here, dolerite intruded into the xenolith has resulted in the pyroclastic rocks being altered to a pale grey, hard rock sometimes assuming an almost homogeneous appearance. The relicts of mainly sedimentary fragments are often visible but are not very common.

The weathered surface of these more intensely metamorphosed pyroclastic rocks may be described as "warty" due ot the resistance of some of the lapilli to weathering relative to the rest of the rock. In the field the presence of needle-like hypersthene was evident from the fine,

TABLE II.

Abridged modal analyses of three samples of lapillistone.

(Values in volume per cent).

Sample no.	$T_1/1$	X28	X17
Sedimentary clasts	5,3	19,0	7,4
Igneous clasts	30,7	13,7	42,1
Groundmass	64,0	67,3	50,5
Total	100,0	100,0	100,0
No. of counts	1592	4369	1213

(See Table IX for sample designation).

PLATE 1 : The northern portion of the Cairn xenolith caps the tops of the hills and it is here where the best exâmples of contaminated dolerite and metasomatic granophyre are encuontered.

PLATE 11 : The metasomatic granophyres outcropping south-east of the stone cairn. The dashed line represents the approximate zone of hybridization between the underlying dolerite and the granophyres which cap the hill.

elongated pits that have developed on the weathered surfaces.

Metasomatising fluids emanating from the dolerite are believed to have played a part in the production of these altered rocks. Mineralogical and chemical data will be presented later that will help to illustrate the processes involved.

The precise contact between the intensely metasomatised rocks and the underlying dolerite sheet was never precisely determined due to its being obscured by talus on the slopes. This capping of altered rocks is more resistant to weathering than the underlying dolerites.

The effects of metamorphism on the pyroclastic rocks along the outer margin of the xenolith are variable. The pyroclastic rocks have, on the one hand, been baked and on the other there has been production of glassy rocks. The development of quartz paramorphic after tridymite is a feature of these metamorphic rocks and was found partly developed in samples collected up to 20 metres away from the contact.
Extreme metamorphism has resulted in almost complete merging of the lapilli with the groundmass, producing dark-gray to black, recrystallized rocks. Nowhere along the outer contact of the xenolith are pyroclastic rocks, resembling those around the cairn, found.

2. The sandstones and sandstone-tuf

Sandstone and sandstone-tuffs underlie the pyroclastic rocks and are also interbedded with them. These are cream-coloured, medium-grained rocks. Sedimentary fragments produced by explosive volcanic action may or may not be present in these rocks. The term "sandstone-tuff" refers to material where these fragments are clearly visible in the arenaceous matrix.

Bedding or other sedimentary structures are more common in these rocks and from the data obtained it appears as though this xenolith dips to the north, the angle of dip being between 10 and 25 degrees. Narrow bands of shale interbedded with the sandstones were helpful in mapping this xenolith. Cross-bedding was observed in the sandstones in three small outcrops. However, the extent of development of this sedimentary structure was not determined as the outcrops were very small.

Metamorphism of the sandstone-type rocks for the most part has been limited to recrystallization of the constituent minerals. The partial development of tridymite is a common occurrence, as is the development of a spotted appearance at an early stage during metamorphism. However, the effects of extreme metamorphism are found locally along the margin of the Cairn xenolith.

Spectacular development of metamorphic rocks in the sandstone-tuffs in a small outcrop was found in the south-eastern corner of the xenolith (grid ref. E6 and E7). Grey and black, brittle, spotted rocks, and a black, banded hornfels exhibiting the effects of flow, have been produced by metamorphism and metasomatism. This hornfels has been named a "potassium adinole" and the contorted layers are composed of alternating fine and coarse crystalline material. The degree of contortion of the bands is high, (an indication that plastic flow has occurred) and the contact with the dolerite is sharp.

Metasomatism of the sandstone-tuffs, similar to that exhibited by the pyroclastic rocks in the vicinity of the cairn, was found along the outer contact of the xenolith with the dolerite. Two small, weathered outcrops occur, the metasomatic rocks in this case not being as resistant to weathering as their counterparts originating from the pyroclastic rocks.

Metamorphism of the narrow shale bands has resulted in the production of a buchite. The original shale appears to have contained clastic volcanic material as green-coloured "patches" occur that resemble those found in the pyroclastic rocks. Buchites are regarded as having originated from fusion of argillaceous rocks and this example appears to be typical of these rocks. It is a black, brittle glassy rock, shattering when hit with a hammer. In outcrop it has a gray weathered surface. These fusion products are of local occurrence and are found within a few feet of the contact.

The baking of these sandstones has resulted in their becoming intensely jointed.

The sandstones interbedded with the pyroclastic rocks are more or less identical to those underlying the pyroclastic rocks, with one exception. In the central and western part of this xenolith (grid ref. A4 and B4) two narrow beds of white, rather porous, arenaceous sandstone occur in the pyroclastic rocks. No indication was found in the field that these two bands are the same horizon as brecciation of the xenolith in this area has obscured the relationship between them. From petrological examination they could well be the same horizon. The thickness of these beds is about three metres.

3. <u>The periphery of the Cairn xenolith.</u>

The metamorphic phenomena along the margin of this xenolith have been described and only a few points need be added.

The contact between the xenolith and the dolerite, where it is visible, is sharp and for the most part relatively regular. However, on the farm Lemoenfontein, where the contact runs roughly north-south (on longitudinal grid reference line between B2 and B3, and C2 and C3) the contact becomes irregular and ingestion of the sediments has occurred. About 20 cm. from this contact a sample of dolerite was found containing rounded disseminations of sulphide mineralization. The disseminations are about 2 mm. in diameter and are about 2 cm. apart.

At three points along the contact on the western side of the xenolith there is evidence of fusion of the sediments. The buchite and glassy recrystallized pyroclastic rocks are examples of the rocks that have been produced.

4. Dolerite within the xenolith.

Dolerite occurs as sheets, sills and irregular bands in the xenolith. Booth (1971, pp. 68-69) presumed dolerite sills in the Smuts Pass xenolith to be of greater age than the bell-jar intrusion. However, it appears that the dolerite intruded into the xenolith during the stoping of these large blocks of sediment. Brecciation of the xenolith during the stoping process enabled the dolerite to force its way along fracture planes that formed in the sediments. South-west of the cairn (grid ref. B4 and B5) shearing and brecciation of the pyroclastic rocks has resulted in the dolerite being intruded into the xenolith as irregular sheets.

A further example of the stresses in this area is seen in a small outcrop of sandstone about 300 metres south-east of the brecciated zone (grid ref. B5) where a small, well jointed anticline has developed. The strike of this anticline is more or less parallel to the prominent direction of shearing in the zone of brecciation, having a bearing of about 50°. The angles of dip in this structure are 75 - 80° to the south-east and 25 - 30° to the north-west. It is possible that the zone of brecciation and this folding have resulted from a combination of three processes, namely:

a) pressure exerted on the xenolith by the magma during the engulfment of this large block of sediment.

b) the dolerite of the bell-jar being forced along planes of weakness in the sediments.

c) plastic flow due to high temperatures.

There is variation in both grain-size and colour of the dolerites intruded in the xenolith. The grain-size varies from fine in the thinner sheets to medium at the centres of the thicker sheets. The colour varies from grey-black to light grey in colour. The lighter grey dolerites are found adjacent to and underlying sediments exhibiting a high degree of metasomatism. They commonly contain irregular patches of white quartzo-feldspathic material up to 30 mm. in size. Needless of opaque material (probably hematite) are developed in these patches. These are acidified dolerites of similar origin to those at Coedmore Quarries, Durban, that were described by Mountain (1959). At Coedmore progressive acidification of dolerite has resulted from incorporation of Table Mountain Sandstone. Walker and Poldervaart (1942, p. 292) described an acidified dolerite below the metasomatic granophyre in the Rietkop sill. They note that acidification and contemporaneous decomposition become more intense towards the granophyre. They suggest that there was a metasomatic transfer of material from the granophyre to the dolerite producing the rocks which they termed "transition dolerites", a process which retained a sharp contact between the dolerite and the granophyre. In the Bird's River area poor outcrop and talus obscure the contacts where this acidified dolerite occurs and it was not possible to determine if the contacts are sharp. However, gradual change in rock-type was noted close to the contact in one or two places. An actual contact was never seen, which suggests that hybridization may have occurred between the sediment and the dolerite resulting in contamination of the dolerite.

A further possible indication that the pale grey dolerite has been produced by a process of acidification rather than a magmatic process such as fractionation was seen about 300 metres north of the cairn. On the north-eastern face of the hill, below the outcrop of heavily metasomatised pyroclastic rocks (grid ref. C3 and C4), ingestion of the pyroclastic rocks has occurred. This ingestion into the dolerite has produced a rock similar in character to the metasomatic rocks capping the hill. In this case the transition between the dolerite and the ingested material is not sharp and the surrounding dolerites exhibit varying degrees of acidification. It is possible that the pyroclastic material was only partly consolidated at the time of the intrusion and as a result the sediment was easily sucked into and "mixed" with the dolerite. The possibility that the pyroclastic material may have been unconsolidated would indicate an extra source of volatiles which would have enhanced the process of metasomatism of the sediments as well as the acidification of the dolerites.

The largest intrusion of dolerite into the xenolith has the form of a sheet that outcrops along a line running north-west of the cairn (grid ref. B3, C3, C4 and D4) and has been named the Cairn dolerite sheet. This dolerite has produced the metasomatic rocks that cap the hills in the vicinity of the cairn, and in the process has itself become partly acidified. At the western termination of this dolerite sheet (grid ref. B3) horizontal streaks of glass occur in the sheet. It is possible that this glassy dolerite, which was more than 90 per cent crystalline, was cooled extremely quickly as a result of intrusion into wet, partly consolidated sediments.

C. THE GROOTKLOOF XENOLITH.

The Grootkloof xenolith occurs in the eastern portion of the map, very close to the margin of the bell-jar. The size of the xenolith is approximately 3,0 x 1,0 km. It is very similar to the Cairn Xenolith in lithology, viz., it is composed of lapillistones, sandstone-tuffs and sandstone. Pyroclastic material containing large blocks of dolerite was not found in this xenolith, the largest fragment recorded being about 50 mm. in diameter.

The sandstones and associated tuffs vary in colour in the field from light brown and grey to creamy white. The latter colour is very prominent near the dolerite contact for here the sandstones are baked. The baking has resulted in intense jointing having been developed in these sediments near the contact. Sedimentary structures such as bedding, which is often well-developed in these sandstones, has not been destroyed on baking. A buchite has been produced by fusion of a shale horizon in the southern tip of the xenolith (grid ref. H7). It appears, as in the case of the Cairn xenolith that fine bands of shaly material are interbedded with the sandstone.

The lapillistones overlie the sandstones, but no sharp contact between the sandstones and the lapillistones was found, indicating that they may grade into each other.

The lapillistones exhibit metamorphism and metasomatism such as was found in the Cairn xenolith, except that the metasomatised pyroclastic rocks that were found at Grootkloof are at the periphery of the xenolith, having been produced by reaction directly with dolerite of the bell-jar and not by a smaller intrusion into the xenolith.

The example of metasomatised pyroclastic rocks occurs along the top of the Grootkloof cliffs (grid refs. G7, H7 and H8). Sheets and tongues of dolerite from the bell-jar pierce the sediments all along this southern contact resulting in acidification of the dolerite. The acidified dolerite that underlies the pyroclastic rocks is similar to that found in the Cairn xenolith, as is the uncontaminated dolerite.

At Grootkloof, as in the Cairn xenolith, the degree of metasomatism varies from slight to extreme, with the more intense degrees of metasomatism occuring in localized patches. The effects of the dolerite on the sediments were noted up to 30 metres above the contact.

PLATE III: Grootkloof from the east; A marks the southern margin of the Grootkloof xenolith and B marks the position of the deep gorge.

PLATE IV: The dolerite cliffs on the northern side of Grootkloof. The dashed line represents the capping of pyroclastic rocks.

The north-eastern part of this xenolith forms a sharp ridge, the highest point of which is the "Glass Ridge" (grid refs. G5 and H5). Investigation of the glasses of this ridge by electron-probe micro-analysis has been carried out by Eales (1974). All that need be said about it at this stage is that fusion of pyroclastic rocks has occurred as a result of dolerite magma streaming past between the xenolith and the margin of the intrusion, a process which produced an exceptional degree of heating.

The Grootkloof xenolith dips to the south-west at angles ranging between 10 and 20 degrees. The fact that sediments occur at about the same altitude at the top of Grootkloof and on the opposite side of the valley in the Cairn xenolith seems to support the idea that originally these two xenoliths were a single mass. However, the force of the dolerite streaming past between the Grootkloof xenolith and the margin of the intrusion may have caused this xenolith to break away from the Cairn xenolith. The angle of dip at the Glass Ridge is steep ($\pm$ 70 degrees to the south-west), and the general dip is in the opposite direction to the Cairn xenolith indicating that the latter xenolith may well have broken away from the Grootkloof xenolith.

D. <u>OTHER SMALL XENOLITHS.</u>

A number of minor xenoliths occur in the bell-jar in the area illustrated by the map. Most of these xenoliths are composed of cream-coloured, baked sandstones, often intensely jointed. They vary in size and range up to 150 metres in diameter.

The largest of these xenoliths occurs in the western portion of the map (grid ref. A3). It is roughly triangular in shape and is composed of a medium-grained, brown, sugary sandstone, overlying a bed of shaly material, most of which has undergone fusion producing a buchite. The sediments in this xenolith dip to the north at 25 degrees.

E. VEINING PHENOMENA IN THE DOLERITE.

Rheomorphic veins composed of light grey quartzitic material are found in the dolerite near the north-western corner of the Cairn xenolith (grid ref. B2). Vugs of quartz up to 5 mm. occur in the veins. Eight parallel veins up to 45 mm. wide run subparallel to the dolerite sediment contact and the most distant of these is 30 metres from the contact. In this area the dolerite underlies recrystallized sandstones. The angle between the plane of the contact and the strike of the veins is about 10 degrees, the veins dipping to the east. Narrower veins are found in joints that are almost perpendicular to the contact.

The contact between the rheomorphic veins and the dolerite is sharp and a zone of dolerite-pegmatite, up to 15 cm. wide, is developed along this contact. Crystals of pyroxene up to 10 mm. in length were recorded in the pegmatites.

These veins appear to have originated as a result of fusion of the

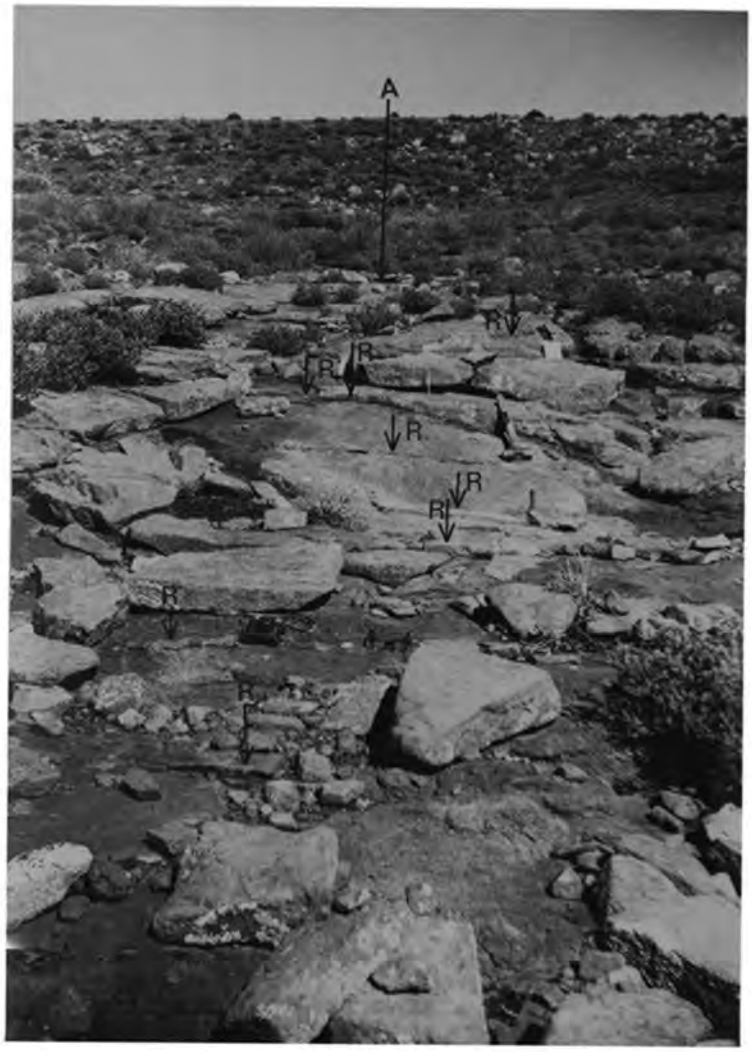


PLATE V: The rheomorphic veins; the arrows marked R mark the positions of 6 rheomorphic veins in the gabbro. These veins run parallel to the contact between the gabbro and the overlying sandstones. The arrow A points to the approximate position of the contact between the sediments and the underlying dolerite.

PLATE VI: One of the rheomorphic veins that is illustrated in Plate V. Note the sharp contact between the vein and the gabbro. This vein is 20 - 30 cm. wide for most of its length but widens to 60 cm. between the sledge hammer and the map board.

overlying sandstone-tuff, although no flow structures are visible in these veins. Walker and Poldervaart (1949, p. 675) regard rheomorphism of sediments by Karroo dolerite as a common phenomenon.

F. THE DOLERITE OF THE BELL-JAR INTRUSION.

Booth (1971) has given an adequate description of the mode of occurrence of the bell-jar dolerites and only a few additional comments are necessary.

Away from any contact with sediments the dolerites of the bell-jar are essentially gabbroic. They are dark grey in colour and are of generally uniform grain-size. Close to the xenoliths, however, the dolerite becomes fine-grained, developing a porphyritic texture. These contact dolerites are found within 30 cm. of the sediments and are characterized by their fine-grained groundmass in which the phenocrysts are visible.

Irregular patches and schlieren of dolerite-pegmatite are commonly developed in the gabbro, especially within the section 40 - 50 metres below the xenoliths. The best examples of dolerite-pegmatite were seen below the eastern part of the Cairn xenolith (grid ref. E6) and are especially well-developed directly below the outcrop of adinole. In this area narrow zones of dolerite-pegmatite have concentrated along joints in the gabbro. These joints are well-developed and run both parallel and perpendicular to the contact with the sediments. Feldspar laths up to 5 mm. and curved blades of augite up to 15 cm. serve to make the pegmatite clearly distinguishable from the surrounding gabbro.

A similar occurrence of dolerite-pegmatite developed along possible joints has already been noted occurring in conjunction with the rheomorphic veins. It appears as though there was a concentration of volatile material along these joints, enhancing the development of dolerite-pegmatite along them. Walker (1953, p. 59) in a paper on the pegmatitic differentiates of basic sheets, regards dolerite-pegmatite as a post-injection differentiate of the normal basic rock forced into rifts in the crystal mush when crystallization is far advanced. These rifts would be related to the joint pattern that would ultimately develop. McDougall (1962, p. 306) also relates the distribution of dolerite-pegmatites in the Tasmanian dolerites of Red Hill to rifts that have developed in the crystal mush.

Walker and Poldervaart (1942, p. 289) record an occurrence of dolerite-pegmatite adjacent to a xenolithic body at Alewyn's Gat. They believe that the only way in which the adjacent sediments could possibly have contributed to its formation is in the supply of volatiles, thus enhancing the growth of large crystals.

G. THE LAVAS.

Two small outcrops of green-coloured, amygdaloidal lava are found in the two xenoliths (grid refs. D6, F4 and F5). The amygdales are widely scattered and are mostly composed of zeolite.

H. SUMMARY OF THE GEOLOGY OF THE NORTH-EASTERN PORTION OF THE BIRD'S RIVER COMPLEX.

Two large xenoliths, probably originally one body and composed of the upper part of the Cave Sandstone Formation, occur in the north-eastern corner of the bell-jar intrusion. These xenoliths are composed of pyroclastic sediments overlying and interbedded with cream-coloured sandstones and sandstone-tuffs. Sills, sheets and irregular bands of dolerite, of the same age as the bell-jar gabbros, have been intruded into these xenoliths. A dolerite dike of younger age than the bell-jar dolerites has intruded into one of the xenoliths and probably represents the last stage of igneous action in the area.

The dolerite both within and without the xenoliths has reacted with the sediments producing a variety of metamorphic and metasomatic rocks. 'In places the dolerite has itself become acidified.

The pyroclastic rocks appear to have undergone more metasomatism than the associated sandstones. Intense metamorphism and metasomatism of the pyroclastic rocks has resulted in complete recrystallization with the original texture being destroyed, producing a rock of almost homogeneous and equigranular nature, while in the early stages of reaction with the dolerite, the pyroclastic rocks have been baked and as will be seen, a small degree of chemical interchange has taken place.

Metamorphism of the sandstones has for the most part been limited to recrystallization and baking, with jointing often becoming well-developed. More intense metamorphism and metasomatism has occurred resulting in the production of spotted spilosites and the potassic adinole. Mobilization of the sandstones has resulted in injection of the dolerite by rheomorphic veins. Narrow shale bands interbedded with the sandstone have undergone fusion with the production of a buchite.

CHAPTER FOUR.

THE PETROGRAPHY OF THE DOLERITES.

INTRODUCTION.

From thin-section examination the dolerites found in the vicinity of the xenoliths may be classified as follows:

A. Dolerites.

1. Contact dolerite.
2. Glassy dolerite.
3. Fine-grained dolerite.
4. Poikilophitic olivine dolerite with quartz.

B. Dolerite-pegmatites.

1. Roof-zone rocks.
2. Dolerite-pegmatite.

C. Contaminated Dolerites.

Micrometric and mineralogical data are included in tables in this chapter.

A. DOLERITES.

1. Contact dolerite.

These are the fine-grained, dark-coloured dolerites that are found around the margins of the xenoliths up to about a metre away from the dolerite-sediment contact. A problem regarding these rocks arises out of contamination by sedimentary material. In all cases the rocks examined showed a certain degree of contamination and the sample of contact dolerite selected for chemical analysis (analysis 18, TABLE XIV) contained, from estimates based on thin section examination, one per cent by volume of sedimentary material.

The contact dolerites examined were those in contact with the xenoliths only, and showed but slight variation between specimens. Essentially, these rocks are composed of plagioclase, augite and altered olivine phenocrysts in a fine-grained groundmass of augite and feldspar or turbid cryptocrystalline devitrified glass. An orange-brown to olive-green alteration material probably pseudomorphic after olivine is common in all these contact rocks. Orthopyroxene phenocrysts showing a symplectic intergrowth with iron ore material were found in a contact dolerite adjacent to the small xenolith in the western part of the area (grid ref. A3) and also in an example from the Grootkloof xenolith contact.

The plagioclase phenocrysts are fresh, unfractured and are zoned, and may exhibit ophitic texture against the augite. Both normal progressive and oscillatory zoning were observed. The plagioclase phenocrysts are calcium-rich, containing 77 per cent anorthite molecule. The $2V_z$ of this plagioclase is 92°.

Augite phenocrysts are subhedral to euhedral in shape. This mineral is unaltered and the grains average about 0,6 mm. in length. The data from optic axial angle and refractive index determinations show that the augite is close to $Ca_{37}\ Mg_{59}\ Fe_{4}$.

The symplectic intergrowth of orthopyroxene and ore material (mostly subgraphic) was found in two examples of contact dolerite. Polished sections of a fine-grained dolerite also showing this texture indicated that the ores appear to be an assemblage of titanomagnetite altering to hematite and ilmenite. This texture has a further development in the sample of contact dolerite adjacent to the small xenolith in the western part of the area. In this sample this pyroxene with the associated ore material occurs as the mantle around a core of green pleochroic chlorite. Occasionally there is a core of quartz inside this green alteration material.

In the rest of the contact dolerites this alteration material also occurs and varies in colour from deep orange-brown to olive-green and is probably formed by deuteric alteration of olivine. This material has a low 2V, is optically negative, exhibits pleochroism and has rather patchy extinction. Poldervaart (1946, p. 86) notes that chlorophaeite occurs pseudomorphic after fayalitic olivine in the marginal tholeiites of the Mount Arthur complex. Walker and Poldervaart (1949, p. 633) stated that under the influence of hyperfusible elements, olivine is frequently altered to green bowlingite and brown iddingsite.

Deer, Howie and Zussman (1962, Vol. 1, p. 18) list some of the alteration products of olivine in basic lavas. These include reddish-brown iddingsite, green bowlingite and light-orange to deep-green chlorophaeite. Confusion appears to exist as to what the alteration products of olivine are. Sarbadhikari and Bhattacherjee (1966) describe the alteration of clinopyroxene, iron ore and primary glass in the Raj Mahal basalts of India. They found that the yellow, brown and green secondary products, although termed chlorophaeite and palagonite, are montmorillonoids and vermiculites and they question the use of the terms chlorophaeite and palagonite. It is worth recording that palagonite is regarded by Wentworth and Williams (1932, p. 47) as a yellow or orange isotropic mineraloid formed by hydration and alteration of basaltic glass (sideromelane). Stokes (1971), however, showed that chlorophaeite and palagonite differ both structurally and chemically and that they cannot be regarded as simple substances, but rather as multiphase composites. He made the observation that chlorophaeite is restricted to basic igneous rocks, which cooled more slowly and which appear to have suffered a period of late-stage hydrothermal activity. No indication is, however, given by this author as to whether chlorophaeite may be produced by alteration of olivine. Haggerty and Baker (1967) studied the alteration of olivine in basaltic and associated lavas at high temperature. They concluded that at high temperature oxidation of olivine may produce either magnetite plus enstatite, or hematite plus forsterite, the former association being an intermediate and metastable assemblage. The magnetite forms microsymplectic intergrowths with the enstatite, and Fe-Ti oxides which accompany the development of magnetite and enstatite are pseudobrookite, rutile and titanohematite formed by oxidation after original titanomagnetite and ilmenite. A progressive transformation of vermicular magnetite to lamellar hematite takes place with progressive oxidation. Baker and Haggerty (1967) in a separate paper on the intermediate and low temperature alteration of olivines in lavas show that at low temperatures they break down to essentially chloritic materials and at very low temperatures, probably below 140°C, "iddingsite" is produced which is an orientated assemblage of goethite and interstratified phyllosilicates also containing a smectite.

In the contact rocks of Bird's River it appears, from petrographic evidence, that the green alteration material is a chlorite and when brown-coloured may either be "iddingsite" produced by low temperature deuteric alteration or orientated assemblages similar to the "iddingsite" produced by weathering. In the samples where the composite grains were found a possible hypothesis for their origin would be that before the magma came into contact with the xenoliths, oxidation of the early formed olivine phenocrysts had already commenced forming the symplectic magnetite orthopyroxene assemblage. The sudden cooling of the magma when it came into contact with the sediments of the xenoliths resulted in further alteration of the olivine taking place at lower temperatures, producing the chlorite core. The association of the quartz with the chlorite is not understood but it

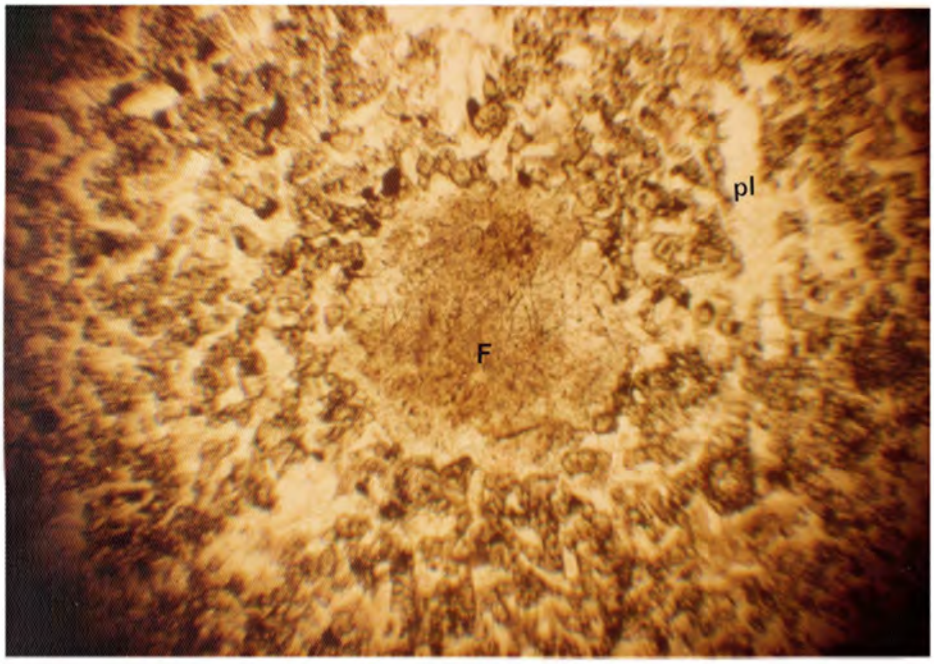


PLATE VII: Recrystallised sandstone fragment (F) in contact dolerite. The plagiocalse phenocryst (pl) is in a groundmass of augite and plagioclase. (Magnification = 30X) may be a by-product of alteration or it may be due to sedimentary contamination.

The groundmass of these contact rocks varies from a turbid, devitrified glassy assemblage containing fine particles of opaque minerals to a finely crystalline assemblage, having an intergranular texture, with clinopyroxene and plagioclase feldspar. The feldspar is generally too fine to perform accurate composition determinations, however, a rough determination indicated that the composition of the groundmass plagioclase is less rich in anorthite molecule than the plagioclase phenocrysts.

The contact "basalts" in nearly all cases exhibit some degree of contamination by relatively small particles of incorporated sedimentary material. The mode of occurrence of this sedimentary material varies between the specimens examined. In one example the small xenoliths have undergone recrystallization with an assemblage of potassium feldspar, plagioclase (composition = $\pm$An 49), quartz and fine rods of opaque material (probably hematite) being produced. These micro-xenoliths average about 0,5 mm. in diameter and are generally round or oval in shape. No noticeable change in the compostion of the groundmass of the dolerites was noted in the vicinity of these xenoliths (see Plate VII).

In another example of contact dolerite, taken on the southern contact of the Grootkloof xenolith (grid ref. F5) abundant sedimentary material occurs in the groundmass. The xenoliths vary from individual quartz grains (0,1 mm. in diameter) to relatively large fragments of sediment (up to 8,0 mm. in diameter). Some of the xenoliths appear to be stretched and distorted and are partly broken up into smaller fragments. No recrystallization of the quartz is evident. However, the quartz grains become turbid towards their margins (a possible indication of incipient inversion to tridymite). Some of the fine pyroxene of the groundmass seems to have migrated into these fine xenoliths.

A fine rheomorphic vein whose texture differs from that of the included xenoliths was observed in a thin section of a sample from the Grootkloof contact. The vein is about 2 mm. wide and is composed of fine "tridymite granophyre" (the tridymite having subsequently inverted to quartz). No visible change in the character of the groundmass is apparent adjacent to these rheomorphic veins and fragments of the groundmass have been broken off and have migrated towards the centre of the vein.

2. The glassy dolerites.

Samples of glassy dolerite were collected where the Cairn dolerite sheet dies out in the west (grid ref. B3). In some of the specimens collected the glass is clearly visible with the naked eye as elongated patches a few millimetres in length.

Samples of material from the contact as well as from the centre of the sheet were collected. The dolerite collected from the contact is similar to the contact "basalts" previously described except that in this case brown glass occurs in the groundmass and olivine is only partly altered to a green-brown pleochoric material [probably the intermediate-temperature chloritic alteration product of olivine (Baker and Haggerty, 1967, p. 272)].

The more coarsely crystalline dolerite from the centre of this narrow sheet proved to be more interesting in that it contained more brown glass (8,8%) than the contact dolerites (±4%) and the olivine in them appears to have been completely altered to a bright orange-brown chloritic mineral. The glass is interstitial to the other mineral components.

Microlites occur in the glasses which appear to be mostly slender, often sub-parallel rods of pyroxene. Microlitic crystals of feldspar with hopper terminations occasionally occur as well as particles of ore material. In a study of microlites in silicic glassy volcanics Ross (1962) states that pyroxenes are the characteristic type of microlite and sanidine with hopper terminations is the characteristic feldspar. The glass in these dolerites contains rounded particles of dark orange-brown fine-grained devitrified material. These are gas bubbles and it is possible that the gas has probably reacted with the glass producing this devitrified material.

The refractive index of the glass in the dolerite from the centre of the sheet is 1,508. Moorhouse (1959, p. 203, after W.O. George, J. Geol, vol. 32, 1924) gives a diagram from which it is possible to determine the SiO_2 content of the glass from the index of refraction. The value obtained for a refractive index of 1, 508 is $\pm$68 per cent SiO_2 indicating that this glass (ie. the late stage liquid) was much enriched in silica since the crystallization process began. Chemical analysis shows that this rock contains 52,3 per cent silica, (see Table XIV, Analysis 16). Work by Muffler, Short, Keith and Smith (1969) gives a value 48,0 per cent SiO_2 for an unaltered Triassic basaltic volcanic glass from Alaska. The average silica content for Karroo chilled basalt is 51,9 per cent. (Walker and Poldervaart, 1949, p. 49). The difference between the values of basaltic glasses and the SiO_2 value of this glassy dolerite serves to indicate to some degree the silica enrichment that has occurred in the residual liquid during crystallization of the magma.

This rock is slightly porphyritic in that there are definite phenocrysts but the difference in size between these and the crystals of the groundmass is small. At the same time no discernable difference was noted in the anorthite content of the groundmass plagioclase and the plagioclase phenocrysts. The composition of the plagioclase is An_{75} with a minimum value of An_{54} at the grain margins. The plagioclase generally exhibits normal gradational zoning with occasional oscillatory zoning present in some of the grains. The plagioclase grains are slightly fractured.

Three pyroxenes are present, namely augite, pigeonite and orthopyroxene. Compositional determinations on the augite gave the value $Ca_{40} Mg_{51} Fe_9$. The pigeonite has a low 2V of about 5°. The plagioclase and the clinopyroxene exhibit ophitic texture.

The orthopyroxene occluding symplectic opaque ore material occurs in small amounts and has an intergranular relationship towards the associated feldspar.

3. Fine-grained dolerite.

These are fine- to medium-grained, porphyritic to equigranular, holocrystalline dolerites that occur close to the xenoliths between the contact dolerites and the gabbro or in sheets within the xenoliths. They are regarded as the fine-grained equivalent of the poikilophitic gabbros that comprise the bulk of the associated dolerites. The close proximity of these rocks to cooler sedimentary material has dictated the grain size of these rocks and as a consequence a slight variation in texture relative to the poikilophitic gabbros has resulted. An example of dolerite collected 15 cm. from the sedimentary contact of the Grootkloof xenolith is rather heterogeneous in character in that it contains elements of grain size of both the contact basalts and these fine-grained dolerites within the area of a thin section and these are well-defined relative to each other.

The plagioclase and pyroxene which constitute the bulk of these rocks exhibit ophitic texture which is often not well-developed. The plagioclase laths average 0,8 x 0,2 mm., having a composition of An_{74}

Both augite and orthopyroxene are present. The anhedral augite crystals average about 0,6 x 0,2 mm. and have the composition $Ca_{38} Mg_{41} Fe_{21}$. The augite sometimes poikilitically encloses grains of ore material but not to the extent that is seen in the orthopyroxenes. The orthopyroxenes are often heavily charged with fine particles of subgraphic ore material, which, from polished section examination, are titanomagnetite and ilmenite, possibly with hematite being produced by alteration.

Olivine is present and is heavily altered along cracks and grain boundaries to a green chloritic product. This chlorite is sometimes heavily charged with fine particles of ore material. The presence of a high temperature oxidation product of early-formed olivine, ie. the orthopyroxene charged with symplectic ore material, and the low-temperature chloritic alteration product of a later olivine, appears to fit the suggestions of Haggerty and Baker (1967). This appears to contradict the generally accepted theory of crystallization of pyroxenes where two pyroxene phases are commonly formed in earlier stages of fractional crystallization of basic magmas especially in the tholeiitic suite where the association of a calcium-rich and a calcium-poor pyroxene is a characteristic. Deer, Howie and Zussman (1963) review the considerations of workers in this field of pyroxene crystallization and they describe the trend of crystallization of pyroxenes noting the general existence of two pyroxenes in tholeiite. Thus the orthopyroxene found in these fine-grained dolerites,as well as the contact basalts and glassy dolerites, has two possible origins:

a) It is an early-formed calcium-poor orthopyroxene that is contemporaneous with augite in tholeiites; or

b) this orthopyroxene is a high temperature alteration product of olivine.

Walker and Poldervaart (1949, p. 642) suggest that, before implacement, plagioclase, olivine and augite, or plagioclase and bronzite began to precipitate from the Karroo magma. From the assemblage of minerals constituting phenocrysts in the contact basalts at Grootkloof, ie. augite, plagioclase and the orthopyroxene (with associated alteration products), it appears as though the former assemblage of Walker and Poldervaart had crystallized from the magma before intrusion and it is quite possible that high temperature oxidation of the olivine produced the orthopyroxene.

The question as to why this orthopyroxene + ore symplectic intergrowth is present in the fine-grained dolerite that crystallized under hypabyssal conditions is difficult to answer. However, a tentative alternative to this orthopyroxene being one of the primary major silicate phases would be that it is a high-temperature alteration product of olivine and as it appears that the fine grain-size of these dolerites is due to close proximity to the sediments, it is possible that cooling was quick enough to prevent the destruction of this metastable orthopyroxene + Fe-Ti oxide phase.

These fine-grained dolerites contain minor amounts of cryptocrystalline and olive-green mesostasis. Apatite, occurring in small euhedral crystals, is associated with this mesostasis.

Both oxide and sulphide ore minerals are present in these dolerites. These include fine-grained Fe-Ti oxides, mainly magnetite, titanomagnetite and ilmenite and occur as follows:

a) As the symplectic intergrowth in the orthopyroxene.
b) Occluded in the chloritic low-temperature alteration product of olivine.
c) As small subhedral particles poikilitically enclosed by augite.
d) As anhedral particles sometimes subpoikilitically enclosing plagioclase and pyroxene.

The sulphide is pyrite and occurs only in one of the specimens found near the contact along the northern margin of the Cairn xenolith. The rounded pod-like disseminations of pyrite are scattered throughout the rock and have a diameter of about 3 mm. Polished-section examination revealed that no other sulphide phases are associated with the pyrite. The pyrite appears to have been introduced after crystallization of most of the rock as the mineralization has taken place along grain boundaries and cracks in the constituent minerals. The sulphides constitute about 4 per cent of this rock.

4. Poikilophitic olivine gabbro with quartz.

The poikilophitic olivine dolerites constitute the bulk of the igneous rocks in the vicinity of the xenoliths and are fully developed outside a zone about two metres wide from the xenolith margins. Booth (1971, p. 63) described these dolerites (also see Table I) and used the term poikilophitic to describe the texture of these rocks because large augite grains (up to 3,0 mm.) enclose smaller plagioclase laths (averaging about 0,5 mm. in length).

Comparison of the various optical and compositional parameters obtained by Booth and the author for plagioclase and augite in these dolerites is given in Table III. The composition of the augite determined by electron microprobe (Eales and Booth, 1974) is also included as these data are more reliable.

Booth (1971, p. 63) states that this rock type occurs very abundantly in this intrusion and generally has a high plagioclase content. The agreement between the values of Table III serves to indicate the homogeneous nature of this dolerite throughout most of the intrusion as Booth and the author used different samples from different positions in the intrusion. This conclusion is further supported by comparison of the modal analyses (see Table V, analyses 7 and 8) which are also very similar. The electron microprobe data, however, are slightly different.

