THE BIRDS' RIVER
DOLERITE COMPLEX.

by

P.W.K. Booth. B.Sc.(Hons.).

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ABSTRACT.

A plug-like intrusion of Karroo dolerite, near Dordrecht in the Eastern Cape of the Republic, is described. Field mapping with the aid of aerial photographs has revealed that the contact of the intrusion, for the most part, dips very steeply outwards. In the south-eastern and eastern areas, however, sheet- or sill-like forms appear to be given off from the main intrusion.

In plan view the intrusion is roughly oval shaped, its longer axis being aligned in a north-westerly direction. Its surface area measures approximately 60 square kilometres (24 square miles).

A large number of xenoliths composed exclusively of Stormberg sediments, pyroclastic rocks and minor lavas, are to be found cropping out within the dolerite intrusion. These xenoliths, many of which occur in positions far above or below their normal stratigraphic elevation, are extremely variable in size - the largest having an area of approximately 15 square kilometres (6 square miles). The xenoliths represent fragments of the original "roof" of sediments and pyroclastics which have collapsed into and been engulfed by the dolerite magma. This type of dolerite intrusion is known as a "bell-jar" intrusion.

A superficial classification of the dolerites, based chiefly on textural and certain mineralogical features, is presented. In the area surrounding the main intrusion are a number of dolerite dikes and sheets. The youngest phase of igneous activity is represented by the Dragon's Back dike, which cuts across the complex in a north-westerly direction.

Several veining phenomena, as well as an interesting variety of metamorphic and metasomatic rocks, are associated with the main dolerite intrusion.

Six diatremes are situated in the vicinity of the intrusion. Pyroclastic rocks are represented by a variety of types, and are to be found outside the area of the intrusion, and as xenoliths within it.

A tentative interpretation of the mechanism of formation of the intrusion, which appears to be related to volcanic activity and cauldron subsidence, is presented.

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Professor H.V. Eales, Head of the Department of Geology at Rhodes University, acted as supervisor in this research project. His consistent encouragement throughout my studies and willingness to assist, both in the field and in the laboratory, acted as a stimulus during a very worthwhile year of study. Professor Eales allowed me to make use of unpublished chemical analyses of the bell-jar intrusion, as well as aerial photographs and maps he had obtained prior to my commencing work in the Birds' River area. I wish also to thank him for suggesting improvements and offering constructive criticism to the manuscript.

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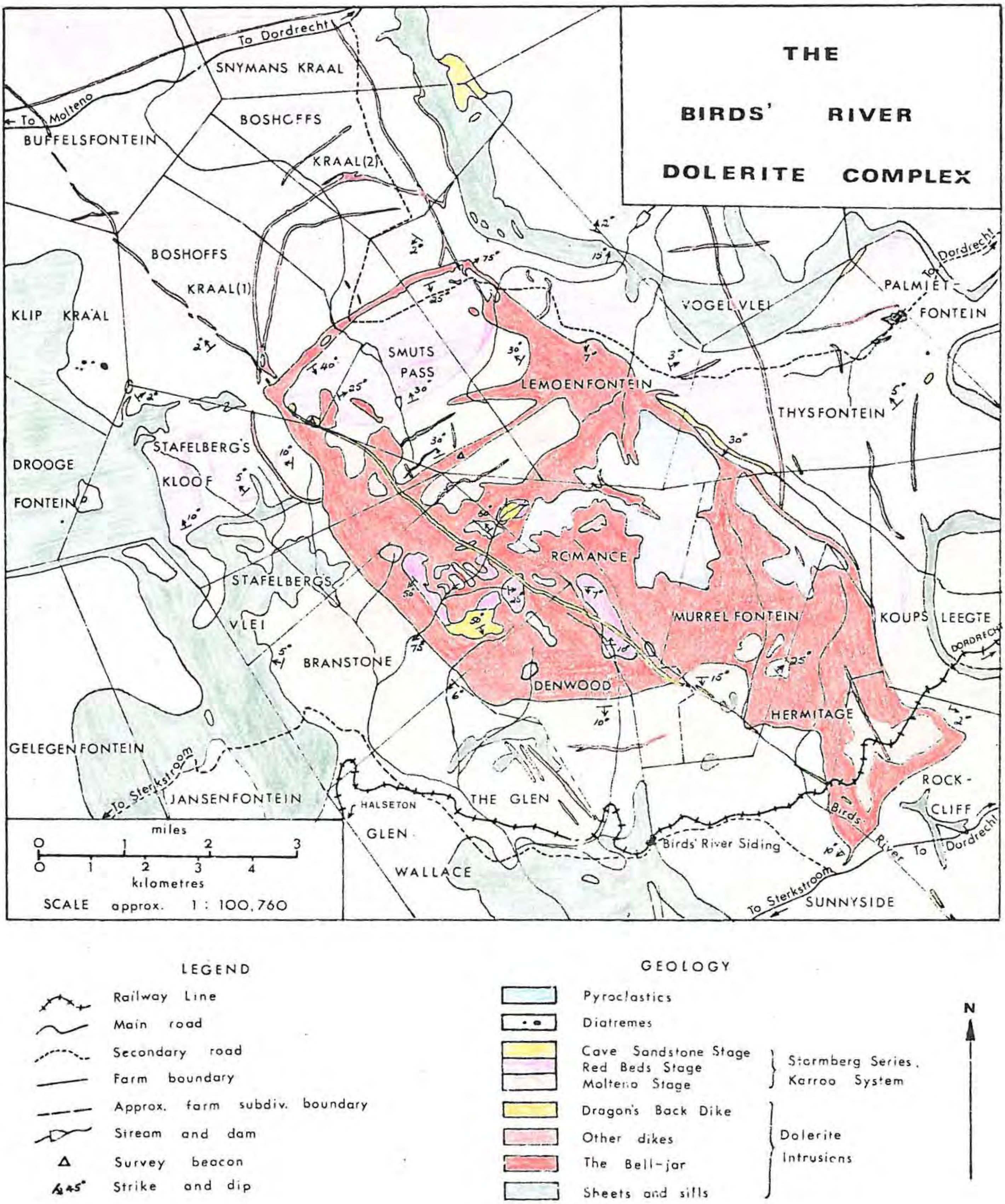

Fig. 1: Map of the Birds' River Dolerite Complex.

CHAPTER ONE

INTRODUCTION

General Statement:

In this chapter an outline is given on previous work that has been done in the Birds' River area. Other relevant work is also briefly mentioned, with particular reference to an intrusion in East Griqualand, which appears to be very similar to the Birds' River intrusion, (i.e. a bell-jar intrusion).

The writer outlines the topics covered in the present investigation in the Birds' River area, and describes the techniques adopted in the field and in the laboratory. This chapter is therefore subdivided as follows :-

A. Previous and Other Relevant Work.
B. Scope of Present Investigation.
C. Field and Laboratory Procedure.

A. PREVIOUS AND OTHER RELEVANT WORK.

The term "bell-jar" was first used by Du Toit in 1920 to describe the shape of three unusual dolerite intrusions he had mapped in the Eastern Cape and East Griqualand. Du Toit envisaged the essential feature of these intrusions to be the steep outward dips of the contacts, with the "roof" of the original sediments and lavas having collapsed and sunk within the dolerite magma. The xenolithic fragments of the original "roof" are today exposed within this type of intrusion through extensive erosion by streams which have carved deeply into the complexes. A reconstruction of the original shape of the intrusion is given in Fig. 3. The very apt term "bell-jar" intrusion has been used many times since in geological literature.

The first account of the bell-jar intrusion north of Birds' River Siding was given by Du Toit in 1905 (Du Toit, 1905, pp.130-132). He described portion of the intrusion occurring on Stafelberg's Vlei, and referred to it as, "A most curious complex of igneous and sedimentary rocks". The noteworthy features of this intrusion, as seen by Du Toit, were that the dip of the dolerite was steep on the south-western side with the sedimentary rocks on the outside of the intrusion being almost horizontal, while those within the intrusion were tilted to steep angles, in many cases.

Du Toit pointed out that steeply dipping sediments of all three Stages of the Stormberg Series occur on Stafelberg's Vlei, surrounded by dolerite. These sediments appear to have been dislocated from their original stratigraphic position, invaded by dolerite, and bent into the shape of a dome (see Fig. 2). Metamorphism in this particular area has been intense, Du Toit having recorded the presence of a cordierite glass.

The next reference to the dolerite complex in this area was made in 1911 (Du Toit, 1911, pp.133-134). Du Toit described the presence of the largest foundered roof fragment in the northern portion of the complex, and commented on its synclinal shape. He drew attention to a thick and extensive bed of volcanic ash to be found on Wagenpad's Kloof (now renamed Romance), and noted that it had been indurated at both upper and lower contacts.

Du Toit also mentioned that a dolerite intrusion similar to that occurring north of Birds' River Siding, but smaller in size, is to be found on Droogefontein, a few miles to the west.

The general features of this particular type of intrusion were summed up by Du Toit in 1920 (Du Toit, 1920, pp.10-11). He described it as a "bell-jar" shaped intrusion, where "Magma welled up along a fracture that was oval in plan, and thus came to isolate a vertical, and presumably cylindrical mass of sediments from the surrounding horizontal strata. It then spread out at the top, thus severing the enclosed column from the formation above; the nature of the base is purely conjectural" (1920, p.10).

The "roof" of sediments then collapsed into the invading

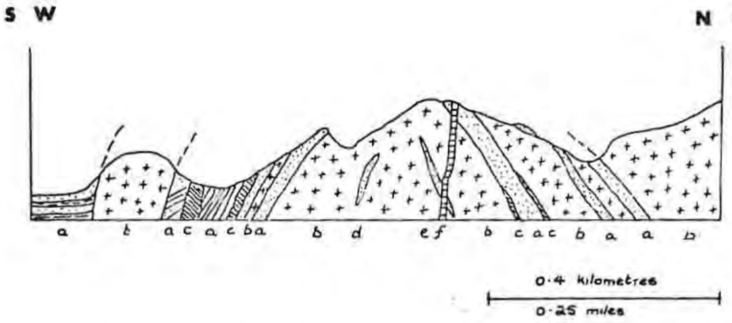

Fig. 2: Section across complex on Stafelberg's Vlei (after Du Toit, 1905). (The larger portion of the original farm Stafelberg's Vlei is now called Branstone - across which the above cross-section was drawn.)

- a. Sandstones and shales.
- b. Karroo dolerite.
- c. Intrusions earlier than b.
- d. Hornstone.
- e. Cordierite glass.
- f. Intrusions later than b.

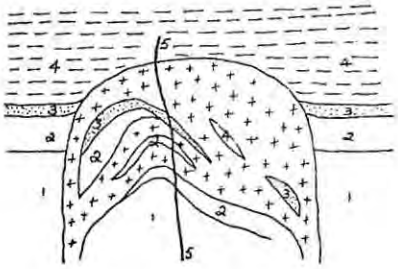

Fig. 3: Diagrammatic Cross-section through the Stafelberg's Vlei - Lemoenfontein "Bell-jar" Intrusion (after Du Toit, 1920). (This cross-section corresponds approximately to a west to east section from Branstone to Lemoenfontein.)

1. Molteno Beds.
2. Red Beds
3. Cave Sandstone.
4. Volcanic Ash and Basalt.
5. Younger dolerite dike.

magma which fractured and bent them, so that some of the xenoliths acquired a dome shape, while other xenoliths assumed random positions upon cooling and solidification of the magma (see Fig. 3).

Du Toit described the bell-jar intrusion north of Birds' River Siding as being elliptical in shape while the smaller bell-jar intrusion on Droogefontein is circular.

In the Mount Currie district of East Griqualand, Du Toit has described an intrusion which appears to be similar to the Birds' River bell-jar intrusion (Du Toit, 1929, pp.23-24). Much later, Poldervaart gave a detailed account of the intrusion (Mount Arthur) with emphasis on the petrology of the dolerites (Poldervaart, 1946, pp.83-110).

The Mount Arthur intrusion is pear shaped, in plan, and measures 11 kilometres by 6.4 kilometres (7 miles by 4 miles). This is approximately the same area as the larger intrusion in the Birds' River area.

Both the Birds' River and Mount Arthur intrusions contain large blocks of sediments within plug-like masses of dolerite, some of which have been displaced considerable distances from their original stratigraphic position. Both intrusions have contacts which dip steeply outwards, for the most part, with evidence of an inwardly dipping contact in a few places.

In both areas initial stages of volcanic activity are represented by diatremes which are situated in the vicinity of the bell-jar intrusions.

The bell-jar intrusions have been intruded into the three sedimentary Stages of the Stormberg Series. In the Mount Arthur area erosion has exposed the Upper Beaufort Beds in the southern portion of the area, thus revealing their contact with the bell-jar intrusion.

In the Birds' River area a large volume of pyroclastic material is to be found, some of it having been metasomatized by the dolerite intrusions. These rock types were apparently not encountered in the Mount Arthur area.

Poldervaart recognised three phases of igneous activity in the Mount Arthur complex. A marginal tholeiite was initially intruded along an outer ring dike. This was followed by cauldron subsidence within the ring dike, and the subsequent intrusion of an olivine dolerite magma. Interaction of this olivine dolerite magma with resurgent volatiles from the enclosed sedimentary xenoliths produced a tholeiitic rock type surrounding the xenoliths. The final phase of magmatic activity is represented by a few narrow dikes and thin sheets.

Walker and Poldervaart refer to the three abovementioned bell-jar intrusions in their paper on the Karroo dolerites of the Republic of South Africa (Walker and Poldervaart, 1949, p.610). They sum up, in broad outline, the habit of these intrusions. These authors have classified the Karroo dolerites into four main types, with eleven variants. The classification is based on a petrographical study of dolerite samples taken over most of the area of dolerite occurrences in the Republic of South Africa. One of the main types, the Kokstad Type, occurs particularly abundantly in dolerite intrusions in the Transkei and Eastern Cape. The dolerites of the bell-jar intrusions also appear to be largely of the Kokstad Type.

Frankel makes brief reference to the structure of bell-jar intrusions in the chapter on "Intrusive Igneous Rocks" of the Poldervaart treatise on rocks of basaltic composition (Poldervaart and Hess, 1967, p.79).

B. SCOPE OF PRESENT INVESTIGATION.

The larger bell-jar intrusion, north of Birds' River Siding was chosen as the topic for the present investigation. The writer was fortunate in having Professor H.V. Eales of Rhodes University introduce him to the area and point out some of the structural complexities of the intrusion, as well as suggesting methods of field description to be adopted by the writer. Many of Professor Eales' original ideas have been incorporated in this thesis.

The main aims of the present investigation have been :-

(i) to produce a map of the Birds' River bell jar intrusion, and the area immediately surrounding it.

(ii) to describe the rock types in this area, largely as seen in the field.

(iii) to classify the dolerites of the area into specific types.

(iv) to present a structural interpretation of the mechanism of formation of the bell-jar intrusion, based on field evidence.

The present investigation was therefore approached largely as a field project. Certain aspects of the complex have as a result been only superficially investigated, and these are still open for comprehensive investigations. These latter aspects, which would merit more detailed study, include :-

(i) A study of the sediments, especially as regards the definition of the contacts between the various Stages of the Stormberg Series. The writer believes that a study of heavy minerals in the sediments might prove fruitful for correlation purposes. This study would prove to be one of considerable magnitude and was not attempted by the writer, as it falls beyond the scope of the present investigation.

(ii) The pyroclastics, which need to be studied in greater detail, in view of their striking variations and relationship towards other sediments. The writer has attempted to subdivide the pyroclastics into various types, as seen in the field, but he has not indicated the boundaries between these types on any of the maps.

(iii) A more thorough investigation of the petrology of the dolerites of the bell-jar intrusion. The writer has based the present classification of these dolerites into specific types on a somewhat unsystematic collection of rocks over most of the area of the bell-jar intrusion, from which thin sections were subsequently made and examined.

(iv) Further investigations into the petrology of the diatremes.

(v) The changes produced in metasomatic rocks and certain metamorphic types. These are at present being investigated by Mr. A.K. Kenyon, of this University, and will form the subject-matter of his M.Sc. thesis. The writer has therefore given no more than a general outline and summary of the metasomatic and certain metamorphic effects associated with the complex, and wishes to thank Mr. Kenyon for his co-operation as regards the area he has mapped and is at present describing.

C. FIELD AND LABORATORY PROCEDURE.

A preliminary aerial photograph study of the area was carried out with the aid of a Toko mirror stereoscope, with magnifying accessories, and photographs of approximately 1:30,000 scale. Even though three-dimensional images appear greatly exaggerated with respect to height, use of this instrument proved of great value as a guide to contacts between intrusive and sedimentary rocks, especially with respect to certain structural features of the bell-jar intrusion.

A period of three months, at the beginning of 1970, was spent in the field, with three visits being made to the Birds' River area during the remainder of the year. The latter, shorter visits were made mainly for the purpose of elaborating on mapping data, or, in some cases, to collect further samples.

1. Field Procedure.

Field procedure entailed the following :-

(a) Geological Mapping on Aerial Photographs.

(b) Plane-tabling.

(c) Height Recording, with the Aid of an Aneroid Barometer.

(a) Geological Mapping on Aerial Photographs.

Geological mapping was carried out with the use of aerial photographs and transparent overlays. Aerial photographs of approximately 1:10,000 scale were obtained from the Trigonometrical Survey. (These photographs are approximately three times the size of the standard 22.8 cm. by 22.8 cm. (9 inches by 9 inches) contact prints with a scale of approximately 1:30,000.)

Each photograph was cut into four equal portions measuring approximately 35 cm. by 35 cm. (14 inches by 14 inches). This size was found to be more practical for use in the field. Photograph numbers were noted on their corresponding overlays, and reference marks were made on each photograph and its respective overlay. In this way the overlays could always be correctly positioned before data was plotted on to them.

The method of using overlays was found to be satisfactory, as incorrectly plotted data could be more easily rectified on the overlays, than if mapped directly on to the aerial photographs.

Where contacts between intrusive rocks and sediment were exposed in the field, dips were measured with a clinometer, as were strike and dip directions of sediments. The geological boundaries and other relevant data were then plotted on to the correctly positioned overlays.

Rock samples were collected during the field mapping stages. Each sample position was marked on the overlay, and, by pricking a hole through the appropriate position on the aerial photograph with a pin, that same sample position was recorded on the back of the photograph. Descriptions of rock types and other data were noted in a field note-book.

(b) Plane-tabling.

A limited area of the northern corner of the bell-jar intrusion, on the farm Lemoenfontein, was mapped by plane-table on a large scale necessitated by certain structural complexities in this area. The moderate relief at this particular locality proved suitable for plane-table work. The area surveyed measured approximately 1,048,000 square metres (11,500,000 square feet) and is represented by Map No. 3.

A base line 28.85 metres (938 feet 5½ inches) in length was laid out on a horizontal portion of ground and accurately measured with a surveyor's chain. The magnetic bearing of this base line was measured from each end with a prismatic compass.

A suitable number of resected positions was established on either side of the base line, within the area to be surveyed, and marked with temporary beacons. Their positions were such that they were visible from both ends of the base line.

The plane-table mapping around each secondary station was carried out on a scale of 1:2,000, with the aid of a Wild Heerbrugg telescopic alidade, with stadia wires and scales for elevation and depression reading to 46 minutes of arc, and a surveyor's staff. The assistance of the third year Geology students, who served as staff bearers, is acknowledged.

Details were mapped in by plotting along sight lines the distances yielded by staff readings, taken at suitably spaced intervals along the dolerite-sediment contacts, and by joining up the corresponding plotted points on the plane-table.

The magnetic bearing of strike and amount of dip of the sediments, and of fault zones, were measured with a clinometer and recorded. The remaining features appearing on the map, e.g. "dongas", roads, and house, were plotted on the plane-table by pacing off distances from known positions on the ground, to the respective sites.

(c) Height Recording, with the Aid of an Aneroid Barometer.

A Paulin precision altimeter (HF Type Palbo, which reads from -1,000 feet to +10,500 feet) was used to obtain spot heights at various positions within the area, so that topographical profiles, and corresponding geological cross-sections could be drawn. Readings are noted from the barometer once the instrument has been levelled, and its recording needle correctly positioned. Errors of parallax are reduced to a minimum through the aid of a small mirror positioned below the recording needle, so that readings can be accurately read from the instrument. The barometer used by the writer, however, only recorded differences in elevation greater than 2 feet (0.6 metres).

The position of each barometer recording was marked on the appropriate aerial photograph. Survey beacons of known heights were used as base points. The barometer height recordings were checked at the beacon positions, as frequently as was conveniently possible during the period of taking barometric heights, in order to determine the variation of atmospheric pressure during the day.

A graph of time against height variation was plotted, and the readings taken during that particular day were corrected accordingly. These corrected readings were used for plotting the topographical profiles for the geological cross-sections. It is appreciated that the method of correction adopted is not entirely reliable, but this procedure was adopted because the barograph normally used to standardize the barometer was in need of repair at the time that the field work was under way.

2. Laboratory Procedure.

Laboratory procedure included the following :-

(a) Compilation of the Maps.

(b) Compilation of Flight-line Overlays and Plotting of Data on the Maps.

(c) Thin-section Analysis and Mineral Identification.

(d) X-Ray Diffraction.

(a) Compilation of the Maps.

A Hilgar and Watts Radial-Line Plotter was used to compile a partially controlled geological map of the area investigated, from aerial photographs, with about 60% overlap, on a scale of approximately 1:30,000. As the area was not excessively large (approximately 247 square kilometres (94 square miles)), the Radial-Line Plotter method was chosen to produce a map of the area. Certain inaccuracies of positions were found to be present during compilation of the map, mainly caused by such factors as :

(i) tilt of the aeroplane while taking the photographs, and

(ii) variation of scale along the flight lines.

Due to the high relief in most of the area, certain inaccuracies in compiling this map were inevitable, but the result using this method was found to be satisfactory. Corrections for the defects were made by averaging out the positions of points that did not coincide when matching adjacent flight strips.

The writer was guided by the procedures advocated by Compton (1962, pp.165-169), in using the Radial-Line Plotter. The ruled template method was used in assembling the overlays along photographic flight lines, and the steps in the following section were taken in compiling the maps.

(b) Compilation of Flight-line Overlays and Plotting of Data on the Maps.

(i) The centre points, and points to be intersected (pass points) were marked on each aerial photograph, as well as the transferred centre points from the two adjoining photographs. The latter two points formed the control points, which, together with each photograph's original centre point, indicated the direction of the flight line.

(ii) Transparent overlays were placed over each photograph and radial lines drawn from the centre point of each photograph to all control and pass points.

(iii) The control points, and pass points, were then marked on each overlay.

(iv) The overlays were then set out in their correct order, care being taken to align each flight strip correctly along its flight line, at the same time ensuring that the radial lines through pass points intersected as accurately as possible, from adjacent flight strips. After each overlay was correctly adjusted it was taped to the previously positioned overlay.

(v) All the overlays being thus securely fastened to each other, were placed on a drawing sheet, and the position of the centre point of each overlay was pricked through on to the drawing sheet.

(vi) The thus transposed centre points of each adjacent pair of photographs were then used as a base line for plotting all the geological data, with the aid of the Radial-Line Plotter.

(vii) The field data, as well as farm boundaries and beacon positions were then transferred from the 1:10,000 field mapping photographs with overlays, to 1:30,000 scale photographs, for use with the Radial-Line Plotter. In this way geological contacts, farm boundary directions, streams, roads, railway-line, and farm houses were plotted from the 1:30,000 aerial photographs on to the drawing sheet, the Radial-Line Plotter correcting for topographical distortion, but not for tilt and scale variation in the way that more sophisticated instruments do.

(viii) The scale of the final map was determined from 1:50,000 scale maps. The Trigonometrical Survey issued the following pre-prints of the forthcoming maps of the Birds' River area :-

3126 EH 78 BIRD RIVER
3126 EH 56 BROSTERLEA
3127 AD 34 ROSSCUW

The writer wishes to acknowledge and thank the Trigonometrical Survey for the use of these pre-prints, and Professor Eales, who obtained the pre-prints from the Trigonometrical Survey, and allowed the writer to make use of these maps.

The scale of the map compiled by the writer was calculated by comparing known distances on the 1:50,000 pre-prints with those on the compiled map. These distances were measured in several directions across both the pre-prints and the compiled map. A slight variation of scale in these different directions was found to be present in the compiled map, and a mean value for the scale of the latter was therefore given. The scale error thus incorporated in the map was calculated to be about 1%.

(ix) Dips and strikes of sediments and of intrusive contacts were then plotted on the completed base map.

(x) Co-ordinate and meridian lines were inserted from the 1:50,000 scale maps issued by the Trigonometrical Survey.

(xi) The co-ordinate lines were further arbitrarily subdivided into ten portions, a grid pattern being thus superimposed on the map. The purpose of the grid was purely for convenience of reference in the text. The map thus compiled is designated Map No. 1.

(xii) An Ott precision pantograph was used to enlarge the size of the map of the bell-jar intrusion by a linear factor of two relative to Map No. 1, so that more detail could be plotted (see Map No. 2). The pantograph was also used to reduce the scale of Map No. 1 to approximately 1:100,760, to produce a small scale map which could with convenience be inserted in the text (see Fig. 1).

(xiii) Cross-sections A-B and C-D were then drawn from Map No. 2, using the barometric height recordings for the topographical profile.

These cross-sections were designed mainly to illustrate the nature of the bell-jar intrusion across its shorter axis (C-D), and the size and structure of the foundered roof block - the Smuts Pass xenolith (A-B). It must therefore be pointed out that in both cross-sections A-B and C-D, the interpretation of sub-surface geology is partly diagrammatical. Individual sandstone and mudstone beds of the Molteno and Red Beds Stages shown in cross-section A-B, for example, do not necessarily occur as such in the field; they were inserted in the diagram merely to indicate dip directions, and thereby illustrate the attitude of the xenoliths.

FOOTNOTES:

1. Official Farm Names and Boundaries.

The maps used for obtaining officially approved farm names and farm boundaries were :-

(i) The 1:250,000 topocadastral map, issued by the Government Printer, and dated 1966.

(ii) Two 1:50,000 pre-prints of the forthcoming maps of the Birds' River area (EH 56 and EH 7?) issued by the Trigonometrical Survey.

It is important to note that discrepancies in the spelling of farm names appear in the two different series of maps. Farm subdivisions shown on the smaller scale map are in many cases no longer valid at the time of writing. The more recent 1:50,000 pre-prints were accepted by the writer as the more authoratative reference, chiefly for the latter reason, and the spelling of the farm names in these maps has been adhered to. Certain farm subdivision boundaries not appearing on these maps, were obtained from individual farmers' large scale maps of their individual farms. The writer has taken these boundaries to be approximate, and they have therefore been drawn in as broken lines on his maps.

Many of the farm names appearing on Du Toit's map of the area (Dordrecht - Barkly East, Sheet 26, 1912), as well as farm boundaries, have therefore been replaced by new ones. In the southern half of the area, in particular, streams and the railway-line now form the boundaries to a number of farms. In the north of the area the farm called Die Smuts Pass divides the original farm Boshoffs Kraal into two portions, both of which are still named Boshoffs Kraal. In order to avoid confusion in the text the writer has added the figures (1) and (2) behind these names (see table I, Map Nos. 1 and 2 and Fig. 1).

2. Colours and Abbreviations used in the Maps.

The writer has used different colours forthe various Stages of the Stormberg sediments to those employed by the Geological Survey in their 1:250,000 scale published sheets, since 1966. The brown colour used by the writer for the Molteno Stage approximates that used by the Geological Survey. Various shades, and mixtures, of brown, accompanied by a superimposed printed pattern (in the case of the Cave Sandstone Stage) are used by the Geological Survey for the remaining two Stages of the Stormberg Series. The reasons for not adhering to this colour scheme are as follows :-

(i) The exact colour of each of the Stages of the Stormberg Series, with superimposed printing, used by the Geological Survey is difficult to reproduce by normal non-professional methods.

(ii) The colours used by the Geological Survey do not bring out the contrast in the Stages of the Stormberg sediments. This contrast is particularly desirable, for example, in a quick visual recognition of the xenoliths within the bell-jar intrusion.

The colours used for the dolerites, and remaining rock types, were arbitrarily chosen, the intention being chiefly to differentiate the various intrusive forms.

The letter abbreviations (with accompanying colours) used by the Geological Survey in their 1:250,000 scale published sheets since 1966, for the Stages of the Stormberg Series, have been adhered to in the compiled maps (e.g. K_4m = Molteno Stage).

TABLE I.

A List of Old and New Farm Names Appearing in the Birds' River Area.

Farm Names appearing on Du Toit's map. (Dordrecht - Barkly East Sheet 26, 1912)	Subdivided Farms, and present Farm Names used on the maps compiled by the writer.
BIRDS RIVER	(i) HERMITAGE (ii) SUNNYSIDE (iii) portion of ROCKCLIFF
BOSHOFFS KRAAL	(i) BOSHOFFS KRAAL (1) (ii) portion of DIE SMUTS PASS (iii) BOSHOFFS KRAAL (2)
BUFFELSFONTEIN	BUFFELSFONTEIN
DROOGEFONTEIN	DROOGEFONTEIN
GELEGENFONTEIN	GELEGENFONTEIN
HOPE	(i) DENWOOD (ii) THE GLEN (iii) GLEN WALLACE
JANSENFONTEIN	JANSENFONTEIN
KLIP FONTEIN	KLIP KRAAL
KOUPS LEEGTE	KOUPS LEEGTE
LIMOEN FONTEIN	(i) LEMOENFONTEIN (ii) portion of DIE SMUTS PASS
MURRELFONTEIN	MURRELFONTEIN (Western boundary slightly modified)
PALMIETFONTEIN	PALMIETFONTEIN
SNYMANS KRAAL	SNYMANS KRAAL
STAFELBERG'S KLOOF	STAFELBERG'S KLOOF
STAFELBERG'S VLEY	(i) STAFELBERG'S VLEI (ii) BRANSTONE
THYSFONTEIN	THYSFONTEIN
VOGEL VLEY	VOGEL VLEI
WAGENPADS KLOOF	ROMANCE (Eastern boundary slightly modified)
WITTEBOOYS KRAAL	(i) portion of ROCKCLIFF

(c) Thin-section Analysis and Mineral Identification.

Thin-sections were cut from a variety of rocks, but chiefly from the dolerites. Properties of minerals such as 2V angles and composition were obtained with the use of a four-axis universal stage. A more detailed account of the procedure adopted in identifying the minerals will be given in section II of chapter three. Micrometric analyses of thin sections were determined with a Swift Point Counter.

In the identification of individual minerals, e.g. the zeolites, optical properties, particularly refractive indices, were obtained from crushed fragments immersed in liquids of calibrated refractive index values. The refractive indices were, however, accurately determined with the aid of monochromatic light, and their values checked against a Jelly-Leitz refractometer. Use was made of identification tables by Winchell (1957, p.11), and properties of the minerals checked against descriptions of individual minerals in Winchell (1933), and Deer, Howie and Zussman (1963).

(d) X-Ray Diffraction.

A GEC XRD 3 diffractometer, using a tube with a copper target and an applied voltage of 30 k.v.p. at 20 milliamps was used for the X-ray diffraction study. The scanning speed was 2^{o} per minute, the chart data permitting a reading accuracy of $\pm 0.1^{o}$ at this scanning speed.

The mineral samples were ground to a very fine powder in an agate mortar and mounted on glass slides which were coated with a very thin layer of grease. The diffraction patterns obtained by reflecting X-rays from these samples are given in figures 5 and 6, and the X-ray powder diffraction data are given in tables II and III.

* * * * *

TABLE II.

X-Ray Powder Diffraction Data for Stilbite

2θ	d Å(1)	I(1)	d Å(2)	I(2)
9.7	9.110	100	9.10	90
16.5	5.365	30	5.40	20
19.0	4.666	50	4.68	70
20.8	4.266	20	4.30	30
21.9	4.055	100	4.08	100
26.2	3.398	30	3.41	50
28.0	3.183	30	3.20	50
29.4	3.035	40	3.03	70
32.1	2.785	30	2.79	30
24.0	2.704	10	2.69	20
35.9	2.499	10	2.59	20
44.0	2.056	10	2.04	20
49.6	1.836	10	1.83	10
50.9	1.792	10	1.78	10

2θ = Angle of diffraction.

d Å(1) = Spacing between lattice planes of stilbite specimen.

I(1) = Relative intensity of peaks yielded by stilbite specimen.

d Å(2) = Spacing between lattice planes of stilbite, obtained from the A.S.T.M. Powder Diffraction File Index 10-433 (Vol. No. PD1S - 10iRB).

I(2) = Relative intensity of peaks of stilbite (Index 10-433).

TABLE III.

X-Ray Powder Diffraction Data for Heulandite

2θ	d Å(1)	I(1)	d Å$(2)_{\text{obs.}}$	d Å$(2)_{\text{calc.}}$	I(2)
9.9	8.926	100	8.845	8.909	80
11.1	7.964	20	7.796	7.945	70
13.1	6.752	10	6.631	6.659	60
16.8	5.272	10	5.277	5.256	50
17.4	5.092	10	5.096	5.077	70
19.0	4.666	20	4.646	4.639	60
20.2	4.392	2	4.364	4.369	20
22.5	3.948	60	3.917	3.923	100
23.8	3.735	2	3.723	3.726	20
25.0	3.558	10	3.562	3.565	20
26.1	3.411	20	3.420	3.428	70
26.8	3.323	1	3.320	3.329	10
28.0	3.183	20	3.186	3.177	50
28.5	3.129	2	3.132	3.129	40
30.0	2.976	40	2.959	2.957	90
31.9	2.802	20	2.805	2.802	70
32.8	2.728	2	2.730	2.735	40
36.0	2.492	10	2.529	2.531	20

2θ = Angle of diffraction.

d Å(1) = Spacing between lattice planes of heulandite specimen.

I(1) = Relative intensity of peaks yielded by heulandite specimen.

d Å$(2)_{\text{obs.}}$ = Observed spacing between lattice planes of heulandite.

d Å$(2)_{\text{calc.}}$ = Calculated spacing between lattice planes of heulandite.

I(2) = Relative intensity of peaks of heulandite.

After A.B. Merkle and M. Slaughter (1968).

CHAPTER TWO

SITUATION, PHYSIOGRAPHY AND CLIMATE

A. SITUATION.

The Birds' River dolerite complex lies some 20 kilometres (13 miles) west-south-west of Dordrecht, in the Eastern Cape of South Africa, and forms part of the mountainous area of the Stormberg (see Fig. 4).

The complex is situated just to the north of Birds' River Siding (on the Sterkstroom - Indwe railway-line), and is accessible from two main roads that lead off the Queenstown - Aliwal North national road, viz. the Molteno - Dordrecht road in the north, and the Sterkstroom - Dordrecht road in the south (see Plate I, Fig. 1).

The area represented by Map No. 1 measures some 247 square kilometres (94 square miles). It is bounded in the north by the Molteno - Dordrecht main road, the southern boundary being a little to the south of the Sterkstroom - Indwe railway-line. The 26° 43' east meridian forms the western boundary, while the 26° 55' east meridian forms the eastern boundary of the area investigated.

Evidence as to a former means of access across the Stormberg mountains in this area has been historically recorded in some of the farm names. Deeply scoured wagon tracks across the farm Romance (originally called Wagenpad's Kloof) reveal the route taken by transport wagons carrying heavy machinery from coastal ports for inland mining development. The farm "Die Smuts Pass" is also indicative of a passage of access exploited during the Anglo-Boer War by the Commandos of the South African forces.

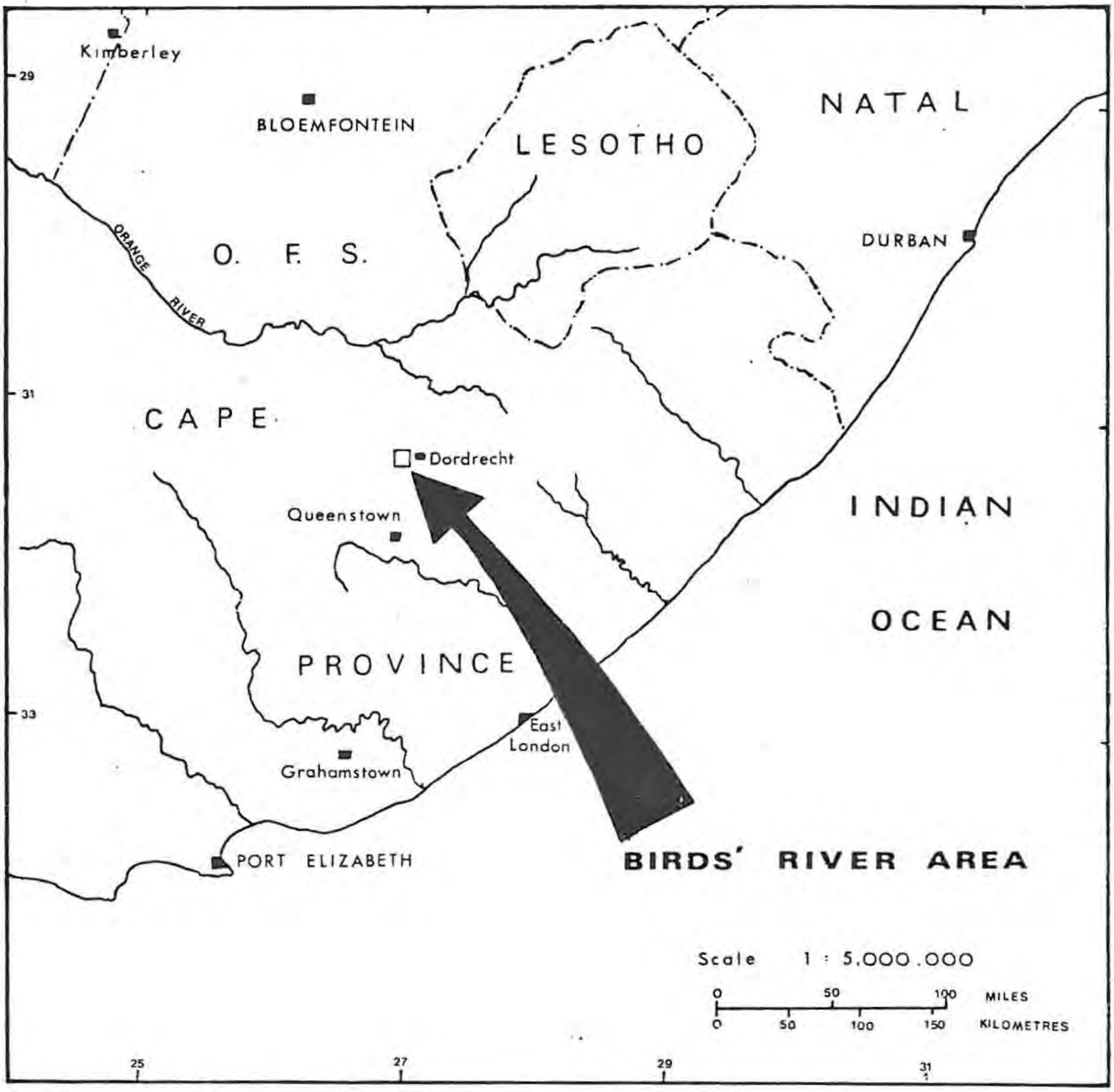

Fig. 4: Locality Map of the Birds' River Area.

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Fig. 1: Picture taken from Birds' River Siding (on the Sterkstroom - Indwe railway-line), with dolerite hills of the bell-jar intrusion in the background. Facing north.

Fig. 2: The undulating plain at 1500 metres (5000 feet), cut across Molteno sediments with dolerite hills of the bell-jar intrusion in the background. Picture taken from Sunnyside, facing north-west.

B. PHYSIOGRAPHY.

This region lies astride the principal watershed that separates drainage northwards to the Orange River from that via the White and Great Kei to the Indian Ocean. This watershed forms part of the crest of the Stormberg range, and lies everywhere above 1800 metres (6000 feet). In the area under investigation it runs east-west and rises to 2079 metres (6821 feet) on Boshoffs Kraal (1) in the west, and to 2039 metres (6692 feet) on Wolvekop, just off the eastern margin of the map. The watershed follows approximately the line of farm boundaries separating Boshoffs Kraal (1) and Stafelberg's Kloof in the west, through to that separating Thysfontein and Koups Leegte in the east. As can be seen from Map No. 1, it approximately bisects the area.

The escarpment on the south side of the watershed overlooks a topographic basin formed by the headwaters of the Hex River and, in the region of the present survey, of the Groot· Vlei spruit which drains into the White Kei. This basin separates the Stormberg range from what are now detached portions of the interior plateau on its southern side, e.g. the Andriesberg. Because of this the local relief in this escarpment, from its crest to the floor of the basin, is in places little more than 300 metres (1000 feet).

The bell-jar intrusion lies astride the principal watershed. On this watershed and north of it dolerites of this intrusion, and xenoliths outcropping within it, form elevated ground rising to 2079 metres (6821 feet) on Boshoffs Kraal (1) and always above the level of the plain at 1800 metres (6000 feet) on its northern side. The latter plain occupies the northern half of Map No. 1 and is cut across Red Beds sediments. Dolerite sheets to the west and east of the bell-jar intrusion form the high ground as well. South of the watershed the main intrusion, and xenoliths in it, crop out in, and reach to the foot of the escarpment. The prominent plain in the southern part of the region, cut across Molteno sediments at 1500 metres (5000 feet), stops rather abruptly against the bell-jar intrusion (see Plate I, Figs. 1 & 2).

