GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

BULLETIN 123

THE GEOLOGY OF THE BLACKSTONE REGION WESTERN AUSTRALIA

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by

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PREFATORY NOTE

As a part of the Geological Survey's regional geological mapping programme, the four 1:250,000 sheets Bentley, Scott, Talbot and Cooper were mapped. The regional geology was of such interest that this Bulletin was prepared to record in more detail the findings in this remote area of Western Australia, situated near the junction of the South Australian and Northern Territory borders.

The Giles Complex, which has been mapped and described here, is one of the world's major layered basic intrusive complexes, comparable with the Bushveld, Stillwater and Skaergaard intrusions. The author describes his findings and conclusions which are based on his extensive field observations supported by a limited amount of laboratory study.

This Bulletin gives the reader the first detailed description of the regional geology of this area. It should stimulate research workers and others to study the area further and investigate the mineral prospects.

J. H. LORD,
Director.

1st February, 1972.

THE GEOLOGY OF THE BLACKSTONE REGION, WESTERN AUSTRALIA

by J. L. Daniels

CONTENTS

	Page
SUMMARY	15

CHAPTER 1. INTRODUCTION

Location, communications, settlement and climate	18
Acknowledgements	20
Fauna and Flora	20
Physiography	22
Early exploration	26
Previous geological investigations	28

CHAPTER 2. THE OLDER BASEMENT ROCKS OF THE MUSGRAVE BLOCK

Definition of the Musgrave Block	33
Granulites and related rocks	33
Basis for subdivision	33
Poorly banded granulites and related rocks	34
Michael Hills region	34
Area between Mount Holt and Mount Gosse	35
Summary	38
Well banded granulites	38
Summary of granulite history	41
Western part of the basement	43
Adamellite and related rocks	43
Granulite remnants	46
Quartzite and quartz-muscovite schist	47
Summary of the origin of the western part of the basement	47

CHAPTER 3. THE BENTLEY SUPERGROUP AND ASSOCIATED ROCKS

Introduction	49
Pussy Cat Group	49
Glyde Formation	50
Kathleen Ignimbrite	52
Tollu Group	54
MacDougall Formation	54
Mummawarrawarra Basalts	54
Smoke Hill Volcanics	55
Hogarth Formation	56
Metabasalts in the Jameson Range region	56
Unnamed metamorphosed basaltic rocks	57

Page

Cassidy Group 57
Acid volcanics 58
Zoning of macrostructures in the Hilda Rhyolite .. 58
Spherulitic zone .. 58
Turbulent flow zone 58
Laminar flow zone 59
Zoning in other cooling units 63
Source and volumes of the flows 66
Sequence of events 67
Petrography 68
Wururu Rhyolite 68
Gombugurra Rhyolite 68
Chemistry 72
Basic volcanics 75
Gurgadi Basalt 75
Warubuyu Basalt 76
Miller Basalt .. 76
Sedimentary rocks .. 77
Mission Group 77
Gamminah Conglomerate .. 77
Frank Scott Formation 78
Lilian Formation .. 80
Milesia Formation .. 81
Townsend Quartzite 81
Cauldron subsidence areas 84
Scamp cauldron 85
Skirmish Hill cauldron 86
Palgrave cauldron .. 87
Palgrave volcanic association 91
Winburn Granite 94
Non-porphyritic granophyre 94
Porphyritic granophyre .. 96
Porphyritic microgranite 96
Aplite 97
Summary and petrogenesis 97
Phase 1 98
Phase 2 98
Phase 3 98

CHAPTER 4. THE GILES COMPLEX

Introduction 100
Igneous layering in the complex 102
Rhythmic layering .. 102
Gravity differentiated units 103
Reverse graded bedding 105
Cross-bedding .. 106
Winnow banding 107
Ripple marks .. 107
Slump structures 108
Cryptic layering 108

Page
Phase layering 109
Zone layering 109
Convection current patterns, subdivision of the complex, and form of the main intrusions 110
General descriptions of the main gabbro sheets 114
Jameson Range Gabbro 114
Zone 1 116
Zone 2 119
Zone 3 122
Zone 4 124
Sheared gabbroic rocks 125
Blackstone Range Gabbro 129
Zone 1 131
Zone 2 131
Zone 3 131
Zone 4 135
Michael Hills Gabbro 138
Zone 1 140
Zone 2 140
Zone 3 143
Zone 4 145
Hinckley Range Gabbro 146
Mount West Gabbro 146
Minor gabbroic bodies 146
Granophyres and related acidic bodies 147
Marginal facies 149
Development of contaminated gabbro, net-veined complexes, recrystallized granulites and anatectic granite 149
Changes in the country rock 150
Development and origin of the contaminated gabbro 153
Distribution of the fine-grained hypersthene gabbro 159
Mineralogy 159
Brown amphibole 159
Plagioclase 164
Comparison of chemical and optical data 167
Spatial distribution and range of composition 168
Strontium content 170
Orthoclase component 171
Orthoclase/strontium relationships 171
Olivine 172
General characteristics 172
Alumina content 175
Pyroxenes 178
General characteristics 178
Ferrous iron/magnesium partition in coexisting pyroxenes 179
Differentiation 184
Whole rock analyses 184
Mineral data 188
Plagioclase 188
Michael Hills Gabbro 188

Page
Blackstone Range Gabbro 188
Jameson Range Gabbro 188
Olivine 189
Blackstone Range Gabbro 189
Jameson Range Gabbro 189
Concluding discussion 189

Chapter 5. Miscellaneous Topics of the Precambrian Rocks

Geology of the Giles area 194
Dolerites 195
Granitic rocks 195
Blackstone region south of the Cobb Depression 195
Post-Tollu Group granite 196
Giles area 196
Ovoid granite 196
Giles porphyry 196
Granite younger than the main unconformity 196
Proterozoic glacial rocks 197

Chapter 6. The Phanerozoic Rocks

Possible Ordovician 198
Table Hill Volcanics and possible correlatives 198
Permian 199
Tertiary 200
Laterite and lateritic gravel 200
Calcrete 200
Quaternary 203
Colluvium, alluvium and dry lakes 203
Sand ridges 203
General characteristics 203
Regional distribution 205

Chapter 7. Structure

Granulites 208
Marginal shearing and block rotation 208
Pseudotachylyte 209
Faulting 209
Regional pattern 209
Ring faults 212
Small circular structures 214
Tilting of the Cassidy and Mission Groups 214
Form of the Townsend Quartzite outcrop 214
Structure of the Officer Basin 215

Page

CHAPTER 8. GEOLOGICAL HISTORY 216

CHAPTER 9. ECONOMIC GEOLOGY

Introduction 220
Nickel, cobalt and chromium 220
Vanadium 221
Zone 2, northeast of Jameson Range 222
Zone 4, southwest of Jameson Range 225
Southeast Jameson Range region 226
Platinum metals 231
Uranium and associated vanadium 231
Copper 231
Copper and lead 233
Copper in the Giles Complex 234
Fluorite 235
Agate 235
Graphite 235
Water 235
Gold 236
Petroleum 236

GLOSSARY 237

BIBLIOGRAPHY 239

INDEX 246

LIST OF PLATES

Plate 1.	Physiographic units of the Blackstone Region	In back pocket.
Plate 2.	Tectonic sketch map of the Blackstone Region	
Plate 3.	Geological map of the Blackstone Region	

LIST OF FIGURES

Figure		Page
1.	Sketch map of locality of Blackstone Region, Western Australia	18
2.	View from Borrows Hill region looking north to the almost horizontally layered gabbros of the Cavenagh Range	23
3.	Porphyritic granite forming monadnock in southeast corner of Cooper Sheet area	24
4.	Effects of spheroidal weathering on granite immediately east of MacDougall Bluff, Cooper Sheet area	25
5.	Polished hand specimen of charnockite gneiss showing well developed flaser structure from 4 miles southeast of Mount Holt, Scott Sheet area	36
6.	Well banded garnet-sillimanite granulite, near Cohn Hill, Cooper Sheet area	39
7.	Hypothetical conditions prevailing during development of granulite of the Blackstone Region	42
8.	Stereographic plot of folded single lineation represented by its orientation at 20 consecutive points each separated by a distance of 3 inches except 8 and 9 which are 1 inch apart	45
9.	Folded lineations in downgraded granulite from near Yulun-Kudara in the northeast Bentley Sheet area	46
10.	Stretched pebbles, up to 6 inches long, near the base of the quartz-muscovite schist near Neena Mogura Waterhole, Bentley Sheet area	48
11.	Glass shard shapes preserved near the top of the Kathleen Ignimbrite, Mount Kathleen, Talbot Sheet area. Ord. light	53
12.	Zig-zag fold in flow-banded rhyolite of Smoke Hill Volcanics, Tollu Group, Tollu, Cooper Sheet area. Scale is 2 feet long	55
13.	Specimen of weathered, spherulitic rhyolite from near top of Hilda Rhyolite, 2 miles north of Frank Scott Hill	59
14.	Planar partings with rough surfaces near base of Hilda Rhyolite, 1½ miles west of Mount Talbot	60
15.	View almost normal to parting showing crudely developed "rough surface rolls". Hilda Rhyolite, 1½ miles west of Mount Talbot	61
16.	Diagram showing subdivision of the Hilda Rhyolite, the main characteristics of each zone and comparisons of the orientations of linear features	61
17.	Flow-lineated porphyritic acid volcanic from laminar flow zone near top of Hilda Rhyolite 1½ miles west of Mount Talbot	62

Figure		Page
18.	"Triangular shadows" on planar partings in Hilda Rhyolite, 1½ miles west of Mount Talbot	63
19.	Deduced regional flow patterns for rhyolites of the Cassidy Group	65
20.	Inferred form of Hilda Rhyolite and related features	66
21.	Form of inclusions in plagioclase phenocrysts in acid volcanic rocks of the Warburton Region:	70
	1. Plagioclase in extremely fine-grained groundmass in thin, basal, well banded, spherulitic zone of Gombugurra Rhyolite. Groundmass cut by the Warburton Region:	
	2. and 3. Plagioclase from spherulitic top of Gombugurra Rhyolite showing well developed zonal arrangement of inclusions. Traces of twin planes indicated by thin lines. Groundmass is extremely fine grained with pronounced radiating texture related to spherulite development. Quartz mosaic is developed marginal to some phenocrysts and as veins. A small biotite aggregate in seen in 3.	
	4. Skeletal plagioclase with lobate inclusions in acid volcanic rock from Palgrave volcanic association. Groundmass is fine grained and shows patchy extinction and dark, lobate areas. Quartz mosaic at base is part of a "vein band".	
22.	Plots showing relationships of various features of acid volcanic rocks and granophyre from the Blackstone Region	73
23.	Acid volcanics of the Cassidy Group plotted on quartz-albite-orthoclase ternary diagram. For explanation see text	74
24.	Comparison of differentiation trends of acid volcanics of the Cassidy Group and acid volcanics related to the Creede Caldera, Colorado	76
25.	Algal structure from Frank Scott Formation, near Frank Scott Hill, Talbot Sheet area	79
26.	Columnar jointed basalt at top of Frank Scott Formation, 4½ miles south-southeast of Mount Talbot	80
27.	Sketch map showing locations and simplified geology of cauldrons in the Blackstone Region	84
28.	Suggested flow pattern for Scamp Rhyolite	85
29.	Sketch map showing distribution of main rock types in the Palgrave cauldron subsidence area	88
30.	Agglomerate showing zoned reaction edges, east of Mount Palgrave, Talbot Sheet area	89
31.	Deduced regional flow pattern of acid volcanics in the Mount Palgrave region	90
32.	Cross section through rotated medium-grained acid volcanic fragment (toned) included in foliated cryptocrystalline rhyolite from the Palgrave volcanic association	91

Figure		Page
33.	Diagrammatic illustration of textural variations in some acid volcanic rocks from the Palgrave volcanic association	93
34.	Comparison of thicknesses and major subdivisions of the main sheets of the Giles Complex, Western Australia	101
35.	Banded gabbro, northwest end of Bell Rock Range. The two prominent mafic bands are respectively a normally graded band on the left and a reverse graded unit on the right. The two bands are approximately 4 inches apart	104
36.	Cross-bedded gabbros in the northwest end of Bell Rock Range. Blackstone Range Gabbro	105
37.	Close-up of cross-bedded unit in gabbro at northwest end of Bell Rock Range. Blackstone Range Gabbro	106
38.	Possible ripple marks in banded gabbro, Bell Rock Range. Blackstone Range Gabbro	107
39.	Slump structure in fallen block of gabbro on northwest end of Bell Rock Range. Blackstone Range Gabbro	108
40.	View of Michael Hills from Sphinx Hill showing benched slopes of Michael Hills Gabbro caused by igneous layering	110
41.	Sketch map of Giles Complex in Western Australia showing deduced convection current pattern	111
42.	Structural interpretation of the Michael Hills region	113
43.	Variation in An content of plagioclase with height in Jameson Range Gabbro. Solid circles—chemical determinations; open circles—optical determinations	115
44.	Rhythmic layering in Zone 3, Jameson Range Gabbro, Jameson Range	116
45.	Glomeroporphyritic gabbro, Zone 1, Jameson Range Gabbro, Jameson Range	117
46.	Photomicrograph of gabbro from near base of Zone 1, Jameson Range Gabbro, Mount Finlayson, showing corona development. Ord. light	118
47.	Photomicrograph of unsheared olivine gabbro from Zone 3, Jameson Range Gabbro, Turkey Hill. Ord. light	123
48.	Outcrop of titaniferous magnetite Zone 4, Jameson Range Gabbro, southwest of Jameson Range	124
49.	Photomicrograph of sheared troctolite from Zone 3a, Jameson Range Gabbro, Jameson Range. Ord. light	126
50.	As Figure 49. Crossed nicols	127
51.	Zonal scheme and distribution of An values of plagioclase in the Blackstone Range Gabbro. Approximately 8 miles west of Blackstone Camp	129
52.	Variation in An content of plagioclase with height in Blackstone Range Gabbro. Solid circles—chemical determinations	130
53.	Photomicrograph of olivine norite from top of Zone 2, Blackstone Range Gabbro, Blackstone Range. Ord. light	132

Figure Page

54. Photomicrograph of hypersthene troctolite from base of Zone 3, Blackstone Range Gabbro, Blackstone Range. Ord. light 133

55. Photomicrograph of troctolite, Blackstone Range Gabbro, Bell Rock Range. Ord. light 134

56. Sketch map of Bell Rock Range showing distribution of An values of plagioclase 136

57. Variation in An content of plagioclase with height in Michael Hills Gabbro. Solid circles—chemical determinations; open circles—optical determinations 137

58. Suggested zonal scheme for Michael Hills Gabbro 139

59. Photomicrograph of kinked orthopyroxene from Zone 1 of Michael Hills Gabbro. Ord. light 141

60. Photomicrograph of sample from Zone 2 of Michael Hills Gabbro showing abundant plate-like inclusions in the pyroxenes and the slightly antiperthitic nature of the plagioclase. Ord. light 142

61. Photomicrograph showing igneous lamination displayed by gabbro of Zone 2 in Michael Hills Gabbro, 3 miles west-southwest of Latitude Hill. Ord. light 144

62. Northwest end of Hinckley Range showing rounded ridges of charnockitic gneiss with intervening areas of more easily weathered contaminated gabbro. The horizontal linear features in the centre of the photograph are the surface traces of dolerite dykes 150

63. Slightly modified granulite showing banding and original folds. Northeast Hinckley Range 151

64. Recrystallized granulite showing development of porphyroblasts of feldspar and intrusion of basic material. Northeast Hinckley Range 154

65. Granulite gneiss stoped by basic material. Northeast Hinckley Range 154

66. Modified granulite fragments in process of being assimilated by basic material. Northeast Hinckley Range 155

67. Basic material carrying abundant minute blebs of leucocratic material. Rock represents near end product of assimilation of granulite by gabbroic material. Northeast Hinckley Range 155

68. Comparison of Sr and An contents of plagioclase from marginal facies, with plagioclase from Michael Hills Gabbro 157

69. Relationship of ppm Sr to An content of plagioclase in gabbroic rocks of the Giles Complex in Western Australia 169

70. Range of orthoclase component relative to anorthite content of analyzed plagioclase samples from the Giles Complex in Western Australia 170

71. Relationship of ppm strontium content of plagioclase to orthoclase component x100 of plagioclase in gabbroic rocks in the Giles Complex in Western Australia 172

72. Optical properties and density of olivines from Giles Complex 176

Figure		Page

73. Relation of Al_2O_3 content of olivine to depth in intrusion for Jameson Range and Blackstone Range Gabbros. Overburden thickness above intrusions not known. For explanations see text 177

74. Mafic index—felsic index diagram for rocks of the Giles Complex in comparison with other differentiation trends given by Simpson (1954) 187

75. Compositions of coexisting olivine and plagioclase for various layered basic intrusions. For explanation see text 191

76. Map of portion of southeast Cooper 1:250,000 Sheet area showing discordance between sand ridge system and linear features in underlying calcrete body (Photo 5452 Cooper Run 15) 201

77. Distribution of calcrete in Blackstone Region 202

78. Sand ridge characteristics approximately 5 miles east of Skirmish Hill (Photo 5493 Cooper Run 7) 204

79. Sand ridge characteristics 26 miles north of Mount Fanny (Photo 5407 Scott Run 8) 205

80. Examples of dune convergences 206

81. Dune pattern and deduced causal wind directions for the Blackstone Region 207

82. Interpreted fault and joint pattern in the Lehmann Hills area 210

83. Interpreted fault and joint pattern in the Mount Finlayson region 211

84. Interpreted fault and joint pattern in the Tollu region 212

85. Circular structures southwest of Jameson Range 213

86. Photomicrograph of ultramafic rock from Zone 2, Jameson Range Gabbro. Rock consists of titaniferous magnetite, anorthite, olivine, kaersutite, orthopyroxene and clinopyroxene. Ord. light 223

87. Plot of V_2O_5 against FeO for titaniferous magnetites from the Jameson Range Gabbro 227

88. Ratio mol. % FeO, Fe_2O_3, TiO_2 for titaniferous magnetites from the Jameson Range and Blackstone Range Gabbros 229

89. Sketch map of known distribution of Proterozoic conglomerates in the Cooper Sheet area 232

90. Sketch map of fluorite occurrences near Mount Elvire 234

LIST OF TABLES

Table		Page
1.	Stratigraphic column of the Blackstone Region	29
2.	Analyses of acid volcanic rocks from the Bentley Supergroup	51
3.	Norms of acid volcanic rocks from the Bentley Supergroup	52
4.	Sequence and dimensions of rhyolite formations of the Cassidy Group	67
5.	Normative quartz, orthoclase and albite of analyzed acid volcanics of the Cassidy Group	72
6.	Observed stratigraphic thicknesses of Townsend Quartzite, Talbot Sheet area	83
7.	Partial analyses of acid rocks from the Winburn Granite	95
8.	Classification of sedimentary-type structures in the Giles Complex	103
9.	Modal analyses of gabbroic rocks from the Jameson Range Gabbro	115
10.	Analyses of brown amphibole-bearing ultramafic rocks from the Jameson Range Gabbro, Zone 2	120
11.	Modal analyses of gabbroic rocks from Bell Rock Range	135
12.	Modal analyses of gabbroic rocks from the Michael Hills Gabbro	138
13.	Analysis and norm of granophyre from the top of Blackstone Range Gabbro, Tollu	148
14.	Approximate modes of granulite and modified granulite enclosed in fine-grained basic rock from the western end of Hinckley Range	152
15.	Analysis of brown amphibole from Jameson Range Gabbro and comparison analyses	160
16.	Summary of main properties of brown amphiboles	163
17.	Relation of Fe^{3+}/Fe^{2+} to (OH,F,Cl) in kaersutites	164
18.	Chemically determined compositions of plagioclase from the Giles Complex	164
19.	Calculated compositions and optical determinations of plagioclase from the Michael Hills Gabbro	166
20.	Calculated compositions and optical determinations of plagioclase from the Blackstone Range Gabbro	166
21.	Calculated compositions and optical determinations of plagioclase from the Jameson Range Gabbro and associated rocks	167
22.	Chemical, physical and optical properties of olivines from the Blackstone Range Gabbro	173
23.	Chemical, physical and optical properties of olivines from the Jameson Range Gabbro	174
24.	Unit cell dimensions of olivines from the Giles Complex	175
25.	Comparison of Al_2O_3 content of olivine with depth in Jameson Range and Blackstone Range Gabbros	178
26.	Refractive indices of coexisting pyroxenes in the Giles Complex	179
27.	Chemical, physical and optical properties of orthopyroxenes from the Jameson Range Gabbro	180
28.	Chemical, physical and optical properties of clinopyroxenes from the Jameson Range Gabbro	182
29.	K_D values for coexisting pyroxenes from igneous and metamorphic rocks	183
30.	K_D values of around 0.62 to 0.66 for coexisting pyroxenes from various rocks	183
31.	K_D values for coexisting pyroxenes in the Jameson Range Gabbro	184

Table		Page
32.	Whole rock analyses of gabbros from the Giles Complex	185
33.	Summary of ranges of selected oxides in rock analyses from the Blackstone Range, Michael Hills and Jameson Range Gabbros	186
34.	Analyses of titaniferous magnetites from Bell Rock Range	222
35.	Analyses of titaniferous magnetites from Zones 2 and 4, Jameson Range Gabbro	224
36.	Partial analyses of laterites developed on Zone 2, Jameson Range Gabbro	225
37.	Analyses of titaniferous magnetites from the area southeast of Jameson Range	228
38.	Summary of various oxides in the titaniferous magnetites from various localities in the Jameson Range Gabbro	228
39.	Reserves of Western Australian vanadium ore excluding Jameson Range	230

Note: Figure captions have not been metricated. Conversion factors used in the text are:

1 foot = 0·3048 metres (m).

1 mile = 1·60934 kilometres (km).

1 square mile = 2·58998 square kilometres (km^2).

1 cubic mile = 4·16815 cubic kilometres (km^3).

Summary

CHAPTER 1. This bulletin reports the results of a 4-year study of the geology of the Blackstone Region of Western Australia. The area is limited by latitures 25° and 27° south and longitudes 126° and 129° east. The area is remote from any major town but two small settlements, at Warburton Mission and Giles are contained within the region. A large variety of fauna and flora is present but this is only briefly mentioned. A seven-fold subdivision of the physiography is suggested and is shown to be related to the interplay of the hard rock geology and the younger extensive sand ridge fields. A summary of the early exploration is given and the previous geological investigations described. The area is covered by Scott, Cooper, Bentley and Talbot 1:250,000 Geological Sheets produced by officers of the Geological Survey of Western Australia.

CHAPTER 2. The older basement rocks of the Musgrave Block are described. This is a convenient term referring to a general area in central Australia limited on the south by the younger sedimentary rocks of the Officer Basin and on the west and northwest by younger sedimentary rocks of the Canning Basin. The rocks of the block consist of a wide variety of igneous and high-grade metamorphic rocks. A complex history is suggested for these rocks. Rock types mostly consist of granulites, migmatites and granites. The granulites are subdivided into two units: a poorly banded orthoclase-bearing variety and a well banded microcline-bearing variety. The former are probably orthogneisses and possibly represent an older basement on which was deposited a thick sequence of dominantly arenaceous sediments, now represented by the well banded granulites. At the contact of the two units a quartzite is sometimes developed. The orthoclase-bearing variety is thought to have developed as a consequence of deeper burial than the microcline-bearing variety. The granulite complex is seen as the product of a period of high pressure-temperature conditions, acid igneous injections and variations in shearing stress intensity. The western part of the basement consists of migmatized granulites injected with a large volume of adamellitic material. Some subsequent shearing is locally developed. Unconformably overlying the migmatized granulites and adamellites is a series of quartzites and quartz-muscovite schists. These have been recumbently and isoclinally folded along northeast and north-northeast axes. Probably during this folding they were also regionally metamorphosed. They are older than the Bentley Supergroup.

CHAPTER 3. The Bentley Supergroup includes all sedimentary and volcanic rocks in the Blackstone Region younger than the granulites and related gneisses and schists, and older than the Upper Proterozoic glacials. A subdivision into four groups, the Pussy Cat Group, the Tollu Group, the Cassidy Group and the Mission Group is made. Of these the first two named are probably lateral equivalents. Each of the groups is further subdivided into a number of formations. The Pussy Cat Group is developed north of the Warburton Range and consists of a thick sequence of basic lavas, tuff, shale, siltstone, dolomite, quartzite, sandstone and a major ignimbrite horizon. The Tollu Group, developed in the Cooper Sheet area consists of a thick mixed volcanic sequence with a basal sandstone and conglomerate. The Cassidy Group unconformably overlies the Pussy Cat Group and is characterized by an alternating sequence of acid and basic volcanics with minor associated sedimentary rocks. The acid volcanics of the Cassidy Group have been studied in a little detail. The macrostructures are described and three major zones for each cooling unit defined. These zones are, from top to bottom, a spherulitic zone, a turbulent flow zone and a basal laminar flow zone. A minor spherulitic zone may occur at the base of some flows. Linear structures, related to the preconsolidation flow of the body, were measured and used to construct a flow diagram for each of the acid volcanic cooling units. The flow lines were extrapolated and, together with other evidence, used to predict the source and the total

volume of material involved. Variations in the petrography of the acid volcanics are described and show that, although each of the units is generally very similar, minor variations are present especially in a vertical sense within each cooling unit. The acid volcanic units show minor but progressive variations in their chemistry. This has been used to show that their origin is most likely to be anatectic and not a result of progressive crystallization differentiation. The acid volcanics of this group are thought to have been produced from enormous nuées ardentes being the superheated acid material selectively melted out of a crust by the heat from a basic intrusion at a depth of between 1½ and 4 miles (2.5 and 7 km).

The Mission Group conformably overlies the Cassidy Group and consists of approximately 12,000 feet (4,000 m) of conglomerate, basalt, dolomite, shale and quartzite. Algal fossils have been found in the dolomite. The Townsend Quartzite, a shallow-water deposit, is here included in the Bentley Supergroup. It is apparently conformable on the Mission Group in the west but is unconformable on several units of widely differing ages in the east. Tectonic modification of the basal contact of the Townsend Quartzite is strongly suspected in the Hocking Range area.

Three cauldron subsidence areas, named Scamp, Skirmish Hill and Palgrave are recognized in the Blackstone Region and these developed during Bentley Supergroup times. The smallest is Skirmish Hill with a present exposed area of approximately 95 square miles (245 km^2). The largest is Scamp with an estimated original area of 1,435 square miles (4,415 km^2). Flow structures in the acid volcanics of Scamp and Palgrave have been mapped and have led to the discovery of the main centres of activity. A plug of granophyre has been located in Palgrave. Each cauldron shows a similar association of acid volcanics and intrusive granitic material with only minor basic igneous activity. Ring structures are well developed in Palgrave. Three phases of activity are recognized in Palgrave. They are an early acid volcanic phase, explosive in its early stages, a later minor basic intrusive phase and a younger acid intrusive phase.

CHAPTER 4. The Giles Complex comprises a series of basic plutonic masses which are subdivided into several discrete masses of several ages. Rhythmic layering, cryptic layering, phase layering and zone layering are described from the various masses. Particular attention is given to the similarity of some of the rhythmic layering structures to normal sedimentary structures. Using cross-bedding structures in the gabbros it was possible to determine the pattern of convection currents present while the gabbros were crystallizing.

The Jameson Range Gabbro is 18,000 feet (5,480 m) thick and has been subdivided into four main zones. Rock types include glomeroporphyritic gabbro, lherzolite, troctolite, anorthosite, gabbro and titaniferous magnetite. Part of the intrusion has been sheared.

The Blackstone Range Gabbro is approximately 11,000 feet (3,350 m) thick and consists of troctolite, mafic troctolite, norite and gabbro.

The Michael Hills Gabbro is 21,000 feet (6,400 m) thick. Its rock types include gabbro, anorthosite and pyroxenite.

The Hinckley Range Gabbro is possibly 8,500 feet (2,740 m) in thickness and is composed principally of norite and gabbro.

Granophyric masses possibly related to the gabbros are present as dykes and cappings to some parts of the gabbros.

A marginal facies of contaminated gabbroic material is found in several areas. It is very common in the Hinckley Range where its derivation by contamination of gabbro by granulitic country rock can be demonstrated. The Michael Hills Gabbro is thought to be the parent gabbro for the marginal facies.

Of the minerals present in the gabbros, brown amphibole, plagioclase, olivine, hypersthene and clinopyroxene have been studied in varying detail. The brown amphibole from the lherzolites of the Jameson Range is a kaersutite with only a moderate TiO_2 content and slightly more total iron than is normal for kaersutites. Apart from the overall variation in An content of the plagioclases of the various intrusions their K_2O and Sr contents have been studied. Optical determinations on the plagioclases are in good agreement with results from chemical determinations. Sr/An relations of the plagioclases are fairly distinctive for each intrusion but the Or/Sr relations are shown to be critical for the subdivision of the complex into both discrete intrusions and zones within the masses.

Several analyses of olivines from the Jameson Range and Blackstone Range Gabbros are given. They show a narrow range of composition, and an unexplained increase in alumina with depth. For the Jameson Range Gabbro the rate of increase in alumina content of olivine is 0.034 per cent per 100 feet (30 m) depth. For the Blackstone Range Gabbro the equivalent value is 0.032 per cent.

$K_{D(Mg-Fe^{2+})}$ for coexisting pyroxenes in the iwo rocks from the Jameson Range Gabbro are 0.624 and 0.659. Their implication is discussed.

The gabbros of the Giles Complex do not show differentiation trends of the "normal" type. Variations noted in individual minerals are characterized by irregular trends with limited ranges of composition. It is suggested that the irregular trends noted may be caused by an interplay of adjacent convection cells cooling at different rates and subsequently mixing as the liquid part of the intrusion became progressively thinner. Multiple intrusion is a possibility in the Jameson Range gabbro.

CHAPTER 5. The Giles area consists of a suite of granites and acid gneisses unconformably overlain by sediments and volcanic rocks which were all intruded by quartz-feldspar porphyry and granite.

Four varieties and ages of granites are recognized in the area south of the Cobb Depression. Three types of granitic rocks are found in the Giles area.

Proterozoic glacial rocks are developed south of and overlying the Townsend Quartzite. They are unconformably overlain by the Table Hill Volcanics and the Permian glacials.

CHAPTER 6. Basic volcanics of possible Ordovician age are present in two areas south of the Townsend Quartzite. They are referred to as the Table Hill Volcanics and consist of tholeiitic basalt with a well developed pumice agglomerate horizon. Rocks of Permian age are poorly exposed but are extensively developed fringing the Musgrave Block. Most of these rocks are of glacial or fluvioglacial origin. Much of their area of development is overlain by pisolitic limonite, calcrete and sand ridges.

CHAPTER 7. The oldest folding of the area is represented by north-south foliation and lineation trends within the granulites. Faulting and subsequent block rotation is suggested to account for some of the structural features of the area. The regional faulting pattern as deduced from photolineaments is simple. Fault directions are northeast, northwest, north and east. Ring faults appear to bound all three of the cauldron subsidence areas.

CHAPTER 8. The granulite complex was followed by the development of three main events: the deposition of the Bentley Supergroup, the formation of cauldron subsidences and the intrusion of the Giles Complex. It seems likely that these three events are not completely separate entities but related phenomena, each of which progressively developed over a given, but unknown, period of time. Folding and faulting of several ages is known. Afterwards, the region entered a glacial period. In Phanerozoic times Ordovician volcanism was followed by another glaciation. Subsequently the area was extensively lateritized and the drainage lines were calcreted. Extensive dune fields developed at a later date but are not, on the whole, presently mobile.

CHAPTER 9. The region contains ore deposits of lateritic nickel, several prospects for vanadium and copper, some minor mineral occurrences, and several areas on which various ideas regarding possible mineralization should be tested.

CHAPTER 1

Introduction

LOCATION, COMMUNICATIONS, SETTLEMENT AND CLIMATE

For the purposes of this Bulletin the Blackstone region of Western Australia includes the area covered by the Bentley, Scott, Talbot and Cooper 1:250,000 Sheet areas, and is bounded by latitudes 25° and 27° south and longitudes 126° and 129° east (Fig. 1). The area covered is of the order of 26,000 square miles

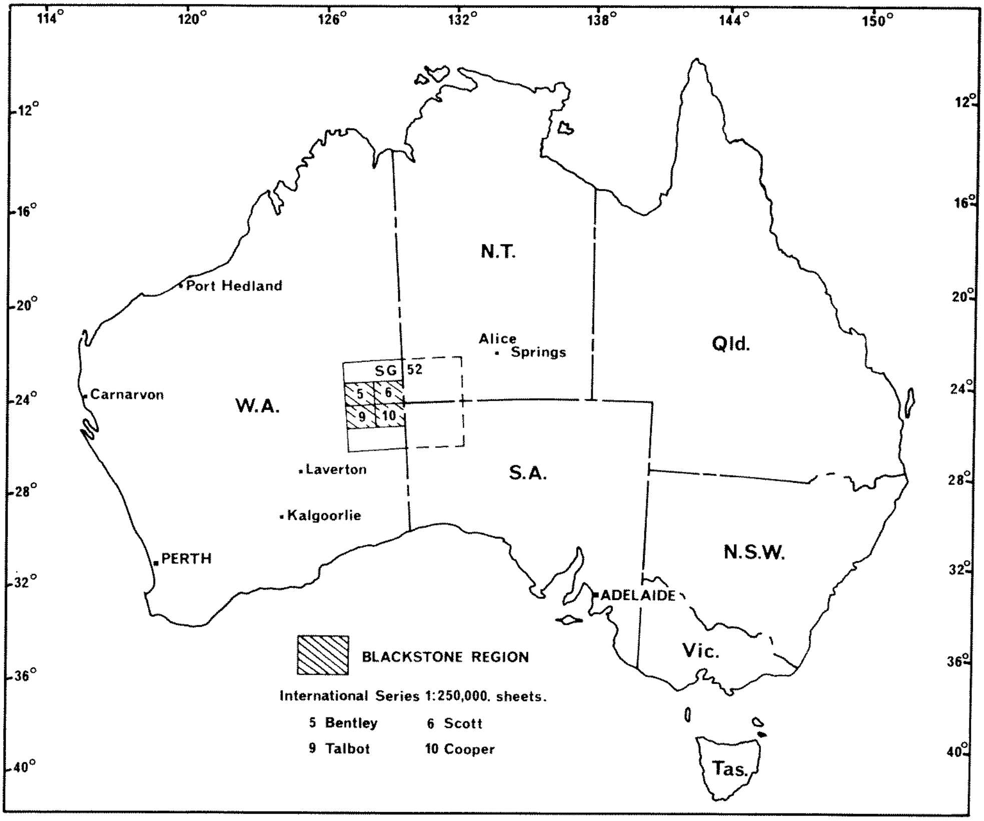

Figure 1. Sketch map of locality of Blackstone Region, Western Australia.