TABLE III.

Mineralogical compositions of plagioclase and augite in poikilophitic olivine quartz dolerites.

	Booth (1971)	Kenyon	Eales (1974)*
Plagioclase			
Composition	An_{75} and An_{78}	An_{76}	—
Augite			
$2V_z$	46,5	45,9	—
N_y	1,691	1,695	—
Composition	Ca_{39} Mg_{44} Fe_{16}	Ca_{39} Mg_{41} Fe_{20}	Ca_{40} Mg_{47} Fe_{12} (core) Ca_{36} Mg_{42} Fe_{22} (margins)

* From Eales and Booth (1974).

Augite and pigeonite are present and the symplectic intergrowth of orthopyroxene and ore minerals is no longer present. This is interesting, as outcrops of the fine-grained dolerites are no more than a few metres away from this olivine-quartz-dolerite.

The olivine is partly altered to a green alteration product. A rough estimation of the composition of the olivine based on 2V determinations gave a value of Fa_{30}. Eales and Booth (1974, p. 5) analysed the olivines by electron microprobe. These have a wide range in composition from $Mg_{74}Fe_{26}$ to $Mg_{44}Fe_{56}$.

The mesostasis is composed mainly of an intergrowth of quartz and potassium feldspar. The potassium feldspar has the properties of sanidine (ie. optically negative and low 2V) and is seen in thin section as small rectangular euhedra in a granophyric intergrowth with the quartz. A mesostasis of finely crystalline chloritic material is also present. Apatite is generally associated with both types of mesostasis.

Anhedral and sometimes skeletal grains of ore material up to 1 mm. in size are relatively common. Polished-section examination showed that the bulk of the ore material is ilmenite exhibiting fine twinning lamellae along $(10\bar{1}1)$ (see Ramdohr, 1969, p. 965). Dusty grey patches along cracks in the ilmenite may be due to incipient alteration. Minor amounts of magnetite are present.

Sulphides in the form of chalcopyrite and pyrite may occur in these rocks.

B. DOLERITE-PEGMATITES.

The dolerite-pegmatites are the late-stage, post-injection differentiates of the dolerites. In this area investigated at Bird's River they are present as irregular patches and schlieren in the gabbro extending to about 50 metres below the xenoliths. Dolerite-pegmatite is also well-developed along joints and rheomorphic veins that lie parallel and perpendicular to the contacts with the overlying sediments.

The dolerite-pegmatites are coarse-grained rocks composed of plagioclase laths up to 10 mm. and pyroxene blades up to 15 mm. in length. The texture is variable but for the most part is subophitic. Fracturing of the feldspar grains is intense and the more calcic cores of some of the plagioclase laths are altered. The composition of the plagioclase is An_{62}.

Augite and pigeonite are the pyroxene representatives. The augite exhibits zoning of such a high degree that accurate compositional determinations were difficult, especially refractive index determinations. The compositional value obtained optically was $Ca_{26}Mg_{20}Fe_{54}$ for the augite.

The abundant mesostasis in these rocks consists mainly of tridymite granophyre. Plate IX illustrates the distribution of Al, K, Fe and Si in the "tridymite granophyre" adjacent to a pyroxene grain. A Jeol JXA-5A electron microprobe was used to determine the distribution of these elements. Figs. 1 and 2 respectively, are 300X- and 600X-magnification back-scattered electron images of this intergrowth. A pyroxene grain with high reflectivity occupies the left portion of the figures. The acicular quartz grains paramorphic after tridymite have lower reflectivity than the enclosing potassium feldspar. The distribution of Al and K (Plate IX figs. 3 and 4) verify the presence of potassium feldspar in this intergrowth while the distribution of Fe outside the pyroxene grains pinpoints the distribution of the orange-brown alteration material commonly associated with the mesostasis. The most important conclusion that arises is that potassium is abundantly present in the last part of the dolerite magma to crystallize. This fact will be further considered when considering the chemistry of metasomatism.

The portion of the intergrowth illustrated in Plate IX is fine-grained but towards the centre of the intergrowth there is an increase in grain-size and the quartz does not appear to be paramorphic after tridymite. (Plate VIII is a photomicrograph of the dolerite-pegmatite mesostasis which illustrates this). This indicates crystallization at lower temperatures. Reaction between the mesostasis and plagioclase is a common occurrence. Apatite is associated with the mesostasis.

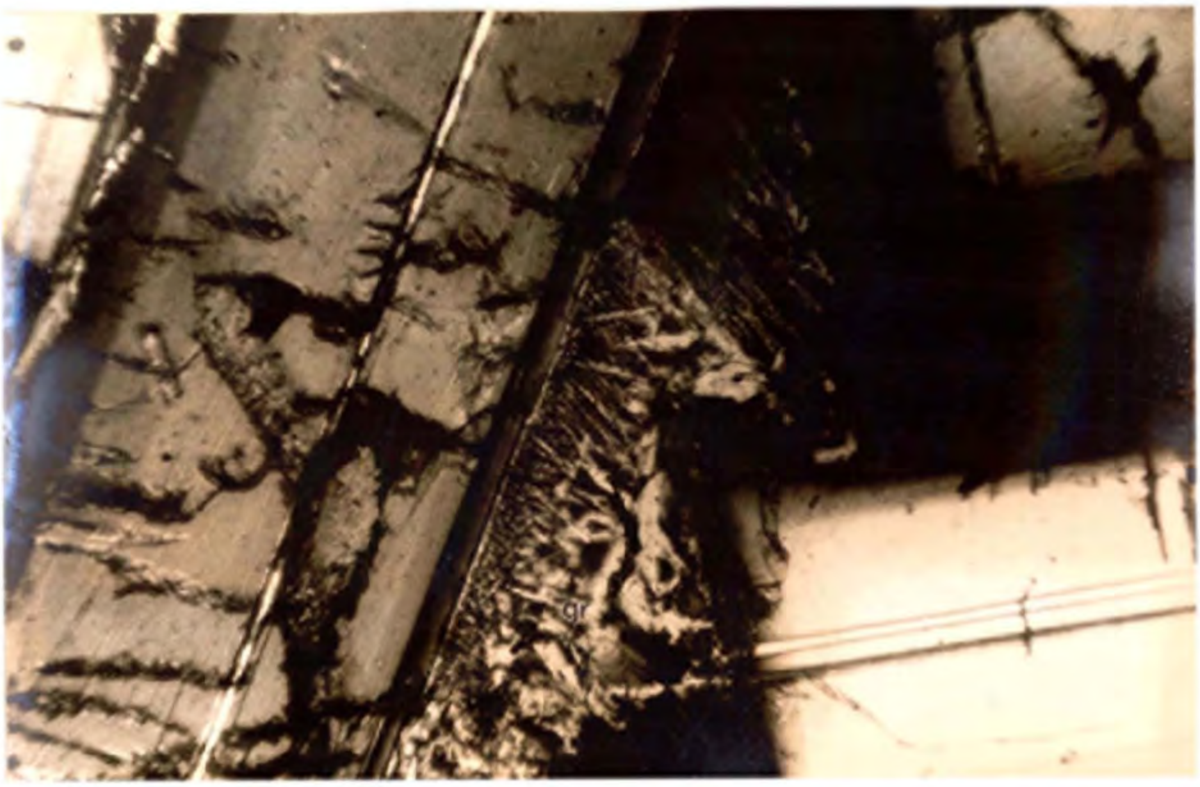


PLATE VIII : Granophyric mesostasis (gr) in dolerite-pegmatite. This mesostasis consists of an intergrowth of quartz (paramorphic after tridymite) and sanidine. (Crossed nicols, magnification = 50X)

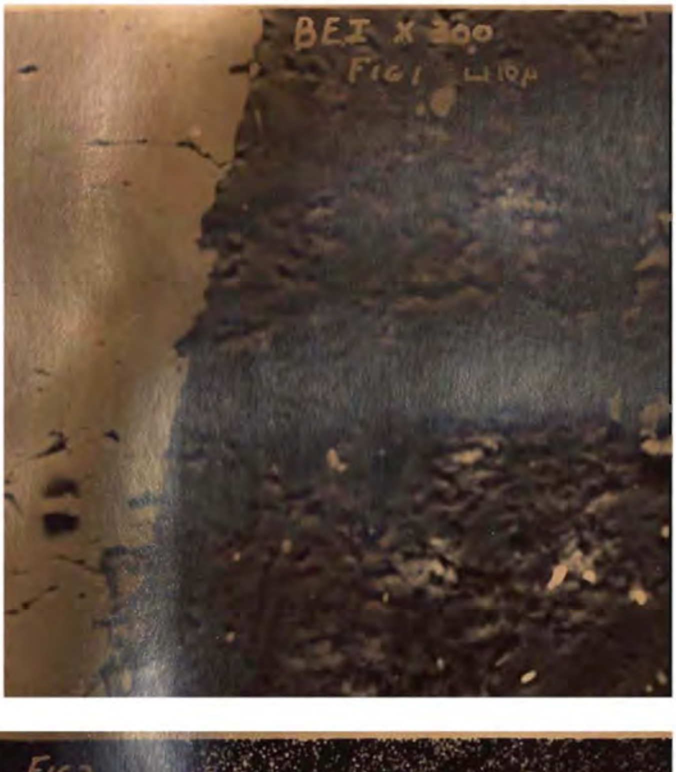
Key to plate IX (see over page)

1	2
3 Al	4 K
5 Fe	6 Si

Figure 1: Back-scattered electron image of the granophyric mesostasis in the dolerite-pegmatite. The pale grey mineral is augite and the darker grey material is the granophyre. (Linear magnification = 300X).

Figure 2: Magnified back-scattered electron image of portion of the intergrowth illustrated in figure 1. (Linear magnification = 600X).

Figures 3 - 6: Distribution of Al, K, Fe, and Si respectively in the portion of the granophyre illustrated in figure 2.


BEI x 200
FIG 1
10μ


BEI X600
10μ
FIG 2


FIG 3.
AL


FIG 4
K.

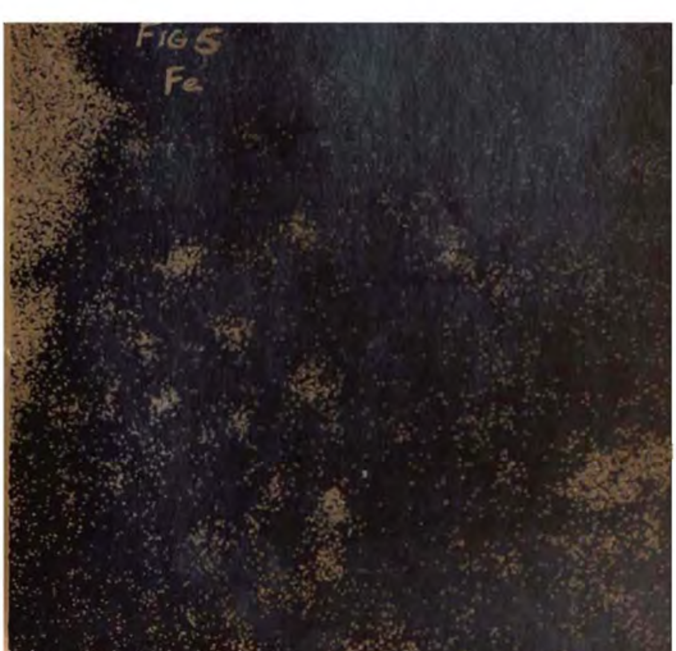


FIG 5
Fe


FIG 6
Si

The development of dolerite-pegmatite along joints and rheomorphic veins in the dolerite.

It has been mentioned that dolerite-pegmatite is developed along parallel joints and rheomorphic veins below the Cairn xenolith. Certain questions arise as to the origin of this development, namely:

a) Were the rheomorphic veins intruded along these joints before or after the development of the dolerite-pegmatite?

b) Were the joints developed before the dolerite was completely crystalline?

c) Were the joints "passageways" for the movement of liquids from the dolerite to the sediment and vice versa?

The parallelism of the rheomorphic veins and the development of dolerite-pegmatite along both "barren" joints and the rheomorphic veins indicates that the veins were introduced along already developed joint planes. Further, these two modes of occurrence of dolerite-pegmatite indicate;

a) that the dolerite of the bell-jar may not have been completely crystalline when these planes were formed and,

b) that volatiles must have accumulated or migrated along these planes in order to produce these differentiates.

At Hangnest, Walker and Poldervaart (1941, p. 443) noted that rheomorphic veins emerging from both the upper and lower contacts of the sill were injected into already solid contact basalt. From the minor brecciation caused by the intrusion of a small rheomorphic vein into an example of contact basalt found near the Grootkloof xenolith it appears as though the contact basalt was solid in the case of the Bird's River intrusion as well. This does not indicate, however, whether the dolerite away from the contact zone was solid at the time of the intrusion of the rheomorphic veins. In the centre of the Hangnest sill Walker and Poldervaart (1941, p. 445) believe that the intrusion of rheomorphic veins was into incompletely solidified dolerite. They describe veins that do not show sharp margins against the dolerite and some of the mobilized sediment was introduced interstitially within the crystal framework of the dolerite.

In the Bird's River Complex the contact between the dolerite and the rheomorphic veins is very sharp, which, along with the parallel and regular nature of these veins, indicates that the veins must have been intruded when the dolerite was solid or very nearly so. From this it appears that the rheomorphic veins need not have been the source of volatiles required for the development of the dolerite-pegmatites along these planes.

Walker (1953) notes that the three ways in which dolerite-pegmatites occur in sills are as lens-shaped or tabular schlieren parallel to contacts; as irregular nests or patches; and as cross-cutting veins. No reference is made of the development of dolerite-pegmatite along joints and no reference could be found in the literature relating to this mode of occurrence of dolerite-pegmatite along joints in dolerite intrusions.

It thus appears that cooling joints developed before the dolerite had completely solidified and probably formed along planes of weakness in the dolerite. The late-stage magma rich in volatiles concentrated along these joints producing the dolerite-pegmatite. It is possible that these joints may have been "passageways" for the migration of metasomatising fluids into the overlying sediments which acted as a flux causing the rheomorphism of the sediments. In the Khale Dolerite sheet, Eales (1959, p. 93) suggests that volatiles have segregated from the magma and migrated upward causing the development of pegmatite schlieren in the upper part of the sheet. The concentration of pegmatite at Bird's River is along the cooling joints below the xenoliths and these joints acted as passageways along which the volatiles migrated into the sediments.

C. THE CONTAMINATED DOLERITES.

Preliminary statement.

Acidified or contaminated dolerite produced by incorporation of Table Mountain Sandstone at Coedmore Quarries, Durban, is described by Mountain (1958). He noted (p. 217) the following features as being characteristic of the series of acidified rocks he examined:

a) Secondary pyroxene may develop as a marginal phase of the augite but more commonly the augite is altered to chlorite or hornblende.
b) Labradorite has been converted to andesine or altered to zoisite,

PLATE X: Contaminated dolerite from below the Cairn showing a crystal of pyroxene (py) ophitically intergrown with plagioclase (pl) in an aggregate of turbid tridymite granophyre (gr). (Crossed nicols, magnification = 50X)

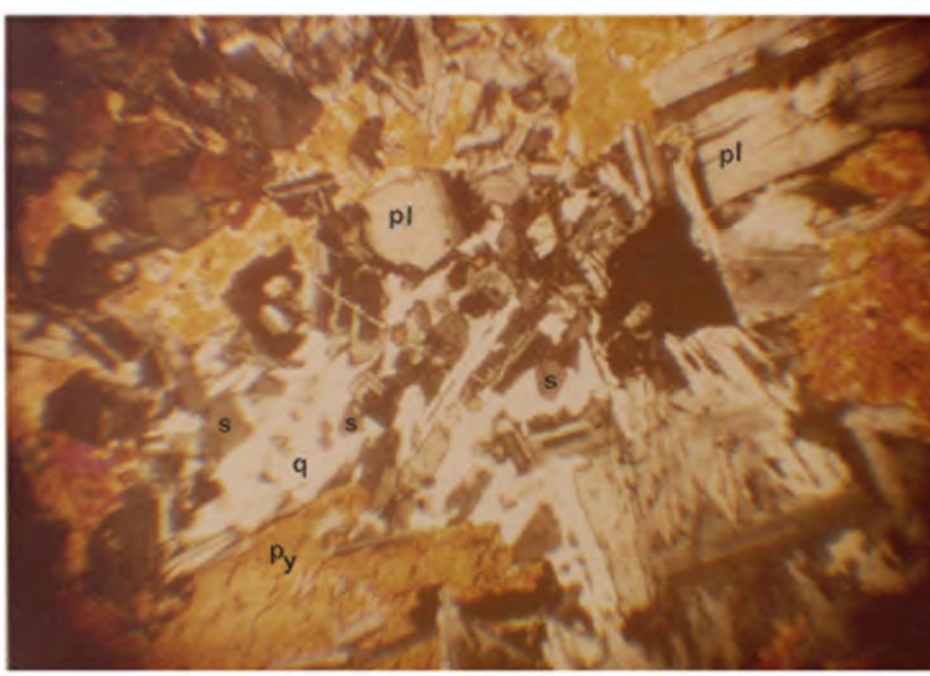


PLATE XI : Tridymite granophyre (gr) in an example of contaminated dolerite. The granophyre consists of an intergrowth of quartz paramorphic after tridymite (q), and sanidine (s). The ophitic intergrowth of pyroxene (py) and plagioclase (pl) can be seen. (Magnification = 30X) prehnite or other fine-grained aggregates.

c) Quartz has been introduced and appears in various forms.

d) Micropegmatite seems to appear first followed by granular quartz, skeletal quartz crystals (possibly paramorphic after tridymite) and spherulitic intergrowths of quartz and feldspar.

e) Calcitization has occurred and may be partly due to introduced $CaCO_3$ and partly from decomposition of plagioclase.

f) The development of chlorite and of quartz-feldspar intergrowths shows a similarity to the metamorphosed sediments.

It will be seen shortly that the contaminated dolerites from the Bird's River Complex have rather different features to those encountered by Mountain. Walker and Poldervaart (1942, p. 292) describe a contaminated dolerite below the metasomatic granophyre in the Rietkop sill. They record that this "transition" dolerite is richer in micropegmatite and poorer in mafic minerals, indicating transference of silica and alkalis from the sediment.

Petrography of the Bird's River contaminated dolerite.

As has been mentioned in a previous chapter, the contaminated dolerites in the Bird's River Complex are found at the top of a sheet intruded into the Cairn xenolith (grid ref. C4) and along the southern contact of the Grootkloof xenolith, (grid refs. G7 and H8). Both examples underlie intensely metasomatized sediments and are often associated with tongues of pyroclastic rock that have been ingested by the dolerite.

That contamination of these dolerites has occurred is evident from a number of the hand specimens collected, where irregular white patches of felsic material up to 20 mm. in diameter were recorded. Generally these contaminated dolerites do not contain patches quite as clear as in the example just described but are generally pale grey, equigranular, holocrystalline rocks that possess faint irregular mottling.

These rocks are composed of plagioclase ophitically intergrown with augite, and either pigeonite or hypersthene, or both. Felsic material mostly in the form of tridymite granophyre constitutes a large part of these rocks (see Plate XI).

The plagioclase, in the form of subhedral, often intensely fractured laths 1,0 mm. in length, is labradorite (An_{69}) in the Cairn xenolith and bytownite (An_{74}) at Grootkloof. The plagioclase possesses normal zoning with the margins of the grains being as sodic as An_{40}. Twinning is generally according to the Albite or Carlsbad laws. Alteration to a sericitic product is developed in the more calcic cores of the plagioclase grains.

Anhedral augite of variable compostion (see Table XI, analysis 6 and 7) occurs ubiquitously along with either or both hypersthene and pigeonite. The latter two minerals often occur as cores within augite overgrowths. Opaque ore material is often accumulated along pyroxene grain boundaries.

The pigeonite contains very fine exsolution lamellae parallel to the (001) crystal face.

When hypersthene only is present with the augite, the pyroxenes become distinctly lath-like in habit, a feature, as will be seen, that is similar to the mode of occurrence of the hypersthene in the rocks regarded as highly metasomatized. Alteration of the pyroxene is confined to small amounts of turbid green and brown products.

The felsic contamination consisting mainly of quartz and potassium feldspar is present in the following forms:

a) A medium-grained assemblage of quartz and subgraphic to euhedral sanidine. The two phases constituting the intergrowth are in optical continuity amongst themselves.

b) A medium to fine-grained intergrowth of quartz needles (probably inverted from tridymite) intergrown with sanidine. As before, each phase exhibits optical continuity.

c) A turbid, often spherulitic, fine-grained mass of feldspathic material containing relatively few needles of quartz.

The sanidine has a faint pink tint when fresh, has 2V=15-20° and is optically negative. In a number of rocks examined the sanidine is a turbid brown colour due to alteration. The felsic material occurs as large patches averaging 6,0 mm. in diameter, or as smaller patches which are interstitial between the constituent plagioclase and pyroxene crystals. Incipient reaction between this acid material and the plagioclase is common. The pyroxene grains often appear to have been broken up by the contaminating material. Rods of ore minerals and orthopyroxene and fine clear needles of what appears to be sillimanite are associated with this felsic material in its various forms.

Minor quantities of biotite and apatite occur in some of the specimens examined. Polished-section examination indicated the presence of titanomagnetite, ilmenite, magnetite and pyrite. The titanomagnetite contains very fine exsolution lamellae of ilmenite.

D. MICROMETRIC DATA.

The micrometric analyses listed in Tables IV and V are in volume per cent. For reasons of comparison a number of analyses carried out by Booth (1971, Tables IV, VI and VII) are quoted as well as the modes of an average dolerite-pegmatite (Walker and Poldervaart, 1949). The micrometric data relating to the contaminated dolerites will be given along with further discussion at the end of the next chapter as the association of these rocks with the metasomatic granophyres is important.

At this stage only two features of the data presented in Tables IV and V will be considered. These are:

a) The close correlation of analyses 4, 5 and 6 is interesting. Booth (1971, p. 69) argues on a petrographic basis that the fine grain-size, greater proportion of pyroxene in the rock and presence of a trace of biotite serve to indicate that the dolerite sills in the Smuts Pass xenolith are older than the Bell-jar dolerite. Sample

TABLE IV.

Micrometric Analyses of the Dolerites.

	1	2	3	4	5
Sample number	X10	-	X24	T_1/4A	X58
Plagioclase	49,0	54,8	37,5	52,2	57,3
Pyroxene + alteration ..	44,0	42,3	46,8	36,8	34,9
Olivine + alteration ...	2,0	0,6	2,3	3,5	2,0
Opaque minerals	4,4	2,3	4,6	4,8	4,2
Mesostasis + granophyre + quartz	-	-	-	2,7	1,6
Other	$0,6^+$	-	8,8*	-	-
	100,0	100,0	100,0	100,0	100,0

1 = Contact dolerite from northern margin of Cairn Xenolith (+ = volume per cent of contamination by microxenolith).

2 = Chill zone from Branstone (Booth, 1971, Table VI).

3 = Glassy dolerite from sill in Cairn Xenolith (* = volume per cent brown glass).

4 = Fine-grained dolerite from sill in Cairn Xenolith.

5 = Fine-grained dolerite from below Grootkloof Xenolith.

(Micrometric analyses 1, 3, 4 and 5 performed by the author).

TABLE V.

Micrometric analyses of the dolerites.

	6	7	8	9	10
Sample number	-	X63	-	X74	-
Plagioclase	51,7	59,3	61,9	42,0	35
Pyroxene + alteration ...	35,4	25,4	27,2	28,9	28
Olivine + alteration	5,9	2,0	1,3	-	-
Opaque minerals	3,1	2,6	2,9	2,5	8
Mesostasis + granophyre + quartz	3,9	10,1	6,7	25,5	25
Other	-	0,6	-	1,1	4
	100,0	100,0	100,0	100,0	100

6 = Sill within Smuts Pass Xenolith presumed to be older than the bell-jar intrusion. (Booth, 1971, Table VII).

7 = Poikilophitic olivine dolerite with quartz, 180 metres below Cairn Xenolith.

8 = Average of 4 analyses of poikilophitic olivine dolerite (Booth, 1971, Table IV).

9 = Dolerite-pegmatite below Cairn Xenolith.

10 = Average mode of Karroo dolerite-pegmatite. (Walker and Poldervaart, 1949, p. 619).

(Micrometric analyses 7 and 9 performed by the author).

X58 (analysis 5) found near a sedimentary contact outside a xenolith (ie. in the bell-jar dolerite) is similar petrographically to specimen T_1/4A (analysis 4) taken from a sill in the Cairn xenolith. The pyroxene content of these rocks is intermediate between that of the poikiliophitic olivine-quartz dolerites and the contact dolerites, they all have a fine grain-size, and although no biotite was found in either example examined by the author, contaminated dolerites occur close to both outcrops of this fine-grained dolerite that do contain biotite. From these data it is suggested that the sills within the xenolith are of the same age as the dolerite of the bell-jar.

b) The close correspondence between modal analyses obtained by Booth and the author on samples of the poikiliophitic olivine dolerites collected at different localities within the intrusion suggests a homogeneity of these rocks throughout the intrusion.

Mineralogical data.

Table VI summarizes the mineralogical parameters relating to the various dolerites and contaminated dolerites. The data presented in this table will be considered together with the data to be presented for the metasomatic rocks. One point that is further emphasised, however, is the fact that the compositions of the feldspar and pyroxene of the fine-grained dolerite both inside and outside the xenolith as well as that of the poikilophitic olivine dolerite and quartz dolerite correspond closely, agai n indicating a possible similarity in age.

TABLE VI

Optical properties of plagioclase and augite.

	Sample number	Augite		Plagioclase	
		$2V_z$	N_y	$2V_z$	Plag. comp.
1.	X10	49,5	1,671	92,5	An_{77}
2.	X24	49,5	1,680	87,5	An_{75}
3.	T_1/4A	46,0	1,694	89,0	An_{73}
4.	X11	47,0	-	88,0	An_{74}
5.	X63	46,0	1,695	89,0	An_{74}
6.	X74	40,5	1,725	-	An_{63}
7.	T_1/3A	44,0	1,698	85,0	An_{68}
8.	T_1/2	44,0	?	86,0	An_{69}
9.	X53	?	1,710	-	An_{74}

KEY

1 = Contact dolerite from northern margin of Cairn xenolith.

2 = Glassy dolerite from sill in Cairn xenolith.

3 = Fine-grained dolerite from sill in Cairn xenolith.

4 = Fine-grained dolerite 0,5m. from outer contact of Cairn xenolith.

5 = Poikilophitic olivine dolerite with quartz, 180m. below Cairn xenolith.

6 = Sample of roof-zone dolerite-pegmatite from below Cairn xenolith.

7 = Contaminated dolerite from sheet in the Cairn xenolith.

8 = Contaminated dolerite from sheet in the Cairn xenolith.

9 = Contaminated dolerite from below the Grootkloof xenolith.

CHAPTER FIVE.

THE MINERALOGY AND PETROGRAPHY OF THE THERMALLY METAMORPHOSED PYROCLASTIC ROCKS OF THE XENOLITHS.

Introduction.

Quartz paramorphic after tridymite, often as part of a granophyric intergrowth with potassium feldspar, is prominent in the metamorphosed sediments in the two xenoliths examined and relevant aspects of the mode of occurrence and other general features of this mineral will be discussed first. Incorporated in this discussion will be certain points pertaining to its occurrence in the dolerites.

The two major sedimentary types constituting the xenoliths are pyroclastic sediments and sandstone, both apparently of Cave Sandstone age. This chapter consists of description of the pyroclastic rocks along with their metamorphosed associates.

Two points of clarification should be made at this stage. Firstly, the term metamorphism should here be taken to include the phenomenon of metasomatism and secondly, the term sandstone used here may be taken to include sandstone-tuffs. These sandstone-tuffs generally contain scattered lithic fragments in a quartzitic matrix and in the field closely resemble the sandstones and will be considered in Chapter Six.

A. TRIDYMITE.

1) General statement.

Quartz, paramorphic after tridymite in the form of needles, laths and wedge-shaped crystals is prominent in the bulk of the metamorphic rocks examined and also occurs in the mesostasis of the dolerite-pegmatites and in the contaminated dolerites. In the two latter varieties and also in the more extremely metamorphosed sediments it is generally in the form of a granophyric intergrowth with potassium feldspar (sanidine).

Tridymite has been used in the study of the paragenesis of rocks in which it is present. However, its use as a geothermometer is rather limited as will be seen in the following discussion.

2) The temperature and pressure relationships of tridymite.

The classical investigation of the stability relations of silica minerals carried out by Fenner (1913) indicated that below 870°C (±10°C) quartz is the stable phase, between 870°C (±10°C) and 1470°C (±10°C) tridymite is the stable phase and at temperatures above 1470°C cristobalite is formed. Tuttle and Bowen (1958, pp. 28 - 35) determined the inversion points of the various silica phases taking into consideration the effects of pressure. They recorded that the inversion is sensitive to pressure and that a pressure of 1000 kg/cm^2 raised the inversion temperature by about 180°C.

Prior to this work by Tuttle and Bowen, Black (1954) presented physico-chemical data that indicated that the presence of tridymite in rocks points to high temperatures and low pressures. He recorded that the greatest pressure under which tridymite can possibly form from quartz is about 960 kg/cm^2 and is probably not more than 650 kg/cm^2. These pressures indicate an overburden of 3850 and 2650 metres thickness respectively, assuming the specific gravity of the rock to be 2,5.

It is generally well knownthat the presence of foreign elements plays a part in determining the temperature at which this mineral will crystallize. Deer, Howie and Zussman (1963, vol. 4, p. 192) remark that the chemical compositions of all natural tridymites appear to depart in varying degrees from 100 per cent SiO_2 and, possibly as a result of the more open structure of tridymite, relatively large ions of the alkali and alkaline earth groups can be accommodated within the structure. It appears as though tridymite crystallizes most readily from systems containing alkali metals. Roy, Isaacs and Shafer (1957) found that tridymite can be prepared in the system $SiO_2 - H_2O$ at pressures as low as 100 kg/cm^2 at about 900°C and as Na + Al is substituted the temperature of formation of tridymite decreases more or less regularly, so that with about 10 mol. per cent $NaAlSiO_4$, tridymites have been obtained as low as 550°C, thus rendering invalid the use of tridymite in a rock as an indicator that temperatures were above 870°C.

A controversy has subsequently arisen as to the true nature of tridymite. Some writers have excluded tridymite as a stable silica phase in the system SiO_2, contending that it is a compound or a solid solution between silica and an additional chemical constituent. Holmquist (1961) heated mixtures of silica and alkali chlorides or alkali oxides at various temperatures within the range 860° to 1150°C and certain of his more relevant conclusions are:

a) When quartz was heated with 2 per cent alkali oxide, tridymite formed directly at 872° to 898°C with Na_2O, at 883° to 902°C with K_2O, and above 1005°C with Li_2O.
b) The formation of tridymite can be strictly a solid state process.
c) When quartz plus sodium chloride was heated, tridymite did not form but cristobalite started to form at 1050°C.

Holmquist suggested that the conversion of silica to tridymite, in the presence of solid or liquid silicates is brought about by the solution of alkali oxides in the silica structure. He pictured tridymite as a binary incongruently melting phase containing a small amount of metal oxides and having a stability range which varies with the stabilizing oxide. Rockett and Foster (1967) performed experiments in order to gauge the stability of purified tridymite and concluded that the closer tridymite approaches pure silica, the more stable it becomes which would be expected if tridymite is a SiO_2 polymorph. The stability of a compound or solid solution of tridymite involving additional ions would decrease markedly on approaching pure SiO_2. They also found that tridymite persisted 200°C above the 1470°C stability limit for tridymite/cristobalite inversion and hence argued that sluggishness of inversion increased with increased purity of the transforming phase. Holmquist (1968) objected to these findings on the grounds that it was doubtful if the methods employed by the two former authors to purify tridymite worked and in actual fact they had not purified the tridymite phase proper but its environment. Forster (1968), however, stated that the tridymite they used contained less and less alkali regardless as to how it was present and the percentage alkali in their leached tridymite was about 0,02 per cent.

Two important factors arise out of the data presented in the above review of some of the literature relating to tridymite;

a) The use of tridymite as a geothermometer is dubious due to the effects of alkali and alkaline-earth contamination resulting in shifting of the inversion points. If tridymite is present in thermal metamorphic rocks one can only state that conditions of low pressure and probably high temperature prevailed. Many authors have used tridymite as an indicator of P-T conditions (eg. Black, 1954). However, the utilization of other parameters relating to associated minerals in conjunction with those of tridymite may be helpful in determining the P-T conditions prevailing at the time of formations of the rocks. (See Spry and Solomon, 1964, pp. 528 - 532).

b) It appears from Rockett and Foster's work that tridymite may be regarded as a SiO_2 polymorph and not as a compound or a solid-solution mineral.

3) The distribution of tridymite.

Tridymite generally is found in acid and basic volcanic rocks and in domains of high thermal metamorphism. Brown (p. 151, see Hess, 1967) states that in basaltic rocks it is mostly confined to lavas and is found inverted to quartz in all but the most recent flows. Wager and Brown (1968, pp. 132, 135 and 138) record the presence of tridymite in certain of the rocks in the Skaergaard Intrusion. In the Upper Border Group rocks of this intrusion tridymite occurs in the mesostasis along with decomposed alkali feldspar. These authors believe the tridymite to have formed by thermal metamorphism produced by the intrusion of the Basistoppen Gabbroic sheet. Tridymite is also found in the melanogranophyres of Skaergaard in a granophyric intergrowth. Wager and Brown (p. 140) believe that these granophyres were produced by a filter-press action on the partly melted gneiss inclusions as well as on the partly solidified Upper Border Group rocks.

Wager et al. (1953) recorded this mineral in a Tertiary intrusive granophyre from the Isle of Skye. Quartz paramorphic after tridymite occurs in both the "Main Granophyre" and its chilled margin. These authors suggest that this granophyre may have been produced by fusion of sandstone adjacent to a basic intrusion. In subsequent work on the granitic rocks of the Isles of Skye and Rhym, Brown (1963) conducted melting experiments on Tertiary granophyres and Torridonian arkose at 1000 kg/cm^2 water vapour pressure in relation to the system $NaAlSi_3O_8$ - $KAlSi_3O_8$ - SiO_2 - H_2O. He constructed P-T curves for the Skye granophyres and, viewed in relation to the stability of tridymite, the depth and temperature of emplacement were estimated. Brown concluded that these Tertiary granitic rocks were produced through partial melting of Basement rocks by basic magmas and further, subsidiary amounts of granitic magma were similarly derived at higher levels, within the Torridonian arkose group.

Tridymite is commonly recorded in sediments that have undergone intense thermal metamorphism. The presence of this mineral in metamorphic rocks generally classifies them in the sanidinite facies of thermal metamorphism (Fyfe, Turner and Verhoogen, 1958, p. 214; Winkler, 1967, p. 43; Turner, 1968, pp. 238 - 240). Accepting that the inversion point between quartz and tridymite is 870°C it becomes clear that this temperature would only be reached by basic or ultra-basic intrusions.

Reynolds (1940) records quartz rods paramorphic after tridymite produced by contact metamorphism of sandstone by a Tertiary dolerite dike. Wyllie (1961) found tridymite in fused Torridonian Sandstones, the high temperatures having been produced by a picrite sill. Wyllie believes that the quartz fused early in the metamorphic process and tridymite crystallized from the interstitial melt forming fringes around the partly resorbed quartz grains. Similar occurrences have been described by Butler (1961) and Smith (1969) where dolerite plugs metamorphosed and partly fused the adjacent sediment resulting in the production of tridymite. Spry and Solomon (1964) describe buchites having columnar jointing adjacent to a Tertiary basalt neck. These buchites also contain quartz as corroded angular fragments, some of which are fringed with tiny hexagonal needles of tridymite. Stevenson (1963) has described quartz paramorphic after tridymite occurring as blades radiating from quartz xenocrysts or adjacent to quartzite xenoliths in the Upper Contact Phase of the Sudbury micropegmatite, Ontario.

Within the Karroo dolerite province the occurrence of tridymite in metamorphosed sediments is rare (Walker and Poldervaart 1949, p. 675). However, a few occurrences have been recorded. Frankel (1950) described vitrified Karroo sediments in the Barkly East district of the Cape Province where the tridymite occurs as small laths fringing quartz grains. Similarly, vitrification of Middle Ecca arkose by a Karroo dolerite sheet near Heilbron in the Orange Free State has resulted in the production of tridymite (Ackerman and Walker, 1960).

Eales (1974) has conducted an examination of quartz paramorphic after tridymite in the North-Eastern Cape. He has examined some of the rocks containing tridymite that occur in the Bird's River Complex and at the same time noted the occurrence of this mineral in other localities. He draws conclusions regarding a general pattern of distribution in the North-Eastern Cape. These are;

i) No evidence has been found that reveals the formation of tridymite in rocks occurring beneath the Molteno formation.

ii) Out of 21 samples taken above the base of the Molteno formation, only eight contain tridymite.

iii) Many dolerite contacts against Stormberg Group sediments show no evidence for the formation of tridymite.

One of the features that arises from the presence of tridymite in the contact aureole rocks is that intense fusion often occurs, indicative of the high temperatures that are produced.

4. <u>The habit of tridymite.</u>

Hawkes (1916) recognised two forms of tridymite, namely:

a) A complex of lamellae branching out from one another at different angles. Several lamellae may form one individual of common optical orientation, the laths forking without change in optical properties, while one straight lath may be composed of many individuals.

b) A single quartz individual showing traces of original complex lamellae running through the grain.

Wager et al.(1953), Skelhorn (1962) and Wager and Brown (1968) have reported on quartz paramorphic after tridymite occurring as narrow rectangular areas in granophyres. The long sides of these grains which appear to represent the basal pinacoid of tridymite are well-defined and straight while the ends are not clearly bounded. Ray (1946) along with Wager et al. (1953) and Skelhorn (1962) all show that the optic axis of the quartz is not perpendicular to the former basal pinacoids of the tridymite. Skelhorn illustrates this feature with examples of tridymite rods that have been replaced by 1 to 12 quartz individuals. These new quartz individuals do not usually have their edges perpendicular to the original basal pinacoid of the tridymite and are likened by Skelhorn to wedges in which the tapered end has been truncated.

In metamorphic rocks tridymite occurring as small laths forms fringes around original quartz grains. These fringes are in optical continuity with the original quartz grains (Reynolds, 1940; Frankel, 1950; Ackerman and Walker, 1960; Wyllie, 1961; Butler, 1961; Spry and Solomon, 1964; Smith, 1969). Wyllie (1961) regards the tridymite as crystallizing from an interstitial melt and forming the fringes around the quartz grains. The most relevant classification of the habits of tridymite has been made by Eales (1974, p. 40). This classification is quoted and is as follows;

"i) Quartz grains fringed by outgrowths of fine tridymite needles,

ii) clusters of robust tridymite plates retaining a core of quartz which failed to invert,

iii) euhedral froms,

iv) tridymite in igneous rocks, where the lath-like, acicular or reticulate habit is most common."

B. THE PYROCLASTIC ROCKS AND THEIR METAMORPHOSED EQUIVALENTS.

General statement.

The classification of the pyroclastic rocks to be described is based on the degree of metamorphism they have undergone. The classification is as follows:

1) The unmetamorphased pyroclastic rocks.

These are mainly lapillistones which constitute the bulk of the pyroclastic material that has been metamorphosed.

2) The metamorphosed pyroclastic rocks.