Neither of the two plains in the area covered by this investigation is specifically identifiable on the very small scale map of King's cyclic denudational landsurfaces of Africa (1962, Fig. 119, p.100), the only up to date map of his surfaces in this region.

Mr. A. Ruddock of Rhodes University informs me that the unpublished results of a preliminary investigation carried out by him, of the erosional surfaces in the Kei basin, and of the plateau in a wide area surrounding the present area of investigation, permits a tentative correlation with specific landsurfaces of King's scheme. It seems probable that the plain at 1800 metres (6000 feet) and the residual hills rising above it on the plateau belong to King's "African" landsurface, but there is no local evidence to indicate the actual age of this surface. However, in the area covered by the present investigation, it is not dissected by the streams that flow over it. This correlation is supported by the fact that these plains are separated by erosional escarpments from plains bordering the Orange River, near Aliwal North, in a region which according to King's map (1962, Fig. 119) is characterized by post-"African" erosional landsurfaces. Within the area of investigation there are no plains on the summits of the highest hills to suggest the existence of an older cyclic landsurface than the plain at 1800 metres (6000 feet).

The 1500 metre (5000 foot) landsurface lies right at the foot of the escarpment on which the costal rivers rise. Here, as elsewhere along the escarpment bordering the interior plateau, there is abundant evidence in the relief and drainage pattern that this escarpment has been actively retreating for some time. The fact that the 1500 metre plain lies at the foot of the retreating escarpment, and at most 15 metres (50 feet) above the beds of only recently mature streams, probably means that this surface developed, locally, rather late in the Cainozoic.

The plain occurring at 1800 metres (6000 feet) to the north of the bell-jar intrusion has several residual hills rising up out of it (see Plate XXIII, Fig. 1). Most of these hills are ridge-like, reflecting the structural control of vertical or dipping dolerite intrusions, or Cave Sandstone. Level summits appear to be absent. Free faces are generally formed by Cave Sandstone, the arenaceous beds of the Red Beds Stage and dolerite sheets, e.g. the Vogel Vlei sheet. Constant slopes are present below each free face and occur predominantly in the argillaceous beds of the Red Beds Stage. The junction between the hills and the plain is concave. Dissection by intermittent streams flowing across the plain is not very marked. In fact the depressions are represented mainly by vleis and pans. These features indicate that the plain to the north of the bell-jar intrusion is composed of a number of pediments.

In the southern half of the area the plain at 1500 metres (5000 feet) is preserved in broad interfluves of rivers descending from the escarpment. The plains slope away from the escarpment, and descend to the rivers through marginal convex slopes. When viewed in an easterly direction this plain is seen to rise through concave slopes into the escarpment. There are plains generally less than 100 metres (300 feet) wide, adjacent to streams some 7 metres (20 feet) below the plain at 1500 metres (5000 feet). These streams do not have true meanders but some, for example the Birds' River, have an irregular, winding course, on a scale comparable with the width of the valley floor. In some places the valley floors are very flat in transverse profile and are flanked by low undercut scarps, but in others they are gently concave and pass gradually into bordering scarps. Coarse-grained Molteno sandstone beds normally form the free faces and often large blocks of sandstone are to be found in the valley sides where stream erosion has undercut the resistent beds.

No river gravels were observed in the entire area, the plains being covered with a thin layer of soil or alluvium.

The topographic features produced in dolerite can largely be related to the form of intrusion. A sharp ridge defines the outer edge of the Vogel Vlei sheet, with columnar jointing developed on the scarp slopes and exfoliation surfaces on the dip slopes. The Dragon's Back dike forms a prominent topographic feature along almost its entire length (see Plate X, Fig. 1). The bell-jar intrusion gives rise mainly to dome-shaped hills caused by exfoliation weathering (see Plate VIII, Fig. 1). The latter is particularly well developed in the south-eastern part of the intrusion where streams have cut steep V-shaped valleys through the dolerite, for example Grootkloof (see Map No. 2). Other steep valleys in this locality include Tierkloof and Waskloof. Gansnek forms the outlet to one of the broadest valleys in the dolerite hills which make up the bell-jar intrusion.

The streams in the area are normally intermittent. In past years, however, more consistent summer rainfall provided constant flow of streams throughout the year by means of natural springs.

Sugarloaf Hill, an isolated protruberance of dolerite on the farm Rockcliff, forms part of the southern margin of the bell-jar intrusion (see Plate II, Fig. 1).

C. CLIMATE.

Rainfall figures for this region were obtained from Government weather stations on Buffelsfontein in the north-west, and on Willow Park to the south-east. The latter weather station is situated just outside of the present area under investigation. The figures for the last ten years (excluding 1970) show the following average rainfall per year :-

Buffelsfontein	552.45 mm.	(21.75 inches)
Willow Park	575.81 mm.	(22.67 inches)

Rain falls mostly in the form of thunderstorms during the summer months from September to April, while heavy snowfalls and frost are commonly recorded in the winter months.

The yearly total rainfall figures from both the above weather stations, reveal a marked decline in total annual precipitation since 1963. The resulting draught conditions

PLATE II

Fig. 1: "Sugarloaf Hill" (nearest the observer), forming part of the southernmost margin of the bell-jar intrusion. Picture taken from Rockcliff, facing north north-west.

Fig. 2: Dolerite of the bell-jar intrusion in contact with a mylonite. Northern corner of the intrusion (grid reference J 6).

are reflected in the general deterioration of the natural vegetation in this area, during the last few years. The climate of this area is somewhat dictated by such facters as the high altitude and inland situation.

The region is one of natural grasslands, mixed grassveld occupying the plains, while a stunted bush growth makes its appearance in the kloofs of the mountainous areas.

* * * * *

CHAPTER THREE

INTRUSIVE ROCKS - THE DOLERITES

General Statement:

Perhaps the most valuable aspect of the preliminary aerial-photograph study has been the interpretation of some of the structural relationships of the bell-jar intrusion. On Branstone and Denwood, for example, a series of parallel ridges within the dolerite, which appear to be parallel to and conformable with the contact, can be seen on the aerial photographs. These ridges give rise to a characteristic "grain" along the southern and western edges of the bell-jar intrusion. This trend becomes particularly noticeable in the south-eastern part of the intrusion, on Hermitage and Murrelfontein, where it acquires an east-west direction, and is no longer conformable with the south-eastern contact of the bell-jar intrusion.

On Branstone the courses of streams flowing across this series of parallel ridges, in a south-westerly direction, often make sharp right-angle bends where they cut across or lie parallel to them (note particularly grid reference I 13).

A petrographic investigation into a series of dolerite samples taken along the course of the above-mentioned stream (grid reference I 13) favours the successive intrusion of several dolerite types, in separate vertical sheets, during the formation of the bell-jar intrusion.

This chapter is divided into two main headings :-

I Field Relationships, and

II Petrography of the Igneous Rocks.

I FIELD RELATIONSHIPS.

The field relationships of the different forms of dolerite intrusion in this area are here described. In the description of the bell-jar intrusion particular emphasis is placed on features such as its shape and size, nature of the contact, effects on the structure of the country rock, nature of the dolerite in the field, dolerite sills within the bell-jar intrusion, the foundered roof fragments and veining phenomena.

The field relationships are described under the following headings :-

A. The Bell-jar Intrusion.

B. Sheets in the Area Surrounding the Bell-jar Intrusion.

C. The Dolerite Dikes.

A. THE BELL-JAR INTRUSION.

1. Shape and Size of the Intrusion.

In plan view, the intrusion is roughly oval in shape, its south-eastern extremity extending south-eastwards in an irregularly shaped "tongue". The longer axis, measured along a north-westerly direction along the entire continuous occurrence of dolerite, is approximately 13.5 kilometres (8.4 miles). The shorter, north-easterly axis measures approximately 6 kilometres (3.8 miles).

The dolerite hills of the bell-jar intrusion rise to more than 457 metres (1500 feet) above the plains to the south, and form the high ground for the most part of this area (see Plate I, Figs. 1 & 2, and Plate II, Fig. 1).

2. Nature of the Contact.

In several places where stream erosion has been more active, and in some artificial exposures such as quarries, the nature of the contact can be established with reasonable certainty. In the south and south-east of the intrusion extensive talus slopes conceal the true nature of the contact. The writer has therefore, in these areas, drawn an inferred contact on the maps.

Along the western margin of the intrusion the contact can be seen to be either vertical or dipping steeply outwards (see grid references J 14, I 13, H 12 and G 11). Along the northern margin of the bell-jar intrusion the dolerite has intruded in the form of a dike some 200 metres (600 feet) wide. This dike merges into the dolerites of the bell-jar intrusion at either extremity.

In the northern corner of the intrusion (grid reference J 6), the dolerite has intruded partially along a sinuous north-westerly trending fault zone (see Map No. 3). The dolerite contact is revealed, in the most northerly "donga" on this map, as dipping steeply outward. At this particular place the dolerite is in contact with a grey, fine-grained rock. Under the microscope this rock is seen to be composed largely of quartz grains, surrounded by a brownish glass. The quartz occurs as anhedral rounded grains, some showing strain shadows. Iron ore is disseminated throughout the rock. The rock is perhaps best described as a mylonite (see Plate II, Fig. 2).

The north-westerly trending fault zone in the northern corner of the intrusion appears to be made up on a conjugate set of faults, with indications that the displacement is not very great. The strike of this fault zone, as measured on slickensided surfaces. is approximately 10° west of magnetic north, while the dips were measured as follows :-

(i) towards the east : from 62° to 82°;

(ii) towards the west : from 50° to 60° (see Plate III, Fig. 1).

Along the eastern margin of the intrusion two quarries, on the farm Lemoenfontein, reveal that the intrusion becomes sill- or sheet-like in character with the contact dipping

PLATE III

Fig. 1: Slickensided surfaces indicating fault zone in the northern corner of the bell-jar intrusion (grid reference J 6).

Fig. 2: Dolerite of the bell-jar intrusion where the margin is sheet-like in character. Picture taken on Lemoenfontein (grid reference L 7).

inward at very shallow angles (see Plate III, Fig. 2). Further south, on Lemoenfontein and Thysfontein, the attitude of the contact is nowhere clearly revealed. In view of the fact that several thin sheets of dolerite, conformable with the contact and therefore most probably linked with the bell-jar intrusion, are to be found intruded into the country rock in this area, it has been assumed that the general nature of the eastern contact, from the quarry on Lemoenfontein (Plate III, Fig. 2) southwards to Thysfontein, is locally sheet-like in nature (i.e. with the contact dipping inward towards the centre of the bell-jar intrusion, see cross-section C-D).

Field evidence does not show a break in continuity between the dolerite occurring in sheet-like form and the dolerite of the bell-jar intrusion. Microscopically, however, the former are ophitic tholeiites, while the latter are chiefly poikilophitic types.

On Murrelfontein (grid reference P 11) the dolerite of the bell-jar intrusion can be observed in contact with pyroclastic rocks. Along this outer margin metamorphism of the pyroclastics, by the dolerite, has made them survive as ridges at, and for a few metres away from, the contact. The exact nature of the contact is again not clearly defined, but it appears to be vertical.

In the extreme south-eastern portion of the bell-jar intrusion, the contact with country rock is not exposed in the field. The attitude of this south-eastern portion of the intrusion is therefore conjectural. Certain observations, however, were taken into account in deciding the shape of the intrusion in this area. Firstly, the southernmost tip of the intrusion (grid reference Q 18) appears to be sheet-like in nature. Secondly, a few very small occurrences of dolerite, which have the same appearance and weathering characteristics as the dolerites of the bell-jar intrusion, but which form bodies separate to the main intrusive mass, are to be found in this area (grid references O 16, P 15 and Q 15). It would appear that these bodies, although no information as regards their attitude could be gained in the field, are linked below the present erosion surface to the nearby bell-jar intrusion.

Thirdly, as mentioned previously, the "trend" of dolerite ridges within the bell-jar intrusion, noted on the aerial photographs, is west to east on the farm Murrelfontein, while the contact swings southwards for some distance. This trend extends on to Hermitage, but it is no longer apparent further south, on Rockcliff and Sunnyside.

The above-mentioned factors suggest that the south-eastern portion of the bell-jar intrusion, extending southwards from a point at least 1 kilometre (0.6 miles) north of the railway-line, is an offshoot from the main intrusive mass of the bell-jar intrusion, in the form of a flat lying "tongue".

The floor of the intrusion as a whole appears to be nowhere exposed, but as the dip of the contact for the most part is either vertical or steeply outward, it may be regarded as a discordant intrusion, i.e. a plug, from which sill-like offshoots are given off.

3. Effects of the Bell-jar Intrusion on the Attitude of the Country Rocks.

Along most of the contact of the bell-jar intrusion, it is remarkable how little the attitude of the sediments has been affected by such a large intrusion. This feature recalls similar aspects of the "space problem" encountered with granite plutons. In cases where the country rock has not suffered much structural disturbance through intrusion of a granite pluton, it is difficult to envisage an intrusive habit of the latter unless stoping or metasomatism had taken place. The bell-jar intrusion, however, was emplaced at a much higher level in the earth's crust, and there is no doubt as to its intrusive habit.

The sediments, for the most part, dip away from the contact of the bell-jar intrusion at only shallow angles. Exceptions to this general picture are to be found in the following areas :-

(i) Along the eastern margin of the bell-jar intrusion, on Thysfontein and Lemoenfontein, where Red Beds, Cave

Sandstone and pyroclastic rocks dip in towards the bell-jar intrusion (see Plate IV, Fig. 1). Dips, generally of the order of 30°, were recorded in Red Beds sediments in this area, and, although lack of bedding in the Cave Sandstone and pyroclastics does not permit an accurate dip measurement, it does appear that the latter two Stages dip even more steeply in towards the bell-jar intrusion, as has been indicated in cross-section C-D.

It is very important to note that the Cave Sandstone along this eastern margin of the bell-jar intrusion, for a distance of approximately 3 kilometres (1.9 miles), is situated at a considerably lower elevation (at least 150 metres) than that of other outliers of Cave Sandstone (except the xenoliths within the bell-jar intrusion) in the surrounding area. The relevance of this fact is discussed in the chapter dealing with the structural interpretation of the mechanism of formation of the bell-jar intrusion.

(ii) Along the southern contact, on Murrelfontein (grid reference N 14), where Molteno sediments have been turned up vertically at the contact.

4. Nature of the Dolerite in the Field.

Dolerites of the bell-jar intrusion may generally be recognised in hand specimen by their coarse grain-size, and an orange-red weathered surface. The rocks often have a knobbly appearance in the field, due to certain minerals being more resistant to weathering than others.

Exfoliation weathering is very common in the interior of the bell-jar intrusion, giving rise to dome-shaped hills (see Plate VIII, Fig. 1) and smooth sides to the steep gorges, as in Grootkloof (see Plate IV, Fig. 2). Spheroidal weathering is commonly developed at the contact with the Stormberg sediments.

Jointing, approximately 2 or 3 centimetres apart, is a frequent characteristic of the coarse-grained rocks, while closely spaced parallel joints tend to occur in the

Fig. 1: Picture taken of the dolerite hills forming the rim of the bell-jar intrusion, from Thysfontein, facing south-west. Cave Sandstone on the right, forming the steeper slopes.

Fig. 2: Exfoliation weathering in dolerite. Picture taken at the head of Grootkloof valley, facing north-west. Metasomatized rocks form the summit of the hills in the background.

finer-grained varieties of the bell-jar intrusion. Columnar jointing in dolerite is fairly well developed at the base of a "glassy ridge", which forms part of a pyroclastic xenolith in the south-east sector of the bell-jar intrusion. This glass-rich ridge is approximately 370 metres (1200 feet) long and forms the highest ground in the immediate vicinity (see Plate IV, Fig. 1 and Plate V, Fig. 1).

Patches of dolerite pegmatite are common and usually occur within the upper portion of the bell-jar intrusion. Elongate pyroxene crystals may reach up to 50 millimetres (2 inches) in hand specimen.

On Murrelfontein, just below a nearly horizontal "blanket" of pyroclastics which forms a large xenolith within the bell-jar intrusion, a distinctly different dolerite rock-type is to be found. This rock is lighter in colour than other dolerites of the bell-jar intrusion, and sometimes a distinct parallel arrangement of plagioclase crystals within the rock can be noticed in hand specimen.

5. Dolerite Sills within the Area of the Bell-jar Intrusion.

A number of dolerite sills are to be found within some of the sedimentary xenoliths of the bell-jar intrusion. The largest foundered roof fragment, the Smuts Pass xenolith, occurs in the northern portion of the bell-jar intrusion. Several dolerite sills have been intruded into the sedimentary beds, which dip in a north-westerly direction and strike approximately east-north-east (see grid reference I 9).

It would appear from Du Toit's map of 1912 (Sheet 26) that he considered these sills to be of a different age to the dolerites of the bell-jar intrusion. The sills were presumably regarded as older, for they are not shown cutting the dolerites of the bell-jar intrusion.

Skerprand forms the spine of the thickest and most prominent of the sills in the northern portion of the bell-jar intrusion (see Plate V, Fig. 2 and grid reference I 10). This intrusion calls for further comment for it appears to be of a different age to that of the other sills within the

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Fig. 1: The "glassy ridge", some 370 metres (1200 feet) long, forming the irregular crest of the hill in the centre of the picture. Picture taken from Grootkloof valley, facing east.

Fig. 2: Skerprand, a dolerite sill dipping towards the north-west. Picture taken on Lemoenfontein, facing south-west.

xenoliths in this particular area. The Skerprand sill is approximately 3 kilometres (1.9 miles) long, and along line of section A-B it measures approximately 50 metres (150 feet) in thickness. Towards its eastern end the sill becomes very much thinner. The sill appears to dip conformably with the sediments of the xenoliths at angles varying between 30° and 35° to the north-west.

At neither extremity of the sill was convincing field evidence found to suggest its truncation by the dolerites of the bell-jar intrusion. In fact the dolerite of the Skerprand sill appears to merge into the latter, and the two have been regarded by the writer as belonging to the same intrusive phase, and therefore of the same age. This interpretation is adopted in cross-section A-B.

The base of the Smuts Pass xenolith is therefore at present considered to be defined by the Skerprand dolerite sill. The reasons for this interpretation will be discussed in the following section.

In general, no satisfactory field evidence could be gained as regards the relative ages of the remaining sills, which have been intruded into the Smuts Pass xenolith. It seems quite possible that these sills could have been intruded into the sediments before the xenolith had become disrupted by the dolerites of the bell-jar intrusion. This interpretation is, however, tentative as a more thorough investigation needs to be undertaken before the relative ages of these intrusions can be established.

6. The Foundered Roof Fragments.

The majority of the larger roof fragments have been subjected to deformation by engulfment in the dolerite magma of the bell-jar intrusion. Sediments of the Stormberg Series have been bent into various basin and dome shapes. The foundered roof fragments occupy a large area within the bell-jar intrusion and show great diversity in size, attitude and rock types. In size they vary from 4.4 kilometres (2.75 miles) across, to small xenoliths measuring only a few metres across.

For recognising the original stratigraphic position of these xenoliths and hence identifying the xenoliths themselves, criteria such as colour and grain size of the sediments were largely relied upon. The writer appreciates the uncertainties that can be encountered in correctly identifying the xenoliths using these criteria, for previous writers have emphasised their unsuitability in many cases where field mapping of sediments is concerned (e.g. Botha, 1968, p.103). However, where mudstone horizons and their associated arenaceous beds occur together in the larger xenoliths and show characteristic colours, they have been assigned to the stratigraphic stage which they most closely resemble in the sediments outside the area of the bell-jar intrusion, e.g. reddish mudstone beds with interbedded yellowish medium-grained sandstone beds were placed within the Red Beds Stage.

Identification of the xenoliths belonging to the Cave Sandstone Stage was more satisfactory than that of the other two Stages of Stormberg sediments, because of the presence of agglomeratic material that is here most often associated with the fine-grained sandstone.

Where smaller xenoliths composed entirely of sandstone or mudstone beds are encountered, identification in the field becomes exceedingly difficult, and most often impossible. This is due to metamorphism having completely bleached out the original colours in the rock, and new rock types being produced, e.g. mudstones are usually metamorphosed to lydianite. On Romance, however, a bright red hue is characteristic of some of the original mudstone (now lydianite) xenoliths. This is attributed to oxidation of the magnetite in the lydianite, which was recrystallized through metamorphism from the original haematite or other oxide in the sediments. The red colouration within the lydianite xenoliths was taken to indicate that haematite and perhaps other oxides were originally deposited within these sediments - suggesting that the latter belonged to the Red Beds Stage.

The foundered roof fragments are described under the following headings :-

(a) The Smuts Pass Xenolith.
(b) The Branstone Xenoliths.
(c) The Xenoliths of Pyroclastic Rocks.
(d) The Remaining Xenoliths.

(a) The Smuts Pass Xenolith.

This foundered roof fragment forms by far the largest xenolith within the bell-jar intrusion. It occupies the northern portion of the bell-jar intrusion, and straddles the farms Boshoffs Kraal (1), Die Smuts Pass and Lemoenfontein (grid references: west to east, from F 8 to K 7 and, north-east to south-west, from J 6 to H 10).

The xenolith measures 3 kilometres (1.9 miles) in a north-westerly direction, and about 4.4 kilometres (2.75 miles) in a west to east direction. The southern margin of the xenolith, as previously mentioned, is defined by the Skerprand dolerite sill. In plan view the xenolith then approximates the shape of a rectangle with a highly irregular outline; the irregularity being caused by sheets, sills and dikes of dolerite invading the xenolith.

Molteno sediments, dipping fairly consistently at 30° to the north-west make up the southern portion of the xenolith. According to Du Toit (1911, p.133) these sediments have been brought up about 300 metres (1000 feet) above their normal stratigraphic position. At approximately the position of the southernmost dam on Die Smuts Pass (grid reference H 9), the Molteno beds pass conformably into the Red Beds Stage. The top of the Molteno Stage in cross-section A-B occurs at 1850 metres (6070 feet) above sea level while the base of the Molteno Stage crops out at 1910 metres (6270 feet). The writer has accepted the 1676 metres (5500 foot) contour line as defining the contact between the Red Beds and Molteno Stages in the Birds' River area, for reasons which will be explained in Chapter Four. From the figures given above it appears that the top of the Molteno Stage within the

Smuts Pass xenolith, along line of section A-B, has been brought up at least 174 metres (570 feet) while the base of the xenolith has been brought up at least 234 metres (770 feet) from its original elevation. These figures reveal that the Molteno sediments of this xenolith have not been displaced quite as much as that originally suggested by Du Toit.

(i) Rock Types within the Xenolith.

The Molteno sediments are composed of cross-bedded, medium- to coarse-grained sandstone beds, sometimes containing very thin mudstone lenses and pellets, at the base of the xenolith, to very coarse felspathic grits, interbedded with grey mudstone beds, towards the upper limits of this Stage. The sandstone beds protrude as a series of parallel ridges in this area, while valleys are cut in the interbedded mudstone beds (see Plate VI, Fig. 1). As mentioned previously, a number of dolerite sills have been intruded into these Molteno beds (see Plate VI, Fig. 2).

Within some of the sandstone horizons a few occurrences of breccia are to be found. The occurrences of these breccias average about one metre (3 feet) across, the breccias being composed of angular blocks of coarse-grained sandstone, set in a siliceous matrix of material similar to the blocks. Although their outline is not clearly defined, some appear to be pipe-like masses and it may be quite possible that these breccias represent small diatremes which were formed by short-lived gaseous activity.

A marker bed, which is noticeably different to the usual Molteno sediments of this xenolith, is present near the base of the xenolith (see Map No. 2, grid reference J 9). The bed appears to be only about one metre (3 feet) thick, and at its base, toward its eastern extremity, the grain size is very coarse, with occasional very well rounded quartzite pebbles, cobbles and boulders (see Plate VII, Fig. 1). The sandstone has a deep brownish colour and has occasional faint imprints of plant stems. Peculiar nodular concretions, of sizes varying up to that of a man's fist, are developed on the bedding-plane surfaces. Towards the western extremity of this marker

Fig. 1: Cross-bedded, coarse-grained Molteno sandstone of the Smuts Pass xenolith, dipping towards the left (north-west). Picture taken facing north-east.

Fig. 2: Dolerite sill intruded within the sediments of the Smuts Pass xenolith (grid reference I 9).

bed the proportion of clay material incorporated with the sandstone increases from the base of the bed upwards.

The contact between the Molteno and Red Beds Stages of sediments within the xenolith, drawn on the maps, is somewhat arbitrary; it was taken to be at the level where the first medium-grained sandstone beds overlying a thick grey mudstone bed appear in the field.

Near their base, the Red Beds sediments dip at approximately 30° to the north-west, but do in places increase their dip to as much as 55° to the north-west (see grid reference H 8). Further northwards the sediments have a shallower dip and finally they flatten out just south of the secondary road from Die Smuts Pass to Lemoenfontein. Along the northern dike-like margin of the bell-jar intrusion, the Red Beds sediments are turned up and dip in the opposite direction, i.e. towards the south (see cross-section A-B). The dip of the sediments along this margin may be as high as 55°.

The Red Beds sediments of the Smuts Pass xenolith are composed of yellow and reddish coloured, medium-grained sandstone beds with some finer grained, finely cross-laminated purple sandstone beds, and argillaceous horizons. Occasionally, clay pellets are present within the sandstone beds. A conglomerate dipping at 45° to the south occurs in the north-east of the xenolith (see Plate VII, Fig. 2).

An agglomeratic rock is present near the base of the Red Beds sediments (see Map No. 2, grid reference I 8). The attitude of the agglomerate in relation to the sediments could not be satisfactorily determined in the field, due to its lack of bedding, but it is believed to be interbedded with the sediments, as indicated in cross-section A-B. The agglomeratic rock is composed almost entirely of angular sandstone and mudstone fragments in a siliceous matrix. The presence of this rock type within the Red Beds Stage is significant in that it indicates that volcanic activity took place as early as Red Beds times in the Birds' River area.

Extending across the secondary road on Die Smuts Pass, and at the northern dam wall on this farm are two outcrops

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Fig. 1: Well rounded pebbles in Molteno sandstone of the Smuts Pass xenolith.

Fig. 2: Conglomerate within the sediments of the Smuts Pass xenolith (south-east corner of grid reference J 6).

of an intrusive rock which appears rather different to most dolerites in hand specimen (see grid reference H 7). Microscopically, it shows phenocrysts of plagioclase, pyroxene and quartz in a fine-grained matrix of felspar and pyroxene crystals. Short stumpy apatite crystals are associated with the quartz phenocrysts. The rock has been regarded by the writer as a dolerite, both outcrops most probably representing sheets which have been intruded into the sediments of the xenolith.

Two small occurrences of Cave Sandstone conformably overly the Red Beds sediments in the western extremity of this xenolith (see grid references F 9 and G 9). The more southerly occurrence forms the highest ground of the bell-jar intrusion and carries the Boshoffs Kraal beacon. (The latter is 2079 metres (6821 feet) above sea level.) The dip appears to be towards the north. Du Toit regards the Cave Sandstone here as being at its normal elevation (Du Toit, 1911, p.134). The northern occurrence of Cave Sandstone appears to be slightly synclinal in attitude.

(ii) The Northern Corner of the Xenolith.

In the northern corner of the Smuts Pass xenolith (grid reference J 6) a number of structural disturbances can be studied within the sediments of the xenolith. As indicated previously, with regard to the nature of the bell-jar contact, the dolerites of the bell-jar intrusion have invaded partially along a fault zone trending north-west. The sediments to the north and east of the dolerite contact dip generally at shallow angles away from this contact, while those of the xenolith in this area have been greatly disturbed (see Map No. 3).

Du Toit mentioned that the dolerite occupying the northern dike-like portion of the bell-jar intrusion was intruded along a fault zone with upthrow to the south (Du Toit, 1911, p. 133). Evidence of faulting in a south-west direction in the sediments of the northern corner of the Smuts Pass xenolith strongly suggests that this interpretation is correct.

The dolerites of the bell-jar intrusion, in this particular area, have been intruded in the form of dikes and sheets, which form an "interfingering" network in the sediments of the xenolith. Some of the intrusive forms appear as inliers in this area (grid refernce J 6 and J 7), and other areas of the xenolith (grid references G 8, H 8 and H 9).

In the extreme northern corner of the Smuts Pass xenolith the sediments have been subjected to intense structural disturbance, with strike of the outcrops, measured within short distances or each other, being vertually in any direction. The amount of dip varies greatly as well, but their inclination is largely towards the south.

Along the north-eastern margin of the xenolith, an exposure of very coarse-grained felspathic grits and medium-grained sandstones has been steeply turned up against the contact with the dolerite. Due to their striking lithological similarity to the Molteno sediments, they have been indicated as such on Map No. 3 (grid reference J 6).

In this area a younger dolerite dike cuts the dolerite of the bell-jar intrusion in a north-westerly direction.

Evidence of normal faulting in the sediments in the remaining area of the xenolith is shown on exposed slickensided surfaces in the sediments. Displacement has, in general, been very slight; in one case at least a narrow northerly trending dolerite dike has intruded along one of these faults within the Molteno sediments (straddling grid references I 9 and J 9).

(iii) The Structure of the Xenolith as a Whole.

Along most of the margin of the Smuts Pass xenolith the sediments generally dip away from the dolerite contact, and are therefore largely tilted towards the central area of the xenolith. The structure of the xenolith as a whole is thus seen to be that of a basin-shaped mass of sediments, with Molteno sediments, forming the base of the xenolith in the south, occurring far above their normal elevation in the surrounding region. Red Beds sediments form the larger exposed portion of the synclinal structure in the northern portion of the xenolith, as indicated in cross-section A-B, and occur at a lower absolute elevation than the exposures of the Molteno sediments of the xenolith.

The approximate thickness of the sedimentary unit making up the Smuts Pass xenolith, as calculated from cross-section A-B, is as follows :-

Molteno sediments (with average angle of dip 30°) = 500 m. (1640 ft.)
Red Beds sediments (with average angle of dip of 22° 30') = 462 m. (1500 ft.)
Total for the unit 962 m. (3140 ft.)

The figures above show that almost the entire sequence of the Red Beds Stage is represented along the line of section A-B of the Smuts Pass xenolith, for the thickness corresponds very closely to that given by Du Toit as a maximum for the Red Beds Stage in the Elliot district, Eastern Cape, (Du Toit, 1954, p.295). The Molteno sediments of the xenolith fall short of their maximum thickness for the Stage, as given by Du Toit (1954, p.295) by only some 120 metres (360 feet).

As can be seen from the maps an elongate xenolith occurs immediately to the south of Skerprand (from grid reference I 10 to L 9). Lithologically it appears very similar to the Molteno sediments of the Smuts Pass xenolith, and it has the same attitude as these sediments as well. These features very much suggest that this elongate xenolith could be a southward continuation of the Smuts Pass xenolith. Now if the Skerprand dolerite sill were to be regarded as older than the dolerites of the bell-jar intrusion, and therefore not to form the base of the Smuts Pass xenolith, then, due to the presence of the elongate xenolith to the south of Skerprand, the north west - south east dimension of the Smuts Pass xenolith will have to be increased by a maximum of something like another 1000 metres (3280 feet). The thickness of the Molteno Stage would then be increased by another 500 metres (1640 feet). This would give the total thickness of Molteno Stage sediments in the Smuts Pass xenolith as 1000 metres (3280 feet) which is far in excess of the maximum thickness of Molteno Stage sedimentation (609.6 metres (2000 feet)) given by Du Toit (1954, p.295). In this case sediments of the lower 300 metres (1000 feet) of the xenolith to the south of Skerprand could possibly belong to the Upper Beaufort Stage. In the field the sediments in the eastern portion of the latter xenolith are largely obscured by talus, but towards the western extremity yellowish, medium-grained sandstone beds crop out. These beds appear similar lithologically and have the same attitude as those immediately to the north of Skerprand, which are considered to belong to the Molteno Stage.

It could be, however, that the sediments of the elongate xenolith occurring to the south of Skerprand belong to the Red Beds Stage. This interpretation would require that the Skerprand dolerite sill forms part of the dolerites of the bell-jar intrusion, in order to have allowed this xenolith to move relative to the Smuts Pass xenolith, within the molten mass of the bell-jar intrusion. The relative movement in this case would have been quite considerable in order to position Molteno sediments above Red Beds.

On field evidence the writer has accepted the interpretation that the Skerprand dolerite sill forms part of the bell-jar intrusion, i.e. that the sill merges at either end into, and is linked in depth with, the main intrusive mass of the bell-jar intrusion, and therefore forms the base of the Smuts Pass xenolith (see cross-section A-B). This interpretation is given further weight by petrographical and chemical evidence yielded by study of the Skerprand dolerite sill.

(b) The Branstone Xenoliths.

In the western portion of the bell-jar intrusion, on the farm Branstone, a number of foundered roof fragments of all three Stages of the Stormberg Series occur in steeply tilted attitudes. Du Toit has described these sediments as being bent into a dome shape, with Molteno sediments on the north-eastern, Red Beds on the western and Cave Sandstone on the southern side of the "dome", while dolerite has invaded along and across their bedding planes (Du Toit, 1905, p.131).

The structure of the larger xenoliths that have been bent into a dome shape, is described in the following section. A brief indication of their lithology is given. In this area it becomes particularly noticeable how most of the larger xenoliths have been deformed by the dolerite. Other interesting xenoliths, occurring immediately outside this area, e.g. on Romance, are also described here. The smaller xenoliths of the bell-jar intrusion in general do not show any structural complexities, and in most cases will not be individually described.

(i) The Molteno Xenoliths.

Towards the northern corner of Branstone there is a large xenolith dipping between 60° and 70° towards the north-west (see centre of grid reference J 11 and Plate VIII, Fig. 1). Lithologically, the xenolith is composed of yellowish, cross-bedded, medium- to coarse-grained sandstone beds, with interbedded mudstones. The latter beds are generally covered with soil and vegetation and only in the north-west portion of the xenolith were greyish to pale green, thin mudstone beds actually exposed. The total thickness of sediments in this xenolith is approximately 430 metres (1300 feet).

The cross-bedding noted within the sediments of this xenolith appears to be in the normal orientation, and the xenolith as a whole is therefore not inverted. A few very thin, highly weathered basic dikes (measuring only 2 to 3 cm. in thickness), cut across the bedding planes of some of the sandstone beds, near the base of the xenolith.

Directly south of this xenolith are two smaller Molteno xenoliths, also dipping steeply to the north-west (see bottom of grid reference J 11). The sediments in the southernmost xenolith are typical coarse-grained felspathic sandstones and grits of the Molteno Stage, while the northern one is composed of less coarse-grained rocks than the southern xenolith, but the sandstone beds have large-scale trough bedding, which

Fig. 1: Xenolith of Molteno sediments in the foreground, dipping steeply towards the left (centre of grid reference J 11). Picture taken on Branstone, facing north-east. In the background is another xenolith composed largely of Cave Sandstone. Dolerite of the bell-jar intrusion forms rounded and dome-shaped hills in the background.

Fig. 2: Flow structure within a rheomorphic glassy vein emplaced within a tilted xenolith, on Romance (north-west corner of grid reference K 11).

is another characteristic of the Molteno beds in the Birds' River area.

(ii) The Red Beds and Cave Sandstone Xenoliths.

The Red Beds sediments occurring as xenoliths in this area appear as masses largely of elongate habit, with elongation directed along the strike of the sediments. The sediments dip in south-westerly and north-easterly directions, forming an anticlinal structure (see Fig. 2). Dips in the western limb of the anticline vary from 35^{o} to 70^{o}, while in the eastern limb a dip of 65^{o} was measured.

The dolerite of the bell-jar intrusion has extensively invaded along and across the bedding planes of this anticlinal structure; this has resulted in the presence in this area of a number of smaller, mostly elongate xenoliths, with similarly directed, but varying degrees of dip.

Lithologically the sediments are composed of yellowish, medium-grained, sandstone beds, and purple, red and greyish coloured mudstone beds. Towards the south-western extremity of these xenoliths, dolerite sills, which appear to be of a different age to the bell-jar dolerites, have intruded along the bedding planes of the sediments. Du Toit gives the age of these sills as older than the dolerites of the bell-jar intrusion (see Fig. 2).

An example of the ability of the invading dolerite to deform the larger xenoliths is illustrated by the rapidly changing strike direction and the varying amount of dip measured in a xenolith occurring in the east of this area (south-west corner of grid reference K 12). The xenolith is composed almost entirely of yellowish, medium-grained, sandstone beds, dipping towards the east and south-east. The strike of the sediments is approximately north in the northern half of the xenolith, but swings progressively around to a north-easterly direction in the south of the xenolith. The amount of dip measured in the sediments also increases very rapidly in this direction.

An arcuate strip of sediments, composed of Red Beds and

Cave Sandstone, forms the outer margin to the dome-like form defined by the disconnected Branstone xenoliths (grid references: western portion of I 12, extending on to I 13, then swinging north-east into J 13 and J 12). The Red Beds dip mainly to the south-west in the western portion of the arc, and to the south-east in the eastern portion of the arc. The direction of strike within the Red Beds sediments is variable in the western portion of the arc, while the amount of dip recorded varies from 15° to 70°, mostly towards the south-west.

The Cave Sandstone Stage overlies conformably the Red Beds in the south of the arc, and dips steeply towards the south (grid reference J 13). The Cave Sandstone here occurs more than 300 metres (1000 feet) below its normal stratigraphic elevation and is composed of a very fine-grained sandstone, with associated patches of pale-green, highly weathered agglomerate. Large-scale cross-bedding is present near the base of the sandstone. Du Toit has recorded that this occurrence of Cave Sandstone measures fully 107 metres (350 feet) in thickness (Du Toit, 1905, p.131). Along its eastern margin particularly, the Cave Sandstone has been baked to a fine-grained quartzite, which is highly jointed at its contact with the dolerite of the bell-jar intrusion. North of this mass of Cave Sandstone a strip of Red Beds conformably underlies it, and dips towards the south-east.

Inside of the southern portion of the arcuate strip of sediments just described, there occurs a smallish xenolith of Red Beds which does not conform to the normal dome-like structure defined by the Branstone xenoliths (western margin of grid reference J 13). The xenolith is composed almost entirely of cross-bedded, medium-grained sandstone beds, dipping between 25° and 45° to the north. As indicated by the cross-bedding, the xenolith does not appear to be inverted. Its southern contact is not exposed in the field, and, in view of the fact that the xenolith appears to dip in the opposite direction to the general pattern of dips of most of the xenoliths in this area, the writer has interpreted this as an isolated xenolith, and therefore not part of the mass of Cave Sandstone occurring immediately to the south.

(iii) Xenoliths not forming part of the Dome Structure.

Towards the western corner of Romance, and situated immediately to the north-east of the largest Molteno xenolith previously described on Branstone, occurs a large xenolith of interesting lithological and structural complexity (north-west corner of grid reference K 11; also see Plate VIII, Fig. 1). This appears to be composed of Cave Sandstone, Red Beds and pyroclastic rocks.

In its central portion a yellowish coloured, often spotted, fine-grained sandstone, with patches of greenish, weathered agglomerate are to be found. These features are characteristic of the Cave Sandstone Stage in the Birds' River area. Bedding is not clearly defined in the sandstone, but the dip appears to be approximately 30° to the north.

The patches of agglomerate, associated with the sandstone, do not occur in any defined orientation that might suggest clear interbedding with the sandstone. In some places the agglomerate appears to be vein-like, but the possibility of the agglomerate having an intrusive habit is not favoured by the writer, as no metamorphic effects were noted at the contact with the sandstone.

Within the Cave Sandstone Stage there is a vein of what appears, in the field, to be a black glassy rock. The vein, generally less than 1 metre (3 feet) thick, does not form a continuous outcrop and trends in a north-westerly direction, swinging progressively westwards till the trend becomes west. The dip is approximately 45° to the north-east, in the east, but acquires a more northerly component as the strike-direction changes.

There are signs of a brecciation at the contact with the sandstone, while the vein itself shows flow structure (see Plate VIII, Fig. 2). The lines of flow within the vein conform with the attitude of the vein, i.e. they are parellel to the contact at, and a few centimetres away from the contact, but in the centre of the vein they become haphazard. As regards the formation of this vein, an origin by melting and flowing of sedimentary material caused by gas streaming through a fissure in the rock, is favoured by the writer.

The nature of the sediments changes towards the margin of this xenolith. Further north from the Cave Sandstone and agglomerate exposures, as one progresses downhill into the valley, the sediments gradually become coarser in grain size and clear indications of small-scale cross-bedding can be found. Dip measurements within these sediments, just below the Cave Sandstone Stage, show that the dip is very shallow, but in the opposite direction to the Cave Sandstone. In the stream bed itself the sediments appear to be vertical, while along the northern margin of the xenolith they dip steeply towards the south. Medium- to coarse-grained sandstones form the southern margin of the xenolith and everywhere they appear to dip away from the dolerite contact.

Due to their marked difference in grain size, and the presence of small-scale cross-bedding, the sediments forming the northern, western and south-western margin of the xenolith have been interpreted as belonging to the Red Beds Stage of sediments, which conformably underlies the Cave Sandstone Stage. The south-east portion of the xenolith is composed of pyroclastic rocks with an amygdaloidal lava flow forming the base of the pyroclastics. The eastern margin of the xenolith is not clearly defined in the field. A necessary result of the interpretation of the eastern boundary given above is that a thin sheet of dolerite separates the xenolith in question from the larger pyroclastic xenolith occurring further east.