(67,300 km^2) and includes the western margin and part of the southern margin of the Musgrave Block (Daniels and Horwitz, 1969), a major Proterozoic structural unit in Central Australia. It is bordered on the southern and western sides by the younger sediments of the Officer Basin. The eastern limit of the area is purely geographic, being the line of longitude dividing Western Australia from Northern Territory and South Australia.

The following list gives the straight line distances to the nearest main centres from the centre of the Blackstone region:

Perth	795 miles (1,283 km)
Kalgoorlie	473 miles (761 km)
Alice Springs	426 miles (685 km)
Adelaide	887 miles (1,427 km)

A small settlement exists at Warburton Mission, towards the western end of the Warburton Range and a meteorological station is permanently manned at Giles, immediately south of the Rawlinson Range near the northern boundary of the Blackstone region. No other settlements exist in the region, though prospecting camps with airstrips have been established for some time at Wingelinna, in the northeast corner of the Scott Sheet area, and also near Warburton Mission. Other prospecting camps were set up at Blackstone, Tollu and Jameson Range, but these have since been abandoned.

A few nomadic Aborigines roam the region but most of them now live close to the Mission. There are no pastoral stations, but a few cattle, belonging to the Mission, are grazed near the western end of Warburton Range.

Warburton Mission is connected with Laverton, 310 miles (500 km) to the southwest, by a moderately good dirt road. A branch road to the north connects the settlement with Giles Meteorological Station, 132 miles (212 km) to the northeast. Another track connects Warburton Mission with Wingelinna, some 148 miles (238 km) east, near the South Australian border. A minor track joins Warburton Mission with Neale Junction 160 miles (257 km) south. Several bulldozed, straight tracks cross much of the west and southwest part of the Talbot Sheet area. These were put in for geophysical purposes by Hunt Oil Company during their investigation of part of the Officer Basin.

The main track from Laverton, through Warburton Mission and eastward, is part of the road connecting Kalgoorlie with Alice Springs. This road is gradually being improved and is becoming popular as a tourist route.

Graded dirt roads connect Wingelinna with South Australia to the east, and Giles Meteorological Station 100 miles (161 km) to the north-northwest.

A few minor prospecting tracks run south from the Warburton to Blackstone road and give reasonable access to the hilly region in the northern part of the Cooper Sheet area.

Crossing the Bentley Sheet area from south to north is a badly kept road, which connects Warburton Mission, 9 miles (14 km) south of the southern boundary of the Sheet area, with Giles Meteorological Station in the Rawlinson

Ranges. From this a branch road proceeds 235 miles (378 km) west to Carnegie homestead. The only other track in the region is an old track trending approximately northeast from near Scamp Hill to the low hills 20 miles (32 km) southeast of Bedford Range. This track is part of the old route from Warburton Mission to Giles Meteorological Station. It was used before the other road, part of the Gunbarrel Highway, was made to improve access within the Woomera Rocket Range.

Access to areas off the main tracks is generally slow and tedious, being hindered by abundant sand dune fields, patchy thick mulga, and spinifex.

Limited rainfall records are available only from Warburton Mission and Giles Meteorological Station. Warburton Mission has a mean annual rainfall of 8.53 inches (216.6 mm) and Giles Meteorological Station has an average of 7.16 inches (181.9 mm).

At Warburton Mission the annual rainfall since 1941 has ranged from 1.37 inches to 27.19 inches (34.8 to 690.6 mm). It is unreliable and shows no consistent seasonal bias. The generally higher elevation of the country in the Tomkinson Ranges probably attracts slightly more rain than at the two recording stations. Southwestern Mining Company Limited recorded a rainfall of 15.29 inches (388.3 mm) at Wingelinna between August 11, 1966 and August 10, 1967.

Surface water is almost non-existent and consists of occasional rock holes which only contain water for short periods after rain and rapidly become polluted. The capacity of most of these rock holes is only of the order of a few gallons; a large one may contain a few hundred gallons.

ACKNOWLEDGEMENTS

The author wishes to acknowledge the help of the many people and organizations who in various ways aided in the production of this Bulletin. These, in particular, include the Western Mining Corporation Ltd., Southwestern Mining Company Limited, the Native Welfare Department, the Royal Flying Doctor Service, Dr. Storr of the Western Australian Museum for details of the fauna of the region, Mr. Dave Barber our helicopter pilot for a few days, and my wife for assistance with the history of exploration of the area.

FAUNA AND FLORA

Of the large variety of fauna present in the Blackstone Region the birds and reptiles are well known, the mammals moderately well known, and the other groups not known in any detail.

The larger mammals include the Plains (Red) Kangaroo which mostly inhabits the grassy plains around the ranges. In the ranges themselves the Euro (Hill Kangaroo) and the Rock Wallaby are to be found.

The Dalgite (Rabbit-eared Bandicoot), which is extinct in many other parts of the State, is fairly common in this area.

Though rarely seen, the marsupial mole is known and thought to be moderately abundant. Marsupial mice are common and form part of the diet of the Aborigines.

A number of introduced mammals, including rabbit, mouse, dingo, feral cat and camel, inhabit the region. The rabbits favour calcrete or limey gravel soils for excavating their warrens. Their population is controlled mainly by rainfall and locally by Aborigines.

Snakes are not abundant but include Gwardar, Mulga snake, Desert Death Adder and Python.

Various species of Dragon lizard, including the Mountain Devil inhabit the region. In some of the rocky ranges the Ring-tailed Dragon may be found. Skinks are the dominant family of lizards inhabiting the spinifex areas. Geckos, a smaller version of the common variety, are numerous, goannas are not uncommon and in many areas there exists an abundance of small varieties of lizards.

Only one species of frog is known from the area. This is the Water-holding Frog, which, in the dry season, buries itself in creek beds after having filled its stomach with water. It is valued by the Aborigines as a source of water.

The Numbat (Banded Anteater) and the Brush-tailed Possum are thought to have recently become extinct in this area.

Birds which live almost entirely in the ranges include the Top Knot, Galah, Plumed Pigeon (Rawlinson Range only), Zebra Finch, Port Lincoln Parrot and Red-browed Pardalote. Small resident avifauna inhabits mulga and similar bush: included are Babblers, Thornbills, Blue Wrens, Red Cap Robin, Rufous Whistler, Bourke Parrot and the Crested Bell Bird. On spinifex plains, birds are scarce but include the Rufous Grass Wren, the Blue Wren and the White Wren: Emu-wrens (Rufous-Crowned Emu Wren) are to be found on the sand dunes. The Mulga Parrot may be found around gum creeks near ranges. Magpies, crows, eagles and emus are found scattered throughout much of the area.

After rains various nomadic birds arrive. These include the Brown Songlark which lives on grassy flats, and Masked Wood-Swallows, Crimson Chats and Budgerigars which live in wooded country.

Regular migrant birds which arrive in the spring breeding season include the Red-backed Kingfisher and the White-winged Triller.

No books specifically dealing with the natural history of this area have been published. However, more details may be obtained from publications dealing with certain aspects of the natural history of Western Australia (Serventy and Whittell, 1962; Glauert, 1950, 1961; Troughton, 1941).

A surprising density and wide variety of trees, shrubs and smaller plants is to be found in the Blackstone Region. A recent detailed and comprehensive account of the flora of the desert regions is given by Beard (1969).

PHYSIOGRAPHY

The major feature of the physiography of the Blackstone Region is the east-west belt of hills and ranges straddling the 26° parallel and extending from Warburton Mission in the west to the eastern border of Western Australia. The belt continues farther east as the Musgrave Ranges.

To the north and south this belt is flanked by extensive, undulating plains covered by abundant longitudinal sand dunes of the Gibson and Great Victoria Deserts respectively. In the extreme northeast of the region are small portions of the Rawlinson and Petermann Ranges.

More detailed subdivision into seven major physiographic units is possible (Plate 1):

(a) mountain ranges, prominent hills and ridges
(b) widely separated hills and low ridges with intervening plains. The plains may contain variable sand dune cover
(c) alluvial flats. These are confined to the margins of some of the larger ranges
(d) plains with few sand dunes and occasional low outcrop. Frequent dense mulga growth is present
(e) sand dune country
(f) undulating laterite country. Some breakaways, and light dune cover are present usually in valleys
(g) salt lake country.

The distinction between groups (a) and (b) is arbitrary, the latter representing the results of more advanced erosion.

As might be expected the individual characters of the various ranges, hills and ridges depend partly on lithology, although much of their primary form is typical of that produced in arid climates.

Gabbroic rocks form the highest point in the area at Mount Hinckley and are responsible for several of the prominent ranges, the Blackstone and Bell Rock Ranges being examples.

A feature of many of the gabbroic masses is the presence on the hill slopes of large areas of almost black-weathered, large, angular boulders separated by areas of lighter tone. The black-weathered skin on these boulders is only a few millimetres thick and is a type of etching, tending to accentuate primary igneous banding features of the gabbro. The lighter tone is caused partly by the colour of the rocks and also by the presence of abundant small spinifex bushes. Present day weathering of much of the gabbro involves the production, by a process of spalling, of smooth rounded boulders of a light brown or orange tone. This spalling removes the black weathering and hence it is thought that the dark-weathered areas represent relicts of an older weathering.

Acid volcanic rocks generally form rounded hills and prominent, rounded strike ridges. The Warburton Range is the best example. It is formed of strike ridges of acid volcanic rocks with interbanded, more easily weathered, basic volcanics and minor sediments extending intermittently for approximately 50 miles (80 km).

Two prominent features whose trends are noticeably different from the main regional pattern are Barrow Range and Skirmish Hill.

Barrow Range and its extension to the north consists of various acid volcanic rocks with associated agglomerates, intruded by a large volume of granitic material. Skirmish Hill is similarly composed of acid volcanic rocks and intrusive granitic rocks. Both these masses are thought to be roughly oval-shaped cauldron subsidence areas. (Compare the physiographic map (Plate 1) with the simplified regional, solid geology map (Plate 3).)

Granitic rocks of various types form prominent monadnocks or low scattered outcrops. The larger masses weather to form rugged features (Fig. 2), but a few rounded exfoliated surfaces are present (Fig. 3). On these, rounded granite boulders are sometimes found, representing remnants of a previously more extensive, thick exfoliation sheet or a weathered joint system. A good example of this is to be seen at Winburn Rocks in the northwest of the Cooper Sheet area.

Some of the granitic rocks are susceptible to a type of spheroidal weathering which produces a number of thin onion skin type layers. An excellent example

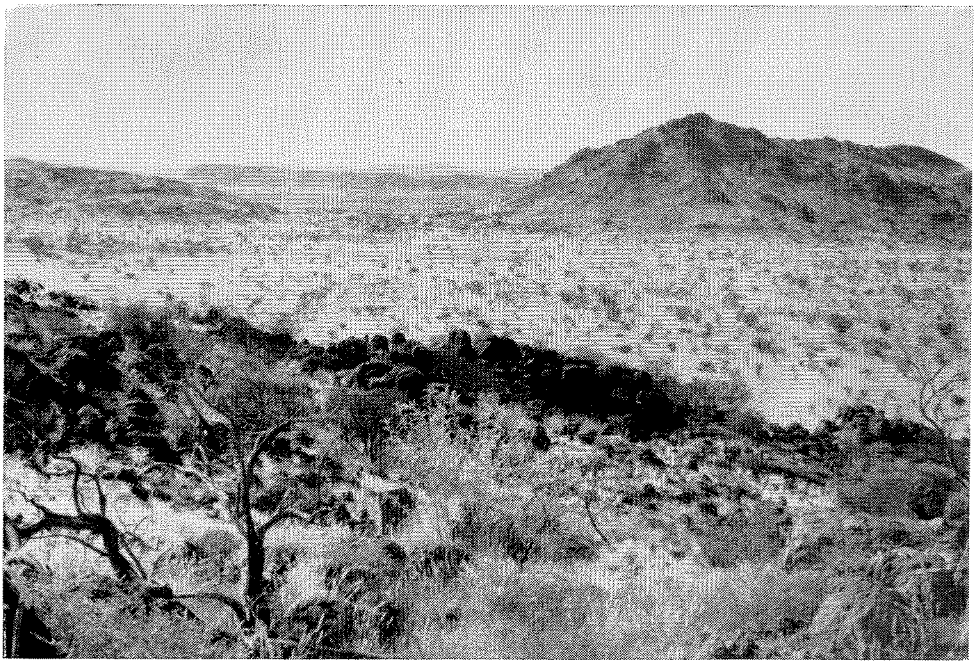

Figure 2. View from Borrows Hill region looking north to the almost horizontally layered gabbros of the Cavenagh Range.

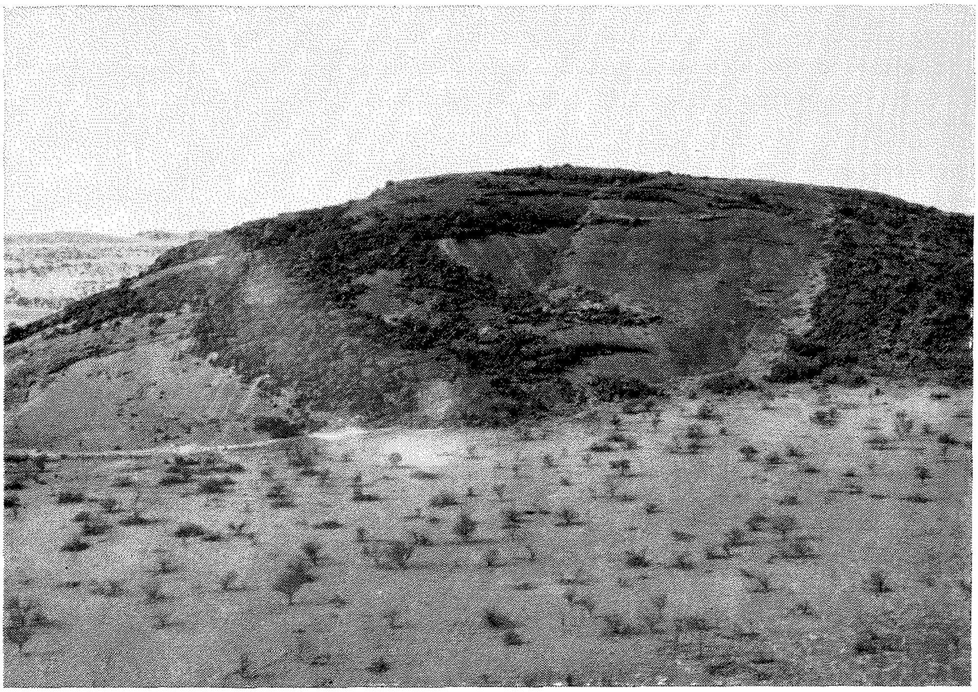

Figure 3. Porphyritic granite forming monadnock in southeast corner of Cooper Sheet area.

of this occurs immediately east of MacDougall Bluff in the Cooper Sheet area (Fig. 4).

The Townsend Ridges and their lateral extensions form a very prominent feature in the Talbot Sheet area. They mark the southernmost extension of the group of hills straddling the 26° parallel and are composed of quartzite and sandstone. West of Warburton Mission the quartzite is covered by superficial deposits while east of Hocking Range it peters out into a thin quartzite intermittently exposed and frequently rising no more than a few tens of feet above sand dune country.

The most noticeable feature of the whole area is Mount Aloysius which, although a few feet lower than Mount Hinckley, is more striking as it rises out of an almost featureless plain. Mount Aloysius consists of granulites and migmatites, rock types which elsewhere form features of very variable elevation.

Alluvial flats are confined to narrow areas at the base of the larger ranges. They are usually confined to small stream valleys and their outwash fans. Only the larger ones have been included on the map (Plate 1).

Large areas of colluvium are present throughout the region. They form the base on which the sand dunes developed and frequently support a dense mulga growth.

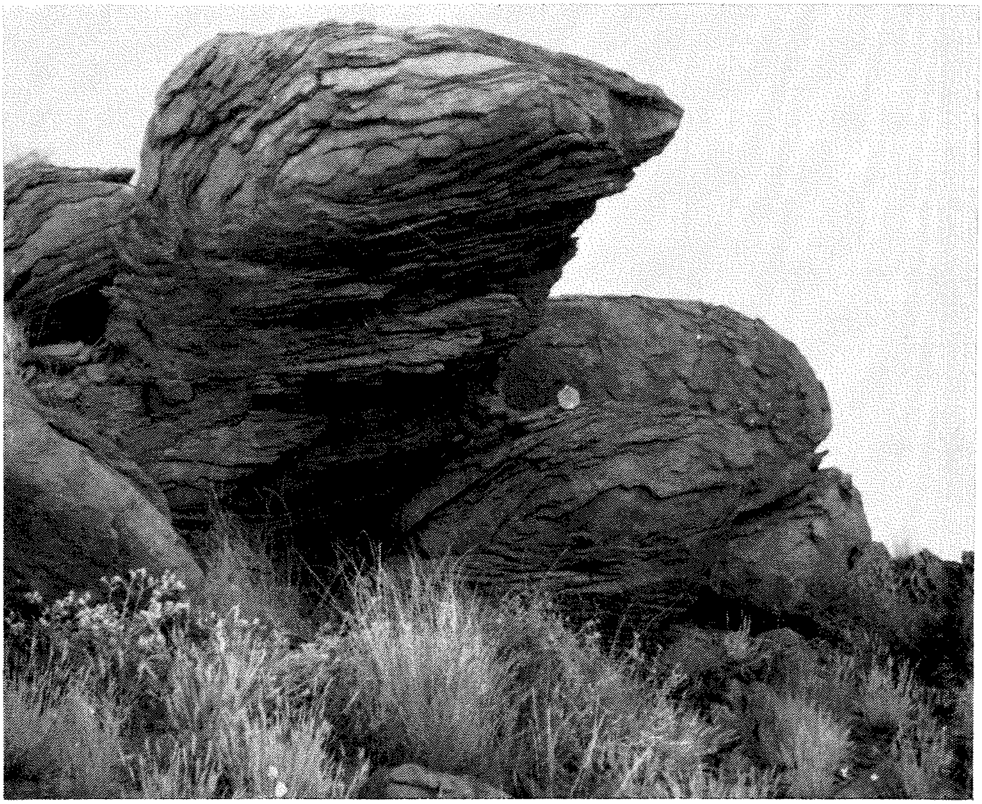

Figure 4. Effects of spheroidal weathering on granite immediately east of MacDougall Bluff, Cooper Sheet area.

Very extensive sand ridge fields cover a large part of the Blackstone region. The sand ridges are from 10 to 60 feet (3 to 18 m) high and up to several miles long. While very few, if any, of the ridges are active at present, many show mobile crests. A sparse covering of spinifex, low shrubs and a few larger trees have fixed the dunes. More detail of the dune morphology and causal wind system is given elsewhere.

The Phanerozoic rocks of the western and southern sections of the area have given rise to extensive undulating laterite country variably covered by dune fields and isolated dunes. Recent erosion has produced a number of low breakaways and exposed the underlying Phanerozoic rocks.

Well-defined drainage is almost entirely confined to the small streams near the main ranges. These connect with an ill-defined old drainage system which is represented by the large calcrete masses (Fig. 77). These calcrete masses are now largely covered by dune fields. All the salt lakes of the area are along these old drainage lines. The majority of these lakes are less than 4 miles

(6.4 km) long. Baker Lake is an exception, being approximately 8 miles (12.8 km) square.

EARLY EXPLORATION

Central Australia was virtually inaccessible to explorers prior to the completion of the Overland Telegraph Line from Adelaide to Darwin in 1872. During the years 1873 to 1875 there was intensive exploration west of the Line, which the explorers were able to follow from Adelaide. The chain of wells and the track which were put in by the contractors remained in use in the centre and north until the establishment of the Flying Doctor Service in the 1930s (Holmes, 1963).

The first explorer to enter this region was William Christie Gosse, who led an expedition organized by the South Australian Government (Gosse, 1874).

His expedition, consisting of 5 Europeans, 3 Afghans, a native boy, camels and horses, set out from Alice Springs on 23rd April, 1873. The main object of the expedition was to explore the area between the Finke River and Fremantle. It was on this expedition that Gosse found Ayers Rock and named it after Sir Henry Ayers, Premier of South Australia. In the Blackstone region he found and named the Barrow Ranges after the Treasurer of South Australia, and the Cavenagh Range after the Commissioner of Public Works.

After reaching an area of extensive sandhills, Gosse decided that it would be perilous to continue and reluctantly turned back towards the Telegraph Line (Calvert, 1896).

The major exploration of the area was carried out by Ernest Giles. Having resigned his position as clerk in the Melbourne County Court, he became a member of several exploring trips to Queensland before leading his own expeditions (Calvert, 1896).

On 4th August, 1873 an expedition consisting of Giles, W. Tietkins, Alfred Gibson and James Andrews, set out from Ross' Water Hole in the Alberga Creek, one of the main tributaries of the Finke River. The party travelled with 20 pack horses, 4 riding horses and 2 small dogs. Giles' aim was to cross to the coast of Western Australia. As with his expedition in 1872, this aim was not fulfilled, but he spent some time travelling in the Blackstone region. It was during this expedition that Gibson disappeared in search of water, and was never seen again. Giles named the area between Rawlinson Range and "the next permanent water that may eventually be found to the west", Gibson's Desert (Giles, 1889).

Giles entered Western Australia on September 30, 1873. He ascended and named Bell Rock, for "the blocks rang with the sound of my iron-shod boots, while moving over them, with such a musical intonation and bell-like clang, that I called this the Bell Rock". He set up a depot camp at the eastern end of the Rawlinson Ranges and from here he explored to the west, southwest and north. Giles named many places in the area, some after well known people, friends and relatives, but a large number after incidents in the expedition. Shoeing Camp was the name given to one place because they spent 4 days there shoeing horses, mending packbags and undertaking general repairs. He named Mount Aloysius after the Governor of Western Australia, Sir A. F. Weld. The Rawlinson Range was named after Sir Henry Rawlinson, President of the Royal Geographic Society of London.

Gosse and Giles were in the area at the same time but although Giles came across Gosse's tracks several times they did not meet. At the beginning of November, 1873 Giles found Gosse's tracks returning to South Australia.

The first recorded earthquake activity in the area was noted by Giles in the middle of the day, on 15th December, 1873. Giles (1889) says "a most pronounced shock of earthquake occurred, the volcanic wave, which caused a sound like thunder, passing along from west to east right under us, shook the ground and the gunyah so violently as to make me jump up . . .". As the wave passed he heard to the east ". . . great concussions, and the sounds of smashing and falling rocks hurled from their native eminences rumbling and crashing into the glen below". Giles later found that a stream in the nearby glen, which had dried up, was once again in full flow. He was puzzled by this and attributed it to the earthquake. At 4 pm on December 23, 1873 Giles felt another earthquake on arrival at camp and was told by Gibson that two shocks had occurred in his absence.

There was little true exploration carried out in the Blackstone region in the early days and although Giles spent some time in the area during his 1873-1874 expedition, most of this was spent wandering around from place to place in search of water and areas off direct lines of traverse were seldom explored.

The next explorer to visit the area was John Forrest, later to become the Hon. Sir John Forrest, K.C.M.G., F.R.G.S., F.G.S. and first Premier of Western Australia. John Forrest was born near Bunbury, W.A., was educated in Perth and at the age of 18 joined the Survey Department. The expedition, which took him through the Blackstone area, was to travel from Champion Bay on the west coast of W.A. to a point on the Overland Telegraph Line (Calvert, 1896). Forrest kept a very precise diary of his trip (Forrest, 1875).

He left Perth on March 18, 1874, with a party consisting of 4 Europeans, 2 natives and 20 horses. The main aim of the expedition was to explore the area from which flow the Murchison, Gascoyne, Ashburton, De Grey and Fitzroy rivers. Consequently he only passed through the Blackstone area, more or less on the 26° parallel, taking about 2 weeks in the process. Forrest also spent time looking for water in the area, and named several of the waterholes in the Warburton Range region. He came across tracks of Gosse from 12 months before and observed by their condition that there had been little rain during that preceding period. He also found evidence that Giles had been in the area and observed that Gosse and Giles were only a few miles from each other at the one time but did not meet. Forrest named Elder Springs after his friend the Hon. Thomas Elder.

Giles passed through the area from west to east in 1876, while returning to Adelaide after his trans-Australia trip of 1875. His intention was to ascertain the extent of the Gibson Desert beyond the Alfred and Marie Range, which he named, but which he had been unable to reach on his journey in 1874 (Giles, 1889). On reaching the Alfred and Marie Range he felt that the exploring part of his journey was over, having twice traversed Australia.

PREVIOUS GEOLOGICAL INVESTIGATIONS

Part of an Aboriginal tale from this region relates in general to the belt of hills straddling the 26° parallel and in particular to Lake Harry in the southeast portion of the Bentley Sheet area. This dry lake is taboo to the Aborigines. It is related that should a man dig in this lake all the hills in the region would collapse. This is because he would have released a gas, which by way of a series of subterranean tunnels, connected to the lake, provides the pressure necessary to support these hills. The same gas is also said to affect the minds of men and make them go mad.

This is quite an interesting early geological theory and is perhaps based on the fact that a small hill immediately to the northeast of Lake Harry carries quartzite, which when broken gives off a strong, sickly, smell of hydrogen sulphide produced from the breakdown of enclosed sulphides.

Talbot and Clarke (1917) made a more thorough geological study of the Warburton Range area in 1916 and their report includes a summary of earlier investigations. Later work includes a petrographic study of some of the Warburton Range rocks by Fletcher (1932, 1933), studies of the stratigraphy and regional correlations by Forman (1932, 1933), Sofoulis (1962a) and Horwitz and Sofoulis (1963), early investigations of the Giles Complex (Sprigg and Wilson, 1959), and evaluations of the water supplies by Sofoulis (1962b) and Farbridge (1968).

Other studies include a regional geological and geophysical survey of the Officer Basin by the Hunt Oil Company and detailed prospecting for copper by Western Mining Corporation Ltd. in the Warburton Range area. Southwestern Mining Company Limited undertook regional mapping and detailed prospecting for nickel and copper throughout most of the Giles Complex and are evaluating a lateritic nickel deposit at Wingelinna. Westfield Minerals undertook some exploration of a vanadium prospect in the Jameson Range.

Much of the area has been covered by a regional gravity survey by Lonsdale and Flavelle (1963).

The northeast corner of the region has been studied by Wells and others (1964) and Forman (1966) in relation to the Amadeus Basin.

A systematic geological investigation of the Scott, Cooper, Bentley and Talbot 1:250,000 Sheet areas was undertaken by the Geological Survey of Western Australia between 1966 and 1968. A simplified geological map and a structural sketch map are given in Plates 3 and 2 respectively. The stratigraphic column for the whole region is given in Table 1.

Table 1. Stratigraphic Column of the Blackstone Region

Age		Group	Formation	Lithology	Thickness (feet)	Remarks
Cainozoic	Quaternary			Alluvium and river gravel	10–20	Aquifer
				Lake deposits. Clay and gypsum		
				Eolian sands	up to 60	Occurs as sheets or as dune fields. Holds water after rain, but poor aquifer
				Partly consolidated silty sand		Sheet form deposits
	Tertiary			Calcrete and calcareous gravel with opaline silica	?50–100	Probably very good aquifer
				Laterite and lateritic gravel	?25–50	Mostly residual on Phanerozoic
				UNCONFORMITY		
Palaeozoic	Permian			Sandstone, porcelanous siltstone and pebble beds		Fluvioglacial and glacial deposits containing abundant striated pebbles
				UNCONFORMITY		
	?Ordovician		Table Hill Volcanics	Basalt, pumice, agglomerate and rare tuff		Correlated with Kulyong Volcanics of South Australia
				UNCONFORMITY		
U. Proterozoic				Glacial deposits. Boulder beds and sandstone. Chocolate, cream and green shale		
M. Proterozoic	Bentley Supergroup		Townsend Quartzite	Quartzite, sandstone and pebble beds	840	Well-defined bedding. Cut by thin quartz veins
				?UNCONFORMITY		
		Mission Group	Milesia Formation	Basalt, conglomerate, quartzite, greywacke and shale	9,500	
			Lilian Formation	Shale, tuff, basalt, chert, conglomerate and rare dolomite	3,000	
			Frank Scott Formation	Thin bedded dolomite, siltstone chert and sandstone	800	Carries stromatolites
			Gamminah Conglomerate	Conglomerate and coarse, cross-bedded sandstone	1,500	Development restricted to small region north of Frank Scott Hill

Age		Group	Formation	Lithology	Thickness (feet)	Remarks
Middle Proterozoic	Bentley Supergroup	Cassidy Group	Miller Basalt	Basalt. Mostly epidotic and vesicular	2,400	Numerous flows, mostly 25 ft to 50 ft thick
			Hilda Rhyolite	Porphyritic rhyolite	1,300	Single cooling unit
			Warubuyu Basalt	Epidotic, vesicular and amygdaloidal basalt	500	Several flows
				Shale, siltstone, marl and tuff	400	
			Thomas Rhyolite	Porphyritic rhyolite	1,000	Possibly three cooling units
			Gurgadi Basalt	Epidotic, vesicular and amygdaloidal basalt	1,600	Several flows
				Fine-grained silty sedimentary rocks Some sandstone	300	
			Gombugurra Rhyolite	Porphyritic rhyolite	850	Probably single cooling unit
				Fine-grained silty sedimentary rocks Some sandstone and pebble beds	150	
			Wururu Rhyolite	Porphyritic rhyolite	1,800	Probably single cooling unit. Group is unconformable on Pussy Cat Group
				Porphyritic acid volcanic rocks Minor basic volcanics		Termed Skirmish Hill volcanic association and preserved in a probable cauldron subsidence area
				Porphyritic acid volcanic rocks Some "white", pyritic rhyolite Devitrified obsidian with abundant perlitic cracks Agglomerate of acid volcanic fragments Feldspathic, grey-green tuff with thin conglomerate containing rhyolite pebbles Quartzite and minor acid lava and tuff		Collectively termed the Palgrave volcanic association and preserved in a probable cauldron subsidence area

Age	Group	Formation	Lithology	Thickness (feet)	Remarks
Middle Proterozoic Bentley Supergroup			Porphyritic rhyolite. Some "white" pyritic rhyolite. Abundant flow banding Basalt, and agglomerate composed of basic volcanic fragments Felsite. Fine-grained, saccharoidal rock. Altered Ɛsa		Collectively termed the Scamp volcanic association and preserved in a probable cauldron subsidence area
	Tollu Group	Hogarth Formation	Basic volcanics		Group is unconformable on granulites and gneisses
		Smoke Hill Acid Volcanics	Rhyolites and minor agglomerates		
		Mummawarra-warra Basalts	Epidotic vesicular basalts Rare tuffs		Probably equivalent to Pussy Cat Group in west
		MacDougall Formation	Quartz pebble conglomerate and sandstone	50–250	
	Pussy Cat Group	Glyde Formation	Basic, epidotic, amygdaloidal lava, tuff, shale, siltstone and dolomite		Regionally metamorphosed in western outcrop
		Kathleen Ignimbrite	Ignimbrite, largely welded. Carries undistorted shards in upper 50 ft	approx. 1,000	Much flow banding and many flow lineations. Could be rheoignimbrite in lower parts
			Amphibolite and garnet amphibolite. Originally amygdaloidal basic lavas		Occurs as small plugs and possible flows in northeast of Sheet area, and as lava flows in southeast
			Quartzite and quartz-muscovite schist. Well bedded. Relict cross-bedding		Unconformable on gneisses mainly confined to Bentley Sheet area

Age	Group	Formation	Lithology	Thickness (feet)	Remarks
		Dean Quartzite	Quartzite. Minor phyllite		Possible equivalent to quartzite and quartz-muscovite schists of Bentley Sheet area, Dean Quartzite and Mount Harris Volcanics interdigitate
		Mount Harris Volcanics	Acid and basic volcanics with minor sandstone and conglomerate. Sheared		
			Granulites. Mainly well banded. Some migmatite. Contain microcline microperthite		Probably largely sedimentary origin
			?UNCONFORMITY		
			Granulites. Poorly banded. Mainly carry orthoclase microperthite		Probably dominantly igneous origin

Note: 1 foot = 0.3048 metres

CHAPTER 2

The Older Basement Rocks of the Musgrave Block

DEFINITION OF THE MUSGRAVE BLOCK

The Precambrian portion of the area, occupying some 9,700 square miles (25,120 km^2), is part of a much more extensive Precambrian outcrop in central Australia covering an area of approximately 56,000 square miles (140,000 km^2). It has been variously termed the Pitjentara Shield (Chewings, 1935; Ellis, 1937), the Pitjandjara Archaean Block (Johnson, 1963), the Musgrave-Warburton Block (Wilson, 1954), the Musgrave Block (Wilson, 1953; Hills, 1965; Thomson, 1966) and the Musgrave-Mann Complex (Brown, and others, 1968). The term Musgrave Block seems to be most generally used and is favoured as a general term in this report. Provided that strict definitions are not applied to the term "Block" or its limits, the term Musgrave Block is a convenient way of referring to a general area in central Australia which is bounded on the south by the younger sediments of the Officer Basin and on the west and northwest by younger sediments of the Canning Basin. To the north are the Phanerozoic sediments of the Amadeus Basin while to the east lies the Great Artesian Basin. The Musgrave Block is probably connected in surface outcrop to the Precambrian of the Kimberley area, and to the Arunta Block of the Northern Territory by way of a narrow strip of country on the eastern side of the Canning Basin.

GRANULITES AND RELATED ROCKS

BASIS FOR SUBDIVISION

The charnockitic and associated high-grade regional metamorphic rocks of the Musgrave Block have been the subject of much study by Wilson (1947, 1950, 1952, 1953, 1954, 1959, 1960a,b). He broadly divides these high-grade metamorphics into two classes; an older group of orthogneisses and paragneisses, and a younger group of charnockitic granodioritic and adamellitic rocks which intrudes the older group. Wilson regards the younger group as derived palingenetically from the older group. His subdivisions can be extended into the Blackstone Region.