No sharp boundaries can be defined between the various types and the broad classification is based on the degree of recrystallization of the quartz and inversion of quartz to the tridymite form, the degree of devitrification of the glass lapilli and the merging of the lapilli with the groundmass. A separate category includes the rocks that have undergone fusion with the production of glass. Thus the classification is as follows:

i) Slight to moderately metamorphosed pyroclastic rocks. Most of the quartz has been recrystallized with substantial inversion to tridymite. Devitrification of the vitreous lapilli has taken place with the ultimate production of fine pyroxene in a fine cryptocrystalline matrix. Zircon is present and sillimanite began to develop in the more extreme varieties.

ii) Intensely metamorphosed pyroclastic rocks without metamorphic glass. Almost all the quartz has inverted to tridymite. Devitrification and merging of the glassy igneous lapilli with the groundmass is at its greatest and in the most intense cases few of the larger lapilli remain. Only the larger sedimentary lapilli are still recognisable and these have been completely recrystallized. The bulk of the ingested pyroclastic rocks are also included in this category. No zircon was observed and sillimanite is a common constituent.

iii) Intensely metamorphosed pyroclastic rocks with metamorphic glass.

At two localities fusion of the pyroclastic rocks has occurred with the production of glass and, in one instance, accompanying green hypersthene. Only the larger lapilli may be distinguished in the hand specimen. No zircon was recorded.

1) The unmetamorphosed pyroclastic rocks.

General statement.

Because of the lack of fresh unaltered pyroclastic rocks to be found in the area investigated the descriptions that follow are based on samples exhibiting some degree of weathering.

These pyroclastic rocks are variable in character with lapillistone forming the bulk of these grading into pyroclastic breccia towards the central part of the Cairn Xenolith . Most of the metamorphosed pyroclastic rock appears to be of the lapillistone type. Booth (1971, pp. 105 - 106) attempted to classify the pyroclastic rocks on the basis of the percentage of igneous fragments present in them.

This classification may be irrelevant to a certain extent as the variation of the content of igneous fragments in specimens collected as close as possible to the metamorphic rocks varied between 14 and 40 per cent with no regular distribution pattern of the varieties being observed in the field.

Generally these rocks are composed of pyroclastic fragments of both igneous and sedimentary origin in a medium-grained brown matrix. The variety in size of the fragments has been described in Chapter III. The samples to be described are lapillistones containing fragments averaging 3 mm. in diameter. Fragments, mostly of sedimentary origin, were found ranging up to 40 mm. along their longest axis. Bedding is absent and poor sorting of the constituents is evident. Accessory crystalline fragments of dolerite material are rare and occur more commonly in the pyroclastic breccias that are found near the supposed vent in the central part of the Cairn xenolith.

The groundmass.

The groundmass is composed of mostly angular quartz fragments set in a turbid brown matrix. The quartz is of uniform grain size averaging 0,2 mm. in diameter with a maximum diameter of 0,4 mm. being recorded. Scattered fragments of plagioclase, fine particles of ore material and subrounded zircon grains make up the rest of the groundmass.

The sedimentary lapilli.

Argillaceous fragments constitute the bulk of the sedimentary lapilli and are generally pink to dark brown in colour. These have extremely fine grain-size and are composed mainly of fine clay material containing varying quantities of fine quartz grains. Bedding and accompanying structural features such as shearing perpendicular to a bedding plane are commonly found in these fragments.

Light to medium brown arenaceous sandstone fragments are less common and

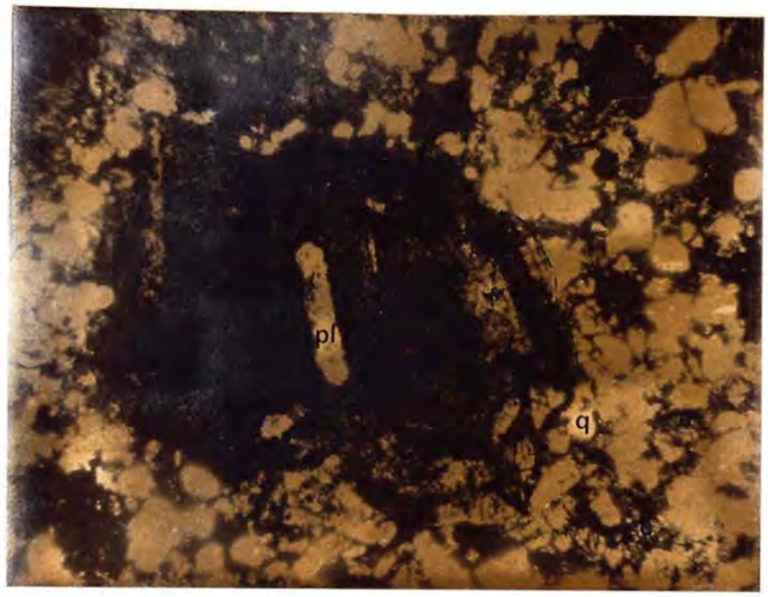


PLATE XII: A photomicrograph of a zoned basaltic glass clast (f) containing a relict plagioclase phenocryst (pl) in a lapillistone specimen. The groundmass consists of angular quartz crystals (q) and clay minerals (c). (Ordinary light, magnification = 30X)

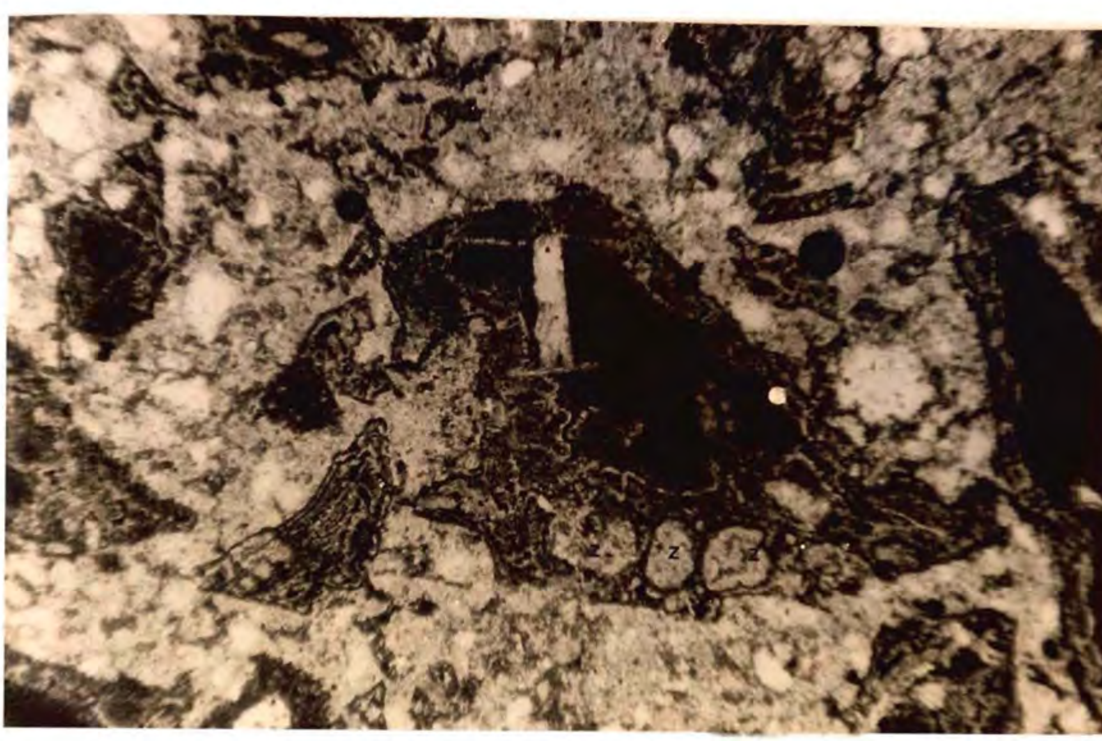


PLATE XIII: Angular, distorted, zoned glass clasts in the turbid groundmass of a slightly metamorphosed lapillistone. Note the particles of foreign material (z) that were incorporated in these clasts during their deposition. (Ordinary light, magnification = 20X) mostly composed of angular to subrounded quartz or quartzitic sandstone fragments about 0,3 mm. in diameter. The boundary between these arenaceous fragments and the groundmass is often rather vague.

The igneous lapilli.

The bulk of the igneous fragments are irregular to subrounded, often bent and twisted glassy forms containing subhedral phenocrysts of plagioclase and occasional augite. (See Plates XII and XIII). The glass is basaltic. The augite phenocrysts may poikilitically enclose the feldspar. Fragments of quartz are commonly incorporated in the glass fragments.

These vitreous lapilli are generally composed of two zones, namely a narrow, dark brown outer margin and an orange-brown core. (See Plates XII and XIII). A sharp boundary separates the two zones with the outer zone appearing to have undergone slight devitrification. Fine particles of ore material are much more abundant in the outer zone and scanning with the electron microprobe for Fe indicated that the glass of the outer zone is richer in this element than the core. In a number of these lapilli this outer zone is clearly separated from the core by a definite crack and it is possible that the zoning has been produced as a result of droplets of basaltic magma falling into water or damp unconsolidated sediments. Compositional determination of the plagioclase phenocrysts gave a composition of An_{74}.

Fragments of wholly crystalline igneous material are rare in the lapillistones and those observed consist of narrow subparallel laths of plagioclase and chloritic alteration material.

Origin of the pyroclastic rocks.

Parsons (1969) reviews the criteria for recognition of volcanic breccias and, based on his data, these rocks have two possible origins:

a) They are vulcanian breccias produced by aerial ejection during explosive eruptions; or
b) They are lavaric breccias produced by debris flows and mudflows of volcanic origin.

Support for the suggestion that these are vulcanian breccias is that:

a) The glassy lapilli are not broken as one would expect in a mudflow;
b) Although poorly sorted, there is a concentration of rock containing large blocks of material within a relatively confined area indicating that a major vent may be close by (in this case about 1 km. away).

2) The metamorphosed pyroclastic rocks.

Introduction.

The effect of the dolerite on the sediments is variable as material exhibiting slight degrees of metamorphism may be found at the contact only metres away from outcrops of intensely metamorphosed sediments. This effect is possibly due not only to variation in temperature but also to the varying degree of transfusion of material from the dolerite into the sediment along the contact.

i) The slight to moderately metamorphosed pyroclastic rocks.

At an early stage of metamorphism the pyroclastic rocks become hard and brittle, generally breaking with conchoidal fracture. The metamorphic effects are exhibited in samples collected up to 80 metres from the dolerite.

The groundmass.

The assemblage constituting the groundmass is basically similar to that of the unaltered material with recrystallized quartz being the predominant mineral. The groundmass of the least altered rocks generally has a turbid appearance in thin section and this is partly due, either to fine flakes of chlorite and other clay material occurring between the quartz grains, or the commencement inversion of the quartz to tridymite towards the grain boundaries of the quartz. Reynolds (1940, p. 466) described quartz-grain boundaries having a grey shaded appearance which she attributed to the presence of minute dots and rods of a dark material associated with minute gas inclusions. Associated with this phenomenon described by Reynolds is the development of fringes of tridymite around the quartz-grains. It is possible also that this turbidity may have been partly due to incipient reaction between the quartz grains and metasomatizing fluids that began diffusing through these rocks.

With progressive metamorphism, recrystallization of the quartz becomes more intense, resulting in the greater development of interlocking grains. Tridymite has developed as lath-like crystals which form a fringe around the remaining uninverted quartz grains and with subsequent inversion of the tridymite back to quartz a single unit presenting complete optical continuity has developed. The development of turbid subhedral potassium feldspar appears to accompany the development of tridymite. This feldspar has probably formed as a result of reaction between the previously mentioned dark brown clay matrix of the groundmass, the metasomatizing fluids and the quartz. Scattered patches are found where complete inversion of the quartz to tridymite has produced a granophyric intergrowth of tridymite and sanidine.

In some of the more highly metamorphosed varieties fine crystals of orthopyroxene occur. These may have been produced by reaction between the vitreous igneous lapilli and the metasomatizing fluids, by the heating and slow cooling accompanying metamorphism which resulted in the devitrification of the smaller fragments, or from chlorite present in the lapillistones. The further development of this mineral appears to accompany the devitrification of these lapilli. (See Plates XIV and XV).

The original plagioclase present in the groundmass is unchanged and occurs as clear anhedral crystals. Universal stage determinations indicate that this feldspar has a composition of An_{48}.

Very fine particles of ore minerals occur interstitially and to some

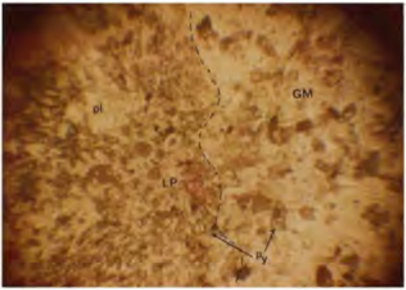


PLATE XIV: A photomicrograph of a metamorphosed pyroclastic showing the development of fine pyroxene crystals (py) in a devitrified basaltic lapillus (LP) and also in the groundmass (GM). The romanent lapillus illustrated here contains relict plagioclase crystals (pl). The dashed line represents the boundary between the lapillus and the groundmass. (Ordinary light, magnification = 30X)

PLATE XV: The grade of metamorphism illustrated in this photomicrograph is slightly higher than that in PLATE XIV. Rods of hypersthene have developed in the lapillus (LP). (Ordinary light, magnification = 30X) extent may contribute to the turbidity of the groundmass. Scattered flakes of biotite occur. Zircon is present, mostly as subrounded grains. Fine needles, probably sillimanite, were found in some samples nearer the contact.

Sedimentary lapilli.

The argillaceous fragments exhibit complete crystallization of their quartz, often with the development of fine tridymite. These fragments have lost their dark colour as the clay material that formed the bulk of these lapilli has been broken down to a slightly turbid extremely fine-grained feldspathic assemblage. Very fine particles of pyroxene have also developed within these fragments. In thin section the boundary between these fragments and the groundmass is sometimes vague with the lapilli tending to merge into the groundmass in the more metamorphosed varieties. Fine particles of ore material have developed in these argillaceous fragments.

Complete recrystallization of the quartz in the arenaceous fragments, with the partial development of tridymite and turbid feldspathic material, makes distinction of these from the groundmass difficult.

The igneous fragments.

In the least affected pyroclastic rocks there has been a colour change of the glass lapilli in thin section in that the original brown colour has now changed to a translucent grey with the marginal zone being slightly more transparent. In these lapilli devitrification has produced a fine cryptocrystalline aggregate with the occasional development of chlorite in patches or as fine flakes. Fine ore particles occur in the lapilli and are coarser in the marginal zone than in the cores of the lapilli. In those rocks where the metamorphism is more intense devitrification has produced an assemblage of fine orthopyroxene crystals (about 0,05 mm. in diameter) set in a crypto-crystalline feldspathic matrix. At this stage merging of the groundmass with the vitreous lapilli commenced with the development of fine orthopyroxene in the groundmass. (See Plates XIV and XV).

The plagioclase phenocrysts in these lapilli have been only slightly affected by the metamorphism in that they have become fractured and slightly altered to a sericitic alteration product. In a few of the samples fine flakes of chlorite have developed within the plagioclase crystals and in the examples that exhibit a more intense degree of metamorphism partial recrystallization of the plagioclase has occurred. Compositional determinations of the plagioclase in the lapilli give similar values as before. In this case the values obtained on three samples from different localities are An_{74}, An_{73-75}, and An_{72}. The original augite phenocrysts have been partly broken down to an olive-green to deep-brown chloritic alteration product.

The original crystalline feldspathic basalt and dolerite fragments appear to have been only slightly affected by metamorphism in that alteration of the constituent pyroxene has taken place.

Degree of metamorphism relative to distance from contact.

Table VII illustrates the development of metamorphism in a series of three samples collected along a traverse above Grootkloof. The inhomogeneity of the pyroclastic rocks, lack of outcrop, and irregular distribution of the metasomatic rocks along the contact made it difficult to obtain a more comprehensive suite of samples along a traverse. However, the three samples detailed in Table VII were selected because of their close resemblance to each other and because they were collected along a traverse. X48 and X49 are regarded as exhibiting slight to moderate degrees of metamorphism while X47 is one of the samples exhibiting the intense metamorphism to be described shortly.

From a petrographic point of view there is a definite increase in the metamorphic character of these rocks towards the contact. The amount of tridymite granophyre in the groundmass increases significantly, the sedimentary lapilli change their character and devitrification of the vitreous lapilli results in the production of progressively coarser pyroxene crystals. An interesting feature is that the number of zircon grains per gram of rock decreases as the contact is approached. (See zircon analyses ahead).

These rocks are believed to have undergone a certain amount of metasomatic change relative to the unmetamorphosed pyroclastic rocks (see following chapter). The inhomogeneity of these rocks, however, makes it difficult to determine the extent of metamorphism.

TABLE VII

Development of Metamoprhism Relative to the C ntact in the Grootkloof Xenolith.

Sample No.	Vertical Distance above dolerite	Nature of groundmass	Nature of sedimentary lapilli	Nature of vitreous lapilli	No. Zircons/ gm. rock	Composition of lapilli plagioclase
X49	10,7 m	Incipient inversion of quartz to tridymite. Isolated patches of tridymite granophyre occur.	Argillaceous fragments are highly turbid. Incipient formation of tridymite. Vague definition of lapilli boundaries.	Devitrification of lapilli with formation of fine pyroxene in cryptocrystalline matrix.	5	
X48	4,6 m	Further development of tridymite and tridymite granophyre	Argillaceous fragments recrystallized to clear assemblage. Tridymite more abundant Vague of definition lapilli boundaries.	As X49 but the pyroxene is coarser. Definition of lapilli boundary due to apparent migration of pyroxene into groundmass.	-	An_{74}
X47	0,5 m	Tridymite abundant commonly as granophyre Sillimanite is present	Similar to X48	Pyroxene coarser and matrix developing as finely crystalline feldspar. Vague definition of lapilli boundaries is common.	1	An_{72}

ii) Intensely metamorphosed pyroclastic rocks without metamorphic glass.

These rocks occur in localized patches along contacts with the dolerite and may be encountered up to 20 m. from the contact. They may occur adjacent to those described above and it appears as though localized conditions existing in the dolerite resulted in larger quantities of metasomatizing fluids being introduced into these rocks. These rocks are limited to the following localities:-

a) In the sediments overlying the Cairn dolerite sheet. (grid refs. C3 and C4).
b) A small capping of sediments overlying the dolerites west of Grootkloof. (grid ref. H8).
c) Small patches along the Grootkloof contact, probably produced by fingers of dolerite forcing their way into the sediments (grid ref. G7).

The amounts of relict lapilli vary between "common" in the less intensely metamorphosed varieties to "widely scattered" and "rare" in the most extreme types. In most of these rocks the finer lapilli disappear first. This is particularly true of the sedimentary lapilli where only the larger lapilli remain. Extreme metamorphism has produced rounded remnants of the lapilli in all the extremely altered rocks. These lapilli are set in an equigranular, medium to fine-grained, pale grey to blue-grey groundmass. As the degree of metamorphism increases so the rock becomes more igneous in appearance and the more intense types resemble a fine-grained igneous rock.

The inhomogeneity of the original pyroclastic sediments as well as the erratic distribution of metamorphic phenomena has resulted in the production of metamorphic rocks with similar basic characteristics but possessing a number of finer features that differ. The metamorphic rocks where the lapilli are still recognisable but poorly defined are intermediate between the previously described slight to moderate metamorphic pyroclastic rocks and the metamorphosed pyroclastic rocks where almost complete disappearance of the lapilli has occurred. Thin section description of the rocks was based on the following categorization of the specimens;

a) Those rocks where lapilli are still relatively abundant and recognisable;

b) Those rocks where the lapilli have mostly disappeared leaving widely scattered relicts and called the metasomatic granophyres.

The metamorphosed pyroclastic rocks with relatively abundant lapilli.

The original sedimentary texture of the groundmass has by this stage been completely destroyed (see Plates XVI and XVII). Most of the quartz has inverted to tridymite during metamorphism and more potassium feldspar has formed. The granophyric intergrowth of tridymite and the sanidine has developed further and is much coarser in texture. The sanidine is also abundant as fine discrete turbid crystals or as clusters of crystals. Pyroxene which now is quite a common constituent of the groundmass is present most commonly as rods or anhedral crystals of hypersthene, and minor augite, or as anhedral crystals of pigeonite and augite. It is possible that the hypersthene forms on devitrification of the igneous lapilli at

PLATE XVI: A further stage of metamorphism of the pyroclastic rocks. Note the ragged rods of quartz paramorphic after tridymite (q) and also the fully crystalline lapillus (LP). The dashed line marks the boundary between the lapillus and the groundmass. (Crossed nicols, magnification = 30X)

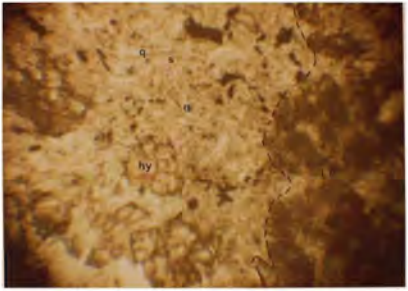


PLATE XVII: Relict lapilli (LP) in metasomatic granophyre. The designation of the minerals is as follows: hy = hypersthene, q = quartz paramorphic after tridymite, s = sanidine. The dashed line marks the approximate boundary between the groundmass and the lapillus. (Ordinary light, magnification = 30X) lower temperatures while pigeonite occurs in the higher temperature varieties. The hypersthene laths vary in length from 0,05 to 0,5 mm. Crystals of plagioclase are more common in the groundmass and are believed to have formed both by the introduction of Ca and Al into these rocks from the dolerite and the reconstitution of some of the original plagioclase present in the groundmass. These plagioclase grains are slightly more calcic than those in the less metamorphosed rocks, having composition of An_{80}.

In thin section it is no longer possible to distinguish between the groundmass and the original <u>sedimentary</u> lapilli. However, relatively large patches of quartz paramorphic after tridymite occur that are probably the remains of these lapilli.

The assemblage formed as a result of devitrification by metamorphism of the original basaltic glass is very similar in texture to the groundmass of the contact basalts. Here fine laths of plagioclase occur with subrounded granular clinopyroxene (probably augite). The original plagioclase phenocrysts are still present although most of the grains appear to have partly or completely recrystallized. Relict augite phenocrysts are rare and appear to have been altered to a green chlorite. Some of the igneous lapilli commonly contain quartz paramorphic after tridymite as well as tridymite granophyre formed from clastic quartz fragments that had been incorporated in the lapilli during deposition. As metamorphism becomes progressively more intense, the lapilli merge more and more with the groundmass leaving only the phenocrysts of plagioclase more or less intact.

A mesh of fine clear, very pale blue needles of sillimanite (identified by X-Ray diffraction) now occurs ubiquitously in these rocks. Minor quantities of anhedral biotite flakes may be present and the ore material, which is present in minor amounts, occurs as very fine subhedral cubic grains (probably magnetite) and as rods (probably hematite).

The metamorphosed pyroclastic rocks with few remnant lapilli (the metasomatic granophyres).

The rocks belonging to this group have probably undergone the greatest degree of alteration of all the pyroclastic rocks. Both in the field and in thin section they appear almost homogeneous. Relict pyroclastic fragments up to 10 mm. in diameter still occur. (see Plates XX and XXI).

Below the cairn the rocks are fine-grained while the rest, including the rocks capping the hills 200 metres north of the cairn (grid ref. C4) and west of Grootkloof (grid ref. H8) are medium-grained. The average grain-sizes of the major constituent minerals of the two varieties are as follows;

	Fine-grained type	Medium-grained type
Plagioclase (laths)	0,2mm	0,4mm
Orthopyroxene (rods)	0,3mm	0,6mm
Orthopyroxene (crystals)+		0,2mm

	Fine-grained type	Medium-grained type
Tridymite granophyre (intergrowth) *	0,6mm	1,0mm
Sillimanite needles	0,2mm	0,2mm

(+ = diameter of orthopyroxene crystals in types where the orthopyroxene is not rod-shaped).

(* = diameter of complete intergrowth).

The rocks are composed primarily of a turbid assemblage of quartz, sanidine, plagioclase and pyroxene. The sanidine is generally turbid due to incipient alteration and generally occurs with the quartz as a tridymite granophyre.

Plagioclase is now relatively abundant (see Table VIII) and generally is the most abundant constituent of these rocks. It occurs as subhedral, fractured, zoned, lath-like crystals having sharp, straight boundaries. Compositional determinations on the plagioclase of a number of samples gave a value of An_{76-78} for the fine-grained type and An_{69-73} for the medium-grained type with a value down to An_{36} for the grain margins.

Hypersthene and augite are the pyroxenes. The hypersthene most commonly occurs as rod-like subophitic crystals with rough grain boundaries, often with a narrow zone of small augite crystals partly enclosing the grain. (see Plates XVIII and XIX). In the outcrop at Grootkloof the hypersthene crystals are more equidimensional and are enclosed by a more substantial zone of augite crystals. The augite also occurs as isolated

PLATE XVIII: A composite pyroxene rod in a metasomatic granophyre where the core is hypersthene (hy) and the margin is clinopyroxene (cpx). The bulk of the material surrounding the pyroxene is tridymite granophyre. (Crossed nicols, magnification = 30X)

PLATE XIX: As PLATE XVIII but showing the fine subohitic plagioclase (pl). Other mineral designations are hy = hypersthene, tr = tridymite granophyre. (Crossed nicols, magnification = 20X)

PLATE XX: This photomicrograph illustrates a rare relict lapillus (LP) of sedimentary origin in a metasomatic granophyre. Tridymite granophyre has developed in this lapilli. The mineral designations are as follows; hy = hypersthene, pl = plagioclase, q = quartz paramorphic after tridymite, s = sanidine, sl = sillimanite. Ordinary light, magnification = 30X)

PLATE XXI: As PLATE XX but with crossed nicols.

individuals. Small crystals of pale brown biotite, and green chlorite are commonly associated with the pyroxenes and may be alteration products.

The sillimanite is in the form of very fine pale blue needles commonly having an elongation of greater than 10. It appears to be most commonly associated with the tridymite granophyre.

The opaque minerals are, mostly, as before. Remnant lapilli that are still clearly definable are rare. One of the best developed lapilli found was examined in thin section. This round patch 20 cm. in diameter, has a core consisting primarily of sanidine as anhedral equidimensional crystals averaging 1 mm. in diameter. The $2V_x$ of the sanidine is 12° and Ny is 1,527. The optic plane is parallel to (010) indicating the existence of a high temperature form. The values of 2V and refractive index from compositional diagrams indicate that the approximate composition of this sanidine is Or_{65} (Heinrich, 1965, p. 349, fig. 12.20 and Mackenzie and Smith, 1956, p. 406 fig. 1). Fine needles of rutile occur as inclusions in the sanidine. A 2mm. wide band consisting of spherulitic plagioclase (An_{67}) with minor quartz forms the margin of this lapilli. This plagioclase is in the form of fine, often curved needles that radiate outwards from the lapilli.

It is interesting to compare the assemblage of quartz and sanidine (commonly occurring in a granophyric intergrowth), plagioclase (An_{70}) orthopyroxene, clinopyroxene, sillimanite, ores, minor biotite and chlorite in the extreme type of metasomatic granophyre as found at Bird's River to those found at other places within the Karroo Province. Walker and Poldervaart (1942, p. 292) described the assemblage at Hangnest, Alewyn's Gat and Rietkop as "ragged prisms" of clinopyroxene embedded in a matrix of plagioclase (An_{35}), quartz and micropegmatite. They also record the presence of biotite, rod-like ore and sphene as accessories. The Burghersdorp Sandstone that has been metasomatized by the New Amalfi sheet (Poldervaart, 1944) consists mainly of quartz, micropegmatite, plagioclase (An_{28}), pyroxene or biotite. Moore (1965, p. 94) described a metasomatic granophyre associated with the Gap dykes of the Transkei. This rock is composed of serpentine-chloritic rods probably pseudomorphic after pyroxene in a coarse granophyric matrix and plagioclase is present in minor quantities. The common features amongst these rocks appears to be the ubiquitous presence of granophyre and the common occurrence of rod-like pyroxene and also of iron ore. It is also interesting to note that the plagioclase found in the Bird's River rocks is very much richer in the calcium end member than the granophyres that have been described from other localities within the Karroo dolerite province. The Bird's River rocks, however, are shallow seated compared to the other occurrences.

Pyroclastic material that has been ingested into the Cairn dolerite sheet (grid ref. C4) is basically identical to the rest of these metamorphic granophyres just described.

Only the rocks belonging to this category where the lapilli have been almost completely destroyed will be referred to as metasomatic granophyres. To avoid confusion the 'metamorphosed pyroclastic rocks' outside this group (ie. where lapilli are still recognisable in thin section) will be referred to as such.

iii) <u>Intensely metamorphosed pyroclastic rocks with metamorphic glass.</u>

Metamorphism and accompanying fusion of some of the pyroclastic rocks within a metre or so of the contact has produced large amounts of glass in the rocks. Eales (1974) has examined the finest example of these, namely the "glass ridge" (grid ref. G5 and H5). He examined a dolerite-pegmatite clast from these fused pyroclastic rocks in order to study the melting relationships of such a rock in relation to the significance of tridymite in contact zones.

Two varieties of these rocks were encountered along the north-western margin of the Cairn xenolith. The main difference between the two varieties is that in one the glass is altered and partly devitrified while in the other a fresh, brown coloured glass was encountered

The type containing the altered glass also contains quartz, cordierite, sillimanite and feldspar (confirmed by X-Ray diffraction). The quartz is paramorphic after tridymite and constitutes the bulk of the groundmass along with the altered glass. The rounded remnants of assorted lapilli occur in the groundmass. Most of these lapilli are glassy and are dark

PLATE XXII: Photomicrograph of a fused pyroclastic rock. Note the needle-like sections of quartz paramorphic after tridymite (tr). Other mineral designations are hy = hypersthene, gl = brown glass, f = feldspar. (Ordinary light, magnification = 30X) grey in colour and they contain irregular rod-like grains of ore material, needles of sillimanite and clear fine cordierite crystals and laths of turbid feldspar. Sillimanite occurring as a mesh of fine needles is quite abundant in the groundmass.

The metamorphosed pyroclastic containing fresh glass occurs within 5 cm. of the dolerite and only remnant sedimentary lapilli occur in it. The groundmass consists of quartz, turbid potassium feldspar, highly pleochroic hypersthene and brown glass. The quartz occurs as narrow plates up to 0,5 mm. in diameter and sections through the plates show that tridymite inverted to a number of quartz individuals along the length of the plates. These individuals resemble wedges with their tapered end truncated (similar to those described by Skelhorn, 1962, pp. 140 - 1, fig. 1). Quartz grains also occur with a fringe of tridymite needles. In this example the brown glass is the most abundant constituent of the groundmass (see plate XXII).

C. MICROMETRIC DATA.

The results of the micrometric determinations of contaminated dolerites, metasomatic granophyres, metamorphosed lapillistone and lapillistones are to be found in Tables VIII and IX. The contaminated dolerites are listed here for purposes of comparison. The analyses are listed from 1 to 12 in order of decreasing volume per cent of plagioclase and increasing volume per cent of quartz + K-feldspar + associated material.
The determinations were hampered by a number of factors:

TABLE VIII

Micrometric analyses of contaminated dolerites and metasomatic granophyres

	1	2	3	4	5	6
Sample Number	T_1/5A	X53	T_3/4	T_6/T3	T_4/1A	X52
Plagioclase	58,7	44,4	42,8	43,0	44,1	27,5
Pyroxene + alteration	25,3	26,7	19,4	23,3	21,4*	16,7
Olivine + alteration	-	2,5	6,6	-	-	-
Opaque minerals	4,5	2,2	2,7	2,0	1,7	1,7
Granophyre and quartz + K-feldspar	11,5	24,2	28,5	31,1	32,1	53,5
Other	-	-	-	0,6	0,7	0,6
	100,0	100,0	100,0	100,0	100,0	100,0

1. = Contaminated dolerite from sheet in the Cairn xenolith.

2. = Contaminated dolerite from below Grootkloof xenolith.

3. = Contaminated dolerite from sheet in the Cairn xenolith.

4. = Metasomatic granophyre taken from above the dolerite sheet in the Cairn xenolith. Sample taken from the capping of granophyre 200 metres north of the cairn (grid ref. C4).

5. = Ingested metasomatic granophyre from the dolerite sheet in the Cairn xenolith (* = chlorite constitutes 7,2% of the rock and appears to be an alteration of the pyroxene). Sample taken in the Cairn dolerite sheet along the latitude grid ref. line between grid refs. C3 and C4.

6. = Metasomatic granophyre from above bell-jar dolerite at Grootkloof (grid ref. H8).

(All analyses were performed by the author).

TABLE IX

Micrometric analyses of the lapillistone, metamorphosed lapillistones and metasomatic granophyres where lapilli are still recognisable in thin section.

	7	8	9	10	11	12
Sample number	$T_1/7$	X19	X49	$T_1/1$	X17	X28
Plagioclase	21,6	10,5	1,7	2,5	2,0	3,1
Pyroxene + alteration	24,2	14,6	5,1	2,8	9,5	-
Quartz + K-feldspar + matrix in groundmass or granophyre	49,0	41,1	42,0	57,9	38,4	63,0
Opaque minerals	3,5	1,7	1,2	0,8	0,6	1,2
Sedimentary lapilli	-	2,3	11,9	5,3	7,4	19,1
Igneous lapilli	1,7	29,8	38,1	30,7	42,1	13,6
	100,0	100,0	100,0	100,0	100,0	100,0

7. = Metasomatic granophyre where lapilli are still recognisable from the outcrop at the cairn. (grid ref. C4).

8. = Metamorphosed pyroclastic rock taken 2 m. above the dolerite (grid ref. C3).

9. = Metamorphosed lapillistone with granophyre from top of Grootkloof (grid ref. G7).

10. = Metamorphosed lapillistone with minor granophyre taken 60 metres below the Cairn dolerite along the Thysfontein/Romance farm boundary fence (grid ref. D4).

11. = Metamorphosed lapillistone from the Cairn xenolith 30 metres above the bell-jar dolerite. (grid ref. B3).

12. = Lapillistone. Average analyses of two samples collected below Cairn dolerite sheet. (Grid ref. C3).

(All analyses performed by the author).

a) The inhomogeneity of the samples is illustrated by the disparity between analyses 10 and 11 of Table IX.

b) The fine grain size and general turbidity of these rocks make exact mineral identification a difficult task. Also the formation of granophyre and the development of tridymite in the sequence of metamorphism is a gradual process, and accordingly quartz + matrix, K-feldspar and the granophyric intergrowth have been grouped together.

c) With the increase in the degree of metamorphism the exact boundary between lapilli and groundmass becomes more and more indefinite.

The following deductions may be drawn from the analyses:-

a) The analyses reveal that the relative proportions of the various constituents of the contaminated dolerites overlap with those of the metasomatic granophyres. There are, however, a number of petrographic differences between the two types.

b) Plagioclase and pyroxene become abundant as metamorphism becomes more advanced. The paragenesis of the plagioclase is not entirely clear and it is possible that some of the plagioclase may represent recrystallized phenocrysts that originated in the vitreous lapilli. The fact that the anorthite content of the plagioclase in the granophyre is similar to that of the original phenocrysts in the lapilli seems to support to support this argument. It is also possible that the calcic plagioclase developed as a result of crystallization of the basaltic glass in the lapilli. The role played by the metasomatizing fluids was probably the greatest in the formation of calcic plagioclase as the addition of sodium to the pyroclastic rocks is very minor compared to calcium. This would facilitate the development of a calcium-rich plagioclase.

c) The quartz content becomes less with increasing metamorphism and the quartz that remains has been progressively inverted to tridymite and incorporated in granophyre. At the same time potassium feldspar becomes more abundant, especially as part of the granophyric intergrowth. From chemical data it appears as though potassium has been removed from the sediments to a certain extent and entered the dolerites. This is reflected in the strong development of granophyre in these contaminated rocks.

d) The lapilli of igneous origin merge progressively with the groundmass as the intensity of metamorphism increases. The sedimentary lapilli, although appearing to be affected by metamorphism earlier than the igneous lapilli, at the later stages do not merge into the groundmass by migration of material from them but rather the opposite holds and they contribute to the production of the homogeneous final product by migration of material into them from the groundmass.

D. MINERALOGY.

This section includes a comparative study of the metamorphosed pyroclastic rocks, metasomatic granophyres and the doleritic rocks. Tables X and XI list the optical properties of augite, plagioclase, and potassium feldspar in the metamorphosed pyroclastics and metasomatic granophyres.

TABLE X

Optical properties of augite and composition of plagioclase in the lapillistones and the metamorphic equivalents.

	Sample number	Augite $2V_z$	Augite N_y	Plagioclase An composition
1.	X28	-	-	74%
2.	X17	-	-	48%
3.	X39	-	-	73 - 75%
4.	X48	-	-	74%
5.	X49	-	-	72%
	X49	-	-	48*
6.	$T_3/3$	-	-	78 - 80%
7.	X19	-	-	74 - 76%
8.	$T_1/7$	-	-	76 - 78%
9.	$T_4/1A$	-	-	69%
10.	X52	44,0	1,710	75%
11.	T_6/T_3	43,5	1,707	78%

* = Composition of original groundmass plagioclase.

1. = Lapillistone from Cairn dolerite sheet (Grid ref. C3).

2. = Metamorphosed lapillistone from the Cairn xenolith 30 metres above the Bell-jar dolerite. (Grid ref. B3).

3. = Metamorphosed lapillistone from the Cairn xenolith below Cairn dolerite sheet 50 metres above sample X28 (Grid ref. C3).

4. = Metamorphosed lapillistone from Grootkloof, 3,0 metres from contact. (Grid ref. G7).

5. = Metamorphosed lapillistone from Grootkloof, 0,5 metres from contact. (Grid ref. C7).

TABLE X (CONTINUED).

6. = Metamorphosed pyroclastic from above Cairn dolerite sheet. (Grid ref. C4).

7. = Metamorphosed pyroclastic above Cairn dolerite sheet, taken at point where outcrop of the sheet turns towards the south. (Grid ref. C3).

8. = Metasomatic granophyre from Cairn above the dolerite sheet. (Grid ref. C4).

9. = Ingested metasomatic granophyre from in the Cairn dolerite sheet. (Grid ref. C3 and C4).

10. = Metasomatic granophyre from above bell-jar dolerite at Grootkloof. (Grid ref. H8).

11. = Metasomatic granophyre from above the Cairn dolerite sheet (Grid ref. C4).

TABLE XI

Augite compositions. (Utilizing optical data of Hess, 1949, p. 634).

	Sample number	Ca%	Mg%	Fe%
1.	X10	37	59	4
2.	X24	40	51	9
3.	T_1/4A	38	41	21
4.	X63	39	41	20
5.	T_1/5A	37	45	18
6.	X52	33	30	37
7.	T_6/T_3	33	33	34
8.	-	38	48	14
9.	-	41	50	9
10.	-	37	42	21

1. = Contact dolerite.

2. = Glassy dolerite.

3. = Fine-grained dolerite.

4. = Poikilophitic olivine dolerite with quartz.

5. = Contaminated dolerite.

6. = Metasomatic granophyre (Grootkloof xenolith).

7. = Metasomatic granophyre (Cairn xenolith).

8. = Tholeiite (Booth, 1971).

9. = Poikilophitic olivine dolerite (Booth, 1971).

10. = Quartz dolerite (Booth, 1971).

i) The plagioclase.