The dolerite of the bell-jar intrusion separating this xenolith from the larger Molteno xenolith immediately to the south-west, appears in hand specimen to contain a large proportion of sedimentary inclusions. This is not surprising, for the two large xenoliths that it separates belong to different stratigraphical horizons, and these xenoliths must have moved relative to each other a total distance of some 500 metres (1500 feet), within the dolerite magma, in order to occupy their present position at approximately the same elevation above sea level. In so doing a certain amount of abrasion between the xenoliths most probably took place.

The thin sheet of dolerite separating the two xenoliths, acting as the "lubricating agent" between them, most probably incorporated a certain amount of the abraded material released by this process.

A further illustration of a xenolith that has been deformed by the dolerites of the bell-jar intrusion is to be found to the north-west of the Red Beds xenoliths which form part of the dome shape of sediments on Branstone (straddling grid references H 11 and H 12). This xenolith is composed of coarse- and medium-grained sandstones and mudstones, which have been metamorphosed at their contact with the dolerite. The outer margin of the xenolith dips steeply away from the dolerite contact while shallow angles of dip were measured within the xenolith.

(c) The Xenoliths of Pyroclastic Rocks.

Within the eastern and south-eastern areas of the bell-jar intrusion occur two very large xenoliths of pyroclastic rocks. The larger of these two extends from Branstone in the west to Thysfontein in the east (a distance of 4.2 kilometres (2.5 miles)). Its shorter north-south axis measures approximately 3.5 kilometres (2.2 miles).

Due to the largely unbedded nature of the pyroclastics in this xenolith only a few dip measurements could be taken over its entire surface area. It appears, from the shallow angles of dip that were measured, that the xenolith as a whole has not been subjected to very much structural disturbance by the dolerites. Its present structure is therefore one of an almost flat-lying blanket, which has been extensively invaded by dolerite sheets of the bell-jar intrusion. Because of its flat-lying attitude, and because erosion has removed a considerable portion of the pyroclastic material, it would be difficult to estimate the original thickness of this xenolith.

Du Toit suggests that this xenolith is a huge inclusion of volcanic ash which has been torn off from the Cave Sandstone Stage, and isolated in the dolerite of the bell-jar intrusion (Du Toit, 1911, p.134). The detailed mapping by the writer, however, reveals that it is much larger and has a very different shape to that pictured by Du Toit.

A great variety of pyroclastic and metamorphic rock types are to be found within this xenolith. The writer intends to give here only an outline of the rock types and their distribution; a more detailed description of the pyroclastic and metamorphic rocks will be given in the appropriate chapters.

The pyroclastics vary from a volcanic breccia which appears to be composed almost entirely of sedimentary blocks set in a siliceous matrix, through tuffs, to agglomerates with varying proportions of igneous and sedimentary inclusions. Occasional amygdaloidal lava flows occur within the pyroclastics (see grid reference N 11). Siliceous material of sedimentary origin, resembling normal sandstones, tends to predominate towards the base of the xenolith, with the proportion of agglomeratic material and igneous inclusions increasing upwards. Veins and irregular patches of zeolites are to be found within the pyroclastic rocks, especially towards the western extremity of the xenolith, where they occur in abundance.

Metamorphism of the pyroclastics by the dolerite of the bell-jar intrusion has been very intense. Black to bluish, flinty, baked pyroclastics are commonly found in contact with the dolerite, while several occurrences of spotted rocks (resembling hornfelses) occur along the south-eastern edge of this xenolith. Parallel jointing is strongly developed within the pyroclastics and for a few metres away from the contact with the dolerite.

An area of rocks of metasomatic origin occurs in the south-eastern corner of Lemoenfontein (see grid reference N 10 and Plate IV, Fig 2). Mr. A.K. Kenyon of Rhodes University is at present making a study of these rocks to determine the changes brought about in metasomatic rocks through dolerite solutions. This study will form part of the subject-matter for his M.Sc. thesis.

At the head of the Grootkloof valley, and to the east of the metasomatic rocks (approximately north-east corner of grid reference N 10, but not indicated on the maps) there occurs, within the pyroclastic xenolith, an outcrop of yellowish to white, massive, fine-grained sandstone. The contact of this outcrop is obscured by soil and vegetation cover in the field. The outcrop of sandstone is most probably a bed of Cave Sandstone that occurs interbedded with the pyroclastics. Several thin strips of sandstone, of similar appearance to this, are to be found within the pyroclastics in the north-eastern portion of this xenolith.

Towards the centre of this xenolith, occasional large blocks of Molteno and Red Beds sediments are to be found. In the extreme western part of the xenolith, on Romance, large blocks of dolerite characterize the upper portion of a particular area of the xenolith. (The latter occur within grid reference K 11.) The agglomerate containing these large dolerite blocks is a particularly interesting rock. Its mode of formation will be discussed in Chapter Five.

The smaller of the two very large xenoliths of pyroclastic rocks, lies to the east of the one just described, on Murrelfontein. It has an elongate shape, with an irregular outline. The larger axis measures almost 3 kilometres (1.7 miles) while the broadest shorter axis has a maximum length of 1 kilometres (0.6 miles).

The latter xenolith has a somewhat basin-like structure, with its eastern margin tilted up to form the high ground in the area. Dips as high as 40° were measured along the "glassy ridge", which forms part of the base of the xenolith (see Plate V, Fig. 1), but they flatten out rapidly westwards. Sheets of dolerite and a north-north-westerly trending dolerite dike are exposed within the southern portion of the xenolith.

Along the western and northern contact of this same xenolith there is what appears in hand specimen to be a highly weathered, fine-grained quartzite (grid reference P 11). The proportion of agglomeratic material and igneous inclusions in the pyroclastic rocks increases rapidly towards the centre of the xenolith; at the "glassy ridge" dolerite inclusions in the pyroclastics are not uncommon.

Metamorphism of this xenolith along its contact with the dolerite of the bell-jar intrusion has been very intense. This is illustrated by the "glassy ridge" where the pyroclastics have become fused to a rock which contains a large proportion of glass. At the southernmost tip of the xenolith there occurs a rock very similar in appearance to the metasomatized rocks of Lemoenfontein (grid reference Q 12).

Lithologically this xenolith appears very similar to the larger one described previously. It seems most probable that the two once formed a single unit which has become separated through subsequent erosion.

The remaining pyroclastic xenoliths are very much smaller in size and are randomly situated within the bell-jar intrusion.

(d) The Remaining Xenoliths.

Only the remaining few larger xenoliths of the bell-jar intrusion will be described. The smaller ones, displaying no additional points of interest, will not be individually mentioned.

On Denwood there is an interesting xenolith which is composed of a rock type not encountered elsewhere in the Birds' River area (see grid reference K 14). A southward-flowing stream has cut a narrow V-shaped valley through it and the dolerites. The xenolith, being more resistant than the surrounding dolerite, forms prominent krantzes on the sides of this valley.

This latter xenolith is composed of a bluish to gray-coloured flinty rock with elongate felspar crystals, measuring up to 2 centimetres in length and haphazardly orientated within the rock. In hand specimen the texture of this rock resembles that of a metasomatic granophyre, recorded by Walker and Poldervaart, at Alewyns Gat, near Beaufort West (Walker and Poldervaart, 1949, p.680). Microscopically the rock is composed largely of anhedral quartz grains, with felspar, magnetite, sphene and a glassy matrix making up the rest of the rock. The texture appears to be one of metamorphic origin, with evidence of replacement by certain minerals. The rock will be described in greater detail in the chapter on metamorphic and metasomatic rocks. The xenolith has therefore been interpreted by the writer as a large inclusion of metamorphosed Molteno sediments. Metamorphism has destroyed all signs of original bedding in the sediments, but it does appear that the entire xenolith is inclined gently towards the north.

To the north-east of the xenolith just described is another Molteno xenolith, composed mostly of coarse-grained felspathic sandstones. This xenolith occurs at the summit of a ridge, and, when viewed from across the broad valley on Romance, i.e. a few kilometres to the east, it appears to be in a nearly vertical attitude. Further mapping indicates that the sediments are nearly vertically inclined at the southern end, while the dips flatten out towards the northern extremity.

On Romance there is an elongated xenolith measuring almost 2 kilometres (1.2 miles) in length (see grid references L 12 to M 13). The shallow dips measured within the sediments reveal that it has a gently synclinal structure. It is composed of yellowish, greenish and reddish medium- to coarse-grained felspathic sandstones and mudstone beds, the latter being largely metamorphosed to lydianite. The sediments of this xenolith, and another smaller one occurring immediately to the south-east, have been regarded by the writer as belonging to the Red Beds Stage, although evidence in favour of this interpretation is not entirely satisfactory.

A north-westerly trending dolerite dike cuts through the sediments in the northern portion, while the Dragon's Back dike cuts across the southern portion of this xenolith.

On Murrelfontein there are a few large Molteno xenoliths but they do not appear to display any additional points of structural interest (see grid references O 13 and P 14).

The southernmost occurrence of sediments within the area of the bell-jar intrusion occurs on Rockcliff, and is traversed by the Sterkstroom - Indwe railway-line. Erosion has been more concentrated within this occurrence of sediments than the surrounding dolerite; this has resulted in a wide gap being formed between the southern margin of the bell-jar intrusion (represented by Sugarloaf Hill) and the main mass of dolerite towards the north (see Plate II, Fig. 1). Two north-westerly trending dolerite dikes cut across these sediments. The sediments as a whole do not appear to be structurally disturbed; they tend to retain the attitude of those occurring immediately outside the bell-jar intrusion. As the intrusion more than likely becomes sheet-like in nature in the south-eastern area, this occurrence of sediments most probably represents part of the original "roof" of sediments which has not been detached by the dolerite of the intrusion.

Small xenoliths of volcanic breccia are to be found on Die Smuts Pass (grid reference G 9), and Lemoenfontein (grid reference K 8). Very small xenoliths of glassy rock also occur in the same vicinity.

Along the northern margin of the complex a few small Red Beds xenoliths occur within the dike-like portion of the bell-jar intrusion.

7. Veining Phenomena within the Bell-jar Intrusion.

The following veining phenomena are to be found within the bell-jar intrusion :-

(a) Rheomorphic Veins in Dolerite.

(b) Rheomorphic Vein in Sedimentary Xenolith.

(c) Zeolite Veins within the Xenoliths.

(d) Quartz Veins.

(a) Rheomorphic Veins in Dolerite.

A number of rheomorphic veins are to be found within the bell-jar intrusion, just below the largest pyroclastic xenolith on Lemoenfontein (grid reference M 9). In width they vary from approximately 8 centimetres (3 inches) up to 45 centimetres (18 inches) and occur along horizontal joints in the dolerite. In certain parts the veins are characterized by vugs filled with quartz crystals (see Plate IX, Fig. 1).

The rock making up these veins is composed of quartz grains, some of them showing strain shadows, and occurring in clusters, with felspar making up by far the greater proportion of the constituent minerals, while pyroxene and iron ore ? are present in minor amounts. A micropegmatitic intergrowth of quartz and felspar occurs in parts of this rock and is very similar to that found in some of the metasomatic rocks within the pyroclastics, on Lemoenfontein. The rheomorphic veins therefore most probably originated from the pyroclastic xenolith, which they underly, but they cannot be shown to be directly connected. They were probably drawn, in a plastic state, into the cooling and largely crystallized dolerite magma. This must be so, otherwise no connection with the joints in the igneous rock should be shown.

(b) Rheomorphic Vein in Sedimentary Xenolith.

This vein occurs within a xenolith composed of Cave Sandstone, Red Beds and pyroclastics in the north-west corner of Romance, and has been described earlier on in this chapter (north-west corner of grid reference K 11).

(c) Zeolite Veins within the Xenoliths.

Within the pyroclastic xenoliths, notably on Romance and Lemoenfontein, an abundance of zeolitic material occurs in the form of veins, but also as fillings in the pore spaces in the pyroclastics, and joints in some of the sedimentary xenoliths.

Two varieties of zeolites were identified by the writer, viz. stilbite, showing the typical radiating structure noticed in some zeolites, and heulandite, which occurs in

PLATE IX

Fig. 1: Rheomorphic vein within the dolerite of the bell-jar intrusion. Note small vugs in the vein (grid reference M 9).

Fig. 2: Slickensided surface within sediments near the contact with the more northerly ring dike on Boshoffs Kraal (2). Rooiberg, a hill composed of Red Beds sediments, is in the background. Picture taken facing north-east.

tabular crystals. The following optic properties which appear to be consistent with those given by Deer, Howie and Zussman (1963, p.377), were measured :-

Stilbite	Heulandite
Nx = 1.490	Nx = 1.497
Nz = 1.498	Nz = 1.500
Nz - Nx = 0.008	Nz - Nx = 0.003
Biaxial negative	Biaxial positive
2V approx. 25°	2V approx. 30°

For confirmation of their identity these two minerals were determined by the powder diffractometer method. Each mineral was ground to a fine powder, mounted on a glass slide and X-rays from the GEC XRD 3 diffractometer allowed to pass through it. The diffraction pattern for stilbite is recorded in Fig. 5 and that for heulandite in Fig. 6. The diffraction data are recorded in tables II and III.

The 2θ angles were obtained directly from each diffraction pattern and the corresponding d spacings were read off from the appropriate tables. Comparative results of the d spacings and intensity peaks for stilbite and heulandite are included in tables II and III. The values for stilbite were obtained from the A.S.T.M. powder diffraction file, index 10-433. Those for heulandite were taken from Merkle and Slaughter (1968). From tables II and III it can be seen that for each of the two minerals, stilbite and heulandite, the d spacings match fairly well, although the relative intensities show discrepancies. Such discrepancies might well be expected from this superficial examination, in which no effort was made to eliminate the effects of preferred orientation in the powder mount.

According to Dana (1949, p.644) all zeolites are secondary minerals. They occur most commonly in cavities in basic rocks where the soda and lime have chiefly been yielded by felspar.

The origin of the zeolites occurring within the xenoliths of the bell-jar intrusion, is most probably largely related

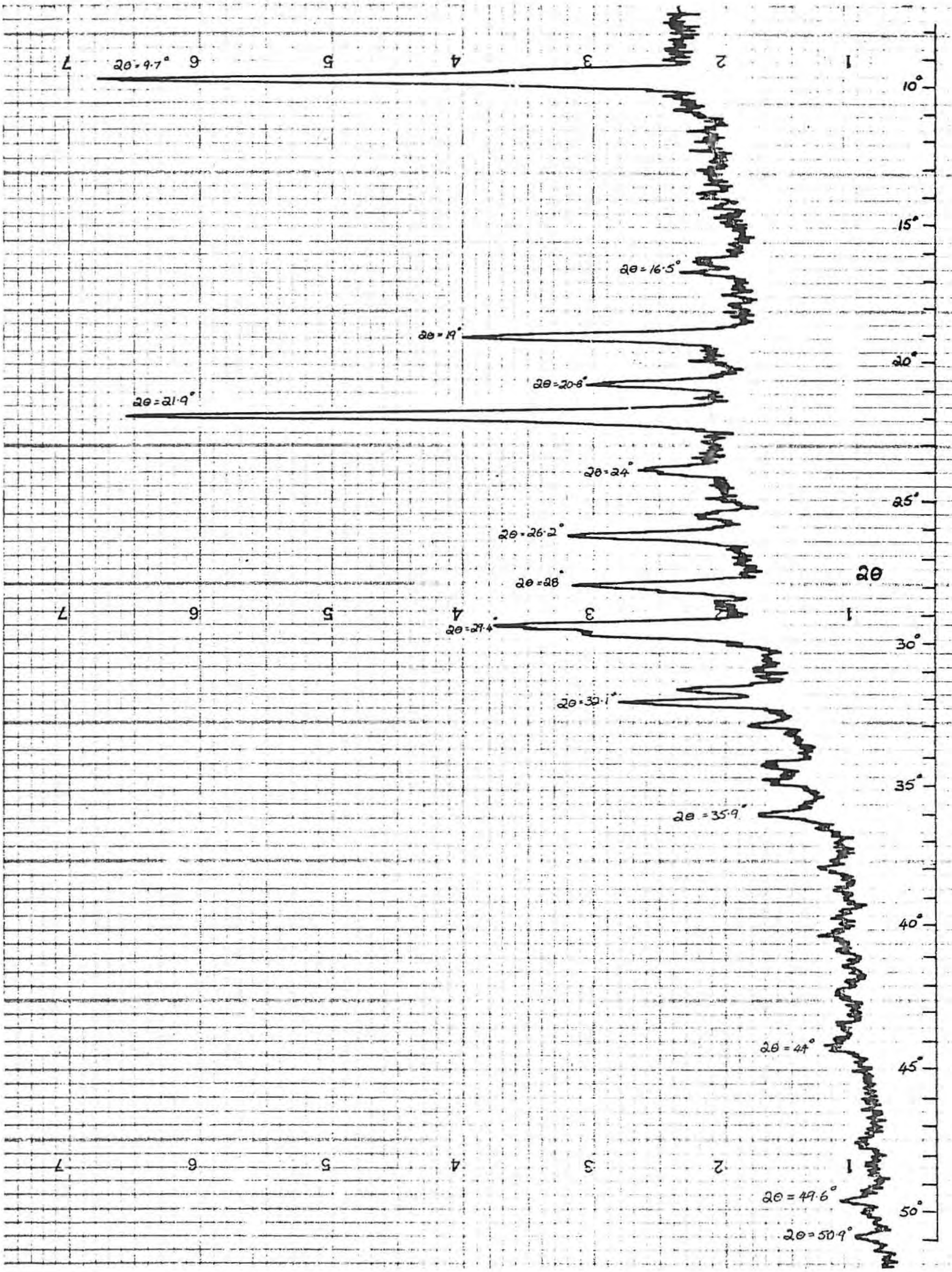

Fig. 5. Diffraction record of stilbite

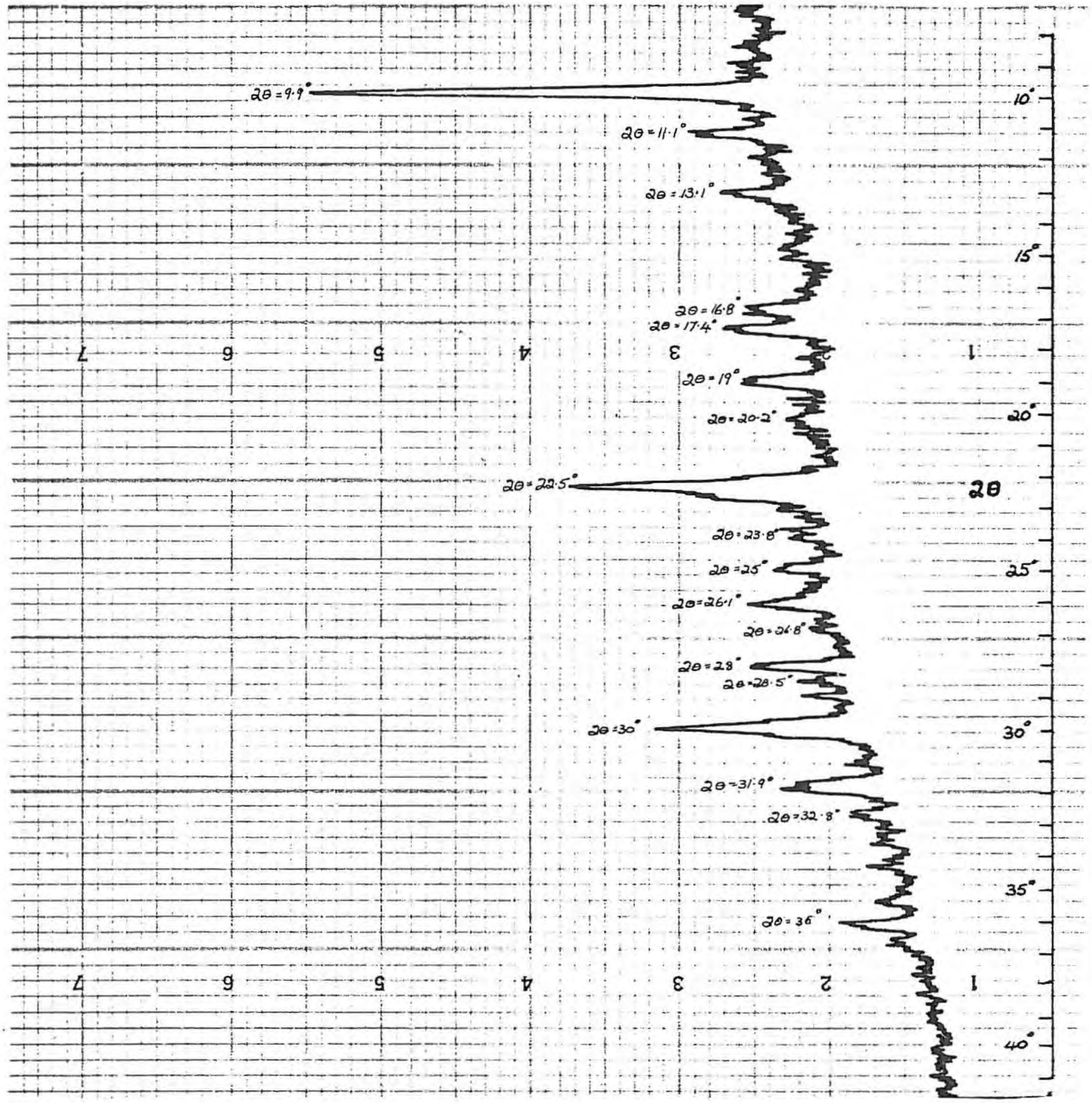

Fig. 6. Diffraction record of heulandite

to dolerites of the bell-jar intrusion, for they appear to occur most often in close proximity to this rock, especially near the upper parts of intrusive bodies.

(d) Quartz Veins.

On the southern slope of a dome-shaped hill approximately in the centre of the bell-jar intrusion, on Lemoenfontein, occur a few pale-coloured veins (grid reference L 10). The veins do not appear to exceed 2.5 centimetres (1 inch) in width, and are composed essentially of quartz.

B. SHEETS IN THE AREA SURROUNDING THE BELL-JAR INTRUSION.

Numerous dolerite sheets of variable sizes occur in the area surrounding the bell-jar intrusion. In the northern half of the area shown on Map No. 1, the larger sheets tend to form the high ground, and give rise to rugged topography. The sheets intruded into the Molteno sediments in the south are generally very flat lying and form part of an undulating plain which occurs at approximately 1500 metres (5000 feet) above sea level.

For descriptive purposes the larger sheets will be referred to by farm or other locality names, although in most cases the sheets do extend across several farms, e.g. the Birds' River sheet, in the south of the area shown on Map No. 1, extends from Glen Wallace in the west, across The Glen and Denwood, to Sunnyside. The sheets in the area surrounding the bell-jar intrusion will be described under the following names :-

1. The Vogel Vlei Sheet.
2. The Koups Leegte Sheet.
3. The Birds' River Sheet.
4. The Stafelberg's Kloof Sheet.

1. The Vogel Vlei Sheet.

To the north-east of the bell-jar intrusion is a very thick dolerite sheet which has an arcuate shape, and which extends from Snymans Kraal in the north, through Boshoffs Kraal (2), Lemoenfontein, Thysfontein and then swings north into Vogel Vlei. An eastern extension of this sheet becomes very much thinner where it appears on Palmietfontein.

The sheet as a whole extends further north, beyond the area of Map No. 1. It has an arcuate shape with the longer axis of the arc measuring approximately 9.6 kilometres (6 miles). Where it occurs on Map No 1, the sheet is everywhere inclined toward the centre of the arc (except for its eastern extension), and on Lemoenfontein (grid reference M 6) its dip was measured as varying between 15^{o} and 20^{o} towards the north-east.

The southern, outer limit of the sheet is exposed as a steep cliff face of columnar-jointed dolerite, and forms the high ground of the area immediately to the north-east of the bell-jar intrusion.

The sheet occurs largely in Red Beds sediments, but on Snymans Kraal and Boshoffs Kraal (2), in the northern area of Map No. 1, as well as in the northern corner of Thysfontein, it has penetrated the Cave Sandstone Stage.

It appears that the sheet is a composite intrusion, for a fine-grained rock is present near the base, and a very much coarser-grained rock occurs in the central portion of the intrusion. The coarse-grained rock has a spotted appearance on a freshly cut surface of the rock, while its weathered surface is often uneven and knobbly, similar to the dolerites of the bell-jar intrusion.

2. The Koups Leegte Sheet.

Occurring on the farm Koups Leegte, to the east of the bell-jar intrusion, is a dolerite sheet which appears very similar to the Vogel Vlei sheet. It has an oval shape (only half of the intrusion appears on Map No. 1), but it is much smaller in size than the Vogel Vlei sheet, and it does not, for the most part, form the high ground of this area. Where it appears on Map No. 1 the sheet dips towards the centre of the arc.

The sheet has been intruded largely across the Molteno - Red Beds contact in this area. The characteristic vivid colouration of the Red Beds sediments has, as a result, been largely bleached out by the dolerite.

The Koups Leegte sheet is composed of a coarse-grained dolerite, very similar in appearance to that occurring within the Vogel Vlei sheet.

3. The Birds' River Sheet.

The Birds' River sheet, to the south of the bell-jar intrusion, extends from Glen Wallace in the west, across The Glen and Denwood, to Sunnyside, and continues southwards, out of the area shown on Map No. 1. The sheet is flat-lying, and forms part of the undulating plain cut across the Molteno sediments in the south. The dolerite of this sheet is a medium-grained rock, and is highly weathered in several places within the intrusion.

The smaller sheets occurring on The Glen, to the north of the Birds' River sheet, most probably represent remnants of a once continuous network of dolerite sheets in this area.

4. The Stafelberg's Kloof Sheet.

To the west of the bell-jar intrusion occur a number of ramifying dolerite sheets which have invaded Red Beds and Molteno sediments from Klip Kraal in the north to Jansenfontein in the south.

In the west of Stafelberg's Kloof and on Droogefontein, a dolerite sheet forms the high ground (approximately 1800 metres (6000 feet) above sea level) in this area, while further south, on Stafelberg's Vlei, Jansenfontein and Gelegenfontein, the dolerite sheet merges with the undulating lower plain which has been cut across the Molteno sediments. In several areas where the dolerite crops out within this plain, it is highly weathered.

The sheet on Stafelberg's Vlei does not appear to be cut by, or to link up with the bell-jar intrusion (see grid reference G 12). The relative ages of these two intrusions can therefore not be stated with certainty, but it does seem more likely that the sheet is of a greater age than that of the bell-jar intrusion. This argument is based on a general impression that the dolerite sheets in the Birds' River area appear to be the oldest, and dikes the youngest intrusive forms. As the bell-jar intrusion is cut by several dikes in this area, but apparently not by any sheets, its age is presumed to be less than that of the sheets, and definitely greater than that of the dolerite dikes which cut across it.

On the boundary between Stafelberg's Kloof and Boshoffs Kraal (1) (see grid reference E 8) there is an isolated dolerite sill. This sill most probably formed part of the Stafelberg's Kloof sheet which occurs to the west of it.

C. THE DOLERITE DIKES.

The dolerite dikes of the Birds' River area can conveniently be grouped into the following categories :-

1. The Ring Dikes.
2. The Dragon's Back Dike.
3. Other Dolerite Dikes.

1. The Ring Dikes.

To the north of the bell-jar intrusion occur two strongly curved dolerite dikes, and a third, less continuously developed, outer one (see grid reference G 3). The two more continuous dikes are of variable width and in places appear to broaden out into small "blows" (see grid references H 4 and F 5). On Boshoffs Kraal (1) they join and give the impression of crossing over (see grid reference F 8). One of them continues south-eastwards from this position, and, although evidence of its being cut off, or joining up with the bell-jar intrusion, is not clear in the field, the former interpretation has been adopted by the writer, as will be discussed in Chapter Eight. The outer ring dike continues southwards from this area, but fails to crop out for a distance of approximately 500 metres (1640 feet), until it reappears on Stafelberg's Kloof, where it swings eastwards and is apparently cut off by the bell-jar intrusion. The interpretation given above also applies here, viz. that field evidence is not entirely convincing, as regards the relative ages of the ring dikes and the bell-jar intrusion, but the structural interpretation of the mechanism of formation of the bell-jar intrusion becomes clearer if the ring dikes are regarded as older in age than the bell-jar intrusion.

Evidence of faulting and other structural disturbances, especially within the sediments between the two more continuous ring dikes on Boshoffs Kraal (1), and near the contact of the dikes, is indicated by the numerous exposures of slickensided surfaces within the Red Beds sediments (see Plate IX, Fig. 2). It appears then that these dolerite dikes have been intruded into arcuate fault zones in this area.

Dips measured on slickensided surfaces in the sediments near the contact with the dikes vary from 45° to 60° towards the centre of the arcs, but no direct dolerite - sediment contact could be found in the field. The steeper dips were, however, recorded near the outermost fracture zone (grid reference G 3). Thus the true nature of the angle of dip of the ring dikes was not established, but it does seem likely that they dip steeply in toward the centre of their arc shape. The ring dike of Stafelberg's Kloof, however, does appear to be vertical. Holmes (1965, p.262) notes that dips of ring dikes are either vertical or that they may dip inwards according to the erosion level at which they are now seen, and therefore they need not necessarily always be outwards. The arcuate features to the north of the bell-jar intrusion could quite possibly represent cone sheets. The writer does not, however, favour this interpretation for the following reasons :-

(i) The steepest slickensided surfaces observed were those near the contact of the most northerly dolerite intrusion (those furthest away from the centre of the arc) (grid reference F 4). This observation is not consistent with Holmes' (1965, p.261) interpretation of cone sheets for he writes, "The outer-most sheets tend to flatten towards the surface, suggesting that their three-dimensional form may resemble the outward opening end of a trumpet".

(ii) The curved north-westerly trending dike on Stafelberg's Kloof, which appears to be in continuity with the arcuate features to the north of the bell-jar intrusion, is vertical, and is apparently truncated by the latter intrusion (see grid reference G 10), although no conclusive evidence of this could be gained in the field. Because of its vertical attitude the writer has interpreted this dike as a true ring dike.

To the south of the bell-jar intrusion, on Denwood, there is a narrow dolerite dike, trending in an easterly direction, parallel to the contact of the bell-jar intrusion. There is a possibility that it may be another ring dike, although there is no convincing evidence, in the field, that it has been intruded along a fracture zone.

2. The Dragon's Back Dike.

The Dragon's Back dike cuts across the complex in a north-westerly direction. As can be seen on Map No. 1 it appears to have been intruded in an offset manner along some of its length (see Plate X, Fig. 1), and to cut through most other intrusive forms and sedimentary formations. The dike therefore represents the youngest phase of igneous activity in the Birds' River area.

The Dragon's Back dike forms a prominent topographic feature along almost its entire length (see cross-section C-D), and on Branstone it protrudes as a sheer wall several metres above the invaded rock.

Fig. 1: The Dragon's Back dike, intruded in a north-westerly direction across the complex. Facing south-east (south-east corner of grid reference H 10).

Fig. 2: Rooiberg, to the north of the bell-jar intrusion. Picture taken from the Molteno - Dordrecht road, facing east, illustrating sharp contact between Red Beds and Cave Sandstone.

The dike varies between 6 to 10 metres (20 to 30 feet) in width, and is composed of a gray, fine-grained doleritic rock. Columnar jointing, perpendicular to the walls, is well developed within the dike. Towards its southern extremity, the dike crops out less continuously.

3. Other Dolerite Dikes.

The remaining dolerite dikes, presumably older in age than the Dragon's Back dike, are fairly numerous in the Birds' River area. The majority form linear features of extremely variable length.

One of the longest dikes is to be found in the east of this area. It trends in a northerly direction from Vogel Vlei, through Thysfontein to Murrelfontein. Its continuity further southwards could not be traced beyond the contact with the bell-jar intrusion, on Murrelfontein. The dike is therefore presumed to be cut by the latter intrusion. This makes it older in age than the bell-jar intrusion, but younger than the Vogel Vlei sheet, for the dike appears to cut through the latter (see grid reference O 7).

Near its southern extremity on Murrelfontein (grid reference P 10) the dike does appear slightly bent in toward the bell-jar intrusion, as well as being steeply inclined towards the east. This feature is more obvious in the field than is indicated by the maps.

Immediately to the south of this dike, within a pyroclastic xenolith, there is another dolerite dike which could quite possibly be a southward continuation of the Thysfontein dike just described. However, the writer feels that further confirmation is needed for this interpretation to be accepted.

Some of the remaining dikes are of a younger age than the bell-jar intrusion, as they cut across the latter complex (see grid references J 6 and I 6). The relative ages of the majority of the dikes cannot be determined on field evidence.

The dikes in general are composed of a gray to black, fine- to medium-grained dolerite showing spheroidal weathering at their contacts with the country rock. The majority of these dikes in the Birds' River area appear to trend in a north-westerly direction, with a complimentary set approximately at right angles to this.

* * *

II PETROGRAPHY OF THE IGNEOUS ROCKS.

A superficial investigation into the petrography of the igneous rocks was undertaken by the writer. The findings may be grouped into the following headings :-

A. Dolerite Types.
B. Micrometric Data.
C. Chemical Data.

Methods Used:

Optical constants, such as optic axial angles and extinction angles, were measured on a four-axis universal stage. Measurements were designed to :-

(i) Obtain the composition of plagioclase crystals by making use of albite and pericline composition planes, and cleavage directions in albite twins. The composition was determined from the extinction angles given by Chudoba and Kennedy (1933, p.45).

(ii) Determine 2V angles of augite, as in the method outlined by Hess (1949, p.629). The accuracy of 2V angle measurements, after applying a correction for errors caused by the differences in refractive index values between the glass hemispheres of the universal stage and those of the pyroxenes, is ± 0° 30'. The corrected reading in most cases was approximately 1° 30' less than the observed 2V angle reading.

Ny values of augite were obtained by immersion methods. The refractive index liquids used were standardized with a Jelly-Leitz refractometer after each determination was made, but temperature control was not taken into account. The accuracy of the refractive index values is therefore ± 0.002.

A. DOLERITE TYPES.

General Description:

Samples taken over most of the area of the bell-jar intrusion indicate that there are several varieties of basic rock. These vary from fine- to coarse-grained dolerites, with essential minerals in each case being plagioclase and pyroxene, while minor constituents include olivine, apatite, iron ore, micropegmatite and quartz.

The various rock types of the bell-jar intrusion may be distinguished, very broadly, on a textural and grain-size basis, as well as by the presence, or absence, of certain minerals. The contact rocks are fine and medium grained, while the major portion of the bell-jar intrusion consists of coarse-grained types.

Some of the sheets and dikes in the area surrounding the main intrusion share certain petrographical similarities with the latter.

For purposes of description the dolerites have been divided into those occurring in :-

1. The Bell-jar Intrusion.
2. Dolerite Sheets Surrounding the Bell-jar Intrusion.
3. Dolerite Dikes.

1. The Bell-jar Intrusion.

In this preliminary study a superficial and tentative classification of the dolerites is given 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.

Other aspects of interest, such as the dolerite sills within the area of the bell-jar intrusion, the order of crystallization of the minerals in the dolerite, and variations shown by rocks and their constituent minerals, are included. The dolerite pegmatites have not been investigated.

(a) Contact Rocks.

(i) Tholeiite.

This rock is to be found along the eastern margin of the intrusion, on the farm Lemoenfontein. Microscopically, the rock is medium grained with an ophitic texture. Occasional glomeroporphyritic aggregates of broader plagioclase crystals, sometimes containing irregular inclusions, and generally of greater length than the rest of the plagioclase laths, are to be found.

Plagioclase forms approximately half of the rock, by volume. The larger, glomeroporphyritic aggregates of plagioclase are of more sodic composition (An_{60}) than the narrower laths contributing to the ophitic texture, where a maximum value of An_{80} was measured. Zoning in the former plagioclase is less marked than in the latter, where the range may be as much as 26% of anorthite molecule. Some of the plagioclase crystals are bent and fractured.

Clinopyroxenes, pigeonite and augite, occur as anhedral grains generally not longer than 2 millimetres. Pigeonite and augite appear as individual grains. Augite yielded the following optic properties :-

$2V_z = 44.5^{\circ}$, $Ny = 1.686$.

Olivine is anhedral, and has been slightly altered to pale green serpentine, and a reddish brown mineral with a high birefringence. The latter mineral has not been identified by the writer; its general appearance corresponds closely to iddingsite, a hydrothermal alteration product of olivine.

Wisps of microlites in a greenish glassy mesostasis are characteristic of this rock type. Small, irregular grains of iron ore occur disseminated within the mesostasis, and are sometimes found to surround pyroxene crystals. Thin needles of apatite are frequently associated with the mesostasis and sometimes occur in grains showing parallel orientation.

The distinguishing features of this rock are its medium grain size, ophitic texture and glassy mesostasis.

(ii) Intergranular Type.

This rock type occurs in the chill zone along the western margin of the bell-jar intrusion, on Branstone. The rock is fine grained, with an intergranular texture, and occasional phenocrysts of zoned plagioclase and pyroxene crystals (see Plate XI, Fig. 1).

All the minerals have an anhedral shape, indicating that the rock cooled too rapidly against the invaded sediments to allow development of distinctive crystal habits.

Small grains chiefly of augite, with a very small amount of olivine, are surrounded by a network of plagioclase grains. Iron ore appears to be fairly evenly disseminated throughout the rock.

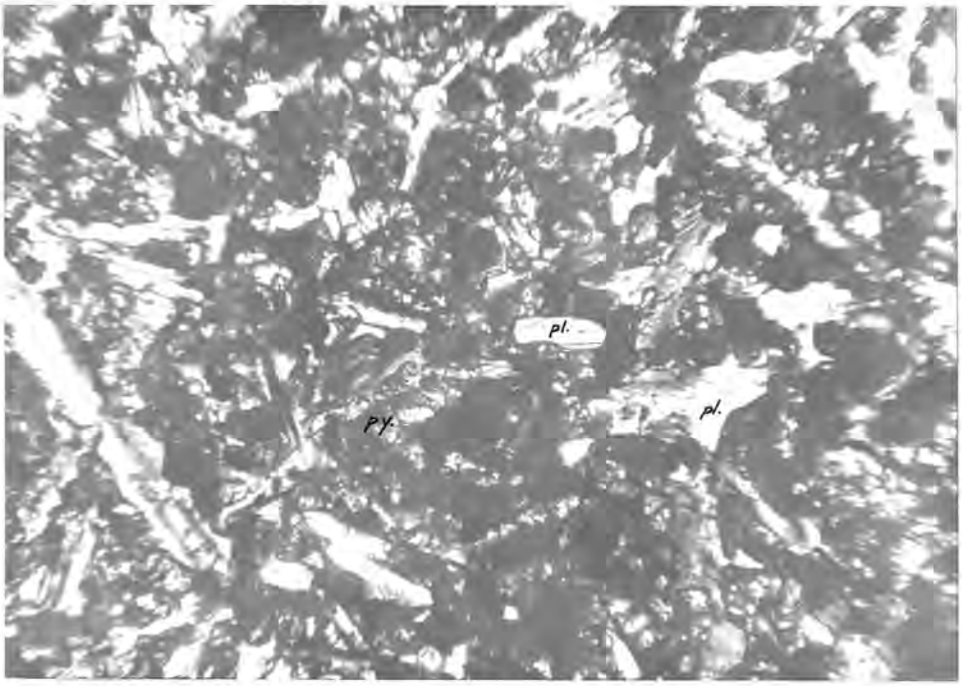

Fig. 1: Photomicrograph showing intergranular texture in dolerite. X 12, crossed nicols. Note anhedral grains of plagioclase (pl) and pyroxene (py).

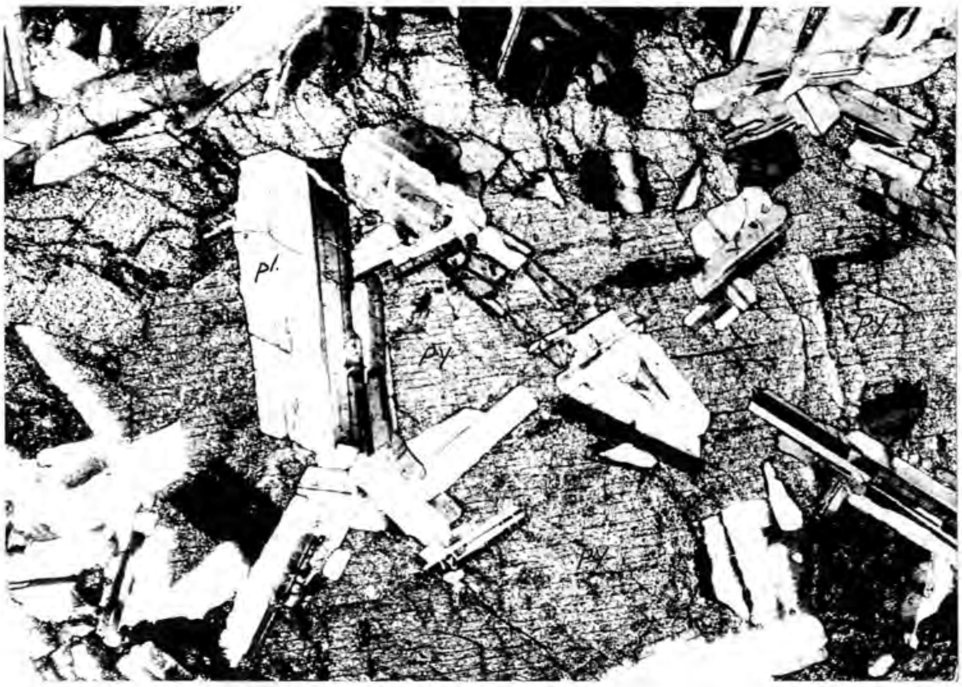

Fig. 2: Photomicrograph showing poikilophitic texture in dolerite. X 12, crossed nicols. Laths of plagioclase (pl) are wholly enclosed by large crystal of pyroxene (py).