Current work on the granulites of the eastern part of the Musgrave Block is being undertaken at Adelaide University and at the Australian National

University. Geochemical investigations have been made, also in the eastern part of the Musgrave Block, by Lambert and Heier (1968).

Age determinations and Sr isotopic studies have been made by Arriens and Lambert (1969) on granulite facies gneisses from near Ernabella Mission. From these rocks an isochron of 1,380 ± 120 m.y. was obtained which is very close to the figure of 1,390 ± 130 m.y. obtained by Compston and Arriens (1968) for, presumably, other gneisses from the same area.

Several areas of high-grade metamorphic rocks are exposed in the Bentley, Scott and Cooper Sheet areas, in particular at Mount Aloysius; between Lightning Rocks and Winburn Rocks; at Mount Holt; and southeast of Michael Hills. These rocks have developed in the high amphibolite and granulite facies, but in detail their metamorphic history is complex. They may be subdivided into two main units:

1. poorly banded granulites and related rocks
2. well banded granulites and related rocks.

Some evidence is available to suggest that the well banded granulites and related rocks are metamorphosed sediments and that they were deposited unconformably on at least some of the poorly banded variety. The suspected unconformity may be seen approximately 4 miles (6.4 km) southeast of Mount Holt. It is deduced to be present at the level at which the Michael Hills Gabbro was intruded. A little below the base of the Michael Hills Gabbro are several disconnected masses of garnetiferous quartzite in the poorly banded granulites. Banded quartzite is found in a structurally similar position on the northern side of the Hinckley Range 10 miles (16.0 km) southeast of Mount Fanny. These may represent basal sandstones, but no confirmation is available and the evidence for the presence of this unconformity is scanty.

POORLY BANDED GRANULITES AND RELATED ROCKS

MICHAEL HILLS REGION

Below the Michael Hills Gabbro in the area immediately north and northeast of Latitude Hill is a heterogeneous assemblage of acid gneisses. In the field the rock types may be subdivided into banded gneisses, grey, green and red gneisses with minor amounts of somewhat sheared graphic granite, and garnetiferous quartzites which are possibly fragments of the well banded granulites. Some of the gneisses are charnockitic.

A sample of the high-grade gneisses collected at one locality is pale green with a greasy texture suggesting charnockitic affinities. The colour fades rapidly on exposure and after several weeks the rock is a uniform light grey. It consists of a granular aggregate of perthite and quartz with accessory brownish-green amphibole, brown amphibole, red-brown biotite, opaques, zircon and apatite. The perthite consists of approximately equal proportions of plagioclase and untwinned potash feldspar, with the former occurring as abundant rods. No plagioclase occurs as discrete crystals. The brownish-green amphibole and some of the red-brown biotite are secondary after brown amphibole. The rock shows moderately well developed flaser structure. However nearly all the quartz grains and a large proportion of the perthite have been replaced by a fine-grained mosaic, without destruction of the older flaser structure.

Similar rocks are common throughout the area and vary according to the degree of development of flaser structure and the intensity of the younger mylonitization. In the vast majority the type of perthite and mafics is similar.

One sample from approximately 3 miles (4.8 km) north of Latitude Hill shows the relationship of the flaser structure to the mylonitization very well. The older mineral banding, apparent as mafic bands and flaser structure, is crossed at a high angle by the mylonite bands with partial reorientation of the primary banding.

A banded mafic augen gneiss from the same locality shows poor mineral banding and no flaser structure. It consists of augen of plagioclase, quartz and minor potash feldspar (rarely perthitic), with irregular mafic bands of green-brown hornblende, opaques, abundant apatite, red-brown biotite and very rare relict pale green clinopyroxene. Thin mylonite bands cut the rock and much granulation has occurred along grain boundaries.

Immediately southwest of Latitude Hill a porphyritic, unsheared, charnockite occurs. The rock underlies the Michael Hills Gabbro and is structurally at the same level as the granulites and related rocks northeast of Latitude Hill. The rock consists of antiperthite, microcline perthite and quartz, with clots of brown hornblende, hypersthene, opaques and apatite, and zircon. Exsolved rods of clinopyroxene occur in the hypersthene. The feldspars are present in approximately equal proportions and hence the rock may be termed a hornblende-hypersthene-adamellitic charnockite. It does not show either flaser structure or the effects of the younger mylonitization.

Cutting the acid gneisses in the Michael Hills region are a few basic dykes. These have a granular texture and consist of orthopyroxene, clinopyroxene, labradorite and accessory red-brown biotite and minor opaques. Both pyroxenes are unaltered but some of the plagioclase grains show bent twin lamellae. Mylonite bands, common in the host rocks, are absent. The assemblage closely resembles that displayed by much of the granular basic igneous material related to an early phase of the Giles Complex.

AREA BETWEEN MOUNT HOLT AND MOUNT GOSSE

A variety of granulites and acid gneisses, including some closely resembling those beneath the Michael Hills Gabbro, are present between Mount Holt and Mount Gosse in the Scott Sheet area. Field evidence shows that much of the region has been subjected to at least two periods of folding.

The rocks carry quartz and orthoclase perthite typical of the granulites and related rocks beneath the Michael Hills Gabbro. Some show a few per cent of

Figure 5. Polished hand specimen of charnockite gneiss showing well developed flaser structure: from 4 miles southeast of Mount Holt, Scott Sheet area.

discrete plagioclase and minor myrmekite. Accessories vary: some rocks contain coexisting orthopyroxene and clinopyroxene; others orthopyroxene alone. Red-brown biotite and green amphibole are sometimes present but appear to be secondary after pyroxenes. Minor accessories may include garnet, opaques, apatite and zircon.

Four miles (6.4 km) southeast of Mount Holt is a particularly good example of charnockitic gneiss with well developed flaser structure (Fig. 5). It consists of blue-green orthoclase perthite and smoky quartz with accessory pleochroic hypersthene, opaques, red-brown biotite, apatite and small rounded zircons showing multiple overgrowths. Post-flaser structure mylonitization has produced a finely crystalline mosaic of the quartz bands and granulated the grain margins in the perthite-rich areas. Partial granulation of the hypersthene has also occurred with the production of a rim of finely granular hypersthene which is often accompanied by small laths of red-brown biotite.

More intensely mylonitized gneisses are very common in this general region. The mylonitization is accompanied by, and probably responsible for, alterations affecting the mafic minerals. The alterations involve the replacement of mafic minerals by other anhydrous mafics and sometimes biotite. The lack of amphiboles in this group may only reflect the availability of water during the process and hence need not be another age of mylonitization distinct from the type mentioned above, which is frequently accompanied by the transformation of pyroxenes to green hornblende and biotite.

A form of alteration accompanying the mylonitization, and common in the Mount Gosse region, consists of the replacement of mafic minerals by garnet. One example showing this feature well consisted, before the mylonitization, of plagioclase, orthoclase and quartz with accessory hypersthene, red-brown biotite, opaques, apatite and zircon. Subsequent shearing sheathed the biotite laths with very fine-grained granular garnet. The hypersthene is similarly sheathed, but frequently there exists an intermediate zone between the hypersthene and garnet consisting of fine-grained biotite, opaques and possible cordierite.

A very coarse augen gneiss forms the eastern portion of Mount Gosse. It consists of augen of red orthoclase microperthite, up to 2 inches (5.0 cm) long, in a groundmass of granular orthoclase, plagioclase, quartz and a small proportion of mafic minerals in concentrations. Many narrow mylonite bands cut the rock. Individual aggregates of mafic minerals, all of which are very finely granular, consist of varying proportions of either pale green clinopyroxene and opaques, or garnet, clinopyroxene and opaques. Sphene may accompany both assemblages and appears to have been derived at least in part from the opaques. This mode of occurrence strongly resembles that of the mafics in nearby rocks and suggests that the mafic assemblage has been derived from pre-existing mafics as a result of adjustment to new conditions imposed by the mylonitization. The two different assemblages suggest a source from two different mafic minerals (perhaps hypersthene and the brown amphibole respectively) although no remnants of the original minerals remain.

Large areas of rocks of granitic composition which do not display flaser structure occur in several areas. These are probably older than the Tollu Group. An example from the western half of Mount Gosse is a modified porphyritic granite, intrusive into mylonitized augen gneiss forming the eastern portion of the mass. The granite consists of plagioclase, quartz and orthoclase with green-brown hornblende, opaques and apatite. Subsequent alteration, possibly related to the mylonitization, has caused the replacement of much of the hornblende by either granular garnet, garnet with biotite and opaques, or a symplectic intergrowth of garnet and cordierite.

SUMMARY

These gneisses are predominantly acidic and show an early phase of high-grade regional metamorphism with the development of well-defined mineral banding including flaser structure. The presence of relict orthopyroxene and clinopyroxene together with abundant microperthite carrying a high percentage of plagioclase, suggests that metamorphism took place in the granulite facies. The colour of some of the samples in the field suggests that they have charnockitic affinities and this is confirmed by the occasional presence of relict pleochroic hypersthene.

These gneisses have been subjected to a later period of mylonitization, possibly responsible for some of the mineralogical changes. These changes are adjustments to lower facies conditions and involve the replacement of brown amphibole by a green variety, and the replacement of pyroxenes by green amphiboles and biotite. However the dynamic effects are the most noticeable in thin section.

WELL BANDED GRANULITES

Well banded granulites and related rocks are found in several areas. The principal locations include Mount Aloysius and the area between Winburn Rocks and Lightning Rocks. They are complexly folded and frequently migmatized. Many of the banded granulites are now represented by relict masses, some of which may be seen northwest of Mount Gosse, between Mount Fanny and Mount Daisy Bates and on the northeastern side of the Jameson Range.

Migmatization of these rocks has been quite extensive in the Mount Aloysius and Mount Holt regions. The granitic material migmatizing the granulites is generally a leucocratic porphyritic granite with distinctive bronzy-weathering phenocrysts of potassic feldspar.

A variety of igneous and sedimentary rocks is probably represented in the banded granulites. On the whole the composition is dominantly acidic; basic rocks are rare and confined to narrow bands.

The basic "granulitic" rocks forming much of the Hinckley Range are considered to be genetically related to the Giles Complex and referred to as marginal facies rocks, and are not part of the granulite suite. Some bands of basic rock, of similar mineralogy to the marginal facies rocks, occur in the granulites, and without further work along the lines suggested (p. 149) it would be impossible to categorize these rocks satisfactorily.

The granulites of the northwest portion of the Cooper Sheet area are well foliated and lineated quartzo-feldspathic rocks, with variable amounts of mafics. Their most noticeable field characteristics are their fine banding, well developed flaser structure and presence of dark red garnets up to half an inch (1.3 cm) in diameter (Fig. 6). Migmatization comparable with that affecting similar rocks at Mount Aloysius is almost absent and has only produced minor quartz-feldspar-muscovite pods.

Figure 6. Well banded garnet-sillimanite granulite, near Cohn Hill, Cooper Sheet area.

Immediately south of Lightning Rocks, thinly banded leucocratic and mafic granulites are exposed. The leucocratic varieties consist of granular quartz mosaic with up to 25 per cent microcline microperthite. Scattered throughout the rock are abundant minute sillimanite needles and small irregular grains of opaques. Other accessories include zircon and a trace of biotite.

One of the associated dark bands consists of embayed crystals of pyroxene, (both orthopyroxene and clinopyroxene are present, with the former predominating) poikiloblastically enclosing opaques, quartz and some pale green actinolitic amphibole. The pyroxenes are set in a granular matrix of cordierite, quartz, opaques and actinolite.

Individual bands in other granulites of the same general area may consist of the following assemblages:

1. quartz-plagioclase-potassic feldspar
2. quartz-plagioclase-potassic feldspar-hypersthene

3. quartz-plagioclase-potassic feldspar-biotite
4. quartz-plagioclase-potassic feldspar-hypersthene-garnet
5. quartz-potassic feldspar-sillimanite ± garnet
6. quartz-garnet-sillimanite-spinel ± biotite.

In all the above assemblages zircon, apatite, and graphite may occur as accessory minerals. In the last two assemblages cordierite may occur as a secondary mineral.

Some of the sillimanite shows rimming by potash feldspar, possibly indicating derivation from muscovite. In other specimens the sillimanite may be partially or completely pseudomorphed by a fine-grained symplectic intergrowth of dark green spinel and cordierite. Both minerals in the symplectite have been identified by X-ray powder diffraction. The spinel has a cell edge of 8.162 ± 0.002 Å (Government Chemical Laboratories determination). Sillimanites so altered are always in close proximity to garnet which shows peripheral replacement by cordierite. The latter generally carries vermicular inclusions of another colourless mineral with a similar refractive index. It is tentatively identified as quartz. Many examples of partially replaced sillimanite grains exist showing replacement only on the garnet-facing side of the sillimanite. The relationships indicate that both the sillimanite and the garnet must be involved in the reaction since no garnet partially replaced by cordierite exists without there being sillimanite in close proximity. Also no partially replaced sillimanite exists without there being garnet nearby which shows a rim of cordierite. The reaction is indicated by the following equation:

sillimanite + garnet → cordierite + spinel + ?quartz

The garnet was probably an almandine with a moderate pyrope content, hence it may be expected that the cordierite is moderately rich in iron.

This reaction is particularly well illustrated in a nodule from this locality. The original composition of the nodule appears to have been sillimanite and garnet with very minor opaques (probably graphite) and a trace of granular green spinel. The reaction has almost entirely used up the garnet which only remains as small corroded grains in a medium-grained mosaic of cordierite carrying vermicular inclusions which are probably quartz. This assemblage is surrounded by the spinel-cordierite symplectite "eating" into the sillimanite.

Red-brown biotite is frequently closely associated with the cordierite surrounding the garnets. Its presence may be accounted for by the additional reaction:

sillimanite + garnet + potash feldspar + silica ⟷ cordierite + spinel + biotite

Cordierite in the granulite facies is generally thought to be stable under conditions of deficient shearing stress. Hence in those rocks with well developed flaser structure, but with no oriented fabric associated with the cordierite, the cordierite could only have been produced after the shearing which produced the platy quartz.

SUMMARY OF GRANULITE HISTORY

The petrographic and structural relations exhibited by the granulites and related rocks forming the pre-Tollu Group "basement" indicate that they have undergone a complex series of processes. Some of their structural features may be recognized over large areas, and, without further contradictory evidence, may be used tentatively to help establish a sequence of events.

This sequence, in the northeast part of the Cooper Sheet area, could well have begun with the unconformable deposition of dominantly arenaceous sediments on an acid igneous rock basement of unknown metamorphic state. The latter is exposed in the core of the Michael Hills anticline below the Michael Hills Gabbro. The assemblage was intruded by some acid igneous bands in the Mount Aloysius region and elevated to the high pressure-temperature conditions of the granulite facies. During this period shearing stress was apparently active throughout all the region with the consequent development of flaser structure and perhaps also the augen gneisses of eastern Mount Gosse.

Granitic material was emplaced in the Mount Gosse region and minor granitic veins were intruded near Michael Hills. This occurred with the falling off of the shearing stress but probably while pressure-temperature conditions remained high.

Another, areally extensive period of shearing followed, whose main effect was the production, by mylonitization, of granular quartz and feldspar without the complete destruction of the older flaser structure. The mafic minerals suffered both mechanical breakdown and replacement by other species, especially garnet, indicating high pressure-temperature conditions.

After the mylonitization had ceased, an adamellitic charnockite was emplaced in the area south of Latitude Hill. The minerals in this charnockite show no preferred orientation or mylonitization and indicate high pressure-temperature conditions with no shearing component.

Cordierite is common in the western part of the Cooper Sheet area between Winburn Rocks and Lightning Rocks. It is a post-flaser structure development. Neither the cordierite nor the host rocks show the effects of the mylonitization, and as these rocks are correlated with similar rocks at Mount Aloysius it must be assumed that the effects of the mylonitization did not extend as far west as Lightning Rocks. The time of production of the cordierite is not certain, but it must have been produced after the cessation of the regional stress that produced the flaser structure and while pressure-temperature conditions were in the granulite facies. This may have been at the end of the time of development of the flaser structure or at any subsequent time before the emplacement of the adamellite at Lightning Rocks. It is considered unlikely that the Lightning Rocks adamellite could have caused the production of cordierite by contact metamorphism. In the nearby granulites, hercynite, a characteristic mineral of the granulite facies, is present in close association with cordierite. The adamellite does not appear ever to have reached the necessary pressure-temperature conditions.

The granulite complex is seen as the product of a period of high pressure-temperature conditions, acid igneous injection and variations in shearing stress intensity. No continuity of physical conditions prevailing throughout the time of development of the granulite complex can be guaranteed, but this may well have been the case. Two periods of shearing, one producing flaser structure, the other being a regional mylonitization, seem well established and both of these took place under conditions of high pressure and temperature. Possibly at least three periods of acid igneous rock emplacement occurred during the granulite complex formation.

A diagrammatic representation of the physical conditions prevailing during the development of the pre-Tollu Group "basement", together with the suggested periods of igneous activity is given in Figure 7.

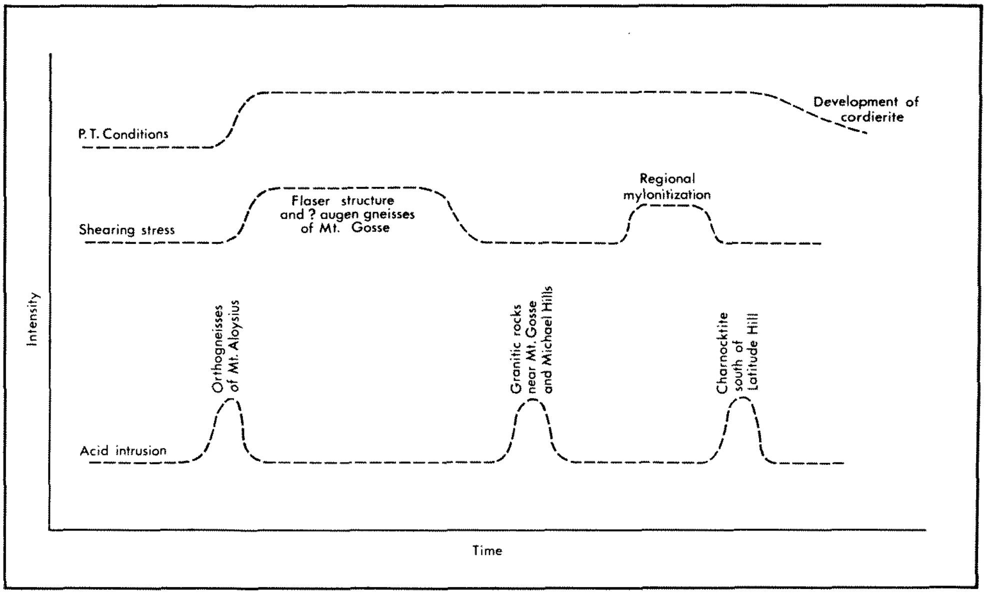

Figure 7. Hypothetical conditions prevailing during development of granulite of the Blackstone Region.

An important feature of the interpreted regional structure of the granulite suite is its two-fold subdivision into a lower poorly banded group and an upper well banded group. The lower group is characterized mineralogically by the presence of orthoclase microperthite while the upper unit carries only microcline microperthite. Between the two groups is a poorly developed zone of migmatites which is not always present.

The orthoclase-type granulite is thought to have been formed low down in the structural succession and to have undergone more intense geological processes than the structurally higher microcline-type granulites. The most important of these processes would probably involve higher temperatures and much higher pressures.

Since the intrusion of the Giles Complex, the region of orthoclase granulites below the Michael Hills Gabbro has been uplifted by some 50,000 to 100,000 feet (15,200 to 30,500 m) which would indicate that these granulites were involved in likely burial pressures of up to 9 Kb. Smaller depths of burial would be indicated for microcline granulites which lie at a higher structural level.

A similar structural arrangement of potassium feldspar types is noted by Pu and Fu-Tao (1965) in the Tsining Metamorphic Series. In their four-fold subdivision of this series the upper part carries microcline, the middle orthoclase and microcline, and the lowest part orthoclase only.

WESTERN PART OF THE BASEMENT

An extensive area of poorly exposed crystalline rocks occupies the northeast portion of the Bentley Sheet area and the western part of the Scott Sheet area north of Jameson Range. These rocks are noticeably different from the granulites and related rocks farther east and southeast, but appear to grade into them. They are therefore regarded as part of the pre-Tollu Group "basement".

Much of the area under discussion consists of adamellite gneiss and migmatite in which lie isoclinally and recumbently folded remnants of quartzite and quartz-muscovite schist.

The gneisses and migmatites which form the basement to the quartzites and quartz-muscovite schists have undergone a complex series of events which is not fully understood on account of the very poor exposure. Basically it appears that the sequence of events started with the formation of a high-grade metamorphic complex probably equivalent to the granulites to the southeast in the Scott and Cooper Sheet areas. These metamorphics were intruded by a very large and extensive mass of hornblende-biotite adamellite. Subsequently, orthoquartzites and argillaceous sandstones were laid down unconformably on the granulite-adamellite complex and the whole was recumbently folded and regionally metamorphosed at moderate grade. The granulites were consequently down-graded, the adamellite developed a gneissic texture, and the sediments were converted to quartzite and quartz-muscovite schist. Neither the sediments nor the isoclinal folding and accompanying metamorphism is recognized in the pre-Tollu "basement" in the Cooper Sheet area.

The above suggestion of the likely sequence of events may be illustrated by descriptions of a few of the main rock types.

ADAMELLITE AND RELATED ROCKS

A small mass of unsheared adamellite occurs in the region of Gungungmura Waterhole in the northeast of the Bentley Sheet area. It consists of small mafic clots in a medium-grained groundmass of poorly twinned oligoclase, orthoclase perthite and quartz. The mafic clots carry hornblende, biotite, ilmenite and minor garnet, sphene, apatite, zircon, hematite and ?monazite. The hornblende

(α = straw, β = dark brownish green, γ = 1.726 = dark bluish green) occurs as unoriented, irregularly shaped grains with enclosures of ilmenite, quartz, zircon, apatite, and biotite. Biotite (γ = 1.693 = dark brown) exists as independent laths or occasionally as a replacement of hornblende.

Approximately 500 yards (450 m) to the west is a moderately well lineated and foliated acid gneiss (biotite-hornblende-adamellite gneiss) which mineralogically closely resembles the hornblende-biotite adamellite and was apparently derived from the latter by simple shearing accompanied by minor mineralogical changes. In the gneiss, the mafic clots are less well defined than in the previous example, having been somewhat stretched by the deformation. They consist of biotite (γ = very dark brown), hornblende (α = straw, β = dark green, γ = 1.712 = blue green), sphene, apatite, zircon and ? orthite. The groundmass consists of plagioclase, microcline, quartz and minor myrmekite. The gneiss has probably been derived from the adamellite and the following mineralogical changes are suggested by a comparison of the petrography of the two rock types.

hornblende-biotite adamellite	Shearing	Biotite-hornblende-adamellite gneiss
hornblende	⟶	biotite. Increase in size of laths.
ilmenite	⟶	sphene. Reaction requires calcium which may be obtained from hornblende on conversion to biotite.
orthoclase perthite	⟶	microcline.
orthoclase + oligoclase	⟶	myrmekite (small quantity).

Similar adamellitic gneisses occur farther south at Mitika Waterhole. These gneisses are extremely well lineated, but display only a poor foliation. The lineation is defined by elongated biotite aggregates. The gneisses are cut by thin, irregular biotite-bearing pegmatites crudely parallel to the poor foliation. Thin quartz veins cross-cut the mass. The leucocratic minerals of the gneiss consist of microcline and oligoclase in approximately equal amounts, and quartz. Biotite (γ = very dark brown to black) is the only other essential constituent. Accessories include fluorite as frequent irregularly shaped grains, and small euhedral to subhedral crystals of zircon.

At Lightning Rocks, in the northwest of the Cooper Sheet area, is a mass of hornblende-biotite adamellite with patchy foliation. This resembles, in the field, some of the foliated acid gneisses in the northeast of the Bentley Sheet area, though it is of somewhat different composition. On the south side of Lightning Rocks the adamellite is in contact with the older, well banded granulites. The contact is probably an intrusive one.

The rock is somewhat porphyritic and moderately foliated, though this is patchy. It is crossed by many thin shears which healed before the mass was intruded by abundant aplite veins. The latter carry xenoliths of the host rock. Locally the veins are abundant and ramifying, and the association may be termed a net-vein complex.

Microcline, plagioclase (An_{33}), quartz and myrmekite are the main constituents of the rock, with accessory hornblende, biotite, opaques, apatite and orthite. The microcline is generally crowded with rounded and vermicular inclusions of quartz, often in optical continuity throughout much of the host crystal. In shape, the inclusions resemble the quartz in the myrmekite, but are larger. The hornblende (α = straw, β = dark green, γ = dark blue green) usually occurs as ragged

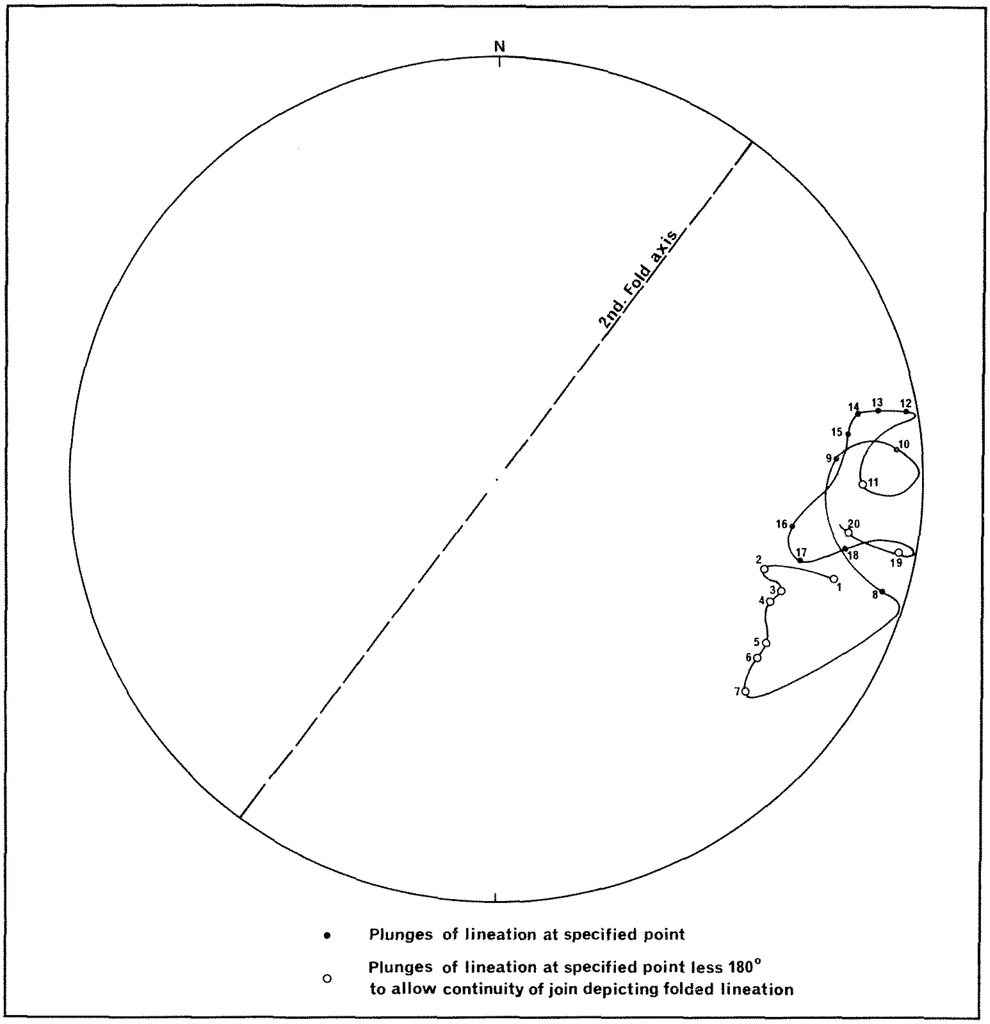

Figure 8. Stereographic plot of folded single lineation represented by its orientation at 20 consecutive points each separated by a distance of 3 inches except 8 and 9 which are 1 inch apart.

grains partly replaced by biotite. Both the biotite replacing hornblende, and that occurring independently, are of a dark red-brown variety, often with inclusions of quartz and microcline.

Apart from the much finer grain size, the aplites resemble the host granite in mineral content, with minor differences. The microcline is slightly microperthitic and carries similar inclusions to those in the host granite, but of a smaller size. The biotite ($\gamma = 1.673$ = dark brown) is generally rimmed by a granular opaque mineral while the hornblende ($\gamma = 1.706$ = dark green) shows incipient alteration to biotite.

GRANULITE REMNANTS

Remnants of the older metamorphic rocks occur as rare xenoliths of banded granulite in the unsheared adamellite near Gungungmura Waterhole. Larger masses of migmatitic gneisses occur farther east in the Yulun-Kudara and Gungarungal areas. These gneisses are well foliated and dominantly acidic, and show abundant evidence, in the form of folded lineations, of having been folded at least twice. The youngest folding took place along northeast to north-northeast

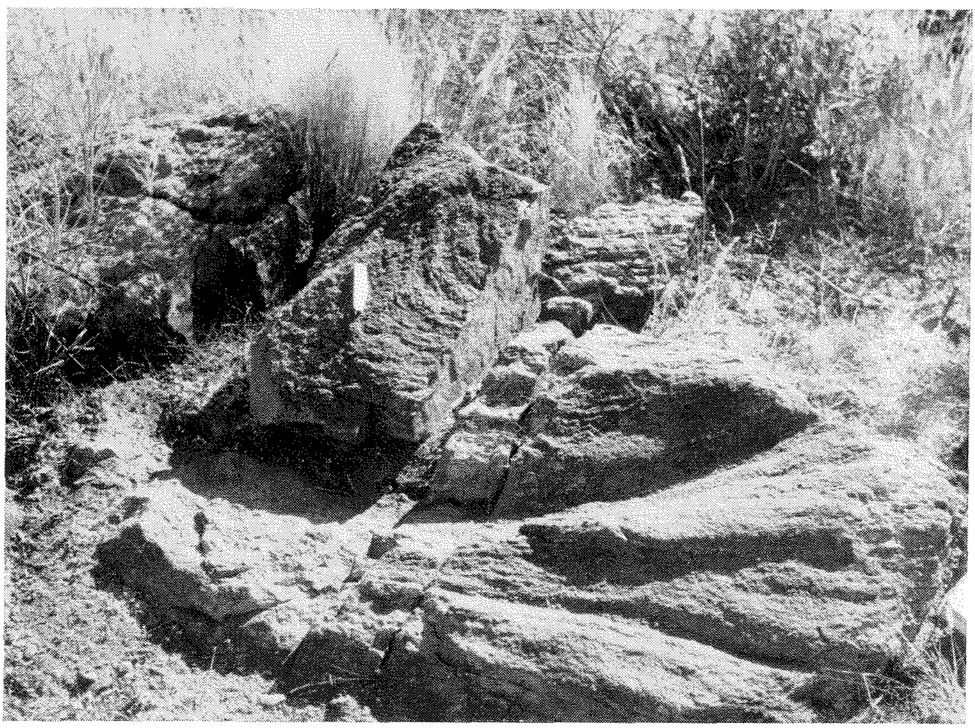

Figure 9. Folded lineations in downgraded granulite from near Yulun-Kudara in the northeast Bentley Sheet area.

axes, similar to that which affected the quartzites and quartz-muscovite schists (see below).

The complex nature of this second folding seen near Yulun-Kudara is illustrated in Figure 8. Measurements were made every 3 inches (7.6 cm) along the folded lineation and it had to be assumed, for the exercise to be valid, that the single lineation was linear before the onset of the second folding. The diagram shows that the second folding did not simply rotate the primary structure around a minor circle with the second fold axis as pole, but that a considerable amount of axial plane shear was also involved. This may account for the extreme development of lineations in some of the adamellite gneisses. An example of folded lineations from near Yulun-Kudara is given in Figure 9.

In the more complexly folded areas the symmetry has broken down. Foliations have become detached from one another and reacted independently. Hence measurements of lineations on adjacent foliations show widely different trends of little use in understanding the regional structure.

QUARTZITE AND QUARTZ-MUSCOVITE SCHIST

The prominent ridges of the Bedford Range, the unnamed range 2 miles (3.2 km) east of Mitika Waterhole and several minor ridges and outcrops of the northern part of the Bentley Sheet area consist of quartzite and quartz-muscovite schist representing a metamorphosed sequence of sandstone and argillaceous sandstone. The rocks are well bedded and often display relict cross-bedding.

At several localities, for example near Neena Mogura Waterhole, abundant stretched pebbles are present in a quartz-muscovite matrix (Fig. 10). Their frequency and size increases towards the contact with the stratigraphically lower adjacent adamellite gneiss, and the deposit is regarded as a modified basal conglomerate. The unconformity is rarely exposed, but may be seen in the low hills approximately 8 miles (13 km) southeast of Mitika Waterhole.

Mineralogically the rocks are simple, consisting generally of varying proportions of quartz and muscovite with minor accessory opaques. In the most southerly exposure of the rock type, 20 miles (32 km) southwest of Mitika Waterhole, garnet and kyanite are present in one small band.

The deposits have been recumbently and isoclinally folded along northeast to north-northeast axes. Probably during this folding they were also regionally metamorphosed.