Comparison of the anorthite content of the plagioclase of the dolerites, the pyroclastics and metamorphosed pyroclastics (see Table VI and X) shows that with the expected exception of the dolerite-pegmatites and groundmass plagioclase of the less metamorphosed pyroclastic rocks, there is little significant variation in composition of the plagioclase. Some of the contaminated dolerites show slight enrichment of soda while on the other hand some of the metamorphosed pyroclastic rocks contain plagioclase slightly richer in anorthite. As sodium appears to have played a minor role in the metasomatic processes and as calcium appears to have been introduced into the pyroclastic rocks (the chemistry is fully described in Chapter 7) the secondary plagioclase that developed in the metamorphic rocks had a composition tending slightly more towards the anorthite end member than that in the vitreous lapilli phenocrysts. This is seen on examination of Table X where generally the plagioclase in the more intensely metamorphosed varieties is one to eight per cent richer in the anorthite molecule than the plagioclase encountered in the lapilli phenocrysts in the unmetamorphosed pyroclastic rocks.

ii) Augite.

A summary of the compositional variations of the augite in the metasomatic granophyres and the dolerite is given in Table XI. These are average values and are based on N_y and $2V_z$ determinations. The values determined by Booth (1971) for a contact zone tholeiite and a differentiated quartz dolerite are also quoted. Fig. 2 illustrates graphically the trend of

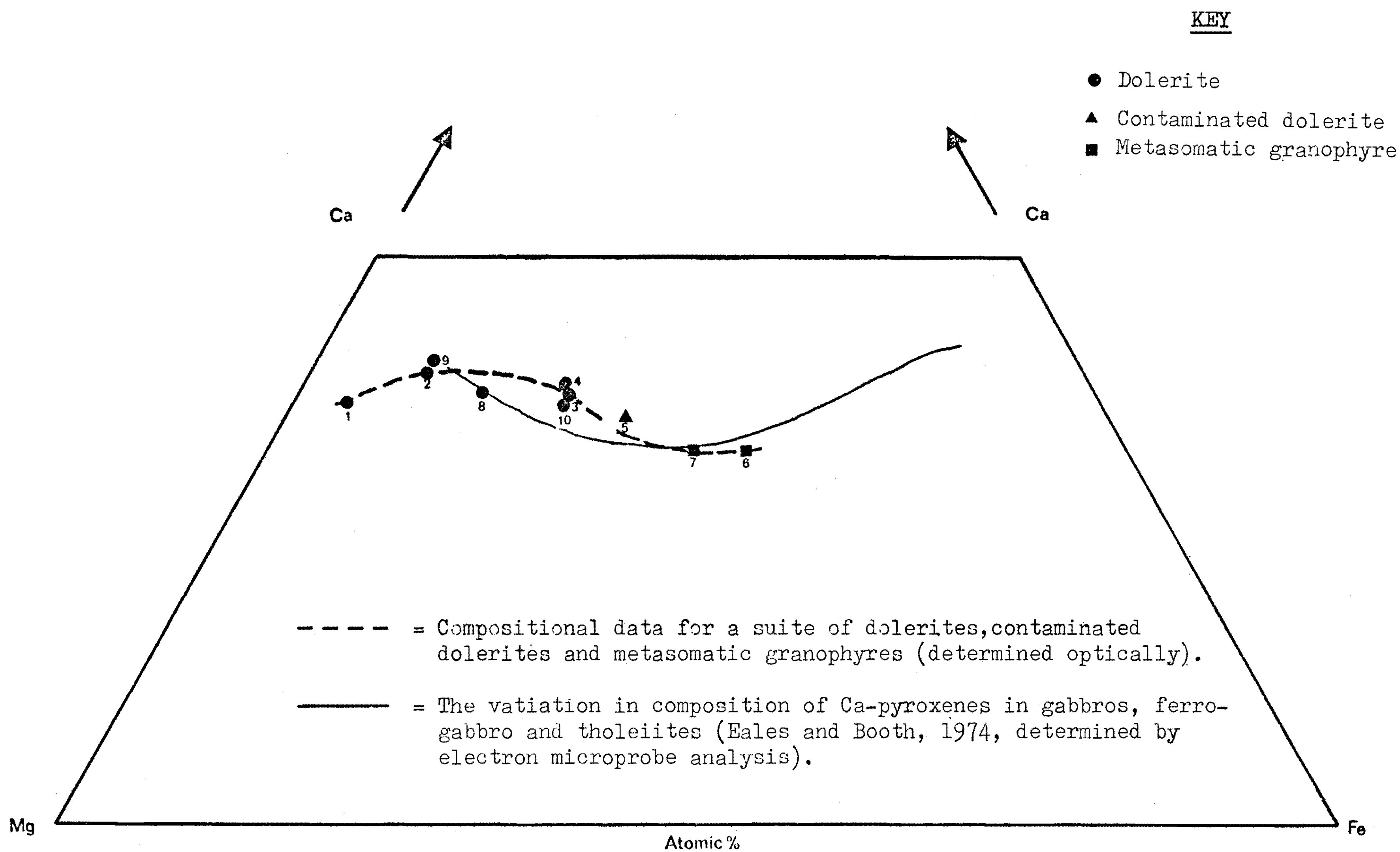


Fig. 2. The crystallization trend of the calcic clinopyroxenes in the Bird's River Complex rocks. The numbers refer to data in Table XI.

crystallization of clinopyroxenes of the dolerites of the Bird's River Complex as well as the composition of the augites in the contaminated dolerites and metasomatic granophyres to this trend. The variation of composition of Ca-rich pyroxenes in gabbros, ferrogabbro and tholeiites of the Bird's River Complex as determined by Eales (1974, p. 8) is also illustrated in this diagram.

The composition of the augite in both the contaminated dolerite and the metasomatic granophyre is roughly intermediate in Fe and Mg Composition between those of the poikilophitic gabbros and associated rocks, and the fractionated tholeiites. Fig. 2 shows that although the author's optical data and the microprobe date of Eales and Booth (1974) do not quite correspond, there is the suggestion that the contaminated dolerites and the metasomatic granophyres might have been derived by crystal fractionation of the gabbros. This does not appear to be the case, however, because:-

a) The presence of calcium-rich palgioclase in the metasomatic granophyres;
b) The fact that relict lapilli occur in the metasomatic granophyres;
c) The gradation from pyroclastic rocks to dolerite indicates that contamination and metasomatism have occurred.
d) The presence of sillimanite and probably also its occurrence with tridymite in these metasomatic granophyres indicates metamorphism.

It thus appears that excess iron (see Chapter 7) introduced into the system during metasomatism was taken up during the formation of augite in the metasomatic granophyres to produce a pyroxene very similar to that expected in a differentiated granophyre.

iii) The zircons.

A study of the zircon distribution as well as variation of its habit was carried out on the pyroclastic and metamorphosed pyroclastic rocks. The data are listed in Table XII and are semi-quantitative.

The examination was performed on a heavy concentrate from weighed portions of the minus 60 mesh fraction of crushed samples. Crushing was performed as gently as possible to avoid breaking the zircons. The heavy liquids used for separation of the concentratrates were bromoform and methylene iodide. The latter medium proved to be more satisfactory as it yielded cleaner concentrates.

The prepared concentrate was mounted on a glass slide in oil and examined under the petrographic microscope. The zircon grains were of uniform size, about 0,2 - 0,3 mm. Larsen and Poldervaart (1961, p. 80) examined the habits of zircon in granite batholiths and devised a classification of typical zircon shapes. A simple classification has been devised by the author which would apply more to sedimentary and metamorphic rocks and is based on the degree of rounding of the zircons. The classification is as follows;

Type Z1: Euhedral, doubly terminated, prismatic crystals with sharp edges between crystal faces.

Type Z2: Euhedral, doubly terminated, prismatic crystals with rounded edges between crystal faces.

Type Z3: Rounded terminations on crystals with straight prismatic faces.

Type Z4: Oval and rounded grains.

Larsen and Poldervaart (1957, p. 553) could find no evidence of severe breakage of zircons due to crushing of rock samples even down to fine size. They stated that broken zircons in a rock may result from imperfect crystallization, or from breakage due to partial alteration and differential expansion of the main constituent minerals. In Table XII the broken zircons have been counted separately as most do not exhibit the effects of rounding and thus were regarded as a separate subset.

Table XII lists the distribution percentage of the habits of the zircon crystals in the pyroclastic and metamorphosed pyroclastic rocks, the number of grains counted, the approximate number of grains per gram of crushed rock and the percentage of the total number of grains that were broken. Analyses 1 to 6 are in order of decreasing degree of metamorphism based on petrographic examination and field data. Several samples all exhibiting degrees of metamorphism greater than sample $T_1/3$ (analysis 1) were examined and no zircons could be found. This suggests that zircon has been destroyed at quite an early stage of metamorphism in the sanidinite facies. The upper stability temperature of zircon is 1676 ± 7°C (Butterman and Foster, 1967) and thus the disappearance of the zircons as the degree of metamorphism increases cannot be explained on the basis of temperature alone. Saxena (1966, pp. 21 - 22) noted the possibility that dissolution of a zircon may be brought about by the action of alkaline solutions. He

TABLE XII

Zircon habit analyses.

	1	2	3	4	5	6
Sample number	$T_1/3$	X47	X49	$T_1/1$	X17	X28
Type Z1	-	0	1	0	1	4
Z2	-	11	9	16	8	9
Z3	31	42	48	29	45	29
Z4	69	47	42	55	46	58
	100	100	100	100	100	100
No. of crystals counted (including broken crystals)	15	25	157	125	129	126
Approximate no. of grains per gram.	1	1	5	25	23	25
Percentage of total crystals that were broken	13	24	20	29	26	31

1. = Metamorphosed lapillistone from above Cairn dolerite sheet. (Grid ref. C4).

2. = Metamorphosed lapillistone 0,5 metres from contact from Grootkloof. (Grid ref. G7).

3. = Metamorphosed lapillistone 11,0 metres from contact from Grootkloof. (Grid ref. G7).

4. = Metamorphosed lapillistone taken 60 metres below Cairn dolerite sheet. (Grid ref. D4).

5. = Metamorphosed lapillistone from Cairn xenolith 30 metres above the Bell-jar dolerite. (Grid ref. B3).

6. = Lapillistone from below Cairn dolerite sheet. (Grid ref. C3).

(Note: The analyses 1 to 6 are in order of decreasing degree of metamorphism. Sample $T_1/3$ is regarded as having undergone metamorphism of medium grade).

notes the lack of work that has been performed on the chemical resistance of zircon. In the Bird's River rocks there is a definite decrease in the number of zircons as the contact is approached. Samples 0,5 and 11,0 metres from the contact (see analyses 2 and 3) taken along a traverse show a decrease in zircon content towards the contact. It is possible that the percolating metasomatic solutions become more reactive with increasing temperature (ie. closer to the dolerite) and the overall result was dissolution of the zircons.

The majority of the zircons encountered exhibit rounding. The groundmass quartz of these pyroclastic rocks, when unmetamorphosed, is angular. Quartz is slightly less resistant than zircon and thus one would also expect quartz to exhibit a certain degree of rounding. Saxena (1966) stressed that zircon rounding may be highly deceptive as a criterion for their detrital origin and observed that authigenic and metamorphic zircons may also exhibit rounding. Thermal metamorphism does not appear to have much effect on the rounding as the total percentage of zircon habits Z3 + Z4 remains relatively constant for analyses 2 to 6. The higher value for analysis 1 is regarded as anomalous as only 15 grains were recorded.

Thus the important aspect to emerge from this examination is the decrease in the zircon content of the rock as metamorphism becomes more intense. Dissolution of the zircons in the probably highly reactive metasomatic fluids that percolated these rocks might explain their disappearance.

E. THE DIFFERENCE BETWEEN THE CONTAMINATED DOLERITE AND THE METASOMATIC GRANOPHYRE.

The question that immediately arises when considering the contaminated dolerites and the metasomatic granophyres is: Are the supposed metasomatic granophyres not contaminated dolerites or vice versa? From field and petrographic evidence it appears as though there is a gradual change from pyroclastic rocks through metamorphosed pyroclastic rock, metasomatic granophyre and contaminated dolerite ultimately to common dolerite. Thus along certain of the dolerite-pyroclastic contacts a form of hybridization has occurred which appears to have been accompanied by metasomatism. The effect of metasomatism was carried into the sediments outside the zone of hybridization producing the rocks that have been termed metamorphosed pyroclastic rocks and metasomatic granophyres. As a result where metasomatic granophyres and contaminated dolerites occur no sharp contacts exist between the various rock types. The extreme form of metasomatic granophyre always appears to be separated from the underlying dolerite by contaminated dolerite. This development with the Bird's River contact appears to fit the account given by Turner and Verhoogen (1960, p. 87) on assimilation.

From petrographic examination no sharp distinction could be found between the two varieties of rock. However, significant differences do occur which could indicate which side of the 'fence' they originated. The differences are;

a) In handspecimen the contaminated dolerite may contain large irregular patches of felsic material or the rock may have a white mottling. The latter effect is due to the presence of small, abundant, and commonly interstitial, patches of felsic material.

b) The metasomatic granophyres all contain scattered, commonly rounded, remnants of relict lapilli.

c) The texture of the contaminated dolerites is strongly ophitic (see Plate X) (sometimes tending towards poikilophitic) while the metasomatic granophyres occasionally exhibit ophitic to subophitic texture (see Plates XVIII and XIX).

d) In the contaminated dolerite augite is the dominant pyroxene while in the metasomatic granophyres hypersthene, commonly as rods and needles, dominates. The pyroxene of the contaminated dolerites is also generally coarser than in the metasomatic granophyres. In the contaminated dolerites containing larger patches of felsic material, rod-like hypersthene is commonly developed within these patches.

CHAPTER SIX.

THE SANDSTONES AND SANDSTONE-TUFFS AND THEIR METAMORPHOSED EQUIVALENTS.

Introduction.

The bulk of the sediments that constitute the two xenoliths is sandstone and sandstone-tuff. These occur as narrow bands interbedded with pyroclastic rock and as a thick horizon underlying the pyroclastic rock. A similar sequence to that found in the xenolith occurs outside the intrusion along its north-eastern margin (see map). Narrow bands of shaly rock occur in the sandstones. In the pyroclastic rocks, south of the cairn, narrow horizons of white arkosic rocks occur (grid ref. A4 and B4).

The effect of metamorphism on the sandstones is mostly limited to recrystallization of the constituent minerals but metasomatism producing granophyres similar to those found in the lapillistones has occurred on a local scale. There has been the development of spilosites and a "potassium" adinole along the south-eastern margin of the Cairn.

A. THE SANDSTONES AND SANDSTONE-TUFFS.

Most of the sandstone rocks are light brown to brown in colour and are fine to medium-grained. When they have a mottled appearance due to the presence of commonly rounded, lithic fragments they have been termed sandstone-tuffs. Even in the sandstones widely-scattered lithic clasts occur. Bedding is commonly developed and cross-bedding was noted in one or two localities.

Angular to subrounded, often turbid quartz, and turbid anhedral feldspar, (probably a potassium-rich variety) are the main constituents of the rock. These minerals are set in a dark brown translucent matrix. When present, the lithic fragments are composed of an assemblage very similar to the sandstones but the matrix is more prominent. X-ray powder diffraction indicated the presence of quartz, feldspar, illite, and chlorite. Subrounded zircon grains are common.

B. RECRYSTALLIZED SANDSTONES AND SANDSTONE-TUFFS.

Most of the baked sandstones are pale grey to pale cream, fine to medium-grained rocks. The average grain-size is 0,1 to 0,2 mm. Some of these rocks are spotted, a feature noted in the sandstones near the dolerite contact in the south-eastern portion of the Cairn xenolith and also in the smaller xenoliths that occur in the dolerite.

Thin section examination of the sandstones reveals that the quartz has been partly or wholly inverted to tridymite on metamorphism. In the less intensely metamorphosed varieties, the quartz grains are commonly fringed by laths and wedges of tridymite with the whole entity being in optical continuity. The rocks are turbid in thin section which is mainly due to incipient alteration of the subspherulitic potassium feldspar. The interstitial clays and chlorite disappear with the increase in intensity of metamorphism.

Other minerals present in the metamorphosed sandstones in minor quantities are subhedral laths of plagioclase ($\pm An_{38}$) and biotite. Zircon occurs in all the specimen encountered.

The lithic fragments in the sandstones generally exhibit the same effects as the rest of the rocks. The sandstone that occurs above the adinole (grid ref. E6) contains scattered round spots. These spots are composed of a green core of altered garnet, quartz paramorphic after tridymite and ore material, and a margin of quartz grains and turbid altered feldspar. The spots average 0,5 to 10,0 mm. and probably reflect the incipient formation of the spilosites to be described shortly.

C. THE GRANOPHYRIC ROCKS.

Metasomatism, similar to that seen in the pyroclastic rocks has affected the sandstones and sandstone tuffs. The metasomatic products of the sandstones exhibit the effects of slight weathering and outcrop along the Cairn xenolith's contact with the dolerite about 300 metres west-south-west of the exposure of adinole (grid refs. E6 and E7) and also along the contact near the northernmost extremity of the Cairn xenolith (grid ref. C2).

The example from near the exposure of adinole is a pale grey, fine-grained rock containing scattered, rounded inclusions. On the weathered surface needle-shaped grooves, 2 - 4 mm., were noted and are probably due to the plagioclase crystals being weathered out of the rock.

This rock is composed of "hopper" crystals of plagioclase (An_{45}) and tridymite in a highly altered feldspathic matrix. (See Plate XXV). The latter appears to be a potassium feldspar and is the most abundant constituent of the rock. Chlorite and minor amounts of biotite occur and there has been the development of fine needles of sillimanite. As in most of the metamorphic rocks examined the ore material is in the form of fine needles and rods and as fine euhedral cubic forms appearing to be hematite and magnetite respectively. Ore material is relatively abundant.

The development of "hopper" crystals is due to either high supersaturations or undercooling of a melt inducing the nucleation of new growth layers at corners and edges where the supersaturation is higher than at the centres of the faces. (Spry, 1969, p. 145).

The outcrop in the northern part of the xenolith is different in that it contains diopside. The plagioclase also occurs as "hopper" crystals.

D. THE BUCHITES.

Fusion of the finer-grained sandstones and shaly rocks, with the production of glassy rocks was observed in both the Cairn xenolith (grid ref. B3, area marked "glass") and the Grootkloof xenolith (grid ref. H7, area marked "glass").

The outcrop in the Cairn xenolith, exposed along the banks of a stream, consists of black material having a distinctly glassy appearance and containing round, dark-green inclusions up to 30 mm. in diameter.

Under the microscope the rock is seen to be composed of a patchy clear greyish to brown slightly devitrified glass containing abundant crystallites and fine ore material. X-Ray powder diffraction indicated the presence of cordierite, feldspar and hematite. The rock contains over 75 per cent glass.

The development of cordierite appears to be universal in the buchites. Frankerl (1950, p. 288) records fine cordierite, having hexagonal outlines in vitrified sediments near Barkly East (C.P.) and Heilbron(O.F.S.). Work carried out by Ackermann and Walker (1960) on the Heilbron example revealed that cordierite microlites develop by reaction between glass and feldspar in the sediments. Butler (1961, p. 872) and Spry and Solomon (1964, p. 526) also record the presence of cordierite in buchites. Wyllie (1959) gives a detailed description of idioblastic cordierite in fused Torridonian arkose. In the example from Bird's River no idioblastic cordierite was found. However, the fine clusters of cordierite microlites are vaguely hexagonal in outline.

The plagioclase in the Bird's River buchite appears to be the primary plagioclase of the original sediment. This is based on the observations of Ackerman and Walker (1960, p. 244) who recorded that due to the refractory nature of plagioclase it persists even in the intensely vitrified glasses. The ore minerals are abundant and occur ubiquitously and are commonly associated with the clusters of cordierite microlites.

E. RHEOMORPHIC VEINS.

Rheomorphism of the sandstones, producing veins in the dolerite, is well developed near the northern part of the xenolith (grid ref. B2). The veins consist of grey fine-grained (average grain-size $\pm$ 0,2 mm.) rocks containing vugs of large quartz crystals.

Granophyric material with quartz showing the acicular habit of tridymite is extremely well developed and constitutes about 70 - 75 per cent of the rock. The potassium feldspar in the intergrowth is sanidine (2V = 10°). Clinopyroxene, chlorite, plagioclase (An_{40}) and ore minerals make up the rest of the rock. The augite occurs as ragged needles and is partly altered, and occasionally is subophitic with the plagioclase. The chlorite generally occurs as fibrous spherulitic patches and is pleochroic. The chlorite appears to have formed as a result of alteration of the clinopyroxene.

The quartz that constitutes the bulk of the vugs is strained and commonly granulated. The vague outlines of original plagioclase laths that cut across quartz grain boundaries occur. This plagioclase has been completely replaced by the quartz in the vugs. (See Plate XXIV). Altered sanidine is a constituent of these vugs and is also partly replaced by quartz.

Mountain (1960) examined a number of examples of rheomorphism in the Eastern Cape Province and could fine no criteria to distinguish with certainty between veins of magmatic and sedimentary origin unless the veins can be traced into types of known origin. The mineral assemblage of the Bird's River rheomorphic veins is very similar to that found in the metamorphosed sandstones that overlie the dolerites in the vicinity. Also, the veins are orientated in such a way that they appear to have originated from the sediments. However, lack of outcrop and erosion make it impossible to trace the rheomorphic veins into the sediments.

F. THE ADINOLE AND ASSOCIATED ROCKS.

These rocks outcrop at the base of the Cairn xenolith on Murrelfontein, south-west of the Grootkloof gorge (grid ref. E6 and E7). The two outcrops are small, running for about 50 metres along the contact. This contact with the underlying gabbro is sharp.

These rocks appear to have been produced by thermal metamorphism and metasomatism of Cave Sandstone. The sandstones in the vicinity are all recrystallized and contain widely scattered spots.

1. The spilosites.

Agrell (1939, p. 314) uses the word 'spilosite' (see p. 10 for definition) to describe spotted rocks which are intermediate between slates and metasomatic adinoles. At Bird's River two types of spilosite are encountered, viz. pale grey spilosites and black spilosites.

(a) Pale grey spilosites.

Eales (1974, p. 46) described this rock and analysed both the rock and its derivative glass. He called this rock a grey hornfels. However, the similarity to the black spotted rock adjacent to the adinole indicates that it may be regarded as a spilosite (a spotted hornfels). This rock consists of numerous, small ($\pm$ 1 mm.), dark grey spots in a pale grey, fine-grained groundmass. The spots consist primarily of fine subspherulitic quartz and minor feldspar (probably sanidine), and fine particles of ore material. The margins of these spots are stained brown, probably due to iron oxide staining.

The groundmass consists of quartz needles paramorphic after tridymite, partly devitrified colourless galss, mullite (Eales 1974, p. 46) and minor amounts of cordierite and feldspar. The quartz is paramorphic after tridymite, occurring as rod- and plate-like forms. Accessory zircon as subrounded grains is present.

(b) Black Spilosites.

This rock contains fewer and larger spots than the grey spilosite. These are set in a black, fine-grained brittle groundmass. The average diameter of these spots is 2 mm.

The spots in this rock are identical to those in the grey spilosite but the groundmass is different. The groundmass consists of a turbid grey partly devitrified glass in which occurs a mesh of abundant

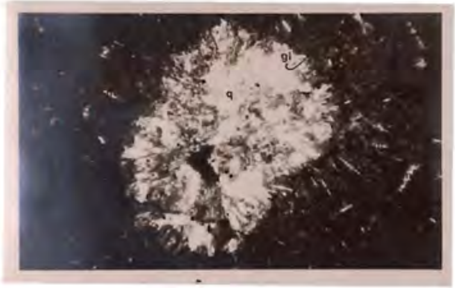


PLATE XXIII: A large quartz spot (q) in the grey, turbid glassy groundmass of a black spilosite. Other mineral designations are gl = glassy groundmass and m = mullite. (Crossed nicols, magnification = 30X)

PLATE XXIV : Portion of a vug of coarse-grained quartz in a rheomorphic vein. The quartz (q) appears to have replaced plagioclase of which relicts still exist (arrowed). The bulk of the rheomorphic rocks consist of tridymite granophyre (tr). (Crossed nicols, magnification = 30X)

PLATE XXV: Hopper crystals of feldspar in the turbid felsic groundmass of a metasomatised sandstone tuff. (Ordinary light, magnification = 30X) mullite needles and minor amounts of cordierite and grey-green alteration material. Opaque minerals (mostly magnetite) are very abundant throughout the rock, occurring mostly as a very fine dust. (See plate XXIII).

2. The Adinole.

The term potassium adinole is used to describe this rock as the word adinole implies sodium metasomatism. The black rock encountered at Bird's River exhibits highly contorted banding made up of alternating layers of fine- and coarse-grained material. The development of these contortions is probably due to plastic flow.

The most striking features of this rock are the great abundance of feldspar, and the banding. Two types of banding varying between 5 and 20 mm. in thickness, were encountered in thin section. In one type, clear, subhedral to euhedral feldspar crystals occur in a groundmass of turbid, spherulitic sanidine, fine magnetite, cordierite, and sillimanite. The grain-boundaries between the potassium feldspar are poorly defined and to a large extent obscured by the fine magnetite dust that is present in this rock. Staining (following Bailey and Stevens, 1960) confirmed the abundance of potassium feldspar and also served to show up the presence of cordierite which occurs as clusters of pinitized grains widely scattered throughout the feldspar groundmass. The clear feldspar is mostly zoned plagioclase (composition An_{56}). It occurs in oval-shaped spherulites of needle-shaped crystals (See Plate XXVII) or as clots or individual rectangular composite grains. The

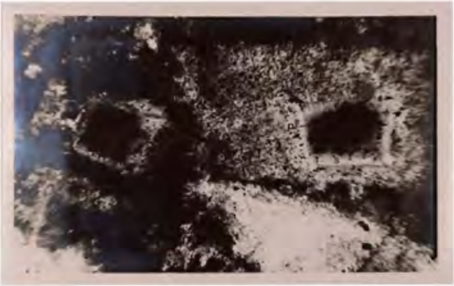


PLATE XXVI : Composite feldspar crystals in the adinole. These consist of a core of plagioclase (pl) and a margin of sanidine (s) in a groundmass of sanidine (s) and fine magnetite dust. (Crossed nicols, magnification = 30X)

PLATE XXVII : A spherulitic cluster of plagioclase laths (pl) in the adinole. (Crossed nicols, magnification = 20X) latter consists of a core of plagioclase and a margin of sanidine, with a sharp boundary between the two phases (See plate XXVI). The sanidine associated with the plagioclase is less turbid than the adjacent groundmass sanidine. Universal stage data indicate that the composition plane of the plagioclase albite twinning is parallel to the plane of vibration of α and γ of the sanidine.

The second type of banding is similar to that just described except that the groundmass is very much finer, there is less magnetite and quartz is a prominent constituent. These bands are generally narrow. A rough modal analysis of 3 sections of this rock indicates that it contains 65% K-feldspar, 15% plagioclase, 10% opaque minerals and 5% quartz and 5% sillimanite (or mullite?) and cordierite.

A semiquantitative microprobe examination was performed across a selected composite feldspar grain. Fig. 3 (a) diagramatically illustrates the grain and the points within the grain on which 20-second X-Ray intensity counts were made for sodium, potassium and calcium. The results of the counts are detailed in Table XIII, and fig. 3 (b) is a graph illustrating the variation of these elements. These data show that there is a gradual increase in the Ca content inwards from the margin of the sanidine shell and once the boundary is crossed into the plagioclase portion of the grain the Ca content increases less sharply. For K, there is a sharp decrease in this element inwards from the margin of the sanidine shell and it then becomes

TABLE XIII

Electron Microprobe X-Ray intensity counts across a composite feldspar grain

(See also Fig, 3)

Point	Distance from edge of grain (mm.)	20 sec. X-Ray intensity counts		
		Ca	K	Na
1	0,6	77586	5001	5059
2	0,3	66412	6066	5771
3	0,2	50519	8698	7016
4	0,1	40955	-	-
5	0,05	4121	52519	3262

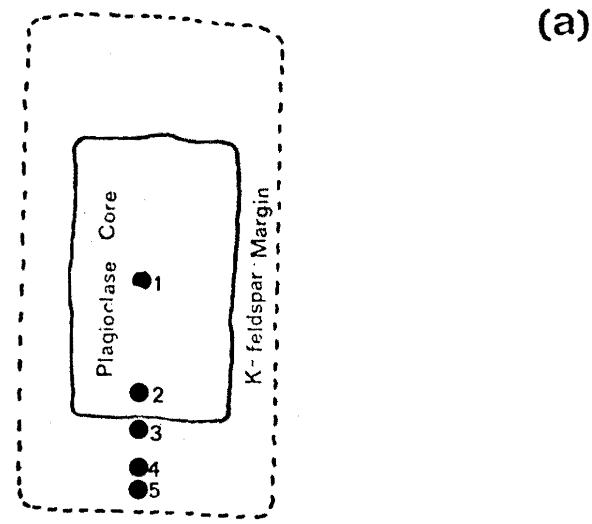


Fig. 3a . Schematic diagram of a composite feldspar grain in the potassium adinole showing the points in the grain where X-Ray intensity counts were taken.

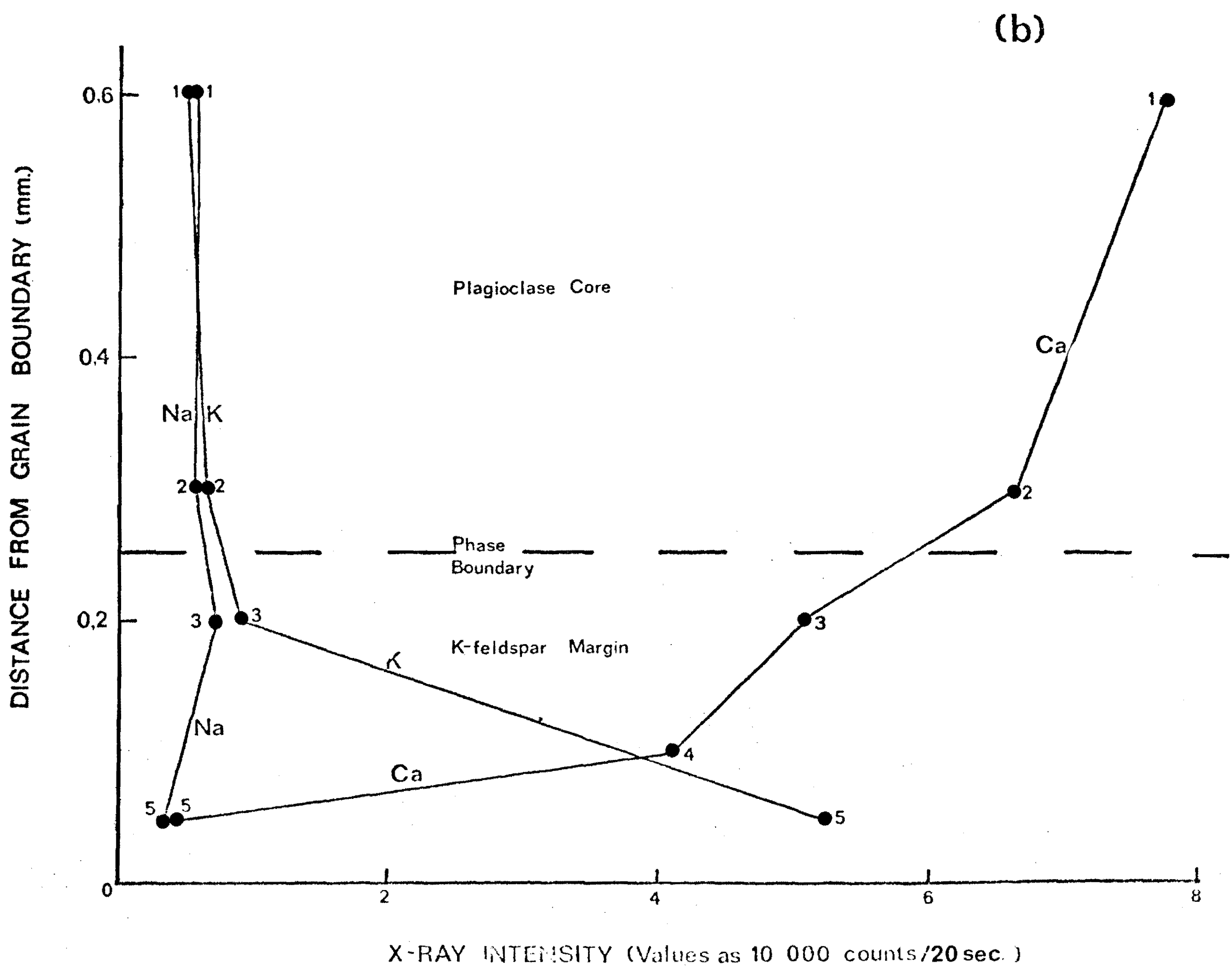


Fig. 3b. Variations in Na, K, and Ca (determined as X-Ray intensity counts in the electron microprobe) across the grain in Fig. 3a.

constant in the plagioclase. There is no significant variation in the Na content across the grain.

Nemec (1967), from examination of this phenomenon in igneous rocks concluded that there exist two extreme types of parallel overgrowths. He designated these as follows;

a) isomorphous overgrowths, where the development of the K-feldspar shell represents an immediate continuation of the growth of the core plagioclase. This growth is regarded as similar to the zones of different basicity encountered in plagioclases, in for example dolerites.

b) epitaxic overgrowths, where the plagioclase core acted as a seed for the nucleation of the K-feldspar. The crystal lattice of the plagioclase influenced the arrangement where nuclei in a parallel position in the crystal faces of the plagioclase seed the growth of the K-feldspar and from this point its growth proceeds independently of the underlying plagioclase core.

Nemec (p. 150) suggests a method for determining the nature of these overgrowths based on the study of overgrowths with plagioclase cores twinned according to laws of higher order, ie. laws which exist both in plagioclases and monoclinic K-feldspars. From the few grains examined in the adinole it appears that these overgrowths are of the isomorphic type where the K-feldspar of the shell and the core plagioclase are twinned according to the same laws with the composition planes forming a straight line right through the whole grain.

The microprobe data plotted in fig. 3 appears to confirm the presence of isomorphous overgrowths. This suggestion is based on the fact that the curves for Ca and K are continuous across the boundary between the two feldspar phases.

CHAPTER SEVEN.

INTERPRETATION OF CHEMICAL DATA.

General Statement.

Table XIV lists the analyses of the Bird's River dolerites and metamorphosed pyroclastic rocks relevant to this dissertation. CIPW norms have been calculated for these analyses and are included in Table XV. Table XVI contains the analyses of these Bird's River rocks recalculated 100 per cent water free. Tables XVIII to XXI contain data pertaining to the adinole and associated rocks. Table XXII lists analyses of relevant Karroo dolerite metasomatic associations and Table XXIII lists their respective Barth Standard Cells. Analyses are by the author, except where otherwise indicated.

In this chapter the possibility that the granophyres and adinole were produced by metasomatism is examined using the chemical data available. A statistical examination of the chemical interchanges that have taken place between sediment and dolerite has been carried out by calculating of the Barth Standard Cells. These results are supported by further examination of the data applying a method devised by Gresens (1967), to a suite of metasomatic rocks derived from the pyroclastic rocks. This method entails the calculation of quantitative models of chemical transfer during metasomatism taking into account any volume changes at may occur during the process.

TABLE XIV

Chemical Analyses of the Bird's River Rocks

Analysis Number	1	2	3	4	5	6	7	8	9	10
Sample Number	X28	$T_1/1$	X52				$T_5/2$	$T_1/7$	X19	$T_4/1A$
SiO_2	71,17	66,83	65,10	64,69	64,04	63,73	63,35	63,09	62,61	61,22
TiO_2	0,66	0,74	0,97	0,89	0,90	0,97	0,96	0,97	0,92	1,02
Al_2O_3	11,17	13,22	15,58	13,38	13,86	14,54	13,30	14,32	13,83	15,07
Fe_2O_3	2,76	1,49	0,87	0,97	1,25	1,19	1,24	1,39	1,35	1,49
FeO	0,95	3,88	4,76	5,10	5,03	5,53	5,17	5,32	4,94	5,35
MnO	0,08	0,19	0,05	0,29	0,08	0,08	0,10	0,06	0,11	0,08
MgO	1,66	3,18	1,96	2,04	2,85	2,55	3.65	3,47	3,07	2,57
CaO	1,40	4,04	4,54	4,59	5,08	4,39	5,44	5,26	5,70	4,60
Na_2O	2,76	2,68	2,04	2,56	2,28	2,80	2,22	2,40	2,76	3,80
K_2O	3,60	1,94	2,00	2,08	2,00	2,44	1,86	1,98	2,04	3,00
P_2O_5	0,29	0,15	0,17	0,28	0,26	0,30	0,16	0,18	0,36	0,19
H_2O+	2,56	1,50	1,38	1,64	1,17	1,69	2,03	0,82	1,08	0,93
H_2O-	1,44	0,68	0,94	0,75	0,62	0,57	0,48	0,51	1,01	0,84
TOTAL	100,50	100,52	100,36	99,26	99,42	100,78	99,96	99,77	99,78	100,16

TABLE XIV (CONTINUED)

Chemical Analyses of the Bird's River Rocks

Analysis Number	11	12	13	14	15	16	17	18	19	20
Sample Number	69/33	X53	T_6/T_3	T_1/5A	69/43	X24	X63	X10	T_1/4A	St4
SiO_2	60,76	60,44	60,20	57,17	56,58	52,29	52,09	52,06	51,29	50,72
TiO_2	1,28	1,04	1,11	1,17	1,39	0,76	1,37	1,04	1,12	1,15
Al_2O_3	14,16	13,02	14,41	14,18	13,85	16,66	17,01	16,45	14,83	15,08
Fe_2O_3	1,47	1,32	1,33	1,74	3,18	1,19	1,56	1,78	2,44	1,09
FeO	6,16	6,73	6,11	7,16	6,55	8,06	8,08	7,90	8,19	9,44
MnO	0,21	0,12	0,06	0,13	0,19	0,01	0,14	0,28	0,13	0,17
MgO	3,83	3,72	4,18	5,21	4,30	6,64	4,87	7,02	6,75	7,04
CaO	5,97	6,94	5,91	7,46	7,04	10,37	9,86	10,14	10,35	10,76
Na_2O	2,44	2,04	2,38	2,56	3 05	2,41	2,72	2,32	2,48	2,98
K_2O	2,04	1,76	1,66	1,68	1,95	0,66	0,76	0,52	0,40	0,41
P_2O_5	0,16	0,19	0,42	0,24	0,37	0,21	0,30	0,08	0,28	0,30
H_2O+	1,53	2,21	1,84	1,57	0,74	0,47	0,94	0,89	0,77	0,67
H_2O-	0,42	0,35	0,73	0,53	0,66	0,30	0,54	0,49	0,41	0,59
TOTAL	100,43	99,88	100,34	100,80	99,85	100,03	100,24	100,97	99,44	100,40

TABLE XV.