(b) Coarse-grained Rocks.

(i) Poikilophitic Olivine Dolerite.

Slightly further in from the chill zone on Branstone, i.e. towards the centre of the intrusion, this rock type is to be found. It is characterized by its very coarse grain, poikilophitic texture, and the presence of three pyroxenes.

The poikilophitic texture is most distinctive in this rock type where the individual grains of pyroxene may measure up to 8 millimetres, and usually wholly enclose small euhedral plagioclase chadacrysts (see Plate XI, Fig. 2). The pyroxene oikocrysts are in turn surrounded by euhedral plagioclase laths, individual crystals measuring up to a maximum of 1.5 millimetres.

Plagioclase chadacrysts appear to be of slightly higher anorthite content (An_{78}) than the crystals surrounding the oikocrysts (An_{75}). Zoning in the latter may illustrate a variation of up to 19% of anorthite molecule, while in the chadacrysts zoning is not as marked. This is significant in that the relative age of the plagioclase is indicated. Some of the plagioclase crystals are fractured and bent. Plagioclase generally makes up more than half of the rock by volume.

Clinopyroxenes pigeonite and augite, as well as the orthopyroxene, hypersthene, appear in this rock. Pigeonite occurs as individual grains, with pronounced curved fractures across the grains. Augite, like pigeonite tends to occur as large, discrete grains enclosing plagioclase chadacrysts. The following optic values were measured on augite :-

$2V_z = 49.5^{\circ}$, $Ny = 1.681$.

Hypersthene is present as small anhedral grains with low birefringence. Exsolution lamellae of clinopyroxene parallel to (100) characterize the grains. This type of intergrowth has been recorded from many larger basic intrusions, and is the result of exsolution taking place under subsolidus conditions of cooling. In this case orthopyroxene (hypersthene) has exsolved clinopyroxene lamellae in the plane of closest structural similarity to the two minerals, viz. (100).

According to Hess (1941, p.526) exsolution phenomena in hypersthene occur when the MgO : FeO molecular ratio in hypersthene becomes more iron rich than approximately 7 : 3. Pyroxene, as a whole, forms less than one third of the rock by volume.

Olivine is present as anhedral grains, generally rounded in shape, with irregular cracks across the grains. Alteration to serpentine is generally present along these cracks.

Other accessory minerals include small proportions of iron ore, apatite and an interstitial mesostasis.

(ii) Poikilophitic Olivine Dolerite, with Quartz.

This rock shows most of the characteristics of that described immediately above, except that micropegmatite and quartz appear in place of the mesostasis, and olivine is usually present in smaller proportion than before. The rock occurs very abundantly in the intrusion, and generally has a high plagioclase content.

The poikilophitic texture is again a distinctive feature of this rock, with large individual pyroxene grains wholly enclosing small stumpy plagioclase chadacrysts, the latter being sometimes glomeroporphyritically arranged within the pyroxene oikocrysts. As in the previous rock type, plagioclase laths, individually measuring a maximum of 1.5 millimetres, surround the pyroxene oikocrysts, the anorthite content of plagioclase crystals being the same as in the previous type. Some plagioclase crystals exhibit bending and fracturing. Plagioclase generally makes up more than 60% of the rock, by volume.

Only clinopyroxenes, pigeonite and augite, are present in this rock. Pigeonite occurs as cores to augite, indicating its earlier crystallization, or both pigeonite and augite may occur as individual grains. Pigeonite sometimes has characteristic curved cracks across the grains. Augite, forming large crystals, yielded the following optic values :-

$2V_z = 46.5^{\circ}$, Ny = 1.691.

The proportion of pyroxene as a whole is slightly less than in the previous rock type.

Olivine occurs as small inclusions within pyroxene crystals, or sometimes appears with the plagioclase crystals which surround the pyroxene oikocrysts. Anhedral grains may occur individually or in clusters. Alteration, along irregular cracks in the grains, yields a reddish brown mineral (iddingsite?), and pale green serpentine.

Skeletal and anhedral grains of iron ore form a small proportion of the rock by volume. Slender needles and stumpy crystals of apatite are usually associated with the late acidic residium. Interstitial material includes quartz and micropegmatite, with the latter sometimes showing a tendency to corrode plagioclase.

(iii) Quartz Dolerite.

This rock type occurs, for example, in the northern dike-like margin of the bell-jar intrusion, and on Branstone where it forms a distinctive intrusive rock type. It differs from rocks described thus far in its texture and absence of olivine.

Microscopically it is coarse grained and has an ophitic texture. The plagioclase laths are generally larger than in the poikilophitic types, and measure up to 3 millimetres in thin-section. Crystals exhibiting normal zoning, from the northern margin of the bell-jar intrusion, have a maximum anorthite content of An_{70} at their cores, while those from Branstone have an anorthite content of 78%. As in the previous rock types, some of the crystals are fractured.

Pyroxene also assumes an elongate habit, with maximum length approximately the same as plagioclase. Pigeonite appears as cores to augite (see Plate XII, Fig. 1), but also as individual crystals. Augite from quartz dolerites on Branstone yielded the following optic values :-

$2V_z = 44.5^\circ$, $Ny = 1.693$.

Some pyroxene grains show alteration along their margins to a reddish brown mineral which has not been identified by the writer.

Quartz and micropegmatite occur interstitially, and in places micropegmatite can be seen to have replaced

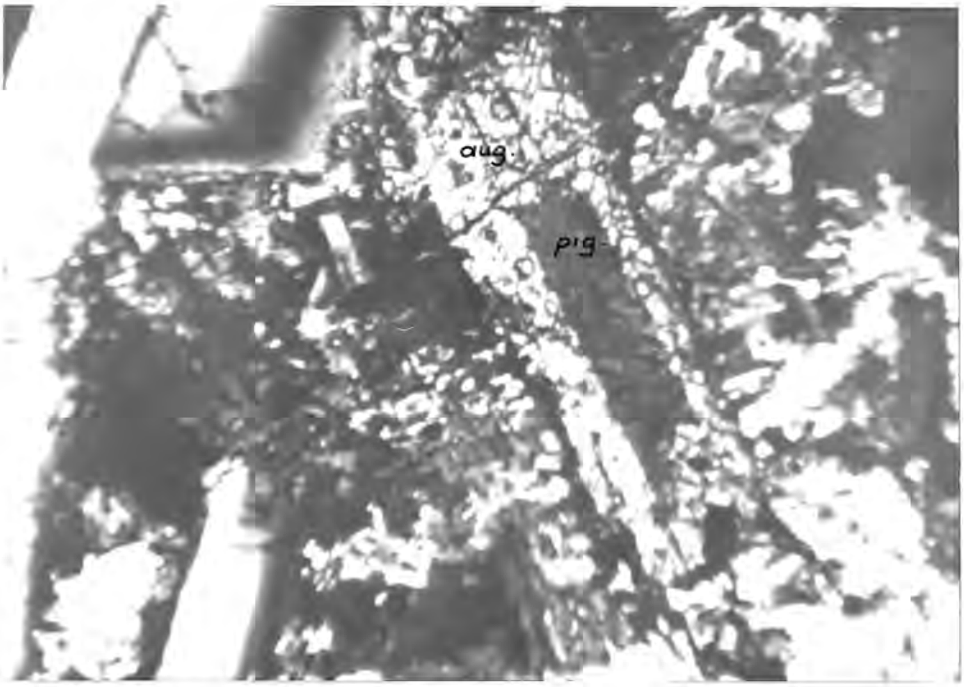

Fig. 1: Photomicrograph of quartz dolerite. X 12, crossed nicols. Note pigeonite core (pig) to augite (aug) crystal.

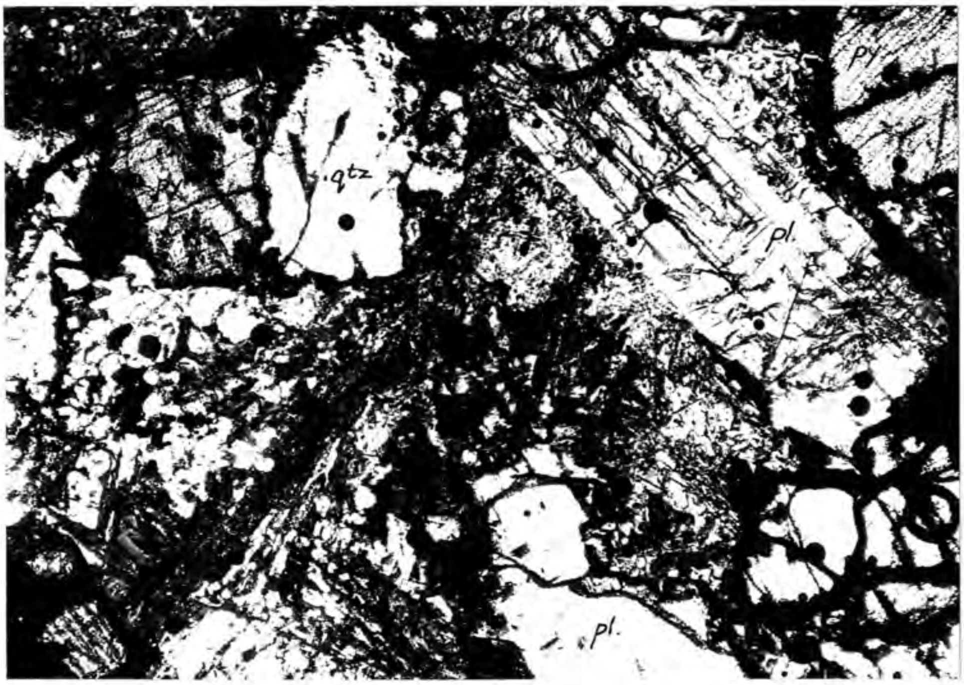

Fig. 2: Photomicrograph of Roof Zone dolerite. X 12, crossed nicols. Note broad plagioclase crystals (pl). Pyroxene = py, quartz = qtz.

plagioclase. Slender needles of apatite are generally associated with this material. Some euhedral, but mostly skeletal and anhedral, grains of iron ore make up a slightly greater proportion, by volume, than in rock types previously described.

(iv) Roof Zone Rocks.

This type of dolerite which has formed beneath a blanket of pyroclastic rocks forming part of the original roof, is to be found on Murrelfontein. It is a coarse-grained rock with an intergranular texture and a large proportion of acid material (see Plate XII, Fig. 2).

In hand specimen the plagioclase crystals exhibit a certain measure of parallelism, suggesting that they had moved within the magma and had assumed an orientation with their largest surface area horizontal, just beneath the "roof" of pyroclastics.

These rocks appear to be analogous to the coarse-grained gabbros and diorites in the Upper Border Group of the Skaergaard intrusion in East Greenland, which have been described by Wager and Brown (1968, pp.131-137). In some of the coarse-grained gabbros of the Skaergaard intrusion there is a marked igneous lamination which is indicated by tabular plagioclase crystals oriented parallel to the general attitude of the roof of the intrusion. According to Wager and Brown this parallel arrangement is due to orientation of primocryst plagioclase crystals through flow of the magma, parallel to the roof of the intrusion. Central ascending convection currents are considered to have carried the plagioclase primocrysts upwards.

In the Tranquil Division of the Marginal Border Group of the Skaergaard intrusion occur what Wager and Brown have termed, "Perpendicular-felspar and wavy-pyroxene rocks" (pp.110-113). The perpendicular-felspar rock contains elongate felspars which are oriented perpendicular to the margins of the intrusion. Wager and Brown do not, however, regard this arrangement of felspar crystals as the result of orientation of the felspars by flow of the magma; it appears more likely that the felspar crystals grew inwards from the margin of the intrusion, into the cooling magma. The crystals of the wavy pyroxene rocks apparently occur as roughly horizontal sheets elongated at right angles to the margin. They have a similar distribution, in the outer part of the Main Border Group, to the perpendicular felspar rock.

As in the case of the Skaergaard intrusion, the plagioclase crystals in the Roof Zone rocks on Murrelfontein are of tabular habit, but they do not attain the lengths of those within the perpendicular-felspar rock of the Skaergaard intrusion. In the Upper Border Group of the latter intrusion the plagioclase crystals are often 5 millimetres or more in length, while in the perpendicular-felspar rock the felspar tablets measure about 25 millimetres in length. The plagioclase laths of the Murrelfontein Roof Zone rocks measure up to 10 millimetres, the original cumulus crystals being very much broader than in previous rock types. The most calcic crystals showed a composition of An_{63}, but the majority of crystals appear to be slightly less rich in anorthite than this. The plagioclase crystals of this rock are larger in size and have a notably lower calcium content than any of the other types previously described. This is most probably the result of magma fractionation, with a late-stage liquid tending to accummulate beneath the roof of pyroclastic rocks. The crystals are all moderately zoned, and are traversed by diagonal cracks. Replacement by micropegmatite is very pronounced.

Anhedral grains of clinopyroxene do not generally measure more than 3 millimetres. Both pigeonite and augite occur as individual grains, with alteration to a reddish brown mineral taking place along the edges, and along cracks across the grains. The following optic values were measured on augite :-

$2V_z = 43^{\circ}$, $Ny = 1.720$.

The large Ny value of augite observed in this rock indicates that a greater proportion of iron is present in this clinopyroxene than was noted in rock types previously described. This strongly suggests that iron enrichment has taken place within the residual magma that formed this rock type. Iron enrichment is also illustrated by intercumulus augite in the Upper Border Group of rocks of the Skaergaard intrusion (Wager and Brown, 1968, p.132).

In the Murrelfontein Roof Zone rocks interstitial micropegmatite and quartz form a large proportion of the rock by volume. A reddish brown alteration product of pyroxene occurs interstitially with the micropegmatite and quartz, and was included with the latter two in the micrometric analysis of this rock.

Slender apatite needles are associated chiefly with the late acid stage. Iron ore appears as large anhedral grains. Olivine is entirely absent from this rock type.

(c) Dolerite Sills Within the Area of the Bell-jar Intrusion.

As previously noted in the section dealing with the field relationships, a number of dolerite sills, of which Skerprand is the thickest and most prominent, have been intruded into the Molteno sediments of the Smuts Pass xenolith, in the northern part of the bell-jar intrusion. Du Toit indicates their age as being greater than that of the main intrusive phase.

(i) Skerprand.

Samples taken near the base and towards the centre of this sill reveal a medium- to coarse-grained dolerite with ophitic to subophitic texture. Most of the plagioclase laths, which reach a maximum length of 1.5 millimetres, exhibit normal zoning, with a maximum anorthite content of 75%, measured in the cores of crystals. A significant number of grains show oscillatory zoning to be present. Some plagioclase laths exhibit bending and fracturing.

Clinopyroxenes, pigeonite and augite, are present in the rock, both being slightly zoned. Pigeonite, as does augite, occurs as discrete grains, and displays characteristic curved cracks across the grains. 2V angle measurements, taken at the centre of grains give a value of 48.5° for augite.

Olivine occurs in minor proportions. It is in an advanced state of alteration to pleochroic serpentine, especially in samples taken near the base. In the latter samples an interstitial glassy mesostasis, containing wisps of microlites remarkably similar to those seen in the tholeiite, forms a significant proportion of the rock. Further away from the base of the sill the mesostasis gives way to micropegmatite and large individual grains of quartz containing irregularly distributed globulites which were not identified by the writer. The rock as a whole resembles the poikilophitic types of the bell-jar intrusion, except with respect to texture.

It is most probable that the interstitial material, represented by micropegmatite and quartz in the coarser-grained portion of the sill, is the result of slower cooling in tholeiitic rocks, as proposed by Wilkinson (Hess and Poldervaart, 1967, p.181). Wilkinson notes that, "The glassy mesostasis is more commonly preserved in dikes and chilled facies of the larger intrusions. On slower cooling, the place of glass is taken by quartz-alkali felspar mesostasis or micropegmatite (more rarely by small amounts of interstitial quartz), a characteristic feature of the quartz diabases."

Iron ore and apatite, with a very small proportion of calcite, make up the remaining accessory minerals.

(ii) Sills Presumed to be of Greater Age than the Bell-jar Intrusion.

Samples taken from two of these sills indicate that the sills are composed of a fine-grained dolerite with texture varying from ophitic to intergranular.

Plagioclase laths do not generally exceed 1 millimetre, while some of them are apparently bent and fractured. Anhedral pyroxene grains sometimes forming equidimensional grains, have a maximum length of 2 millimetres, and form more than one third of the rock with ophitic texture. Augite appears to be the only pyroxene present.

Olivine is generally present as small anhedral grains, slightly altered to serpentine. In the ophitic rock a very small proportion of a greenish mesostasis and quartz appear interstitially, with stumpy apatite crystals. A trace of biotite also appears in this rock.

As indicated above, petrographic differences such as the fine grain size, greater proportion of pyroxene in the rock, absence of pigeonite and presence of biotite serve to distinguish these sills from the dolerites of the bell-jar intrusion.

(d) Order of Crystallization.

From a survey of the dolerite types of the bell-jar intrusion, an interpretation is here presented as to the sequence of crystallization of the minerals using terms proposed by Wager, Brown and Wadsworth (1960, pp.73-85). Although the terms used by these authors imply massive crystal settling on the floor of an intrusion, their application to the dolerites of the bell-jar intrusion is meant to imply the same process. The bell-jar intrusion does not appear to have a floor and therefore crystal growth, i.e. the formation of primocrysts and intercumulus crystals, must have taken place partially within a deeper magma chamber, and partially after the magma had been explaced into a new environment.

It appears that olivine, and at least some of the plagioclase had crystallized within the magma chamber prior to emplacement, i.e. these were intratelluric. Wager, Brown and Wadsworth regard the initial formation of olivine as due to its easier nucleation. H.V. Eales (personal communication) has suggested that the fractured nature of some of the plagioclase crystals found in most of the rock types, which has repeatedly been mentioned, indicates that they had most probably crystallized within a deeper magma chamber, before being emplaced in the place where now found. The fracturing most probably resulted from the latter event.

The poikilophitic rock types indicate that olivine and some of the plagioclase laths, were formed as primocrysts, as they have become enclosed by later crystals growing from the intercumulus liquid. Wager and Brown (1968, p.121) explain the poikilitic texture as due to the very slow and tranquil cooling of the intercumulus liquid, resulting in only relatively few and widespread centres of crystallization being established, which grew into extensive poikilitic crystals. Because cooling and crystallization were slow, this allowed adequate time for diffusion of the appropriate ions towards the widespread centres of crystallization.

As a result of cooling and further growth of chiefly olivine, the intercumulus liquid became supersaturated with respect to plagioclase and pyroxene, and nucleation of the latter two became easier. Thus plagioclase and pyroxene crystallites grew larger by diffusion between the primocryst crystals, from the intercumulus liquid. The remaining accessory minerals, viz. the acid residuum, crystallized as pore material within available space within the framework of crystals.

In the quartz dolerites of the bell-jar intrusion, pigeonite crystallized prior to augite, as pigeonite often occurs as cores to augite crystals. In the other rock types crystallization of these two clinopyroxenes appears to have been simultaneous, judging from their presence as individual crystals.

In the Roof Zone rocks the broader cumulus plagioclase crystals and their more sodic composition indicate that a certain amount of adcumulus growth might have occurred while a somewhat fractionated residual magma was collecting under the blanket of pyroclastics. If adcumulus growth had taken place within the plagioclase primocrysts, this process was not carried into the advanced stages, as is exhibited by the moderate zoning in plagioclase crystals of these rocks.

(e) Trends of Variation Exhibited by Rocks and their Constituent Minerals.

A variety of textures is illustrated within the dolerites of the bell-jar intrusion, while there appears to be a definite trend in composition of augite towards iron enrichment, from the contact of the intrusion, inwards. Plagioclase of the different rock types also appears to exhibit a trend in composition with the most calcium-rich occurring in the contact rocks and the more soda-rich plagioclase occurring in the Roof Zone rocks.

These trends within the dolerites became apparent after a study of a series of samples taken on Branstone, from the contact of the bell-jar intrusion inwards for a distance of approximately 400 metres (1300 feet). It is in this vicinity that a series of parallel ridges within the dolerites of the bell-jar, is evident on the aerial photographs. The present petrographic investigation illustrates the presence of several dolerite types within the bell-jar intrusion.

(i) Texture.

A variety of textures is present, both within the chilled and coarse-grained rocks. The contact rocks, as has already been indicated, display an intergranular texture in the marginal chill zone on Branstone (the western margin of the intrusion) while the tholeiites, on the eastern margin display a typical ophitic relationship between plagioclase and pyroxene.

Of the coarse-grained rocks, that occurring most abundantly within the bell-jar intrusion has a markedly poikilophitic texture, exhibited by the very large pyroxene crystals wholly enclosing smaller laths of plagioclase (see Plate XI, Fig. 2). The quartz dolerites have an ophitic to subophitic texture, while the Roof Zone rocks have an intergranular texture closely resembling that of a gabbro (see Plate XII, Fig. 2).

This sequence of textures, with the exception of those exhibited by the tholeiites and Roof Zone rocks is clearly revealed in the series of samples taken on Branstone. The intergranular type is exposed in the chill zone. This is followed inwards by the poikilophitic types; firstly, the olivine dolerites with three pyroxenes, and then the poikilophitic olivine dolerite with quartz. The rock type furthest away from the contact, along this traverse, is a subophitic quartz dolerite.

(ii) Composition of Augite.

The composition of augite in each rock type of the bell-jar dolerites was estimated by plotting the optic axial angles ($2V_z$) and Ny on Hess' diagram (Hess, 1949, p.634). An average value for Ny was taken for a particular rock type and the composition of augite is therefore an approximate value. The results have been plotted in Fig 7 and they reveal a distinct variation of augite composition between the basic and more acid rock types, the trend being towards iron enrichment. The broken line in Fig. 7 represents the normal trend of crystallization of clinopyroxenes from common mafic magmas, according to Hess (1941, p.585). From the diagram it can be seen that the trend of crystallization of augite in the dolerites of the bell-jar intrusion corresponds very closely to this line.

The following compositions of augite were accepted as representative averages :-

Tholeiite	$Ca_{37.5}$	$Mg_{48.0}$	$Fe_{14.5}$
Poikilophitic olivine dolerite	$Ca_{40.5}$	$Mg_{50.0}$	$Fe_{9.5}$
Poikilophitic olivine dolerite, with quartz	$Ca_{39.0}$	$Mg_{44.5}$	$Fe_{16.5}$
Quartz dolerite	$Ca_{37.0}$	$Mg_{42.0}$	$Fe_{20.5}$
Roof Zone rocks	$Ca_{29.0}$	$Mg_{23.0}$	$Fe_{48.0}$

(iii) Composition of Plagioclase.

A definite trend in maximum anorthite content of crystal cores is also apparent in plagioclases of the bell-jar dolerites. The most calcic plagioclase occurs within the tholeiites where a value of An_{80} was observed. The larger plagioclase crystals within glomeroporphyritic clusters within this rock type are less rich in anorthite (An_{60}).

Plagioclase chadacrysts in the poikilophitic dolerites are of slightly more calcic composition (An_{78}) than the crystals surrounding the pyroxene oikocrysts where a maximum value of An_{75} was measured. This feature suggests a difference in age between the two plagioclase varieties.

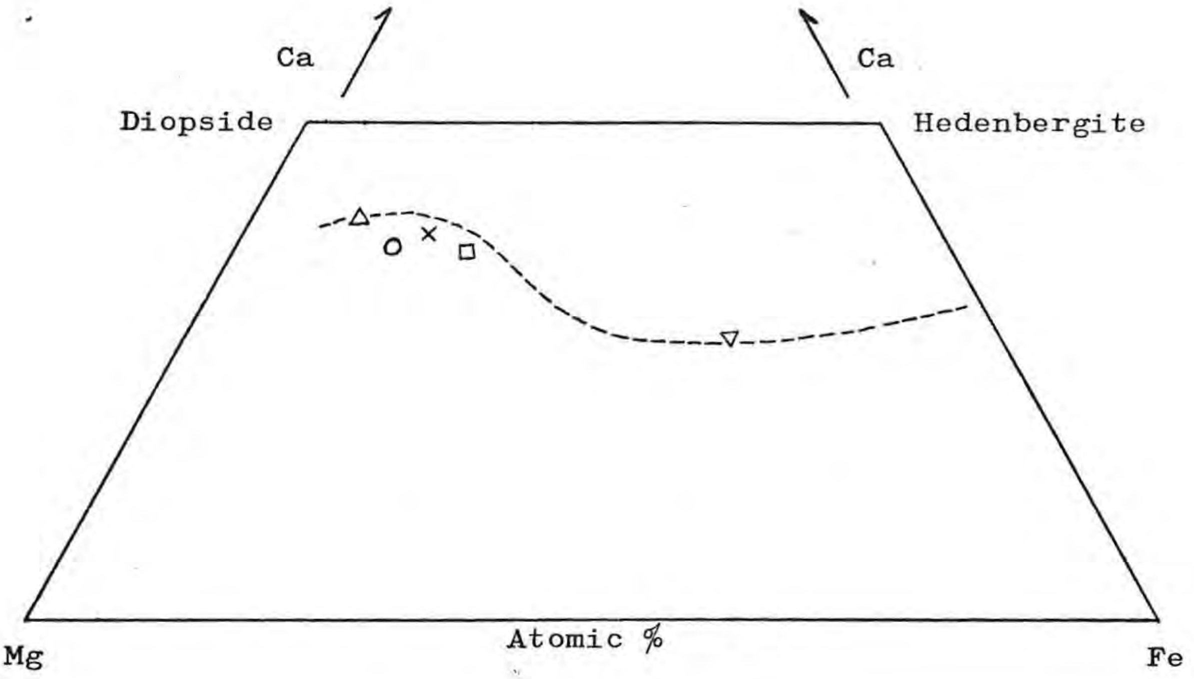

Fig. 7: Diagram to show estimated composition of augite in the different rock types of the bell-jar intrusion (after Hess, 1949). The broken line in the diagram above represents the normal trend of crystallization of clinopyroxenes from common mafic magmas.

▽	Roof Zone rocks.
□	Quartz dolerite.
×	Poikilophitic olivine dolerite, with quartz.
△	Poikilophitic olivine dolerite.
○	Tholeiite.

The quartz dolerites generally have a maximum anorthite content of An_{70}, but on Branstone a quartz dolerite gave a maximum value of An_{78}. The Roof Zone dolerite contains the most sodic plagioclase, the most calcic species observed having a composition of An_{63}.

2. Dolerite Sheets Surrounding the Bell-jar Intrusion.

Samples taken from a number of sheets in the area surrounding the bell-jar intrusion reveal petrographic similarities with dolerites of the main intrusion. The essential minerals are in all cases plagioclase and pyroxene. The accessory minerals include olivine, micropegmatite with quartz, iron ore and apatite.

The coarse-grained dolerites of the Vogel Vlei and Koups Leegte sheets, which appear spotted in hand specimen, reveal a typical poikilophitic texture with large plates of pyroxene enclosing smaller narrow laths of plagioclase. Plagioclase crystals are moderately zoned and reach a maximum of 1.5 millimetres in length, some exhibiting bending and fracturing.

Slightly zoned clinopyroxene crystals, pigeonite and augite, are present as large individual grains, but in the Vogel Vlei sheet pigeonite may also occur as cores to augite crystals.

The accessory minerals include anhedral olivine with alteration to serpentine having taken place along irregular cracks in the grains, iron ore, apatite and a small amount of a greenish mesostasis.

The above-mentioned coarse-grained rocks appear to resemble the poikilophitic dolerites of the bell-jar intrusion.

The fine-grained variety within the Vogel Vlei sheet has a subophitic texture, the pyroxene grains being of approximately the same size as the plagioclase laths.

A sample taken from the Birds' River sheet, near Birds' River Siding, is composed of a medium-grained dolerite with an ophitic texture. Plagioclase laths are moderately zoned with slight replacement by an altered mesostasis having taken place. Augite occurs as discrete grains. Interstitial quartz is fairly abundant while other accessory minerals include apatite and iron ore. No olivine was observed in the thin section of this rock.

One of the isolated sheets occurring near the bell-jar intrusion, on The Glen, is composed of a fine-grained dolerite with an ophitic texture. Plagioclase laths have a noticeably elongate shape and some of them appear to have been bent. Pyroxene is also present as elongate grains. Olivine is largely altered to serpentine, while the remaining accessory minerals include a small amount of iron ore, apatite and interstitial quartz.

Two samples taken from sheets occurring on Stafelberg's Vlei and Jansenfontein show that these sheets are composed of fine to medium-grained dolerites with an intergranular texture. Pigeonite, with characteristic curved cracks across the grains, and augite are present as discrete, slightly zoned crystals. Accessory minerals include interstitial quartz, iron ore (occasional grains being euhedral) and apatite. A very small amount of biotite was noted in a sheet on Jansenfontein.

3. Dolerite Dikes.

(a) Ring Dikes.

Dolerites of the ring dikes are very similar petrographically to the tholeiites of the bell-jar on Lemoenfontein. In thin section they have an ophitic texture with thin laths of plagioclase penetrating anhedral plates of pyroxene. Occasional glomeroporphyritic aggregates of broader plagioclase laths are also present.

Clinopyroxenes pigeonite and augite occur as individual crystals. Early primocrysts of olivine are partially altered to serpentine and iddingsite (?) along irregular cracks across the grains.

A brown interstitial mesostasis containing microlites of an undetermined mineral, and needles of apatite, constitutes the pore material. Iron ore is fairly evenly disseminated throughout the rock as euhedral and skeletal grains.

The resemblance of these rocks to the tholeiites of the main intrusion indicates that they have had a similar cooling history to the marginal facies of intrusions that took place after the initial cauldron subsidence in this area.

(b) Dragon's Back Dike.

Microscopically this is a fine-grained rock with intergranular texture, and alteration rather marked in all samples that have been collected and sectioned. Plagioclase laths are generally not greater than 0.5 millimetres, while pyroxene is slightly smaller in size and tends to occur as equidimensional grains.

Measurements of the plagioclase composition reveal a maximum 62% anorthite molecule, while the range produced by zoning in single crystals is as much as 15%. Plagioclase is characterized by diagonal cracks across the grains, and it has been actively replaced by an acid mesostasis.

Augite occurs in equidimensional plates with alteration along the edges to amphibole. Crystals are usually zoned with $2V_z$ values ranging between 44.5° and 40.5°. Ny gives a value of 1.693.

Hornblende and biotite are present in very small amounts. An interstitial mesostasis, consisting largely of quartz, appears to have actively replaced plagioclase and pyroxene. A reddish brown alteration product, most probably of pyroxene, occurs with the mesostasis and has been included with the mesostasis and quartz during micrometric analysis. Iron ore, in small euhedral and anhedral grains, and needles of apatite form the remaining accessories.

(c) Other Dolerite Dikes.

A few samples taken of the remaining dolerite dikes reveal that they are largely fine grained and tholeiitic in character. Olivine occurs in subordinate amounts and a glassy mesostasis is present in most of the samples.

B. MICROMETRIC DATA.

Micrometric analyses were carried out on thin sections cut from a variety of doleritic rocks from the Birds' River area, with a Swift Point Counter. As a general rule analyses were carried out so that the total length of traverses across each thin section was more than 200 times the length of the largest crystal occurring in the section. The results are given in tables IV to VII. Two micrometric analyses from the Mount Arthur intrusion have been included for comparative purposes.

1. A Review of the Micrometric Analyses.

Table IV contains the results of analyses of some of the coarse-grained bell-jar rocks. The first analysis is of a poikilophitic olivine dolerite; it shows a fairly high percentage of plagioclase, and olivine, while the proportion of iron ore is very low. Analyses 2 to 5 are of poikilophitic olivine dolerites, with quartz. These reveal a consistently high percentage of plagioclase, and, although the proportion of pyroxene in the rock is variable, it always appears to be less than one third. There is a notable increase in iron ore in this rock type, compared to the previous one. Micropegmatite and quartz do not form a significant proportion of the rock by volume. The average mode of a Kokstad Type dolerite from Mount Arthur (No. 6) has been included in this table to show the very much lower plagioclase content of these rocks.

Table V contains the results of analyses of the remaining coarse-grained rock types of the bell-jar intrusion, viz. the quartz dolerites and Roof Zone dolerites. The percentage of plagioclase is considerably less in the quartz dolerites than in the poikilophitic types, while there is a marked

TABLE IV.

Micrometric Analyses

	1.	2.	3.	4.	5.	6.
Plagioclase	58.8	61.6	62.6	60.8	62.6	47.5
Pyroxene + alteration	31.6	30.5	27.6	27.2	23.4	38.8
Olivine + alteration	7.6	0.7	1.7	2.7	0.2	6.1
Iron ore	0.5	2.2	2.7	2.3	4.2	2.9
Mesostasis + micropegmatite + quartz .	1.5	5.0	5.4	7.0	9.6	4.0
Amphibole + biotite .	-	-	-	-	-	0.7
	100.0	100.0	100.0	100.0	100.0	100.0

1 = Poikilophitic olivine dolerite.

2,3,4 & 5 = Poikilophitic olivine dolerite, with quartz.

6 = Average mode of a Kokstad Type dolerite from Mount Arthur. (After Walker & Poldervaart, 1949).

TABLE V.

Micrometric Analyses

	7.	8.	9.	10.	11.
Plagioclase	54.7	47.0	44.4	44.0	48.4
Pyroxene + alteration	25.2	30.5	27.4	23.2	33.3
Olivine + alteration	-	-	-	-	7.3
Iron ore	7.3	3.5	5.2	3.8	3.4
Mesostasis + micropegmatite + quartz .	12.8	19.0	23.0	29.0	7.6
	100.0	100.0	100.0	100.0	100.0

7 = Quartz dolerite from Branstone.

8 & 9 = Quartz dolerite from northern margin of bell-jar intrusion.

10 = Roof Zone dolerite

11 = Olivine dolerite, near eastern contact, on Lemoenfontein.

increase in the proportion of micropegmatite and quartz, and iron ore. Pyroxene again forms less than one third of the rock by volume. The highest proportion of acid material occurs in the Roof Zone dolerite (No. 10). Olivine is entirely absent from these rock types. Analysis No. 11 is of an olivine dolerite near the eastern contact on Lemoenfontein (from the quarry in the south-east corner of Map No. 3). The rock is much more basic than the poikilophitic and quartz dolerites.

In the tholeiitic rock types of the bell-jar intrusion the proportion of plagioclase decreases to approximately 50%, as is illustrated by analyses 12 and 13 in table VI. The proportion of olivine appears to be relatively high. The dolerite of the chill zone (No. 14) has a notably high proportion of pyroxene. The composition of a slide cut from a dolerite near the base of the Skerprand dolerite sill (No. 15) corresponds fairly closely with the tholeiites of the bell-jar intrusion, while that of one of the presumably older sills within the Smuts Pass xenolith (No. 18, table VII) shows a higher proportion of pyroxene and less micropegmatite and quartz than the Skerprand analysis. An analysis of a sample taken towards the centre of Skerprand (No. 16) shows a plagioclase content of over 50%, while the proportion of pyroxene is greater than one third. The average mode of tholeiite from Mount Arthur (No. 17) shows a very much lower proportion of plagioclase than the tholeiites of the Birds' River intrusion.

Analysis No. 19 (table VII) reveals a close similarity in proportion of minerals to that of the poikilophitic olivine dolerite of the bell-jar intrusion. The analysis of one of the ring dikes (No. 20) also bears a close similarity to the tholeiites of the bell-jar intrusion. The last two analyses (Nos. 21 and 22) reveal a distinct difference in the corresponding proportions of their constituent minerals, in these two dikes of different ages. Hornblende and biotite appear in addition to the other minerals (with the exclusion of olivine) in the Dragon's Back dike, while they are absent from the Thysfontein dike.

TABLE VI.

Micrometric Analyses

	12.	13.	14.	15.	16.	17.
Plagioclase	49.0	53.2	54.8	52.6	55.0	40.0
Pyroxene + alteration	29.2	31.4	42.3	25.2	37.0	36.5
Olivine + alteration	7.4	6.3	0.6	2.6	0.5	-
Iron ore	2.7	1.5	2.3	1.5	3.5	5.7
Mesostasis + quartz .	11.7	7.6	-	18.1	4.0	17.0
Amphibole + biotite .	-	-	-	-	-	0.8
	100.0	100.0	100.0	100.0	100.0	100.0

12 & 13 = Tholeiite from Lemoenfontein.

14 = Chill zone, Branstone.

15 = Base of Skerprand dolerite sill.

16 = Centre of Skerprand dolerite sill.

17 = Average mode of tholeiite from Mount Arthur. (After Walker & Poldervaart, 1949).

TABLE VII.

Micrometric Analyses

	18.	19.	20.	21.	22.
Plagioclase	51.7	58.2	46.9	48.7	53.6
Pyroxene + alteration	35.4	29.3	33.0	36.4	29.0
Olivine + alteration	5.9	6.5	6.5	1.1	-
Iron ore	3.1	1.2	3.0	3.8	3.6
Mesostasis + quartz .	3.9	4.8	10.6	10.0	12.6
Amphibole + biotite .	tr.	-	-	-	1.2
	100.0	100.0	100.0	100.0	100.0

18 = Sill within Smuts Pass xenolith presumed to be older than the bell-jar intrusion.

19 = Coarse-grained dolerite from Vogel Vlei.

20 = Ring dike.

21 = Dolerite dike on Thysfontein.

22 = Dragon's Back dike.

2. General Summary of the Results.

The poikilophitic dolerites of the bell-jar intrusion appear to be the most plagioclase-rich rocks, where the proportion of plagioclase may be as high as 63%. In the remaining rock types of the bell-jar intrusion the proportion of plagioclase is approximately 50%, as in the case of the tholeiites, or less than this.

The proportion of pyroxene in the bell-jar dolerites is usually less than one third, while in dolerites occurring in dikes and sills in the area, pyroxene may form more than one third of the rock by volume.

There appears to be a sympathetic relationship between increase in acid material and proportion of iron ore in rocks of the bell-jar intrusion. In the series of samples taken on Branstone an increase in both acid material (micropegmatite and quartz) and iron ore is discernable from the contact towards the centre of the intrusion. This increase is accompanied by a decrease in the proportion of olivine, until the latter finally disappears in the quartz dolerite.

The results of the micrometric analyses reveal a general similarity, in some cases, in the proportion of minerals of rock types occurring in sheets, sills and dikes, with those of the bell-jar intrusion. The coarse-grained dolerite of the Vogel Vlei sheet, for example, resembles the poikilophitic types of the bell-jar intrusion, while the base of the Skerprand dolerite sill and the ring dikes are similar to the tholeiites of the bell-jar intrusion on Lemoenfontein. These general tendencies would require more thorough investigation before any significant correlations are to be drawn.

3. Comparisons Based on Triangular Diagrams.

By making use of three mineral assemblages and plotting them as end members on triangular diagrams, it is found that particular rock types appear to be grouped into distinct areas within the triangles (see Figs. 8 and 9). The mineral assemblages represented in these diagrams are :-

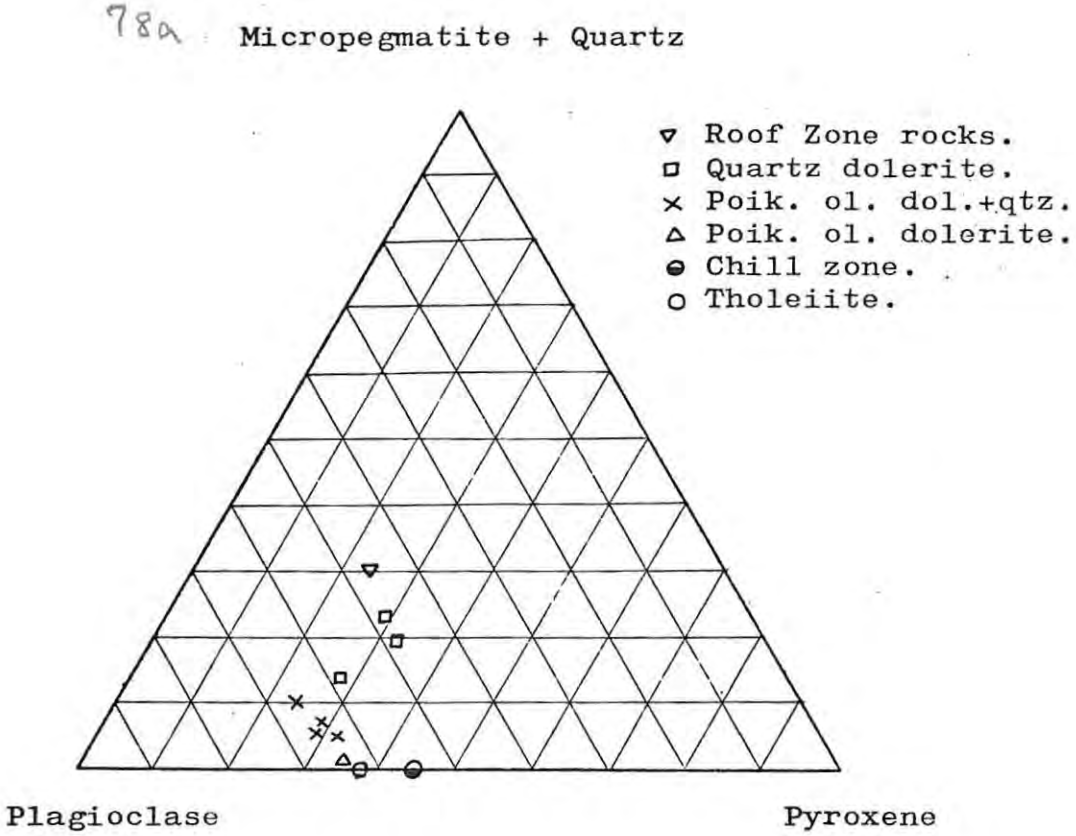

Fig. 8: Diagram to illustrate grouping of types of dolerite in the bell-jar intrusion, using plagioclase, pyroxene and micropegmatite + quartz as end members.