SUMMARY OF THE ORIGIN OF THE WESTERN PART OF THE BASEMENT

The migmatitic gneisses of this area are modified granulites which originally formed the westerly continuation of the extensive high-grade metamorphic belt forming much of the Musgrave Block. It is also thought that the original granulites were intruded, in the northeast of the Bentley Sheet area, by copious adamellite, later unconformably overlain by arenaceous sediments and subjected

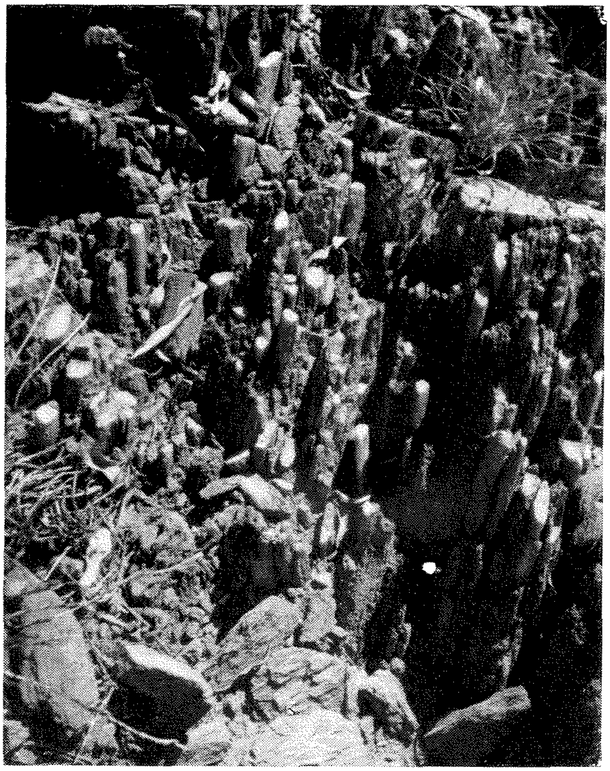

Figure 10. Stretched pebbles, up to 6 inches long, near the base of the quartz-muscovite schist near Neena Mogura Waterhole, Bentley Sheet area.

to a period of isoclinical and recumbent folding and associated metamorphism. This downgraded the granulites, converted most of the adamellite to gneiss and produced quartzite and quartz-muscovite schist from the sediments.

This sequence of events is thought to have taken place before the formation of the Bentley Supergroup.

Correlation of the quartzites and quartz-muscovite schists of the Bentley Sheet area with units in the Giles region is hampered by poor exposure and the Phanerozoic cover of the Cobb Depression. The Bedford Range curves round to the northeast and if this trend is projected it would meet the quartzites of the Rawlinson Range. This appears to be the best fit on scanty evidence and suggests that the quartzites and mixed volcanic rocks of the Giles area are older than the Bentley Supergroup.

CHAPTER 3

The Bentley Supergroup and Associated Rocks

INTRODUCTION

The Bentley Supergroup includes all sedimentary and volcanic rocks in the Blackstone Region younger than the granulites and related gneisses and schists, and older than the Upper Proterozoic glacials. Four groups are included, and two of these are thought to be lateral equivalents of each other. Included also are three volcanic associations. In age these volcanics fall within the limits of the Bentley Supergroup as defined by the four groups, but they are almost entirely confined to cauldron subsidence areas and do not form part of the normal layered sequence.

The Bentley Supergroup is thought to be Middle Proterozoic. An age of 1,060 $\pm$ 140 million years has been obtained from acid volcanic rocks, referred to informally as the Tollu Volcanics, which occur in the Cooper Sheet area south of Blackstone Range (Compston and Arriens, 1968). The Tollu Volcanics have now been formalized as the Smoke Hill Volcanics and form part of the Tollu Group (Daniels, 1969a). A single rhyolite specimen from the Cassidy Group in the Warburton Range fitted the isochron for the Tollu volcanics "without significantly increasing the statistical error" (quote, Compston and Arriens, 1968). As several ages of acid volcanics are present in the area more determinations are needed to discuss age relations properly.

The term Warburton Porphyry (Sofoulis, 1962a) is now dropped. It was used previously for the fine-grained porphyritic rocks forming the prominent, long, rounded ridges of the Warburton Range. They were thought to be intrusives but are now regarded as flows and have been given formal names.

PUSSY CAT GROUP

The Pussy Cat Group is the name given to the rocks lying immediately north of the Warburton Range, stratigraphically under the Cassidy Group and bordered on their northern side by part of the ring fault of the Scamp cauldron. The base of the sequence is not exposed, but it is thought to be laterally equivalent to the oldest major unit of the Bentley Supergroup, the Tollu Group, farther east in the Cooper Sheet area. Hence it is probably unconformable on either granulites or modified granulites similar to those exposed in the northeast of the Bentley Sheet area.

Local divergences of strike between the Pussy Cat Group and the overlying Cassidy Group are noticeable, especially near Mount Shaw. A distinct difference in metamorphic grade is also apparent between the two groups, and differences in style and intensity of folding are apparent. These features suggest that the Pussy Cat Group is unconformably overlain by the Cassidy Group.

North of Warburton Range, rocks of the Pussy Cat Group weather to form low, rounded hills generally of no more than 50 feet (15.2 m) elevation above the surrounding plain. Farther east, in the Whitby Range, much higher relief is present, caused partly by a resistant ignimbrite sheet and partly by intrusive sheets of porphyritic microgranite probably related to the Palgrave cauldron.

A combination of poor exposure, much lateral variation in lithology, and lack of regional marker horizons does not allow the detailed formational subdivision of the group at the scale of mapping used.

An ignimbrite in the Whitby Range is a prominent local feature. It has been given formational status and called the Kathleen Ignimbrite. The rest of the group is referred to as the Glyde Formation.

GLYDE FORMATION

This formation consists of a thick sequence of thin bands and lenses of basic, epidotic, amygdaloidal lava, tuff, shale, siltstone, dolomite, thin quartzite, and dirty sandstone. A minor pebble bed is present approximately 2½ miles (4 km) northwest of Mount Eveline. Basic lava is the most prominent rock type. Coarse clastics are, on the whole, rare and concentrated mainly in the western part of the outcrop.

The siltstones are greyish-green, fine-grained, slightly micaceous rocks generally well banded with individual bands ranging from 1 to 20 mm in thickness. The banding is defined by colour differences and changes in average grain size. A small amount of cross-bedding is present. Some bands are pyritic and crystals up to 3 cm across are not uncommon. A number of the larger crystals have asbestiform quartz developed on one side or two opposite sides, closely resembling the structures developed by ambient pyrite, though on a larger scale.

The dolomites have only been seen in the western part of the outcrop, where they occur as very narrow bands up to 4 feet (1.2 m) thick. They are black or grey and recrystallized to a medium-grained granular marble, and are sometimes interbedded with thin grey-white quartzite bands.

Regional metamorphism in the Mount Clarke area has altered the original rocks to chlorite schist, sericite schist, marble and biotite-hornblende rock. Folding is well developed near Mount Clarke, with dips generally between 40 and 65 degrees. Some recumbent folding is noted and a strong axial plane cleavage has developed. Farther east in the Whitby Range area metamorphism is not apparent, except for some contact metamorphism adjacent to the sheets of porphyritic microgranite. Folding is not intense and is of a more open nature: cleavage is confined to narrow bands along the axes of some of the folds.

TABLE 2. ANALYSES OF ACID VOLCANIC ROCKS FROM THE BENTLEY SUPERGROUP

Spec. No.	A	B	C	23322	23329	23388	23393	23318
SiO_2	73·00	74·60	72·80	74·81	75·11	69·72	70·58	71·34
Al_2O_3	12·60	11·40	12·80	12·29	12·14	13·10	13·26	12·64
Fe_2O_3	2·39	0·16	0·67	1·50	0·36	3·37	3·15	2·73
FeO	1·75	4·00	2·46	1·05	1·31	1·85	1·81	1·72
MgO	0·15	0·13	0·07	0·20	0·62	0·41	0·31	0·79
CaO	1·38	0·90	1·03	0·50	1·12	1·54	0·99	0·60
Na_2O	2·60	1·80	2·40	2·40	3·52	3·25	3·28	2·87
K_2O	5·80	5·90	6·32	6·47	4·85	4·67	5·02	6·13
H_2O^+	....	....	....	0·19	0·40	0·51	0·50	0·34
H_2O^-	....	....	....	0·10	0·06	0·10	0·10	0·14
CO_2	....	....	....	(*a*)	0·04	0·39	0·15	(*a*)
TiO_2	0·44	0·43	0·35	0·20	0·08	0·61	0·49	0·31
P_2O_5	....	....	....	0·17	0·01	0·12	0·09	0·30
MnO	0·09	0·10	0·06	0·03	0·10	0·15	0·13	0·10
Cr_2O_3	....	....	....	(*a*)	(*b*)	(*a*)	(*a*)	(*a*)
V_2O_5	....	....	....	0·01	(*b*)	(*a*)	(*a*)	0·01
NiO	....	....	....	(*a*)	0·004	(*a*)	(*a*)	(*a*)
CuO	....	....	....	0·02	0·01	0·01	0·01	0·01
Li_2O	....	....	....	0·18	0·06	0·08	0·10	0·15
ZrO_2	....	....	....	(*b*)	(*a*)	(*b*)	(*b*)	(*b*)
BaO	....	....	....	(*b*)	(*a*)	0·06	0·05	(*b*)
S	....	....	....	0·01	0·02	(*a*)	0·02	(*a*)
F	....	....	....	0·12	0·34	0·11	0·13	0·13
Loss at 100°C	0·30	....	0·46	....	....	....	....	....
	100·20	99·42	99·42	100·25	100·154	100·05	100·17	100·31
Less O = F, S	....	....	....	0·05	0·14	0·05	0·05	0·05
				100·20	100·014	100·00	100·12	100·26

(*a*) = less than 0·01
(*b*) = not determined
A, B, C } Rhyolites from Tollu. Quoted from Nesbitt, R. W., 1966.
23322—Acid volcanic from Scamp volcanic association.
Analyst: J. Gamble.
23329—Acid volcanic from Whitby Range, Kathleen Ignimbrite, Pussy Cat Group.
Analyst: R. W. Lindsey.
23388—Wururu Rhyolite, Cassidy Group.
Analyst: P. Hewson.
23393—Gombugurra Rhyolite, Cassidy Group.
Analyst: P. Hewson.
23318—Hilda Rhyolite, Cassidy Group.
Analyst: J. Gamble.

KATHLEEN IGNIMBRITE

This formation is developed within the Glyde Formation in the Whitby Range. It forms a prominent ridge overlying a softer, more easily weathered layer of tuff and basalt.

The unit is about 1,000 feet (300 m) thick and apparently thins out towards the western end of Whitby Range. It is an aphanitic, blue-grey, brown-weathering rock with well developed fine-scale banding. Flow lineations are abundantly developed on some surfaces. In thin section the rock is seen as a microfelsitic mosaic of potash feldspar, plagioclase and quartz with a few scattered dark minerals and irregular patches and short bands of more coarsely crystalline quartz. Accessory minerals include brown biotite, sphene, fluorite, piemontite, opaques and muscovite. Rarely the rock carries very small rounded phenocrysts of quartz. Its chemical analysis and norm are given in Tables 2 and 3.

TABLE 3. NORMS OF ACID VOLCANIC ROCKS FROM THE BENTLEY SUPERGROUP

	23322	23329	23388	23393	23318
Q	35·01	32·41	30·45	30·31	29·31
C	0·81	0·00	1·07	1·17	0·89
Or	38·26	28·68	27·62	29·69	36·25
Ab	20·28	29·74	27·46	27·72	24·25
An	1·37	2·96	4·39	3·37	1·02
Di	0·00	1·90	0·00	0·00	0·00
Hy	0·91	2·75	1·02	0·92	2·55
Mt	2·17	0·52	4·88	4·56	3·95
Il	0·38	0·15	1·02	0·93	0·58
Ru	0·00	0·00	0·07	0·00	0·00
Ap	0·40	0·02	0·28	0·21	0·70

23322—Acid volcanic from Scamp volcanic association.
23329—Kathleen Ignimbrite, Pussy Cat Group.
23388—Wururu Rhyolite, Cassidy Group.
23393—Gombugurra Rhyolite, Cassidy Group.
23318—Hilda Rhyolite, Cassidy Group.

The top few tens of feet of the flow at the western end of its outcrop consist of undistorted glass shards now replaced by a fine-grained felsitic matrix. No glass remains, but the original shapes of the shards are clear (Fig. 11).

The relic glass shard shapes at the top of the flow suggest that the unit is an ignimbrite. The banding could have been caused by compression of the shards which have probably been obliterated by welding lower down in the flow. The flow lineations suggest that the rock may be termed a rheoignimbrite, since it is apparent that the rock flowed after welding.

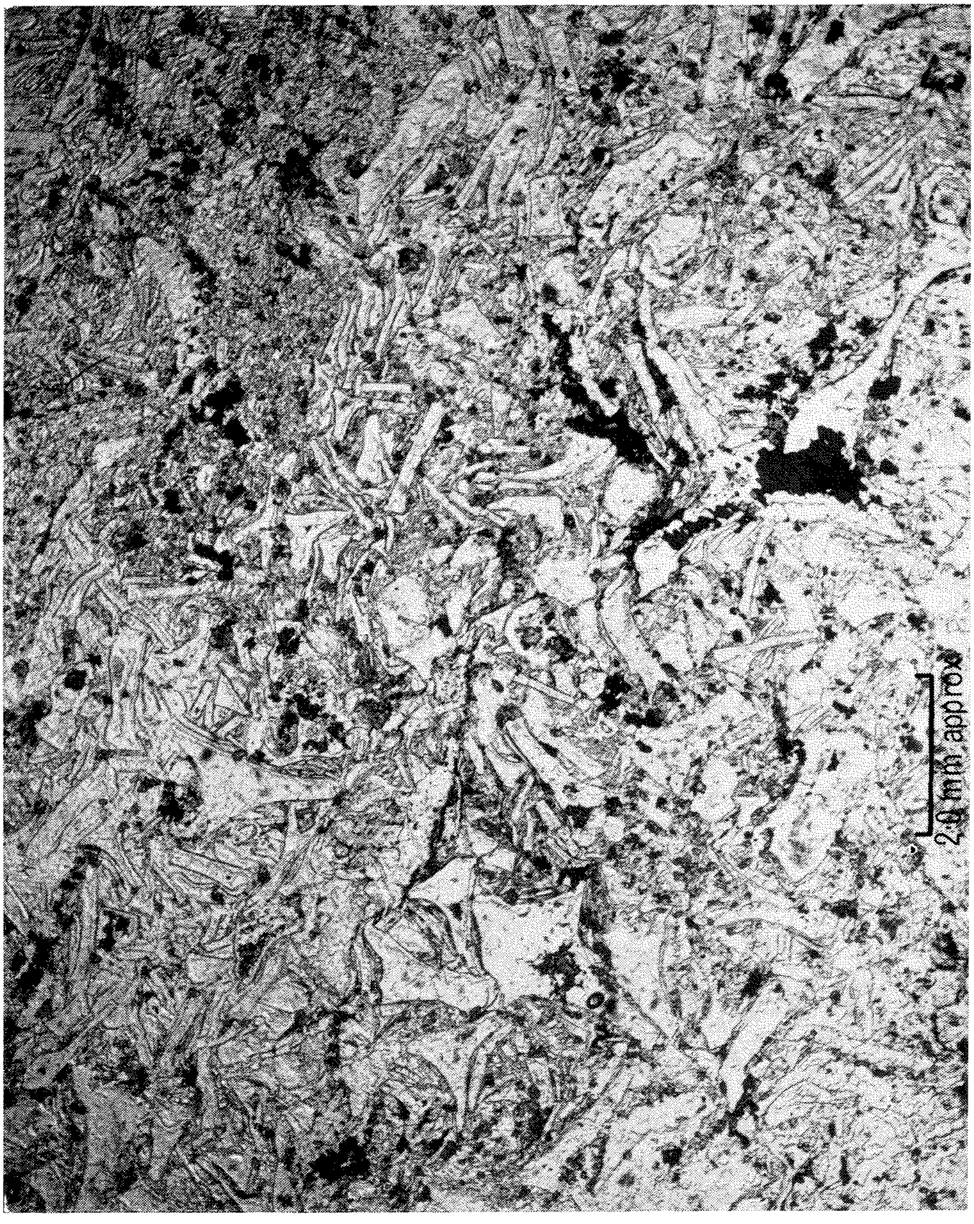

Figure 11. Glass shard shapes preserved near the top of the Kathleen Ignimbrite, Mount Kathleen, Talbot Sheet area. Ord. light.

Since the unit thins to the west and as its flow lineation pattern is oriented in a roughly east-west manner it probably originated from a source to the east. The most likely source is the central region of the Palgrave cauldron. The unit probably represents some of the earliest volcanic activity associated with this feature.

TOLLU GROUP

The Tollu Group in the Cooper Sheet area is thought to be laterally equivalent to the Pussy Cat Group developed north of the Warburton Range. The Tollu Group is the oldest unmetamorphosed group in the area south of the Blackstone Range. It consists of a thick mixed volcanic sequence with a basal sandstone and conglomerate unconformably overlying granulite, granite gneiss and granite. The unconformity is well exposed at MacDougall Bluff and Mount Blyth, approximately 14 miles (22 km) south of Lightning Rocks. The group is intruded by part of the Giles Complex, granite and dolerite dykes, and is cut by cauldron subsidences.

An age of 1,060 ± 140 m.y. has been obtained by Compston and Nesbitt (1967) for acid volcanics referred to informally as the Tollu Volcanics. These have now been formalized as the Smoke Hill Volcanics, a formation within the Tollu Group.

A four-fold subdivision of the group has been made in the north central part of the Cooper Sheet area.

MacDOUGALL FORMATION

The MacDougall Formation is the oldest formation of the Tollu Group and consists of sandstone, pebble beds and conglomerate, varying in thickness from 50 feet to 250 feet (15.2 to 76.1 m). The thickest section and the optimum development of conglomerate occurs at Mount Blyth and the poorly exposed area immediately south. East of MacDougall Bluff, conglomerates are missing and the formation consists of sandstone and quartzite.

Palaeocurrent directions determined from cross-bedding in sandstones are available from a few localities and suggest that during the deposition of the lower part of the formation, a system of currents flowed away from the area between MacDougall Bluff and Mount Blyth.

MUMMAWARRAWARRA BASALTS

Conformably overlying the MacDougall Formation are the Mummawarrawarra Basalts. They are well exposed on Mummawarrawarra Hill, MacDougall Bluff and Mount Blyth, and consist of numerous thin, vesicular and amygdaloidal basalt flows, and rare tuffs. The basalts are often epidotic and frequently show gas-streaming effects. A minimum thickness of approximately 800 feet (240 m) is estimated for the formation at Mount Blyth. Hematite-stained vesicular basalts of this formation are present 9 miles (14.4 km) south of Mount Blyth. Some of the vesicles carry small amethystine quartz crystals.

The formation appears to be missing on much of the northern side of the Tollu syncline, but it may be present as contact metamorphosed basic, amygdaloidal lavas in a sliver of rock under the Blackstone Range Gabbro on the northern side of the range and included in the map in the marginal facies of the gabbro.

This formation is cut by gabbroic intrusions on Mummawarrawarra Hill. Contact metamorphism of the basalts is noted and several xenoliths of the amygdaloidal basalts have been caught up in the gabbro.

These exposures are some of the important ones used in establishing the relative ages of the Tollu Group and part of the Giles Complex.

SMOKE HILL VOLCANICS

The Mummawarrawarra Basalts are overlain by the Smoke Hill Volcanics. These consist dominantly of a thick sequence of rhyolite and dacite flows with smaller amounts of basic and intermediate lava, acid breccia, and tuff.

At Tollu, there occurs a striking, flow-banded and contorted rhyolite (Fig. 12). It is porphyritic and weathers with a black shiny surface. The phenocrysts mostly consist of euhedral, clear orthoclase and slightly dusted euhedral albite with minor rounded quartz showing vague sutured margins. Approximately 90 per cent of the phenocrysts are orthoclase with 5 per cent each of albite and quartz. The ground mass is well banded, microfelsitic and shows abundant

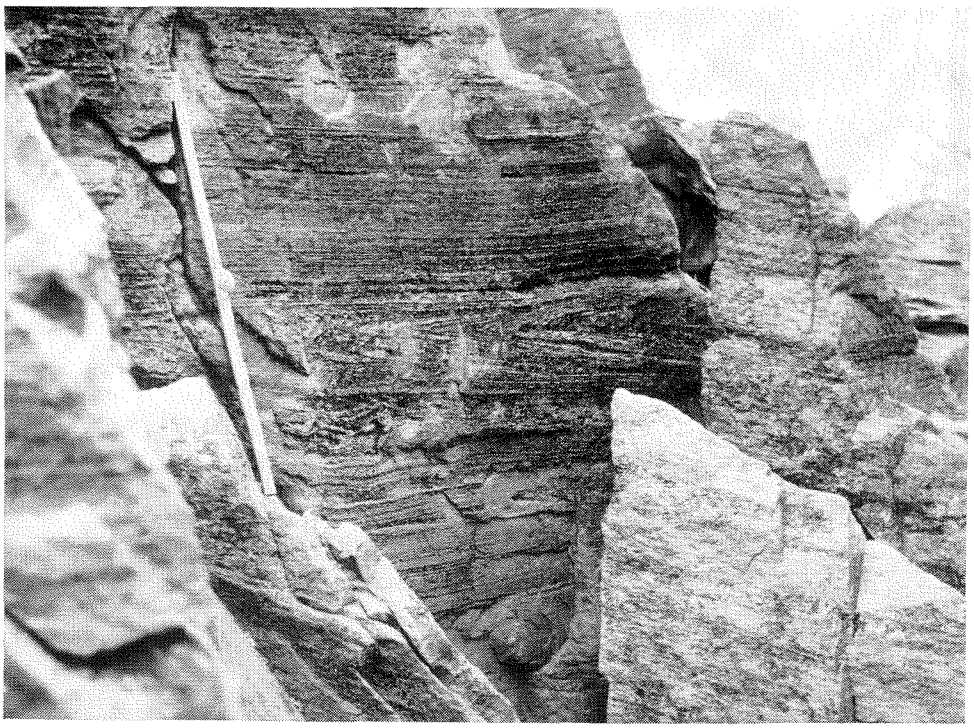

Figure 12. Zig-zag fold in flow-banded rhyolite of Smoke Hill Volcanics, Tollu Group, Tollu, Cooper Sheet area. Scale is 2 feet long.

relict perlitic cracks indicating the former presence of glass. Accessories include green and brown biotite, granular sphene, euhedral zircon, opaques and apatite. Some analyses of these rocks are given by Nesbitt (1966) and are included in Table 2 for comparison with acid volcanics from the Warburton region.

A rhyodacite example from the same area is also well banded and, apart from the presence of plagioclase phenocrysts as well as orthoclase, is comparable with the rhyolite.

At Mount Jane, more acid volcanics of the formation are present. These contain abundant stretched dark inclusions and are probably tufflavas.

Somewhat contact metamorphosed examples of the Smoke Hill Volcanics are present on the northern side of the Cavenagh Range. These are mixed with contaminated gabbro and are indicated on the map as marginal facies. The rocks are fine-grained, porphyritic rhyodacites. The phenocrysts are perthite and albite, and occur either singly or in glomerocrysts with hornblende and biotite. The hornblende is a green-brown variety partly replaced by very pale green hornblende and mosaic quartz rimmed by a continuous growth of blue-green hornblende. Skeletal ilmenite is present, and this is frequently altered to sphene and hematite. The groundmass is fine grained and consists of a mosaic of quartz, microcline, biotite, blue-green hornblende with minor opaques and apatite. Another sample from the same locality is generally similar but the plagioclase phenocrysts are slightly more calcic (An_{14}) and relict pale green pyroxene is present in some of the amphibole phenocrysts.

At the southern side of the hills at Tollu the Smoke Hill Volcanics are intruded by gabbro, at the top of which is a granophyre body. The latter carries rafts of the Smoke Hill Volcanics. These rafts are slightly felsitized but the original volcanic textures are readily apparent.

HOGARTH FORMATION

The Hogarth Formation overlies the Smoke Hill Volcanics and consists of fine-grained, dark, basic lavas, basic to intermediate vesicular lavas, tuffs and agglomerates.

They form the youngest known formation of the Tollu Group.

METABASALTS IN THE JAMESON RANGE REGION

Metabasalts occur as a long thin sliver under the Jameson Range Gabbro and are variously exposed at several points along their strike. Good exposures are near Turkey Hill and Mount Finlayson. In all cases the metabasalts appear to overlie granulites. Metamorphism of the basalts is low grade, and could well be dominantly contact metamorphism. The grade contrasts strongly with that of the underlying granulites and even though the contact of the two rocks is not seen, an unconformity most probably exists between them.

The metabasalts are dark green to black, fine to medium-grained amphibolitic rocks. Occasionally abundant amygdales are present and these often consist of calcite and epidote. They are tentatively correlated with the Mummawarrawarra Basalts, a formation in the Tollu Group, or the Glyde Formation, their broad correlatives in the Warburton Range region.

Some of the metabasalts in the Turkey Hill region are interlayered with thin sills of gabbro and titaniferous magnetite bands.

UNNAMED METAMORPHOSED BASALTIC ROCKS

Four small areas of metamorphosed basic volcanic rocks of unknown age occur near Yulun-Kudara Water Hole towards the northeastern corner of the Bentley Sheet area. The four masses are irregularly shaped. The largest is approximately a quarter of a mile (0.4 km) across and they are thought to be small volcanic plugs.

The rock is metamorphosed amygdaloidal basalt carrying xenoliths of the acid gneisses which form the country rock in that region. It is cut by veins of epidosite and pegmatites composed of quartz, feldspar, epidote, hematite and magnetite. The groundmass of the basic rock consists of a fine to medium-grained mosaic of pale green clinopyroxene, brownish-green hornblende, plagioclase, euhedral garnet, epidote and opaques. Relict phenocrysts of plagioclase are easily recognizable. Amygdales in the rock contain mosaic quartz with small amounts of plagioclase, garnet (partially pseudomorphed by epidote), opaques and sphene.

CASSIDY GROUP

The Cassidy Group unconformably overlies the Pussy Cat Group and is well developed immediately north and northeast of Warburton Mission, where it forms the Warburton Range. The group continues eastward, as a series of low ridges, almost as far as the Hocking Range, where it is unconformably overlain by the Townsend Quartzite. Between Warburton Mission and the region south-east of Mount Weir the Cassidy Group is conformably overlain by the Mission Group.

The unconformity at the base of the Cassidy Group is deduced from regional angular disparities of strike and contrasting styles of folding between the Cassidy Group and the Pussy Cat Group in the area between Mount Clarke and Mount Shaw. In addition, the rocks immediately below the contact of the two groups in the area north and northeast of Mount Talbot have been regionally metamorphosed. No metamorphism is apparent, in the field, in rocks of the Cassidy Group.

An alternating sequence of acid and basic volcanics with some associated thin bands of sediments characterizes the group. Its total thickness in the Mount Talbot areas is 10,300 feet (3,140 m), of which 9,450 feet (2,880 m) are volcanics. The composition of approximately half of the volcanics, a total of 4,950 feet (1,510 m), is acid.

The almost complete repetition of acid and basic volcanics is marred by the apparent lack of basic volcanics between the Wururu and Gombugurra Rhyolites as seen in Table 1. However, a very small amount of basic lava has been found immediately below the Gombugurra Rhyolite about 7 miles (11 km) southeast of Mount Talbot (D. Haynes, pers. comm.).

ACID VOLCANICS

All four of the acid volcanic formations (Table 1) are superficially closely similar. They are brown-weathering, fine-grained, porphyritic rhyolites and range in thickness in the Mount Talbot area from 850 feet (260 m) for the Gombugurra Rhyolite to 1,800 feet (550 m) for the Wururu Rhyolite. Each is probably a single cooling unit except the Thomas Rhyolite, which probably consists of three individual cooling units.

Minor differences in samples from the main bulk of each formation are apparent with the use of a hand lens, and with practice these differences can be used to trace the continuity of the formations. Their remarkable uniformity over large distances is one of their main characteristics.

ZONING OF MACROSTRUCTURES IN THE HILDA RHYOLITE

The vertical variation of the internal structure of the acid volcanic formations is simple. Such variations in a typical section in the Hilda Rhyolite are well displayed 1½ miles (2.4 km) west of Mount Talbot. It appears from the progressive nature of the changes and their non-repetition that the Hilda Rhyolite represents a single cooling unit now 1,300 feet (400 m) thick. The section may be used as a type example of the vertical variation in certain acid volcanics and as a basis for comparison. The origin of the structures is not fully understood, but their characters are recorded for future reference.

Three principal zones are recognized:

Top 1. spherulitic zone
2. turbulent flow zone
3. laminar flow zone.

SPHERULITIC ZONE

The uppermost zone is approximately 50 feet (15 m) thick and consists of black, aphanitic, moderately well banded rock containing abundant, closely packed spherulites ranging from a quarter of an inch to 1 inch (6.3 to 25 mm) in diameter. The larger spherulites occur towards the top of the zone. This feature is a useful facing criterion.

An example from the Hilda Rhyolite is given in Figure 13.

TURBULENT FLOW ZONE

Below the spherulitic zone and passing into it by a fairly sudden decrease in spherulite content, is a black, aphanitic, well banded zone, approximately 50 to 100 feet (15 to 30 m) thick. It is characterized by the absence of spherulites

Figure 13. Specimen of weathered, spherulitic rhyolite from near top of Hilda Rhyolite, 2 miles north of Frank Scott Hill.

and the presence of well developed, contorted, fine-scale banding and an abundance of flow lineations. Zig-zag folds are common and the well developed flow lineations are parallel to the axes of the zig-zag folds. No consistent orientation of the zig-zag fold axes is present, as these have been affected by a younger, more rounded, folding. This rounded folding forms an integral part of the fabric of the turbulent flow zone and is absent in other zones and nearby sedimentary rocks. It is thought to be the result of movement of a nearly consolidated part of the flow; the folding taking place during the final stages of the movement and consolidation of the flow.

LAMINAR FLOW ZONE

The main part of the cooling unit is contained in the laminar flow zone, and is approximately 1,200 feet (365 m) thick.

At the section investigated the basal contact is not exposed, but a few feet above the base the flow consists of well jointed, brown-weathering, slightly porphyritic rhyolite. Joint controlled liesegang colour banding is well developed. Foliation is defined only in a vague manner by the presence of vein banding (see Glossary).

Figure 14. Planar partings with rough surfaces near base of Hilda Rhyolite, 1½ miles west of Mount Talbot.

Some 200 to 300 feet (60 to 90 m) above this, banding becomes more easily noticeable. Individual bands are from 2 inches (5.0 cm) to 1 foot (30.4 cm) thick (Fig. 14) and adjacent bands are indistinguishable petrographically. This feature continues for several hundred feet higher in the flow, giving way gradually to more homogeneous material with few planar partings. The surfaces of these partings are rough and pock-marked and in a number of places show slight undulations half an inch to 1 inch (1.25 to 2.5 cm) in amplitude (Fig. 15). These were called "rough surface rolls" in the field to distinguish them from other more sharply defined linear features. Their orientation was measured, wherever possible, and found to be coincident with the directions, obtained higher up this same zone, of finer scale flow lineations (Fig. 16). The latter are occasionally present on partings with smooth surfaces. An excellent example is given in Figure 17.

Figure 15. View almost normal to parting showing crudely developed "rough surface rolls". Hilda Rhyolite, 1½ miles west of Mount Talbot.

	ZONE	ORIENTATION OF LINEAR FEATURES	
		Mean	Range
Top Approx 50 feet	<u>Spherulitic Zone</u> Abundant spherulites Minor banding Some brecciation at top No linear features		
50 – 100 feet	<u>Turbulent Flow Zone</u> Aphanitic Chaotic banding Zig-zag folds Distorted flow lineations	↓	121° – 237°
Approx 1150 feet	<u>Laminar Flow Zone</u> Parallel banding		
	Triangular shadows	↘	279° – 296°
	Flow lineations	↔	212° – 269°
	Rough surfaces with vague rolls	↔	254° – 278°
	Vein banding		
Base	Leisegang structures		

Figure 16. Diagram showing subdivisions of the Hilda Rhyolite, the main characteristics of each zone and comparison of the orientations of linear features.

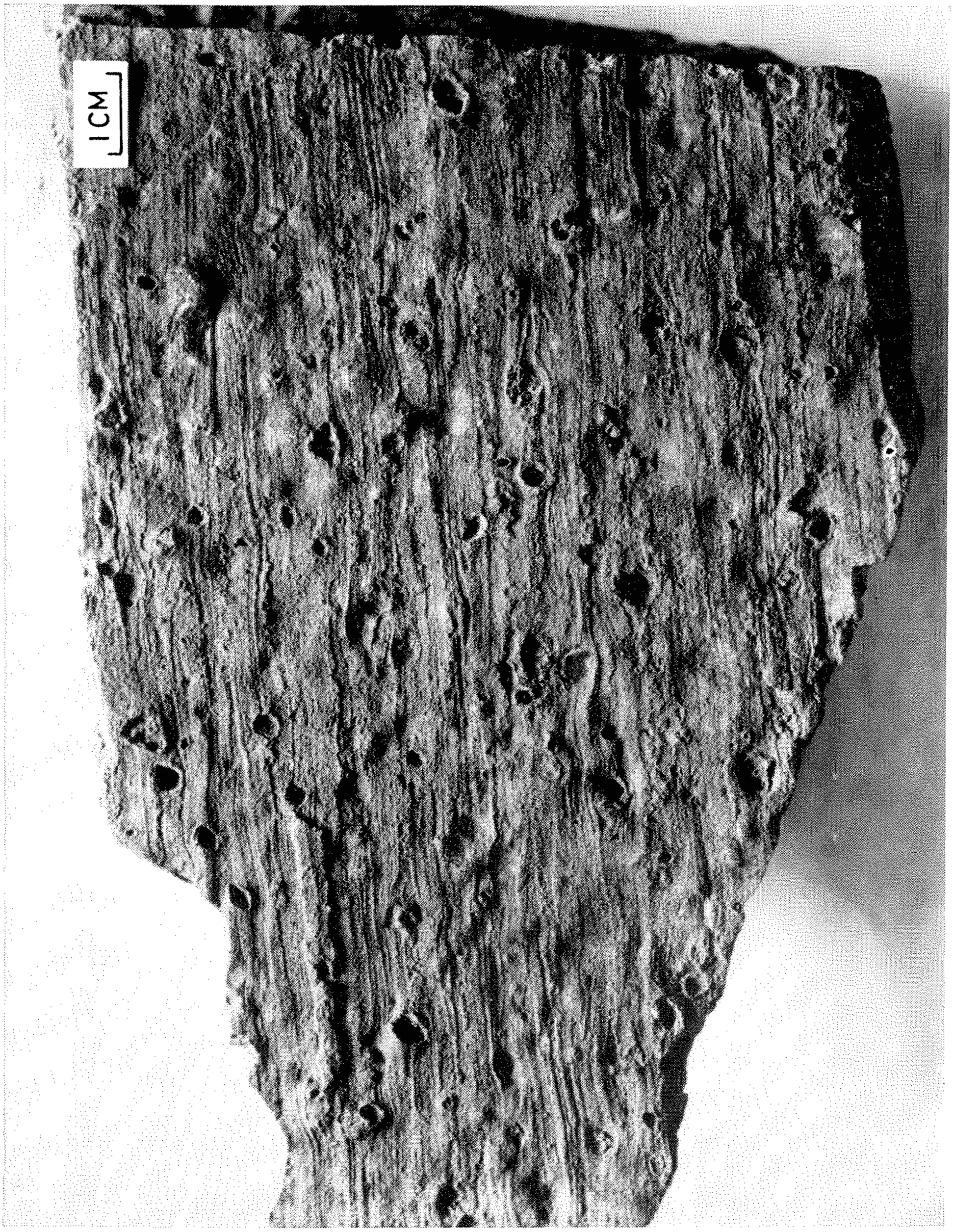

Figure 17. Flow-lineated porphyritic acid volcanic from laminar flow zone near top of Hilda Rhyolite $1\frac{1}{2}$ miles west of Mount Talbot.