Norms of Bird's River Rocks

Analysis Number		1	2	3	4	5	6	7	8	9	10
Sample Number		X28	$T_1/1$	X52	X47	X49	$T_3/3$	$T_5/2$	$T_1/7$	X19	$T_4/1A$
Q		36,90	28,68	29,22	26,82	26,04	22,32	24,78	22,80	21,60	12,66
Or		21,13	11,12	11,68	12,23	11,68	14,46	11,12	11,68	11,68	17,79
Ab		23,06	23,06	17,29	21,48	19,39	23,58	18,34	20,44	23,58	31,96
An		5,28	18,07	21,68	18,90	21,68	19,74	20,85	22,24	19,18	15,29
C or Sil		0,92	-	3,40*	-	-	-	-	-	-	-
Fo		-	-	-	-	-	-	-	-	-	-
Fa		-	-	-	-	-	-	-	-	-	-
En	Di	-	0,20	-	0,40	0,40	0,10	1,20	0,70	1,50	1,30
Fs	Di	-	0,13	-	0,53	0,40	0,13	0,92	0,66	1,19	1,45
Wo	Di	-	0,35	-	0,93	0,81	0,23	2,20	1,39	2,78	2,78
En	Hy	4,10	7,80	4,80	4,70	6,70	6,30	7,90	8,00	6,20	5,10
Fs	Hy	-	5,02	6,47	7,13	6,34	7,26	6,07	6,34	5,28	5,54
Il		1,37	1,37	1,82	1,67	1,67	1,98	1,67	1,98	1,67	1,98
Ap		0,67	0,34	0,34	0,67	0,67	0,67	0,34	0,34	1,01	0,34
Mt		1,16	2,09	1,03	1,39	1,86	1,86	1,86	2,09	2,09	2,09
He		2,08	-	-	-	-	-	-	-	-	-
H_2O		4,00	2,18	2,32	2,31	1,79	2,26	2,51	1,33	2,09	1,77
TOTAL		100,67	100,41	100,05	99,16	99,43	100,89	99,76	99,99	99,85	100,05

(* = Excess alumina calculated as sillimanite ($Al_2O_3 . SiO_2$) in the metamorphic rocks).

TABLE XV (CONTINUED)

Norms of the Bird's River Rocks

Analysis Number		11	12	13	14	15	16	17	18	19	20
Sample Number		69/33	X53	T_6/T_3	T1/5A	69/43	X24	X63	X10	T1/4A	St4
Q		18,66	20,10	19,08	10,57	10,92	2,40	3,60	3,24	3,30	-
Or		11,68	10,56	9,45	10,01	11,12	3,34	4,45	2,78	2,22	2,22
Ab		20,44	17,29	20,44	22,01	25,68	20,44	23,06	19,39	20,96	25,15
An		21,96	20,85	23,63	21,96	18,35	32,80	31,97	33,36	28,08	26,69
Cor		-	-	-	-	-	-	-	-	-	-
Fo		-	-	-	-	-	-	-	-	-	3,22
Fa		-	-	-	-	-	-	-	-	-	2,86
En	Di	1,50	2,50	0,70	3,30	3,30	4,10	3,30	3,80	5,20	5,60
Fs	Di	1,32	2,64	0,53	2,51	2,24	3,17	3,04	2,51	3,56	4,62
Wo	Di	2,90	5,22	1,28	6,03	5,80	7,54	6,50	6,61	9,16	10,56
En	Hy	8,00	6,80	9,70	9,70	7,50	12,50	8,90	13,70	11,70	7,50
Fs	Hy	7,13	6,86	7,92	7,39	5,28	9,37	8,58	9,37	7,79	6,20
Il		2,43	2,13	2,13	2,28	2,74	1,52	2,58	1,98	2,13	2,28
Ap		0,34	0,34	1,01	0,34	1,01	0,34	0,67	0,34	0,67	0,67
Mt		2,09	1,86	,86	2,55	4,64	1,86	2,32	2,55	3,48	1,62
He		-	-	-	-	-	-	-	-	-	-
H_2O		1,95	2,56	2,57	2,10	1,40	0,77	1,48	1,38	1,18	1,26
TOTAL		100,40	99,71	100,30	100,75	99,98	100,15	100,45	101,01	99,43	100,45

TABLE XVI

Bird's River Chemical Analyses recalculated 100,0% water free

Analysis Number	1	2	3	4	5	6	7	8	9	10
Sample Number	X28	T1/1	X52	X47	X49	$T_3/3$	$T_5/2$	T1/7	X19	$T_4/1A$
SiO_2	73,75	67,96	66,40	66,85	65,62	64,69	65,01	64,09	64,09	62,22
TiO_2	0,68	0,75	0,99	0,92	0,92	0,92	0,99	0,99	0,94	1,04
Al_2O_3	11,58	13,44	15,89	13,83	14,20	14,76	13,65	14,55	14,16	15,32
Fe_2O_3	2,86	1,52	0,89	1,00	1,28	1,21	1,27	1,41	1,38	1,51
FeO	0,98	3,95	4,84	5,27	5,15	5,61	5,30	5,40	5,06	5,44
MnO	0,08	0,19	0,06	0,30	0,08	0,08	0,10	0,06	0,11	0,08
MgO	1,73	3,23	2,00	2,00	2,92	2,59	3,75	3,53	3,14	2,61
CaO	1,45	4,11	4,63	4,74	5,21	4,45	5,58	5,34	5,83	4,68
Na_2C	2,86	2,73	2,08	2,65	2,34	2,84	2,28	2,44	2,83	3,86
K_2O	3,73	1,97	2,03	2,15	2,01	2,48	1,91	2,01	2,09	3,05
P_2O_5	0,30	0,15	0,19	0,29	0,27	0,30	0,16	0,18	0,37	0,19
TOTAL	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00
Total Iron as FeO	3,55	5,32	5,64	6,17	6,30	6,70	6,44	6,67	6,30	6,80
S.G. (g/cc)	2,551	2,647	2,660	2,677	2,702	2,686	2,684	2,560	2,714	2,698

TABLE XVI (CONTINUED)

Bird's River Chemical Analyses recalculated 100.0% water free

Analysis Number	11	12	13	14	15	16	17	18	19	20
Sample Number	69/33	X53	T_6/T_3	T1/5A	69/43	X24	X63	X10	T1/4A	St4
SiO_2	61,70	62,10	61,57	57,97	57,47	52,68	52,74	52,27	52,20	51,16
TiO_2	1,30	1,07	1,14	1,18	1,41	0,77	1,39	1,04	1,14	1,16
Al_2O_3	14,38	13,38	14,74	14,35	14,07	16,78	17,23	16,52	15,09	15,21
Fe_2O_3	1,49	1,36	1,36	1,76	3,23	1,20	1,59	1,79	2,48	1,10
FeO	6,26	6,92	6,25	7,25	6,65	8,12	8,18	7,93	8,34	9,52
MnO	0,21	0,12	0,06	0,13	0,19	0,01	0,14	0,28	0,13	0,17
MgO	3,89	3,82	4,28	5,27	4,37	6,69	4,93	7,05	6,87	7,10
CaO	6,06	7,13	6,04	7,55	7,15	10,45	9,98	10,18	10,53	10,85
Na_2O	2,48	2,10	2,43	2,59	3,10	2,43	2,75	2,33	2,52	3,01
K_2O	2,07	1,81	1,70	1,70	1,98	0,66	0,77	0,53	0,41	0,41
P_2O_5	0,16	0,19	0,43	0,25	0,38	0,21	0,30	0,08	0,29	0,31
	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00
Total iron as FeO	7,60	8,14	7,47	8,83	9,56	9,20	9,61	9,54	10,57	10,51
S.G. (g/cc)	2,682	2,755	2,730	2,811	-	2,881	2,876	2,937	2,899	-

TABLE XVII

Barth Standard Cell Compositions of the Bird's River Rocks. (Number of cations based on 160 oxygen atoms)

Analysis Number	1	2	3	4	5	6	7	8	9	10
Sample Number	X28	T_1/1	X52	X47	X49	T_3/3	T_5/2	T_1/7	X19	T_4/1A
Si^{4+}	61,5	59,0	57,9	58,2	57,8	56,7	56,6	57,1	57,0	56,1
Ti^{4+}	0,5	0,5	0,6	0,6	0,6	0,7	0,7	0,7	0,6	0,7
Al^{3+}	11,4	13,7	16,3	14,1	14,7	15,3	14,0	15,3	14,9	16,2
Fe^{3+}	1,8	1,0	0,6	0,7	0,9	0,8	0,8	1,0	0,9	1,1
Fe^{2+}	0,7	3,0	3,6	4,1	3,8	4,1	3,9	4,1	3,8	4,1
Mg^{2+}	2,1	4,2	2,6	2,8	3,9	3,4	4,9	4,7	4,2	3,5
Ca^{2+}	1,3	3,8	4,3	4,4	4,9	4,2	5,2	5,2	5,6	4,5
Na^{+}	4,6	4,6	3,6	4,4	4,0	4,8	3,8	4,2	4,8	6,8
K^{+}	4,0	2,4	2,2	2,4	2,4	2,8	2,2	2,2	2,4	3,6
P^{5+}	0,2	0,1	0,1	0,2	0,2	0,2	0,1	0,2	0,3	0,2
OH^{-}	(14,8)	(8,6)	(8,2)	(9,8)	(7,0)	(10,0)	(12,2)	(4,8)	(6,6)	(5,8)
TOTAL	88,1	92,3	91,8	91,9	93,2	93,0	92,2	92,2	94,7	96,8

TABLE XVII (CONTINUED)

Barth Standard Cell Compositions of the Bird's River Rocks (Number of cations based on

160 oxygen atoms

Analysis Number	11	12	13	14	15	16	17	18	19	20
Sample Number	69/33	X53	T6/T3	T1/5A	69/43	X24	X63	X10	T1/4A	St4
Si^{4+}	55,0	54,8	54,4	52,5	53,1	49,5	49,1	48,8	49,1	48,5
Ti^{4+}	0,9	0,8	0,8	0,8	1,0	0,6	1,0	0,8	0,8	0,9
Al^{3+}	15,1	13,9	15,3	15,3	15,3	18,6	18,9	18,2	16,7	17,0
Fe^{3+}	1,1	0,9	0,9	1,2	2,3	0,9	1,1	1,3	1,7	0,8
Fe^{2+}	4,8	5,1	4,7	5,6	5,3	6,4	6,5	6,4	6,6	7,7
Mg^{2+}	5,2	5,1	5,6	7,2	6,1	9,4	6,9	9,9	9,7	10,1
Ca^{2+}	5,8	6,7	5,7	7,4	7,1	10,6	10,0	10,1	10,7	11,1
Na^{+}	4,4	3,6	4,2	4,4	5,6	4,2	5,0	4,2	4,6	5,6
K^{+}	2,4	2,0	2,0	2,0	2,4	0,8	1,0	0,6	0,4	0,4
P^{5+}	0,1	0,2	0,3	0,2	0.3	0,2	0,2	0,1	0,2	0,2
OH^{-}	(9,2)	(13,4)	(11,0)	(9,6)	(4,6)	(3,0)	(5,8)	(5,6)	(5,0)	(4,2
TOTAL	94,8	93,1	93,9	96,6	98,5	101,2	99,7	100,4	100,5	102,3

KEY TO CHEMICAL ANALYSES IN TABLES XXII AND XXIII.

26. Unaltered Table Mountain Sandstone.

27. Spherulitic granophyre.

28. Dark metamorphic granophyre.

29. Calcitized granophyric dolerite.

30. Calcitized granophyric dolerite.

31. Granophyric dolerite.

32. Granophyric dolerite

33. Typical dolerite.

Analyses 26 to 33 are from Coedmore Quarries, Durban (Mountain, 1958, p. 210).

34. Burghersdorp sandstone from xenolith in the New Amalfi Sheet.

35. Transitional zone around xenolith.

36. Normal granophyre.

Analyses 34 to 36 are from a xenolith in the New Amalfi Sheet, (Poldervaart, 1944, Table VI, Nos. 49, 50 and 51 respectively).

37. Siltstone from centre of xenolith, Alewyn's Gat.

38. Granophyre, upper border of xenolith, Alewyn's Gat.

39. Siltstone above upper contact, Rietkop (W.S.W. face).

40. Granophyre, fine-grained transitional type, Rietkop (W.S.W. face).

41. Granophyre, upper coarse rock, Rietkop (W.S.W. face).

42. Siltstone above upper contact, Hangnest.

43. Granophyre, Hangnest.

Analyses 37 to 45 correspond to analyses 3, 8, 1, 4, 5, 2 and 6 respectively in Walker and Poldervaart, 1942, Table II, p. 297.

44. Beaufort sandstone, Thomas River area (Mountain, 1943, p. 61).

45. Metasomatised xenolith, Thomas River (Moore, 1965, Table VII, No. 4).

(Key to chemical analyses in Tables XIV to XVII continued).

16. Glassy dolerite from western extremity of the Cairn dolerite sheet (grid ref. B3).

17. Poikilophitic olivine dolerite with quartz taken 120 m. below Cairn xenolith.

18. Contact dolerite from northern contact of Cairn xenolith and the bell-jar dolerite (grid ref. C2).

19. Fine grained dolerite from the Cairn dolerite sheet (grid ref. C4).

20. Fine grained poikilophitic gabbro, with glass, from Lemoenfontein.

All analyses carried out by the author except analysis 16.

Analysis 16 carried out by T. Broderick and S. Finnemore.

TABLE XVIII.

Analyses of Cave Sandstone, Spilosite and Adinole.

Analysis No.	21	22	23	24	25
Sample No.	-	-	X59A	X62	RT/7
SiO_2	82,6	81,0	73,7	62,2	58,9
TiO_2	0,1	0,3	0,8	0,9	0,7
Al_2O_3	9,8	9,1	12,4	18,5	20,0
Fe_2O_3	0,3	0,7	2,7	4,8	5,2
FeO	0,5	0,7	0,9	1,7	2,2
MnO	0,0	0,0	0,1	0,1	0,2
MgO	0,3	0,8	1,3	2,2	1,1
CaO	0,1	0,7	1,4	0,8	1,0
Na_2O	2,1	1,1	1,7	2,9	2,5
K_2O	2,6	2,2	1,3	1,1	5,0
P_2O_5	0,0	0,0	0,1	0,2	0,5
CO_2	0,0	0,2	-	n.d.	n.d.
H_2O+	1,3	2,8		3,3	2,1
H_2O-	0,2		4,1*	0,3	0,5
TOTAL	99,9	99,6	100,5	99,0	99,9

* Loss on Ignition

TABLE XIX.

Barth Standard Cell Calculations of Rocks in Table XVIII.

(Number of Cations based on 160 oxygens).

Analysis No.	21	22	23	24	25
Si^{4+}	69,0	67,0	61,2	54,0	52,8
Ti^{4+}	0,1	0,2	0,5	0,6	0,5
Al^{3+}	9,4	8,9	12,1	18,9	21,1
Fe^{3+}	0,2	0,5	1,7	3,1	3,5
Fe^{2+}	0,3	0,5	0,7	1,3	1,8
Mg^{2+}	0,3	1,0	1,6	2,8	1,5
Ca^{2+}	0,1	0,6	1,2	0,7	1,0
Na^+	3,4	1,8	2,8	5,0	4,4
K^+	2,7	2,4	1,4	1,2	5,8
P^{5+}	0,0	-	$<$0,1	0,1	0,4
C^{4+}	0,0	0,3	-	n.d.	n.d.
OH^-	(7,1)	(13,8)*	(29,2)*	(19,2)	(12,4)
TOTAL	85,5	83,2	83,2	87,7	92,8

* Assuming 90% to be combined water.

KEY TO CHEMICAL ANALYSES IN TABLES XVIII AND XIX.

21. Cave Sandstone (Walker and Poldervaart, 1949, Table 15, No. 114).

22. Cave Sandstone recrystallized to sanidine-tridymite granophyre at contact with the tholeiite on Denwood (Eales and Booth, 1974, Table 1, No. 6).

23. Cave sandstone, metamorphosed spotted rock, from Cairn xenolith on Murrelfontein, west of Grootkloof (Eales, 1974, Table IV, NO. 1).

24. Black spilosite, Murrelfontein (grid ref. E6, analyst A.K. Kenyon).

25. Potassium adinole, Murrelfontein (grid ref. E6, analyst A.K. Kenyon).

TABLE XX.

Chemical analyses of the Dinas Head Rocks.

Analyses No.	46	47	48	49	50
SiO_2	56,97	64,70	52,70	70,86	69,03
TiO_2	0,62	0,58	0,64	0,64	0,47
Al_2O_3	22,36	20,77	25,28	15,17	17,42
Fe_2O_3	0,63	0,89	0,68	1,52	0,17
FeO	5,16	1,86	1,59	1,06	0,17
MnO	0,00	tr	tr	0,00	0,00
MgO	2,84	1,52	2,16	1,08	0,47
CaO	0,60	tr	2,48	0,64	1,00
Na_2O	0,51	0,31	3,35	7,58	8,89
K_2O	4,57	4,81	5,16	0,25	0,31
H_2O+	4,32	3,42	3,62	1,05	0,64
H_2O-	0,60	0,65	0,70	0,38	0,24
B_2O_3	-	-	0,15	0,35	0,00
P_2O_5	0,09	0,12	0,12	tr	0,12
CO_2	0,00	tr	1,48	0,00	0,66
C	0,88	0,34	0,00	0,00	0,00
TOTAL	100,15	99,97	100,11	100,44	100,13

46. Black carbonaceous slate with small chlorite-rich spots, Dinas Head. (Agrell, 1939, Table 1, Analysis 3)

47. Black fissile spilosite, Dinas Head. (Agrell, 1939, Table 1, Analysis 5)

48. Spilosite showing albite-rich spots with tourmaline needles in sericite groundmass, Dinas Head. (Agrell 1939, Table II, Analysis 6)

49. Adinole interbanded with 48, and showing fine-grained albite and quartz with needles of tourmaline, Dinas Head. (Agrell 1939, Table II, Analysis 7)

50. Adinole, albite-quartz-rock, Dinas Head. (Agrell, 1939, Table II, Analysis 8)

TABLE XXI.

Barth Standard Cell Compositions of

The Dines Head Rocks in Table XX.

(Number of cations based on 160 oxygens).

Analysis number	46	47	48	49	50
Si^{4+}	50,0	55,4	46,2	61,0	59,6
Ti^{4+}	0,5	0,4	0,4	0,3	0,3
Al^{3+}	23,1	20,9	26,1	15,4	17,7
Fe^{3+}	0,4	0,5	0,5	1,0	0,2
Fe^{2+}	3,8	1,3	1,2	0,8	0,5
Mg^{2+}	3,7	2,0	2,8	1,4	0,6
Ca^{2+}	0,6	-	2,4	0,6	0,9
Na^{+}	0,8	0,6	5,6	12,6	14,8
K^{+}	5,2	5,2	5,8	0,2	0,4
B^{3+}	-	-	0,2	0,5	0,1
P^{5+}	0,1	0,1	0,2	-	-
C^{4+}	-	-	1,8	-	0,8
OH^{-}	(25,2)	(19,6)	(21,2)	(6,0)	(3,8)
TOTAL	88,2	86,4	93,2	93,8	95,9

TABLE XXII

Analyses of other Karroo dolerite metasomatic associations

Analysis number	26	27	28	29	30	31	32	33	34	35
SiO_2	84,20	80,13	74,08	62,10	60,37	54,95	53,36	51,14	76,92	62,64
TiO_2	0,26	0,45	0,57	0,29	0,14	1,50	1,15	1,46	0,20	1,53
Al_2O_3	7,48	11,90	9,10	10,88	14,43	14,41	15,48	15,32	12,38	13,96
Fe_2O_3	0,03	0,05	0,43	0,41	1,36	0,69	0,43	1,08	1,39	1,12
FeO	1,33	0,11	6,15	5,18	3,31	8,59	6,25	9,75	1,45	6,54
MnO	tr	tr	0,09	0,08	0,02	0,10	0,12	0,09	tr	0,13
MgO	tr	tr	2,42	5,89	4,08	2,37	6,47	6,97	0,22	1,83
CaO	1,05	3,42	1,63	8,59	5,09	9,30	9,81	10,14	0,28	3,91
Na_2O	3,93	2,65	2,89	3,02	3,16	3,15	2,13	1,89	2,17	5,02
K_2O	1,19	0,35	0,84	0,36	2,19	2,48	1,71	0,92	3,88	1,90
P_2O_5	0,06	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0,15	tr	0,11
H_2O+	0,40	0,22	1,08	2,03	3,22	1,15	1,31	1,13	0,77	1,02
H_2O-	0,11	0,17	0,18	0,18	0,32	0,19	0,38	0,20	0,39	0,28
CO_2	0,25	1,04	0,60	1,50	2,38	1,45	1,75	-	tr	0,18
TOTAL	100,29	100,49	100,06	100,51	100,07	100,33	100,35	100,24	100,05	100,17

TABLE XXII (CONTINUED)

Analyses of other Karroo Dolerite Metasomatic Associations.

Analysis Number	36	37	38	39	40	41	42	43	44	45
SiO_2	61,84	64,52	59,44	70,86	69,97	66,24	69,26	65,14	71,96	65,92
TiO_2	1,51	0,76	0,92	0,68	0,59	0,69	0,38	0,46	0,46	0,85
Al_2O_3	10,52	16,66	15,76	13,48	13,69	14,26	14,82	14,92	14,37	13,01
Fe_2O_3	3,66	2,23	4,11	0,12	0,13	0,94	0,81	1,18	0,32	1,42
FeO	9,24	3,44	3,44	3,31	3,82	4,48	3,89	5,04	2,24	3,92
MnO	0,23	-	0,08	0,03	0,03	0,04	0,12	0,04	0,03	0,05
MgO	0,56	1,75	3,56	1,52	1,52	2,22	1,88	2,17	0,70	0,52
CaO	4,97	1,24	5,64	2,34	2,02	1,60	1,29	2,49	0,82	6,38
Na_2O	2,83	2,87	2,48	3,07	3,83	2,61	1,78	2,70	2,80	3,20
K_2O	2,58	3,54	1,90	2,06	2,97	3,88	3,42	3,38	3,79	2,74
P_2O_5	0,34	0,06	0,14	0,14	0,09	0,12	0,16	0,20	0,05	0,38
H_2O+	1,82	2,82	2,75	2,08	1,34	2,38	2,23	1,96	1,69	1,78
H_2O-	0,19	0,06	nil.	0,08	0,13	0,49	0,22	0,39	1,69	0,34
CO_2	tr	nil.	nil.	tr	-	tr	-	tr	0,00	0,00
TOTAL	100,29	99,95	100,17	99,77	100,18	99,95	100,07	100,14	99,76	100,53

TABLE XXIII

Barth Standard Cell Compositions of Other Karroo Dolerite Metasomatic Associations

(Number of cations based on 160 oxygen atoms)

Analysis Number	26	27	28	29	30	31	32	33	34	35
Si^{4+}	70,5	66,7	64,2	55,0	52,5	51,2	49,1	48,5	65,9	57,0
Ti^{4+}	0,1	0,3	0,4	0,2	0,1	1,1	0,8	1,0	0,2	1,1
Al^{3+}	7,4	11,7	9,3	11,4	14,8	15,8	16,8	17,1	12,5	15,0
Fe^{3+}	0,1	0,1	0,3	0,3	0,9	0,5	0,3	0,8	0,9	0,8
Fe^{2+}	1,0	0,1	4,5	3,9	2,4	6,8	4,9	7,8	1,0	5,1
Mg^{2+}	-	-	3,1	7,8	5,2	3,3	8,9	9,8	0,3	2,5
Ca^{2+}	1,0	3,0	1,5	8,1	4,8	9,3	9,7	10,3	0,3	3,8
Na^{+}	6,4	4,4	4,8	5,2	3,4	5,8	3,8	3,4	3,6	8,8
K^{+}	1,2	0,4	1,0	0,4	2,4	3,0	2,0	1,2	4,2	2,2
P^{5+}	0,1	-	-	-	-	-	-	0,1	-	0,1
CO_2	0,3	1,2	0,8	1,8	2,8	1,9	2,2	-	-	-
OH^{-}	(2,2)	(1,2)	(6,2)	(12,0)	(18,8)	(7,2)	(8,0)	(7,2)	(4,4)	(6,2)
TOTAL	88,1	87,9	89,9	94,1	89,3	98,7	98,5	100,0	88,9	96,5

TABLE XXIII (CONTINUED)

Barth Standard Cell Compositions of other Karroo

Dolerite Metasomatic Associations

Analysis Number	36	37	38	39	40	41	42	43	44	45
Si^{4+}	56,9	56,2	52,7	61,0	61,1	58,3	59,8	57,7	62,2	58,5
Ti^{4+}	1,1	0,5	0,7	0,4	0,4	0,5	0,3	0,3	0,3	0,6
Al^{3+}	11,4	17,1	16,5	13,7	14,1	14,8	15,1	15,6	14,6	13,6
Fe^{3+}	2,5	1,5	2,8	0,1	0,1	0,7	0,5	0,8	0,2	0,9
Fe^{2+}	7,3	2,5	2,6	2,4	2,8	3,3	2,9	3,8	1,6	3,0
Mg^{2+}	0,8	2,3	4,7	2,0	2,0	2,9	2,4	2,9	0,9	0,7
Ca^{2+}	4,9	1,2	5,4	2,2	1,9	1,5	1,2	2,3	0,8	6,1
Na^{+}	5,0	4,8	4,2	5,2	6,6	4,4	3,0	4,6	4,6	5,4
K^{+}	3,0	4,0	2,2	2,2	3,2	4,4	3,8	3,8	4,2	3,0
P^{5+}	0,3	0,1	0,1	0,1	0,1	0,1	0,1	0,2	0,1	0,3
CO_2	-	-	-	-	-	-	-	-	-	-
OH^{-}	(11,2)	(16,4)	(16,2)	(11,8)	(7,8)	(14,0)	(12,8)	(11,6)	(9,8)	(10,6)
TOTAL	93,2	90,2	91,9	89,3	92,3	90,9	89,1	92,0	89,5	92,1

KEY TO CHEMICAL ANALYSES IN TABLES XXII AND XXIII.

26. Unaltered Table Mountain Sandstone.

27. Spherulitic granophyre.

28. Dark metamorphic granophyre.

29. Calcitized granophyric dolerite.

30. Calcitized granophyric dolerite.

31. Granophyric dolerite.

32. Granophyric dolerite.

33. Typical dolerite.

Analyses 26 to 33 are from Coedmore Quarries, Durban (Mountain, 1958, p. 210).

34. Burghersdorp sandstone from xenolith in the New Amalfi Sheet.

35. Transitional zone around xenolith.

36. Normal granophyre.

Analyses 34 to 36 are from a xenolith in the New Amalfi Sheet, (Poldervaart, 1944, Table VI, Nos. 49, 50 and 51 respectively).

37. Siltstone from centre of xenolith, Alewyn's Gat.

38. Granophyre, upper border of xenolith, Alewyn's Gat.

39. Siltstone above upper contact, Rietkop (W.S.W. face).

40. Granophyre, fine-grained transitional type, Rietkop (W.S.W. face).

41. Granophyre, upper coarse rock, Rietkop (W.S.W. face).

42. Siltstone above upper contact, Hangnest.

43. Granophyre, Hangnest.

Analyses 37 to 43 correspond to analyses 3, 8, 1, 4, 5, 2 and 6 respectively in Walker and Poldervaart, 1942, Table II, p. 297.

44. Beaufort sandstone, Thomas River area (Mountain, 1943, p. 61).

45. Metasomatised xenolith, Thomas River (Moore, 1965, Table VII, No. 4).

The production of the adinoles is also considered using Barth Standard Cell data.

A. THE CHEMISTRY OF THE GRANOPHYRES AND CONTAMINATED DOLERITES.

1. Examination of the process on the basis of the Barth Standard Cell.

Barth (1952, p. 82) based the calculation of the standard cell on the premise that in most igneous rocks, for every 160 oxygen atoms there are about 100 cations. Thus, if the cations that are associated with 160 ions are listed separately, the list will correspond closely to the atomic percentages of all the listed rock-forming elements excluding oxygen. The rock volume containing 160 oxygen atoms is called the standard cell of the rock. The method employed here in calculating the standard cells is as given by Burri (1965, p. 234) and the results of these calculations are in Table XVII.

The data in these tables have been treated as two separate sets, viz., U and V, where U is a set of all dolerites, dolerite-pegmatites and contaminated dolerites, (ie. analyses 12 and 14 to 20) and set V is a set of all metasomatic granophyres, metamorphosed pyroclastic rocks and pyroclastic rocks (ie. analyses 1 - 11 and 13). Set U consists of eight analyses and set V of twelve analyses.

Graphs have been plotted which show the variation of the cations in the standard cell relative to Si^{4+} (see figs. 4 - 13). Straight lines (having the form $y = mX + b$) were fitted to each set of data using a standard linear regression analysis treating Si^{4+} as the independent variable. The constants m and b in the straight-line equation were calculated using the expression

$$m = \frac{N\Sigma XY - \Sigma X \Sigma Y}{N\Sigma X^2 - (\Sigma X)^2}$$

$$b = \frac{(\Sigma Y)\ (\Sigma X^2) - (\Sigma X)\ (\Sigma XY)}{N\Sigma X^2 - (\Sigma X)^2}$$

where:

N = number of samples

Y = the dependent variable (e.g. Mg^{2+})

X = the independent variable (ie. Si^{4+})

m = gradient of the regression line

b = intercept of the regression line on the Y-axis.

The correlation coefficient (r) is given by

$$r = \pm \sqrt{\frac{\text{explained variation}}{\text{total variation}}}$$

$$= \pm \sqrt{\frac{\Sigma (Y_{est.} - Y)^2}{\Sigma (Y - Y)_2}}$$

where $Y_{est.}$ represents the value of Y for given values of X as estimated from the simple straight line equation and Y is the mean of all values of Y. This dimensionless quantity r varies between -1 and +1, the sign depending on the slope of the line. Thus, if there is zero unexplained variation, ie. the total variation is all explained, this ratio is one, and if there is zero explained variation ie. the total variation is all unexplained, this ratio is zero. In all other cases the ratio lies between zero and one.

This linear correlation coefficient (r) was calculated for each regression line using the formula

$$r = \frac{N\Sigma XY - \Sigma X\Sigma Y}{\sqrt{N\Sigma X^2 - (\Sigma X)^2}\,\sqrt{N\Sigma Y^2 - (\Sigma Y)^2}}$$

The values of m, b, and r, for sets U and V are listed in Table XXIV and the calculated regression lines have been superimposed on the data in figures 4 to 13.

McKie (1966, pp. 261 - 294) used the Standard Cell when examining the process of fenitization. He commented that a high value for the correlation coefficient "r" (ie. approaching one) cannot be expected in metasomatism as this process is inhomogenous, and this is especially true in the case of the Bird's River pyroclastic rocks or the gneissic rocks that McKie himself considered to have been fenitized.

Discussion of the data.

Table XXV summarizes the conclusion of the Barth Standard Cell Analysis, in that it details the elementary gains and losses of the metasomatic rocks relative to the sediments, and the dolerites relative to the contaminated dolerites.

TABLE XXIV

Statistical analyses of the variation in concentration of the major elements relative to the Si^{4+} concentration

Cation	Set U (Dolerite affinity) m_u	b_u	r_u	Set V (Sedimentary affinity) m_v	b_v	r_v
Al^{3+}	-0,651	49,72	-0,876	-0,517	44,29	-0,735
$Fe^{2+} + Fe^{3+}$	-0,263	20,83	-0,785	-0,441	29,90	-0,952
Fe^{2+}	-0,310	21,91	-0,872	-0,521	33,48	-0,915
Mg^{2+}	-0,702	43,62	-0,868	-0,442	29,30	-0,759
Na^{+}	-0,086	9,01	-0,288	-0,042	6,93	-0,097
K^{+}	+0,307	-14,33	+0,906	+0,167	-7,00	+0,509
Ti^{4+}	+0,005	0,61	+0,085	-0,055	3,80	-0,885
OH^{-}	+1,073	-47,98	+0,758	+0,507	-20,26	+0,333
Fe^{3+}	+0,045	-0,98	+0,213	+0,079	-3,56	+0,486
Ca^{2+}	-0,726	45,99	-0,963	-0,572	37,35	-0,876

TABLE XXV

Elementary losses and gains in the sediments on metasomatism and in the the dolerites on contamination.

	Set U	Set V
Si	- - -	- - -
Al	+ +	+ +
$Fe^{2+} + Fe^{3+}$	+	+ +
Fe^{2+}	+ +	+ +
Mg^{2+}	+ +	+ +
Na^{+}	(±)	(±)
K^{+}	- -	-
Ti^{4+}	(±)	(±)
OH^{-}	- - -	- -
Fe^{3+}	(±)	(±)
Ca^{2+}	+ +	+ +

Where - - - / + + + = losses/gains for m >0,9
- - / + + = losses/gains for m >0,3
- / + = losses/gains for m >0,1
(±) = sense of change uncertain

From these data it appears as though <u>metasomatism of the pyroclastic rocks</u> has resulted in the introduction of Al^{3+}, total Fe^{2+} + Fe^{3+}, Fe^{2+}, Mg^{2+} and Ca^{2+}, and reductions in the concentrations of Si^{4+}, K^{+}, and OH-. The direction of movement, if any, of Na^{+}, Fe^{3+}, and Ti^{4+} is uncertain. However, the slopes of the regression lines of these elements indicate that minor amounts of Na^{+} and Ti^{4+} are added to the sediments while the concentration of Fe^{3+} decreases.

<u>Contamination of the dolerites</u> has produced exactly the opposite effect, ie. decreases in the concentrations of Al^{3+}, total Fe^{2+} + Fe^{3+}, Fe^{2+}, $Mg^{2+}$and Ca^{2+}, and additions of Si^{4+}, K^{+}, and OH-. Possible minor changes are an increase in Fe^{3+} and a decrease in Na^{+}. The Ti^{4+} concentration appears to be unaffected on contamination of the dolerites by sedimentary material.

Although the sense of slope of the regression lines is the same for metasomatism as it is for dolerite contamination in all of figures 4 to 13, the angle of slope differs, often substantially. Mountain (1958, p. 211) concluded that acidification of dolerite resulted in a broad trend of variation in the dolerite towards an average sandstone. Walker and Poldervaart (1949 p. 683) plotted a normative quartz + corundum, anorthite + femic, orthoclase + albite triangular diagram for Karroo dolerites, dolerite-pegmatites, granophyres and sediments. The purpose of this diagram was to illustrate the tendancy of transfused sediments and dolerite differentiates to approach compositional uniformity. The normative data of analyses 1 to 20 (see Table XV and fig. 16) have been plotted on this diagram and from this it is inferred that a similar tendency towards compositional uniformity in the Bird's River sequence of dolerite-contaminated dolerite - metasomatic granophyre - metamorphosed pyroclastic rock - sediment. It thus appears that there is a merging of the composition of the metasomatic granophyres and the contaminated dolerites. This feature was the object of Mountain's investigations at Coedmore Quarries (1958), however, he was unable to bridge this gap between silicification of dolerite and metasomatism of sediment (see fig. 15).

The point of intersection of the regression lines may be a reflection of the boundary between the effects of metasomatism and contamination. These points of intersection were determined using simultaneous equations of the form $y_u=m_ux_u + b_u$ and $y_v=m_vx_v + b_v$ and determining where $x_u=x_v$ and $y_u=y_v$. The values of $x_u=x_v$ (where x = concentration of Si^{4+}) and $y_u=y_v$ (where y = concentration of K^+, Fe^{2+}, Ca^{2+}, or Mg^{2+}) are given in Table XXVI. These particular ions listed have been selected because they have a linear correlation coefficient $>\pm0,5$. The average value of y is 54,6 Si^{4+} ions in the standard cell which maybe regarded as the boundary between metasomatised sediments and contaminated dolerites. This value corresponds roughly with the zones in figs. 5 - 14 where the contaminated dolerites and the metasomatic granophyres merge with each other. (Between analyses 12 and 13 in Table XIV).

KEY TO FIGURES 4 TO 14.

■ Dolerites

▽ : Dolerite-pegmatite

○ : Contaminated or acidified dolerites

● : Metasomatic granophyres

□ : Metamorphosed pyroclastic rocks

▼ : Unaltered pyroclastic rock

<u>– 0,433</u> : Slope of regression line

Numbers in all these diagrams refer to the analyses in Table XV11.

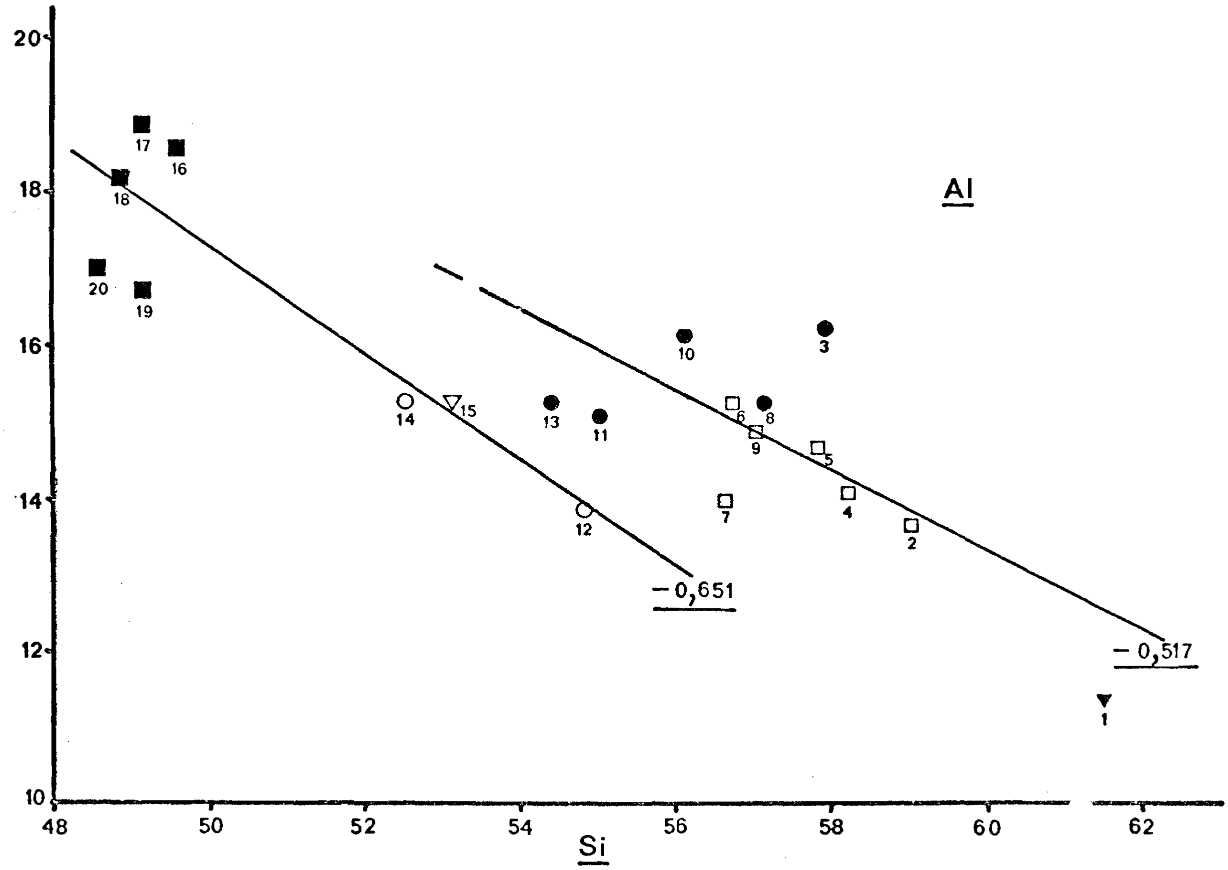


Fig. 4. Plot of Si^{4+} against Al^{3+}.