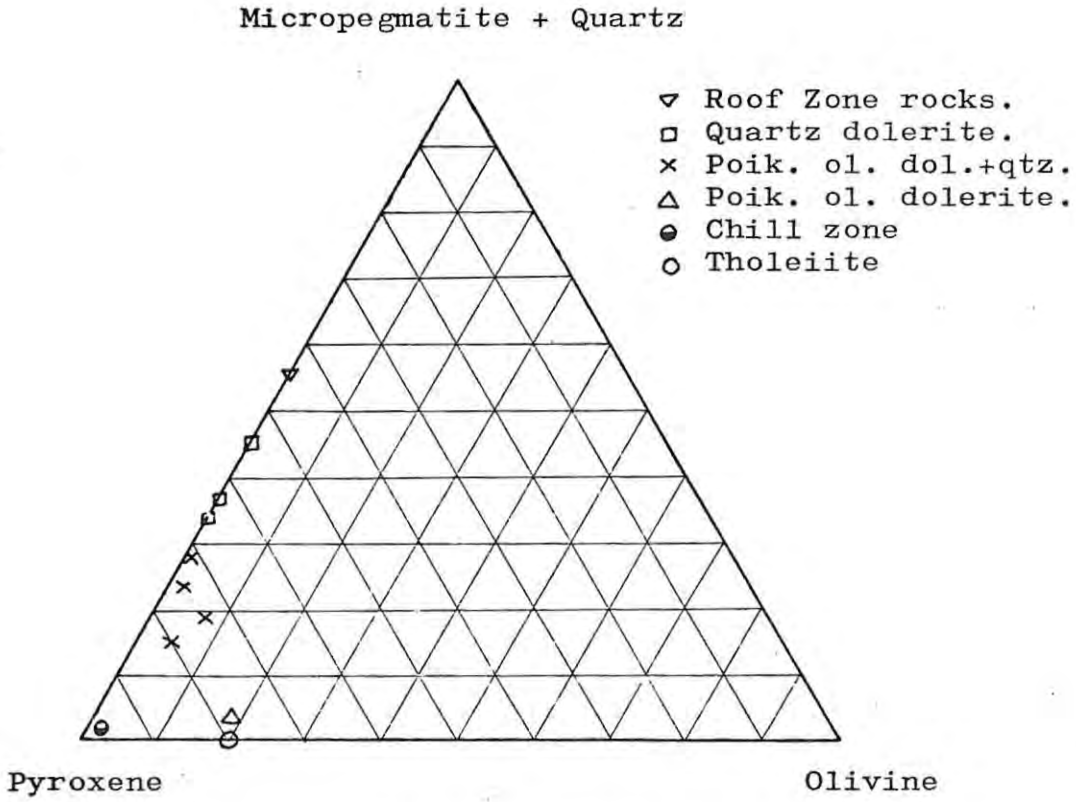

Fig. 9: Diagram to illustrate grouping of types of dolerite in the bell-jar intrusion, using pyroxene, olivine and micropegmatite + quartz as end members.

Fig. 8: Plagioclase, pyroxene and micropegmatite + quartz;
Fig. 9: Pyroxene, olivine and micropegmatite + quartz.

In both cases the proportions of the three mineral assemblages of a particular rock were recalculated to 100% and then plotted on the diagrams.

Figs. 8 and 9 clearly illustrate distinct groupings of rock types, the trend being from the basic rocks occurring at, or near the contact, towards the more acid rocks to be found within the bell-jar intrusion.

C. CHEMICAL DATA.

1. Results of Chemical Analyses.

Three unpublished chemical analyses of dolerites from the bell-jar intrusion, and their norms, are presented in table VIII. The analyses were carried out by the 1969 B.Sc. (Honours) class in the Department of Geology at Rhodes University. A chemical analysis of an olivine dolerite from the Mount Arthur intrusion, and the average chemical composition of Karroo dolerite (after Walker and Poldervaart, 1949, tables 15 and 17) have been included in table VIII for comparative purposes.

Analysis No. 1 is of an olivine dolerite, with quartz, taken from a freshly blasted irrigation canal on the boundary between Boshoffs Kraal (1) and Die Smuts Pass, along the northern margin of the intrusion. Analysis No. 2 is of a sample taken from a quarry on Lemoenfontein (situated in the south-east corner of Map No. 3) near the edge of the intrusion. This analysis of a more basic olivine dolerite is most probably representative of the average composition of the magma upon the initial intrusion into the bell-jar intrusion. Analysis No. 3 is of a coarse-grained dolerite sampled near the eastern extremity of the Skerpirand dolerite sill.

The most striking feature of analyses 1 and 3 is the

TABLE VIII.

Chemical Analyses

	1.	2.	3.	4.	5.
SiO_2	51.73	50.72	52.54	48.77	52.5
Al_2O_3	18.97	15.08	17.51	16.02	15.4
Fe_2O_3	1.02	1.09	0.70	0.89	1.2
FeO	8.33	9.44	6.92	9.27	9.3
MgO	3.75	7.04	6.31	11.71	7.1
CaO	10.05	10.76	10.67	9.13	10.3
Na_2O	1.66	2.98	2.49	1.54	2.1
K_2O	1.47	0.41	0.71	0.50	0.8
TiO_2	1.31	1.15	0.81	0.54	1.0
P_2O_5	0.16	0.30	0.15	tr.	0.1
MnO	0.11	0.17	0.07	0.22	0.2
H_2O-	0.63	0.59	0.73	-	-
H_2O+	1.03	0.67	0.54	1.25	-
TOTAL	100.22	100.40	100.15	99.84	100.0

Norms

		1.	2.	3.	4.
	Q	6.48	-	2.52	-
	Or	8.34	2.22	3.89	2.78
	Ab	13.62	25.15	20.96	13.10
	An	40.03	26.97	34.75	35.31
Ol	Fo	-	2.87	-	6.86
	Fa	-	2.85	-	4.08
Di	En	1.60	5.40	4.00	2.60
	Fs	2.11	4.49	2.77	1.32
	Wo	3.71	10.21	7.08	4.18
Hy	En	7.80	8.00	11.80	16.90
	Fs	10.43	6.60	8.18	9.11
	Il	2.43	2.13	1.52	1.06
	Ap	0.34	0.67	0.34	-
	Mt	1.39	1.62	0.93	1.39
	H_2O	1.66	1.26	1.27	1.25
	TOTAL	99.94	100.44	100.01	99.94

1. Dolerite sample from Smuts Pass-Boshoffs Kraal (1) boundary, N margin of bell-jar intrusion. Analyst - A.K. Kenyon.
2. Dolerite sample from NE margin of the intrusion. Analyst - T.S.A. Grobicki.
3. Dolerite sample from E end of Skerprand. Analysts - D.L. Buchanan and D.A. Glenister.
4. Olivine dolerite from the Mount Arthur intrusion (Poldervaart, 1946).
5. An average Karroo dolerite, from 43 analyses, quoted 100% water-free (Walker & Poldervaart, 1949).

high Al_2O_3 content when compared with that of average Karroo dolerite (No. 5). The percentage Al_2O_3 of analysis No. 2 corresponds very closely to that of average Karroo dolerite, but analyses 1 and 3 show noticeably higher values than this, and these are even slightly higher than that of the olivine dolerite from Mount Arthur (No. 4).

In the micrometric analyses of dolerites of the bell-jar intrusion (table IV) the poikilophitic olivine dolerites, with quartz, generally have a very high percentage of plagioclase. It is not entirely surprising, then, that a chemical analysis of this rock tvpe would yield as high a percentage of Al_2O_3, as is illustrated, in analysis No. 1.

As mentioned previously Eales' suggestion (personal communication) that many of the fractured plagioclase crystals encountered in the bell-jar dolerites could have crystallized as primocrysts within a deeper magma chamber, seems quite feasible. These primocrysts were then most probably caught up with the intruding dolerite magma and fractured upon intrusion into the bell-jar. On slow cooling of the magma, after emplacement, the resulting rock would quite likely contain a significantly greater proportion of plagioclase than is typical of Karroo dolerite (see tables IV to VII). Further differentiation in place could possibly account for a slightly increased proportion of plagioclase as well. From the micrometric data given in tables IV to VII it seems most significant that rocks with a high plagioclase content appear to be those that could have been affected by a sinking away of the ferromagnesian minerals (e.g. olivine and pyroxene), resulting in a felspar-rich rock (see table IV, modes 2 to 5). Those rocks which cooled within relatively narrow bodies or near the margins contain less felspar (see tables V to VII, modes 8, 9, 11-15, 18, 20-22). This suggests differentiation of the magma, after emplacement, was quite significant in the Birds' River intrusion.

The high Al_2O_3 content yielded by the analysis from the Skerprand dolerite sill (table VIII, analysis No. 3) and that of the olivine dolerite, with quartz (analysis No. 1), suggests that the two rocks originated from a similar magma.

These indications then greatly favour the interpretation that the Skerprand dolerite sill forms part of the main intrusive mass of the bell-jar intrusion, as has been previously propounded.

2. The Dolerite Type, and its Distribution.

The dolerites of the bell-jar intrusion, although displaying a variety of textures, are rather similar to the "Kokstad Type" of Walker and Poldervaart (1949, p.616). "Dolerites of this type are coarse-grained, subophitic, olivine-bearing rocks in which the percentage of plagioclase (by volume) is greater than 50%. Olivine occurs in varying amounts, but is generally a magnesian variety. The bulk of the pyroxene is augite (2V: 50°-40°). Orthopyroxene occurs in the dolerites with more than 4 per cent olivine. With less olivine its place is generally taken by pigeonite." (Poldervaart, 1946, p.100).

The poikilophitic dolerites of the Birds' River area correspond very closely to the above definition, except in respect of their texture. The quartz dolerites and Roof Zone rocks of the bell-jar intrusion appear to be the result of differentiation of a parent olivine dolerite magma, with iron enrichment.

According to Poldervaart (1946, p.100) olivine dolerites of the Kokstad Type are abundantly represented in intrusions of East Griqualand and the Transkei, e.g. Mount Arthur, Ingeli, Insizwa, Tonti, Tabankulu, Elephants Head and New Amalfi. These dolerites are generally rich in olivine and have a high MgO content.

Poldervaart (1946, p.108) recognised the following sequence of events in the formation of the dolerites of the Mount Arthur bell-jar intrusion :-

(i) Intrusion of a tholeiitic magma along an outer ring dike. He regards the tholeiites as representing a small portion of the olivine dolerite magma which had differentiated prior to intrusion.

(ii) A cauldron subsidence of the central block of sediments, followed by intrusion of a large volume of olivine dolerite magma.

(iii) Interaction of the olivine dolerite magma with volatiles from the foundered blocks of sediments, to produce a "transfused tholeiite" surrounding the xenoliths.

The changes brought about in the olivine dolerite to produce the transfused tholeiites are as follows :-

> "Olivine is first pseudomorphosed in pleochroic serpentine and finally disappears altogether. Pigeonite forms a prominent part of the pyroxenes. Orthopyroxene is always absent. The interstitial micropegmatite is replaced by a mesostasis which gradually increases in amount as the included sediments are approached. The mesostasis is dark in colour and rich in iron ore and alkalies. Hydrous minerals such as hornblende and serpentine, become more prominent and finally occupy vesicles, together with quartz and calcite. Some tholeiites also contain irregular areas of quartz which are marginally crenulated and converted to tridymite." (1946, p.104)

Although similar changes within the dolerites of the Birds' River bell-jar intrusion might well have taken place, the writer did not encounter, from the thin sections analysed, sufficient evidence to stimulate further study in this field. It appears rather, that the nature of'intrusion of the Birds' River bell-jar was in the form of successive vertical injections of magma which did not allow as much interaction of the volatiles from the foundered roof fragments with the intruding magma, as did happen in the case of the Mount Arthur intrusion. It must be mentioned, however, that Poldervaart's theory to explain the sinking of sedimentary xenoliths to considerable depths within basaltic magma, has been employed by the writer in Chapter Eight to account for similar occurrences in the Birds' River intrusion.

3. Parental Basalt Magmas.

In considering the types of magma which have resulted in the intrusive and extrusive basic rocks found within the earth's crust, three parental basalt magmas are recognised (Kuno, from Hess and Poldervaart, 1968, p.625). These magmas give rise to the three igneous-rock series, as outlined by Kuno (Hess and Poldervaart, 1968, p.633) :-

(i) Tholeiite series; characterized mineralogically by the reaction relation between Mg olivine and orthopyroxene and pigeonite.

(ii) Alkali rock series; characterized by the absence of a reaction relation between olivine and pyroxene.

(iii) High-alumina basalt series; a transition between the above two types, is characterized by an Al_2O_3 content greater than 16.5% in aphyric rocks, and the Na_2O + K_2O contents lie between those of the other two basalt types for a given SiO_2 content.

The calc-alkali series apparently starts from each of the three parental magmas, but enrichment of water in the magma which causes a rise in O_2 partial pressure in the magma, is necessary for the formation of this series.

The Karroo dolerite magma of South Africa is regarded, in general, as typically tholeiitic, and is practically identical in chemical composition to the effusive phase, viz. the Drakensberg lavas (Walker and Poldervaart, 1949, p.648).

4. Differentiation of the Magma.

Differentiation of the tholeiitic and high-alumina basalt magmas results in high iron concentration, while in the alkali and calc-alkali series there is moderate or no iron concentration (Kuno, from Hess and Poldervaart, 1968, p.633).

In the Karroo dolerite magma crystal fractionation, largely within the plagioclase minerals, tends to produce a residual magma rich in SiO_2, K_2O and Na_2O. Crystal fractionation chiefly within the pyroxenes results in a residual magma rich in FeO, Fe_2O_3 and TiO_2 (Walker and Poldervaart, 1949, p.651).

Although crystal fractionation is regarded as the chief cause of differentiation of basalt magmas, gravitational settling of primocryst minerals, segregation of volatile rich phases, incorporation of resurgent volatiles from wall rocks or xenoliths into the magma, and assimilation or metasomatism of sediments are also processes which effect differentiation. In general differentiation of the Karroo basaltic magma is towards iron enrichment during the main period of crystallization, changing toward enrichment in alkalies during the last stages (Walker and Poldervaart, 1949, p.661).

5. Origin of the Magma.

In outlining hypotheses concerning the source of basaltic magma, Green (Hess and Poldervaart, 1968, p.835-839) indicates that the magma is in all probability derived by partial melting within a mantle of peridotite composition. Bowen (1928, p.311-320) considers that basalts may originate from complete melting of a parent rock of basalt composition or partial melting of an ultramafic rock.

Evidence yielded by inclusions of ultramafic rocks in Kimberlite pipes and alkali basalts suggests that these inclusions may represent the source material of basaltic magma. Green (Hess and Poldervaart, 1968, p.837) notes that :-

> "Eclogites have chemical compositions similar in major oxides to the compositions of basalts and in addition have densities and seismic velocities possibly consistent with those immediately beneath the M discontinuity. Complete or near complete melting of an eclogitic mantle or an eclogite layer offers a possible source for basaltic magma."

Although evidence in general favours an origin of the basaltic magma within the earth's mantle the hypotheses at present have to be regarded as speculative due to the impossibility of obtaining samples directly from the mantle.

* * * * *

CHAPTER FOUR

THE SEDIMENTS

General Statement:

All three sedimentary Stages of the Stormberg Series are present in the Birds' River area, erosion having removed the Drakensberg Volcanic Stage. The sedimentary sequence is as follows :-

Cave Sandstone Stage Red Beds Stage Molteno Stage	Stormberg Series, of the Karroo System.

Outside the area of the bell-jar intrusion the upper (at least 100 metres (330 feet)) portion of the Molteno Stage falls within the area under investigation. The full sequence of the Red Beds Stage, with a maximum thickness of 442 metres (1450 feet), is represented in this area, while only small outliers of the Cave Sandstone Stage, none of which measures more than 97 metres (300 feet) in thickness, are to be found.

The nearest outlier of the Drakensberg Volcanic Stage occurs on Pronksberg, approximately 16 kilometres (10 miles) to the north of the bell-jar intrusion, which falls out of the area represented by Map No. 1.

In this chapter the writer outlines various aspects of Stormberg sedimentation which are of interest in the broad scope of the present investigation, viz. the distribution and general nature of the Stormberg Series, and the contacts between the Stages of the Stormberg Series. A field description of the sediments in the Birds' River area is given, while the final section deals briefly with the environmental conditions of deposition of the Stormberg sediments.

A. DISTRIBUTION AND GENERAL NATURE OF THE STORMBERG SERIES IN THE REPUBLIC AND LESOTHO.

The main area of Stormberg sedimentation and lava flows embraces virtually all of Lesotho and includes the neighbouring areas in the Republic of South Africa. The outer margin of Stormberg outcrop extends from the Bethlehem - Senekal area of the Orange Free State in the north to the Molteno area of the Eastern Cape, then eastwards to Cala and Maclear, and up to Matatiele and Bergville. The northernmost outcrop in the Orange Free State is near Memel where the Molteno sediments thin out to a single horizon of grit.

According to Koen (1955) the Molteno Stage may have been deposited as far north as the Waterberg area and the Springbok Flats of the Transvaal. A downfaulted area of Molteno sediments south of Port St. Johns indicates that sedimentation extended beyond the confines of the main sedimentary basin described above.

The sequence of mostly gently dipping Stormberg sediments in the main area of occurrence forms a wedge almost 480 kilometres (300 miles) long, with the maximum thicknesses of Molteno and Red Beds Stages being recorded in the south, and a gradual thinning out of the sediments in a northerly direction.

The Molteno Stage, forming the base of the Stormberg Series, is distinguished lithologically by the absence of striking colouration within the sediments, this normally being a characteristic of the underlying Beaufort and overlying Red Beds. The Molteno Stage reaches a maximum thickness of some 610 metres (2000 feet) in the south (Du Toit, 1954, p.295) and thins out northwards, where Haughton (1969, p.336) notes a thickness of not more than 3.6 metres (12 feet) near Harrismith.

Stockley (1940) has divided the Molteno sediments in Lesotho into a northern facies consisting of a single unchanging unit of grits, and a southern unit containing thick argillaceous members. In the south-west of Lesotho the Stage is 150 metres (500 feet) thick, or more, and in the north it has a uniform thickness of 30 to 50 metres (100 to 160 feet).

The Red Beds Stage reaches a maximum thickness of 500 metres (1600 feet) at Elliot (Du Toit, 1954, p.298) and thins out northwards where, at Verkykerskop near Harrismith, Van Eeden (1937, p.27) has recorded a thickness of 60 metres (190 feet). Stockley notes that the Red Beds Stage is at least 300 metres (1000 feet) thick in south-west Lesotho while in the north-west the thickness is only 30 metres (100 feet).

The Cave Sandstone Stage attains a maximum thickness of 300 metres (1000 feet) in the Orange River valley (Du Toit, 1954, p.300). Van Eeden (1937) has divided this Stage in the north-eastern Orange Free State into :-

(i) Transition Beds which represent a transition from Red Beds to Cave Sandstone, and

(ii) Massive Sandstone, generally light in colour and forming vertical cliffs.

The succeeding effusive phase of Stormberg volcanics, which forms the highest ground in the Republic and Lesotho, was poured out intermittently to attain a total thickness of at least 1350 metres (4500 feet) (Du Toit, 1954, p.301).

The Stormberg sediments are regarded as Triassic to Rhaetic in age (confirmed by the presence of flora in the Molteno Stage), while the plant Otozamites (Du Toit, 1939, p.280), occurring in sandstone interbeds within the volcanic stage, suggests a Lower Jurassic age for the Drakensberg Volcanic Stage.

B. THE CONTACTS BETWEEN THE STAGES OF THE STORMBERG SEDIMENTS.

As sedimentation was virtually continuous throughout the Stormberg epoch, the contacts between the Stages of sedimentation are conformable. The problem of defining these contacts therefore lies in defining changes in the lithological characteristics of the sediments. Although criteria such as grain size and colour of the sediments are commonly employed in identifying the general stratigraphic position of the Stormberg beds, previous writers, e.g. Du Toit (1904, p.91), Botha (1968, p.101) and Van Eeden (1937, p.25), have indicated the unsuitability of these criteria in many cases where contacts within the Stormberg Series have to be drawn in through field mapping.

Du Toit (1904, p.91) notes the general difficulties in defining the base of the Red Beds Stage in the Wodehouse area, due to lithological similarities to the Molteno Stage and the weathering out of colouring matter in the sediments.

According to Stockley (1940, p.449) the contact between the Molteno and Red Beds Stages is well defined in the northern districts of Lesotho, but becomes less clear in the south, due to the presence of an arkosic grit which is similar to the Molteno sediments, but lies at the base of the Red Beds Stage.

The contact between the Red Beds and Cave Sandstone Stages is sometimes sharp, but often gradational as, for example, in the northern Orange Free State where the Transition Beds of Van Eeden represent a gradual transition from Red Beds to Cave Sandstone.

Some writers, e.g. Koen (1955), have made use of a heavy mineral study in aiding correlation between the sediments of the Stormberg Series. J.C. Theron (personal communication) believes that a study of the accessory minerals in the sediments will be the only worthwhile method of delineating the contacts between the Stages.

In the Birds' River area the writer encountered difficulties in satisfactorily defining the contact between the Molteno and Red Beds Stages. In the field the contact is not at all obvious for the following reasons :-

(i) Towards the base of the Red Beds and at the top of the Molteno sediments there is a predominance of fairly thick felspathic sandstone beds (approximately 10 metres thick), their grain size being fairly coarse, but not characteristic of either Stage.

(ii) Due to the abundance of dolerite intrusions in this area the deep colouration chiefly within the argillaceous horizons of the Red Beds Stage has largely been bleached out.

To the east of the bell-jar intrusion, on the farm Koups Leegte, the base of the Red Beds Stage was taken as the lowest occurrence of a reddish coloured argillaceous bed. In the field the argillaceous bed is largely obscured by talus and vegetation, and the red colour is not in any event very obvious. This bed overlies a prominent cross-bedded coarse-grained felspathic sandstone horizon, the general appearance of which suggests assignment to the Molteno Stage of sedimentation. The presence of greyish-coloured mudstone lenses interbedded with the thicker sandstone beds downhill from this position suggests that the latter sediments do indeed belong to the Molteno Stage. For some distance above the contact indicated by the writer the sandstone beds are generally thick, but then tend to become thinner upwards with cross bedding on a smaller scale than is usually found within the sediments of the Molteno Stage. As the characteristically coloured argillaceous beds near the base of the Red Beds Stage are hardly ever exposed, this adds to the difficulty in deciding to which stratigraphic position the sandstone beds above and below them should be assigned.

To the west of the bell-jar intrusion the Molteno - Red Beds contact could similarly not be established with certainty, due to the same difficulties as were encountered on the eastern side. It was noted, however, that the contact indicated by the writer, on Koups Leegte, corresponded very closely to the 1680 metre (5500 foot) contour line on the 1:250,000 topocadastral map (3126 Queenstown, 1960). The contact between the Molteno and Red Beds Stages shown on the maps compiled by the writer therefore corresponds approximately to the position of this contour line.

As mentioned previously, the writer believes that a more satisfactory method of defining the contact between the

Molteno and Red Beds Stages in this area would be through a study of the heavy minerals in the sediments. This would, however, be a task of considerable magnitude and falls beyond the scope of this investigation.

The contact between the Red Beds and Cave Sandstone in the Birds' River area is sometimes sharp, as above Rooiberg to the north of the bell-jar intrusion (see Plate X, Fig. 2), and along the eastern margin of the bell-jar intrusion, while in many cases it is gradational over a few metres.

C. THE SEDIMENTS IN THE BIRDS' RIVER AREA.

1. The Molteno Stage.

Molteno sediments occupy the southern half of the area under investigation and generally dip at shallow angles in a southerly direction. Their outcrops are confined to valleys carved by the small streams in this area. Where these streams have undercut the more resistent arenaceous beds large blocks of sandstone are often found strewing the valley sides, e.g. on Romance. Argillaceous horizons occur less frequently than in the succeeding Red Beds Stage.

The attitude of the sediments has been largely undisturbed by intrusions of dolerite, except right at the contact with the bell-jar intrusion on Murrelfontein (grid reference N 14).

Buff to whitish coloured, very coarse-grained, felspathic sandstones and grits form the most conspicuous outcrops. These horizons appear to be about 5 to 6 metres (15 to 20 feet) thick and often contain well rounded quartzite and quartz pebbles and cobbles. The rock sometimes has a pitted appearance due to the weathering out of felspar. Trough bedding, with troughs measuring 2 to 3 metres (6 to 10 feet) in width, is a common feature of these sandstone beds.

Finer-grained cross-bedded sandstones form a large proportion of the arenaceous beds as a whole. Many of the sandstone horizons have the so called "glittering appearance". Concretions are frequently seen on bedding-plane surfaces. To the west of the bell-jar intrusion, in particular, a type of spheroidal weathering in the sandstone produces numerous rounded balls of sandstone on outcrop. Argillaceous beds, generally much thinner and less conspicuous than the arenaceous beds, are composed of bluish, grey and greenish mudstones and shales.

Towards the top of the Molteno Stage in this area a particular shale bed is of significance for it contains abundant, perfectly preserved, Mesozoic flora. West of, and near the Denwood homestead (grid reference M 15), this bed has been exposed in a small dam site. The bed is composed of a greenish-grey shale not less than 2 metres (6 feet) thick, and dips gently towards the south. On exposure the shale weathers rather rapidly but remarkably well preserved specimens of the plants can be obtained 15 centimetres below the weathered surface.

The following species were collected from the Denwood fossil bed. Mrs. H. Anderson of the Bernard Price Institute for Palaeontological Research, has most kindly made provisional identifications of the specimens. She has stressed that many of the plants need reclassification, although the present names are in use in the current literature :-

Dicroidium odontopteroides (Morris) Gothan.
Dicroidium elongatum (Carr.) Archangelsky.
Lepidopteris stormbergensis (Seward) Townrow.
Taeniopteris immersa (Nathorst).
Phoenicopsis elongatus (Morris).
Baiera schenki (Feistmantel).
Baiera sp.
Yabeiella dutoitii (Oishi).
Pteruchus sp.

(See Plates XIII to XVII).

Although the bed as a whole is richly endowed with plants there are horizons a few centimetres thick that are barren of plants. Species of Phoenicopsis and Dicroidium as

PLATE XIII

Fig. 1: Dicroidium odontopteroides (Morris) Gothan.

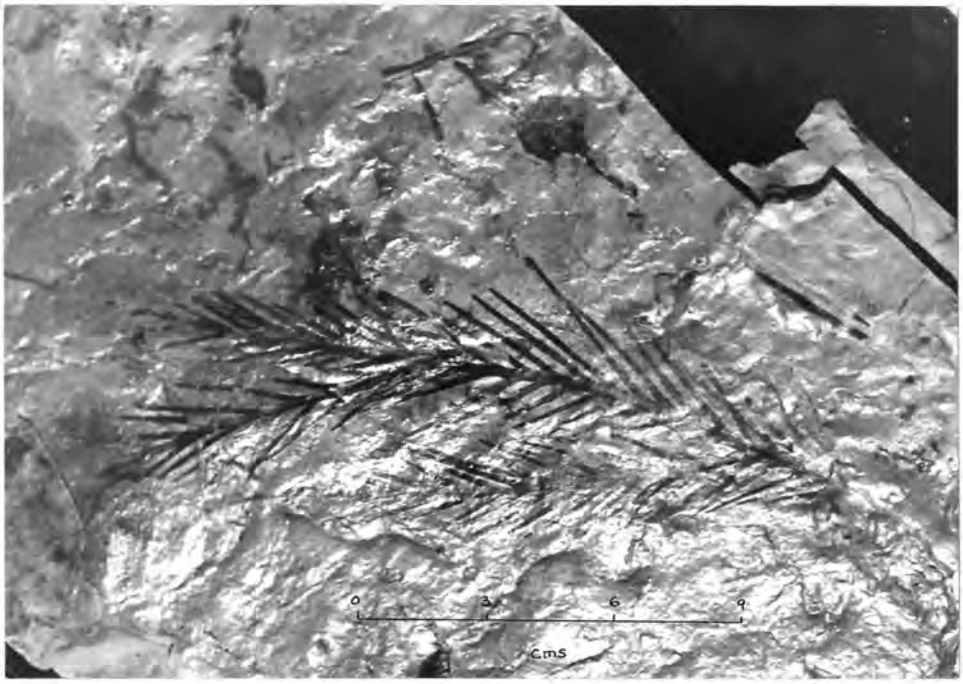

Fig. 2: Dicroidium elongatum (Carr.) Archangelsky.

PLATE XIV

Fig. 1: Lepidopteris stormbergensis (Seward) Townrow.

Fig. 2: Taeniopteris immersa (Nathorst).

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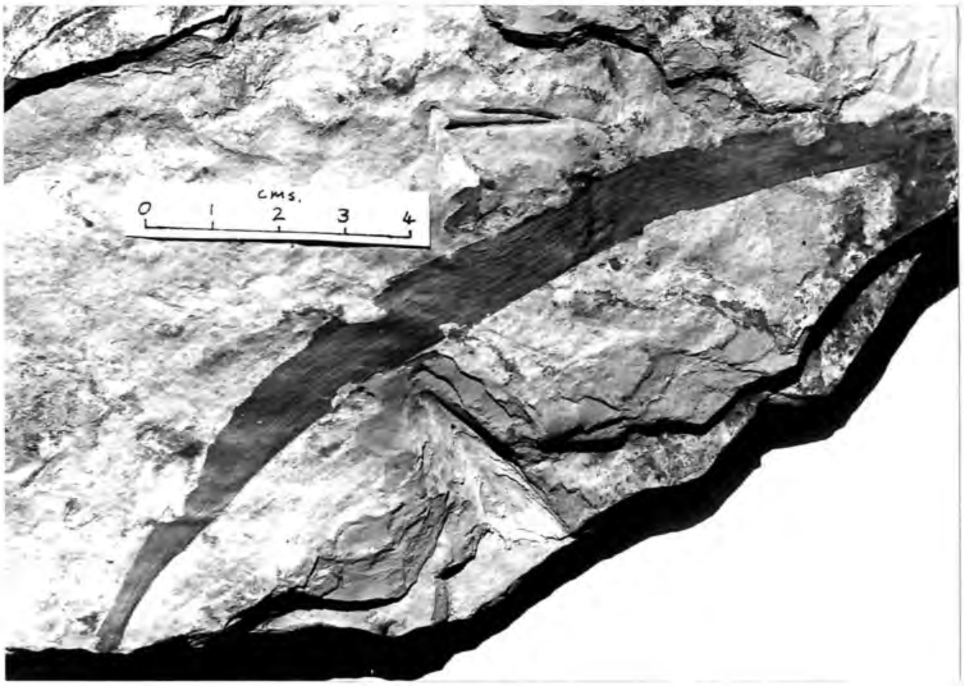

Fig. 1: Phoenicopsis elongatus (Morris).

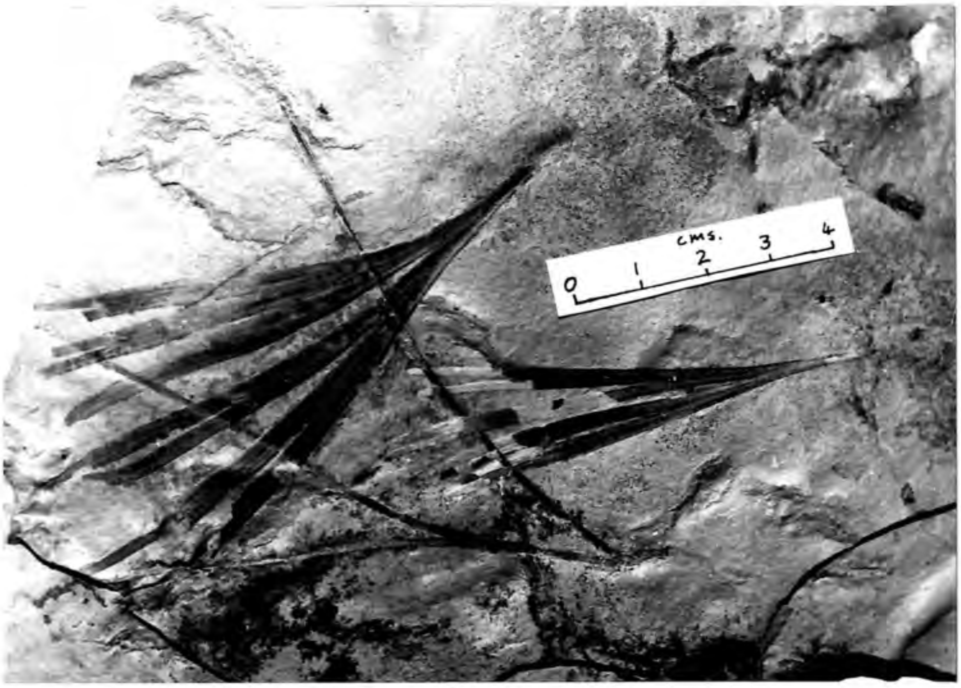

Fig. 2: Baiera schenki (Feistmantel).

Fig. 1: Baiera sp.

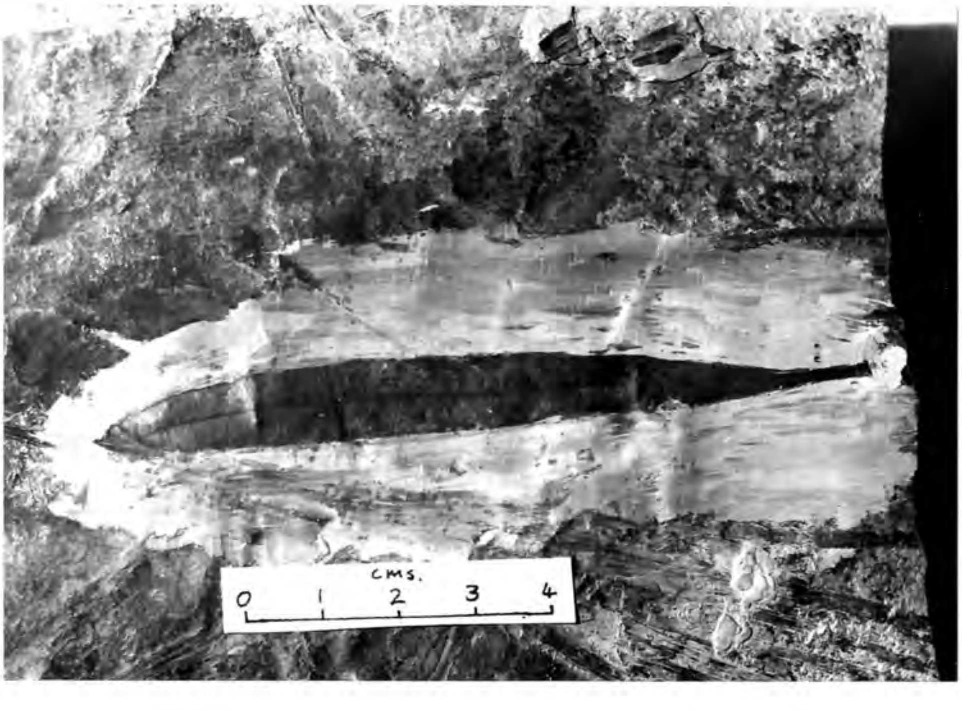

Fig. 2: Yabeiella dutoitii (Oishi).

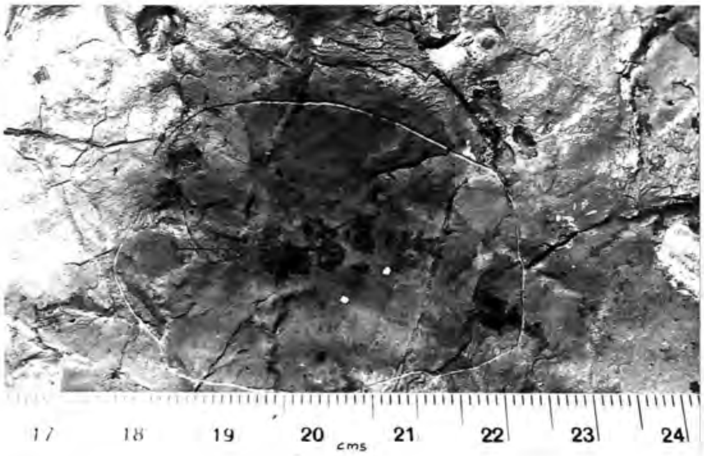

Fig. 1: Pteruchus sp. (ringed).

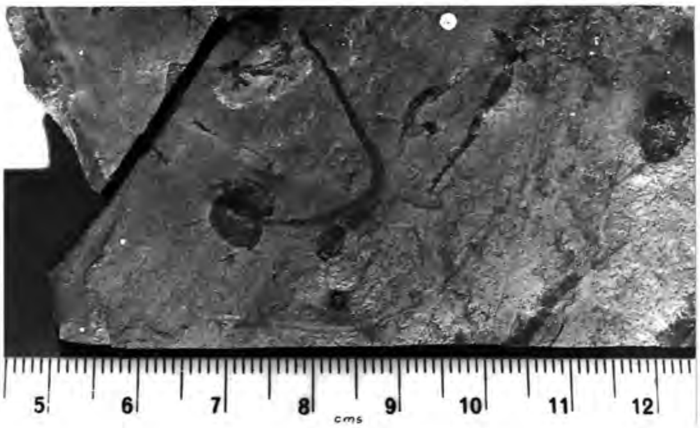

Fig. 2: A winged seed. Unidentified species.

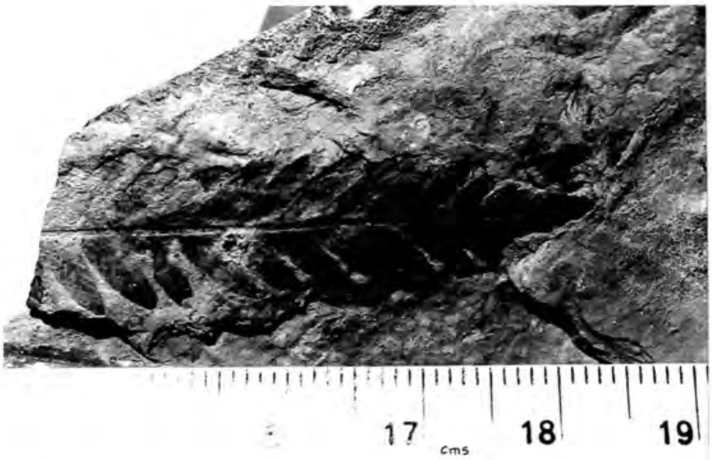

Fig. 3: Unidentified species of fern.

well as Baiera schenki occur most abundantly while Lepidopteris and Taeniopteris are less common. Yabeiella, Pteruchus and a second species of Baiera (see Plate XVI, Fig. 1) are rare. Plant seeds also characterize the bed (see Plate XVII, Fig. 2). Towards the top of the bed carbonaceous material becomes more abundant and resembles an impure form of coal.

Further south in a vlei on Denwood, a silicified tree (Dadoxylon?) occurs in situ in a shale bed.

2. The Red Beds Stage.

The full sequence of Red Beds sediments is represented in the Birds' River area. The greatest thickness of this Stage occurs to the east of the bell-jar intrusion, where the writer measured the relative heights between the base of a Cave Sandstone outlier on Thysfontein and the base of the Red Beds (as previously defined) on Koups Leegte, with a Paulin precision altimeter. The thickness of the Red Beds Stage thus measured was found to be 442 metres (1450 feet), a figure which compares well with the difference in elevation between the 1676 metre (5500 foot) contour, accepted by the writer as the approximate base of the Red Beds Stage, and the contour at the base of the Cave Sandstone outlier. This thickness also corresponds fairly closely to that of the calculated maximum thickness of the Red Beds Stage in the Smuts Pass xenolith.

Du Toit (1904, p.92) notes that the thickness of the Red Beds Stage varies considerably in the Wodehouse district, but is apparently fairly consistent to the west of Dordrecht. At Dordrecht Du Toit recorded a thickness of 198 metres (650 feet) for the Stage, but only 19 kilometres (12 miles) to the east it increases to 457 metres (1500 feet). From the estimated thickness of the Red Beds Stage in the Birds' River area it appears that there is a rapid increase in thickness westwards from Dordrecht as well.

Sediments of the Red Beds Stage dip at shallow angles in a northerly direction. As was previously mentioned, the

Molteno sediments dip in the opposite direction to the Red Beds. This would suggest the presence of an east-west anticlinal axis in this area, approximately bisecting Map No. 1. The Red Beds sediments are composed of mostly yellowish and occasional red, medium- to fine-grained, cross-bedded sandstones and red, purple and greenish mudstone beds. The sandstone beds are generally thicker (6 to 10 metres (20 to 30 feet)) at the base of this Stage, but tend to decrease in size upwards to an average thickness closer to 3 metres (9 feet)(see Plate XVIII, Fig. 1). As in the Molteno Stage, a number of the sandstone horizons have a glittering appearance.