In the same zone, but only rarely developed, are structures for which the term "triangular shadows" has been coined. These are developed on planar partings as small, triangular-shaped slightly raised areas on one side only of the plagioclase phenocrysts (Fig. 18). The orientation of these "shadows" is similar to that of the flow lineations and "rough surface rolls" (Fig. 16) but they do not appear to be consistently developed, over large areas, on the same side of the phenocrysts.

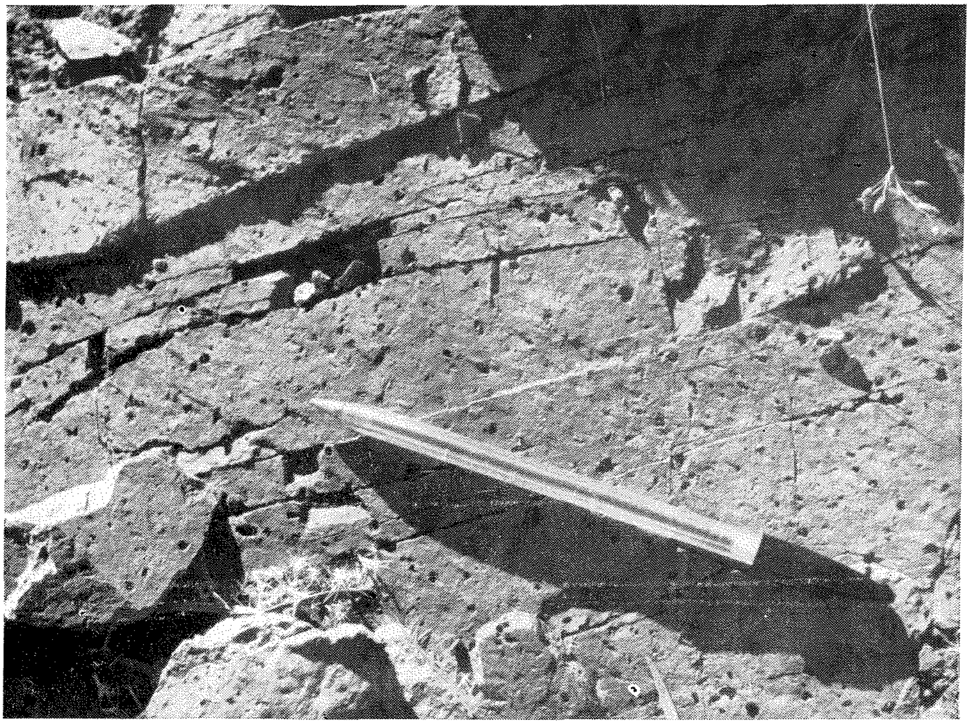

Figure 18. "Triangular shadows" on planar partings in Hilda Rhyolite, 1½ miles west of Mount Talbot.

ZONING IN OTHER COOLING UNITS

Most of the features described above may be recognized along much of the strike of the Hilda Rhyolite and also in the other acid volcanic formations of the Cassidy Group. Important differences exist in some cases.

Another formation whose vertical structural variations were studied in detail is the Gombugurra Rhyolite. The three-fold subdivision into laminar flow zone, turbulent flow zone and spherulitic top is easily recognizable. However, at the very base is a banded, somewhat spherulitic layer, 5 to 10 feet (1.5 to 3 m) thick. The base is sharp, but the top is ill defined and grades into the overlying laminar flow zone. This basal zone is well banded, fine to coarse grained, with individual bands ranging in thickness from a quarter of an inch to half an inch (6 to 12 mm). The banding, which is regular, is defined by colour variations (mauve, grey, light grey) as well as variations in grain size. The zone shows a very variable development of quarter-inch to 1-inch (6 to 25 mm) diameter spherulites, which tend to be preferentially concentrated in certain bands. They have developed across the banding and no deformation of the spherulites was noticed.

The upper part of the formation also shows differences when compared with the Hilda Rhyolite. At the top is a zone of acid volcanic breccia, approximately 50 feet (15 m) thick, overlying a 20-foot (6 m) thick spherulitic zone.

The breccia appears to be part of the formation and consists of angular fragments of fine or coarse-grained, unbanded acid volcanic rock and coarse-grained, well banded acid volcanic rock cemented by very fine-grained acid material.

Underlying the spherulitic zone is a 50-foot (15 m) thick turbulent flow zone consisting of very well flow-banded material with a variable development of zig-zag folds. The strike is apparently constant and does not show the younger rounded folds seen in the turbulent flow zone of the Hilda Rhyolite.

The Thomas Rhyolite appears to consist of three cooling units. A black aphanitic, well banded zone is present some 360 feet (110 m) below the top of the formation which underlies brown-weathering, porphyritic rhyolite carrying well developed rough surface partings and associated rolls. The black aphanitic zone is similar to the rock type developed in the turbulent flow zone of the Hilda Rhyolite and weathers more rapidly than the associated rock. The air-photographs show a well marked minor stream system in this position and existing parallel to the strike for a considerable distance. Approximately 390 feet (120 m) stratigraphically below the aphanitic zone is another parallel minor stream system. Exposures are not good, but it is suggested that the Thomas Rhyolite is composed of at least two and probably three cooling units. From top to bottom these would be 360 feet (110 m) thick, 390 feet (118.8 m) thick and 250 feet (76 m) thick respectively. The composite nature of the Thomas Rhyolite is also suggested by the variation in the mean orientation of the flow lineations for the laminar flow zones of the individual units:

Thomas Rhyolite

Unit defined by secondary stream pattern	Mean flow lineation directions
top unit	286°
middle unit	220°
basal unit	257°

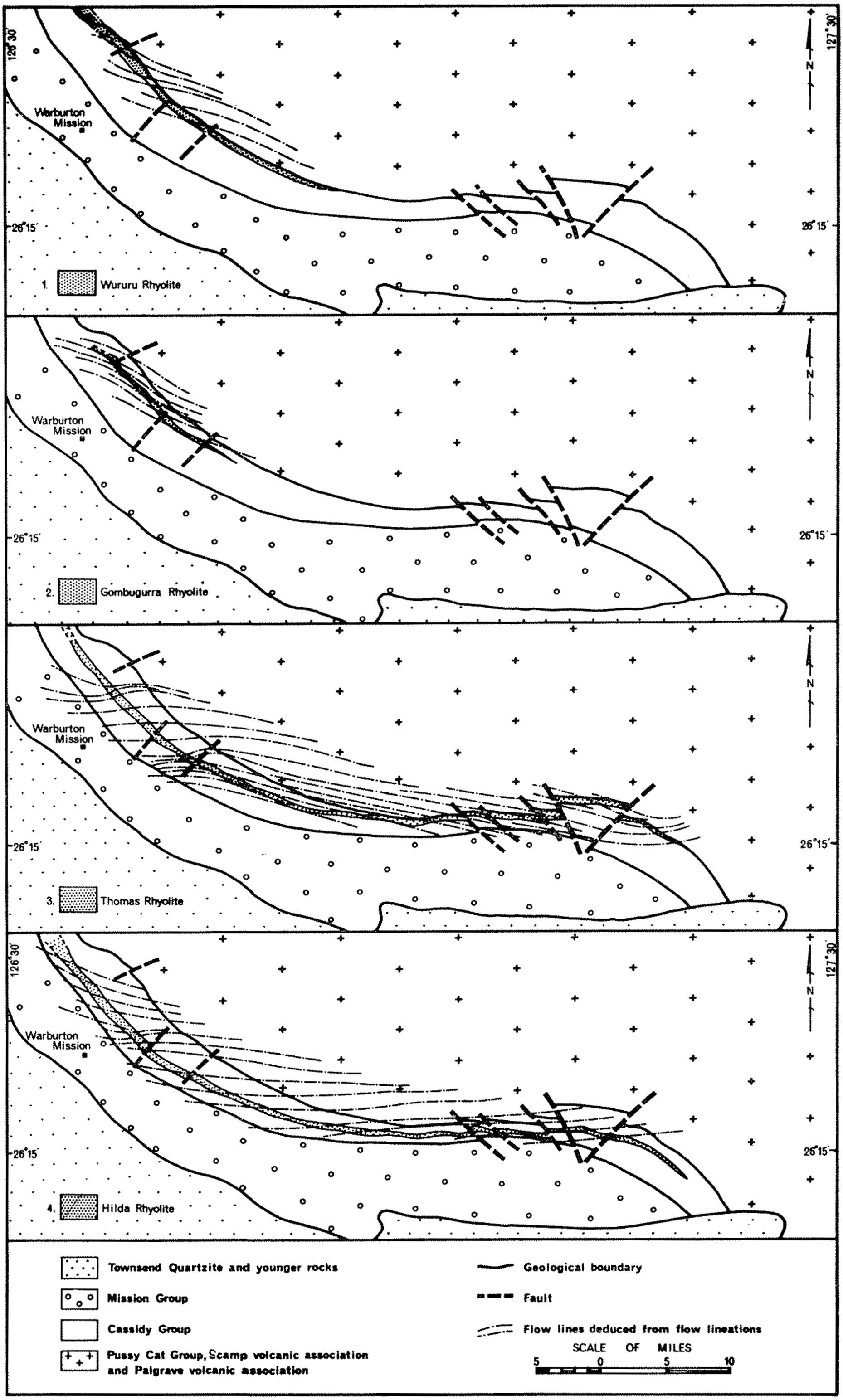

Figure 19. Deduced regional flow patterns for rhyolites of the Cassidy Group.

SOURCE AND VOLUMES OF THE FLOWS

Using flow-lineation orientation measurements taken only from the laminar flow zones of the acid volcanic units over the greater part of their outcrop, a picture of the flow pattern of each of these units can be built up. The deduced flow patterns for each unit are given in Figure 19. The patterns can be used to suggest a source for the material and to calculate a minimum likely volume involved in each event. Because the rhyolites thin out to the east, their source is most likely to be towards the west, or northwest if the northwesterly trend developing in the western outcrops persists under the thin Permian cover of that area.

Approximately 20 miles (32 km) to the east of Todd Ranges in the Bentley Sheet area is an elongated gravity-high, referred to as the Mount Charles gravity-high by Lonsdale and Flavelle (1963). It is suggested that this could indicate the likely source area for the Cassidy Group acid volcanics by comparison with

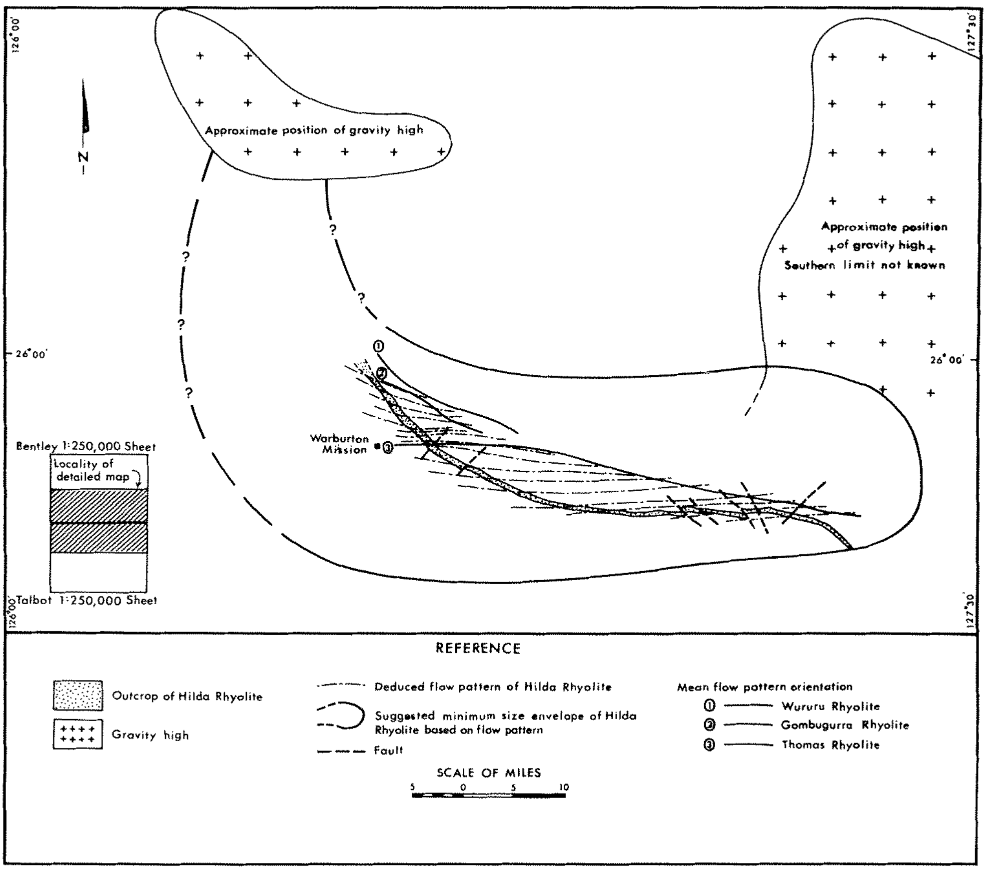

Figure 20. Inferred form of Hilda Rhyolite and related features.

the gravity feature associated with the Palgrave cauldron. This postulated origin, together with the minimum sized envelope suggested by the deduced flow pattern, allows the calculation of a minimum surface area for each of the acid volcanic formations. The pattern for the Hilda Rhyolite is given in Figure 20. The volume of each flow was then calculated assuming two possible cross-sectional shapes:

1. rectangular, with uniform thickness across most of the flow's breadth and very rapid thinning at the margins
2. plano-convex.

For the dimensions involved the rectangular cross section gives almost exactly twice the volume obtained using the plano-convex cross section.

The results obtained for each of the acid volcanic formations are listed below (Table 4). They are minimum values and emphasize the substantial quantities of material involved in each emission.

TABLE 4. SEQUENCE AND DIMENSIONS OF RHYOLITE FORMATIONS OF THE CASSIDY GROUP

Formation	Estimated minimum area		Thickness measured at Warburton Range		Volume Planoconvex section		Volume Rectangular cross section		Notes
	$mile^2$	km^2	ft	m	$mile^3$	km^3	$mile^3$	km^3	
Hilda Rhyolite	1,680	4,350	1,300	400	200	830	400	1,660	single flow
Thomas Rhyolite	1,680	4,350	1,000	300	160	670	320	1,340	?three flows
Gombugurra Rhyolite	280	725	850	260	22	90	44	180	?single flow
Wururu Rhyolite .... (base of sequence)	420	1,090	1,800	550	72	300	144	600	?single flow
Total	....	....	....	....	454	1,890	908	3,780	

SEQUENCE OF EVENTS

An explanation is required for the very large variety of textures found in the acid volcanics of the Blackstone Region and the following possible sequence of events may satisfactorily account for the variation. The sequence of events may stop at any point and this point will depend on the amount of heat available either in the form of excess heat or heat from post-depositional exothermic reactions.

A. *Particulate eruptions*
   1. nuée ardente
   2. deposition

3. welding
4. secondary flow
5. final consolidation
6. devitrification, vein banding, perlitic cracking, production of spherulites.

The last process may affect the products of any of the earlier processes if glass is produced.

B. *Liquid eruptions*

1. flowage with incorporation of foreign matter, contrasting flow characteristics depending on height in the flow
2. solidification
3. stretching of included units in last stages of flow and consolidation
4. devitrification, vein banding, perlitic cracking and production of spherulites.

PETROGRAPHY

WURURU RHYOLITE

The lowest acid volcanic unit in the Cassidy Group is the Wururu Rhyolite. It is probably a single cooling unit, but its structures have not been studied in detail. Generally it has a moderately uniform aspect, poorly developed banding and consistent, though sparse, flow-lineation directions. It tends to be well jointed and several areas resembling hexagonal cooling columns were noted.

A sample was chosen from near the centre of the unit for petrographic and chemical study.

The rock is a slightly porphyritic and glomeroporphyritic, light brown-weathering, very fine-grained rock. The phenocrysts consist of euhedral and subhedral sodic andesine and rare small rounded quartz. The plagioclase is usually well twinned and sometimes zoned with a core of An_{36} to a rim of An_{8}. The marginal zone frequently shows replacement by potash feldspar. Quartz, potash feldspar and plagioclase make up a very fine-grained groundmass mosaic which carries scattered accessories including green and brown biotite, muscovite, opaques, sphene, epidote, fluorite, and zircon.

GOMBUGURRA RHYOLITE

In the thin, banded, spherulitic basal zone of this formation, the groundmass is an extremely fine-grained mosaic of quartz and potash feldspar with minor opaques, epidote, chlorite, tourmaline and sphene. Extinction is in irregularly shaped zones, a feature considered to be a devitrification effect. Relict perlitic texture is suspected.

Occasional phenocrysts of plagioclase (An_{10-12}) and rare quartz are present. Both minerals are frequently well rounded and the former tends to form glomerocrysts.

A distinctive form of inclusion is carried by many of the plagioclase phenocrysts. These are areas with lobate edges consisting apparently of material identical to that of the exterior groundmass. An example from this rock is given in Figure 21, and compared with other similar examples from other acid volcanics of the Blackstone Region. They appear to be similar to the examples referred to as "collocrysts" by Elliston (1963) in similar rocks from Tennant Creek, Northern Territory. The arrangement of the lobate inclusions, sometimes in zones and usually, though not entirely, avoiding the marginal zone of the plagioclase, suggests that they are not resorption features, but rather inclusions of groundmass incorporated during periods of relatively rapid phenocryst growth. The groundmass was probably liquid or viscous liquid at the time. Ewart (1963) described plagioclase crystals, with similarly shaped lobate inclusions, from a Quaternary pumice ash in the Taupo area of New Zealand. In these the inclusions consist of glass. Similarly shaped inclusions have been found by Stevenson (1947) in plagioclase phenocrysts in a pumice from Haylmore, British Columbia. The inclusions consist of glass, and he states that such inclusions "seem to be characteristic of rocks with a glassy groundmass, and especially pyroclastics". Stevenson also reports a personal communication of M. J. Buerger in which Buerger suggests that glass blebs, similar in shape to the ones mentioned above, remain in rapidly forming crystals.

Spherulites of this zone show a fine, radiating structure which has developed in a medium brown base with an indeterminate mineral composition. The base carries multi-lobate grey areas which extinguish uniformly in any single spherulite. The shape of these grey areas resembles that of the plagioclase phenocrysts and is considered to be a form of skeletal growth from a glass.

Several specimens from the main part of the flow, the laminar flow zone, were examined. Overall this zone is moderately uniform with only slight banding apparent.

The lowest specimen in the sequence shows small phenocrysts of plagioclase and opaques in a fine-grained speckled groundmass. This groundmass is more coarse grained than the normal for this suite of rocks, and consists of potash feldspar, quartz and plagioclase forming a pseudomicrogranophyric texture. Other minerals present include minute octahedra of magnetite, chlorite, biotite, sericite, finely granular sphene, calcite, fluorite, and very rare euhedral zircon. Ilmenite is probably also present, as some of the opaques show replacement by granular sphene.

Scattered through the matrix are small mafic clots consisting of biotite, magnetite, fluorite and epidote. The biotite is patchily altered to green biotite.

The phenocrysts are euhedral and subhedral plagioclase with a tendency to aggregate. Lobate inclusions of groundmass material are present. The composition of the plagioclase is approximately An_{32}. It shows moderately well developed simple albite twinning and some chessboard structure.

A few tens of feet higher up the section the groundmass becomes considerably finer grained with no pseudomicrogranophyric texture developed. The

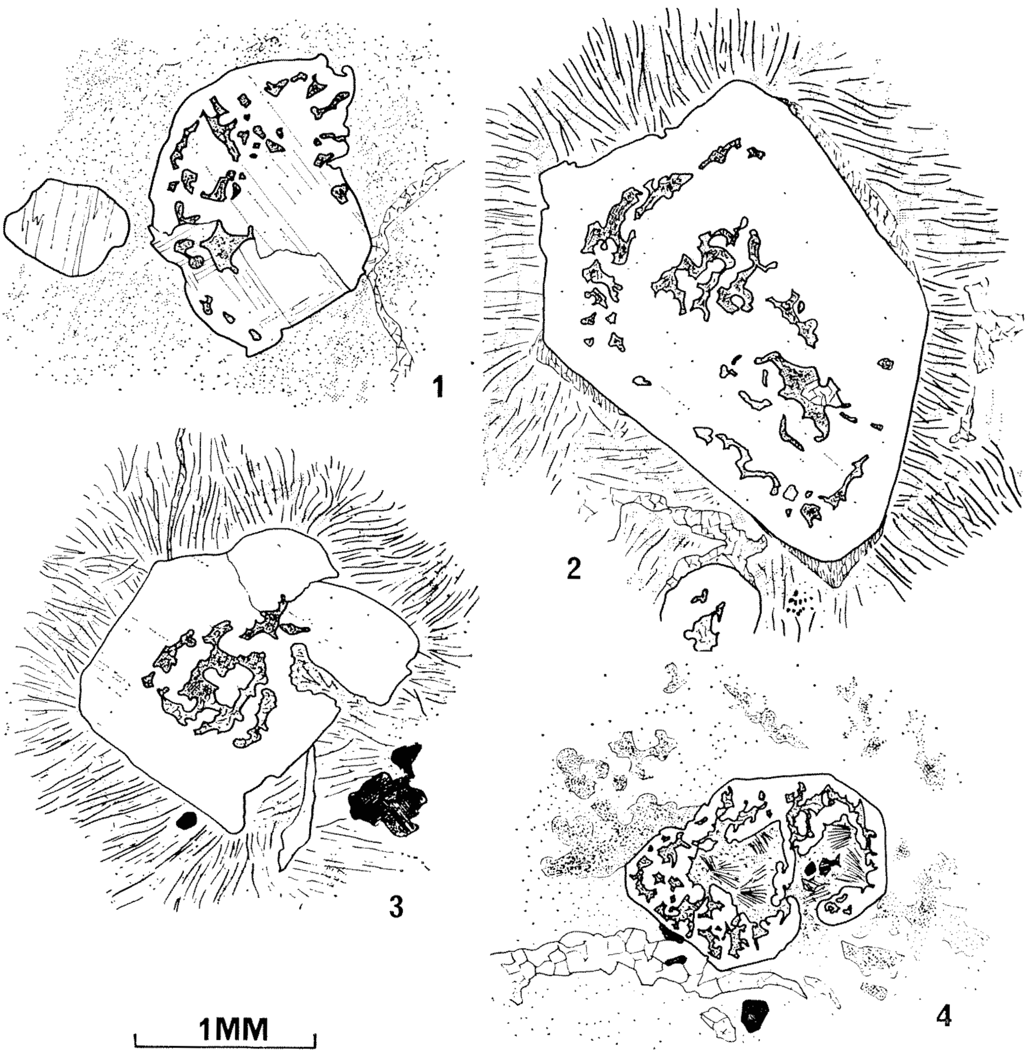

Figure 21. Form of inclusions in plagioclase phenocrysts in acid volcanic rocks of the Warburton Region:

(1) Plagioclase in extremely fine-grained groundmass in thin, basal, well banded, spherulitic zone of Gombugurra Rhyolite. Groundmass cut by thin quartz vein on right.

(2) and (3) Plagioclase from spherulitic top of Gombugurra Rhyolite showing well developed zonal arrangement of inclusions.
Traces of twin planes indicated by thin lines. Groundmass is extremely fine grained with pronounced radiating texture related to spherulite development. Quartz mosaic is developed marginal to some phenocrysts and as veins. A small biotite aggregate is seen in (3).

(4) Skeletal plagioclase with lobate inclusions in acid volcanic rock from Palgrave volcanic association. Groundmass is fine grained and shows patchy extinction and dark, lobate areas. Quartz mosaic at base is part of a "vein band".

mineral composition is similar to that described from lower down in the same zone except that hematite is a noticeable, though minor, addition. Some recrystallization of quartz and plagioclase has taken place in the "shadows" of some of the plagioclase phenocrysts and is accompanied by magnetite, fluorite and biotite.

A little higher stratigraphically, the rock is still closely comparable with that below. Its phenocrysts consist of plagioclase (An_{28}) and opaques partially replaced by sphene. Some of the plagioclase is zoned and shows more albitic rims which are also less well twinned than the cores. Mafic clots are still noticeable and consist of magnetite, fluorite and epidote as in the clots lower in the sequence, but include chlorite instead of biotite and carry, in addition, sphene and apatite. In addition to the normal accessories a small amount of blue-green tourmaline is present.

Rocks of the turbulent zone of this formation are well flow banded, show a variable development of zig-zag folds and weather to produce a dark grey, shiny surface. Plagioclase phenocrysts are noticeable and frequently contain abundant lobate inclusions of groundmass. Thin epidote veins are present and a patchy development of small spherulites with associated quartz and iron sulphides is noticeable. The groundmass of the turbulent zone is very fine grained and consists of quartz, potash feldspar and plagioclase with accessory biotite, muscovite, sphene, opaques, hematite, epidote, piemonite, calcite, apatite and rare zircon. The biotite and muscovite are often intergrown.

Rocks of the spherulitic zone are porphyritic and aphanitic with an abundant development of spherulites from one eighth of an inch to one quarter of an inch (3.2 to 6.3 mm) in diameter. The groundmass is brown and cryptocrystalline with well developed fluidal texture. Relict variolites are apparent as thin, discontinuous, black trails of dust. The spherulites have a lighter tone than the rest of the groundmass and consist of a fine, radiating, extremely finely crystalline material with irregular patches of more coarsely crystalline quartz. The fluidal texture is preserved through the radiating structures, but not through the quartz mosaic. Feldspar phenocrysts are often to be found at the centres of the spherulites and have presumably acted as nuclei for devitrification. The phenocrysts are euhedral to subhedral plagioclase and show well developed lobate inclusions. Some of the inclusions possess a radiating texture resembling that present in the spherulites, strongly suggesting a derivation from original glass. Accessories in the spherulitic zone consist of piemontite, sphene, green biotite, opaques, apatite, sericite, brown biotite, tourmaline and zircon. The rock appears to have been a porphyritic glass with well developed fluidal texture. The rock subsequently devitrified and spherulites grew, preserving the original flow structure. Later, portions of the spherulites recrystallized to a fine-grained mosaic of quartz. Slight physical or chemical differences between adjacent thin bands are suggested by d ffering devitrification characteristics.

Both the top and bottom of the Gombugurra Rhyolite show ample evidence of their original glassy nature, but no evidence for the presence of shards has been found. Plagioclase phenocrysts have apparently crystallized rapidly and enclosed glass or liquid in the process, the texture produced being present in phenocrysts throughout the whole section and not just in the aphanitic margins. For the main mass of the unit the groundmass shows a decrease in grain size upwards. Mineralogical changes are slight: hematite increases upwards, whereas biotite decreases and is replaced partially by a green variety. Vertically, epidote gives place to piemontite.

CHEMISTRY

Samples from three of the four acid volcanic formations in the Cassidy Group (the Wururu, Gombugurra and Hilda Rhyolites) were chosen for chemical analysis. They were selected from fresh looking rock from the laminar flow zone of each formation and in these cases the whole formation is thought to have been a single cooling unit. The results are given in Table 5, along with their normative minerals and various ratios.

TABLE 5. NORMATIVE QUARTZ, ORTHOLASE AND ALBITE OF ANALYSED ACID VOLCANICS OF THE CASSIDY GROUP.

Normative Mineral	Wururu Rhyolite	Gombugurra Rhyolite	Hilda Rhyolite
Quartz	30.45	30.31	29.31
Orthoclase	27.62	29.69	36.25
Albite	27.46	27.72	24.25
	Recalculated to 100 per cent		
Quartz	35.6	34.6	32.6
Orthoclase	32.3	33.8	40.4
Albite	32.1	31.6	27.0

From the flow pattern study it was deduced that all the acid volcanic formations of the Cassidy Group probably originated from the same source, and since the stratigraphic sequence of these units is not in doubt their progressive variations may be studied.

On the basis of normative feldspar proportions, the Wururu and Gombugurra units are strictly speaking, rhyodacites, while the Hilda unit is a true rhyolite.

From the chemistry it is possible to show several consistent trends upwards in the stratigraphic sequence:

1. progressive increase in alkali
2. progressive increase in silica
3. progressive increase in normative orthoclase
4. progressive increase in Li_2O
5. progressive decrease in total Fe_2O_3 and FeO

6. progressive decrease in Fe_2O_3/FeO ratio
7. progressive decrease in An content of normative plagioclase
8. progressive decrease in Fe_2O_3
9. progressive decrease in FeO
10. progressive decrease in TiO_2, CaO, H_2O^+, CO_2, MnO, BaO.

Progressive trends are also illustrated in Figure 22, showing plots of normative plagioclase against normative orthoclase, and An content of normative plagioclase against SiO_2 content of the rock. In both cases a large gap exists between the plots for the Gombugurra and Hilda units and it is tempting to suggest that the Thomas Rhyolite would fall there.

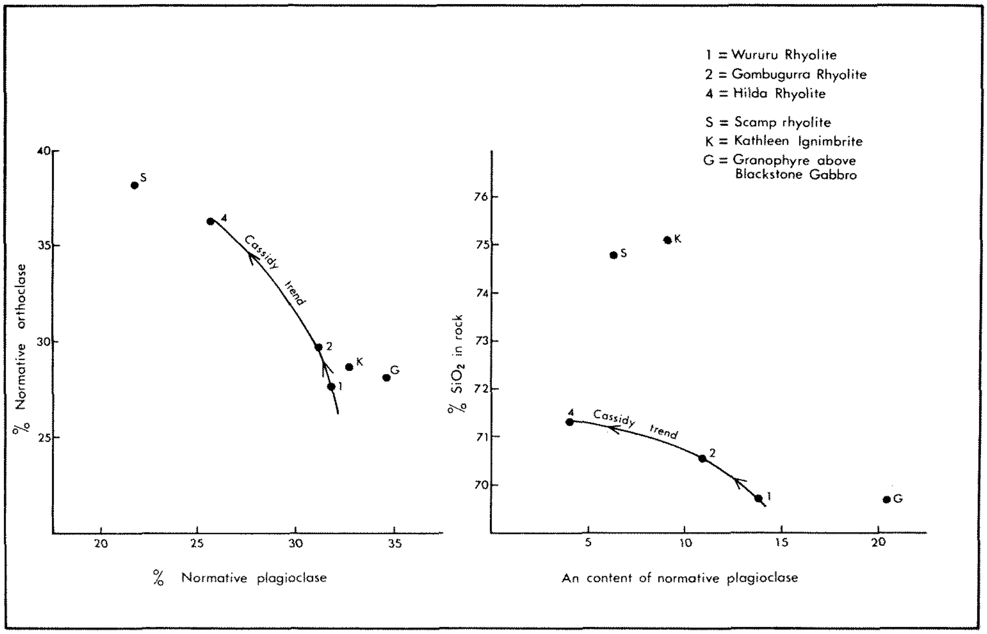

Figure 22. Plots showing relationships of various features of acid volcanic rocks and granophyre from the Blackstone Region.

A plot of the acid volcanic rocks of this group on the quartz-orthoclase-albite ternary diagram is important (Fig. 23). Table 5 gives the normative quartz, orthoclase and albite and their recalculation to 100 per cent.

The point M·5 on the diagram represents the ternary minimum point for the dry system quartz-albite-orthoclase at a pressure of 0.5 kilobars. M1-M4 represent the ternary minima at 1 to 4 kilobars pressure respectively. Increase in pressure consequently moves the cotectic line (E-E[1]) towards the orthoclase-albite margin. At all times the liquidus surfaces slope away from the orthoclase, albite and quartz corners towards the ternary minimum.

The plot of the three analyses of Cassidy Group acid volcanics, in stratigraphic sequence forms a pronounced trend progressing up the liquidus surface

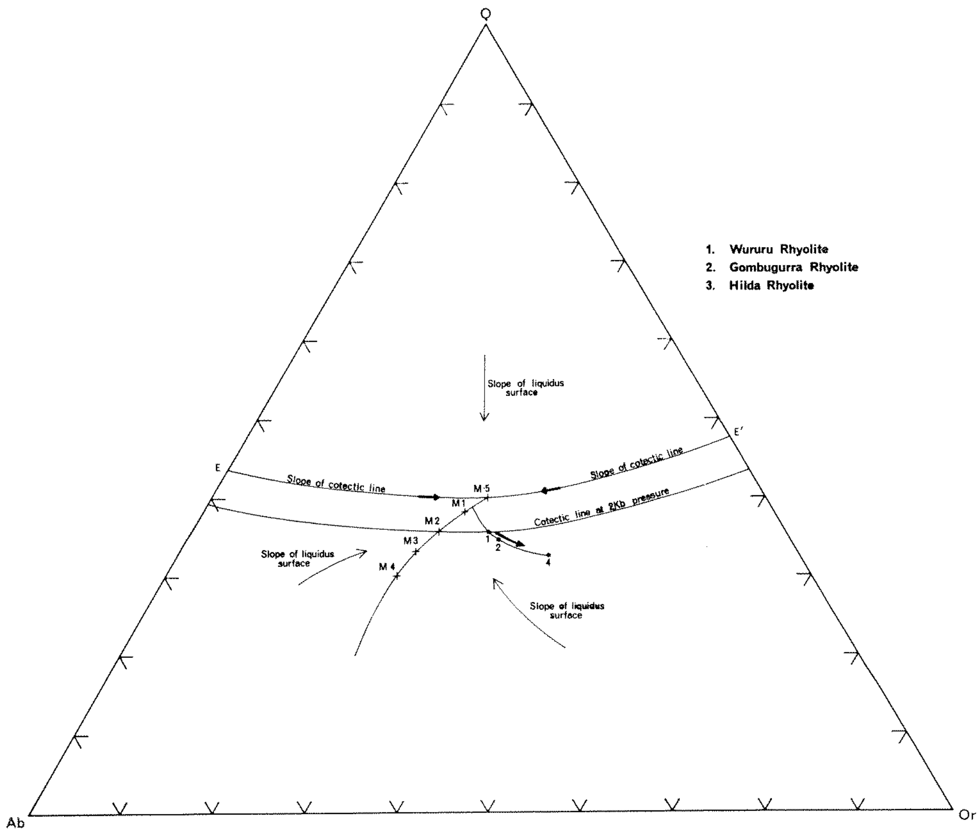

Figure 23. Acid volcanics of the Cassidy Group plotted on quartz-albite-orthoclase ternary diagram. For explanation see text.

nearly parallel to the direction of greatest slope. The inference is that the sequence is unlikely to represent a crystallization differentiation trend, but more probably represents the result of progressive anatexis.