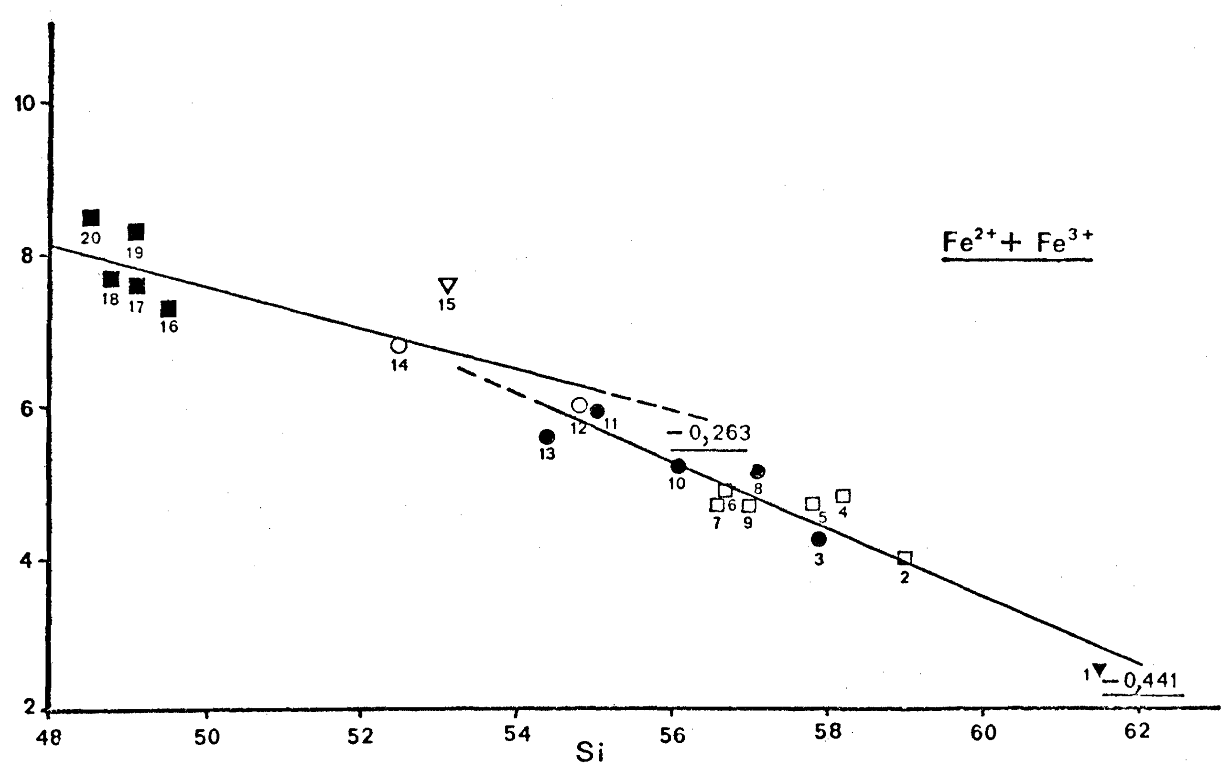


Fig. 5. Plot of Si^{4+} against total $Fe^{2+} + Fe^{3+}$

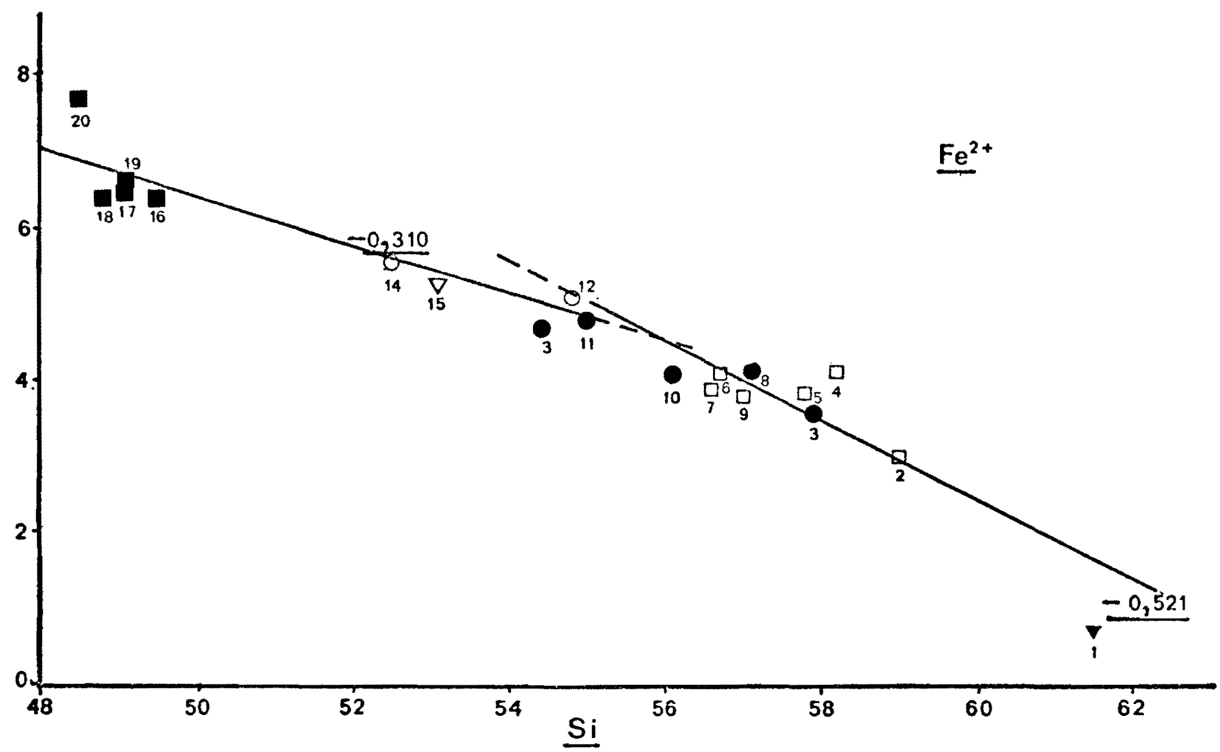


Fig. 6. Plot of Si^{4+} against Fe^{2+}.

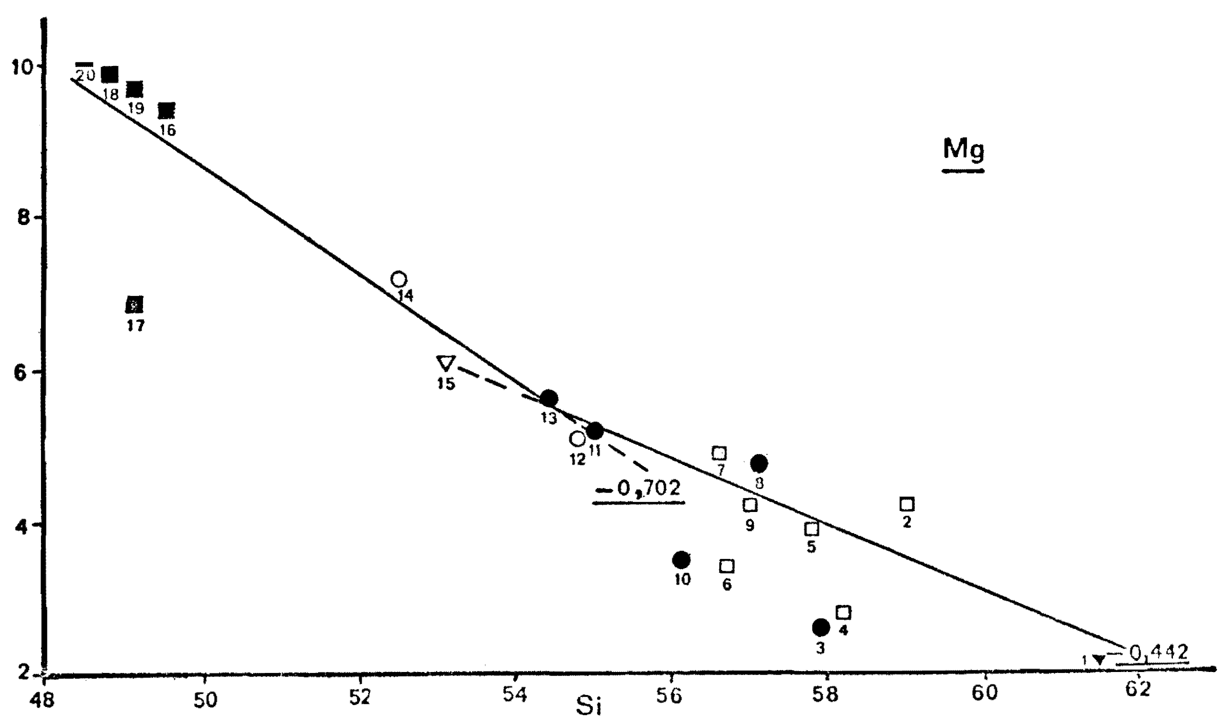


Fig. 7. Plot of Si^{4+} against Mg^{2+}

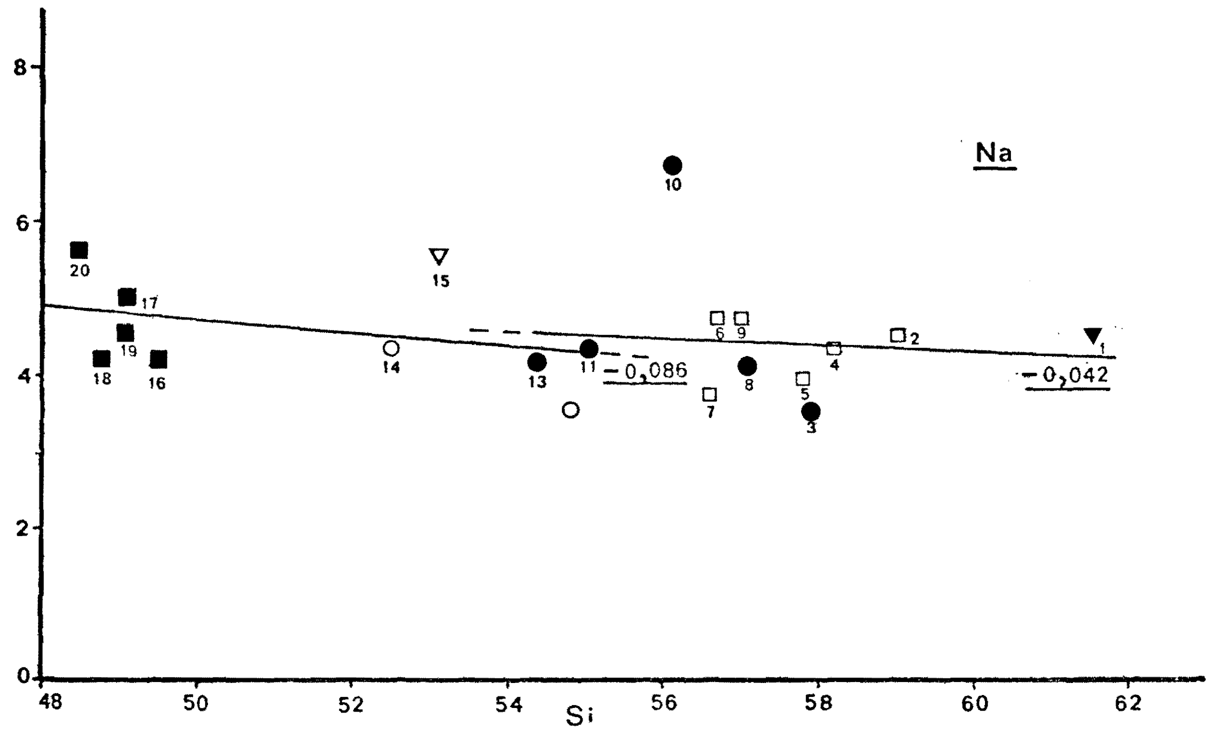


Fig. 8. Plot of Si^{4+} against Na^{+}.

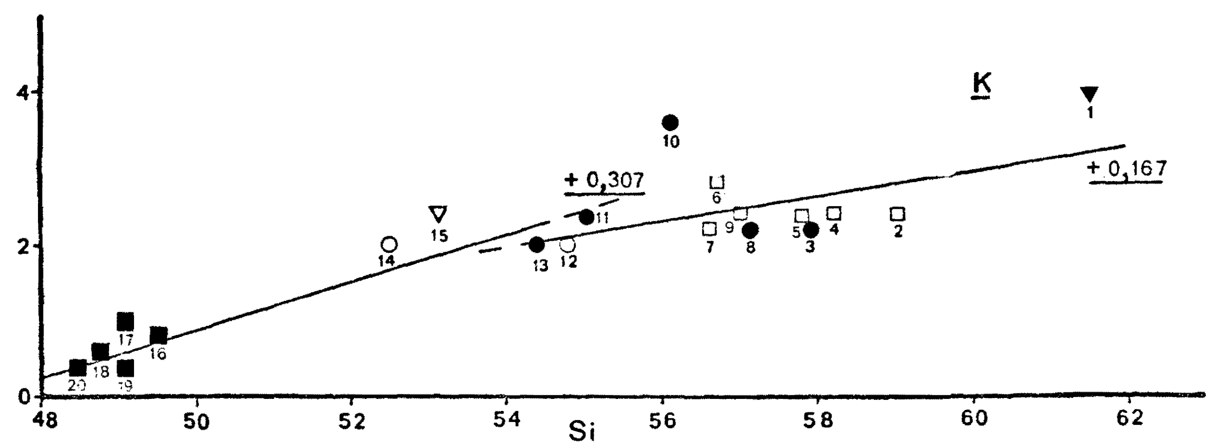


Fig. 9. Plot of Si^{4+} against K^{+}.

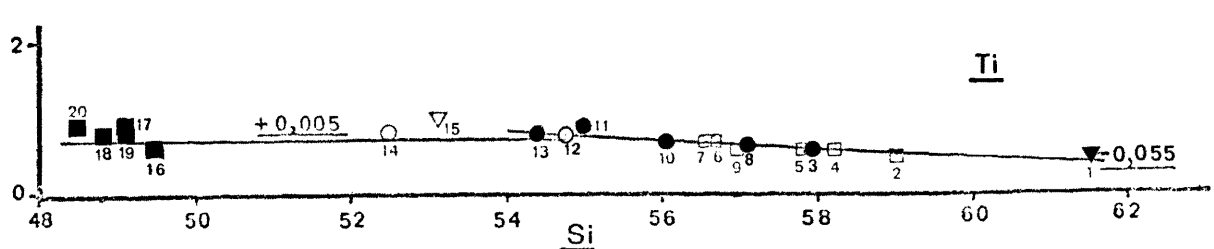


Fig. 10. Plot of Si^{4+} against Ti^{4+}

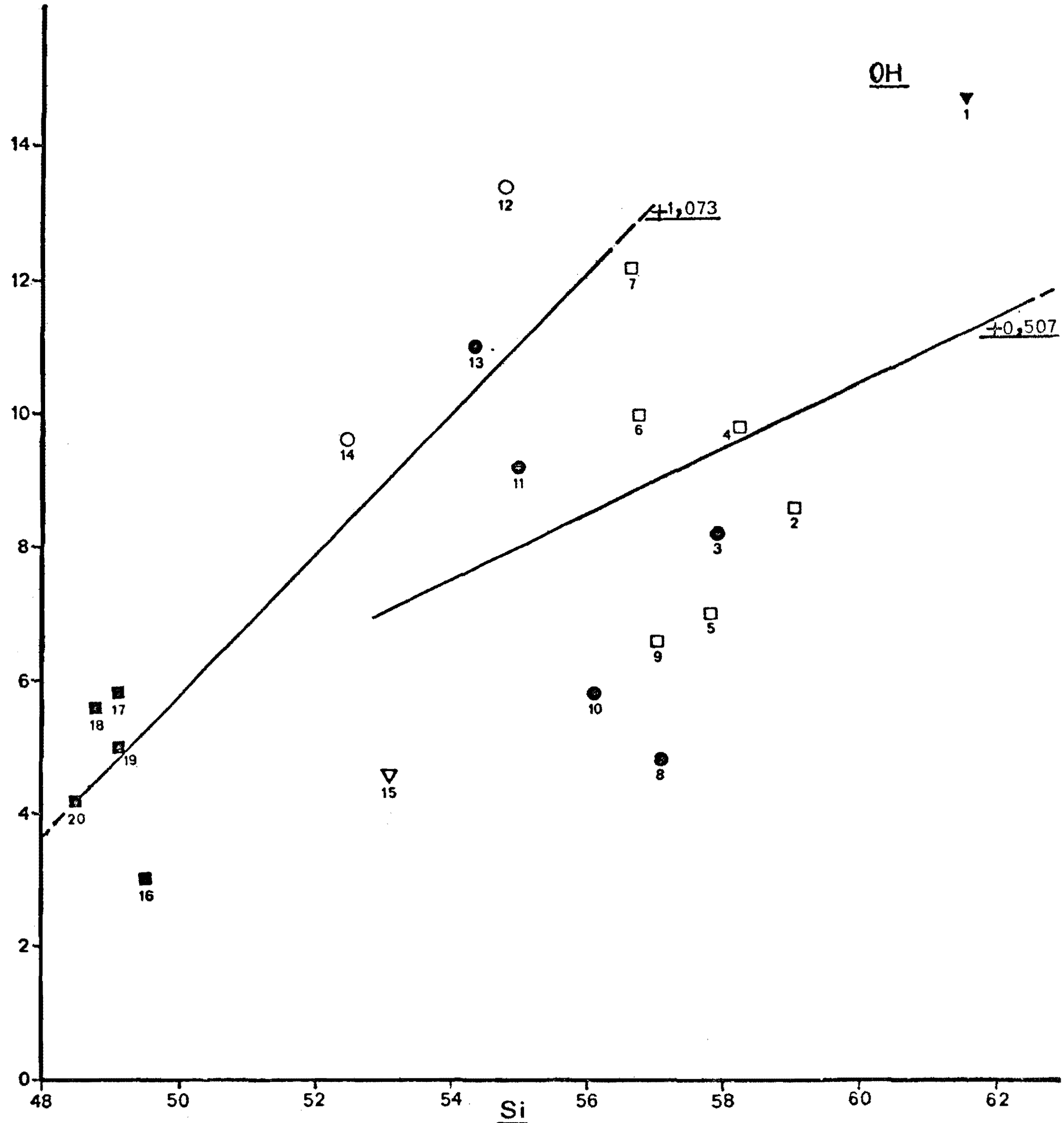


Fig.   Plot of Si^{4+} against OH^{-}

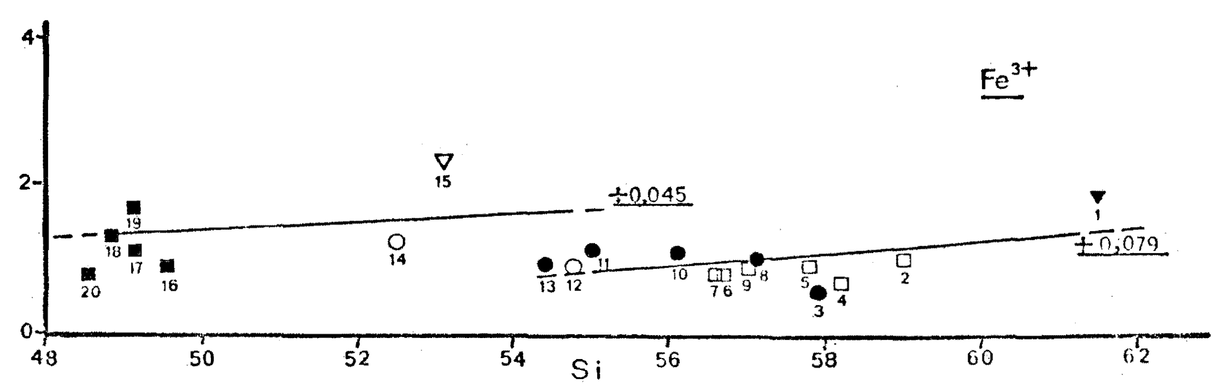


Fig. 12. Plot of Si^{4+} against Fe^{3+}

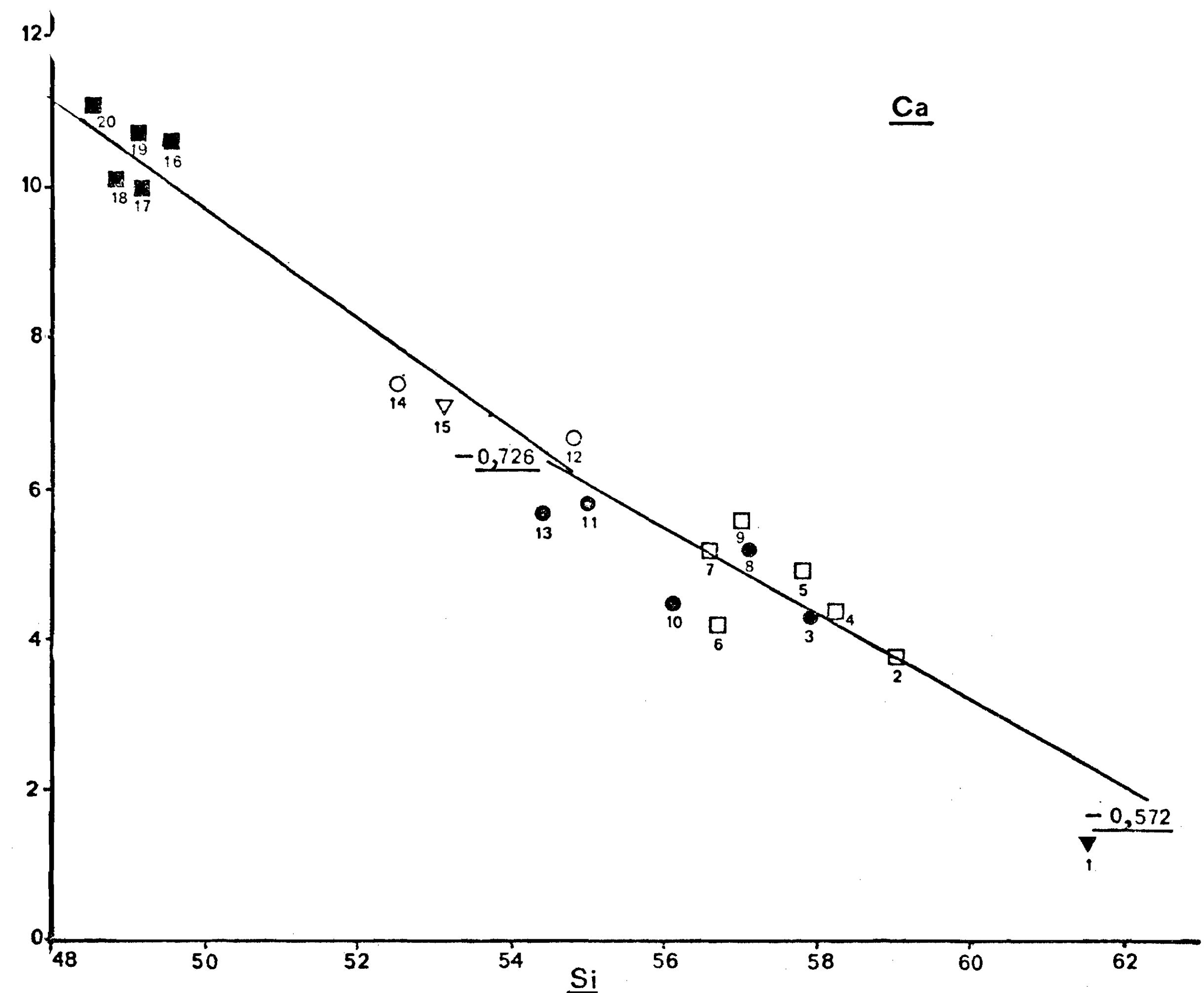


Fig. 13. Plot of Si^{4+} against Ca^{2+}.

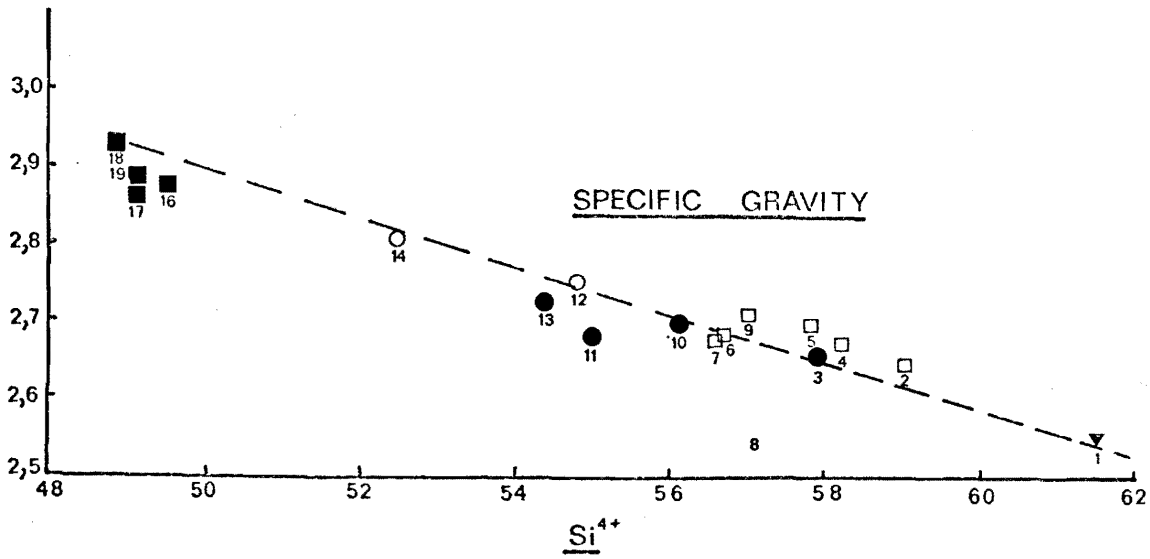


Fig. 14. Plot of Si^{4+} against specific gravity for thr Bird's River rocks.

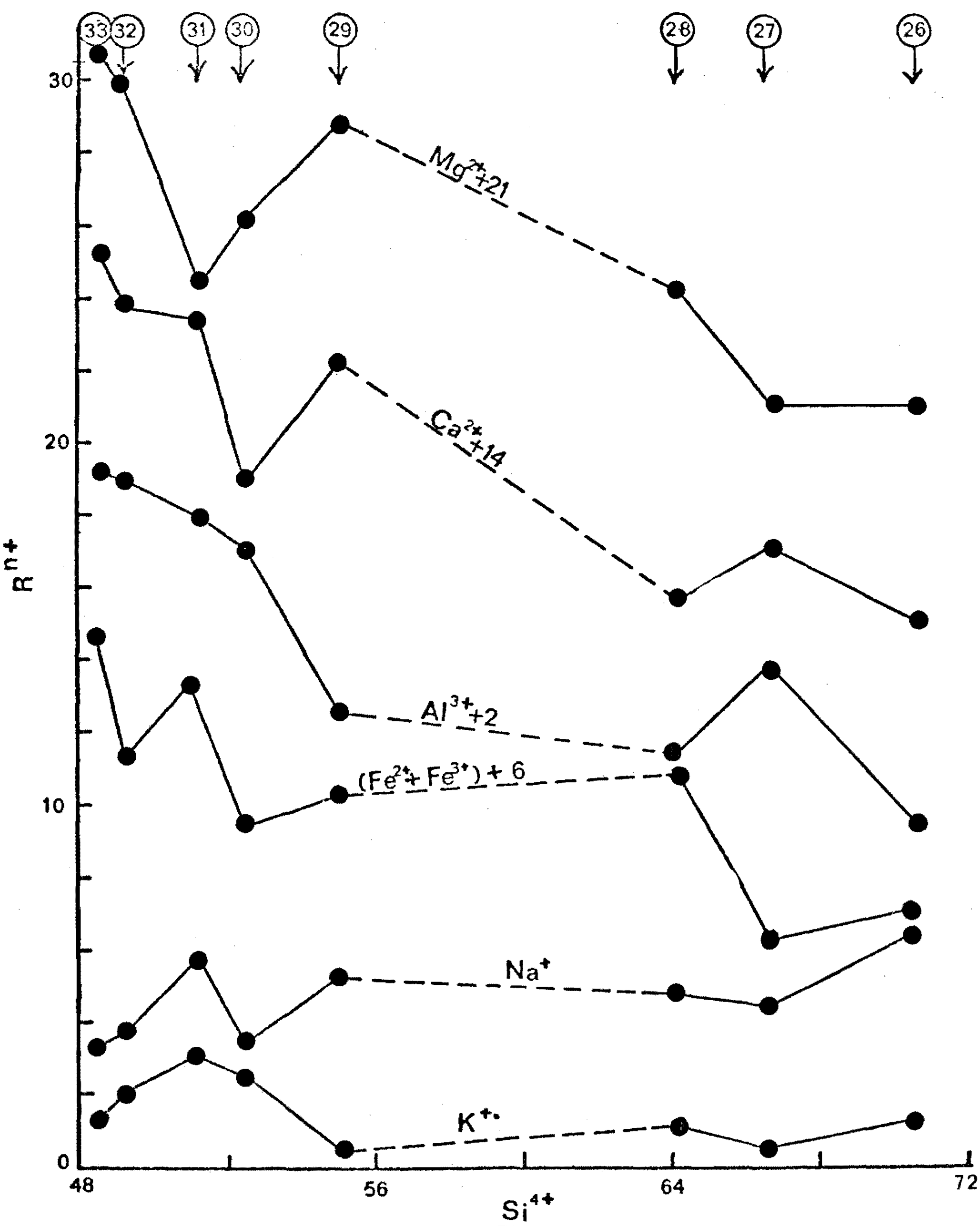


Fig. 15. Plots of Si^{4+} against the other major cations (R^{n+}) for the Coedmore Quarry rocks. The numbers at the top of the diagram refer to data in Table XXIII

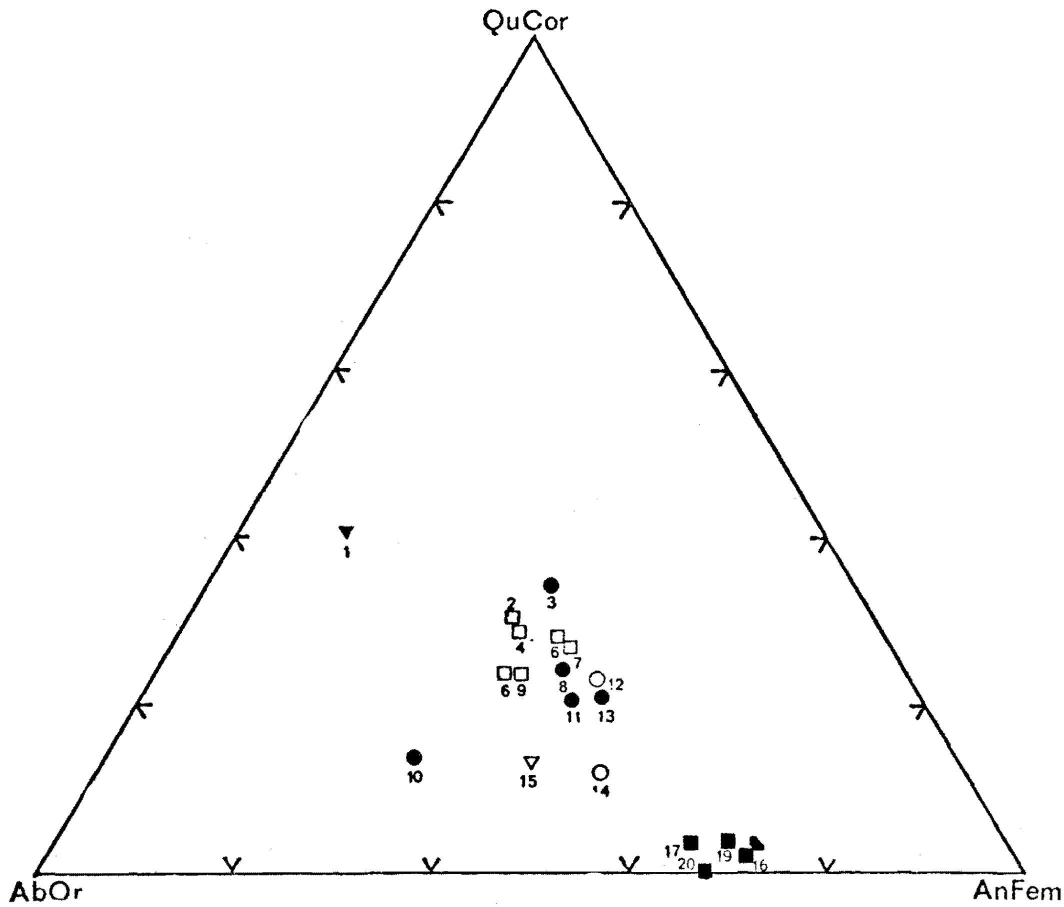


Fig. 16. QuCor - AbOr - AnFem variation diagram. The numbers represent the normative data in Table XV.

Calculation of Barth Standard Cell from Mountain's analyses of the Coedmore Quarry rocks (1958, p. 210) allows comparison to be made between these rocks and the sequence in the Bird's River Complex. Fig. 15 illustrates the trends at Coedmore of the major ions relative to Si^{4+} on the basis of the Barth Standard Cell. Mountain (1958, p. 211) plotted silica percentage against the percentages of the other major oxides and revealed that there was a gap of 12% along the SiO_2 abscissae separating the two groups of respective doleritic and sedimentary origin from each other. In fig. 15 this gap is from 55,0 Si^{4+} (for a calcitized granophyric dolerite) to 64,2 Si^{4+} (for a dark metamorphic granophyre). There are also gaps in the specific gravity, Ca and H_2O values for these Coedmore rocks. Mountain expected that with further information these gaps would be closed. Fig. 14 is a graph showing the variation in specific gravity for different concentrations of Si^{4+} in the Bird's River rocks. The trend is linear, showing a progressive increase in specific gravity with reduction of Si^{4+}. From the data presented here for the Bird's River suite it appears that the contaminated dolerites and metasomatic granophyres overlap each other in terms of their chemistry and are distinguished from each other mainly on a petrographic basis.

2. Calculation of a metasomatic model.

A general set of equations that allows calculation of gains and losses in terms of the chemical analyses and specific gravities of the unaltered and metasomatised rocks has been derived by Gresens (1967). In order to compare the rocks within a suite it is necessary to know or assume knowledge of the volume change or the geochemical behaviour of one

TABLE XXVI

Calculated boundary between contamination and metasomatism relative to the silica content of the rock.

(Values relate to concentration of Si^{4+} in the Standard Cell).

K^{+}	52,4
Fe^{2+}	54,8
Ca^{2+}	56,1
Mg^{2+}	55,1
Average	54,6

component in order to solve the problem. Babcock (1973) used the composition - volume equations to solve a problem of granitization. The metasomatic model for the Bird's River metasomatic suite will be based on Babcocks notation.

i) Derivation of the composition - volume equation.

The mass-action equation, $aA \pm X \rightarrow bB$, is used to represent the process of chemical transfer where; a = grams of parent rock A, b = grams of product rock B, and X = grams of material added or removed. The parent and product rocks should be considered as two different 'phases' in order to fulfill the requirements of mass balance calculations. Each 'phase' would have n components such that;

$$A = \overline{X}_1^{a} + \overline{X}_2^{a} + \ldots\ldots\ldots\ldots\ldots\ldots + \overline{X}_n^{a}$$

$$B = \overline{X}_1^{b} + \overline{X}_2^{b} + \ldots\ldots\ldots\ldots\ldots\ldots + \overline{X}_n^{b}$$

where

$\overline{X}_n^{a}$ = the weight fraction of chemical component n in rock A, and

$\overline{X}_n^{b}$ = the weight fraction of chemical component n in rock B.

The magnitude of chemical transfer for any given component in this system can be expressed in the following manner;

$$dX_n = b(\overline{X}_n^{b}) - a(\overline{X}_n^{a})$$

Terms for volume change and density are substituted and the following expression is derived

$$dX_n = a \left[(K_v . \bar{X}_n^b . \frac{D^b}{D^a})\right] - \bar{X}_n^a \qquad ....(1)$$

where

dX_n = chemical transfer (in grams) of component n between the phases A and B,

K_v = the ratio between final and initial volume of the rock mass,

D^a = the density of rock A (the parent rock), and

D^b = the density of rock B (the product rock).

Equation 1 is the composition - volume equation, and if a = 100 gms., then the values of dX_n are in weight percent. The following information, either known or inferred, is required in order to use equation (1):

(a) The chemical composition of the parent and product rocks. The analyses selected for this exercise are analyses 1, 2, 6, 7, 8, 9, 10, 11, and 13 (Table XIV) - all these analyses are of samples from the Cairn xenolith collected within a square kilometer of each other. Analysis 1 is the parent rock, analysis 13 is the product rock and all the rest are intermediates.

(b) The density of the parent and product rocks. The densities of the selected rocks were with one exception determined by hydrostatic weighing using a wetting agent. The sample of unmetamorphosed pyroclastic rock (analyses 1) was too porous for the density to be determined by hydrostatic weighing and thus the density was determined using a pycnometer. This determination of specific gravity on the pycnometer could introduce an error, however, because the plot of the specific gravity of the unmetamorphosed pyroclastic (point 1 in fig. 14) against Si^{4+} is so close to the straight line it is thought that any error will be small or non-existant.

(c) <u>The volume change of the rock mass or the magnitude of chemical transfer of any chemical component.</u> The composition - volume equation shows that chemical variations are linearly related to volume changes that occur during metasomatism. This relationship is shown in fig. 17 where changes in chemical composition have been plotted against volume changes (for the major oxides) for the conversion of a pyroclastic rock (analysis 1) to a metasomatic granophyre (analysis 13). This diagram yields certain interesting information which is summarized as follows:

(a) If one assumes that there has been no volume change during metasomatism, then Al_2O_3, FeO, MgO, CaO and TiO_2 would be added to the sediments and SiO_2, K_2O and Na_2O would be removed.

(b) The direction of movement of these oxides is the same assuming a 20% decrease in volume.

(c) A 20% increase in volume would result in only K_2O being reduced in the sediments on metasomatism and all the rest of the major oxides being introduced into the sediments.