The mudstone beds are generally thicker in the upper half of the Stage. They are usually covered by talus and vegetation while thin interbedded sandstone beds interrupt their steep slope and protrude as flat-lying ledges. According to Botha (1968, p.110) the red pigment within the Red Beds sediments is finely divided haematite; he emphasizes that the red colour is concentrated largely within the fine-grained sediments.

Where the argillaceous sediments are exposed and have not been affected by the numerous dolerite intrusions, they may display quite magnificent colours. A striking example of their vivid colouration is to be seen at Rooiberg, north of the bell-jar intrusion (see Plate X, Fig. 2). Here the small hill of Rooiberg owes its existence, to some extent, to more resistant red sandstones overlying red mudstone beds. The Vogel Vlei sheet immediately to the east of Rooiberg at one time most probably extended westwards, and thus would have been initially instrumental in protecting Rooiberg from erosion. Present-day erosion is, however, rapidly destroying the hill by undermining the sandstone capping.

Rounded clay pellets and thin mudstone lenses often occur within the yellowish sandstone beds of the Stage. The argillaceous material weathering more rapidly than the arenaceous results in a pock-marked appearance within the latter. Some excellent examples of polychromatic Bushman paintings are to be found within caves in the sandstone beds (see Plate XVIII, Fig. 2).

Fig. 1: A typical outcrop of a cross-bedded, medium-grained sandstone bed, of the Red Beds Stage.

Fig. 2: Bushman paintings in Red Beds sandstone, on Buffelsfontein.

Ripple marks were only rarely encountered in the sandstone beds. An outcrop on Die Smuts Pass (see Plate XIX, Fig. 1) indicates that the current flow was towards the north-west. Ferruginous concretions are commonly developed on sandstone bedding-plane surfaces, and rounded as well as discoidal calcareous nodules occur within the sediments near the contact with the Cave Sandstone, along the eastern margin of the bell-jar intrusion.

Isolated occurrences of pyroclastic material occur interbedded with the sediments. An example, previously mentioned, which is composed of angular fragments of sandstone and mudstone set in a siliceous matrix, is to be found near the base of the Red Beds sediments of the Smuts Pass xenolith. To the north of the bell-jar intrusion, situated next to one of the ring dikes (Map No. 2, grid reference I 4) is a greenish agglomeratic rock with small fragments of sandstone and mudstone cemented in a siliceous matrix. Similar examples of what may be termed a sandstone tuff (Gevers, 1928, p.49) are to be found as narrow lenses interbedded with the sediments of the Red Beds Stage in this area.

3. The Cave Sandstone Stage.

The Cave Sandstone Stage in the Birds' River area is represented by small outliers conformably overlying the Red Beds Stage. The sandstone is generally creamy or whitish, fine-grained and massive. The colour may grade into pale green and buff. In many of the outliers, especially those nearer the bell-jar intrusion, the sandstone has a markedly spotted appearance. The spots are predominantly whitish but a pink colour was also noted. The grain size throughout the rock, however, appears to be fairly consistent. The sandstone is most often very friable, and is composed predominantly of subangular to rounded quartz grains with a small amount of felspar. From heavy mineral analyses of the Cave Sandstone in the Kestell area of the Orange Free State, Koen (1955) has identified several varieties of zircon, tourmaline and rutile in the sandstone, while garnet, apatite, titanite, anatase, biotite, epidote, monazite, leucoxene and ilmenite are also present.

95 a

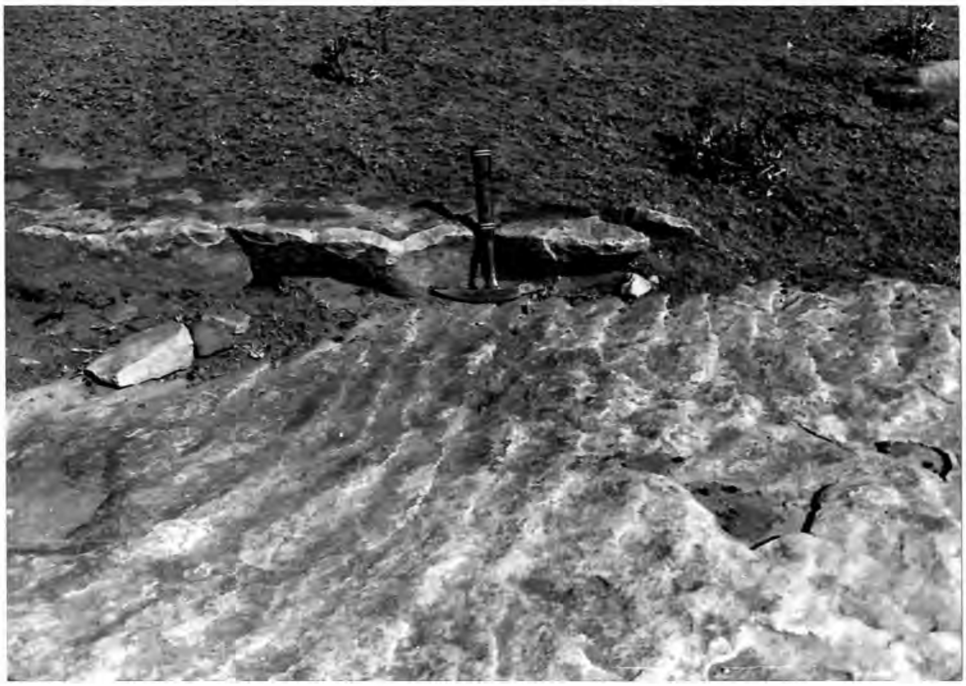

Fig. 1: Ripple marks in Red Beds sandstone, on Die Smuts Pass.

Fig. 2: An outlier of Cave Sandstone, on Snymans Kraal.

Agglomerate, sometimes clearly interbedded with the sandstone, as along the eastern margin of the bell-jar intrusion, and at other localities occurring in irregular patches within the sandstone is characteristically associated with this Stage in the area mapped. The agglomerate is generally highly weathered and greenish in colour. It is composed of angular fragments of sandstone, mudstone, dolerite and lava set in a predominantly siliceous matrix.

Typical "Cave" weathering is generally apparent at the base of this Stage.

The largest of the Cave Sandstone outliers occurs above Rooiberg on the farms Snymans Kraal and Boshoffs Kraal (2). The Vogel Vlei dolerite sheet has split this outlier into a narrower strip on the west and an oval-shaped mass on the east of the sheet, the latter measuring not more than 85 metres (280 feet) in thickness (see Plate XIX, Fig. 2).

The contact with the Red Beds Stage is well defined above Rooiberg but is gradational on the eastern side of the outlier. Cross-bedding, on a large scale, is present near the base of this outlier, with thin, (approximately 30 centimetres) green mudstone interbeds containing rounded sandstone nodules up to 2 centimetres in diameter. The sandstone is generally massive, whitish in colour and has a pitted appearance on the surface of the rock. Concretions are also present within the sandstone.

As mentioned previously, the strip of Cave Sandstone occurring along the eastern margin of the bell-jar intrusion is situated at a distinctly lower elevation than the other outliers in the area, and it dips in towards the bell-jar intrusion. The contact with the Red Beds is fairly well defined and the sandstone is particularly "spotty" in this area. At its southern extremity the Cave Sandstone appears to be faulted down against pyroclastics (see grid reference P 10).

Xenoliths of Cave Sandstone representing foundered roof fragments are to be found several hundred metres below their normal elevation, within the bell-jar intrusion.

D. DEPOSITIONAL ENVIRONMENT OF THE STORMBERG SEDIMENTS.

1. The Molteno Stage.

Rust (1959) regards the Molteno sediments as being derived from a southern provenance area, the source having been approximately 200 kilometres (130 miles) to the south of the present outcrop of Stormberg sediments. Evidence of the Dwyka Series providing the source material is indicated by the presence of pink garnet and felspar; this was followed by denudation of the Witteberg Series (denoted by well rounded quartzite pebbles, cobbles and boulders in the arenaceous sediments), and a granitic area to the south-east. Rust emphasized that sudden uplift, and not just isostatic compensation, must have taken place in the provenance area in order to account for the extremely coarse grain size within the Molteno sediments.

With gradual denudation of the source area, the sediments became less coarse grained; deposition of sandstones succeeded the conglomerates and grits. These were in turn followed by argillaceous material. Finally environmental conditions became suitable for the growth of plants and trees, the vegetation becoming progressively more abundant with the passage of time. This sequence of sedimentation, viz. initial deposition of coarse-grained material, followed successively by finer-grained material and ending up with prolific vegetation, was followed abruptly by another such lithological sequence. Rust has recognised five such cyclothems in the Molteno area. These cyclothems, the result of diastrophic pulses in the southern provenance area, are only represented in the lower half of the Molteno Stage.

Cross-bedding within the Molteno sediments examined by Rust indicates that the sediments were transported in a direction bearing N 10° W.

Climatic conditions were undoubtedly wet and cold, as evidenced by the absence of mud cracks, the presence of felspar and the flora in the sediments. Vegetation was largely of the Dicroidium fern-type and Dadoxylon trees which often grew in swampy areas. Renewed diastrophism in the south resulted in the rapid burial of the vegetation which later formed the coal horizons.

2. The Red Beds Stage.

From a study of palaeocurrent directions in the Red Beds, in the Elliot district, Botha (1968) concluded that the sediments were transported from two source areas, one situated to the north and the other to the south of the present area of Stormberg sediments. Botha (1968, p.112) noted that other features such as ripple marks and scour-and-fill structures indicate that the sediments of this Stage were deposited in intermittently quiet and rough, shallow-water conditions, typical of alluvial flats in a continental environment. Near the top of the Stage the presence of beds of massive sandstone weathering in much the same manner as Cave Sandstone, led Botha to suggest a depositional environment similar to that of Cave Sandstone times.

The red colouration within the mudstone and some of the sandstone beds was derived from pre-existing soils of red colouration and most probably deposited under humid and warm climatic conditions (Botha, p.113). Botha regards the dominance of colours in the argillaceous beds as due to the mechanical sorting out of haematite from the coarser sediments during transport by water. It appears that the greenish and gray mudstones were deposited under reducing conditions, as might be found in stagnant pools.

Environmental conditions were most probably similar to those of Beaufort times. According to Haughton (1969, p.367) the larger, heavy-limbed reptiles characterize the lower part of the Red Beds Stage while the lighter built cursorial types are to be found in the upper part of the Stage.

J.C. Theron (personal communication) believes that the Beaufort and Red Beds were derived from the same source area, as evidenced by garnet being the most important heavy mineral. He regards the deposition of the Molteno Stage as the result of uplift of a new source area which initially shed garnet-impoverished sediments.

3. The Cave Sandstone Stage.

Du Toit (1954, p.300) regarded this Stage as chiefly aeolian in origin while there is evidence that at the base and possibly at the top of this Stage deposition in water must have taken place. In the Birds' River area on Snymans Kraal the generally cross-bedded nature and presence of thin beds of mudstone near the base of this Stage lend support to Du Toit's conclusions.

Occasional vertebrate and silicified wood remains are to be found within the Cave Sandstone Stage but the majority of forms of life and plant growth must have been destroyed with the ensuing arid conditions.

D. Elliot, of the Institute for Polar Studies at the University of Ohio (personal communication) has presented the view that the spotted nature of the Cave Sandstone in the Birds' River area may be the result of volcanic activity at the time of deposition of the sandstone. The possibility of spraying of some type of cementing material (e.g. zeolitic in nature) on to the sandstone is visualized. That volcanic activity did occur in this area is indicated by the presence of a large amount of pyroclastic material; it therefore appears that Elliot's suggestion offers a feasible explanation as to the presence of the spots in the sandstone. On the other hand the spots may simply represent the leaching out of the darker coloured material in the rock.

* * * * *

CHAPTER FIVE

THE PYROCLASTIC ROCKS

The pyroclastic rocks of the Birds' River area exhibit an interesting range of types. An outline of pyroclastic terminology, as applied in the description of these rock types, as well as an interpretation of their mode of formation is given by the writer in this chapter.

A. GENERAL DISCUSSION ON CLASSIFICATION OF PYROCLASTIC MATERIAL.

The term pyroclastic rock is used to denote detrital material that has been expelled into the air by volcanoes. Wentworth and Williams (1932, p.25) point out that the term need not necessarily imply the result of explosive eruptions. This is exemplified by Pele's Hair and pumiceous rocks which are produced under quiet conditions of eruption. The above writers also indicate that the term need not be synonymous with fragmental volcanic, since much of the superficial material of, for example, aa lava flows, is fragmental.

According to Holmes (1965, p.302) and Wentworth and Williams (1932, p.45) pyroclastic materials may be described as :-

> Essential: representing fragments which are of magmatic origin.
> Accessory: consisting of preformed volcanic rocks and pyroclasts of earlier eruptions.
> Accidental: which comprise igneous, sedimentary or metamorphic fragments derived from pre-existing rocks through which the vent or vents passed.

Tephra represents unconsolidated pyroclasts of the 'essential' type.

A complete classification of the pyroclastic rocks should embrace several factors of which Wentworth and Williams (1932, p.24) recognise the following, in their order of importance: size of clasts, mode of origin, composition and texture, and mode of deposition.

The various terms used to describe the pyroclastic rocks of the Birds' River area, especially as regards size and composition of the material making up the rock, are mainly those adopted by Wentworth and Williams (1932). For clarity and uniformity in the descriptions, the definitions of some of the terms used by these authors are outlined below :-

1. The Fragmental Inclusions, and their Size Range.

Bombs are masses of magmatic material plastic at the moment of ejection and having forms, surface markings, or internal structures assumed in response to forces acting during flight through the air. Bombs are greater than 4 millimetres in diameter. Further classifications of bombs are usually based on their overall shape and features which may resemble certain mundane forms, e.g. turtle back, ribbon, breadcrust and cow-dung bombs.

Blocks are fragments of accessory or accidental material, usually angular and larger than 32 millimetres in diameter, and erupted in a solid state.

Lapilli are essential, accessory and accidental ejecta ranging from 32 millimetres to 4 millimetres in diameter, i.e. from the size of a walnut to that of a pea.

Ash is uncemented pyroclastic debris consisting of fragments mostly under 4 millimetres in diameter. Without a qualifying adjective ash should be applied only to essential or juvenile ejecta.

Volcanic dust is pyroclastic detritus composed of essential, accessory or accidental material generally less than $\frac{1}{4}$ millimetre in diameter.

2. Pyroclastic Rock Types.

A breccia is a more or less indurated pyroclastic rock consisting chiefly of angular ejecta 32 millimetres or more in diameter. If the fine tuff matrix be abundant the term tuff breccia seems appropriate.

An agglomerate is a contemporaneous pyroclastic rock containing a predominance of rounded or subangular fragments greater than 32 millimetres in diameter, lying in an ash or tuff matrix and usually localized within volcanic necks (Vent agglomerates) or at a short distance therefrom. The rounding of the fragments is a result of attrition within the vent.

Volcanic rubble is an unconsolidated accumulation of pyroclastics in which the fragments range from the largest sizes down to 4 millimetres in diameter, and in which these are mainly angular. This is the unconsolidated equivalent of volcanic breccia and of some lapilli tuffs.

Tuff is an indurated pyroclastic rock of grain size generally finer than 4 millimetres. The finer-grained pyroclastic materials, viz. ash and volcanic dust, have already been mentioned.

Lithic is an adjective applied to any pyroclastic deposit in which the fragments are composed of previously formed rocks; for instance accidental pieces of sedimentary rock, the accessory debris of earlier lavas in the same cone, or even shattered bits of new magma that first solidifies in the vent and is then blown out.

The use of some of the above terms as adjectives allows broader qualifications of the pyroclastic rocks, e.g. lapilli tuffs, and tuffaceous sandstone.

The terminology, as applied to the mode of formation of the Stormberg volcanoes, is briefly outlined in the next chapter, while that of the pyroclastic material is given below.

Gevers (1928, p.49) has classified the fragmental rocks occurring within the volcanic vents of the western Stormberg in the Republic, into nine types. Some of these rock types, which appear to be very similar to the pyroclastic rocks of the Birds' River area are outlined below :-

(a) Tuffs and agglomerates consisting of fragments of sedimentary rocks set in a matrix of volcanic material : This type of rock was probably formed while the gaseous content of the lava was still very high and explosive action still violent, with the result that practically all the lava material present was rendered highly pumiceous and subsequently powdered to volcanic ash.

(b) Tuffs consisting mainly of fragments of sedimentary material set in an argillaceous matrix : This common rock type was most probably formed during an entirely gaseous phase of volcanic activity.

(c) Tuffs consisting of fragments of sedimentary rocks set in a predominantly siliceous matrix : In this rock type sand is the chief constituent.

(d) Tuffaceous sandstone : This rock type is a sandstone containing lapilli and other fragments of foreign matter introduced by volcanic action.

(e) Sandstone tuff : The material is entirely siliceous. It consists of fragments of sandstone set in a matrix of sandstone.

(f) Sandstone of the vent-filling type : This is a sandstone resembling Cave Sandstone but occurring within the volcanic vents.

B. FIELD DESCRIPTIONS OF THE BIRDS' RIVER PYROCLASTIC ROCKS.

1. Situation and Mode of Occurrence.

Pyroclastic rocks in the Birds' River area are to be found (a) interbedded with Stormberg sediments and (b) as isolated xenoliths within the bell-jar intrusion. Those pyroclastics falling under (a) occur outside the area of the bell-jar intrusion while the xenoliths have already been mentioned in Chapter Three. Virtually all outcrops are highly weathered and are metamorphosed at the contact with dolerite intrusions.

(a) Pyroclastic Rocks Outside the Area of the Bell-jar Intrusion.

The largest occurrence of pyroclastic rocks, in this category, is to be found on Thysfontein and Murrelfontein along the eastern margin of the bell-jar intrusion. For most of the area of outcrop on Thysfontein the pyroclastics are interbedded with the Cave Sandstone, but further south-eastwards on Murrelfontein the Cave Sandstone no longer crops out and the pyroclastics appear to overly Red Beds sediments directly. Due to lack of bedding within these pyroclastic rocks and the Cave Sandstone one cannot be certain of their exact attitude. Judging from the dip of the underlying Red Beds, however, it is reasonably certain that the Cave Sandstone and pyroclastics in this locality dip in toward the bell-jar intrusion. On Murrelfontein, where the outer margin of the bell-jar intrusion has cut through the pyroclastic rocks, it protrudes as a high narrow ridge. The steep slope on either side of the ridge is due to the rapid weathering of the pyroclastic rocks that have not been baked.

As previously mentioned, small occurrences of pyroclastic rocks are to be found within the Red Beds Stage. These are usually interbedded as small lenses, but in many cases their attitude towards the sediments is not clearly defined in the field. Most of this material was observed within the upper portion of the Red Beds Stage on the farms Lemoenfontein and Boshoffs Kraal (1).

The above-mentioned occurrences of pyroclastic rocks serve to illustrate that Stormberg volcanic activity was initiated as early as the Red Beds Stage, in the Birds' River area. These observations lend support to the work of Botha and Theron (1967) who bring to notice the significance of a bentonite bed in Red Beds sediments near Jamestown. They consider this bentonite deposit to be an altered volcanic tuff. This example therefore indicates that Stormberg volcanic activity had commenced within the Red Beds Stage.

Pyroclastic rocks are also to be found within diatremes in the Birds' River area. These rocks will be described in the following chapter.

(b) Xenoliths of Pyroclastic Rocks Within the Bell-jar Intrusion.

The situation of the xenoliths and a brief outline of their petrography has already been given in Chapter Three, but for purposes of convenience their situation and general features will be briefly recapitulated here :-

> The largest xenolith composed of pyroclastic rocks occurs in the eastern portion of the bell-jar intrusion and extends as a blanket across the farms Romance, Lemoenfontein, Thysfontein and Murrelfontein.
>
> The elongate xenolith immediately to the east of that just mentioned is situated largely on Murrelfontein, and is slightly basin shaped.
>
> The remaining xenoliths composed of pyroclastic rocks are mostly of very much smaller size and are randomly positioned within the bell-jar intrusion (see Map No. 2, e.g. grid reference K 8 and K 12).

Only within the larger xenoliths is there some suggestion of bedding in the pyroclastic rocks, but in most cases the bedding is not obvious.

As previously mentioned, pyroclastic rocks are present within the Red Beds sediments of the Smuts Pass xenolith.

2. Petrography of the Pyroclastic Rocks.

In the field there are generally no clearly defined boundaries between the various types of pyroclastic rocks. For purposes of description the pyroclastic rocks may conveniently be divided into four groups. This classification is based on the percentage of igneous inclusions in the rock. The subdivisions of this classification have arbitrarily chosen limits, which appear to conform to particular rock types as seen in the field. The following groups of rock types are recognised by the writer :-

(a) Pyroclastic rocks containing less than 5% igneous inclusions.

(b) Pyroclastic rocks containing between 5% and 25% igneous inclusions.

(c) Pyroclastic rocks containing between 25% and 50% igneous inclusions.

(d) Pyroclastic rocks containing more than 50% igneous inclusions.

(a) Pyroclastic Rocks Containing Less Than 5% Igneous Inclusions.

Within the area of the bell-jar intrusion, occurring mainly as smallish xenoliths, are a number of these pyroclastic rocks. They are composed of angular to subangular blocks of mostly coarse- and medium-grained sandstones (which resemble Molteno and Red Beds sandstones) and occasional blocks of greenish mudstone set in a siliceous matrix (see Plate XX, Figs. 1 & 2). Igneous fragments are virtually absent from this rock type.

The description of this pyroclastic rock would appear to correspond fairly closely to Gevers' definition of a sandstone tuff; yet the predominant size of the fragments being greater than 32 millimetres in diameter (i.e. blocks) it would be more appropriate to call it a breccia, as defined by Wentworth and Williams. As the blocks are composed virtually entirely of Stormberg sediments (predominantly sandstone) it is proposed to refer to this rock type as a sandstone breccia.

(b) Pyroclastic Rocks Containing Between 5% and 25% Igneous Inclusions.

Rocks in this category are generally to be found near the base of the large xenoliths and also, for example, interbedded with the Cave Sandstone on Thysfontein. Associated with them are irregular beds and large blocks of sandstone.

This rock type is composed chiefly of lapilli but also scattered blocks of coarse-, medium- and fine-grained sandstones and mudstones set in a predominantly siliceous matrix. Blocks of lava and dolerite are not very abundant (see

Fig. 1: A sandstone breccia, on Lemoenfontein (grid reference K 8). Note angular blocks of sandstone set in a siliceous matrix.

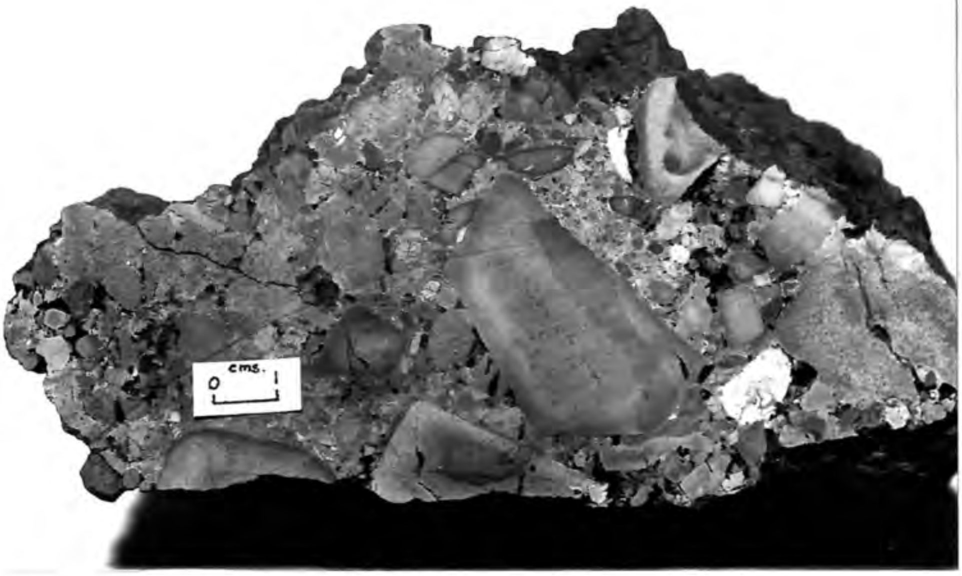

Fig. 2: Sandstone breccia, from Die Smuts Pass (grid reference G 9). Note predominantly angular blocks of sandstone.

Plate XXI, Fig. 1). Some of the lapilli are characterized by reaction rims along their margins (see Plate XXI, Fig. 2). These rims, in most cases, appear to be the result of thermal metamorphism of the lapilli.

On outcrop the rock has an overall pale greenish colour, the lapilli and blocks of sandstone being whitish to pink in colour, while the mudstones are generally greenish. It appears then that the lapilli and blocks are composed largely of Red Beds and Cave Sandstone Stage sediments. As the matrix of the rock is invariably highly weathered at surface it is difficult to state with certainty what it was originally composed of. It seems quite likely that a certain amount of igneous material could be present within the matrix, judging from the igneous or 'essential' lapilli within the rock. In hand specimen it appears , however, that the matrix is composed predominantly of siliceous material, which more than likely represents pulverized Stormberg sediments.

This rock type could conveniently be referred to as a volcanic rubble (after Wentworth and Williams) but following the more specific definition of Gevers, it would most probably correspond closest to a tuffaceous sandstone.

On Murrelfontein the unbedded and chaotic nature of the fragmental material in a fine-grained matrix suggests that at least some of the pyroclastic material grouped in this, and the following section, has been redeposited through mudflows.

(c) Pyroclastic Rocks Containing Between 25% and 50% Igneous Inclusions.

Only one small outcrop on Romance which revealed an undulating contact between this rock type and the previous one was observed. In this rock type blocks are more abundant and are generally of a larger size (see Plate XXII, Fig. 1). The blocks are composed of sandstone, mudstone, basic lava and dolerite while the matrix is most probably a mixture of fine-grained sedimentary and igneous material which has a muddy appearance on outcrop. The surface of the rock often has a reddish stain on it.

PLATE XXI

Fig. 1: Tuffaceous sandstone on Thysfontein (grid reference 0 9). Note lapilli and scattered blocks of sediments and lava in a predominantly siliceous matrix.

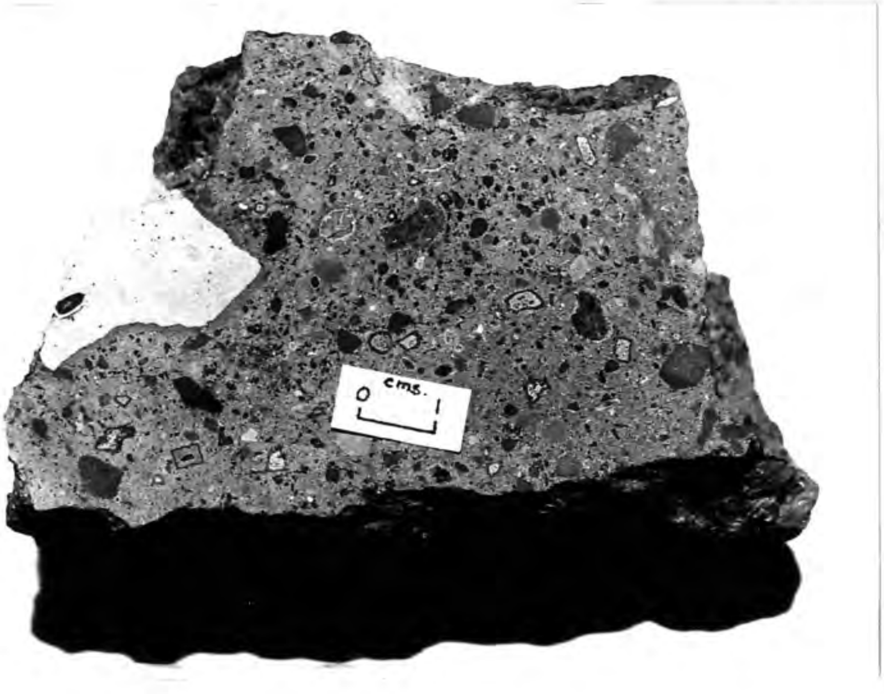

Fig. 2: Tuffaceous sandstone. Note reaction rims around some of the lapilli.

Fig. 1: An agglomerate on Romance (grid reference K 11). Large blocks of sedimentary and igneous material in a predominantly fine-grained matrix.

Fig. 2: Lava flow (top right of photograph) overlying lapilli tuff on Murrelfontein (grid reference P 10). The base of the lava flow dips at 70° to the right (west).

The sandstone blocks are mostly medium grained while some of the mudstone blocks have been metamorphosed to lydianite and appear reddish in colour, as well as a mottled gray and black colour. These features suggest that the blocks of sediments have been derived largely from the Red Beds Stage. As a number of the blocks do show a certain amount of rounding, Wentworth and Williams' definition of an agglomerate seems appropriate to this rock type.

The agglomerate occurs within xenoliths of the bell-jar intrusion and is characterized by abundant veins and irregular patches of zeolites.

(d) Pyroclastic Rocks Containing More Than 50% Igneous Inclusions.

An agglomerate, composed of blocks of Stormberg sediments and lava, and very large blocks of dolerite is to be found near the western boundary of Romance (within grid reference K 11). It occupies the high ground of the largest xenolith and displays a chaotic assemblage of blocks in a fine-grained matrix. There is no evidence of bedding. In places dolerite blocks may form up to 50% of the included fragments in the rock, some of them measuring an astonishingly large size, e.g. up to 5 metres (15 feet) in length. The dolerite blocks protrude as rounded to subrounded features on outcrop and therefore conform closely to Wentworth and Williams' definition of an agglomerate.

A thin section from one of these blocks exhibits a typical glomeroporphyritic texture with zoned plagioclase crystals and pyroxene (pigeonite and augite) crystals grouped into clusters. Olivine is slightly altered to iddingsite (?) while there are small proportions of iron ore, apatite and quartz present. The rock as a whole is coarse grained.

On Murrelfontein the large outcrop of pyroclastic rocks outside the area of the bell-jar intrusion which appears to overly Red Beds sediments directly (see grid references P 10 to R 12), is greyish green in colour and is highly weathered. The majority of included fragments are less than 4 millimetres in diameter and are composed predominantly of igneous, but also some sedimentary material. Due to the presence of scattered lapilli, blocks and possibly some bombs, the rock is best described as a lapilli tuff (see Plate XXII, Fig. 2).

An amygdaloidal lava flow is present within these pyroclastic rocks (see grid reference P 10, and Plate XXII, Fig. 2). It dips steeply, at approximately 70°, towards the west and in places is about 5 metres (15 feet) thick. Large blocks of Stormberg sediments, chiefly of the Red Beds Stage, are to be found within the upper part of this lava flow. Amygdales filled largely with zeolites occur scattered throughout the rock. Most of the amygdales are rounded or oval in shape but some are elongate and resemble pipe amygdales. The latter, however, have a haphazard orientation within the rock and are not confined to the base of the flow. These features suggest that they most probably did not have quite the same origin as those pipe amygdales which form distinctive features at the bases of individual flows in the Barkly East district. A thin section of the lava flow shows a very fine-grained rock with scattered phenocrysts of anhedral plagioclase, pyroxene and olivine in a fine-grained, mainly ferromagnesian groundmass.

Several other amygdaloidal lava flows are to be found within the xenoliths of the bell-jar intrusion. Due to lack of sufficient outcrop their attitude towards the pyroclastic rocks could not be decided in the field.

C. MODE OF FORMATION OF THE PYROCLASTIC ROCKS.

It seems virtually certain that at least some of the area occupied by the Birds' River bell-jar intrusion, especially the eastern portion, was once a site of intense volcanic activity. As the rock types produced by this volcanic action are predominantly of a siliceous nature it appears that gaseous activity in a "central" type of volcano played the principal role in their formation.

Gaseous activity within the area of the bell-jar intrusion commenced with the penetration of small diatremes through Stormberg sediments. Small-scale examples of these diatremes could quite possibly be represented by the small breccia occurrences within the Molteno sediments of the Smuts Pass xenolith. The rock type, previously referred to by the writer as a sandstone breccia, is composed predominantly of coarse-grained angular sandstone blocks in a siliceous matrix. This rock type always occupies small areas, either within sandstone beds, or as xenoliths. It appears then that the gaseous activity was short-lived as evidenced by the angularity of the blocks, and that the diatremes penetrated largely Molteno sediments as is envisaged by the coarse-grained nature of the breccia.

The main focus of volcanic eruption was in all probability concentrated in the eastern portion of the area now occupied by the bell-jar intrusion. It is in this locality that a variety of pyroclastic rocks is to be found, as well as the largest outcrop. The area of outcrop of pyroclastic rocks (if one includes the two largest xenoliths of pyroclastic rocks) measures at least 19 square kilometres (7 square miles). Two important factors have, however, not been taken into account when estimating the figures above, viz. :-

(i) erosion has, more than likely, removed much of the pyroclastic deposits originally laid down,

(ii) the fact that large portions of the pyroclastic rocks have been detached and moved as xenoliths within a body of dolerite magma, i.e. the bell-jar intrusion.

Volcanic eruptions in this area could have taken place through a single vent, but, due to the scattered occurrences of different types of pyroclastic rocks, it would appear more likely that expulsion of volcanic material took place through several vents in the vicinity, or several parasitic vents around a focal point.

After the initial gaseous outbursts which formed the diatremes, a subsequent build-up and explosive release of gaseous pressure would most probably have had the effect of expelling most of the fragmental material and at the same time widening the vent. A certain amount of igneous material is bound to have been incorporated with the fragmental filling of the vent during this stage of eruption. The resulting pyroclastic rock type, viz. a tuffaceous sandstone, would contain largely sedimentary and a few igneous fragments. The latter would comprise lava and dolerite blocks which more than likely represent fragments from pre-existing intrusive and extrusive forms. As this predominantly siliceous pyroclastic rock type is found in association with Red Beds sediments, volcanic activity in the Birds' River area undoubtedly took place as early as this Stage in the Stormberg sequence.

The presence of the agglomerate rock containing large blocks of dolerite on Romance suggests that gaseous pressure within the vent must have been very great indeed, in order to expel these blocks of dolerite as well as sediment. The rounded shape of some of the blocks indicates that a certain amount of attrition had most probably taken place within the vent. Due to the large size of the blocks it seems most likely that deposition of this rock type was either within the vent itself or just outside the vent. The large dolerite blocks presumably originated within the volcanic vent itself. This implication appears to be quite feasible as these dolerite blocks form part of an agglomeratic rock which the writer has interpreted as being expelled from, or simply the products of, a volcanic vent. The blocks of dolerite are predominantly coarse grained, which suggests that the original magma must have cooled very slowly either within the vent between periods of eruption under hypabyssal conditions, or as earlier intrusive forms. In the latter case it would be implied that the volcanic vent had pierced through these earlier intrusive forms and had carried the fragmented blocks of dolerite towards the surface. Whether the dolerite, which now occurs within the agglomerate, crystallized from a magma in the vent or from an earlier intrusion through which the vent pierced at a later stage, it would still be classed as accessory rather than essential material, using the terminology outlined earlier. In either event, the dolerite was already crystalline before expulsion from the vent (exhibited by its coarse grain size) and the resulting fragmental material is correctly denoted by the word "block" rather then "bomb".

The large size of the dolerite blocks within the agglomerate on Romance would imply the presence of at least one vent near the western boundary of this farm. One must not, however, preclude the view that this agglomerate may have been redeposited some distance from the original volcanic vent through a mudflow. The agglomerate bears several characteristics of a mudflow, viz. poor sorting of blocks in a fine-grained matrix, and absence of bedding. Mudflows generally originate through saturation of brecciated material on a slope, e.g. a volcanic cone, thus imparting plastic or fluid properties to the debris and causing it to move downslope. MacDonald (Hess and Poldervaart, 1967, p.25) reviews Anderson's discussions on the origin of mudflows, and points out the following important causes of mudflows :-

(i) The commonest is heavy rain, either normal rainfall, or rain caused by condensation of the steam in the eruptive cloud, falling on loose material on flanks of the mountain.

(ii) Water-saturated brecciated material is erupted directly from the vent.

(iii) Ejection of a crater lake on to debris-covered outer slopes of a volcanic cone.

(iv) Destruction of a crater wall, releasing water from the crater lake.

(v) Melting of ice and snow by eruption of hot material on to them.

It appears that as igneous activity in the Birds' River area increased, so a greater proportion of igneous fragments contributed to the formation of the pyroclastic rocks. This is exhibited by the lapilli tuffs on Murrelfontein. The latter rocks cannot be classified as tephra, due to the presence of accidental and accessory fragments, yet the occasional lava flows within these pyroclastics manifestly represent the products of entirely igneous outpourings. As a result of structural disturbances of the sediments and pyroclastics along the eastern margin of the bell-jar intrusion, and also within the xenoliths, it becomes difficult to reconstruct with certainty the original position of the vent, or vents, which produced these lava flows.

Volcanic activity, seen mainly in the form of Central Type eruptions, continued actively in Cave Sandstone times, as evidenced by the interbedded and patchy nature of the pyroclastics within the Cave Sandstone in the Birds' River area. After the eruptive phase extrusion gradually took the form of lava flows of the Icelandic type. These flows emanated largely from fissures which are now occupied by dolerite dikes, and spread out over large areas to build up the high ground of the Republic and Lesotho. In the Birds' River area, however, erosion has removed all of this Drakensberg Volcanic Stage. The hypabyssal phase of basic intrusions undoubtedly exploited some of the passages created by earlier volcanic activity, as is exemplified by the bell-jar intrusion.

* * * * *

CHAPTER SIX

THE DIATREMES.

A. NOMENCLATURE.

Du Toit (1904, p.165) originally recognised four types of Stormberg volcanic necks. His classification graded from those filled almost entirely with igneous material to those filled predominantly with a fine-grained sandstone.

Gevers (1928, p.46) classified the volcanoes of the western Stormberg into :-

Diatremes, which were entirely gaseous in origin, and had no lava flows poured out of them.

Vents, which had emitted lavas, or at least had magmatic material injected into their fragmental fillings.

The above two groups include all four of Du Toit's types of volcanic necks. The volcanoes represented in the area described by the writer are exclusively of the diatreme type.

Holmes (1965, p.267) refers to the use of the term neck to include "Volcanic pipes from which the broken-up fragments of the original rocks were not completely expelled, any follow up of magma having been limited to intrusive tongues or the products of magmatic spray". Plugs, according to Holmes (1965), are intrusions of compact igneous rocks.

B. LOCALITY AND MODE OF OCCURRENCE OF THE DIATREMES.

Two separate occurrences of diatremes are to be found outside the area of the bell-jar intrusion. The first comprises a group of diatremes to the north-west of the bell-jar intrusion, on Klip Kraal (grid reference B 8). The second occurrence is a single diatreme to the east of the bell-jar intrusion, on Thysfontein (grid reference S 7). In addition there is a very small outcrop of a whitish, fine-grained sandstone on Boshoffs Kraal (1) which could possibly represent another diatreme. Its situation and mode of occurrence, in view of this possibility, are discussed.

1. The Klip Kraal Diatremes.

A group of five diatremes occupying an area of approximately 120,000 square metres, is to be found near the south-eastern corner of Klip Kraal. The Stafelberg's Kloof dolerite sheet, occurring at a slightly lower elevation than the diatremes, is situated to the west of this area. All five of the diatremes crop out along the top of a ridge of Red Beds sediments, two of them being clearly visible from the Molteno - Dordrecht main road (see Plate XXIII, Fig. 1). These two diatremes protrude as conspicuous, rugged, dome-shaped outcrops above the surrounding strata, while the remaining diatremes have been eroded down so that their outcrops merge approximately with the slope of the hilltop.

The easternmost and largest diatreme is roughly oval in plan view, its longer axis measuring approximately 150 metres (300 feet). It is situated at the same elevation as a Cave Sandstone outlier some 500 metres (1640 feet) to the south-east. The diatreme protrudes at least 10 metres (30 feet) above the surrounding strata, and even from fairly close by, it has the appearance of Cave Sandstone (see Plate XXIII, Fig. 2). Superficial weathering features are, however, somewhat different from the majority of Cave Sandstone outliers in the vicinity. The outcrop is characterized by a pitted and rugged shape, as well as being weathered into small caves. At its eastern extremity a "wind hole" has been formed. These irregular features are to some extent due to a form of differential weathering which is caused by a more resistant siliceous coating, observed on some of the material within the diatreme. Many very large blocks, representing fragments broken off from the neck of the diatremes, lie strewing the hillsides.

The contact of this diatreme with the country rock is not clearly defined in the field. The Red Beds sediments which form the country rock, do not appear to have been affected at all by the intrusion of the diatreme for they are

Fig. 1: Two of the Klip Kraal diatremes (arrowed), as viewed from the Molteno - Dordrecht main road. The plain in this picture is cut across Red Beds sediments and occurs at approximately 1800 metres (6000 feet) above sea level.

Fig. 2: The largest diatreme on Klip Kraal (grid reference B 8). Note flat-lying attitude of Red Beds sediments, and also the "wind-hole" towards the left of the diatreme.

flat lying, or dip at only shallow angles, near the contact.

Downhill, and to the north-west of the largest diatreme, there is a second diatreme. The latter's position is not immediately obvious as the neck of the diatreme has been eroded down to conform with the general slope of the hill-side. This diatreme is very much smaller in size than the easternmost one, and it is circular in shape.