Extrapolation of the trend back to the ternary minimum line gives an intersection at M = 0.8 kilobars. The limiting position at the other extreme is given by the intercept of the cotectic line E-E[1] with the ternary minimum line when analysis No. 1 falls on E-E[1]. The intersection falls at M = 2 kilobars.

These values suggest possible limits between which the acid volcanics of the Cassidy Group may have been produced by anatexis. Converted to approximate depths below surface the limits are from 2.5 km to 7 km.

The above estimate uses the simple anorthite-free system, but it is known that considerable modification is necessary if anorthite is also taken into account (Winkler, 1967). The main effects of the addition of anorthite are:

1. displacement of the cotectic line towards the quartz corner.
2. increase in the orthoclase content of the minimum melt
3. increase in the temperature of formation of the minimum melt.

The displacement of the cotectic line towards the quartz corner also displaces the minimum melting points in a direction approximately directly away from the albite corner. The amount of the displacement depends on the albite/anorthite ratio of the original rock. The effect of a small amount of anorthite would be that the depth estimates given above and calculated on the basis of an anorthite-free system are too low. Without knowing the original Ab/An ratio, it is not possible to estimate its full effect. However, the Ab/An ratio of the first acid volcanic in the sequence is moderately high (Ab/An = 6.3) and could indicate that the previous depth estimate is not very much on the low side.

The increase in the orthoclase content of the successive acid volcanics is very noticeable. If progressive anatexis with repeated filter pressing driving off the anatectic melt accounts for this suite of rocks, then the orthoclase increase could be explained by the increase in anorthite content of the residual material, which would also require successively higher temperatures for melting to occur.

It is interesting to speculate on the source of the heat required to produce the postulated anatexis. As described above, one of the main features of the Cassidy Group is the repeated alternation of acid and basic volcanics suggesting a close genetic relationship.

The gravity-high postulated as a source area for the Cassidy Group acid volcanics may be caused by a large mass of basic material (Lonsdale and Flavelle, 1963). Possibly the emplacement of this was responsible for the anatexis, for the postulated filter press action, and for the associated basic lavas. If this was the case, the acid melt could have been heated well above its melting temperature, and may have been extruded extremely violently as enormous nuées ardentes. These would form extensive ignimbrite sheets possessing enough mass and internal heat to weld completely, with the total destruction of shard forms.

Ratté and Steven (1964) in their study of a sequence of ash flow sheets and interlayered lava flows related to the Creede Caldera, Colorado, established a stratigraphic sequence and differentiation trend. They regard the sequence as representing the products of continuing differentiation of a magma. The differentiation trend reproduced from their paper is given in Figure 24. On this diagram has been added the trend of the Cassidy Group rhyolites which is strikingly opposite to that of the Creede Caldera source area and is evidence in support of an anatectic origin for the Cassidy Group rhyolites.

BASIC VOLCANICS

GURGADI BASALT

The Gurgadi Basalt is the lowest named basaltic horizon in the Cassidy Group and consists of 1,600 feet (490 m) of fine to medium-grained epidotic, vesicular and amygdaloidal basalt. Several flows are present, each having a well developed amygdaloidal and vesicular top.

The original rock was probably a porphyritic tholeiite, but has been considerably altered and is now represented by aggregates of oligoclase (An_{12}) and epidote

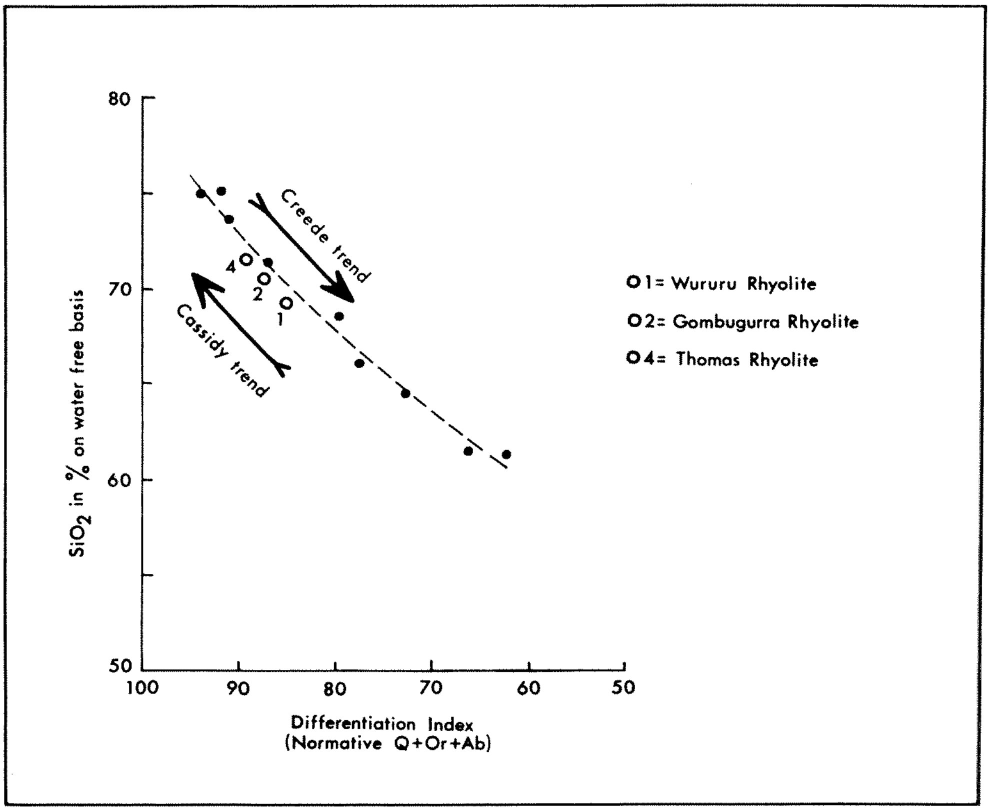

Figure 24. Comparison of differentiation trends of acid volcanics of the Cassidy Group and acid volcanics related to the Creede Caldera, Colorado.

with some tremolite-actinolite, ilmenite and sphene after ilmenite. Green biotite and chlorite occur mainly in amygdales along with epidote, calcite and minor quartz. The original ophitic texture is preserved, and apparently the epidote has pseudomorphed original pyroxene.

WARUBUYU BASALT

This formation is similar to the Gurgadi Basalt and consists of several flows totalling 500 feet (150 m). The rock is a fine-grained epidotic, vesicular and amygdaloidal basalt.

MILLER BASALT

The Miller Basalt, at the top of the Cassidy Group, consists of numerous thin flows mostly 25 to 50 feet (7.6 to 15.2 m) thick, together totalling 2,400 feet (730 m). The rocks were originally porphyritic and amygdaloidal olivine basalts and are now represented by laths of oligoclase (An_{11-17}) often replaced by sericite and epidote, and pseudomorphs after olivine consisting of hematite, epidote, quartz and chlorite. The amygdales carry either mosaic quartz, mosaic calcite, calcite, epidote and quartz, or epidote and chlorite.

Alteration of some of the basalts is intense and has completely obliterated primary minerals, leaving an aggregate of sericite, quartz and epidote.

SEDIMENTARY ROCKS

Above each of the rhyolites, except the uppermost one, thin sedimentary bands are developed. These bands range in thickness from 150 feet to 400 feet (45 to 120m) with the thinnest horizon developed lowest in the sequence, and the thickest developed above the third, or Thomas Rhyolite.

The rocks consist of shale, siltstone, marl, tuff and rarely, in the lowest horizon, ripple-marked sandstone and pebble beds.

MISSION GROUP

The development of the Mission Group (Table 1) is restricted to the low-relief, scrub-covered area between the Warburton Range and the Townsend Ridges. It conformably overlies the Cassidy Group and is itself apparently unconformably overlain by the Townsend Quartzite. The total thickness of the group is approximately 13,300 feet (4,000 m), excluding a wedge-shaped conglomerate horizon developed over a small distance at the base. Apart from the western extension of a dolomite-rich formation, the group is, on the whole, poorly exposed in contrast with the underlying Cassidy Group.

GAMMINAH CONGLOMERATE

The Gamminah Conglomerate conformably overlies the Miller Basalt in the region approximately 2 miles (3 km) north of Frank Scott Hill. In this region the formation is some 1,500 feet (460 m) thick. It thins rapidly to the west and is absent about 3 miles (5 km) northwest of Frank Scott Hill. Outcrops are very poor to the east, and nothing is known about its easterly extension.

The formation is dominantly conglomerate with minor sandstone. Current-bedding is frequently well developed and indicates a source area to the northeast. The clasts are well rounded pebbles and cobbles, up to 9 inches (23 cm) in diameter, and consist principally of rhyolite and basic volcanics with minor, small, cream to white agate pebbles.

The transition from Miller Basalt to Gamminah Conglomerate takes place over a few tens of feet, and consists of a zone of mixed basic volcanics, conglomerate, and finer clastic sediments. Towards the top of the formation the sediments become finer grained and pass gradually into the overlying Frank Scott Formation by the addition of shale and dolomite.

The formation records the results of a local instability which probably manifested itself as a fairly rapid rise of the land to the northeast, allowing deposits of the underlying Cassidy Group to be eroded.

FRANK SCOTT FORMATION

The Frank Scott Formation was previously referred to informally as the Elder Dolomite by Sofoulis (1962a). It is approximately 800 feet (240 m) thick in its western outcrop, 4 miles (6.4 km) east of Warburton Mission, and forms a disconnected series of low rounded hills extending from Elder Creek to near Frank Scott Hill. No sign of thinning of the formation is apparent at either end of the line of outcrops, and it can be assumed that it extends farther.

The air-photograph pattern is distinctive, and consists of a repetition of thin light and dark bands representing the many rapid changes in lithology within the formation. Individual bands are from less than 1 inch (2.5 cm) to a few feet thick, and are laterally persistent for long distances. Minor crenulations in the banding are abundant.

The lithology includes very finely laminated siltstone, dolomitic siltstone, shale, and cream, fawn and grey-weathering dolomite. Of minor importance are sandstones and cherts. Cross-bedding is apparent in some of the dolomites, siltstones and grits. Two and a half miles (4.0 km) west-southwest of Mount Hilda, the sequence is dominantly siltstone, shale and minor dolomite, but it carries some bands of edgewise conglomerate about 1 foot (30.4 cm) thick, and thin chert horizons partly fragmented and somewhat displaced. Pyrite is noticeable in some of the dolomite and siltstone bands.

Immediately north of Frank Scott Hill, approximately 50 feet (15 m) below the top of the formation, interbedded grey-weathering and cream-weathering dolomites are present. Two thin bands of the cream-weathering variety have small colonies of stromatolites sporadically developed, with individual heads up to approximately 9 inches (23 cm) across and 6 inches (15 cm) high (Fig. 25). Cockbain (1967) describes these as possessing irregular, broadly uparched banding, tending to flatten on top. The bands are approximately 1 mm wide, but finer and coarser bands are present. Earlier bands are often truncated by later bands, suggesting erosion of the heads. Branching is rare but one specimen showed two heads forming from a single head. Cockbain remarks that "no closely similar species are known from Australia. The Warburton material resembles the *Cryptozoon australasicum/columnaris* group but differs in the flatter-topped heads and shorter columns. In these features the specimens approach the *Collenia pseudocolumnaris* group but retain separate heads. This particular form has not been recorded from elsewhere in Australia".

The Frank Scott Formation overlies the Miller Basalt between Warburton Mission and Mount Herbert. The transition from one formation to the other takes place over approximately 15 feet (4.5 m) of section which consists of interbanded thin basalt flows, and thin silts and dolomites. Near Frank Scott Hill, however, the Frank Scott Formation rests on a thick lens of conglomerate and sandstone, the Gamminah Conglomerate, which thins out rapidly westward.

The lower part of the Frank Scott Formation near Frank Scott Hill carries much shale and siltstone and passes down with a rapid increase in the number of coarse sandy sediments and pebble beds into the main part of the Gamminah

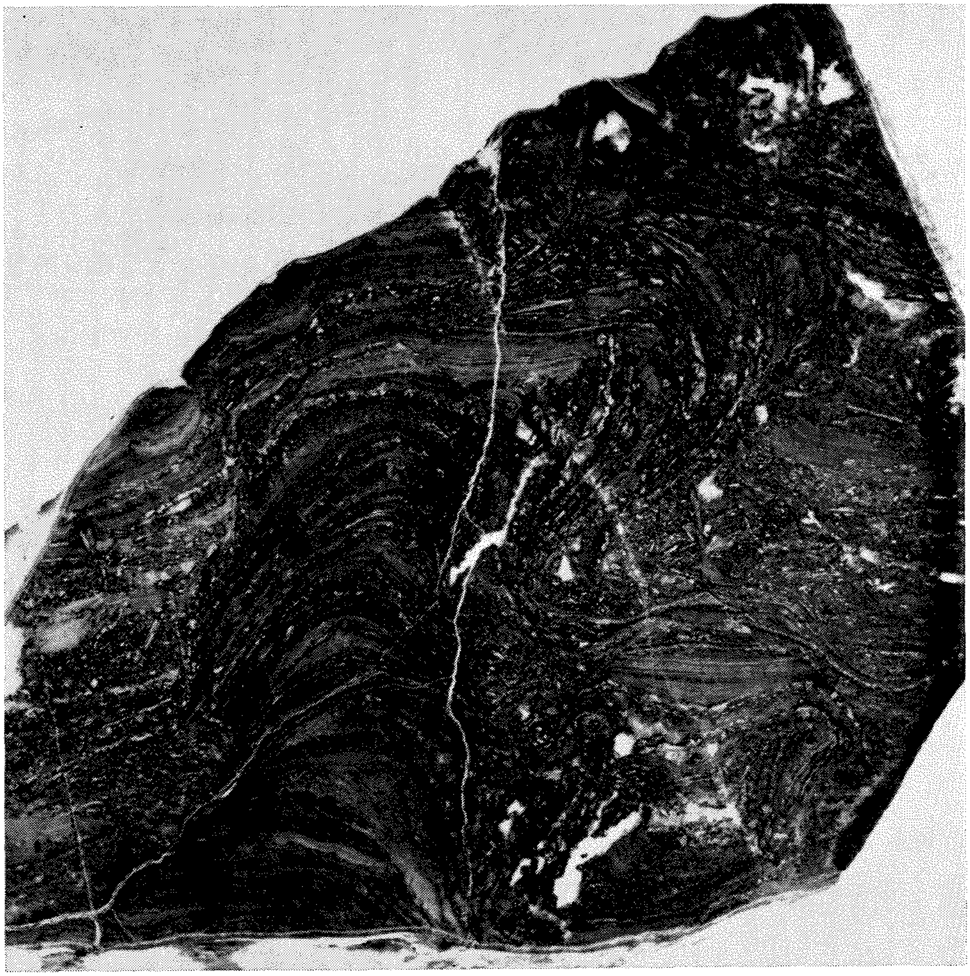

Figure 25. Algal structure from Frank Scott Formation, near Frank Scott Hill, Talbot Sheet area.

Conglomerate. The total thickness of the Frank Scott Formation in this locality is much less than to the west, suggesting that the Gamminah Conglomerate may be, in part, the lateral equivalent of the lower part of the Frank Scott Formation, as developed in the area immediately south of Mount Hilda, and represents a modification of the normal sedimentary sequence caused by local uplift and erosion. The current-bedding in the conglomerate suggests depositional currents flowing from the northeast, while the clasts indicate a landmass composed dominantly of basic vesicular lavas and a variety of porphyritic and non-porphyritic acid volcanic rocks. The fresh nature of the basic lavas suggests that this particular conglomerate was deposited after the Miller Basalt, with insufficient break to allow any chemical breakdown of the clasts.

Four and a half miles (7.2 km) south-southeast of Mount Talbot a small lens of columnar-jointed, slightly vesicular basalt is present in the uppermost 100 to 200 feet (30 to 60 m) of the Frank Scott Formation (Fig. 26). The vesicles in the basalt are elongated in a northeast to southwest direction and probably indicate the orientation of the palaeoslope at the time of extrusion. It is overlain by a few feet of thin, well banded shaly sediments, possibly tuffaceous. This basalt member may equate with a 5-foot (1.5 m) thick basic, vesicular lava 30 feet (9 m) below the top of the formation immediately north of Frank Scott Hill. In the latter locality the lava is overlain by interbedded shales and grey-weathering dolomite. In both areas a possible thin dolerite is present in sediments overlying the volcanic horizon and may be a satellite sill of the overlying coarse-grained dolerite unit referred to by Sofoulis (1962a) as the Hughes Formation. This unit has now been dropped from the stratigraphic column because its intrusive origin is no longer in doubt.

LILIAN FORMATION

Overlying the Frank Scott Formation, but separated from it by a prominent dolerite sill (Hughes Formation of Sofoulis, 1962a) is the Lilian Formation. It

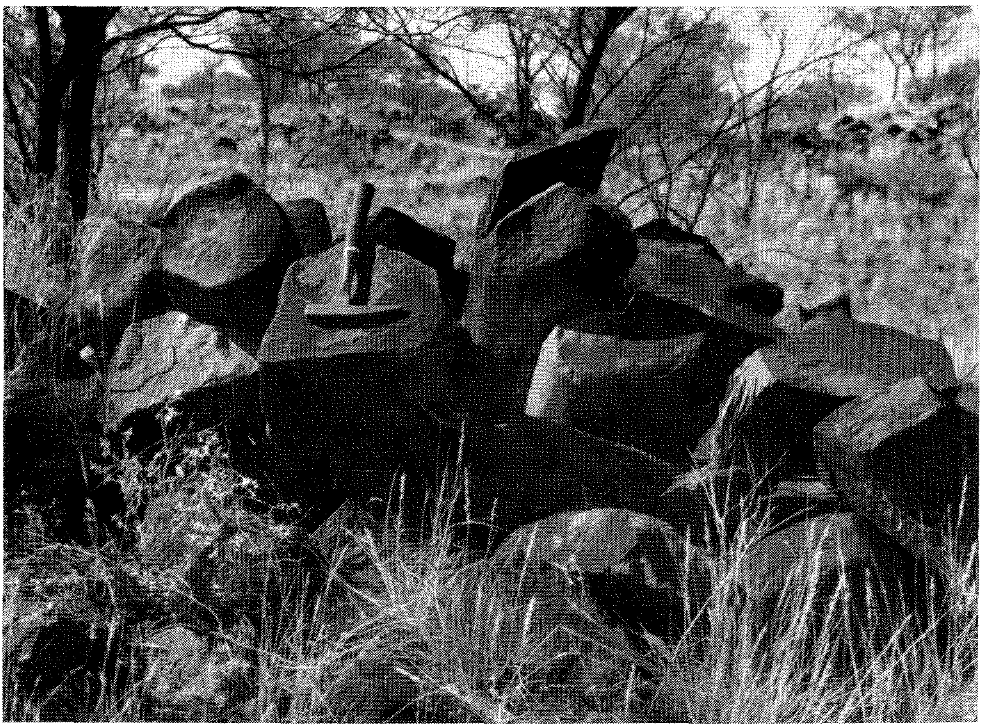

Figure 26. Columnar jointed basalt at top of Frank Scott Formation, 4½ miles south-southeast of Mount Talbot.

is about 3,000 feet (900 m) thick and forms the lower part of the unit termed Ainslie Volcanics by Sofoulis (1962a).

It consists principally of shale with minor intercalated thin basic lavas, minor dolomitic shale and several polymict conglomerates. One principal chert horizon is present in which possible silicified *Collenia* sp. have been identified. The conglomerate horizons carry abundant agates and rounded pebbles of rhyolite.

MILESIA FORMATION

Conformably overlying the Lilian Formation is the Milesia Formation, whose maximum exposed section north of Townsend Ridge indicates a minimum thickness of about 9,500 feet (2,900 m).

It consists principally of basic volcanics with some prominent quartzite lenses, shale, and conglomerate.

TOWNSEND QUARTZITE

The Townsend Quartzite crops out as a prominent broken ridge for a distance of approximately 70 miles (110 km) from Brown Range in the west, immediately south of Warburton Mission, to Hocking Range in the east of the Talbot Sheet area. Farther east in the Cooper Sheet area the formation is present as a series of minor discontinuous ridges, except 5 miles (8 km) south of Skirmish Hill where the outcrop widens and consists of several parallel ridges. Its lateral equivalent is thought to be the Livesay Range, where the unit crops out in a domal structure.

In the western outcrops the general southerly dip of the formation, varying from 20 degrees in the Brown Range to 36 degrees in the Townsend Ridge, gives rise to several steep, prominent, north-facing scarps. Elsewhere its expression is subdued and frequently masked by a thin sand veneer.

The formation overlies the Mission Group. Its contact is not exposed. In the western part of the area, general parallelism of strike and dip of the Townsend Quartzite and the underlying Mission Group suggests that they are conformable. However, in the region immediately north and east of Mount Ranford a very strong divergence of strike is apparent (Plate 2) and an unconformity is postulated. Farther east the Townsend Quartzite overlies a variety of rock types. Nine miles (14.4 km) south of Mount Blyth the formation unconformably overlies conglomerates and basalts of the Tollu Group, while only a few miles farther east granite and granitic gneiss form the basement to the quartzite. Similar acid gneisses underlie the Townsend Quartzite 12 miles (19.3 km) west of Mount Agnes, while immediately south of Skirmish Hill the formation unconformably overlies acid volcanics and associated granophyres of the Skirmish Hill cauldron.

In the upper part of the Mission Group, north of Brown Range, several thin, elongated quartzite lenses appear. These resemble the Townsend Quartzite and could be the forerunners of a much more extensive quartzite inundation. The thin Mission Group quartzites may have been deposited conformably while active uplift and erosion was proceeding to the east. The amount of uplift decreased westward and had little or no effect in the Warburton Mission area. With the temporary cession of uplift and erosion east of Mount Ranford at the eastern end of Townsend Ridge, widespread sand deposition took place—conformably in the west and unconformably in the east. This contact is further discussed below.

The Townsend Quartzite is here included in the Bentley Supergroup to emphasize its possible relationship to the other older groups and formations of the region.

Its relation to the overlying rocks is not well known. Southwest of Hocking Range, steeply dipping glacial deposits of probable Upper Proterozoic age overlie the Townsend Quartzite, but no contact is exposed. Similar glacial deposits overlie the formation south of Townsend Ridge and Brown Range. It is thought that the contact of the Townsend Quartzite and overlying glacial deposits is disconformable.

Good exposures of the formation are present approximately 3½ miles (5.6 km) east of Lilian Gorge where R. A. Farbridge subdivided the Townsend Quartzite into two main units based mainly on differences in sedimentary structures but partly on topographic expression. The following descriptions are by Farbridge.

The lower unit at this locality is 280 feet (85 m) thick. It consists of thin to thick-bedded, flaggy, often feldspathic, slightly micaceous sandstone. Some shale flake horizons and isolated, sparse pebble beds are present. The unit contains abundant planar cross-beds and minor trough cross-beds. The cross-sets are up to 1½ feet (45.7 cm) thick. Also present are abundant asymmetrical ripple marks, some symmetrical ripple marks and occasional interference ripple marks. Desiccation cracks and frondescent markings occur on bedding planes and a possible "mud volcano" was noted.

A thickness of 560 feet (170.6 m) was measured for the upper unit in the same locality. Here the upper unit consists of coarse to very coarse-grained, thick to very thick-bedded sandstone. Cobble-pebble horizons are common with clasts up to 6 inches (17.7 cm) in diameter and consisting almost entirely of quartzite. Minor shale flake horizons are present.

Large-scale cross-bedding with units up to 5 feet (1.5 m) thick are common. The foresets are planar and some show grading. Overturned foresets are not uncommon. The cross-sets are usually tabular. Liesegang rings and stripes have developed locally. No ripple marks were observed.

The variation in the stratigraphic thickness of these two units is given below (Table 6).

Palaeocurrent measurements were made on ripple marks, cross-beds and primary current lineations. On the whole the indicated current directions determined from the ripples are similar to those determined from the cross-bedding and indicate depositional currents flowing mainly towards the southwest and

TABLE 6. OBSERVED STRATIGRAPHIC THICKNESSES OF TOWNSEND QUARTZITE, TALBOT SHEET AREA.

Locality	Upper Unit (feet)	Lower Unit (feet)
3½ miles east of Lilian Gorge (Type section)	560	280
½ mile south of Lilian Gorge	300	68
9 miles west of Lilian Gorge	370	? absent

Note: 1 mile = 1.6 km. 1 foot = 0.3048 metres.

southeast. Some directional structures suggest transport from east or west, but these were probably related to locally generated currents or long shore drift. The most likely source area was probably north or northeast of the present outcrop. The area between Barrow Range and the South Australian border was probably actively rising over a considerable period and could quite likely have been land during the deposition of the Townsend Quartzite. The presence of desiccation cracks in the lower part of the formation in the Lilian Gorge area and also immediately south of Skirmish Hill suggests shoreline conditions.

Slump structures, west of Mount Agnes, indicate a westerly dip to the palaeoslope in that area, whereas near Townsend Ridge a southerly dipping palaeoslope would be suggested by an east to west shoreline and a northerly or northeasterly source area for the sediments.

It is thought that the lower unit of the Townsend Quartzite represents strand-line or near-shore facies and that it was deposited in shallow water in conditions of occasional emergence. The upper unit represents deposition in a deeper water area not subject to emergence.

Included with, and conformably overlying the Townsend Quartzite, are small outcrops of siltstone, previously referred to informally as the Brown Range Siltstone. It is possibly at least 700 feet (210 m) thick. Outcrops are very poor, the best being in the creek immediately south of Ainslie Gorge. It is described by Jackson (1966) as "a weathered, grey to maroon, shaly, very argillaceous, micaceous siltstone. The silt particles are of angular quartz and the matrix is an indeterminate mixture of clay minerals and sericite".

The southern exposures of the Townsend Quartzite consist of well bedded sandstone with occasional thin bands of grey to black silicified oolite.

The domal structure forming the Livesay Range in the western central part of the Cooper Sheet area is composed dominantly of arenaceous sediments tentatively correlated with the Townsend Quartzite.

A section in the range was measured by Hunt Oil Company and is given below:

top

25 feet (7.6 m) —pink to brown, fine to medium-grained, quartz sandstone showing ripple marks

50 feet (15.2 m)—white hard quartzite

10 feet (3.0 m) —yellow ochreous siltstone and sandstone

40 feet (12.1 m)—quartzite.

Neither the top nor the bottom of the whole succession is exposed.

CAULDRON SUBSIDENCE AREAS

Three cauldron subsidence areas, named Scamp, Skirmish Hill and Palgrave, are recognized in the Blackstone Region, and their locations and distribution

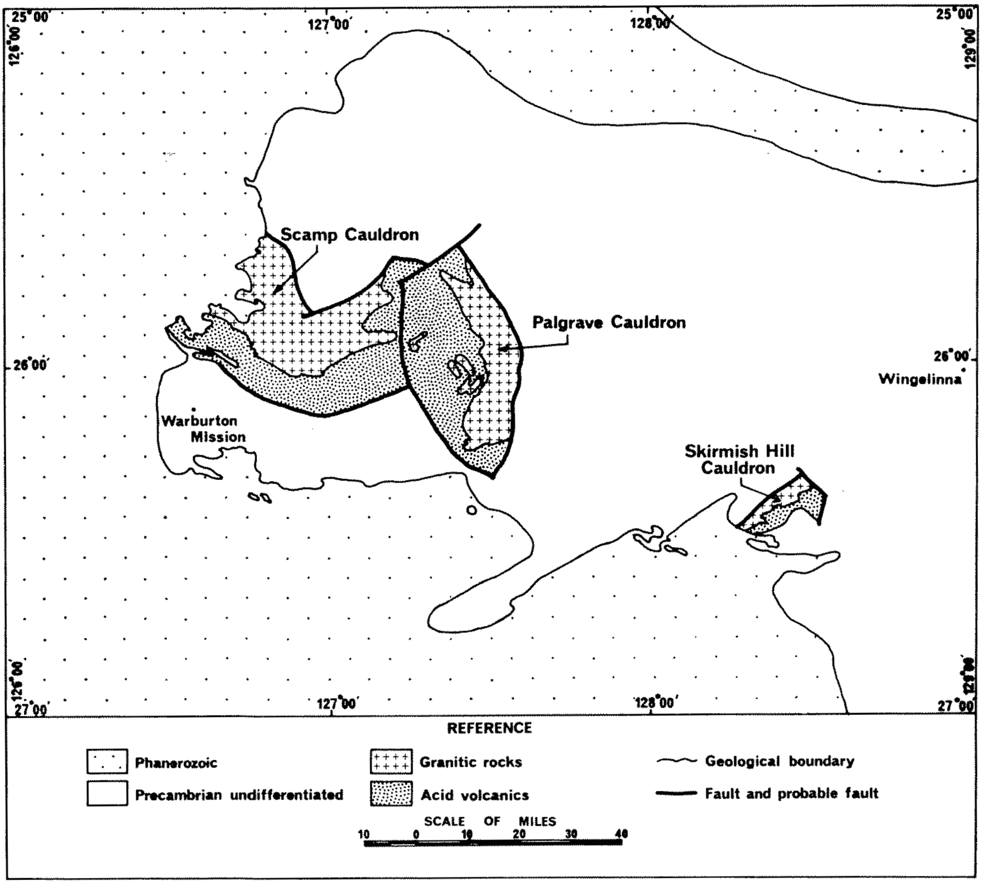

Figure 27. Sketch map showing locations and simplified geology of cauldrons in the Blackstone Region.

are given in Figure 27. Scamp cauldron is older than Palgrave cauldron, but the relative age of the Skirmish Hill cauldron is not known.

The Skirmish Hill cauldron is unconformably overlain by the Townsend Quartzite and the Scamp cauldron cuts the Pussy Cat Group. These relationships allow the inclusion of the volcanic associations within the cauldrons in the Bentley Supergroup.

SCAMP CAULDRON

Scamp cauldron is the name given to the area which contains rocks of the Scamp volcanic association together with the granitic rocks intrusive into these volcanics. It has a roughly east-west elongation, though its overall shape and limits are not completely defined. Much of the southern boundary is a reasonably well-defined fault line, but the northern side is hypothetical, being defined partly by linear features observed in the calcrete and colluvium, and partly by the regional distribution of rock types. The present eastern limits are determined by part of the ring fracture of the Palgrave cauldron. The western limits are unknown because that area is unconformably overlain by Phanerozoic sediments.

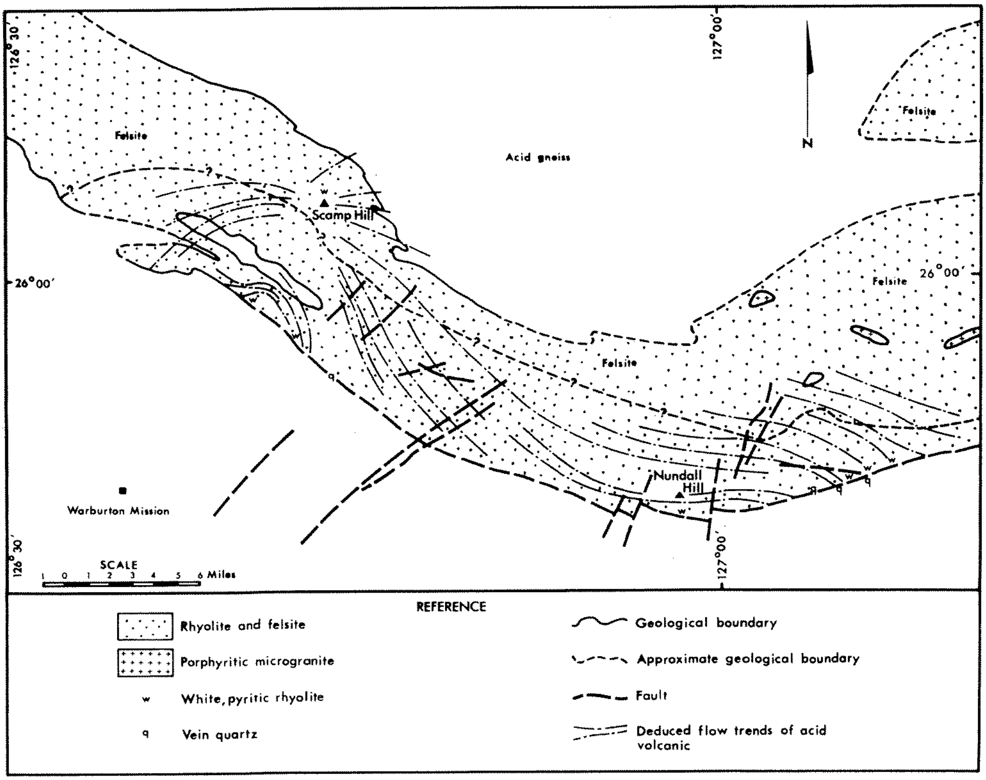

Figure 28. Suggested flow pattern for Scamp Rhyolite.

If these limits are approximately correct then the Scamp cauldron is irregularly shaped, has a minimum area of 927 square miles (2,400 km^2) and is 40 miles (64 km) long by 22 miles (35 km) broad. By extrapolation the possible original area is calculated to have been 1,435 square miles (4,415 km^2).