The percentage volume change may be calculated using the composition-volume equation assuming there has been no change in the various oxide components during metasomatism of the parent rock. These data are recorded in Table XXVII. From these data Al_2O_3 and SiO_2 may yield clues as to the maximum changes in volume that could have occurred on metasomatism

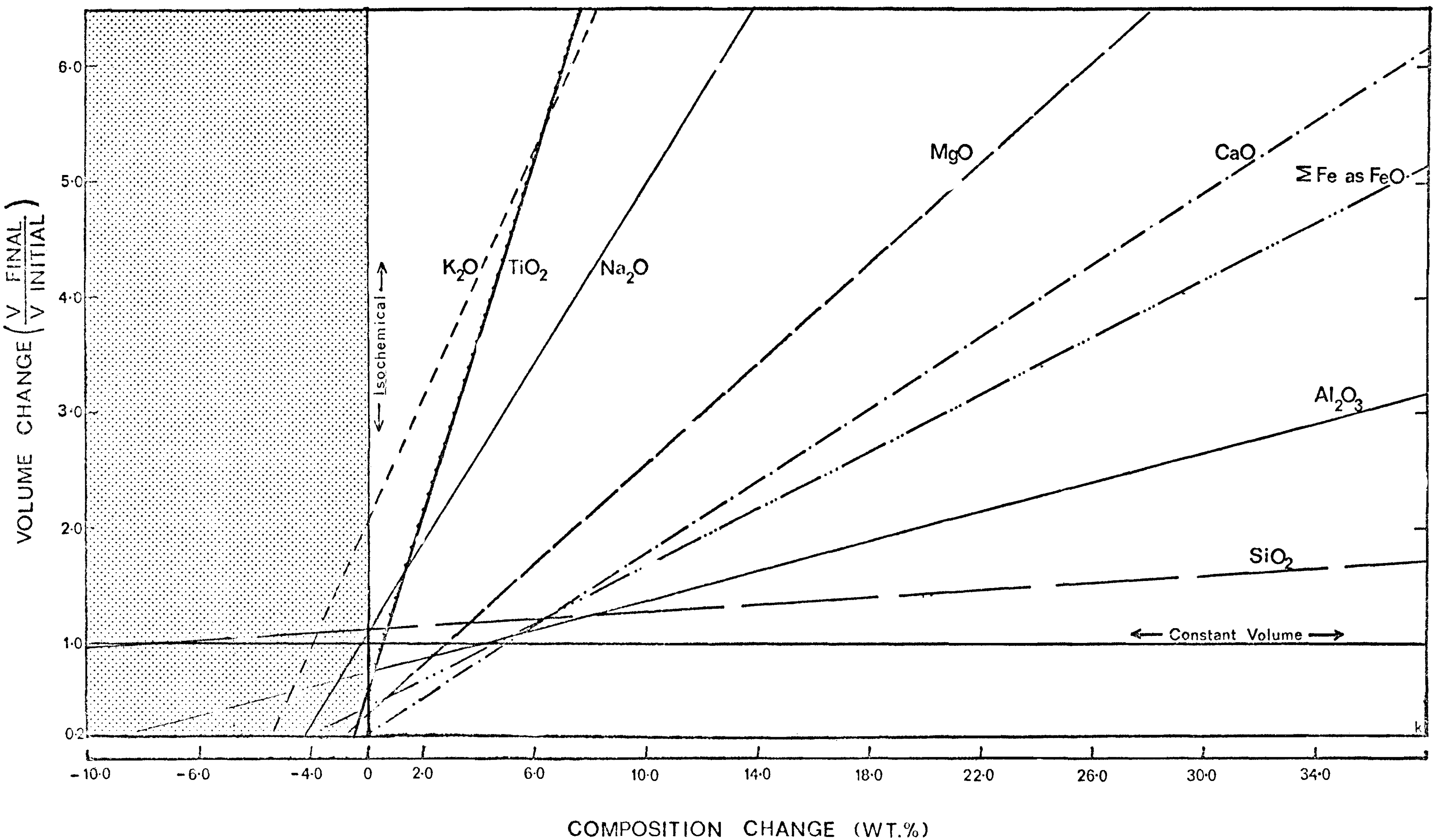


Fig. 17. Compositional variations versus volume change (K_v) for the conversion of a pyroclastic rock (analysis 1, Table XIV) to a metasomatic granophyre (analysis 13, Table XIV). The stippled zone marks the area of negative chemical transfer

of the pyroclastic rocks in the Cairn xenolith. If the amount of Al_2O_3 remained constant in the sediments on metasomatism there would be a decrease of 27% in the volume of the rock. Similarly, for SiO_2 there would be an increase of the rock volume of 12%. Petrographic evidence suggests that substantial amounts of Al_2O_3 may have been introduced into the sediments. This is reflected, in part, by the development of substantial amounts of feldspar and also the presence of sillimanite in the metasomatic granophyres. At the same time SiO_2 is either removed from the sediments or stays in the sediments and is 'diluted' by the metasomatisisng fluids entering them. The quartz content is much too low in the metasomatic granophyres relative to the sediments for SiO_2 to have been introduced into the pyroclastic rocks. Thus if there was a volume decrease of more than 27% it would mean that Al_2O_3 would be transferred to the dolerite, and if there was a volume increase of more than 12% SiO_2 would migrate from the dolerite into the sediments. From petrographic evidence neither of these suggestions is valid and it would appear that the maximum limits of volume change are between +12 and -27%.

No evidence could be found in the field that a significant volume change took place in the pyroclastic rocks on the transfusion of fluids into them although their mass may have been reduced by assimilation by the dolerite. This is supported by there being no substantial evidence of distortion or shearing in either the pyroclastics or the

TABLE XXVII

Volume change in % assuming various oxide components remained constant in the conversion of a lapillistone (analyses 1) to a granophyre (analyses 13).

SiO_2	TiO_2	Al_2O_3	FeO*	MgO	CaO	Na_2O	K_2O
+12	-44	-27	-56	-62	-78	+10	+105

Total iron as FeO

TABLE XXVIII

Hypothetical additive phase required to convert a lapillistone to a granophyre for volume changes = 0 and 10%.

Volume change	TiO_2	Al_2O_3	FeO	MgO	CaO	Total
0%	3,0	22,9	31,2	15,5	27,4	100,0
10%	3,0	26,5	29,3	15,2	26,0	100,0

adjacent dolerites. From the petrographic nature of the contaminated dolerites (where large patches of felsic material occur not completely integrated with the dolerite) it appears that the dolerites adjacent to the metasomatic granophyres were acidified by assimilation of sediments rather than by transfusion of fluid material out of the sediments. Thus the reduction of the proportion of SiO_2 and K_2O in the production of granophyres is perhaps due to 'dilution' on transfusion and probably also by the development of a silica-potash melt which contaminated the adjacent dolerite (see ahead). Thus a slight volume change is presumed to have occurred on metasomatism, probably between -10 and +10%.

Presuming that the metasomatic process was primarily one of transfusion of material into the pyroclastic rock, it is possible to calculate the composition of the hypothetical additive phase required to convert the pyroclastic rocks into metasomatic granophyres. This has been done for volume changes of 0 and +10%. At the same time the compositional changes in the conversion of the pyroclastic into metasomatic granophyres assuming a change in volume of 0 and +10% have also been calculated. The data for the hypothetical additive phase and the compositional changes are in Table XXVIII and XXIX respectively.

From the data listed in Table XXIX it is shown that:
for volume changes of 0 and +10% there has been a reduction in the SiO_2, K_2O and Fe_2O_3 content of the sediments on metasomatism. No significant change in Na_2O and MnO took place. It thus appears that TiO_2, Al_2O_3,

TABLE XXIX

Compositional changes in the chief oxides in the conversion of a lapillistone to a granophyre for volume changes = 0 and 10%

	K_v = 0,0		K_v = 1,1		New Amalfi*		Alewyn's Gat **	
	+	-	+	-	+	-	+	-
SiO_2		7,87		1,28		32,4		11,7
TiO_2	0,54		0,66		3,7		0,5	
Al_2O_3	4,19		5,77		5,5			1,9
Fe_2O_3		1,41		1,26		0,6	5,1	
FeO	5,71		6,38		14,2		0,1	
MnO		0,02		0,01	0,4		0,2	
MgO	2,85		3,31		4,5		4,9	
CaO	5,01		5,66		10,0		11,9	
Na_2O		0,26	0	0	8,1			1,0
K_2O		1,91		1,73		5,1		4,3
FeO*	4,44		5,24		-	-	0,1	

* Total iron as FeO

** Walker and Poldervaart (1949), p. 680, Table 26.

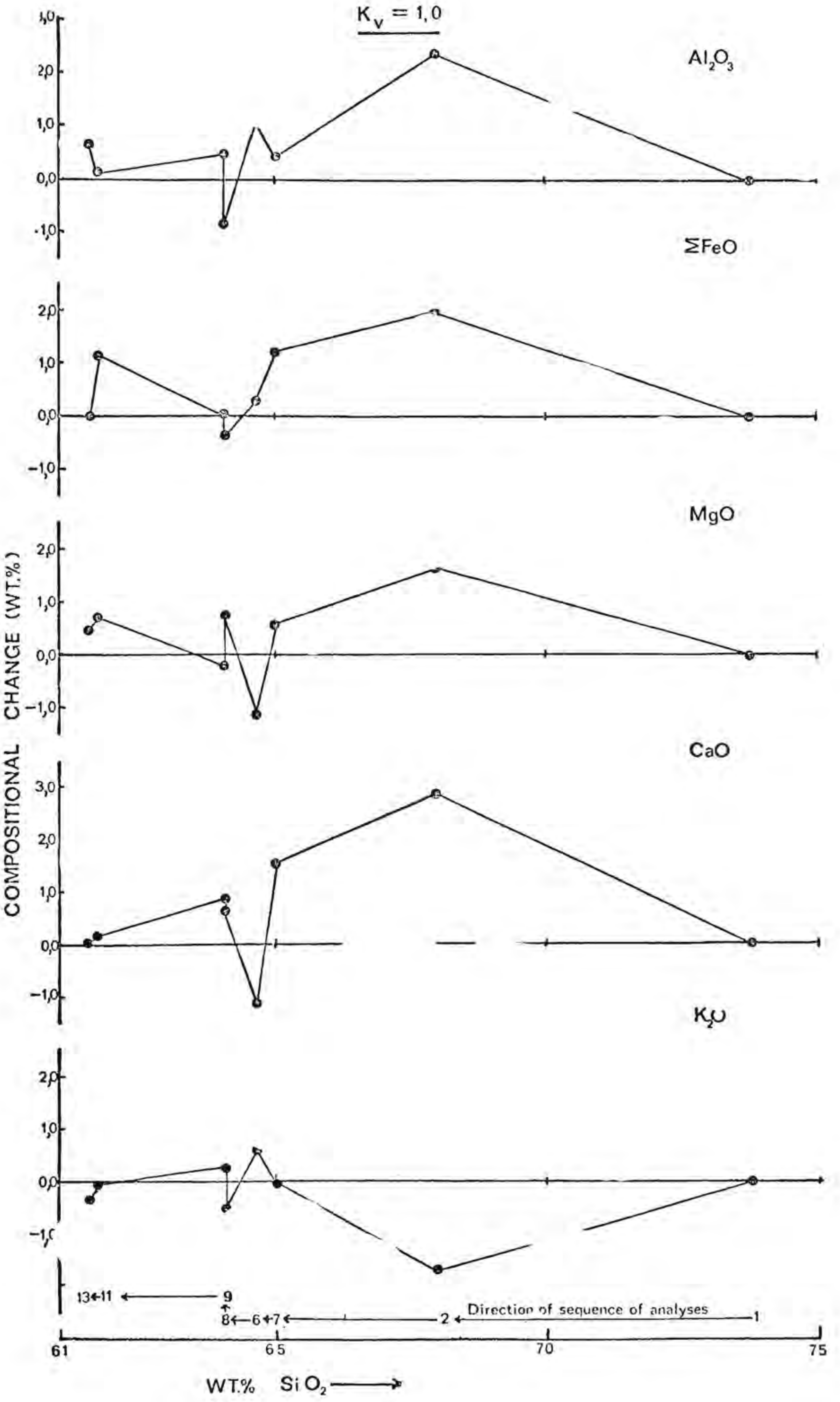
FeO, total iron as FeO, MgO and CaO have increased in the sediments on metasomatism. Up till now little attention has been paid to Fe_2O_3. As weathering of the pyroclastic sample would have oxidized some of the iron and any data relating to this oxide are considered unreliable. Further consideration of these data is given shortly.

ii) Development of metasomatic variation diagrams.

It is assumed that the analyses comprising Table XXX constitute a series of progressively metasomatised rocks, and that analysis 1 (a lapillistone) is the common parent rock of the rest of the series of analyses listed this table. The computation is based on the composition-volume equation assuming no volume change has occurred. The order in the metasomatic sequence is based on the SiO_2 content and the analyses are listed in order of decreasing SiO_2 (based on analyses recalculated 100% water free). The graphical representation of the data in Table XXX comprises figs. 18 (a) to (e). These graphs are metasomatic variation diagrams where compositional change has been plotted against weight per cent SiO_2 for TiO_2, Al_2O_3, total iron as FeO, MgO, CaO, Na_2O and K_2O. Walker and Poldervaart (1949, pp. 680-681) suggest that there are three phases of emanations in the transfusion of sediments, viz., an iron-rich phase (corresponding to basification of the sediments), a sodium-rich phase (corresponding to albitization of the sediments) and a potassium-rich phase (corresponding to granitization). The overall picture presented in figs. 18 (a) to (e) appears to correspond to the iron-rich phase of emanations where Ti, Al, Fe, Mg and Ca are added to

SEE OVER PAGE.

Fig. 18. Variations in the magnitude of chemical transfer of Al_2O_3, FeO, MgO CaO, and K_2O relative to SiO_2 in the series of analyses 1,2,7,6,8,9, 11 and 13, assuming constant volume during metasomatism.



$K_v = 1,0$
Al_2O_3
ΣFeO
MgO
CaO
K_2O
COMPOSITIONAL CHANGE (WT.%)
13←11 ← 9
8←6←7 ← 2 ← Direction of sequence of analyses 1
61
65
70
75
WT.% SiO_2 →

TABLE XXX

Compositional changes in a metasomatic sequence of Bird's River Rocks assuming constant volume during metasomatism.

Analysis Number	1 → 2	2 → 7	7 → 6	6 → 8	8 → 9	9 → 11	11 → 13	1 → 13
Sample Number	X28 → T1/1	T1/1 → $T_5/2$	$T_5/2 \rightarrow T_3/3$	T3/3 → T1/7	T1/7 → X19	X19 → 69/33	69/33 → T6/T3	X28 → T6/T3
SiO_2	-3,23	-2,05	-0,28	-3,61	+3,85	-3,12	+0,97	-7,87
TiO_2	+0,10	+0,25	0,00	-0,05	+0,01	+0,35	-0,14	+0,54
Al_2O_3	+2,37	+0,40	+1,12	-0,89	+0,46	+0,05	+0,62	+4,19
ΣFeO	+1,97	+1,21	+0,27	-0,34	+0,01	+1,21	0,00	+4,44
MgO	+1,62	+0,57	-1,16	+0,77	-0,20	+0,70	+0,47	+2,85
CaO	+2,82	+1,55	-1,13	+0,64	+0,84	+0,16	+0,99	+5,01
Na_2O	-0,03	-0,42	+0,56	-0,51	+0,56	-0,38	-0,01	-0,26
K_2O	-1,69	-0,03	+0,57	-0,56	+0,21	-0,04	-0,34	-1,91

the sediments. This is analagous with the information presented by Walker and Poldervaart (p. 280) for this phase of emanations except that they show that Al is lost to the sediments. Their suggestion that K and Si (also Al) are lost to the sediments by solution in the metasomatizing fluids may not be completely true and it is suggested here that the proportions of these elements have been reduced more by 'dilution than by transfusion of material out of the sediments, or by the migration of a silica-potash melt out of the sediments (see ahead). The metasomatic process in the Bird's River occurrence conforms closely with the occurrences at New Amalfi, Alewyn's Gat, and Thomas River (see Walker and Poldervaart, 1949, Table 26, p. 680). The data for the two former occurrences are also included in Table XXX for comparison.

The graphs in figs. 18 (a) to (e) were initially plotted in order to illustrate the detailed movements of the elements throughout the whole period of metasomatism. To a certain extent the exercise appears to have failed, as the inhomogeneous nature of the rocks tends to mask the detailed movement of the elements (this is reflected in the erratic nature of the graphs). However, they do indicate that the bulk of the were introduced early in the process of metasomatism.

iii) The Alkali Ratios.

Variations in the alkali content of thermally metamorphosed rocks have been discussed by Butler (1961, p. 884 - 892). He plotted weight per cent K_2O against Na_2O on a graph and also compared the Na/K ratios of unaltered parent and metamorphosed product rocks in cases where metamorphism of quartzo - feldspathic rocks by basic intrusions has occurred. He compared these data with the metamorphosed arkoses and pelites in the aureole of the Glenmore dolerite plug and commented that that the movement of alkali is a common feature of metamorphism in this type of environment.

Graphs and Na/K ratios have been calculated and plotted (see fig. 19 and Table XXXI) for selected examples where metasomatic granophyres are associated with Karroo dolerite and the data compared with what is encountered in the Bird's River granophyres. The examples selected are: Coedmore Quarries (Mountain, 1958), New Amalfi (Poldervaart, 1944), Alewyn's Gat, Rietkop and Hangnest (Walker and Poldervaart, 1942) and the the North Gap Dyke (Mountain 1943, Moore, 1965). The two cases in fig. 19 which exhibit very similar trends to the Bird's River are New Amalfi and Thomas River (the Gap Dikes). However, in all the examples, with the exception of Rietkop, there is an increase in the Na/K ratio indicating almost universal loss of K to the sediments on metasomatism. The examples quoted can be divided into categories as follows:

Category 1: Loss of Na, Loss of K.

Coedmore, Alewyn's Gat, Bird's River.

Category 2: Loss of Na, Gain in K.

Rietkop.

TABLE XXXI

Alkali contents of a selection of Karroo metasomatic association rocks.

Analysis No.	Wt.% Na_2O	Wt.% K_2O	Mol. Na/K	Origin
1	2,8	3,6	1,18	Lapillistone; Bird's River.
9	2,8	2,0	2,13	Metamorphosed lapillistone; Bird's River.
13	2,4	1,7	2,14	Metasomatised granophyre; Bird's River.
26	3,9	1,2	4,95	Table Mountain sandstone; Coedmore quarries.
28	2,9	0,8	5,51	Granophyre; Coedmore quarries.
34	2,2	3,9	0,86	Burghersdorp sandstone; New Amalfi.
36	2,8	2,6	1,64	Granophyre; New Amalfi.
37	2,9	3,5	1,26	Siltstone; Alewyn's Gat.
38	2,5	1,9	2,00	Granophyre; Alewyn's Gat.
39	3,1	2,1	2,24	Siltstone; Rietkop.
41	2,6	3,9	1,01	Granophyre; Rietkop.
42	1,8	3,4	0,80	Siltstone; Hangnest.
43	2,7	3,4	1,20	Granophyre; Hangnest.
44	2,8	3,8	1,12	Beaufort sandstone; Thomas River.
45	3,2	2,7	1,80	Metasomatised xenolith; Thomas River.

26,28 : Mountain, (1958).

34,36 : Poldervaart, (1944).

37,38,39,41,42,43 : Walker and Poldervaart, (1942).

44 : Mountain, (1943).

45 : Moore, (1965).

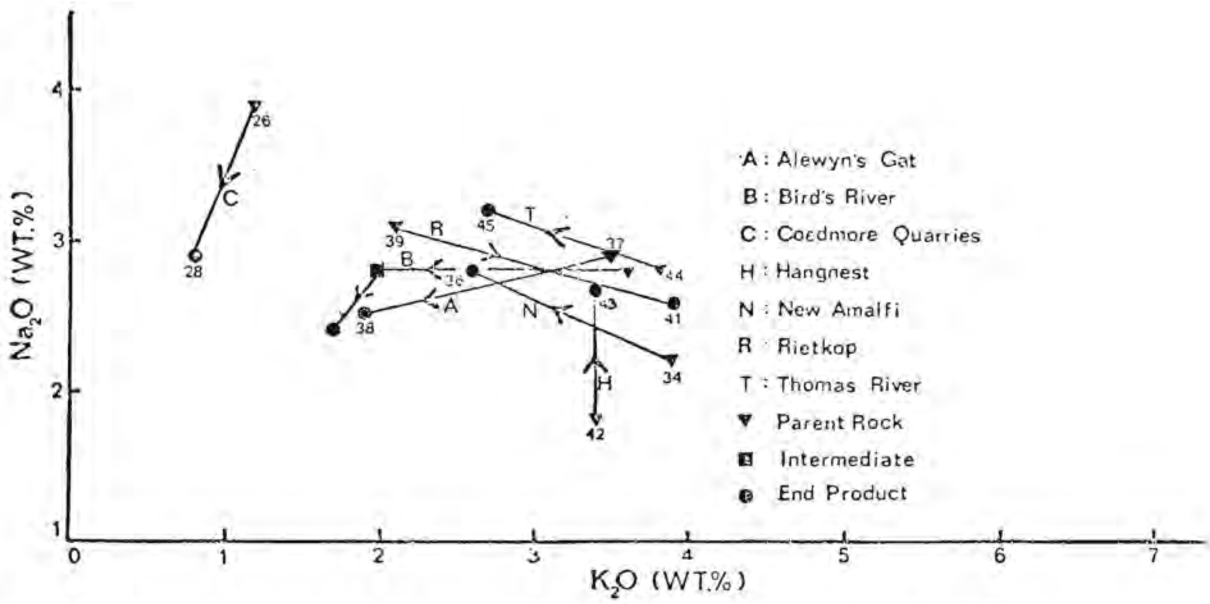


Fig. 19. Variations in alkali contents of rocks associated with metasomatism by Karroo dolerite. The numbers refer to data in Table XXXI.

Category 3: Gain in Na, Loss of K.

New Amalfi, Thomas River.

Category 4: Na or K stay constant with either Na or K being gained or lost.

Hangnest (K constant, gain in Na)

Bird's River (Na constant, K lost)

The above data indicate that the behaviour of alkalis during metasomatism of sediments by Karroo dolerites is not constant and the final effects produced on metasomatism probably depend on the composition of the original sediments and also the composition and hence extent of differentiation of the dolerites which would determine the composition of the fluids entering the sediments.

B. THE CHEMISTRY OF THE SPILOSITE AND ADINOLE.

Chemical analyses were performed on the black spilosite and the banded potassium adinole from the north eastern margin of the Cairn Xenolith. There is a suggestion that these rocks formed by metasomatism of the Cave Sandstone which occurs in poorly developed outcrop in the adjacent areas. The analyses of these rocks are listed in Table XVIII along with an analysis of recrystallized Cave Sandstone (Eales and Booth 1974, Table 1, no. 6) the spotted vitrified pale grey spilosite (Eales 1974, Table 1, no. 1) and the Cave Sandstone analyses of Walker and Poldervaart (1949, Table 15, no. 114). Barth Standard Cell data have been calculated for these analyses and variation diagrams (see fig. 20) have been plotted

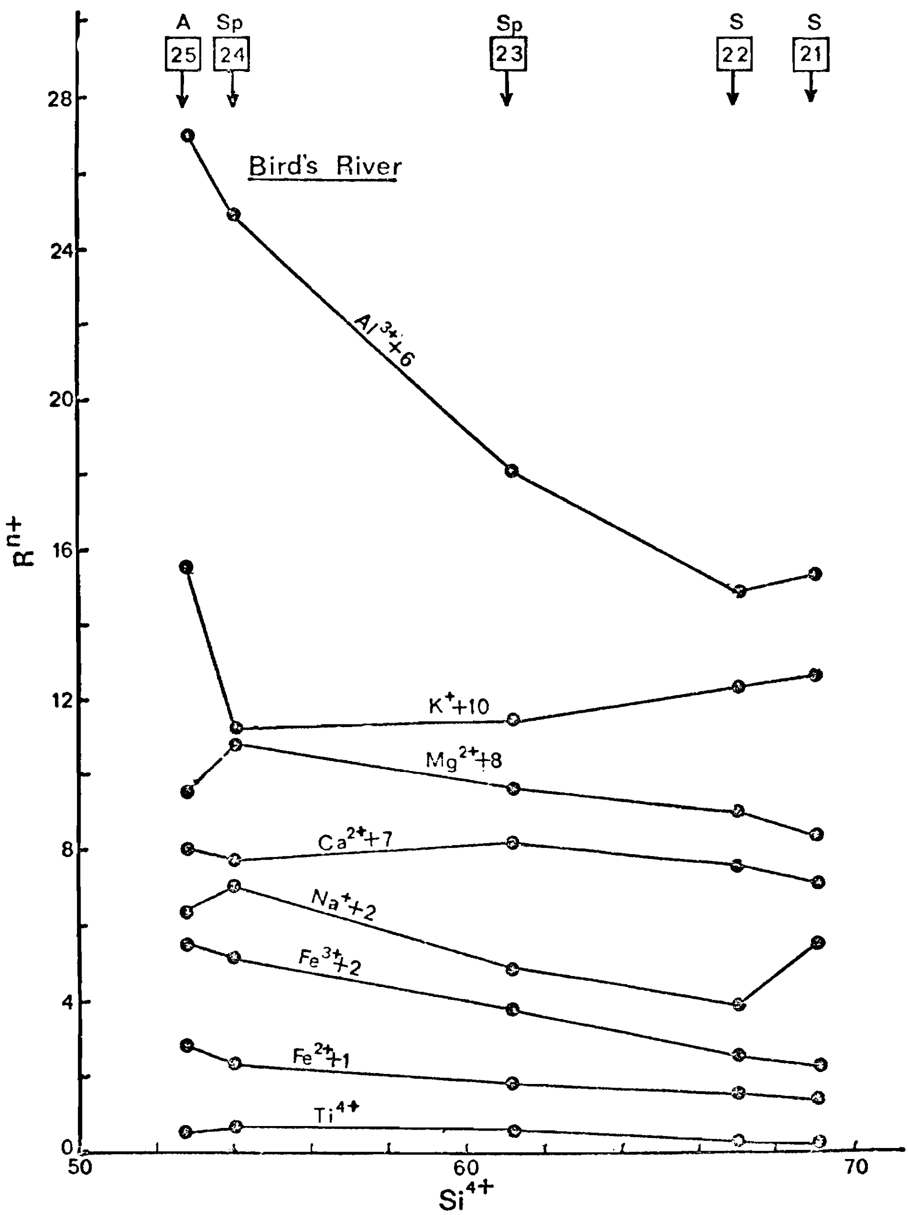


Fig. 20. Plots of Si^{4+} versus the other major cations in the Bird's River spotted spilosite - potassium adinole association. The numbers at the top of the diagram refer to the analyses in Table XVIII. The symbols at the top of the graph are A = Adinole, Sp = Spilosite, S = Sandstone.

which illustrate the variation of Ti^{4+}, Al^{3+}, Fe^{3+}, Fe^{2+}, Mg^{2+}, Ca^{2+}, Na^{+} and K^{+} relative to Si^{4+}.

The most significant aspect of these graphs is the relatively large amount of alumina that appears to have been introduced into the sediments in the production of the adinole. Substantial amounts of potash also have been introduced. Below the contact with the adinole, dolerite-pegmatite has concentrated along well-developed joints in the gabbro of the bell-jar intrusion. These joints are perpendicular to the contact and are believed to have formed before the dolerite was completely solid. These joints may have acted as channels, allowing the transfusing fluids easy access to the overlying sediments. The fact that a late-stage differentiate of the dolerite (ie. the dolerite-pegmatite) is concentrated along these joints indicates that this may be the source of the transfusing fluids. Microprobe analyses of the glass in a partly fused dolerite-pegmatite clast from a volcanic breccia on the farm Murrelfontein (Eales, 1974, p. 47) show that the glass is enriched in K_2O relative to the whole rock while there is slightly less Al_2O_3 in the glass than in the whole rock. Of the other oxides SiO_2 is much more abundant, while iron, MgO and CaO are greatly reduced relative to the parent dolerite-pegmatite. As SiO_2 does not appear to have been present in any significant amount in the fluids entering the sediments it is possible that Al_2O_3 and K_2O could have been the prime constituents of these fluids. The outcrop of the adinole and accompanying spilosite run along the contact for about 100 metres and extend into the xenolith for no more than 30 metres averaging 10 to 15 metres above the contact. It seems possible that sufficient volatile material would be available to produce the rocks when one considers there is a relatively large amount of dolerite-pegmatite present in the gabbro below the contact. Also, the volatiles had easy access to the sediments along the well-developed joints perpendicular to the contact. Huang, (1957, p. 1748) described an example of alumina metasomatism in a Precambrian gabbro-granophyre complex where quartzites and igneous rocks of various compositions have been converted into rocks rich in sillimanite and related minerals by metasomatism where Al_2O_3 -rich fluids were involved. He records that the Al_2O_3 necessary for the metasomatism was derived from the granophyric melt.

From the data in Table XVIII and in fig. 20 it thus is apparent that the production of the adinole by a metasomatic process would result in relatively large amounts of alumina and potash being introduced into the sediments. These data also indicate that small quantities of iron (more ferric than ferrous iron), magnesium, calcium, sodium and possibly titanium were also introduced into the sediments. Silica appears to have decreased by dilution as in the previous case of the metasomatic granophyres.

There is the possibility that the parent rock of the adinole is not Cave Sandstone but rather an argillaceous band or lens interbedded with the sandstone. The very local occurrence of the adinole makes this a strong possibility especially considering that narrow beds of argillaceous sediments are encountered in the Cairn xenolith. Because of the local occurrence of the adinole and because the outcrops of the adjacent sediments are poor it can only be assumed that Cave Sandstone is the parent rock. The grey spilosite, which is similar to the black spilosite that is adjacent to the adinole, outcrops along the same contact about $^1/_2$ km. south of the adinole. The parent rock of this spilosite is Cave Sandstone.

A question that remains unanswered, however, is whether the spilosite and the adinole formed from the same parent rock. Agrell (1939) described the formation of an adinole by soda metasomatism of slates where the fluids originated in an albite-dolerite. He regards the spotted rocks (which he refers to as spilosites) as being intermediate between the slates and adinole. Harker (1932, p. 129) agrees that the spotted spilosite is the intermediate in the soda metasomatism of slates and similar rocks.

The spots in the Dinas Head occurrence described by Agrell consist of either quartz, chlorite and leucoxene, or of albite. The spots in the Bird's River rocks are mainly quartz and minor feldspar. The adinole at Dinas Head consists mainly of quartz and albite. The Bird's River potassium adinole consists mainly of K-feldspar, magnetite, and sillimanite with lesser amounts of plagioclase, quartz and cordierite. However, at Dinas Head sodium metasomatism has occurred - the metasomatizing fluids originating in an albite dolerite, while at Bird's River potassium and alumina appear to have been added to the sediments. Fig. 21 illustrates the variation of the major elements in the Barth Standard Cell relative to S^{4+} in the Dinas Head rocks. Only sodium appears to have been added to the sediments while there has been significant decrease in K, Al and to a lesser extent Mg and ferrous iron.

At Bird's River there is a decrease in K between sediment and spilosite and then it increases sharply between spilosite and adinole. At Dinas Head (excluding the spilosite which contains less silica than the parent rock) there is a very slight decrease in Na between slate and spilosite and then it increases sharply between spilosite and adinole.

Agrell (p. 314) states that the spilosites at Dinas Head occur between the slate and the adinole and it is on this basis that he regards them as intermediates. At Bird's River the problem is more complex, firstly because outcrop is poor away from the contact and secondly because both spilosite and adinole are in contact with the dolerite. This makes it difficult to determine if the spilosite is intermediate between the adinole and the sediment. However, the following comparison with Agrell's description provides circumstantial evidence that the spilosite is associated with the adinole in some way.

The behaviour of the alkalis as described above ie., the sudden increase in alkali content between spilosite and adinole is exhibited in both examples. Plotting K_2O versus Na_2O and determining the Na/K ratio as done previously for the metasomatic granophyres (see fig. 22 and Table XXXII)

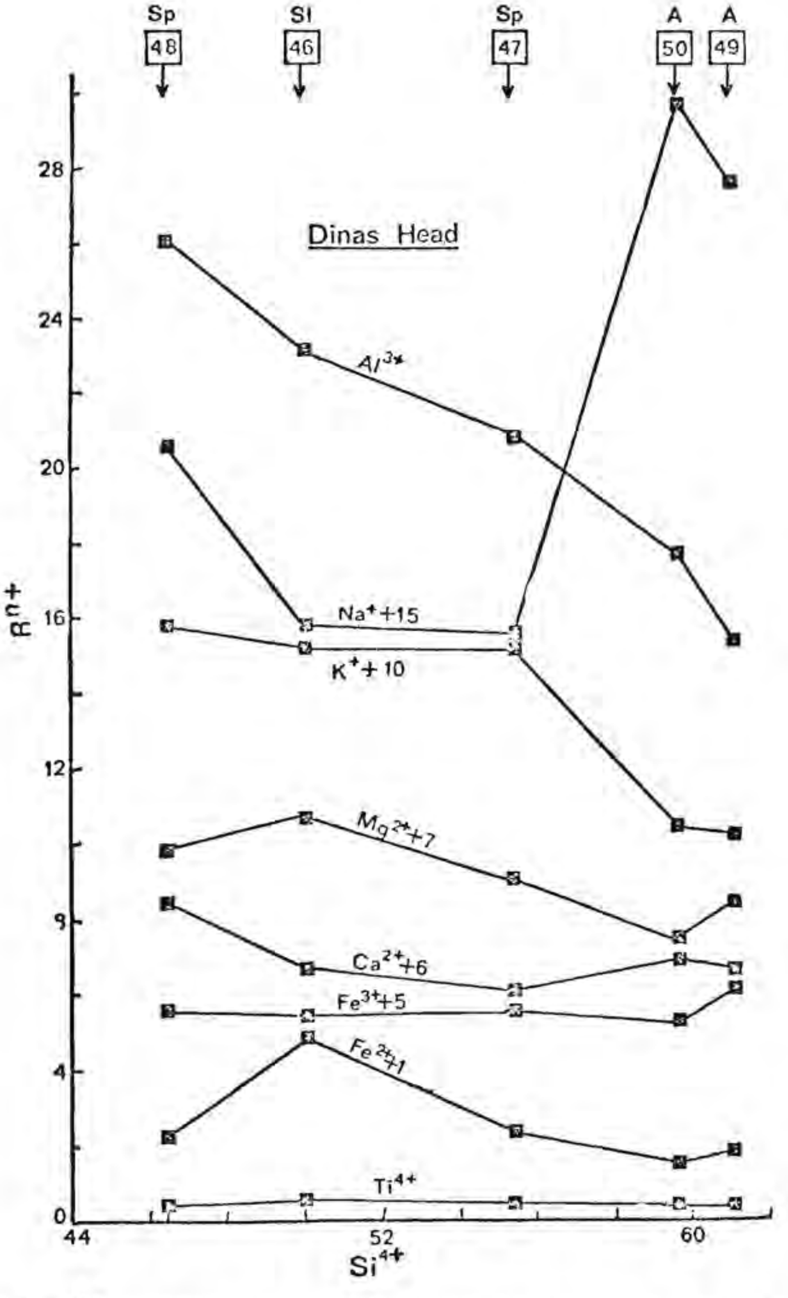


Fig. 21. Plots of Si^{4+} versus the other major cations in the Dinas Head spotted spilosite - sodium adinole association (after Agrell, 1939). The numbers at the top of the diagram refer to the analyses in Table XX. The symbols at the top of the graph imply the following; A = Adinole, Sp = Spilosite, Sl = Slate.

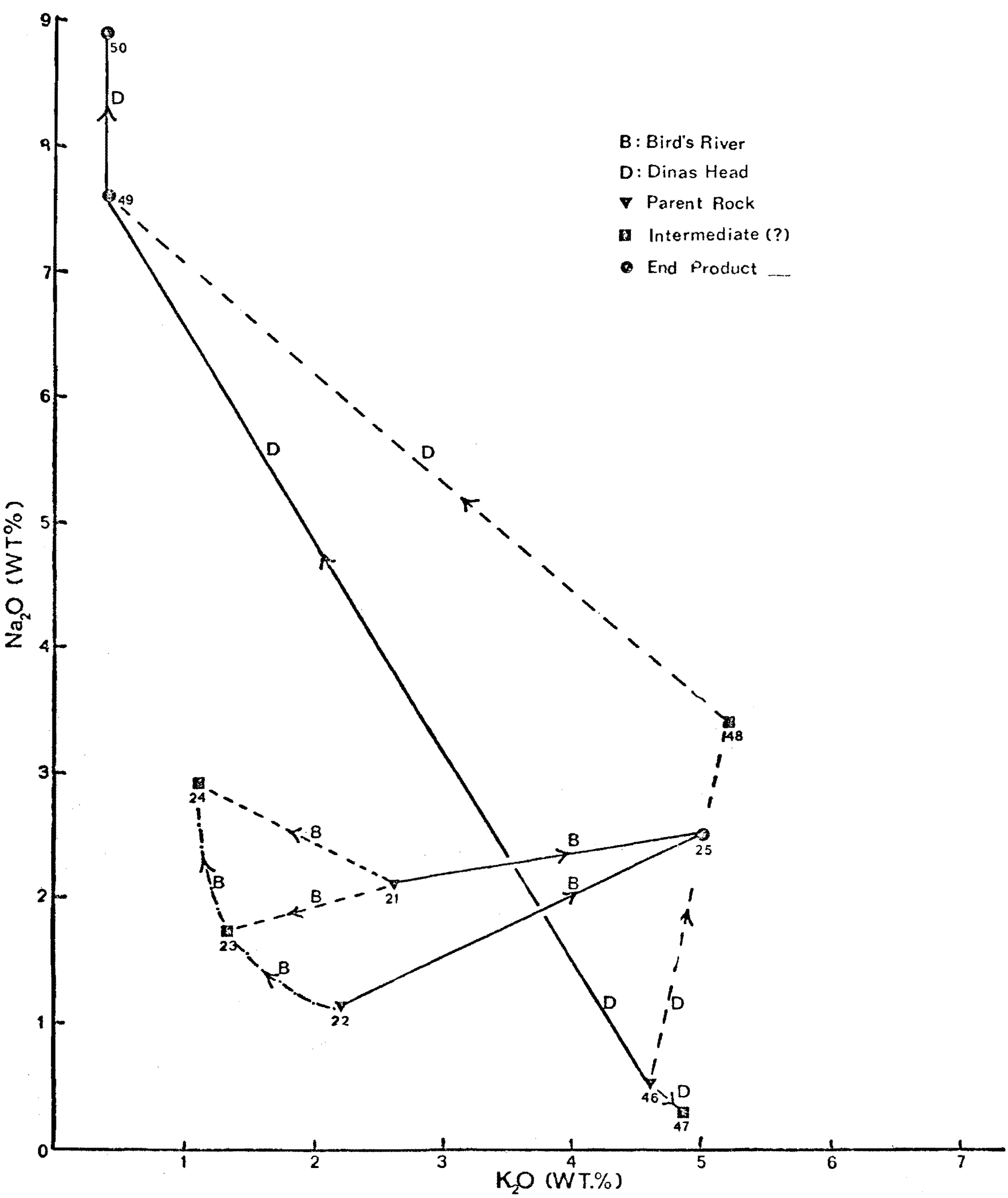


Fig. 22. Variations in alkali contents in the Bird's River and Dinas Head adinole associations. The dashed lines link the parent sediments with the intermediate spotted rocks, and the solid lines link the former with the adinoles. The numbers refer to the analyses in Table XXXII.

shows that the trends between parent sediment and spilosite are different to the trend between parent sediment and adinole, in both cases. This is due to possible variation in the composition of the sediments or there has been a change in the composition of the metasomatic fluids. At Bird's River and Dinas Head there has been a gradual increase in Al_2O_3 between sediment - spilosite and adinole and a sudden increase in K_2O or Na_2O respectively indicating that there was a change in the respective alkali composition of the metasomatic fluids. This is possible when one considers how quickly the late stage magma would be changing composition at this stage.

The adoption of the terms'adinole' and 'spilosite' is based to a certain extent on Agrell's description at Dinas Head for the following reasons:

(i) Alkali metasomatism is associated with both examples.

(ii) Intermediate spotted metasomatic rocks, called spilosites are encountered in both examples.

(iii) Both adinoles are rich in alkali feldspar. viz. albite at Dinas Head and sanidine at Bird's River.

(iv) The two examples possess similar textural features, ie. spherulitic feldspar, banding and feldspar porphyroblasts in a feldspar groundmass.

On this basis it is suggested that the term adinole and spilosite be redefined as follows:

(a) Adinole is the product of alkali metasomatism of quartzo-feldspathic or pelitic rocks. The products of metasomatism contain abundant alkali

TABLE XXXII

Alkali contents of the Bird's River and Dinas Head adinole associations.

Analysis No.	Wt.% Na_2O	Wt.% K_2O	Mol Na/K	Origin
21	2,1	2,6	1,23	Cave sandstone
22	1,1	2,2	0,76	Metamorphosed Cave sandstone
23	1,7	1,3	1,99	Spotted metamorphosed Cave sandstone
24	2,9	1,1	4,00	Dark grey spilosite
25	2,5	5,0	0,76	Potassium adinole
46	0,5	4,6	0,17	Black carbonaceous slate
47	0,3	4,8	0,10	Black spilosite
48	3,4	5,2	0,99	Spilosite with albite-rich spots
49	7,6	0,3	47,0	Adinole
50	8,9	0,3	43,5	Adinole

21 : Walker and Poldervaart, (1949).