The third diatreme protrudes as a mound above the ridge further to the north-west of the two just mentioned, but forms a far less significant feature than the largest diatreme. Near its northern contact the Red Beds dip fairly steeply inwards at about 50^{o} towards the contact. A sandstone tuff is apparently interbedded with the Red Beds sediments in this locality but appears to transgress the bedding slightly in places. This feature suggests that the sandstone tuff has an intrusive origin.

The remaining two diatremes form scarcely noticeable mounds immediately to the south-west of the third diatreme. In plan view the last three diatremes mentioned are either circular or oval in shape and are very much smaller in size than the easternmost diatreme. The Red Beds sediments have a gentle dip, even very close to the intrusive contacts, except near the northern contact of the third diatreme.

2. The Thysfontein Diatreme.

A small diatreme, approximately circular in plan view, is situated near the eastern boundary of Thysfontein (grid reference S 7). It occurs in Red Beds sediments, but its position is not immediately apparent because its surface approximates the steep slope of the hill-side. The contact with the country rock is not very clear. The country rock appears undisturbed as a result of its intrusion.

On Boshoffs Kraal (1) there is a very small, oval-shaped mound composed of a whitish fine-grained sandstone, which resembles Cave Sandstone (see grid reference F 6). This outcrop is situated near the top of a ridge and is at a lower elevation than most Cave Sandstone outliers in the surrounding area. Its elevation and its oval shape suggest that this could possibly be another diatreme. It does not, however, appear to have an intrusive contact. This latter fact need not necessarily rule out the possibility of its being a diatreme, if one considers the mode of origin of some of the diatremes, as advocated by Du Toit. Du Toit (1904) notes that many of the Stormberg diatremes are filled almost entirely with a fine-grained sandstone. He believes this to be the result of sand being blown into a vent from the top, after the vent had expelled its fragmental contents. The writer considers the outcrop in question on Boshoffs Kraal (1) to be an outlier of Cave Sandstone, as field evidence did not satisfactorily establish that it could be a diatreme.

The mode of occurrence of the Klip Kraal and Thysfontein diatremes conforms to the general pattern of distribution of the Stormberg volcanoes, as observed by Du Toit (1904, p.164) and Gevers (1928, p.46). These writers note that the Stormberg volcanoes do not appear to be concentrated along structural lines of weakness (as for example are Kimberlite pipes and fissures), but tend to occur in groups, or individually. Du Toit (1954, p.306) writes that "such an absence of orderly arrangement is paralleled by the Carboniferous volcanoes of Central Scotland, the Permian vents of Fifeshire, those of Eifel, the Swabian Alps, and the Auvergne".

The Stormberg volcanoes are confined almost entirely to the Stormberg Series of beds, for Gevers (1928, p.46) remarks that nowhere were volcanic necks found in sediments of lower stratigraphic position. Much more recently, however, Coetzee (1966) has recorded the presence of a volcanic neck in Beaufort beds near Bloemfontein. A small diatreme, Bowker's Kop, near Queenstown, also occurs in Upper Beaufort sediments (N.C. Taylor, Honours project, 1970).

C. PETROGRAPHY OF THE DIATREMES.

The largest diatreme on Klip Kraal is composed predominantly of a whitish to green, fine-grained sandstone, virtually identical to the Cave Sandstone occurring as outliers in this vicinity. In the centre and towards the eastern portion of the diatreme, however, scattered angular to subangular blocks of whitish to pale green sandstone within a greenish-yellow sandstone matrix confirm the presence of a sandstone tuff. Very occasionally, what appeared to be highly decomposed igneous fragments in hand specimen, were observed. The second diatreme is composed of a similar sandstone tuff.

Du Toit (1904, p.136) has remarked on the frequent occurrence of volcanic necks composed largely of a fine-grained sandstone resembling Cave Sandstone (apparently similar in nature to the largest Klip Kraal diatreme) in the Wodehouse and Herschell districts. In this connection Du Toit (1904, p.136) writes, "Owing to this resemblance it is likely that such necks may occur penetrating Cave Sandstone and may then remain unnoticed."

The three smaller, most westerly diatremes on Klip Kraal are composed of a sandstone tuff of unusual appearance. The rock is whitish in colour and is characterized by an abundance of rounded to subrounded fine-grained sandstone and calcareous sandstone fragments set in a fine-grained siliceous matrix (see Plate XXIV, Fig. 1). The fragments fall predominantly within the lapilli size range and are composed of a fine-grained sandstone resembling the Cave Sandstone. Occasional mudstone fragments are also present within the rock. Some of the sandstone fragments show a concentric structure, but this is most probably a secondary feature. The rounding of the included fragments in this rock type is thought to be due to attrition caused by gases streaming through sand particles within the volcanic pipe - a process more commonly known as "fluidization".

The sandstone tuff which occurs interbedded with the Red Beds sediments near the northern contact of the third

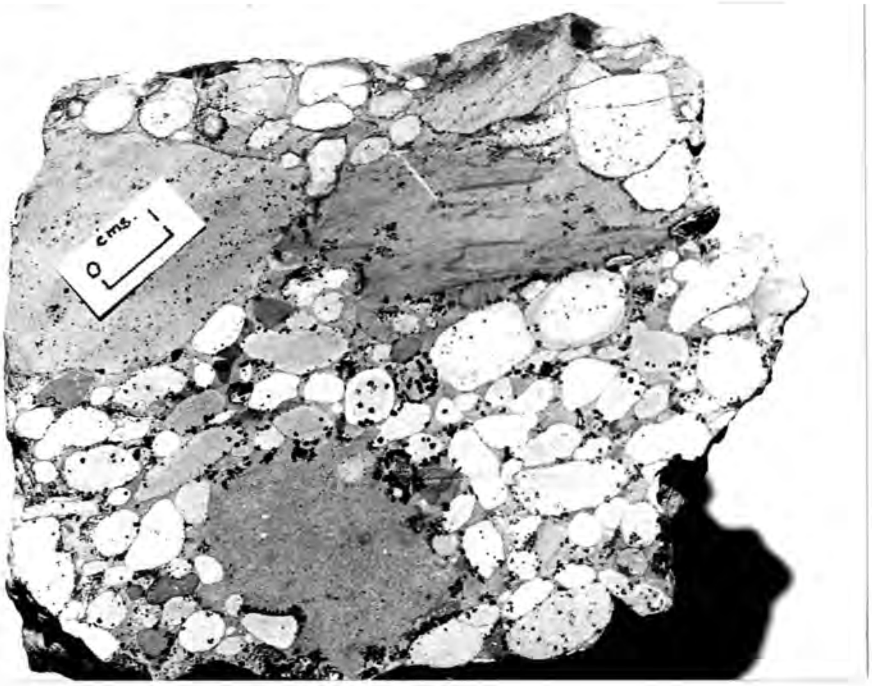

Fig. 1: A sandstone tuff occurring within the three most westerly diatremes on Klip Kraal (grid reference B 8). Note particularly the rounded shape of the fragments.

diatreme previously mentioned, is very similar in appearance to the one just described. A prominent feature, again, is the rounding of the included fragments in the rock. If, as previously suggested by the writer, this sandstone tuff is to be regarded as intrusive due to its apparently transgressive nature, then it should more appropriately be referred to as a tuffisite.

The Thysfontein diatreme is composed of whitish to green sandstone, mudstone and quartzitic fragments set in a siliceous matrix. The fragments show extreme variation in size, the smaller ones being rounded to subrounded in shape while the larger blocks are angular. The fragments appear to be composed largely of Red Beds sediments. In hand specimen the rock may also be regarded as a sandstone tuff. In the Thysfontein diatreme attrition within the volcanic pipe is not as clearly indicated as in the smaller Klip Kraal diatremes.

Gevers (1928, p.47) points out that the nature of the material filling the volcanic pipes may differ with depth; a single pipe would as a result contain several different rock types. He considers the pipes to be funnel shaped, the diameter of the pipe decreasing with depth. The size of a single Stormberg volcano, as well as the rock types contained therein, would then vary according to the level to which the neck has been eroded. It is well known that the diameter of other volcanic pipes formed largely as a result of fluidization (e.g. Kimberlite pipes), tends to decrease in depth and they consequently have a funnel shape.

D. MODE OF ORIGIN OF THE DIATREMES.

The Stormberg diatremes are thought to have been formed through gaseous activity. The source or origin of the gases appears to be intimately linked to the hypabyssal phase of basic intrusions within the Karroo basin. Some speculations by previous writers are outlined below.

According to Du Toit (1920, p.27) the diatremes and volcanic vents are found within an area measuring

560 kilometres long by 240 kilometres broad (350 by 150 miles), with Lesotho as its centre. This area corresponds to the thickest column of sediments in the Karroo geosyncline and consequently the part where the sediments would tend to form a basin shape in depth. Du Toit considers that vadose or magmatic water could have accumulated at the base of the geosyncline, or at the junction of the Cape System with the basement complex. This water, on contact with basic magma in depth, would be converted to steam, which, under enough pressure, might channel its way to the surface, thus forming a diatreme. The diatreme would presumably provide a passage of access for some of the ensuing basic magma to reach the surface.

Gevers (1928, p.60) draws attention to a particularly significant point as regards the distribution of the Stormberg diatremes and volcanic vents, viz. that they are confined to the area of Stormberg sedimentation. Where erosion has removed the Stormberg beds, for example below the Great Escarpment, there is apparently no trace of diatremes, or volcanic vents. As previously noted, however, at least two volcanic necks have been found within Upper Beaufort Beds since Gevers' publication. Gevers' observations led him to postulate a shallow seat of origin for the Stormberg volcanoes, i.e. the explosions took place either within the Molteno beds or just below them. He suggested that the irregular distribution of the diatremes and vents can be related to "satellitic" basic intrusive bodies emplaced within the level of no strain in the earth's crust. The latter intrusions, usually in the form of thick sheets, lopoliths and plugs, have been intruded largely into the Beaufort sediments and at the junction with the Stormberg sediments. Gevers decries Du Toit's theory that steam was the factor responsible for the initial central type eruption, for he points out that the climate at the time of Stormberg sedimentation was largely one of an arid nature (except for the Molteno Stage). This would generally not favour the accumulation of a large quantity of water at the base of the Karroo geosyncline. Judging from the shallow seat of origin and the funnel shape of the volcanoes he suggests that the latter were formed through highly charged magmatic gases.

Lombaard (1952, p.185) postulates that the diatremes are genetically related to conical sheets of dolerite. He points out that a magma rising along conical fractures crystallized to some extent, thereby increasing its vapour pressure. Only when the magma had been intruded above the base of the Stormberg Series of Karroo strata, i.e. where it reached the confines of a lighter load from above, the vapour pressure would find easier access towards the surface, and escape with explosive force to form a diatreme.

The material filling many of the diatremes, especially in the Wodehouse and Herschell districts examined by Du Toit (1904), is a whitish, fine-grained sandstone. The largest diatreme, on Klip Kraal, in the Birds' River area, is an example of this type. Where these necks are exposed at the normal level of Cave Sandstone deposition, as is the above-mentioned diatreme, or are intruded into Cave Sandstone, it becomes increasingly more difficult to recognise them as diatremes. Du Toit (1904, p.168) suggests that this type of vent was formed by initial gaseous activity expelling the contents of the neck. The fine-grained material now occupying the vent was subsequently blown in from the top during Cave Sandstone deposition.

It certainly seems very likely that attrition of the fragmental material within the pipes of the three westernmost diatremes on Klip Kraal must have taken place during the formation of these diatremes. The writer believes that the predominantly rounded fragments within the sandstone tuff filling these pipes are best explained as a result of the process known as fluidization. Holmes (1965, p.270) quotes Reynolds' interpretation of fluidization as follows :-

> "Fluidization is an industrial process in which gas is passed through a bed of fine-grained solid particles in order to facilitate mixing and chemical reaction. At a particular rate of gas flow the bed expands and the individual particles become free to move. With increase in the rate of gas flow a bubble phase forms and travels upwards through the expanded bed in which the particles

> are violently agitated: the bed is now said to be fluidized. With continued increase in the rate of gas flow more and more of the gas travels as bubbles containing suspended solids, until ultimately the solid particles become entirely entrained and transported by the gas."

With the passage of time the particles eventually become worn down to the shape of a sphere. Holmes (1965, p.271) notes that the swiftly moving gas streams within the pipe apparently provide an efficient means of transport. This observation is supported by the presence of eclogite nodules within the Kimberlite pipes. Modern concepts favour the view that these nodules, which are thought to represent material from the earth's mantle, have been brought up from a great depth through fluidization.

The volcanic necks of the Birds' River area crop out either near the top of the Red Beds Stage or at the same elevation as the Cave Sandstone. In the case of the three westernmost diatremes on Klip Kraal where fluidization appears to have played an active part, the material filling the pipes very closely resembles Cave Sandstone. This would suggest that this material has not suffered a great deal of vertical displacement from its original stratigraphic elevation. In the case of the Thysfontein diatreme the material within the pipe appears to largely resemble Red Beds sediments. As the diatreme crops out in Red Beds sediments it also suggests that vertical movement of the material within the pipe was not of a very great order. It appears therefore that within the diatremes of the Birds' River area fluidization had not been as markedly active as, for example, in Kimberlite pipes, where material was brought up from a great depth. These observations lend support to Gevers' hypothesis suggesting a shallow seat of origin for the Stormberg volcanoes.

The theories outlined above in connection with the mode of formation of the Stormberg volcanoes are in substantial agreement that diatremes are the result of gaseous activity, in this case almost entirely within the Stormberg beds. It appears that the doleritic magma, injected into the Karroo System in various intrusive forms, is responsible for instigating the volcanic episode. The diatremes are, as a result, intimately linked to the basic intrusive phase within the Karroo basin. The ramifying and irregular distribution of the basic intrusions would account for the occurrence of the diatremes and vents in clusters or singly, and for them being not arranged along definite structural lines of weakness.

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CHAPTER SEVEN

THE METAMORPHIC AND METASOMATIC ROCKS.

General Statement:

The thermal metamorphic effects produced within some of the xenoliths of the bell-jar intrusion as well as changes brought about in metasomatic rocks are currently being investigated by Mr. A.K. Kenyon of this University, and form the subject matter of a thesis to be presented by him. In this chapter the writer will therefore only give a broad outline of the thermal metamorphic effects produced by the dolerite intrusions, as well as an indication of the changes brought about in the metasomatic rocks. The writer wishes to thank Mr. Kenyon for his co-operation in divulging information derived from his analytical work. Descriptions of the rock types and a general survey of features of rocks that have been metamorphosed and metasomatized by Karroo dolerite will be given under the following headings :-

A. Metamorphism of the Country Rock.

B. Metamorphism of Xenoliths within the Bell-jar Intrusion.

C. Rocks of Metasomatic Origin.

D. General Features of Rocks that have been Metamorphosed and Metasomatized by Karroo Dolerite.

A. METAMORPHISM OF THE COUNTRY ROCK.

In the Birds' River area the dolerite intrusions in the form of dikes, sills, sheets, or the bell-jar, do not appear to have produced much variation in the thermal metamorphic effects on contact with the country rock. The metamorphic aureole surrounding the bell-jar intrusion is remarkably small when one considers the large size of the intrusion. In most places the country rock has been thermally metamorphosed for only a very short distance (approximately 1 metre) from the contact with the intrusion. In other places such as at the contact with the pyroclastic rocks on Murrelfontein (e.g. grid reference P 11) the metamorphic aureole is slightly wider, and may extend for a few metres from the contact. The small metamorphic aureole of the bell-jar intrusion may well be related to the mechanism of formation of the intrusion, which will be discussed in the following chapter.

In general, the thermal metamorphic effects of the country rock are typical of those produced by intrusions of Karroo dolerites. The coarse- to medium-grained sandstones of the Molteno beds and the medium-grained sandstones of the Red Beds have been recrystallized to quartzites. The fine-grained sandstone of the Cave Sandstone Stage has in places been metamorphosed to a rock resembling a porcellanite in hand specimen. The argillaceous beds of the Stormberg Series are commonly metamorphosed to a black flinty rock, lydianite.

In the northern corner of the bell-jar intrusion, as previously mentioned in Chapter Three, a mylonite occurs in contact with the dolerite of the intrusion (see Plate II, Fig. 2). As the mylonite occurs along a fault zone it seems most probable that the rock originated through faulting. It has, no doubt, been thermally metamorphosed by the dolerite of the bell-jar intrusion as well.

The pyroclastic rocks on Murrelfontein protrude as ridges at, and for a short distance from the contact with the bell-jar intrusion. The metamorphosed pyroclastics are grey to blue in colour, and are flinty in nature.

B. METAMORPHISM OF THE XENOLITHS WITHIN THE BELL-JAR INTRUSION.

As can be expected, thermal metamorphism of the xenoliths within the bell-jar intrusion has been more intense than that of the country rock at the contact of the intrusion. In the former case heat from the magma would be concentrated for a longer period upon the xenolithic inclusions of sediments and pyroclastics enclosed within the dolerite, than in the latter, where the heat could more easily be dissipated into the country rock. Optalic metamorphism has produced a variety of rock types at the contact of xenoliths with the dolerite. Du Toit (1905, p.131) noted that some of the finer-grained sediments in the western portion of the complex had become completely fused to a cordierite glass.

In most cases metamorphism at the margins of the sedimentary xenoliths has produced the usual contact metamorphic effects, viz., sandstones have been recrystallized to quartzites and mudstones have been metamorphosed to the black flinty rock, lydianite. Lydianite blocks, forming part of the agglomerate on Romance, often have a mottled grey and black appearance, and in some places they have a bright reddish hue. As previously mentioned in Chapter Three the latter colour in the lydianite is thought to be due to oxidation of magnetite which has been recrystallized from the original haematite or other oxides in the sediments. Metamorphism appears to have been particularly intense near the western margin of the Smuts Pass xenolith where a number of smaller xenoliths show signs of having been thermally metamorphosed to a glassy rock (grid reference G 9 and H 10).

Parallel jointing is usually strongly developed within sedimentary xenoliths and xenoliths of pyroclastic rocks at the contact with the dolerite. Metamorphosed sandstones and mudstones within the xenoliths often display perfect columnar jointing. The rocks at and near the contact of xenoliths composed of pyroclastic rocks, in particular, are flinty in nature and break with a conchoidal fracture.

Along the southern and south-eastern contact of the largest xenolith of pyroclastic rocks on Murrelfontein, an interesting variety of rock types is to be found. Several small outcrops of a spotted rock which is brown in colour and characterized by honeycomb weathering, occur on the contact (grid reference O 12). Scattered very small nodules, resembling buckshot, protrude on the weathered surface of the rock. Metamorphism appears to have destroyed all traces of bedding, and yet the hollowed out weathering features on the surface of the rock suggest a parallel alignment, which might represent differential weathering along original bedding planes. A fresh surface shows that the rock is light grey in colour with black spots approximately 2 millimetres in diameter, scattered throughout it. In hand specimen the rock resembles a cordierite hornfels.

An adinole, composed essentially of felspar and magnetite, also occurs along the south-east contact of the abovementioned xenolith (grid reference O 11). This rock is black in colour and in places shows signs of flow. Further towards the south of this xenolith, near the contact, there is a black rock resembling a lydianite, but it has a well developed flow structure within it (grid reference N 12).

The rocks described above, which occur along the south-eastern and southern contact of the largest xenolith composed of pyroclastic rocks, all indicate that metamorphism by the dolerite has been most marked along this margin of the xenolith.

Metamorphism at the contact of the elongate xenolith composed of pyroclastic rocks, to the east of the xenolith just described, has resulted in the presence of bluish-black baked pyroclastic rocks, and quartzites. Along the eastern margin of this xenolith metamorphism has been particularly intense and has produced a glassy rock which protrudes as an irregular ridge, some 370 metres (1200 feet) long (see Map No. 2, grid reference P 11, and Plate V, Fig. 1). In hand specimen rocks from this "glassy ridge" can sometimes be seen to be made up of approximately 50% of a black glass. Thin sections cut from the "glassy ridge" exhibit the original minerals making up the pyroclastic rock, mainly quartz, felspar and a subordinate amount of pyroxene, surrounded by a brown glass (see Plate XXV, Fig. 1). The glass sometimes contains glass shards which give the rock a hyalopilitic texture (see Plate XXV, Fig. 2). Even some of the minerals of dolerite inclusions within the pyroclastics have become fused to a brown glass. H.V. Eales (personal communication) has suggested that a constant streaming of dolerite magma past this particular area of the xenolith would most probably supply sufficient heat to cause the fusion within these

PLATE XXV

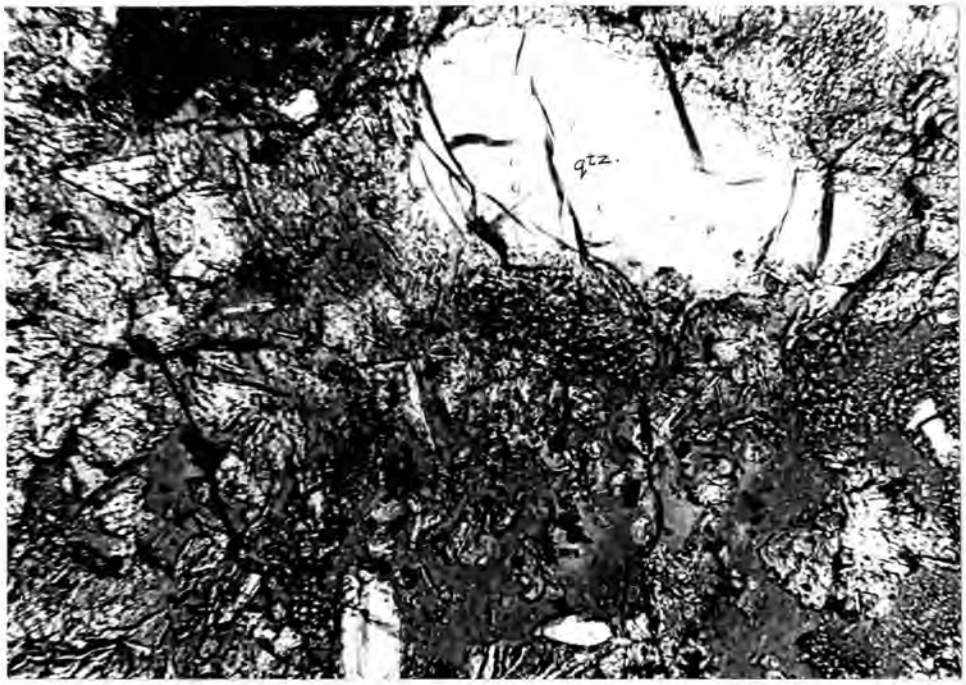

Fig. 1: Metamorphosed pyroclastic showing quartz grain (qtz) surrounded by brown glass. X 36, ordinary light.

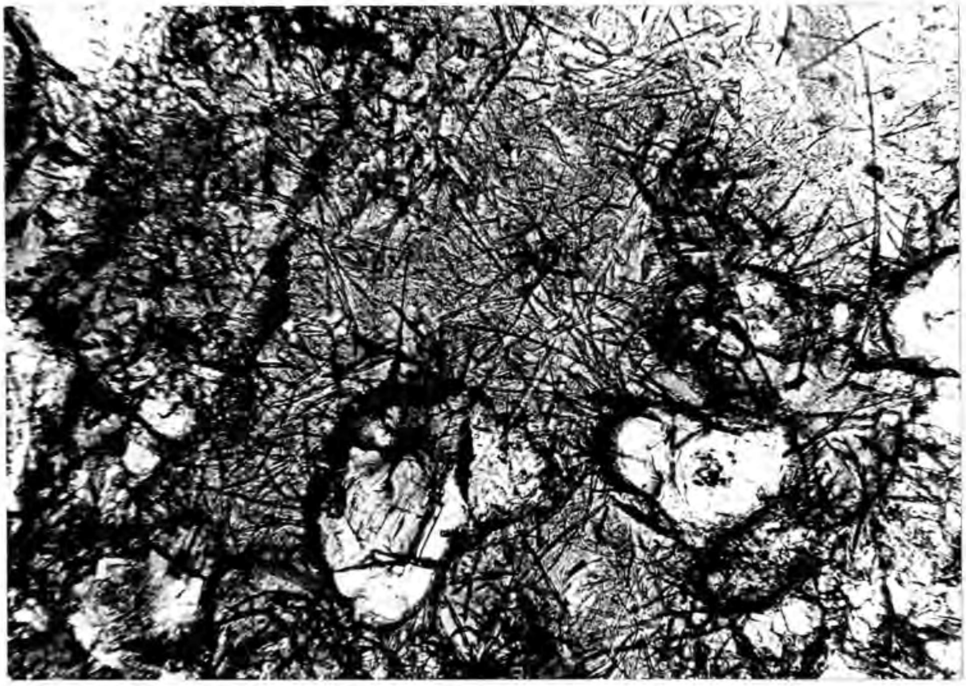

Fig. 2: Hyalopilitic texture in glassy rock. X 40, ordinary light.

rocks. The significance of this mechanism is brought out in the following chapter.

A xenolith on Denwood (grid reference K 14), which has previously been described in Chapter Three, appears to have been subjected to rather stronger metamorphism throughout the entire xenolith than most of the other xenoliths within the bell-jar intrusion. In hand specimen the rock is greyish-blue in colour, and it has a marked granophyric texture. A thin section shows this rock to be composed of quartz, felspar, sphene. iron ore and a brown glassy matrix, and to be characterized by replacement textures. The anhedral quartz grains often display strain shadows and are surrounded by a brown glass. Felspar crystals have an euhedral shape and are characterized by elongate habit. The crystals, which show simple Carlsbad twinning, are most often also surrounded by a brown glass. The felspar grains have, to some extent, been replaced by calcite, replacement being concentrated along the basal (001) plane. Sphene occurs as yellowish brown anhedral grains. Many anhedral iron ore grains exhibit a distinct parallel arrangement of closely spaced needles of iron ore - a texture which suggests that iron ore has formed as a replacement mineral. The xenolith as a whole has been regarded by the writer as a metamorphosed sandstone xenolith (presumably Molteno sandstone, due to the abundance of felspar grains).

Within a sandstone xenolith on Romance (grid reference K 11) there is a vein which the writer has preveously described as a mobilized sediment. The vein has a distinctly glassy appearance with well developed flow structure. It would seem very likely that this vein is the result of partial fusion of sediment by the dolerites of the bell-jar intrusion, and has been injected into the Cave Sandstone of the xenolith.

C. ROCKS OF METASOMATIC ORIGIN.

The metasomatized rocks, i.e. rocks whose chemical composition has been completely changed by molecular replacement of the original minerals through solutions from the dolerite magma, occur in the south-eastern corner of Lemoenfontein (grid reference N 10). Detailed mapping by Mr. Kenyon has revealed that these rocks occur as isolated outcrops at the summit of a ridge extending from the south-eastern corner of Lemoenfontein north-north-westwards, for a total distance of approximately 800 metres (2,600 feet) (see Map No. 2, and Plate IV, Fig. 2). The metasomatized rocks appear to form almost circular, high-lying mounds and merge into pyroclastic rocks which underly them. The distinction between these two rock types has not been indicated on the maps. These pyroclastic rocks are completely surrounded by a sheet of dolerite which has invaded across this portion of the largest xenolith composed of pyroclastic rocks.

It seems almost certain that the rocks of metasomatic origin resulted from magmatic solutions from the dolerite magma being injected into pyroclastic rocks of the above-mentioned xenoliths, from above the present level of erosion. The following observations in the field lend support to this interpretation :-

(i) Rocks of metasomatic origin occur predominantly at the summit of a ridge and are underlain and merge directly into pyroclastic rocks.

(ii) The metasomatized rocks were not observed to be in direct contact with the dolerite, at the present level of erosion.

(iii) The area of pyroclastic rocks, where rocks of metasomatic origin were encountered, is entirely surrounded by dolerite of the bell-jar intrusion. (On the maps drawn by the writer the metasomatized rocks do appear to be in direct contact with the dolerite, but, as previously indicated, no distinction has been made, on these maps, between the pyroclastic rocks, and those of metasomatic origin which overlie them.)

In thin section the metasomatized rocks are seen to be composed predominantly of quartz and felspar with subordinate pyroxene, and an interstitial micropegmatitic intergrowth of quartz and felspar. Chemical analyses at present being carried out by Mr. Kenyon reveal that the metasomatized rocks as a whole have been enriched with respect to alumina and iron, and depleted in their silica content.

There is a possibility that another area of metasomatized rocks occurs at the southern tip of the second largest xenolith of pyroclastic rocks, on Hermitage (grid reference Q 12). In hand specimen the rock appears to be very similar to the metasomatized rocks on Lemoenfontein. Its situation, with regard to the pyroclastic rocks and the dolerite, is also very similar to those on Lemoenfontein. Further detailed study of these rocks by Mr. Kenyon will in due course reveal whether they are of metasomatic origin, or not.

D. GENERAL FEATURES OF ROCKS THAT HAVE BEEN METAMORPHOSED AND METASOMATIZED BY KARROO DOLERITE.

The metamorphosed and metasomatized rocks in the present area of investigation appear to conform to the general pattern of behaviour of Karroo dolerites towards the invaded sediments. Sediments that occur at the contact with dolerite intrusions are commonly metamorphosed to either lydianite or quartzite, depending on the original grain size and composition of the sediments. Walker and Poldervaart (1949, p.674) regard fusion of sediments to a glass and assimilation of sediments as rare phenomena, while metasomatism and rheomorphism of sediments are quite common, where reaction between dolerite and sediment has taken place.

In the Birds' River area the occurrences of glassy rocks, as well as the spotted rocks on Murrelfontein, would seem to indicate that intense thermal metamorphism had taken place within the bell-jar intrusion. Walker and Poldervaart (1949, p.684) suggest that pure melting of sediments by dolerite may be due largely to the unrefractory nature of the former rather than the high temperature of the magma. These authors note that "the fused portion represents alkali felspar and quartz but quartz has been only partially melted for rounded grains still remain scattered through the glassy matrix".

Rheomorphic phenomena in the Birds' River intrusion have been described in Chapter Three. The writer has indicated that rheomorphism of pyroclastic rocks during the advanced stages of cooling of the magma resulted in the pyroclastic material being rendered plastic and drawn into joints in the dolerite of the bell-jar intrusion. The rheomorphic vein of sediment occurring within a sedimentary xenolith of this intrusion, on Romance, has most probably had a similar origin (grid reference K 11).

Walker and Poldervaart (1949, p.678) regard transfusion and rheomorphism of sediments as having begun "after most of the magma had solidified - probably during the stages of iron enrichment when vapour pressure and chemical energy of the partial magmas were near their peak. It is believed to have continued throughout the period of alkali enrichment - i.e. after about 90% of the original magma had crystallized and the partial magma was undergoing rapid changes of composition". These authors note that where xenolithic blocks and sediments either bordering the upper contact of sills, or acting as partings, are to be found, conditions become particularly favourable for transfusion and rheomorphism of the sediments. In these circumstances the strata are either surrounded by magma or occur immediately above the volatile-rich zone. Walker and Poldervaart (1949, p.676) suggest that fluxes such as SO_4 and Cl may have promoted rheomorphism and transfusion of sedimentary material. They advocate that this might be possible if the sediments had a high saline content, as is common in water found in the Karroo basin today.

Quoting examples of transfused and rheomorphic phenomena from New Amalfi, Alewyn's Gat and Rietkop, Walker and Poldervaart proposed that the following sequence appears to have been followed :-

(i) Early emanations during the iron-rich phase of the dolerite magma resulted in the addition of Ti, Fe, Mg and Ca to the affected sediments, with a loss of Si, Al and K to the metasomatizing fluids.

(ii) A sodium-rich phase of emanations from the partial dolerite magma followed shortly after the iron-rich phase.

(iii) The final phase is represented by potassium enrichment.

Thus it is more than likely that chemical and physical changes brought about in the metasomatism and rheomorphism of the sediments by Karroo dolerites is through a fluid medium rather than by solid diffusion. In these processes soda-rich magmatic emanations followed an iron-rich phase. This sequence of changes is comparable with (i) basification (ii) albitization and (iii) granitization.

* * * * *

CHAPTER EIGHT

STRUCTURAL INTERPRETATION

The structural interpretation of the mechanism of formation of the bell-jar intrusion embraces the history of events beginning with the formation of the Stormberg volcanoes. In this chapter the writer presents a tentative interpretation of the sequence of events which appear to have taken place in the formation of the bell-jar intrusion. Expulsion of pyroclastic material from volcanic vents was followed by cauldron subsidence and the subsequent injection of dolerite magma, initially through outer ring fractures. Collapse of the "roof" of sediments and pyroclastics into the dolerite magma resulted in their sinking within and being structurally deformed by the dolerite. The final phase of igneous activity is represented by the north-westerly trending Dragon's Back dike.

The following topics will be discussed in this chapter :-

A. Penetration of the Diatremes.
B. Expulsion of Pyroclastics.
C. Cauldron Subsidence, and Intrusion of Dolerite.
D. Collapse of the "Roof".
E. Structural Deformation of the Xenoliths.
F. Other Dolerite Intrusions in the Area.
G. Intrusions Similar to the Bell-jar Intrusion.
H. The Triassic-Jurassic Dolerites and Lavas.

A. PENETRATION OF THE DIATREMES.

Judging from the small size of some of the sandstone breccia occurrences within the bell-jar intrusion (e.g. within the sandstone horizons of the Smats Pass xenolith) it appears that the Stormberg volcanic episode in the Birds' River area, commenced with the formation of small pipe-like bodies in Stormberg strata (see Fig. 10). The angular nature of the breccia suggests that gaseous activity was ephemeral.

Diagrammatic sections to illustrate the sequence of events in the mechanism of formation of the bell-jar intrusion. CS = Cave Sandstone Stage, RB = Red Beds Stage, M = Molteno Stage, L = Lava, D = Dolerite.

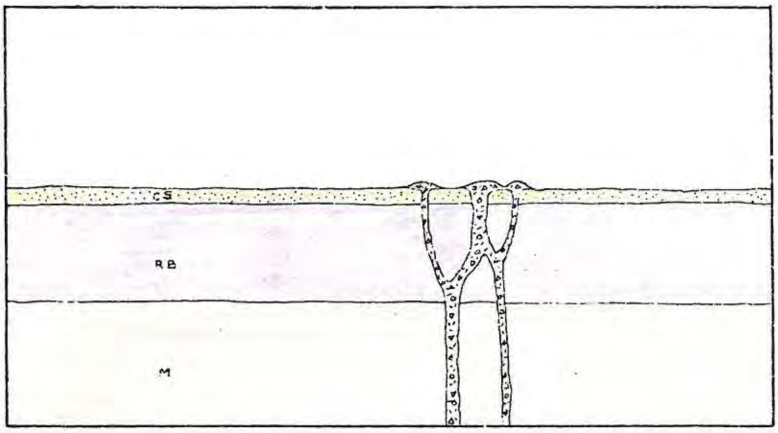

Fig. 10: Penetration of diatremes into Stormberg strata.

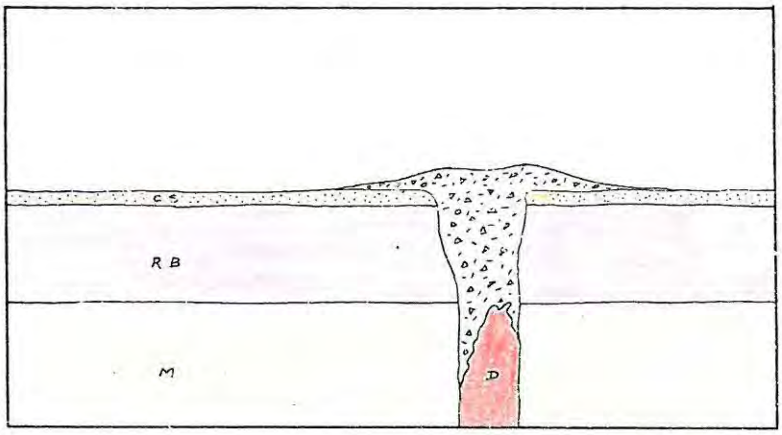

Fig. 11: Expulsion of pyroclastics, with sedimentary clasts.

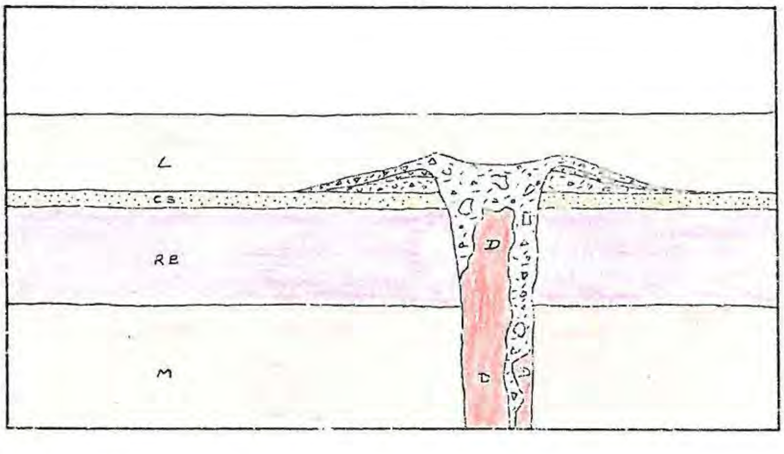

Fig. 12: Expulsion of pyroclastics, with igneous clasts.

The majority of the Klip Kraal diatremes, as well as the Thysfontein diatreme, are of a small size. Within some of them gaseous activity appears to have been prolonged as evidenced by the rounded nature of the fragments within the diatremes. There is no doubt, however, that a later phase of volcanic activity within the eastern portion of the area now occupied by the bell-jar intrusion caused expulsion of a large volume of pyroclastic material. The latter event in all probability resulted in widening of the vents as well, as is indicated in Figs. 11 and 12. It appears that gaseous activity played a major role in the initial expulsion of pyroclastic material. Evidence of the predominantly sedimentary nature of the pyroclastic rocks near and at the base of the xenoliths composed of pyroclastic rocks lends support to this observation. In the area outside the bell-jar intrusion there is evidence that sandstone tuffs and lapilli tuffs were expelled during the Red Beds Stage of deposition. This signifies that volcanic activity in the form of gaseous eruptions, which heralded the Stormberg igneous period, commenced during the Red Beds Stage in the Birds' River area, if not earlier.

B. EXPULSION OF PYROCLASTICS.

After the initial penetration of the diatremes, continued volcanic activity resulted in the expulsion of pyroclastic rocks containing some igneous, but predominantly sedimentary clasts (see Fig. 11). The focus of the eruptions is considered to have been located within the area now underlain by the eastern portion of the bell-jar intrusion, predominantly on Murrelfontein and Romance. In this locality successive build-up and release of pressure within the vent or vents appears to have resulted in an increase in the proportion of igneous clasts within the pyroclastic material (see Fig. 12). Evidence of an increased proportion of igneous inclusions is to be found within the agglomerates on Romance. Intermittent outpourings of purely igneous material are represented by the rare amygdaloidal lava flows overlying pyroclastic rocks on, for example, Murrelfontein and Romance. During the dormant stages basic magma was more than likely ascending and cooling within the vent or vents in this area. Periodic explosive expulsion of this basic material, predominantly as blocks, would account for the igneous inclusions within the pyroclastics.

It seems quite likely that periods of dormancy between some of the eruptions in this area persisted for some considerable time. Evidence in favour of this statement is based on the fact that the large dolerite blocks within an agglomerate on Romance are predominantly coarse grained - a feature which requires slow cooling of the magma. It is important to note, however, that the above argument is only valid if the dolerite blocks did in fact crystallize from a magma within the vent. The dolerite blocks could equally well have originated from an earlier dolerite intrusion through which the vent later passed. In the latter case, particularly, it would be difficult, if not impossible, to prove periods of dormancy between eruptions.

Present-day outcrops of pyroclastic rocks reveal that a large volume of pyroclastic material was piled up over a wide area on Romance, Lemoenfontein, Murrelfontein and Thysfontein. As erosion has more than likely removed a large area of the pyroclastic rocks that were originally laid down, it would be difficult to estimate the original extent of extruded material. It would seem very likely that volcanic extrusions had taken place through several vents in the area, as indicated by the large area of present-day exposures and the variations in the clastic matter of pyroclastic rock types. But, judging from the largely unbedded and poorly sorted nature of the pyroclastics, it might be possible that some of them represent the products of mudflows. In the latter case expulsion of pyroclastic rock could quite likely have taken place through a single vent, situated say, in the north-western corner of Murrelfontein. The expelled material on the slopes of the cone could then have been moved considerable distances from the original vent (and perhaps back into the vent) through the agency of mudflows. Mudflows would then account for the variety of pyroclastic rock types over their present extensive area of outcrop.

C. CAULDRON SUBSIDENCE AND INTRUSION OF DOLERITE.

The escape of what must have been an enormous pent-up gaseous pressure from the magma chamber, resulting in the expulsion of pyroclastic rocks caused a reduction in pressure in the upper confines, i.e. the cauldron area, of the magma chamber. Subsidence of the superincumbent load above the magma chamber, through the aid of ring fractures, resulted in cauldron subsidence of the central block (see Fig. 13). The northern margin of the bell-jar intrusion, for example, where the dolerite forms a dike-like feature some 200 metres (600 feet) wide, more than likely represents an original ring fracture along which dolerite intruded at a later stage. The only direct evidence of faulting in this vicinity, however, is to be found at the northern corner of the intrusion (see grid reference J 6, and Plate III, Fig. 1).

The slickensided surfaces within the sediments, which occur very close to the contacts of curved dike-like features to the north of the bell-jar intrusion, indicate faulting which is most probably related to the cauldron subsidence in this area. As was mentioned in Chapter Three, the angle of dip of the dolerite occupying these fault zones could not be established in the field, yet the slickensided surfaces on sediments, virtually at the contact, indicate a steep but variable angle of dip toward the centre of the arcuate shape.