The orientations of flow lineations on some of the acid volcanics in the cauldron have been mapped, and the regional flow pattern deduced from the measurements. The results, summarized in Figure 28, indicate a major source in the area close to Scamp Hill. The source gave rise to copious material which radiated away from Scamp Hill.

Though Scamp Hill is likely to be the major source, at least one other centre is indicated by the presence of agglomerates 2 miles (3.2 km) northeast of Mount Waugh.

White, pyritic, fluoritic rhyolite is abundantly developed along the southern boundary fault and sporadically near Scamp Hill. The rock is probably related to fumarolic activity associated with the fault and vent respectively, and the zone of alteration may be up to 200 feet (60 m) wide. Intermittently along the fault the white rhyolite is accompanied by vein quartz. This is particularly well developed near Mount Waugh.

The Scamp volcanic association consists mainly of a distinctly flow-banded and flow-lineated, extremely fine-grained acid volcanic rock. It weathers to a medium reddish brown, is slightly porphyritic and carries frequent specks of blue fluorite. Abundant, small, oval-shaped darker rock fragments are often present, and suggest that the rock is a tufflava. Immediately north of Mount Waugh the acid volcanics overlie basalts, together with a variety of coarse agglomerates.

In their northern outcrops the acid volcanic rocks are somewhat coarser grained and are referred to as felsite. The change in grain size is gradational and has not destroyed some of the primary features of the rock, including the spherulitic texture and original banding. The felsitization of this acid volcanic rock is possibly related to the intrusion of granite and porphyritic microgranite into the acid volcanic rock, and subsequent local folding.

The margin of this granite is complex and difficult to trace in the field. Undoubtedly it has been folded along east-west axes, but the folding is only of local significance and is probably confined to the northern half of the cauldron. The folding has impressed a local gneissic texture on to the granite.

SKIRMISH HILL CAULDRON

Although the Skirmish Hill cauldron is the least known of the three recognized cauldrons in the Blackstone Region, it is generally similar to the other two. It is composed of distinctive red and black-weathering acid volcanics and minor basaltic horizons intruded by granophyre. The latter forms the prominent feature of Skirmish Hill.

Its exposed area, 95 square miles (246 km^2), is very much smaller than either of the other two cauldrons. Its southern limits are unconformably overlain by Townsend Quartzite. No estimate of its possible original size can be given and its boundaries are hypothetical. A little evidence exists for the presence of a fault on the northwest side of Skirmish Hill and linear features on the northeast are interpreted as faults.

PALGRAVE CAULDRON

The name Palgrave cauldron is given to the roughly oval-shaped area straddling the 26° parallel at longitude 137° 30′ and depicted on the tectonic sketch map (Plate 2) as an area of acid volcanics intruded by granitic rocks, and surrounded by a roughly oval boundary fault. Its long axis trends north-northwest and measures 44 miles (71 km), while its maximum width is 23 miles (37 km). The cauldron covers an area of approximately 722 square miles (1,870 km^2).

Rocks of the cauldron form the prominent topographic feature known as the Barrow Range and also many smaller hills to the north and northwest. The overall grouping of these hills shows up well on the diagram of the physiographic units of the Blackstone Region (Plate 1). They form a block of country whose trend is noticeably different from the main east to west nature of the majority of the other hills and ranges.

The position of the marginal fault has been deduced from regional considerations. The line of the fault shows up best on the air-photographs of the southwest corner of the Scott Sheet area, but it may also be observed on the air-photographs of the area about 8 to 12 miles (13 to 19 km) south-southeast of Mount Palgrave. Major and minor differences in rock types have been used to define the rest of the margin.

Within the cauldron are preserved a large variety of porphyritic acid volcanics associated with devitrified obsidians, agglomerates, and minor tuffs. These have been intruded by a large volume of granite, named the Winburn Granite, and minor gabbro and dolerite.

A solid geology interpretation of the distribution of the main rock types in the cauldron is given in Figure 29. Its most noticeable feature is the arcuate disposition of much of the volcanic material and the presence of several partial ring dykes of porphyritic microgranite. A possible concentric zonal scheme for the two main facies of the Winburn Granite is also apparent.

The arcuate form of the plan in the central part of the cauldron strongly suggests that the centre of the arc is a source for much of the volcanic material and also controls, in some way, the distribution of the granitic intrusions, especially the minor ones.

On a geometrical basis, therefore, the centre would appear to lie 4½ miles (7.2 km) east of Mount Palgrave. This area is very poorly exposed, being almost entirely covered by colluvium and wind-blown sand. A minor exposure of

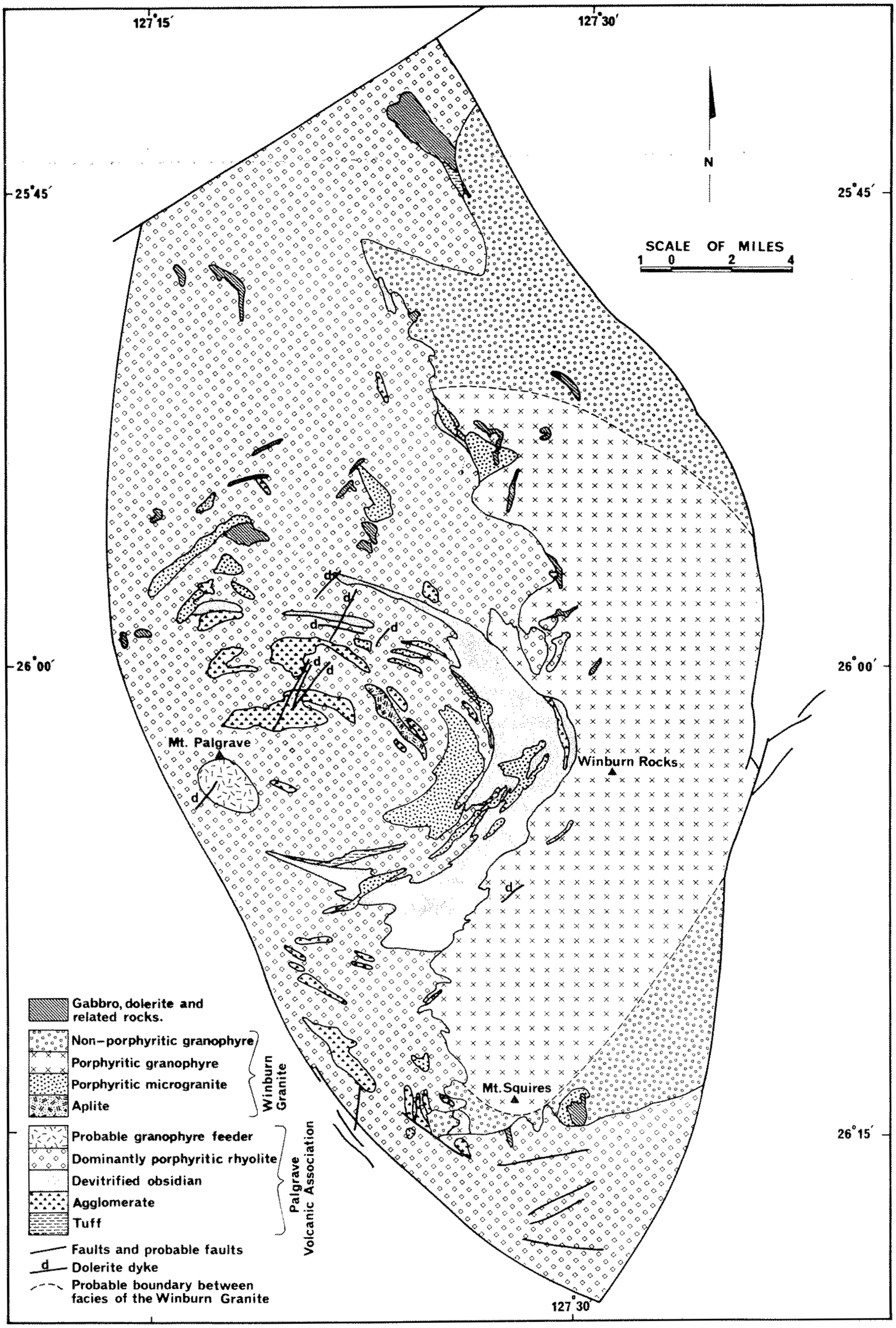

Figure 29. Sketch map showing distribution of main rock types in the Palgrave cauldron subsidence area.

agglomerate was located in this general area. It is noteworthy in that it contrasts with the other agglomerates in having zoned fragment margins (Fig. 30), suggesting post-formation hydrothermal activity.

Several of the acid volcanics in the cauldron show moderately well developed flow lineations. These have been plotted on a map and the regional flow pattern

Figure 30. Agglomerate showing zoned reaction edges, east of Mount Palgrave, Talbot Sheet area.

has been deduced from them (Fig. 31). The pattern is simple, with the flow lines converging on a point close to Mount Palgrave. Immediately south of Mount Palgrave are exposures of a fine to medium-grained granophyre deduced to be a feeder and shown as such on the sketch map.

The flow pattern of the Kathleen Ignimbrite, a formation of the Pussy Cat Group in the Whitby Range, has been added to the diagram. As this unit thins to the west it is suggested that, in combination with the flow pattern, a source

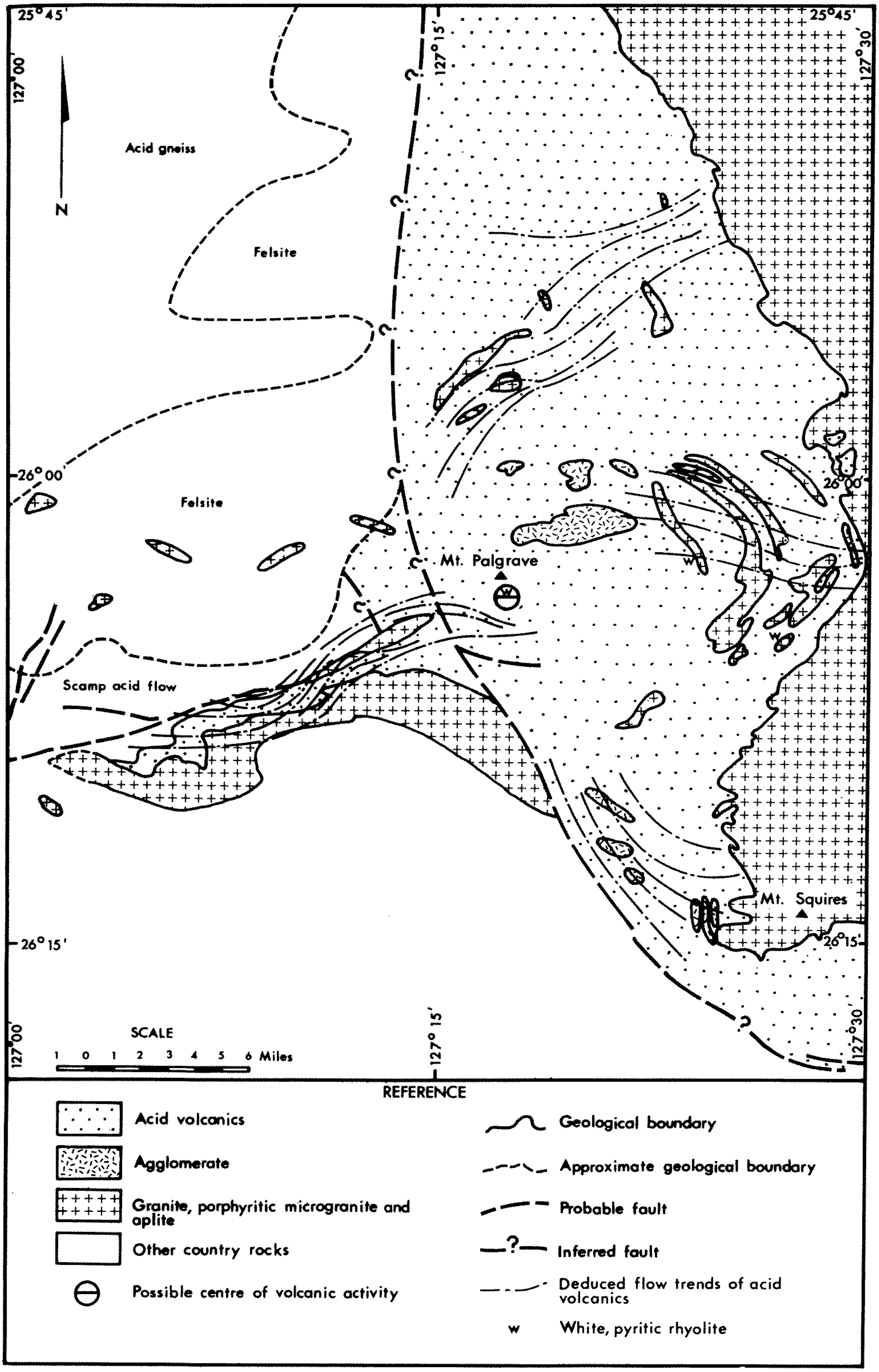

Figure 31. Deduced regional flow pattern of acid volcanics in the Mount Palgrave region.

near or at Mount Palgrave is possible. The ignimbrite could represent some of the earliest ejecta related to the Palgrave cauldron. This would be in agreement with a generally held idea (Gorshkov, 1966) that ignimbrites are confined to the neighbourhood of calderas.

Some small patches of devitrified obsidian in the northern part of the cauldron, and irregularly shaped agglomerate patches, possibly vent agglomerates, suggest the possibility that several other minor feeders may exist. Fumarole activity has possibly occurred in several areas, and their positions are recognized now by the presence of white pyritic zones up to 100 feet (30 m) across in the rhyolite.

PALGRAVE VOLCANIC ASSOCIATION

The volcanic rocks in the cauldron have been called informally the Palgrave volcanic association. This consists of a very large variety of acid volcanic types. Only the broad subdivisions have been mapped.

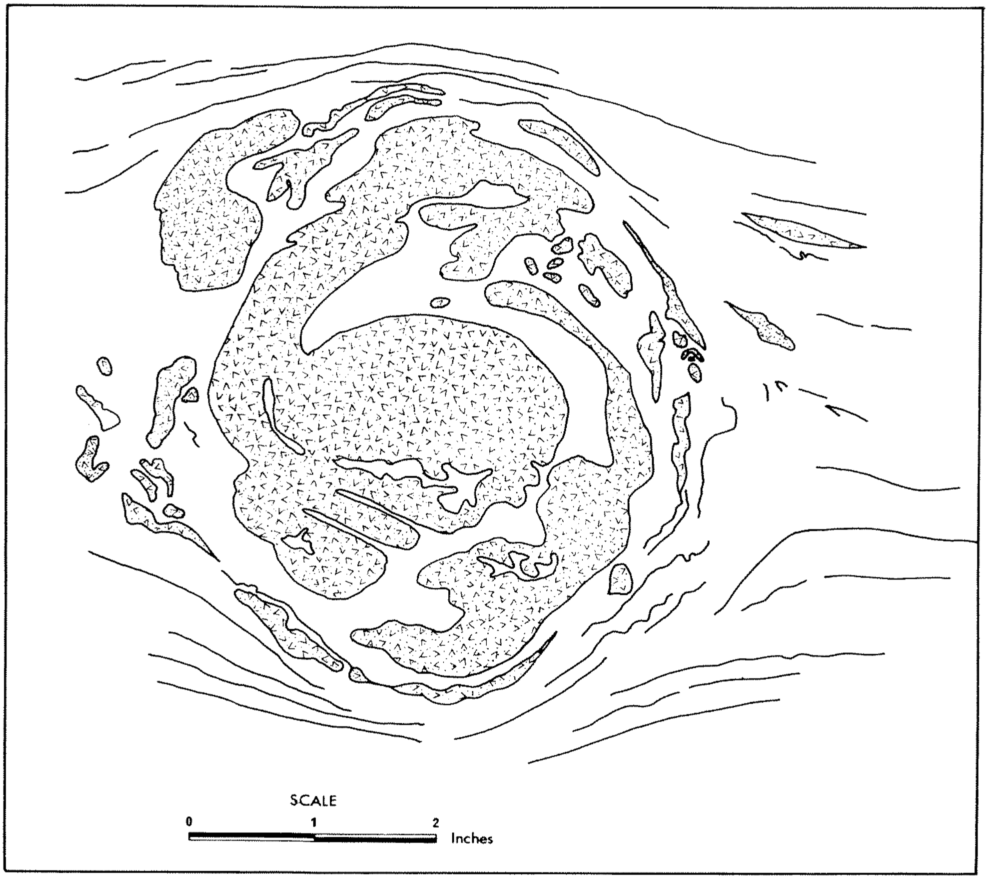

Figure 32. Cross section through rotated medium-grained acid volcanic fragment (toned) included in foliated cryptocrystalline rhyolite from the Palgrave volcanic association.

Field characteristics are very variable. Some show crude columnar jointing and many have spherulitic flow tops with or without some surface brecciation. The spherulites range in size from one-eighth of an inch (3.2 mm) to approximately 9 inches (22.8 cm) across though sizes between half an inch (12.7 mm) and 1 inch (2.5 cm) are most common. In many of the flows the spherulites increase in size towards the top. A few of the flows possess vugs often elongated parallel to the base of the unit and many show thin lenses rich in blue fluorite. Many are pyritic.

Flow banding, flow lineations and vein banding are moderately well developed. The latter is almost entirely developed near the base of the cooling units, and consists of slightly irregularly shaped extensive bands of quartz, 1 to 2 mm thick, parallel to the base of the flow. It appears to be a useful facing criterion in these acid volcanics. Since it is not developed near the tops of the flows, vein banding is probably related to the cooling history of the single cooling unit.

Some of the flow-banded units carry "xenoliths" of more coarsely crystalline rhyolite. These sometimes show a "spiral nebula"-type cross section indicating rotation of a plastic mass during flow (Fig. 32).

Dark stretched inclusions have been noted, probably indicating that some of the rocks are properly called tufflavas.

Perlitic texture is abundant in the eastern exposures a few miles west of Winburn Rocks. Glass shard shapes however have not been recognized, but breccias of fragmented devitrified glass have been seen at the tops of some flows.

Individual bands are very variable in thickness, ranging from a few feet to several hundred feet. Lateral continuity is difficult to establish, except over short distances. A section from approximately 2 miles (3 km) northwest of Winburn Rocks illustrates the variation:

Top *Unit No.*	*Thickness* (feet)	*Lithology*
8	45	coarsely porphyritic rhyolite
7	150	devitrified banded obsidian with spherulitic top
6	75	devitrified obsidian with spherulitic top
5	250	rhyolite showing spherulitic top, a uniform centre and a vein-banded base
4	60	agglomerate or coarse tufflava
3	180	devitrified obsidian with a network of perlitic cracks
2	370	devitrified obsidian
1	240+	agglomerate.

Note: 1 foot = 0.3048 m.

Similar variations are present in areas of predominantly porphyritic rhyolite.

Many of the individual flows are vertically zoned and show major and minor textural variations. An example of the variation may be seen in a single cooling unit approximately 3 miles (5 km) west of Mount Squires. The flow is about 200 feet (60 m) thick, overlies a thin tuff and is overlain by a finely foliated, vein-banded, slightly porphyritic rhyolite. The base of the unit is vein banded and passes up into a zone with abundant perlitic cracks indicating the former presence of glass. Minor, small, corroded phenocrysts of plagioclase and quartz are present. The groundmass is a complex of finely crystalline and cryptocrystalline quartz and feldspar, with abundant granular epidote, green hornblende, opaques and minor calcite. Approximately three-quarters of the way up the unit phenocrysts are slightly more abundant and aggregates of epidote are common. The groundmass is very finely crystalline, still noticeably rich in finely granular opaques and epidote, but amphibole is absent. The top of the flow is markedly brecciated with some fragments up to 6 inches (15.2 cm) across. The groundmass is similar to that immediately below but shows flow texture and carries abundant oval inclusions occupied by mosaic quartz and feldspar with occasional epidote. The inclusions were probably drawn out gas vesicles infilled at a later date.

A comparison of the textural variations in three acid volcanic units from the Palgrave cauldron is given in Figure 33.

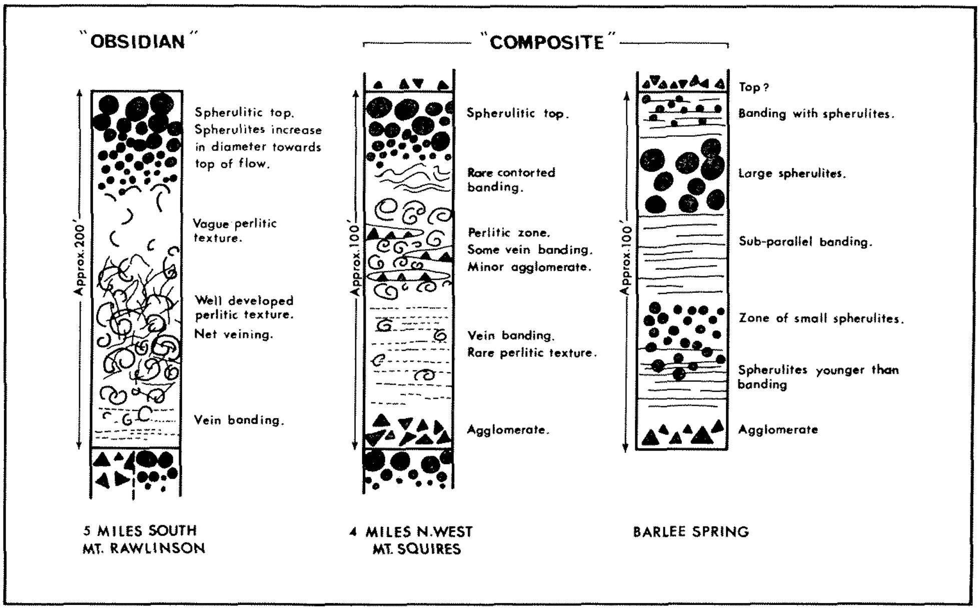

Figure 33. Diagrammatic illustration of textural variations in some acid volcanic rocks from the Palgrave volcanic association.

A rhyolite agglomerate from 3 miles (4.8 km) northeast of Mount Palgrave on the southern side of the large mass of agglomerate (see Fig. 30) shows much secondary alteration, possibly related to the proximity of a vent. The fragments in the rock and their groundmass carry a variety of minerals including calcite, tourmaline, minute dodecahedra of pink garnet, fluorite, pistacite, piemontite, green biotite and ilmenite rimmed by sphene.

WINBURN GRANITE

The Winburn Granite is the name given to a complex of porphyritic and non-porphyritic varieties of granite and granophyre, intrusive into the Palgrave volcanic association.

The main mass forms about one-third of the surface exposure of the cauldron. It is confined to the eastern part of the structure, with apophyses and partial ring dykes in the central section and several isolated areas to the north (Fig. 29). The eastern margin of the granite is defined by the eastern portion of the cauldron boundary fault. The western margin is ragged, the granite having broken off large blocks of acid volcanics and sent apophyses into the main part of the Palgrave volcanic association. The intrusion is devoid of pegmatites and only a few small aplite veins were encountered. In some of the rocks a vague foliation is apparent, defined by the orientation of mafic minerals and is probably a magma flow feature.

The Winburn granite consists of four main rock types. These are non-porphyritic granophyre, porphyritic granophyre, porphyritic microgranite and aplite.

The main mass of the intrusion consists of porphyritic and non-porphyritic granophyre. The porphyritic variety occupies the central part and is flanked on the north and south by the non-porphyritic variety. The boundaries between the two varieties (Fig. 29) were suggested by Lewis (1969) from an examination of thin sections, and are somewhat arbitrary. However, the northern boundary is reasonably well controlled and suggests that the Winburn Granite is a ring complex. The relative ages of the two facies are not known for certain. Some xenoliths of probable non-porphyritic granophyre occur in the porphyritic variety suggesting that the porphyritic facies intrudes the non-porphyritic facies.

The petrographic descriptions of these rocks have been supplied by Lewis (1969). Partial chemical analyses of rocks from the granite are given in Table 7.

NON-PORPHYRITE GRANOPHYRE

Non-porphyritic granophyre occupies the northern and southern parts of the Winburn Granite. The northern occurrence is the more coarse grained.

The principal minerals include perthite, quartz, biotite and hornblende, with lesser amounts of plagioclase, microcline and opaque iron oxide. Accessory minerals include zircon, apatite, sphene and fluorite, with epidote as a frequent alteration product.

Perthite usually occurs as large crystals up to 5 mm across which show an inner area free of quartz and an outer area with a coarse granophyric relationship to quartz. Unlike the perthite of the porphyritic variety there is rarely any indication that growth of the perthite stopped at any point but rather that at a particular stage of crystallization quartz began to crystallize with the perthite. When not involved in the granophyric relationship, quartz can be present as

TABLE 7. PARTIAL ANALYSES OF ACID ROCKS FROM THE WINBURN GRANITE

Spec. No.	Na_2O	K_2O	CaO	MgO	FeO (*d*)	Li	Sr	Ba	Sn	Cu	F	B
	per cent on dry basis					parts per million						
18004	3·24	5·21	0·22	0·01	1·41	7	20	800	20	25	1,200	18
18012	2·30	0·17	2·06	0·03	0·33	(*a*)	420	40	(*b*)	5	70	7
18020	2·91	5·40	0·31	0·05	1·04	2	40	610	10	10	1,300	6
18025	2·91	6·00	0·27	0·08	0·96	4	30	780	15	10	1,600	10
18137	4·05	4·27	0·15	0·04	1·13	(*a*)	30	1,000	(*b*)	30	770	4
18139	3·23	5·37	0·43	0·02	1·29	12	10	100	5	5	3,200	6
18141	4·16	0·19	2·00	0·10	0·39	(*a*)	420	110	10	5	180	8
18142	2·97	4·99	0·28	(*c*)	0·22	(*a*)	45	520	(*b*)	5	60	3
18143	3·07	4·08	1·59	0·40	3·07	10	140	1,200	15	55	560	10
18147	3·65	4·36	1·08	0·36	1·45	3	100	1,000	15	20	760	7
18148	3·05	4·97	0·10	0·01	0·64	(*a*)	40	360	35	5	1,200	5
18152	2·30	5·63	0·01	(*c*)	0·39	(*a*)	55	2,000	5	10	95	5
18233	3·14	5·46	0·07	0·01	0·71	3	30	560	5	5	720	3
18270	3·43	5·50	0·32	0·06	1·22	3	55	800	(*b*)	5	1,700	(*a*)
18274	3·35	5·43	0·18	0·08	0·85	5	65	1,100	5	15	1,100	6
18275	3·72	4·79	0·48	0·09	2·96	(*a*)	85	920	10	10	1,400	11
18277	3·15	5·76	0·27	0·08	1·00	2	40	520	(*b*)	5	1,900	5
18278	3·16	5·59	0·22	0·04	1·09	(*a*)	55	620	(*b*)	5	1,600	3
18279	3·54	4·45	0·25	0·01	1·34	(*a*)	50	1,000	15	5	1,100	2
18281	2·99	5·31	0·52	0·09	1·40	3	65	670	(*b*)	5	1,400	(*a*)
18283	2·88	5·65	0·31	0·13	2·21	7	55	820	(*b*)	10	1,700	2
18287	3·13	5·17	0·36	0·08	1·75	5	60	680	(*b*)	5	1,900	6
18290	2·81	5·58	0·56	0·18	1·34	18	100	930	5	10	2,200	3
18309	3·55	4·74	0·43	0·08	2·07	5	75	930	(*b*)	10	1,500	27
18310	3·06	5·20	0·52	0·13	1·25	5	80	930	10	5	1,000	21
18312	1·50	7·92	0·07	0·08	1·00	3	30	880	(*b*)	5	530	19
18321	4·12	0·25	0·80	(*c*)	0·27	(*a*)	290	30	5	(*b*)	150	3
12278	2·73	5·50	0·28	0·09	1·03	4	30	580	15	(*b*)	1,500	9
12283	2·75	5·41	0·29	0·09	1·29	6	25	580	30	5	2,000	13
12287	3·53	5·19	1·11	0·01	0·37	(*a*)	290	910	15	5	140	(*a*)

(*a*) less than 2
(*b*) less than 5
(*c*) less than 0·01
(*d*) ferrous iron, expressed as FeO.

irregular interstitial masses. In some specimens exsolution of plagioclase from perthite has proceeded sufficiently to give discrete smaller grains of oligoclase and microcline. Some oligoclase may be of early crystallization as it shows zoning to albite.

The most common mafic minerals are hornblende and biotite. The original hornblende was probably a green-brown, strongly pleochroic variety occurring as large ragged crystals. It is now often converted to a blue-green variety. Two varieties of biotite occur. One is pale red brown and is present as secondary small flakes, the other is probably primary and occurs as larger olive-green flakes, pleochroic to dark red brown. The latter variety often forms vermicular intergrowths with quartz.

The opaque mineral is probably ilmenite and is often rimmed by small grains of sphene. Zircon, apatite and fluorite are common.

PORPHYRITIC GRANOPHYRE

The porphyritic granophyre of the Winburn Granite occupies the central portion of the main outcrop (Fig. 29). The rock is comparatively homogeneous and shows much less variation than the non-porphyritic facies. Phenocrysts of quartz and perthite are characteristic and set in a fairly fine-grained granophyric matrix. Biotite is the principal mafic mineral, hornblende being present in only a few examples. Smaller amounts of ilmenite, sphene and fluorite are usually present and zircon and apatite are constant accessory minerals. Tourmaline and allanite are present in some samples and sericite and epidote are present as alteration products.

Microcline perthite phenocrysts generally 2 to 4 mm across commonly form 10 to 15 per cent of the rock and are usually subhedral. A few plagioclase phenocrysts are also found and some are zoned from oligoclase (approx. An_{14}) to albite; the albite being a clear fresh rim to the oligoclase. Plagioclase has usually grown at the expense of perthite, via myrmekite.

Biotite is the usual mafic mineral, occurring as flakes up to 1 mm long, and is strongly pleochroic from pale green or yellow brown to dark olive brown. Smaller flakes of secondary red-brown biotite are also common. Relict fragments of green hornblende occur in a few samples together with a little secondary blue-green hornblende. The opaque mineral is usually skeletal ilmenite often coated with a thick rim of granular sphene. In more epidotized specimens the ilmenite is converted to an aggregate of sphene and leucoxene.

Zircon, apatite and epidote are constant accessory minerals. The first two are usually associated with biotite and ilmenite. Fluorite is found in most specimens.

PORPHYRITIC MICROGRANITE

Though this rock is closely related to the porphyritic granophyre it is a very distinctive rock unit. It occurs as a marginal facies to the porphyritic granophyre and as discrete partial ring dykes. The contacts of the ring dykes with rocks of the Palgrave volcanic association show numerous minor apophyses extending into the host rock. The coarse porphyritic character and intrusive nature of these rocks distinguishes them from most of the porphyritic acid volcanics.

One example, occurring as a marginal facies to the porphyritic granophyre, approximately 5 miles (8 km) northwest of Mount Squires, consists of phenocrysts of quartz, plagioclase and perthite set in a felsite matrix. The following description is typical of the whole suite.

Phenocrysts occupy about 30 per cent of the rock and are predominantly of quartz ranging in size from 1 to 7 mm across. All phenocrysts are corroded and well rounded in outline and the embayments are almost equally spaced 60 degrees from each other, suggesting a crystallographic control. Plagioclase (oligoclase) phenocysts are often in composite groups. Perthite phenocysts are not numerous and are always small.

The groundmass is a fine-grained mosaic of quartz, plagioclase and alkali feldspar with some exceedingly fine granophyric intergrowths between quartz and alkali feldspar. Biotite is the only dark mineral and occurs as small olive-brown flakes scattered throughout the rock. There has been some alteration of biotite to chlorite and some very pale mica might be muscovite or bleached biotite. Apatite, zircon and sphene are accessory minerals and small amounts of calcite and fluorite are present filling minor cracks and veins.

The porphyritic microgranite of the partial ring dykes is very similar, though the groundmass is perhaps a little finer grained. In one such example the groundmass, a felsitic quartz-feldspar mosaic, contains small areas which appear to be rosettes of elongated quartz needles which may indicate the former presence of tridymite.

In the Whitby Range two prominent sills of porphyritic microgranite intrude the Pussy Cat Group. Their affinities are not known for certain, but their close mineralogical similarity to the porphyritic microgranites within the Palgrave cauldron suggests a common origin. Rarely these sills show a slight foliation defined by the mafic minerals. It is not persistent over distances of more than a few feet and is probably a magmatic flow feature.

APLITE

Aplite forms one of the partial ring dykes some 6.5 miles (10.4 km) east-northeast of Mount Palgrave. It is a fine to medium-grained leucocratic rock consisting principally of perthite, quartz, orthoclase and plagioclase, with accessory biotite, sphene and opaques. Alteration products include epidote, chlorite and sericite.

Orthoclase and plagioclase crystallized early and form comparatively large subhedral to anhedral crystals showing much sericitization. Some of the plagioclase forms lath-like crystals of calcic oligoclase (An_{30}) distinctly more calcic than the plagioclase of the other acid rocks of the Winburn Granite, which have a range of composition from An_6 to An_{18} with a mean of An_{10}.

SUMMARY AND PETROGENESIS

Only the very broad outlines of the geology and history of development of the three recognized cauldrons in the Blackstone Region are known. They are very large structures, comparable with many of the Upper Palaeozoic cauldrons and ring complexes of the Georgetown Inlier in North Queensland (Branch, 1966).

The Blackstone Region cauldrons are developed on or near to known gravity ridges defined by Lonsdale and Flavelle (1963). The Palgrave cauldron is developed on a well-defined gravity-high on one of these ridges and the gravity-high is thought to be caused by a large basic mass at a shallow depth. Some form of relationship between the deduced basic mass, the cauldron and its contained acidic rock types is conjectured.

All three cauldrons show a similar association of acid volcanics and intrusive granitic material, with only minor basic igneous activity either as flows or intrusions. The history of development of the Palgrave cauldron is the best understood, and it can be summarized as follows:

Phase 1 acid volcanic phase
Phase 2 minor basic intrusive phase
Phase 3 acid intrusive phase.