22 : Bird's River, Eales and Booth, (1974).

23 : Bird's River, Eales, (1974).

24-25: Bird's River.

46-50: Dinas Head, Agrell, (1939)

feldspar.

(b) A spilosite is a spotted rock intermediate between adinole and quartzo-feldspathic or pelitic sediments.

<u>The relationship between the metasomatic granophyre and the adinole.</u>

It is believed that the metasomatic process began after the bulk of the dolerite had crystallized. Walker and Poldervaart suggested that it commenced "during the stage of maximum iron enrichment when vapour pressure and chemical energy of the partial magmas were near their peak" (1949, p. 678). From the chemical data presented it appears that the metasomatic granophyres were produced during the period of iron enrichment of the dolerite, and the adinole during the period of alkali enrichment. The former rocks were produced by iron-rich emanations entering the sediments, probably originating from an iron-enriched partial magma present in the poikilophitic gabbros at the stage that metasomatism took place. The adinole was produced by potassium-rich emanations originating in partially solidified dolerite-pegmatites.

CHAPTER EIGHT.

SUMMARY AND CONCLUSIONS.

General Statement.

The information collected from field mapping, petrographic and mineralogical examination, and chemical analysis reveals that all the reaction phenomena listed by Walker and Poldervaart (1949, p. 675) were encountered in the two large xenoliths that had foundered into the Bird's River bell-jar intrusion. These reaction phenomena include transfusion or metasomatism of the sediments, assimilation of the sediments, rheomorphism and fusion of the sediments.

A. METASOMATIC PHENOMENA.

Pyroclastic rocks [illegible] lapillistones, have been metasomatised by [illegible] dolerite. These lapillistones consist of an assortment of igneous and sedimentary fragments in a groundmass of abundant angular quartz and turbid brown clay material.

In the initial stages of metamorphism of these rocks, recrystallization of the quartz occurred with the development of turbidity towards the grain margins. With increasing metamorphic grade recrystallization of the quartz in the groundmass become more intense and ultimately rods and plates of quartz paramorphic after tridymite developed as fringes around cores of uninverted quartz. At the same time turbid K-feldspar began forming and devitrification of the glassy lapilli commenced. Eventually the K-feldspar and the quartz became intergrown with the ultimate development of a tridymite granophyre. This granophyre consists of regular forms of K-feldspar intimately intergrown with wedge- and plate-like forms of quartz paramorphic after tridymite. The abundance of this tridymite granophyre increased with increased intensity of metamorphic grade and at the same time devitrification of the glassy lapilli produced a fine-grained assemblage of pyroxene and plagioclase. Some of this pyroxene migrated into the groundmass with the ultimate merging of the groundmass and lapilli. The quartz in the sedimentary lapilli also inverted to tridymite with these lapilli also becoming difficult to distinguish from the groundmass. The final product of metamorphism and metasomatism is a relatively homogeneous rock termed a metasomatic granophyre. These rocks, in which a few isolated lapilli occur, are composed of plagioclase, tridymite granophyre (wedges and plates of quartz paramorphic after tridymite intergrown with sanidine), hypersthene, augite, sillimanite and ore minerals and occasional pigeonite is encountered. Modal analyses of a suite of rocks through the whole metamorphic sequence reveal an increase in plagioclase and pyroxene and a decrease in tridymite granophyre (not to be confused with the increase of tridymite granophyre described above which is relative to the unmetamorphosed quartz - overall the quartz content of these rocks diminishes with increasing grade of metamorphism) as the degree of metamorphism increases. Universal stage data have shown that the plagioclase becomes slightly more basic with increase in metamorphic grade, being An_{74} in the unmetamorphosed pyroclastic and An_{78-80} in the granophyres.

Chemical data tie in with the petrographic data. Using the Barth

Standard Cell calculation and also using a composition-volume equation to calculate a metasomatic model, it has been shown that aluminium, iron, magnesium and calcium may have been added to the sediments on metasomatism. At the same time the silica, potash, and water contents of the sediments were reduced. The overall effect may have resulted in a volume change of between -10 and +10 per cent. The introduction of the Al, Fe, Mg and Ca is reflected in the increase of Ca-plagioclase and pyroxene in the metamorphic rocks relative to the sediments. Portion of the SiO_2 in the sediments can be expected to have entered into the plagioclase and pyroxene minerals.

It is suggested that this metasomatism was produced by an iron-rich phase of emanations from the dolerite. These emanations may have been similar in composition to those which produced the metasomatic rocks at New Amalfi, Thomas River, and Alewyn's Gat (cf. Walker and Poldervaart, 1949, p. 680, Table 26).

Metasomatism of the sandstones that make up the bulk of the sediments in the Cairn Xenolith has produced two small outcrops of granophyre and also an example of a potassium adinole. Associated with the adinole are spotted spilosites composed of gray glass, mullite and fine magnetite. The spots are composed of quartz and minor feldspar. The adinole is a banded hornfels consisting of abundant spherulitic K-feldspar, composite crystals consisting of a core of plagioclase and a margin of sanidine, oval spherulites of plagioclase laths, abundant fine magnetite, cordierite, sillimanite and quartz. Chemical analysis of these rocks indicates that alumina and potash were introduced into them, assuming that the parent rock was Cave Sandstone. There is a possibility that the adinole may have formed from an alumina-rich band in the sediments. However, the presence of relatively abundant amounts of dolerite-pegmatite in the basic rocks immediately below the sediments is of significance. The dolerite-pegmatites have developed along cooling joints which are perpendicular to the contact and it is conceivable that late-stage liquids from the dolerite-pegmatites migrated along these joints into Cave Sandstone, and that these fluids were K_2O - rich.

B. ASSIMILATION PHENOMENA.

The contaminated or acidified dolerites encountered below the xenoliths grade into the metasomatic granophyres with which they are always associated. These doleritic rocks may contain large irregular patches of felsic material but more commonly they are grey mottled rocks where the mottling represents fine interstitial felsic material. This felsic material constitutes between 11 and 28 per cent of these rocks and is composed mainly of quartz (very commonly paramorphic after tridymite) and K-feldspar. These two minerals are commonly intergrown and exhibit granophyric texture. The rest of the rock is composed of labradorite (An_{68-74}, compared with An_{74} in the associated gabbro) augite (of variable composition but richer than the gabbro in the $FeSiO_3$ end member), hypersthene and/or pigeonite, and olivine (the last mentioned mineral occurs only in the contaminated dolerite from the Grootkloof xenolith). Compared to the poikilophitic gabbros these contaminated rocks contain less plagioclase, slightly less or roughly equal amounts of pyroxene and much more felsic material. Chemical analyses reveal that relative to the associated dolerites the contaminated dolerites contain less alumina, iron, magnesium and calcium and more silica, potash and $(OH)^-$.

The association of the contaminated dolerites and metasomatic granophyres.

Mountain (1958) suggested that the chemical gap that existed between the metasomatic granophyres and the acidified dolerites at Coedmore Quarries could be closed if further data were available. Chemical data presented here indicate that there is no gap and that ultimately hybrid rocks are encountered whose affinity is uncertain.

The distinction between rocks of doleritic origin and those of sedimentary origin can be made on an arbitrary basis by determining the points of intersection of the regression lines in figs. 4 to 14. For the Bird's River Complex suite this line is at approximately 60,3% SiO_2. This point of intersection has been determined assuming the petrographic identification of these rocks has been correct.

The significant petrographic information which serves to differentiate the contaminated dolerite from the metasomatic granophyres is as follows:

(i) Large irregular patches of felsic material or a pale mottling effect (due to abundant, small interstitial patches of felsic material) are recognisable in the hand specimen of the contaminated dolerite.

(ii) The texture of the contaminated dolerites is ophitic while the metasomatic granophyres generally exhibit a poorly developed subophitic texture.

(iii) In the contaminated dolerites the dominant pyroxene is augite while in the metasomatic granophyres it is hypersthene.

(iv) Relict lapilli may be observed in the metasomatic granophyres.

C. FUSION OF THE SEDIMENTS.

Fusion of the sediments with the production of glass has occurred in isolated patches along the contacts with the sediments. Both pyroclastic rocks and Cave sandstone exhibit the effects of fusion with the production of glass.

The glass ridge (grid ref. G5 and H5) is an example of intense fusion of the pyrocalstic rocks. Here a continuous stream of dolerite magma moving between the edge of the intrusion and the Grootkloof xenolith produced a huge mass of fused glassy pyroclastic rocks, striking for 250 - 300 metres parallel to the margin of the intrusion.

The examples of fused pyroclastic rocks from the Cairn xenolith examined in thin section were found to be composed of quartz paramorphic after tridymite, sillimanite and K-feldspar and minor plagioclase. In a few cases pleochroic hypersthene was recorded. All these altered rocks may contain 50% or more fresh or altered glass.

The Cave Sandstone in the Cairn xenolith exhibits a number of examples of fusion. These examples include the pale grey and black spilosites associated with the adinole, which are composed of quartz paramorphic after tridymite, K-feldspar, sillimanite, cordierite and glass.

Buchites have been produced by fusion of the fine-grained sandstones and shales that occur in both xenoliths. These buchites consist of more than 70% pale grey or brown slightly devitrified glass. This glass contains abundant fine crystallites of cordierite, plagioclase-feldspar, mullite and ores.

D. RHEOMORPHIC PHENOMENA.

Rheomorphism of the sandstone, producing felsic veins in the dolerite, has occurred towards the North-western side of the Cairn xenolith.

Granophyric material with quartz paramorphic after tridymite is extremely well-developed in these veins, often occurring intergrown with sanidine. Clinopyroxene, partly altered to chlorite, plagioclase (An_{46}) and ore minerals occur in minor amounts. Vugs of relatively coarse-grained quartz occur in these rocks. In the field rheomorphic veins are straight and are orientated parallel to the cooling joints that occur in the dolerite below the outcrop of adinole. Dolerite-pegmatite has developed in the dolerite along the cooling joints below the adinole and also along the margins of the rheomorphic veins. The development of the dolerite-pegmatite along these planes is believed to have taken place after the development of the joints. The late-stage magma, rich in volatiles, concentrated along these joints and veins, producing the dolerite-pegmatite. At the same time volatile material escaped up these joints metasomatising the overlying sandstone (as in the case of the adinole) or the volatiles acted as a flux which fused the sediments (in the case of the rheomorphic veins). These fused sediments at the contact migrated along zones of least resistance ie. the cooling joints, to form the network of veins observed.

For rheomorphism to have takne place there must have been high temperatures. The volatiles escaping into the cooling joints from the dolerite and a high moisture content in the sediments provided the additional boost to produce the rheomorphic veins.

E. ORIGIN OF THE METASOMATIC ROCKS AND CONTAMINATED DOLERITES.

The examples of acidification and metasomatism described by Mountain (1958) and Walker and Poldervaart (1942) are associated with sharp contacts between the dolerite and the sediments and for this reason they suggest that the transference of elements involves a metasomatic process. Turner and Verhoogen (1960, p. 87) discuss the production of contaminated igneous rocks by assimilation where it is not possible to recognise any sharp boundary between the intrusive and country rocks, and where towards the intrusive contact the metamorphosed wall-rock becomes increasingly affected by metasomatism until it acquires a composition close to, or identical with that of the contaminated igneous rock with which it merges. For the magma to melt the sediments, the mineral components of the sediments must belong to the low-temperature end of a reaction series (cf. Bowen, 1928). The groundmass of the pyroclastic rocks consists of quartz and clay minerals. Quartz and

K-feldspar crystallise later from magmas and are commonly regarded as the low-temperature residues of basaltic magma. Clay minerals are also at the lower temperature end of the reaction series. It is therefore possible that basaltic magma is capable of melting granitic or allied xenoliths and the amount of granitic material that can be incorporated into the partial magma depends upon the amount of heat that can be supplied by crystallization of a thermally equivalent quantity of those phases with which the magma is saturated (Turner and Verhoogen p. 149-150).

It is possible that the greatest reaction occurred where the crystallizing Bird's River dolerite was adjacent to portions of the xenoliths that contained slightly more water than the surrounding sedimentary material, or adjacent to portions of the sediments which were only partly consolidated at the time of intrusion. This suggestion helps to explain the very local occurrence of the extreme reaction phenomena in these xenoliths. From the chemical data the emanations that produced the granophyres correspond to Walker and Poldervaart's (1949,p.680) iron-rich phase of emanations. These authors also suggest (p. 678) that the process of metasomatism began after most of the dolerite had solidified. This would be during the stage of maximum iron enrichment when the vapour pressure and the reactivity of the magmas would be at their greatest. From the chemistry of the Bird's River rocks it appears indeed that the bulk of the metasomatism and assimilation occurred during this period of iron enrichment.

It appears that partial melting of quartz and clay minerals in the sediments resulted in the incorporation of a certain amount of felsic material in the crystallizing magma adjacent to the xenoliths - producing a zone of hybridization. The basaltic lapilli which constitute up to 40% of the lapillistones do not appear to have been incorporated into the contaminated dolerites. It thus appears as though there was selective fusion of the sediments by the dolerite.

Wager et al. (1953, p. 272) show that the Coire Uaigneich granophyre falls outside the area of normal granite compositions, towards the SiO_2 corner of the normative Quartz-Albite-Orthoclase triangular diagram and they suggest that the granophyre formed by the total fusion of arkoses or gneisses rich in SiO_2. These authors (p. 274) suggest that rocks such as this granophyre whose composition falls outside the usual "eutectic" composition of granites are unlikely to be late residues from a crystal fractionation process. Butler (1961, p. 883) notes that five out of seven of Walker and Poldervaart's (1949) analyses of metasomatic granophyres fall on the cotectic boundary line close to the position of the ternary minimum and he also concludes that partial melting and metasomatism have occurred. Ackerman and Walker (1960), Wyllie (1961), Butler (1961) and Eales (1974) have all shown that the composition of the glasses derived by partial fusion of quartz-feldspathic sediments are nearer the trough in the Quartz-Albite-Orthoclase diagram than the parent rock. Eales (1974) examined the effects of partial fusion in the Bird's River Complex. The rocks he examined were a partly vitrified siliceous volcanic breccia, a partly vitrified Cave Sandstone containing mullite and a partly fused dolerite-pegmatite clast in a volcanic breccia. Both the derivative glasses from the sedimentary rocks tended towards the ternary minimum of the Qtz-Ab-Or diagram (Eales, 1974, p. 48). This diagram was not suitable in the case of the dolerite-pegmatite because of the anorthitic composition of the dolerite-pegmatite.

An attempt is made here to relate the granophyes and contaminated dolerites of the Cairn Xenolith to the five-component system SiO_2-$NaAlSi_3O_8$-$KAlSi_3O_8$-$CaAl_2Si_2O_8$-H_2O at a constant H_2O pressure of 2000 bars. Von Platen (1965) found that rocks of various compositions containg plagioclase, alkali feldspar and quartz give rise to a "minimum-temperature melt" of practically the same composition if the various bulk rock compositions have the same Ab/An ratio - ie. the Ab/An ratio of any rock that contains plagioclase, alkali-feldspar and quartz, determines the composition of the minimum temperature melt within rather narrow limits. Thus using the diagram of Von Platen, systems containing the An component may be compared directly with the anorthite-free system at the same pressure. The points A - D fig. 23b, represent the minimum melt composition being formed at about 10°C above the actual temperature of commencement of melting at a pressure of 2000 bars. Point E in fig. 23b is the ternary minimum from the anorthite free Qtz-Ab-Or-H_2O system of Tuttle and Bowen (1958). The amount of An component in the melt increases with decreasing Ab/An ratio of the original rock. Winkler (1967, p. 262) notes that even if Ab/An is 1,8 the amount of An in the melt is no more than 5%. Although

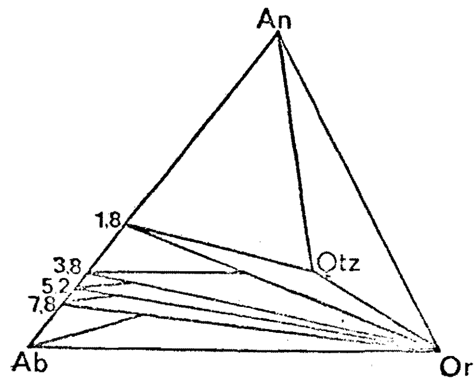


Fig. 23a. Compositional planes within the tetrahedron $NaAlSi_3O_8$ - $KAlSi_3O_8$ - $CaAl_2Si_2O_8$ - SiO_2. The numbers represent the albite/anorthite ratios (in wt.%) for each plane in the tetrahedron. (After von Platen, 1965.)

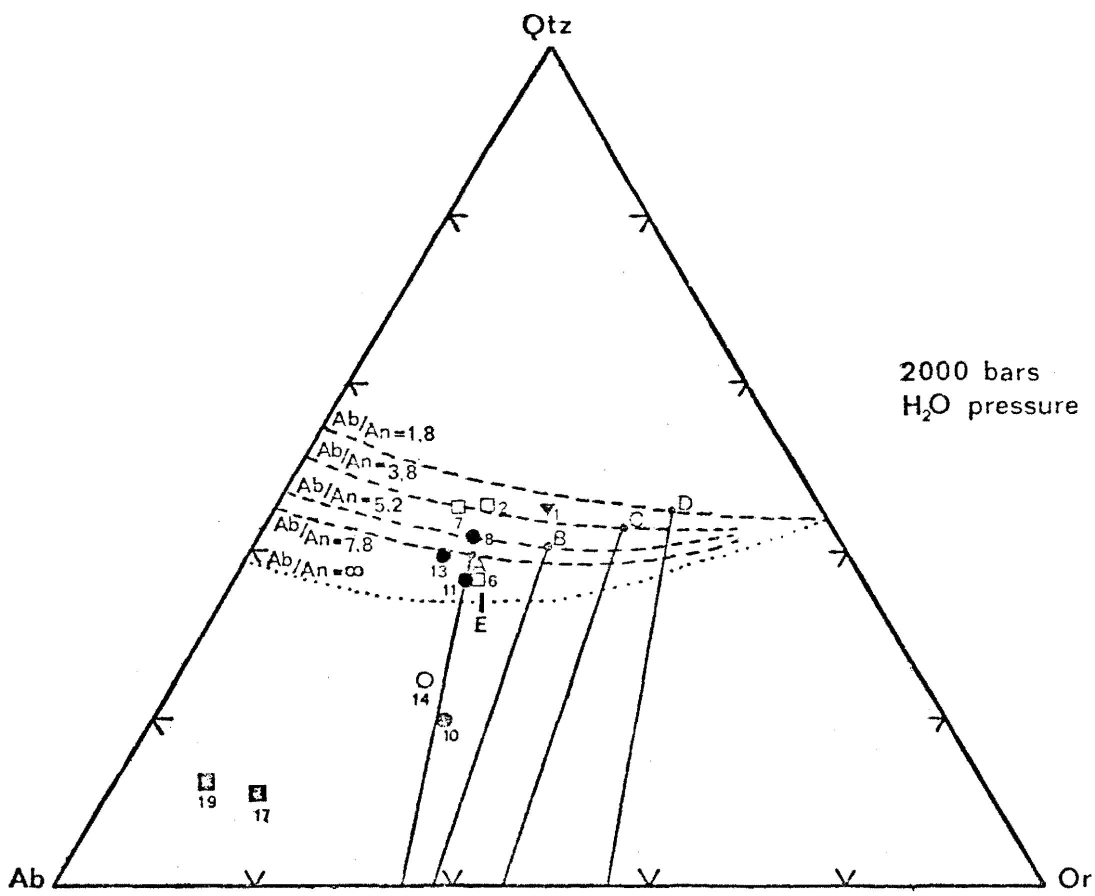


Fig. 23b. A selection of Bird's River dolerites, contaminated dolerites, metasomatic granophyres and pyroclastic rocks plotted on the normative Qtz - Ab - Or ternary diagram. The minimum-temperature melts and boundary curves are from the compositional planes of Fig. 24a. (After von Platen, 1965, and also Winkler, 1967.)

Von Platen's data applies to considerably higher pressures than encountered in the Bird's River Complex it does indicate that fusion of the pyroclastic rock (Ab/An = 4,4) could produce a minimum melt containing Quartz + K-feldspar. A portion of this melt could be expected to contaminate the dolerite with felsic material. The metamorphosed pyroclastics and metasomatic granophyres (having Ab/An ratios of 0,9 to 1,3) tend towards the Ab-An join of the tetrahedron as the degree of metasomatism and metamorphism increases.

The question arises whether the increase in the mafic and decrease in the felsic constituents in the metamorphic rocks relative to sediments is partly due to partial fusion and hence the selective extraction of certain constituents from the sediments by the dolerite. It is for this reason that Smith (1969, p. 45 - 6), suggests that caution must be exercised when interpreting chemical changes in rocks that have partly fused. The pyroclastic rocks contain quartz, clay minerals and K-feldspar which could produce a melt with a composition close to the ternary minimum and would thus enrich the rock in the components less likely to melt, in this case the basaltic lapilli. This would explain the anomalous behaviour of SiO_2 and Al_2O_3 in the sequence of rocks as large scale metasomatic migration of these two elements is unlikely because of their lack of geochemical mobility (cf. Mehnert, 1969, p. 283).

Thus three possible origins of the granophyric rocks and contaminated dolerites can be suggested. These are;

(1) They are late stage differentiates of the dolerite,

(2) The granophyres are the enriched residual rocks produced by removal of a minimum melt and the contaminated dolerites were produced by addition of this minimum melt,

(3) The granophyres were produced by metasomatism.

The first suggestion is discounted for the following reasons;

(a) The rocks can be traced in the field from pyroclastic rock into granophyre - with the proportion of clasts steadily diminishing until only widely scattered relict clasts are seen in the granophyre.

(b) The granophyres contain plagioclase slightly richer in Ca than the dolerites.

(c) The presence of sillimanite and its occurrence with tridymite indicates a high-temperature metamorphic origin for the granophyres.

(d) Chemically the contaminated dolerites and the metasomatic granophyres are unrelated to the gabbro-ferrogabbro-tholeiite series which is encountered in the Bird's River Complex and described by Eales and Booth (1974). The Mafic Indices of the contaminated dolerites, metasomatic granophyres and associated gabbros and dolerites have been plotted against the percentage SiO_2 in fig. 24 and compared to the gabbro-ferrogabbro-tholeiite curve obtained by Eales (1974). This graph confirms that the dolerites associated with the altered rocks are closely related to Eales and Booth's series in that they fall into the gabbro field. The contaminated dolerites and granophyres plot nowhere near this curve, but as would be expected from rocks such as these, they plot in a haphazard manner to the right of this curve

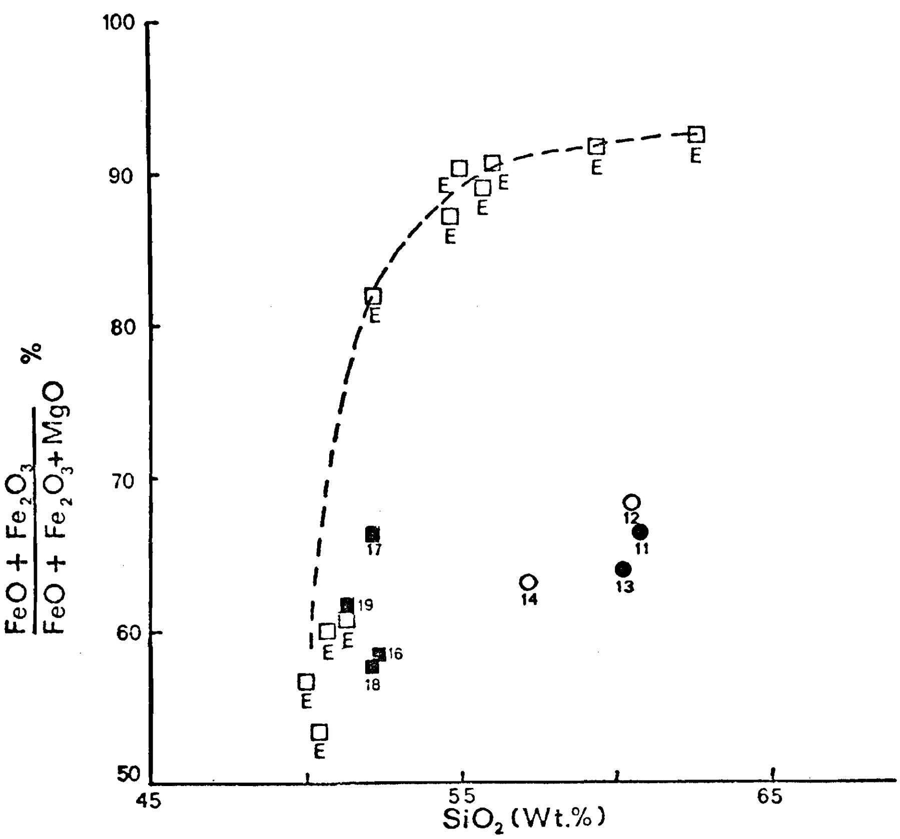


Fig. 24. Plot of SiO_2 (wt.%) versus Mafic Index for Bird's River rocks. The dashed line represents the gabbro - ferrogabbro - tholeiite - series as determined by Eales and Booth (1974). The numbers represent the analyses in Table XIV. The letter "E" represents the plots as determined by Eales and Booth (1974. Fig. 7).

■ = Dolerite

○ = Contaminated dolerite

● = Metasomatic granophyre

indicating that they are completely unrelated to the fractionation of the tholeiites.

From the evidence presented here it is believed that the dolerite was highly reactive below the xenoliths and a combination of metasomatism and fusion produced the metasomatic granophyres and associated rocks. The reasons for this suggestion are as follows:

(a) Sediments that have undergone pure fusion are encountered at a number of places along the contact with the dolerite. Eales (1974, p. 50) suggests that the temperature and pressure limits in the partly devitrified sediments were between 990 and 1175°C, and 70 475 kg./cm^2 respectively. The depth of emplacement of the intrusion was estimated to be between 250 and 1600 metres. On this basis the P-T conditions were of the right order to produce partial melting of the pyroclastic rocks.

(b) Rheomorphic veins occur in the north-western corner of the Cairn xenolith. These veins indicate that the sediments underwent enough fusion so as to have been capable of flow. Mountain (1944 and 1960) and Walker and Poldervaart (1949, p. 683) believed that transfusion played a significant part in the development of the products of rheomorphism. Thus the presence of these veins suggests that fusion coupled with metasomatism may have occurred in the pyroclastic rocks.

(c) Data presented in terms of the Qtz-Or-Ab-An-H_2O diagram indicate that partial fusion of the sediments could have occurred as the pyroclastic rocks contain an assemblage of minerals that would result in the production of a minimum-temperature melt of felsic composition. Petrographic examination of the contact dolerites revealed that micro-xenoliths of country rock have been incorporated in the dolerite along most of the contact with the Cairn and Grootkloof Xenoliths. However, this feature is not the same as that encountered in the contaminated or acidified dolerites. These latter rocks are contact with the sediments but no sharp contact exists and no contact dolerite is encountered in the vicinity of the contaminated dolerites and the metasomatic granophyres. Complete sandstone fragments are encountered in the contact dolerites while the felsic material encountered in the acidified dolerites is completely recrystallised quartz and K-feldspar which is material that would correspond to a low temperature melt.

(d) Metasomatism is believed to have played a significant role in the alteration of the sediments as the increase in iron, magnesia, calcium and also alumina in sediments that retain the bulk of their original texture is too large to be explained just by the removal of a partial melt. Examination of figs. 4, 5, 7 and 13 show that there is a significant increase between, respectively, the Al^{3+}, $Fe^{2+} + Fe^{3+}$, Mg^{2+} and Ca^{2+} contents of analyses 1 and 2. Analysis 1 represents a sample of unmetamorphosed pyroclastic rock and analysis 2 represents a sample of slightly metamorphosed pyroclastic where the quartz has not inverted to tridymite and has only recrystallised. This sample was collected too far away from the dolerite for significant fusion to have taken place, but within reach of the metasomatising fluids.

The calculation of a metasomatic model using the composition-volume equation indicates that metasomatism had contributed to the production of these granophyres.

APPENDIX

LABORATORY PROCEDURES

A) THIN SECTION EXAMINATION

About 150 thin sections were prepared from the samples that were collected in the field. These were examined under the petrological microscope and described as fully as possible. In very many cases alteration and the fine grain-size of the constituent minerals limited these descriptions.

Plagioclase compositions were determined using the Rittman zonal method on a four-axis universal stage as described by Chudoba and Kennedy (1933). The charts used in determining the composition of the plagioclases were from Deer, Howie and Zussman (1963, vol. 4: fig. 55 p. 138) and Chudoba and Kennedy (1933, fig. 43, p. 48). Determination of the 2V of plagioclase and potassium feldspar was done by plotting on a Wulff net. The refractive index of the hemispheres used was 1,554, a value which is very close to the refractive indices of the plagioclases present in the bulk of the rocks examined and hence no correction factor was necessary.

The four-axis universal stage was also employed to perform 2V determinations on the pyroxenes. In many cases, especially in the metasomatic rocks, the values obtained are not highly accurate as the pyroxenes are often turbid.

Refractive index determinations were carried out using immersion liquids standardized on a Zeiss-Opton Abbe Refractometer. Originally a Jelly Refractometer was used for standardization of the liquids but this had no temperature control. The Abbe Refractometer had a build-in thermometer allowing a check to be kept on temperature fluctuation. The most satisfactory arrangement was to work in a cool room not affected much by changes in temperature during the day and to carry out the determinations over the shortest period of time possible.

In the pyroxenes the intermediate refractive index value (ie. Ny) was determined. This value and the 2V value were used to determine the composition of the pyroxene according to the method of Hess (1949, Plate 1). Refractive index determinations were also attempted on the glasses in a dolerite and on potassium feldspars where the grain size was sufficiently large.

Modal analyses were determined on 21 rocks using a Swift Point Counter. In the case of some of the inhomogeneous pyroclastic rocks over four thousand points were counted. The values obtained for the amounts of the various constituents remained essentially constant between thin sections of the same rock.

B) <u>POLISHED SECTION EXAMINATION</u>

Selected samples were examined briefly under the ore microscope for the properties of their ore minerals. The mineralogical and textual features revealed were compared with descriptions in Ramdohr (1969).

C) MICROPROBE EXAMINATION OF SELECTED SAMPLES

Dr R.V. Danchin and Mr B.N. Jackson of Anglo American Research Laboratories very kindly assisted the author in this work. The basis of the techniques employed has been described by Wittkop (1971) and Long (see Zussman, 1967, p. 215 - 260).

The distribution of Al, K, Fe and Si in the "tridymite granophyre" present in a sample of dolerite-pegmatite was examined and photographed (see Plate IX). Figures 1 and 2 of this plate are back-scattered electron images of a selected area while figures 3 to 6 were obtained by monitoring the characteristic X-Rays of the respective elements. All six photographs in Plate IX are the images produced by sweeping the electron beam over an area of the sample and monitoring the data on a series of oscilloscope displays.

The distribution of Ca, Na and K in the composite feldspar grains of the adinole was determined by counting procedures at certain points along a traverse across the grain. As no standards were available this determination was carried out on a semi-quantitative basis.

Short investigations on a similar basis were carried out in order to investigate the distribution of Fe in the glass lapilli of the pyroclastics and cordierite in contact buchites were carried out. Due to lack of allocated time no semi-quantitative determinations were carried out.

D) X-RAY DIFFRACTION

Phillips equipment was used to produce X-Ray diffractograms. Rock samples to be investigated were ground to a very fine powder in a rotary mortar and mounted in special perspex holders. The X-Rays were produced using a Cobalt tube and an iron filter at an applied voltage of 40 kv. and current of 20 mA. The scanning speed of the goniometer was 4° per minute and the d-spacings were read directly off the diffractogram by making use of a perspex scale designed for this purpose.

Determination and verification of the minerals present in the rock were carried out by comparison with the standard ASTM cards, (sets 1 to 22) of the respective minerals.

E) METHODS OF CHEMICAL ANALYSIS

1) Introduction

As the rocks studied were mostly fine grained and altered, and also as a metasomatic reaction is thought to have occurred, it was decided to perform chemical analysis on selected samples. The methods selected were a combination of those laid down by J. Maxwell (1968) and H. Bennett and W.G. Hawley (1965). The methods of these authors proved to be rapid, relatively cheap and reasonably easy to carry out.

2) The oxides determined

The oxides determined were SiO_2, TiO_2, Al_2O_3, Fe_2O_3, FeO, MnO, MgO, CaO, Na_2O, K_2O, P_2O_5, H_2O+ and H_2O-. CO_2 was not determined as it is present in the sediments in minor quantities and has no bearing on the problem to be studied.

3. Selection of rock samples for analyses

Twenty-two rock samples were selected for analysis. Twenty one of these were analysed by the author and one was analysed by T.H. Broderick and S.H. Finnemore as part of their honours course. The samples were selected on the basis of their freshness, their relationship to one another in the field and their petrography. The lapillistone analysed was the freshest available. The sample of dolerite-pegmatite also exhibited slight oxidation.

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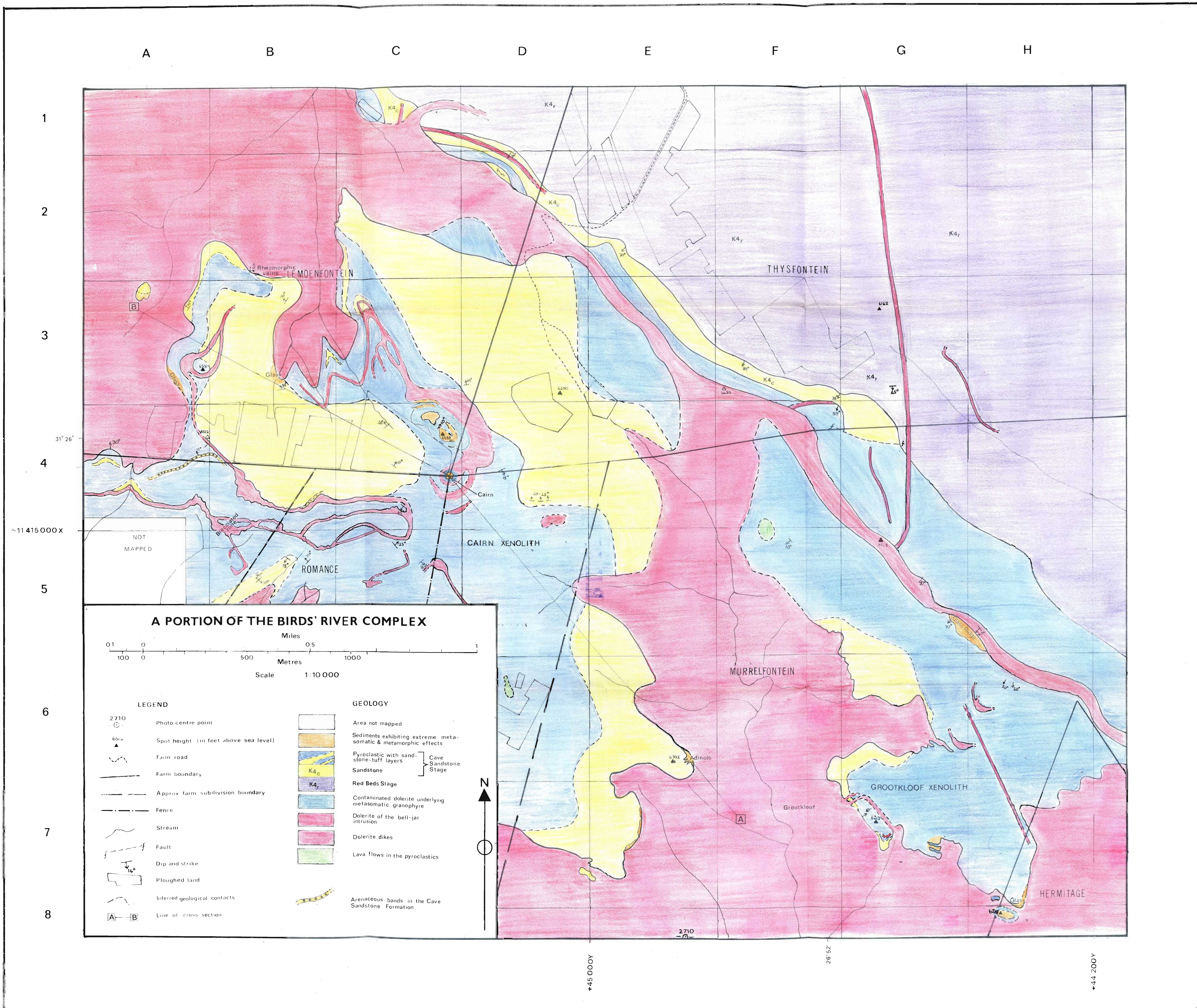
A PORTION OF THE BIRDS' RIVER COMPLEX
Miles
0.1 0 0.5 1
100 0 500 1000
Metres
Scale 1:10 000
LEGEND
2710 Photo centre point
Spot height (in feet above sea level)
Farm road
Farm boundary
Approx farm subdivision boundary
Fence
Stream
Fault
Dip and strike
Ploughed land
Inferred geological contacts
Line of cross section
GEOLOGY
Area not mapped
Sediments exhibiting extreme metasomatic & metamorphic effects
Pyroclastic with sandstone-tuff layers
Sandstone
Cave Sandstone Stage
K4c
K4r
Red Beds Stage
Contaminated dolerite underlying metasomatic granophyre
Dolerite of the bell-jar intrusion
Dolerite dikes
Lava flows in the pyroclastics
Arenaceous bands in the Cave Sandstone Formation
N
A B C D E F G H
1 2 3 4 5 6 7 8
LEMOENFONTEIN
Rheomorphic veins
THYSFONTEIN
CAIRN XENOLITH
Cairn
ROMANCE
NOT MAPPED
MURRELFONTEIN
GROOTKLOOF XENOLITH
Grootkloof
Adinole
HERMITAGE
Glass
31° 26'
-11 415 000 X
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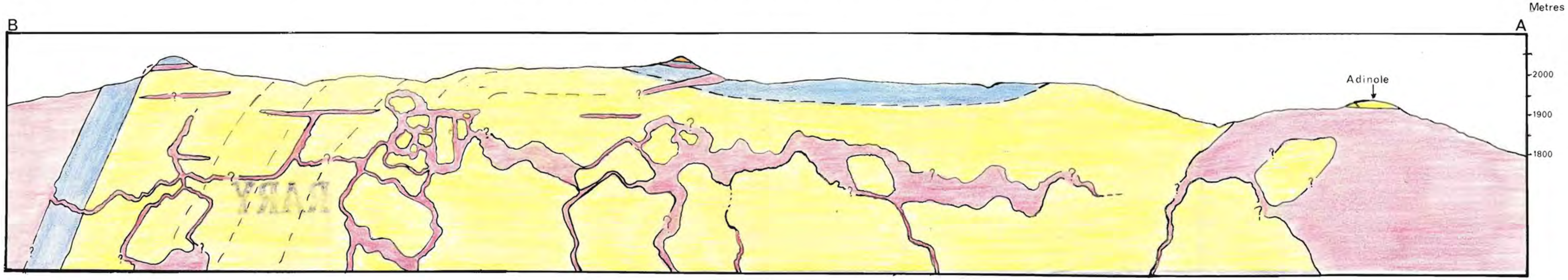
CROSS-SECTION THROUGH THE CAIRN XENOLITH



SCALE : Horizontal – } 1 cm. = 100 metres.
Vertical –

GEOLOGY

Metasomatic granophyre
Pyroclastic rock
Sandstone
Cave Sandstone Stage

Contaminated dolerite
Dolerite of the bell-jar intrusion