The writer has regarded the curved fracture zones occurring to the north of the bell-jar intrusion as being initiated during cauldron subsidence. Tholeiitic magma would be intruded soon after this stage, and is to be found along the eastern margin of the bell-jar intrusion, and within the arcuate fault zones to the north of the intrusion. This magma was presumably intruded along ring fractures and sucked up into the zone of less pressure caused by cauldron subsidence. This was followed by intrusion of olivine dolerite

Diagrammatic sections to illustrate the sequence of events in the mechanism of formation of the bell-jar intrusion (continued). CS = Cave Sandstone Stage, RB = Red Beds Stage, M = Molteno Stage, L = Lava, D = Dolerite.

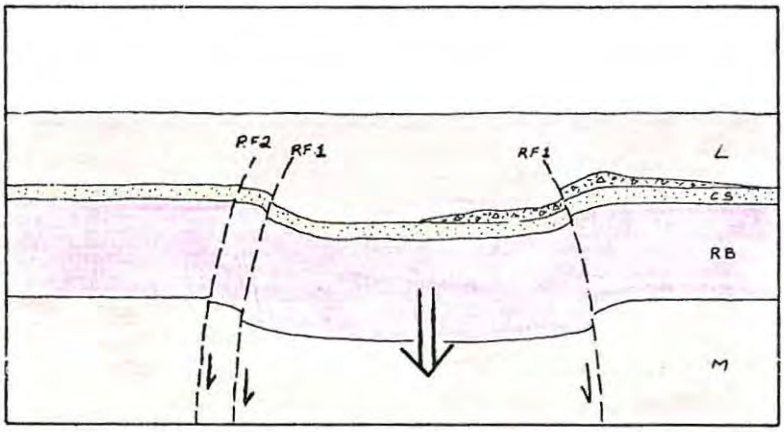

Fig. 13: Cauldron subsidence due to development of ring fractures.

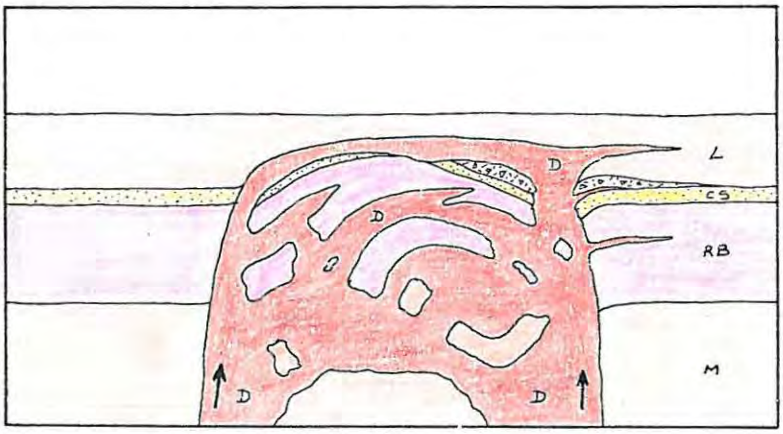

Fig. 14: Intrusion of dolerite magma resulting in collapse of roof, and deformation of xenoliths sinking within the magma.

Fig. 15: A south-west to north-east section across the complex, with present-day erosion surface.

magma which appears to truncate the tholeiitic dolerite occurring within the fault zones. The writer has therefore interpreted the dolerite intrusions within the arcuate fault zones as ring dikes, intruded along ring fractures which were initiated during cauldron subsidence. Cone sheets are considered to have been intruded under conditions of upward tension caused by intrusion of magma. Bearing in mind the order of intrusion of the bell-jar dolerites it seems unlikely that the tholeiitic magma which now occupies the dike-like features to the north of the bell-jar intrusion, and on Lemoenfontein, would be intruded at a later stage than the olivine dolerites.

Judging from the inward-dipping nature of the sediments along the eastern margin of the bell-jar intrusion and the fact that Cave Sandstone occurs at a considerably lower elevation here than in outliers in the vicinity, it appears that cauldron subsidence had either of the following two effects on the country rock in this area :-

(i) A downward drag or sag of the sediments outside the area of subsidence.

(ii) Formation of a caldera above the area of subsidence, during Red Beds sedimentation.

In case (i) the implication is that Stormberg sedimentation was complete or nearly complete, the cauldron subsidence having affected the sequence of strata from at least Red Beds Stage upwards and having caused a down-dragging or sagging effect along an outer ring fracture, as indicated in Fig. 13. In view of the overhanging nature of the fracture, sagging could be even more important than drag. Case (ii) would imply that cauldron subsidence took place during the upper part of the Red Beds Stage, forming a caldera on surface. The upper sequence of Red Beds would then be deposited into the caldera. It seems unlikely that case (ii) above would have taken place as normal deposition of sediments in the caldera would tend to result in a less steep angle of dip upwards in the sequence, as the caldera became filled. As was indicated in Chapter Three, the Cave Sandstone appears to have a steeper dip closer towards the contact with the bell-jar intrusion than the underlying Red Beds. This would tend to suggest that cauldron subsidence, after Stormberg sedimentation had been completed, resulted in a tilting of the country rock along ring fractures. As was also mentioned previously, the longest northerly trending dike on Thysfontein bends in towards the bell-jar intrusion near the contact with the latter (grid reference P 11). This would suggest that the dike has also been tilted along with the sediments by an inward drag caused through cauldron subsidence.

An amygdaloidal lava flow within pyroclastics along the eastern margin of the bell-jar intrusion on Murrelfontein, dips at a very steep angle of 70° to the west (grid reference P 10, and Plate XXII, Fig. 2). Lava flows of the Drakensberg Volcanic Stage appear to have been deposited on fairly flat-lying or gently inclined surfaces. It seems unlikely, then, that the lava flow on Murrelfontein was deposited on a surface with an initial inclination of 70°. The fact that this lava flow dips at such a steep angle strongly suggests that its inward inclination towards the bell-jar intrusion was effected some time after deposition of the lava flow. This argument favours the interpretation that cauldron subsidence in this area took place some time after expulsion of the pyroclastics and lava flows, and after deposition of Cave Sandstone.

It appears then that the strip of sediments showing appreciable amounts of dip along the eastern margin of the bell-jar intrusion represents a tilting effect caused by cauldron subsidence along ring fractures (RF 1. in Fig. 13). At this stage the country rock on the opposite side of the intrusion must also have been similarly affected. Yet, as was noted in Chapter Three, the dip of the sediments in contact with the bell-jar intrusion on the western and northern sides is predominantly away from the contact. This would perhaps best be explained by assuming that the dolerite intruded along a second outer ring fracture (RF 2. in Fig. 13) which had possibly not caused as much drag on the country rock as an inner ring fracture during cauldron subsidence

(RF 1. in Fig. 13). The upward intrusion of the magma would more than likely have had a slight updoming effect on the country rock and thus caused the sediments to dip at low angles away from the contact. In one particular case observed by the writer, on Murrelfontein, (grid reference N 14) Molteno sediments were dragged up by the dolerite and dip steeply away from the contact.

It appears that the initial intrusion of tholeiitic magma, after cauldron subsidence, was along the arcuate fractures to the north of the bell-jar intrusion and along the eastern margin of the latter intrusion on Leroenfontein. It seems most probable that intrusion of the magma that forms the main mass of the intrusion, after cauldron subsidence, was in the form of successive near-vertical sheets of dolerite. This is exemplified by the series of parallel ridges within the south-western and south-eastern portions of the bell-jar intrusion that can be seen on the aerial photographs. A petrographical investigation into the series of parallel ridges on Branstone (see Chapter Three, section II) confirmed the presence of different dolerite rock types within them.

The presence of the relatively small metamorphic aureole surrounding the bell-jar intrusion would best be accounted for by accepting that the intrusion of bell-jar dolerite magma was effected by emplacement of successive sheets rather than a single mass of dolerite. In the former case only the outer contact "sheet" of dolerite would affect the country rock, whereas, if the magma were intruded as one unit, one might have expected a larger metamorphic aureole than is actually present around such a large intrusion. The concept of successive sheets or flows of magma along the eastern margin of the bell-jar intrusion would satisfactorily account for the presence of the glass-rich rocks on Murrelfontein, namely at the "glassy ridge". These rocks resulted from intense thermal metamorphism, the supply of heat being built up from the continuous flow of magma past the eastern margin of the monolith.

Along the eastern and southern portion of the bell-jar intrusion the dolerite magma appears to have given off "tongues" and sheet- or sill-like offshoots from the main intrusion, as is illustrated in Fig. 14. The presence of these offshoots was discussed in Chapter Three.

D. COLLAPSE OF THE "ROOF".

The intrusion of dolerite magma in the oval shape of the "bell-jar" resulted in collapse of the "roof" of sediments and pyroclastics into the magma. The invading magma intruded across and along bedding planes of the sediments that formed part of the original roof, and most probably, portions of the subsided central block as well. The resulting xenolithic blocks have been deformed by subsequent uparching and then sinking within the magma (see Fig. 14).

That xenolithic blocks of sediments from the original "roof" have sunk to considerable depths within the dolerite magma, is exhibited by the occurrence of exposed Cave Sandstone xenoliths at least 300 metres (1000 feet) below their normal elevation, within the bell-jar intrusion. The Birds' River intrusion is, however, also characterized by the presence of large xenoliths of Molteno sediments that occur far above their normal stratigraphic elevation. To account for the presence of these xenoliths below or above their normal level of deposition, obviously two mechanisms are involved, viz.,

(i) Sinking of sedimentary xenoliths within the dolerite magma, and

(ii) Upward movement of the sedimentary xenoliths, presumably effected by the invading sheets of dolerite within the bell-jar intrusion.

The problem of how xenoliths of a lesser specific gravity sink within a medium of greater specific gravity has now to be answered. From a large number of determinations, Poldervaart (1946, p.107) gives the average specific gravity of Cave Sandstone as 2.68 and Molteno sandstone as 2.66, while a specific gravity of 2.98 was recorded from the olivine dolerites of Mount Arthur. Clearly, under normal conditions of gravity it seems quite impossible that xenoliths of Cave Sandstone, for example, should sink within the dolerite magma to such considerable depths as are to be found in the Birds' River and Mount Arthur intrusions. Additional processes which effect the sinking of xenoliths must be involved. Poldervaart (1946, p.106) has explained the sinking of sediments in basaltic magma of the Mount Arthur intrusion as the result of resurgent volatiles enveloping the xenolith, producing a zone of magma of lower specific gravity than the xenoliths. The latter could then, under gravity, sink within this zone of magma of lighter specific gravity. Poldervaart envisages the process of sinking of the xenoliths within the magma as occurring soon after deposition of Cave Sandstone - and before the entire bulk of Stormberg lavas was extruded. At this stage the Stormberg sediments were not yet completely consolidated and as a result they most probably contained appreciable amounts of connate waters. Isolation of the sedimentary xenoliths by the magma caused the production of resurgent volatiles in a zone immediately surrounding the xenolith. Thus a zone of lower specific gravity was created and the xenoliths could sink within the "modified" magma. Poldervaart considers the release of volatiles from the larger xenoliths to have been a prolonged process - this would account for the tremendous depth to which xenoliths have sunk within the magma. Poldervaart (1946, p.107) quotes Du Toit as suggesting that sinking of the xenoliths was most probably assisted by a downward sucking force caused during cauldron subsidence of a central block.

Poldervaart and Du Toit's explanation could be adequately employed to explain the sinking of the xenoliths in the Birds' River intrusion as well, but in the latter intrusion the presence of xenoliths far above their normal stratigraphic elevation calls for further comment. In the latter case it seems more than likely that the upstreaming of sheets of magma, one of which is most probably represented by Skerprand, would assist in the upward movement of the xenoliths. It appears that relative movement of the xenoliths within this intrusion has been at least of the order of 500 metres

(1500 feet). This is exemplified by the presence of two large xenoliths next to each other, one of Molteno sediments, the other of Cave Sandstone and Red Beds, at approximately the same elevation above sea level (grid reference J 11, and Plate VIII, Fig. 1).

E. STRUCTURAL DEFORMATION OF THE XENOLITHS.

Another characteristic feature of the Birds' River intrusion is that the majority of the larger sedimentary xenoliths have been bent into either basin- or dome-shaped features. The largest xenolith, the Smuts Pass xenolith in the north of the complex, has a basin-shaped structure with Red Beds sediments occupying the trough of the syncline, and Molteno sediments forming the southern portion of the xenolith. As was previously noted in Chapter Three, the Red Beds sediments of this xenolith crop out at a lower elevation than the Molteno sediments. This suggests that the Red Beds sediments in depth also occur at a lower elevation than the Molteno sediments, as is indicated in cross-section A-B. The significance of the relative elevations of these particular sediments of the xenolith is perhaps related to the composition of the sediments and the subsequent structural deformation of the xenoliths by the dolerite. Molteno and Red Beds sediments are composed predominantly of quartz and felspar, but the Red Beds in addition contain an abundance of iron oxide minerals. It could be that the latter minerals, in particular, would cause the Red Beds sediments to have a slightly higher specific gravity than the Molteno sediments, although the writer can offer no direct evidence of this. If this assumption is accepted then the relative specific gravities of the Molteno and Red Beds Stages within the Smuts Pass xenolith could have played an important part in the movement of the xenolith within the dolerite magma. The fact that the Red Beds sediments occur at a slightly lower elevation than the Molteno sediments of this xenolith suggests that the former had sunk at a faster rate within the magma relative to the latter, as a result of its higher specific gravity. In addition the upstreaming of sheets of dolerite magma, (represented by Skerprand in this case) would tend to buoy up the relatively lighter Molteno sediments on the southern side of the xenolith. Intrusion of magma along the northern dike-like feature of the bell-jar intrusion has resulted in the Red Beds sediments of the xenolith dipping away from the northern contact.

The Branstone xenoliths have been bent into the shape of a dome, with considerable displacement of the xenoliths as well. Red Beds sediments form an anticlinal feature, dolerite having intruded along and across their bedding planes (see Fig. 2). On their north-eastern side, Molteno sediments dip towards the north while, conformably overlying the Red Beds in the south, Cave Sandstone dips steeply towards the south. The latter occurs more than 300 metres (1000 feet) below its normal elevation in the surrounding area beyond the confines of the complex.

The largest xenolith composed of pyroclastic rocks, does not appear to have suffered much deformation by the dolerite and extends as a large blanket from Romance to Thysfontein. It has, however, been extensively invaded by sheets of dolerite. To the east of this xenolith the second-largest xenolith composed of pyroclastic rocks has been bent into a slight basin shape. The eastern margin of this xenolith has been tilted high above the remaining portion (see Plate V, Fig. 1).

Most of the remaining larger xenoliths have been deformed into basin or synclinal shapes, e.g. grid reference K 11 and M 13. The smaller xenoliths do not appear to have suffered much structural deformation by the dolerite magma.

F. OTHER DOLERITE INTRUSIONS IN THE AREA.

Other dolerite intrusions in the area include sheets, sills and dikes. On field evidence it is difficult to be certain of their relative ages, except in the case of the Dragon's Back dike, which clearly represents the youngest phase of igneous activity in this area. A few dikes appear to cut the bell-jar intrusion which makes them younger than the latter (grid reference I 6). It seems likely that dolerite sheets were the first to be intruded. Dolerite sills were most probably contemporaneous with the sheets, but no conclusive evidence regarding their relative ages could be found in the field. These were followed by a number of dolerite dikes which obviously cut through the sheets, e.g. the longest northerly trending Thysfontein dike (grid reference O 7). The bell jar intrusion appears to have followed intrusion of some of the dikes, e.g. the ring dikes to the north of the bell-jar intrusion. No evidence of the latter cutting across sheets in this area could be found in the field and it has therefore only been assumed that the bell-jar intrusion is of a lesser age than the sheets. If as previously mentioned, the interpretation that the Thysfontein dike was subjected to deformation during cauldron subsidence in this area, is correct (grid reference P 11) then this gives a clue as to the relative ages of these two intrusions. The Thysfontein dike would then be older than the bell-jar intrusion, but, as it cuts through the Vogel Vlei sheet (grid reference O 7), it is younger than the latter. The north-westerly trending Dragon's Back dike cuts all other formations in the area and is therefore the youngest intrusion. As a tentative generalization therefore the relative ages of the different forms of dolerite intrusions may be given as follows, in order of emplacement :-

(i) Sheets, including the Vogel Vlei sheet (sills are most probably contemporaneous).

(ii) Some dikes (including Thysfontein dike).

(iii) Bell-jar intrusion.

(iv) Dragon's Back dike, and dikes cutting the bell-jar intrusion.

The majority of dikes in the Birds' River area trend in a north-westerly direction, which is also the trend of the major axis of the bell-jar intrusion. This may indicate a predominant direction of crustal weakness during the major phase of igneous injections.

G. INTRUSIONS SIMILAR TO THE BELL-JAR INTRUSION.

In the Republic of South Africa, Du Toit (1920, p.11) has recorded the presence of three dolerite intrusions which appear to be of the "bell-jar" type. Two of them occur in the Birds' River area, one immediately north of Birds' River Siding, while the other is situated 16 kilometres (10 miles) to the west on Droogefontein. The third bell-jar intrusion occurs in East Griqualand and was later described in detail by Poldervaart (1946). Tertiary igneous activity in Scotland is represented by several central complexes, similar in mode of emplacement to the bell-jar intrusions of South Africa.

According to Stewart (1965) the Scotland complexes of Mull, Ardnamurchan, Skye, Rum, Arran and St. Kilda cut through thick piles of basaltic lava. The intrusive rocks, which range from ultrabasic to acid in composition, were intruded after cauldron subsidence and are associated with the products of explosion vents, cone sheets, ring dikes and extensive dike swarms. Repeated subsidence of a central block together with portions of earlier intrusions are believed to constitute the mechanism for the formation of the central complexes. In Arran blocks and large masses of sediments and basalt lava within a caldera indicate subsidence of about 1000 metres (3000 feet). In some of these central complexes, for example Skye, Ardnamurchan, Mull and Arran, after the initial cauldron subsidence the centre of igneous activity shifted within each complex, resulting in the production of a wide range of rock types, varying from ultrabasic to acid.

The rock types within the bell-jar intrusions of South Africa do not show as extreme variation as do those of the Scotland central complexes. Poldervaart (1946) recognised three types of dolerite, viz. marginal tholeiite, olivine dolerite and "transfused" tholeiite, in the Mount Arthur intrusion. The writer considers that several rock types are present within the Birds' River intrusion, each apparently representing a dolerite of slightly different composition; these were intruded as successive vertical sheets. In both these cases, however, the rocks forming the bell-jar intrusions are dolerites predominantly of the Kokstad Type as defined by Walker and Poldervaart (1949). The rock types of the bell-jar intrusions obviously do not show as much variation in composition as in the central complexes of Scotland where the rock types may range from ultrabasic to acid in composition.

The essential point of difference between the bell-jar shaped intrusions and the central complexes of Scotland is that in the former the original roof of sediments, which collapsed into the magma, has suffered bending and fracturing by the dolerite magma, while in the latter this does not appear to have taken place. Some of the xenoliths sank to considerable depths within the bell-jar intrusion, while in the Birds' River intrusion there was also definite upward movement of the xenoliths, presumably resulting from uplift by the sheets of dolerite, which formed the main intrusive mass.

The bell-jar intrusions as well as the central xomplexes of Scotland are cut across by younger dikes.

H. THE TRIASSIC-JURASSIC DOLERITES AND LAVAS.

The hypabyssal phase of dolerite intrusions in South Africa is intimately linked with the effusive phase, viz. the Drakensberg Volcanic Stage, with the Stormberg volcanicity most probably preceeding the main intrusive phase (Walker and Poldervaart, 1949, p.265). Counterparts in Antarctica, South America, Australia and Tasmania have been recognised, all of which are considered to have been injected and extruded at the time when the Gondwanaland continent had not yet split up.

The bell-jar intrusions of the Republic represent part of the hypabyssal phase of dolerite intrusions which took place largely within the Karroo basin during Triassic-Jurassic times. According to Walker and Poldervaart (1949, p.684) these intrusions and thick sheets of dolerite in the Kokstad - Mount Ayliff district, are thought to indicate a focus of Karroo dolerite activity to the south and south-east of

Lesotho. Although there appear to be at least four ages of basic intrusions in the Birds' River area there is no doubt that many more successive separate basic igneous injections were emplaced within the Karroo strata throughout the Triassic-Jurassic period.

Three tectonic features dominated magmatic ascent in South Africa during Triassic-Liassic times - the Samfrau Geosyncline, the Karroo basin and the Natal-Lebombo Monocline (Walker and Poldervaart, 1949, p.689). The formation of the Cape Fold Belt, which marked the end of the Samfrau Geosyncline cycle in South Africa, came into being after a long period of sedimentation within the Karroo basin to the north of the Fold Belt. Tension within this basin of sediments, as in other counterparts of Gondwanaland, led to the subsequent injection of basic magma into the sediments. In the Natal-Lebombo Monocline magma which had differentiated before extrusion, poured out along a north-south fissure within Karroo strata. Walker and Poldervaart (1949, p.690) suggest that the basaltic magma which produced the hypabyssal and effusive phase in the focal area was most probably directly linked to a basaltic substratum below the Gondwanaland continent.

In conclusion it appears that the formation of the Birds' River bell-jar intrusion was initiated by the advent of diatremes. Build-up and escape of a large amount of gaseous material caused a large volume of pyroclastic material to be extruded. The latter event resulted in a reduction of pressure above the magma chamber and led to the subsequent cauldron subsidence through the aid of ring fractures. Intrusion of dolerite magma was followed by the collapse of the "roof" of sediments into the magma and their subsequent structural deformation by the dolerite. Thus it appears that each igneous phase, after the diatremes, exploited the passage of access created by a former one. The bell-jar intrusion represents the largest phase, and climax, of igneous activity. The narrow Dragon's Back dike cuts across all other formations and represents the youngest phase of igneous activity in this area.

* * * * *

CHAPTER NINE

SUMMARY AND CONCLUSIONS

To the north of Birds' River Siding, forming part of the mountainous area of the Stormberg, the bell jar intrusion protrudes as a watershed separating two plains of approximately 300 metres (1000 feet) difference in elevation. In plan view the bell-jar intrusion forms a roughly oval-shaped mass of dolerite. Its longer axis is aligned in a north-westerly direction and measures approximately 13.5 kilometres (8.4 miles), while the shorter axis measures approximately 6 kilometres (3.8 miles).

Field mapping has indicated that the dolerite contacts dip either vertically, or steeply outwards along the western margin and in the northern corner of the intrusion. Along the eastern and south-eastern margins the intrusion appears to have given off sheet- or sill-like forms of dolerite from the main mass. The dolerite intrusion is therefore plug-like in nature with offshoots from the main mass in the form of sheets or sills, in the eastern and south-eastern areas.

From a stereoscopic examination of the bell-jar intrusion a definite "grain" can be noticed in the south-western and south-eastern portions of the intrusion. This "grain" is represented by a series of parallel ridges within the dolerite, for the most part parallel to and conformable with the contact of the intrusion. A number of streams flowing across these parallel ridges in the south-western portion of the intrusion emphasize the nature of the ridges by flowing parallel to and at right angles to them. A petrographical investigation of a series of samples taken along the course of one of these streams revealed the presence of several dolerite rock types. It appears that intrusion of the dolerite magma that formed the bell-jar intrusion took the form of successive sheets rather than a single mass of dolerite.

Within the plug-like intrusion of dolerite a large number of xenoliths have been exposed through active erosion by youthful streams. The xenoliths are composed of Stormberg strata and pyroclastic rocks, many of which occur well below and above their normal stratigraphic elevation. Many of the larger xenoliths have been bent into either basin or dome shapes by the dolerite magma.

The largest of the xenoliths, the Smuts Pass xenolith, occurs in the north of the complex. It measures 4.4 kilometres by 3 kilometres (2.75 miles by 1.9 miles) and has a basin-like structure. Molteno sediments form part of the southern side of the xenolith and occur at least 174 metres (570 feet) above their normal stratigraphic elevation. Red Beds sediments crop out in the trough of this folded xenolith. A number of dolerite sills have been intruded into the xenolith, but their ages, relative to the bell-jar intrusion, could not be established on field evidence. The thickest and most prominent of these sills, Skerprand, appears to merge at either extremity with the dolerites of the bell-jar intrusion. It most probably represents the same intrusive phase as the bell-jar dolerites and is therefore considered to lie beneath the base of the Smuts Pass xenolith. Petrographical and chemical evidence favour the interpretation that Skerprand forms part of the bell-jar phase of intrusion.

On Branstone, xenoliths of all three stages of Stormberg sediments have been bent into the shape of a dome. Molteno sediments occur on the north, Red Beds on the west and east, while Cave Sandstone forms the southern portion of the "dome". Dolerites have invaded extensively along and across the bedding planes of the sediments. Some of the xenoliths in close proximity to those forming part of the dome shape, are basin-shaped.

Within the eastern portion of the bell-jar intrusion, two very large xenoliths of pyroclastic rocks do not appear to have been significantly deformed by the dolerite. The larger of these extends as a blanket measuring 4 kilometres (2.5 miles) in length. The smaller xenolith is slightly basin-shaped. An interesting variety of rock types is to be found within these xenoliths, especially on contact with the dolerite. These include spotted, glassy and metasomatic rocks.

The first two are indicative of intense thermal metamorphism by the dolerite, while the metasomatic rocks are those whose original composition has been completely altered by solutions emanating from the dolerite magma.

The bell-jar intrusion is characterized by several veining phenomena, viz., rheomorphic veins of pyroclastic rock within horizontal joints in the dolerite, a rheomorphic glassy vein within a sedimentary xenolith, veins and irregular patches of zeolites chiefly within xenoliths of pyroclastic rocks, and quartz veins. These veining phenomena are more than likely related to the final stages of cooling of the dolerite magma.

From a superficial investigation into the petrography of the bell-jar dolerites the writer has recognised the following types :-

(i) Intergranular type.
(ii) Tholeiite.
(iii) Poikilophitic olivine dolerite.
(iv) Poikilophitic olivine dolerite, with quartz.
(v) Roof Zone rocks.

The intergranular and tholeiite types represent contact rocks and were the first to be intruded. The poikilophitic types are the most abundant types within the intrusion, that without quartz occurring nearer the contact rocks than that with quartz. Quartz dolerite is to be found within the northern dike-like margin of the intrusion, and within a zone some distance away from the contact, on Branstone. The Roof Zone rocks represent the least basic of the dolerites and occur just below a large xenolith of pyroclastic rocks, on Murrelfontein. Elongate and parallel development of felspar crystals within these rocks suggests an origin related to flow of the magma, similar to rocks in the Upper Border Group of the Skaergaard intrusion, in East Greenland.

A limited study of the composition of augite in the rock types listed above reveals a distinct variation in composition from the basic towards the acid types, the trend being towards iron enrichment. Modal and chemical analyses indicate that the poikilophitic dolerites are rich in plagioclase and alumina, much more so than is usual of Karroo dolerites. This is attributed to the formation of plagioclase primocrysts within a deeper magma chamber, and their subsequent emplacement into a higher level in the earth's crust. The fact that some of the plagioclase crystals are fractured lends support to this conclusion.

The sediments in the area under investigation belong exclusively to the Stormberg Series. Erosion has removed all of the Drakensberg Volcanic Stage in this area. Molteno sediments are composed predominantly of coarse- and medium-grained felspathic sandstone beds, with interbedded grey and bluish mudstone and shale beds. A particularly interesting shale bed has been exposed near the southern contact of the bell-jar intrusion, on Donwood, for here it contains a variety of well preserved Mesozoic flora. The Red Beds Stage appears to approach its maximum thickness in the Birds' River area. To the north of the bell-jar intrusion the characteristic vivid colouration of the sediments is exhibited by the small hill, Rooiberg. Ripple marks within medium-grained felspathic sandstone beds of this Stage indicate deposition under shallow-water conditions.

The contact between the Red Beds and Molteno Stages is not normally well defined in the field, due to the fact that the abundant dolerite intrusions in this area have largely bleached out the characteristic colouration of the Red Beds Stage. The contact between the Red Beds and Cave Sandstone Stages is better defined, and often very sharp.

In the area mapped, the Cave Sandstone, with associated pyroclastics, forms small outliers. The sandstone often has a spotted appearance which could be related to vulcanicity at the time of deposition.

Pyroclastic rocks outside the area of the bell-jar intrusion are to be found interbedded with, and as irregular patches within, the Red Beds and Cave Sandstone Stages. They also occur as xenoliths within the bell-jar intrusion. An interesting variety of pyroclastics, ranging from sandstone breccias, through tuffaceous sandstones and agglomerates to lapilli tuffs, is present in the Birds' River area. The pyroclastic rocks have been tentatively classified according to the percentage of igneous inclusions which they contain. There appears to be an increasing proportion of igneous inclusions upwards where these rocks have been exposed. This suggests that the pyroclastic rocks were derived from a vent, or vents, which expelled an increasing proportion of igneous fragments upon each subsequent build-up and release of gaseous pressure. The occasional amygdaloidal lava flows within pyroclastic rocks represent outpourings of entirely igneous material. That the pent-up gases did reach enormous pressure before expelling the contents of the vent, or vents, is exhibited by the presence of very large dolerite blocks within an agglomerate on Romance. The unbedded and poorly sorted nature of the blocks in a fine-grained matrix suggests that at least some of the pyroclastic material on Murrelfontein and Romance may have been redeposited through the agency of mudflows.

The occurrence of pyroclastic material in association with Red Beds sediments is significant in that it indicates commencement of volcanic activity as early as this Stage in the Birds' River area.

The diatremes on Klip Kraal and Thysfontein, outside the area of the bell-jar intrusion, are the result of gaseous activity. which heralded the Stormberg igneous period. The largest diatreme on Klip Kraal is composed predominantly of a whitish to greenish fine-grained sandstone which is virtually identical to Cave Sandstone. The mode of origin of this diatreme is believed to be largely the result of sand being blown in from the top of the vent, after the original contents had been expelled. Some of the smaller diatremes on Klip Kraal are characterized by a sandstone tuff containing rounded fragments of material similar to the Cave Sandstone. These rounded fragments are thought to be the products of fluidization - the result of prolonged gaseous activity within the volcanic pipe.

The formation of the diatremes is in all probability intimately related to the hypabyssal injections of dolerite - representing the initial escape of gases from magma chambers.

The ramifying and scattered occurrences of dolerite intrusions within the Karroo strata would account for the irregular distribution of the diatremes.

The metamorphic rocks, outside, as well as some of those within the area of the bell-jar intrusion, display normal thermal metamorphic effects produced by Karroo dolerite, viz. sandstones have been recrystallized to quartzites while mudstones and shales have been baked to a black flinty rock, lydianite. Within the area of the bell-jar intrusion, however, a greater variety of metamorphic rocks is to be found. The spotted rocks, as well as glassy rocks occurring within xenoliths at their contacts with the dolerite, are indicative of intense thermal metamorphism. The metasomatic rocks in the south-east corner of Lemoenfontein appear to have resulted from mobile solutions being introduced into pyroclastic rocks from above their present level of outcrop.

During the formation of the bell-jar intrusion it appears that, as a result of intermittent gaseous activity within the area of the intrusion, a large volume of pyroclastic material was expelled. This created a zone of reduced pressure above the magma chamber. Through the aid of ring fractures, a central block of sediments and pyroclastics subsided into this zone. This was followed by the intrusion of dolerite magma, initially along the outer margins of the intrusion as tholeiite, and then in the form of successive near-vertical sheets of dolerite. Each succeeding sheet of dolerite appears to be of a slightly different rock type. The "roof" of sediments, pyroclastics and lava then collapsed into the invading dolerite magma and was subsequently fractured, fragmented and bent into various basin- and dome-shaped masses.

Many of the xenoliths have sunk to considerable depths within the dolerite magma while others have been uplifted above their normal stratigraphic elevation. Poldervaart (1946) has explained the sinking of xenolithic blocks of sediment within basaltic magma as the result of generation of resurgent volatiles enveloping the blocks. This produced a zone of "modified" magma surrounding the xenoliths, of a lower specific gravity than the latter, thus allowing them to sink within this magma. This process appears to have been a prolonged one, and allowed sinking of xenoliths to considerable depths within the magma. In the Birds' River intrusion the presence of xenoliths far above their normal stratigraphic elevation is believed to have been caused by upward movement of invading sheets of dolerite within the bell-jar intrusion. These sheets are thought to have played a prominent rôle in the formation of the bell-jar intrusion.

The sheets, sills and some of the dikes in the area mapped appear to be the oldest intrusions in the area, while the Dragon's Back dike, which cuts all other formations, clearly represents the youngest dolerite intrusion. The majority of dikes as well as the longest axis of the bell-jar intrusion are aligned in a north-westerly direction, which suggests a direction of crustal weakness at the time of emplacement of the dolerite intrusions. The hypabyssal phase of dolerite intrusions largely into Karroo strata, and the effusive Drakensberg Volcanic Stage are considered to have taken place during the Triassic and lower Jurassic. This intrusive and effusive phase of basic magma forms part of a widespread igneous episode which took place within the Gondwanaland continent, approximately 150 million years ago.

It appears, then, that the diatremes which penetrated Stormberg sediments initiated the formation of the bell-jar intrusion in the Birds' River area. Each successive igneous phase, viz., expulsion of pyroclastics, cauldron subsidence and intrusion of dolerite, exploited the passageway created by a former one. The climax of the igneous episode is represented by intrusion of dolerite magma to form the bell-jar intrusion. This event was accompanied by collapse of the roof of sediments and pyroclastics and their subsequent distortion by the dolerite. The Dragon's Back dike represents the youngest phase of igneous activity in this area.

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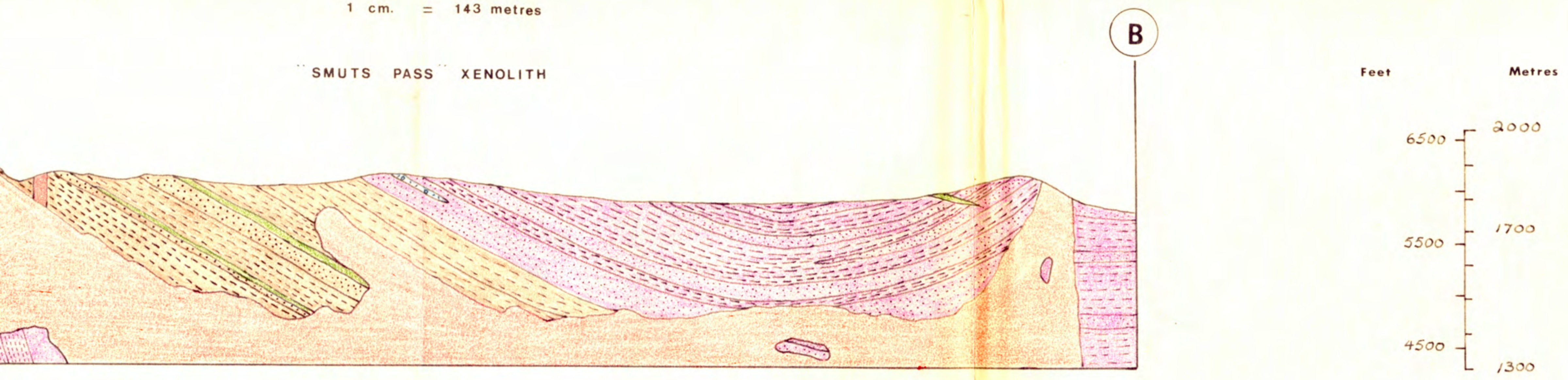
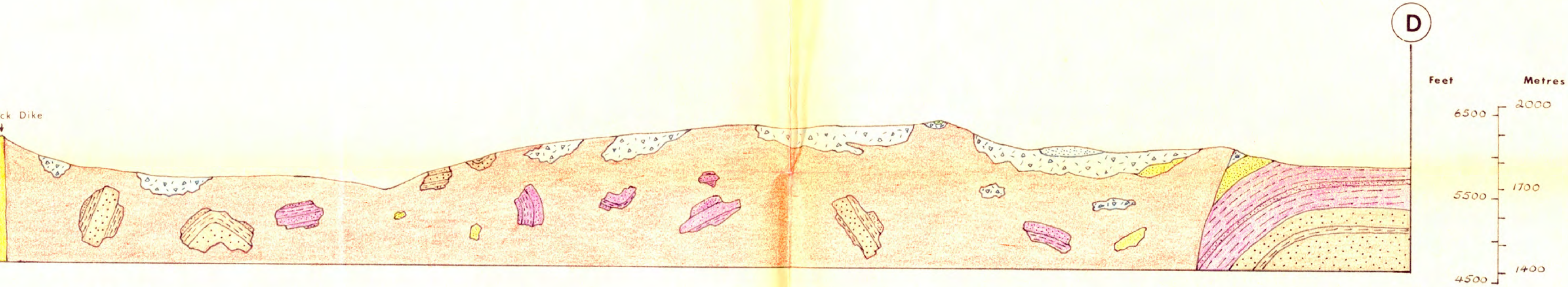
SCALE : HORIZONTAL AND VERTICAL :-

1 inch = 1,190 feet
1 cm. = 143 metres





GEOLOGY

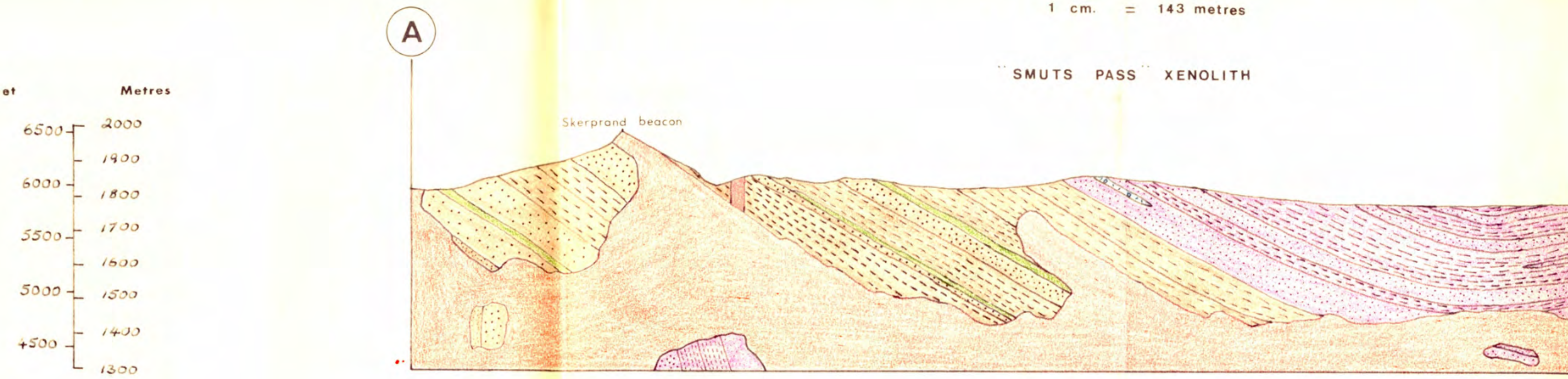
× × × × ×	Metasomatized rock	
▨	Pyroclastics	
▨	Cave Sandstone Stage	Stormberg Series, Karroo System
▨	Red Beds Stage	
▨	Molteno Stage	
▨	Dragon's Back Dike	
▨	Other dikes	
▨	Bell – Jar Intrusion	
▨	Sills	

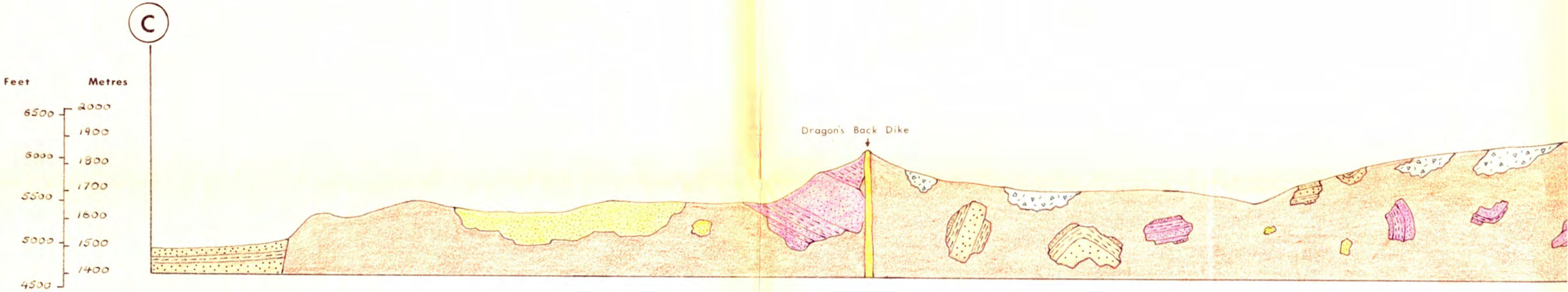
CROSS - SECTIONS

SCALE : HORIZONTAL AND VERTICAL :-

1 inch = 1,190 feet
1 cm. = 143 metres

"SMUTS PASS" XENOLITH





GEOLOGY

x x x x x	Metasomatized rock	
▨	Pyroclastics	
🟨	Cave Sandstone Stage	Stormberg Series , Karroo
🟪	Red Beds Stage	
▨	Molteno Stage	
🟨	Dragon's Back Dike	
🟫	Other dikes	
🟫	Bell - Jar Intrusion	
🟩	Sills	