PHASE 1

If the area between Mount Palgrave and Winburn Rocks may be interpreted as a planed-off section through the volcanic pile, then it can be tentatively suggested that the acid volcanic phase may be subdivided again into three, as given below in order of increasing age:

Top

3. obsidian with minor agglomerate
2. porphyritic rhyolite
1. porphyritic rhyolite and major agglomerate.

The boundaries are gradational.

An even earlier phase of explosive volcanic activity may be indicated by the Kathleen Ignimbrite, which may be related to the very early development of the cauldron.

PHASE 2

The minor basic phase manifests itself as several small dolerite and gabbroic bodies. One of these gabbroic bodies 7 miles (11.2 km) north of Mount Palgrave has a thin granophyric differentiate at its top, possibly indicating the presence of a much larger concealed gabbroic mass.

PHASE 3

The granitic phase is composite and may well be more complex than depicted on the map (Fig. 29). The relative ages of the components of this phase are not known. It is possible that the main mass of the Winburn Granite consists of two major phases: an early non-porphyritic hornblende-biotite granophyre and a younger porphyritic biotite granophyre. There are several associated partial ring dykes of aplite and porphyritic microgranite of unknown relative age.

This simplified three-phase historical development suggested for the Palgrave cauldron is similar to that described by Jacobson and others (1958) for some of the ring complexes of Northern Nigeria, though in their examples the basic dykes and semi-conformable basic intrusions are included in the volcanic phase.

Many of the granitic rocks show rounded and embayed quartz phenocrysts. Two hypotheses have been suggested to account for these features. One regards the form as a growth feature; the other prefers the shape to have been developed by magmatic resorption. A brief summary of the problem is given by Dunham (1968). Tuttle and Bowen's experimental work (1958) supports a resorption hypothesis under conditions of decreasing water vapour pressure. In the natural environment such a decrease in pressure could be brought about by several circumstances. These include loss of water vapour pressure perhaps caused by eruption, intrusion of the granitic mass to a higher level or general uplift of the whole area with consequent boiling off of water and possible related eruption.

In all three cases the granitic material is confined to one side of the structure only. This could be explained by asymmetrical foundering or tilting of the acid volcanic pile during emplacement of the intrusive phase, and it is not unlikely that the main encompassing fracture formed at this time also.

The basic material in the cauldrons, especially the gabbroic examples in the Palgrave cauldron may be part of the Giles Complex, and this suggests a possibility that the acid volcanics and intrusive granitic rocks of the cauldrons may be related to the differentiation history of the Giles Complex. The possible relation of acid volcanics in the Warburton region to the gabbroic rocks farther east was tentatively suggested by Fletcher (1932) and at a later date in more detail by Nesbitt (1966). However, the possible production of the Cassidy Group rhyolites from a gravity-high area, by progressive fusion of the crust, was suggested by the writer (p. 66). This explanation may well apply to the other rhyolites of the area. It was also noted in the western part of the Hinckley Range that at least some of the granitic material forming net-vein complexes was probably produced by fusion of granulites by part of the Giles Complex (p. 149). The possibility therefore exists that the acid volcanics and granitic intrusives of the cauldrons are anatectic and not necessarily differentiation products. In either case it is likely that the Giles Complex and the cauldron formation are not greatly separated in time and may overlap.

All the cauldrons should be investigated for Cu, Pb, Zn, Sn, Au, Ag, Mo, W and Nb mineralization.

CHAPTER 4

The Giles Complex

INTRODUCTION

The Giles Complex is the name given by Sprigg and Wilson (1959) to the many basic plutonic masses and associated ultrabasic and acid differentiates which crop out intermittently, largely as a series of monadnocks, in central Australia. The area in which the complex occurs has an overall east-west elongation and extends from approximately 8 miles (13 km) north of Mount Palgrave in Western Australia to approximately 100 miles (160 km) east of Mount Davies in South Australia, a distance of just over 220 miles (350 km). A few isolated outcrops of banded and somewhat metamorphosed gabbro occur in the Bedford Range area in the northeast part of the Bentley Sheet area, and a large basic or ultrabasic mass is thought to be responsible for a positive gravity anomaly approximately 30 miles (48 km) north of Warburton Mission (Lonsdale and Flavelle, 1963). The distance of 220 miles (350 km) may therefore be regarded as a minimum east-west dimension. The area of the province of the Giles Complex is not known with certainty, but could be a minimum of 8,000 squares miles (21,000 km^2) and possibly up to 13,000 square miles (34,000 km^2).

The complex was earlier regarded as a once continuous lopolith disrupted by folding and faulting (Sprigg and Wilson, 1959). Subsequent work has shown that the complex consists of a number of individual sheets and plugs (Nesbitt and Talbot, 1966; Nesbitt, 1966; Daniels, 1967a; Horwitz and others, 1967).

Several of the individual intrusions in South Australia have been studied. Among these are Mount Woodroffe (Wilson, 1947; Major and others, 1967), Mount Davies (Nesbitt and Kleeman, 1964), Ewarara (Goode and Krieg, 1967) and the Teizi anorthosite body, which may be part of the Giles Complex (Gray, 1967). More detailed studies have included X-ray measurements on plagioclases from Mount Davies (Kleeman and Nesbitt, 1967).

Some detail regarding corona structures is given by Goode and Krieg (1967) and Peers (1969). Studies on the nickel mineralization have been published by Thomson (1963, 1965) and Turner (1968), and a brief report on the vanadium occurrence in the Jameson Range is given by Daniels (1967b). A palaeomagnetic study of some of the intrusions has been made by Facer (1967).

The present work on the Giles Complex in Western Australia has progressed along lines that were designed to help subdivide the complex and to determine the relationship of isolated gabbroic masses to the main sheets. If individual sheets

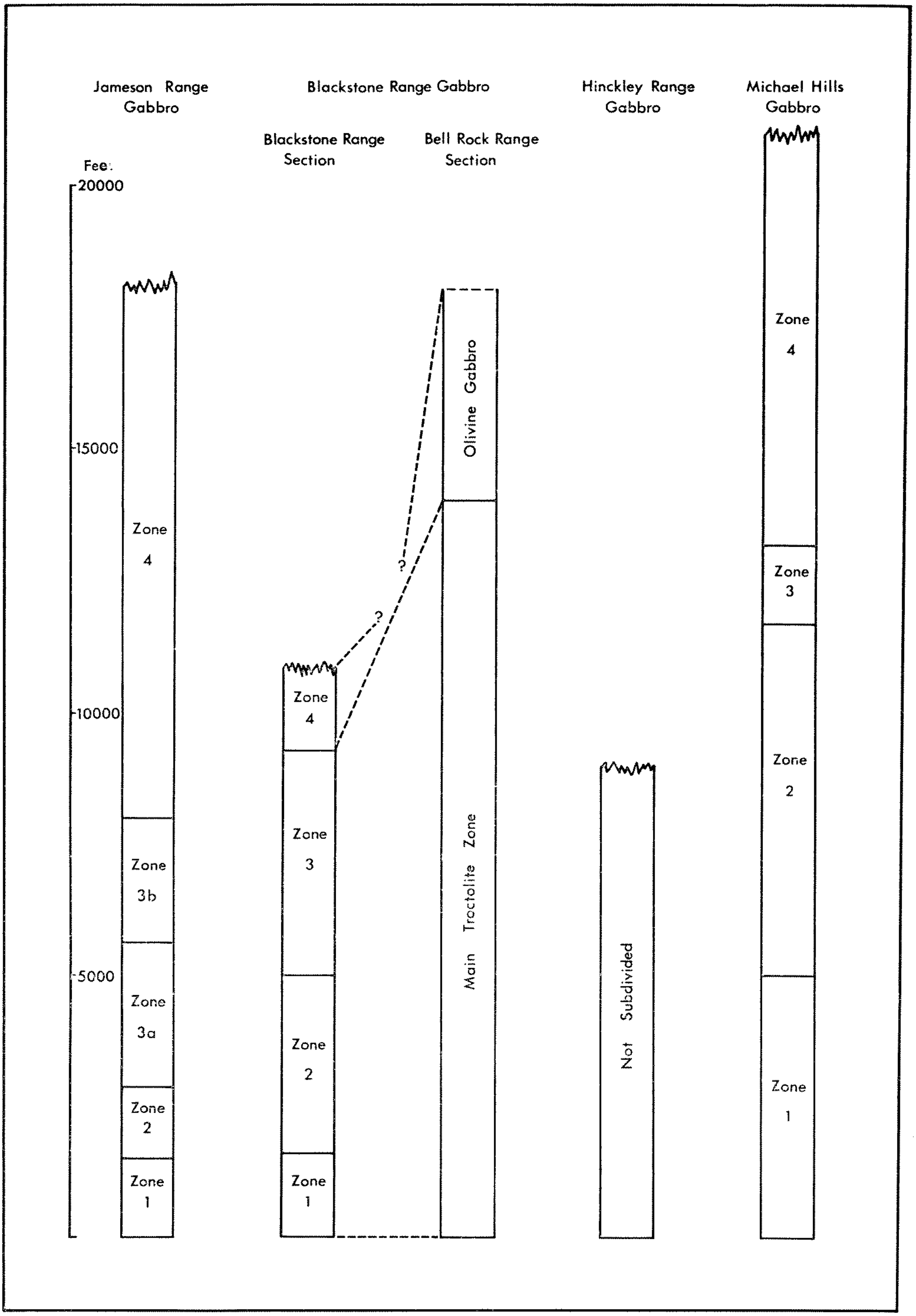

Figure 34. Comparison of thicknesses and major subdivisions of the main sheets of the Giles Complex, Western Australia.

have a chemical bias, then from an economic point of view it is important to know to which sheet each isolated mass belongs. This has been achieved to a large extent, for the Western Australian part of the Giles Complex, by a combination of field determinations and the study of the chemical characteristics of certain minerals.

The number of structurally and chemically distinct bodies is not yet known, but in Western Australia, four main sheets and a number of minor intrusions have been recognized. The main sheets range in thickness from 9,000 to 21,000 feet (2,700 to 6,400 m) and the largest of these extends over an area of approximately 600 square miles (1,500 km^2). A comparison of the thicknesses and major subdivisions of the principal sheets of the Giles Complex in Western Australia is given in Figure 34.

On the whole the basic members of the complex are well banded on a variety of scales. Several ages of intrusion are involved, and structural evidence suggests that the depths of intrusion varied considerably. Rocks of the complex intrude a sequence of charnockites, granulites, porphyritic granites, acid and basic gneisses and porphyritic acid and basic volcanics. The complex is intruded by granite and dolerite dykes. The southwest part of the Jameson Range Gabbro has been truncated by the Palgrave cauldron.

IGNEOUS LAYERING IN THE COMPLEX

A wealth of primary igneous banding features is present in many of the gabbroic rocks of the complex. A study of them is essential in the elucidation of the relationships of disconnected outcrops, and in appreciation of the original shape and mode of formation of some of the individual bodies.

The types of igneous banding or layering in the complex are: rhythmic layering, cryptic layering, phase layering and zone layering.

RHYTHMIC LAYERING

Rhythmic layering is the name given by Wager and Deer (1939) to the small-scale banding, of a few millimetres to several feet in thickness, caused by variations in mineralogical composition of adjacent bands. It is easily the most obvious type of banding seen in outcrops.

Rhythmic layering is probably caused by the action of convection currents in a thick sheet of crystallizing magma, in which the crystallizing phases settle to the bottom. The process of solidification of the magma is therefore considered to take place from the bottom upwards, with minor solidification at the sides and top. The interplay of current strength and crystal supply helps account for the varieties of minor banding present. These varieties resemble similar structures in sedimentary rocks and, if the above explanation is correct, then a direct comparison can be made with sedimentary rock structures, and this allows the classification displayed in Table 8.

TABLE 8. CLASSIFICATION OF SEDIMENTARY-TYPE STRUCTURES IN THE GILES COMPLEX

Depositional	Gravity differentiated units (graded bedding) Reverse graded bedding Cross-bedding Winnow banding Ripple marks
Erosional	Wash-outs
Post-depositional	Slump structures

GRAVITY DIFFERENTIATED UNITS

These consist of thin layers of gabbroic rock, from 1 inch (2.5 cm) to approximately 1 foot (30 cm) thick, in which the majority of the mafic minerals is concentrated towards the base of the unit, and the colour index decreases rapidly and gradationally upwards. The tops and bottoms of the units are sharply defined.

This type of banding has been used in the Giles Complex as one type of facing criterion. Good examples are common, especially in the Bell Rock Range, Michael Hills and Hinckley Range.

The identification of the sharp boundaries is important, since in the Giles Complex, especially in the Bell Rock Range, this feature helps serve to distinguish gravity differentiated units from another common variety termed reverse graded bedding, described below. The latter possesses gradational margins and cannot be used as facing evidence.

The origin of the gravity differentiated units has been explained by Wager and Brown (1968) and Irvine (1965) as being caused by gravity settling from turbidity currents which produces a density graded unit. It seems quite a reasonable supposition that loosely bonded crystals forming on the sides of a crystallizing intrusion would break off periodically with assistance from downward flowing convection currents, and so create a small avalanche or turbidity current. This would settle on the bottom on the intrusion and its various crystal species would differentiate under the influence of gravity.

In the western part of Michael Hills, some of the gravity differentiated units show well oriented plagioclase laths lying parallel to the layering. This feature has been referred to as igneous lamination by Wager and Deer (1939) in their description of similar structures in the Skaergaard Intrusion of East Greenland. The texture is thought to be the result of deposition from a liquid in which currents are active (Wager and Brown, 1968). The currents necessary to orient the plagioclase laths may be likened to the residual currents left after the main flow of a turbidity current has stopped.

Figure 35. Banded gabbro, northwest end of Bell Rock Range. The two prominent mafic bands are respectively a normally graded band on the left and a reverse graded unit on the right. The two bands are approximately 4 inches apart.

Igneous lamination has been used to help indicate the orientation of the presumed convection currents active during crystallization of the Michael Hills magma (Figs. 41 and 42).

In certain aqueous sedimentary environments turbidity currents have the ability to erode the underlying layers to an extent which depends on their loads and velocities. The principal products of this erosion are grooves and flutes, generally recognized as casts on the base of the overlying layer. A diligent search was made for similar features in the Giles Complex, but without success. It is reasonable to assume that such features may occur, but the lack of good layering-parting in the gabbroic rocks precludes an examination of igneous bedding plane surfaces. What may possibly be related to this type of action has been described by Nesbitt and Talbot (1966) as a cut and fill structure. It occurs in the North Mount Davies intrusion, part of the Giles Complex, in South Australia.

REVERSE GRADED BEDDING

This type of banding consists of thin units, generally about 2 to 3 inches (5 to 8 cm) thick, resembling inverted gravity differentiated units, but differing in having diffusely defined margins (Fig. 35). It is often associated with a normally graded type of banding, which also shows diffuse boundaries, and these are often seen together in sections where cross-bedding (see below) is prevalent. Good examples of this type occur on the northwest part of the Bell Rock Range.

The reverse graded bedding can readily be explained by the deposition of crystals accumulating under the influence of a convection current of increasing intensity. It is assumed that convection currents of different speeds are possible in a cooling gabbroic liquid and the evidence available suggests that relatively

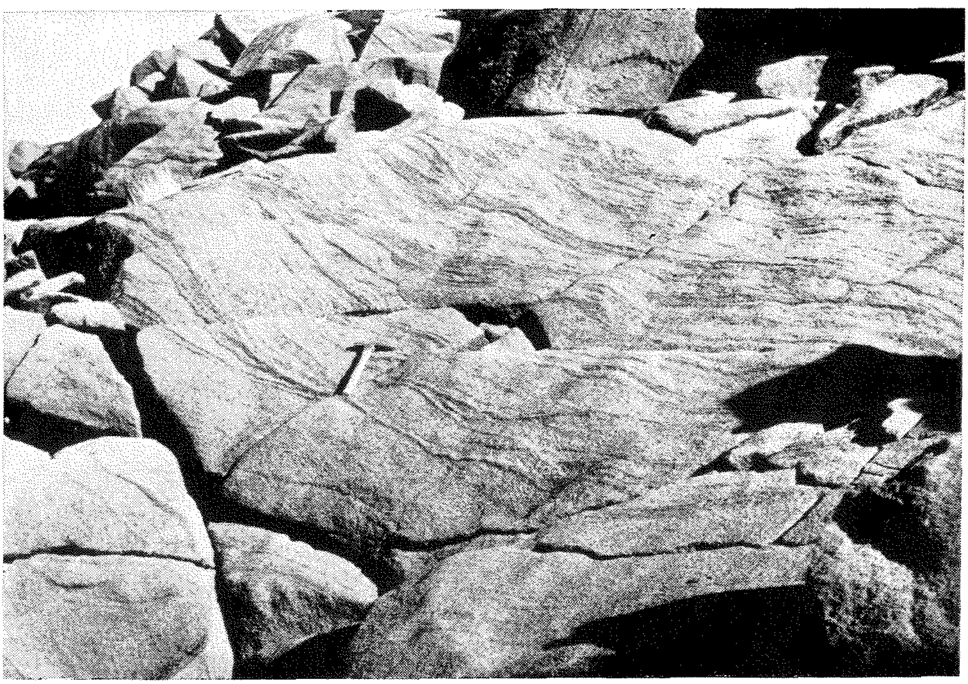

Figure 36. Cross-bedded gabbros in the northwest end of Bell Rock Range. Blackstone Range Gabbro.

strong currents capable of erosion of the bottom layers have acted, as well as slower currents capable of orientation of sinking plagioclase laths. Currents varying in intensity are therefore not impossible.

A slow, steady precipitation of crystals in the basic magma, near the bottom of the liquid and under the influence of a current of increasing intensity, would have its less dense crystals progressively swept away. The denser ones would settle to form a melanocratic layer with upward gradually increasing colour index, resembling inverted normal grading. No sharp boundaries have been seen in these examples and it is therefore suggested that variation in intensity of the convection currents must have been gradational.

With deposition under a current of decreasing intensity the reverse would apply, and hence it is not safe to use these features as facing evidence.

CROSS-BEDDING

The most useful of the sedimentary-type structures seen in the gabbroic rocks of the Giles Complex is cross-bedding. It has been described briefly by Daniels (1967a). It resembles that seen in sedimentary rocks and the units may occur individually or in groups. Many examples are present in each of the major sheets and some of the minor intrusions. The best known examples are on Bell Rock Range (Figs. 36 and 37). Good cross-bedding is also developed in parts of the Blackstone Range. There the units occur in groups which, when traced along strike, pass into normal, parallel, igneous banding devoid of cross-bedding.

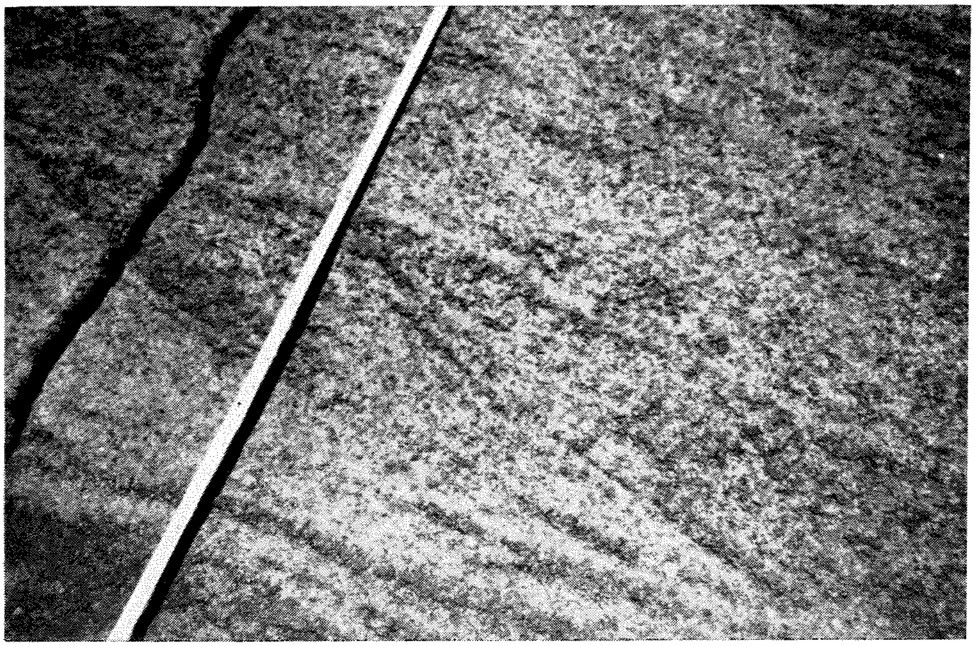

Figure 37. Close-up of cross-bedded unit in gabbro at northwest end of Bell Rock Range. Blackstone Range Gabbro.

It is assumed that cross-bedding in these gabbroic rocks formed in exactly the same way as cross-bedding in sediments. The truncations at the top are often well developed (Fig. 37) and have been used in the Giles Complex as good facing evidence. The structure itself is also a current indicator and wherever possible the direction of the current responsible was determined.

WINNOW BANDING

This is the name given to a type of thin discontinuous layering in the form of elongate lenses giving a pattern of discontinuous streaks on the rock surface. It is probably caused by an irregular distribution of currents of constantly changing intensity. It is frequently associated with cross-bedding.

RIPPLE MARKS

Thin layers of mafic minerals showing regular small undulations may possibly be compared with ripple marks (Fig. 38). Most are symmetrical. In the Hinckley Range Gabbro, in the South Australian portion of the intrusion, asymmetrical ripple marks have been seen. On the whole they are of little or no use in convection current direction determination.

Figure 38. Possible ripple marks in banded gabbro, Bell Rock Range. Blackstone Range Gabbro.

SLUMP STRUCTURES

Several S-shaped arrangements of the banding have been found, especially in Bell Rock Range (Fig. 39). They occur between undisturbed layers and probably are minor slump structures. Where possible, the direction of slumping was determined and found to be in the same direction as the current direction indicated by the cross-bedding.

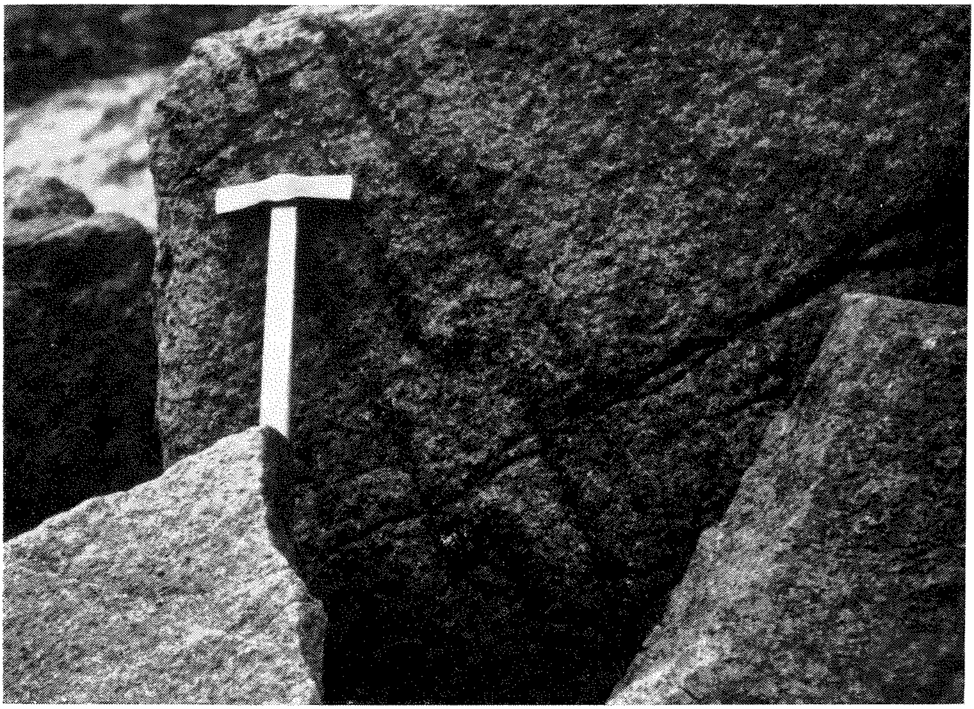

Figure 39. Slump structure in fallen block of gabbro on northwest end of Bell Rock Range. Blackstone Range Gabbro.

Too few measurements are available to generalize with certainty, but the implications are that at least in some areas the floors of the intrusions were sloping, and that the bottom part of the convection current cell flowed down the slope. It may also be implied from the slumping that the original banding was not necessarily laid down on a horizontal plane as is frequently assumed, and that lithification of the crystal sediment is not complete until after at least several inches of overburden have accumulated.

CRYPTIC LAYERING

Cryptic layering was named by Wager and Deer (1939). It is the unseen layering caused by gradual changes in the chemical composition of solid solution series minerals, and induced by fractional crystallization of the magma. Cryptic layering is present in the Giles Complex, but in the Western Australian representatives appears to be of a limited and complex variety.

PHASE LAYERING

Phase layering is the name given by Hess (1960) to layering caused by the entry or exit of cumulus mineral phases and is regarded by Wager and Brown (1968) as a variety of cryptic layering since both are intimately related.

Probably the best example of this type of layering is to be found in the upper parts of the Jameson Range Gabbro where titaniferous mangetite bands are interlayered with gabbroic rocks. On a less spectacular scale, phase layering is present in the Blackstone Range Gabbro and is identified by the entry and exit of clinopyroxene.

ZONE LAYERING

It is often useful to subdivide a thick mass of layered gabbroic rocks into zones, each characterized by one or more features persistent through an appreciable thickness.

In the Skaergaard Intrusion the broad subdivision into zones is based on the entry and exit of certain cumulus phases (Wager and Brown, 1968) and is therefore a type of phase layering. Another method of subdivision is applied by Brown (1956) to the Rhum Ultrabasic Complex. He subdivides the mass into units; each unit being a major rhythmic unit varying in thickness from 30 feet to 480 feet (10 to 140 m). Mathison (1967) subdivides the Somerset Dam layered intrusion into a number of zones determined by the repetition of a certain sequence of rock types. Several methods of subdivision seem to be available, each petrogenetically meaningful and dependent primarily on the problem at hand.

In the Giles Complex the subdivision of the Jameson Range Gabbro, the Michael Hills Gabbro and the Blackstone Gabbro into zones of several hundred to several thousand feet in thickness was determined in the field and, in the case of the first two named, without additional data from petrography and chemistry. The zones are generally easily recognized in the field and their recognition has been useful in determining the structure of the region.

In the Jameson Range Gabbro, and perhaps also in the Michael Hills Gabbro, the zones so defined by the field work may also be distinguished by the Sr/K ratio of the contained plagioclase (p. 171). The zones of these two intrusions therefore have a chemical basis.

Zone 3 of the Michael Hills Gabbro weathers to form benches 20 to 50 feet (6 to 15 m) high (Fig. 40) similar to those developed in the Rhum Ultrabasic Complex. It is possible that the Michael Hills Zone 3 may be capable of further subdivision into units comparable with those determined by Brown for the Rhum intrusion.

The zones suggested for the Blackstone Range Gabbro are based partly on field work and partly on petrography. The plagioclase of each zone is not characterized by a particular small range of Sr/K ratio sufficient to distinguish it

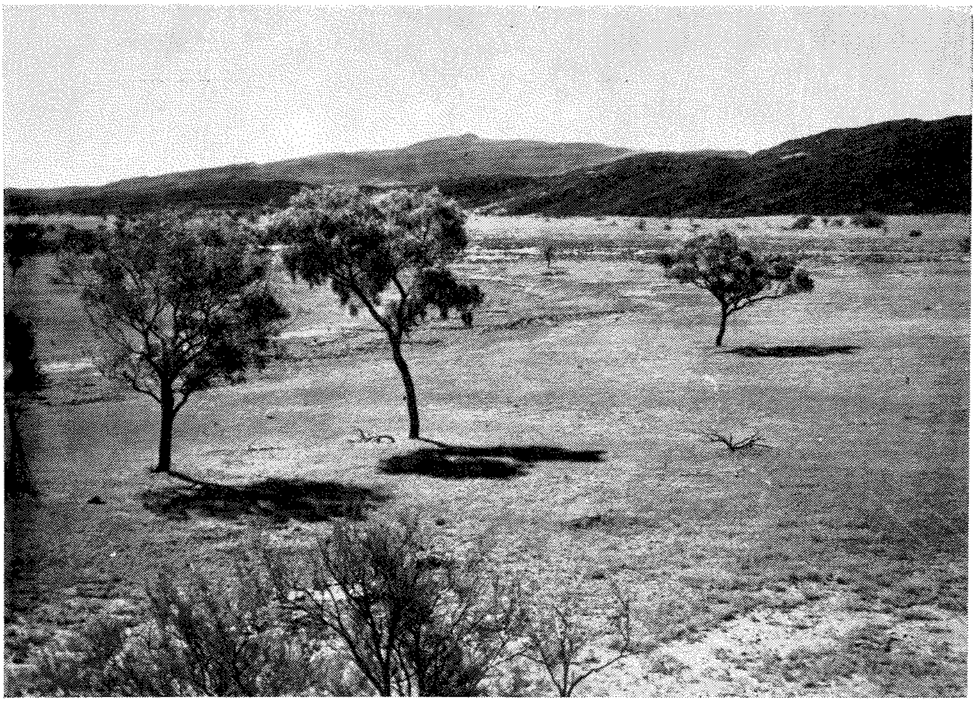

Figure 40. View of Michael Hills from Sphinx Hill showing benched slopes of Michael Hills Gabbro caused by igneous layering.

from plagioclase of other zones. The Blackstone Range Gabbro zones therefore possibly have a petrological basis different from those of the Jameson Range and Michael Hills gabbros.

Much more, and closer sampling will be necessary to define clearly all the major zones and units within each intrusion, and the present study can only be regarded as a preliminary indication of some of the problems that need to be solved.

CONVECTION CURRENT PATTERNS, SUBDIVISION OF THE COMPLEX AND FORM OF THE MAIN INTRUSIONS

In the whole of the Giles Complex in Western Australia, approximately 200 suitably exposed cross-bedding orientation measurements were made and the results are summarized in Figure 41. The resultant patterns are simple, and together with other evidence, for example weathering characteristics and structural layering (Horwitz and others, 1967), can be used to subdivide the complex into a number of separate units. These units represent portions of the Giles Complex which are thought to have had, while still liquid, simple convection current systems, the evidence for which is preserved in the cross-bedded units. The main subdivisions of the Giles Complex have been named:

Jameson Range Gabbro
Blackstone Range Gabbro
Hinckley Range Gabbro
Michael Hills Gabbro

Subsequent chemical work has confirmed this subdivision, while also adding a few minor discrete intrusions whose convection current patterns are unknown or only partly determined.

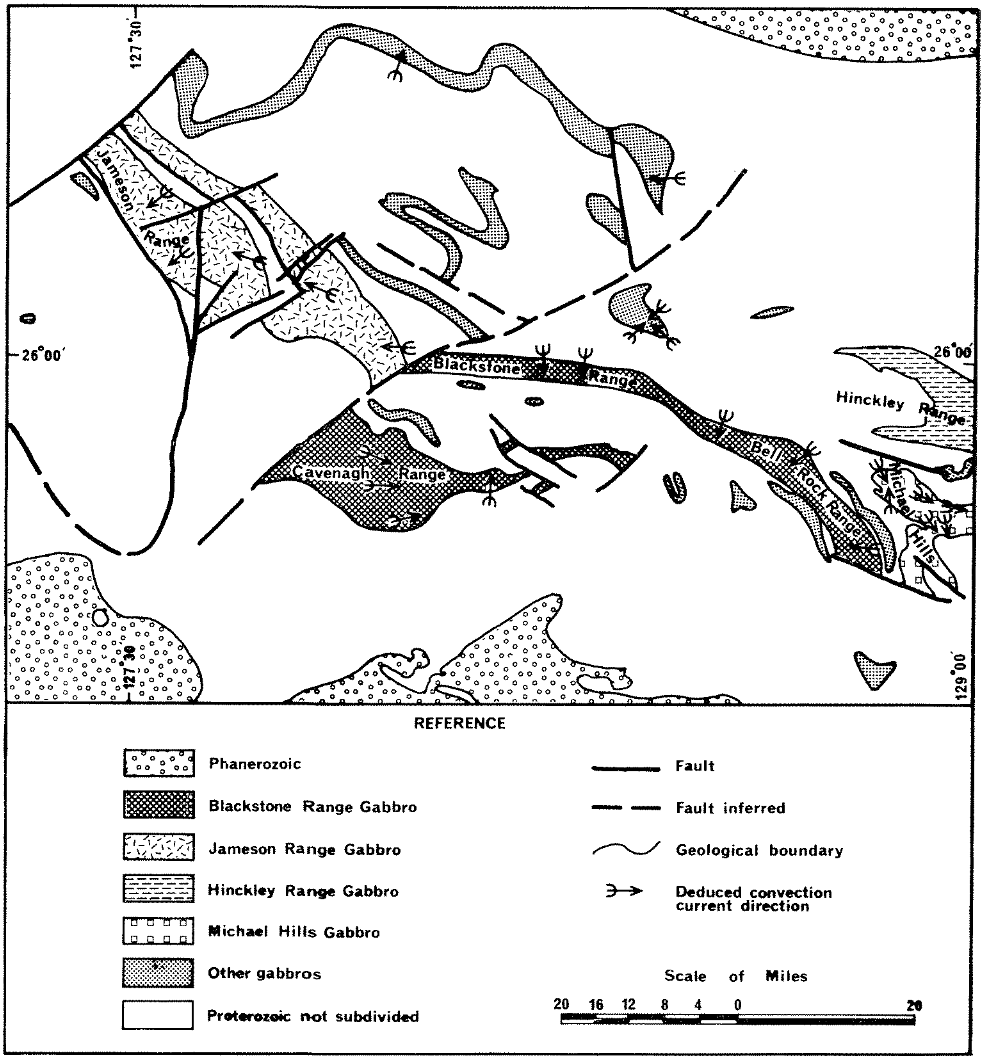

Figure 41. Sketch map of Giles Complex in Western Australia showing deduced convection current pattern.

Each unit named is regarded now as a completely separate intrusion, rather than a part of a disrupted, once continuous, extensive sheet.

The evidence from the slumped bedding shows that at least in some places the floors of the intrusions were not horizontal. Also indicated is the correspondence of the palaeoslope direction determined from the slumping and the current direction indicated by the cross-bedding. If the correspondence can be extended, then the cross-bedding directions probably also indicate the palaeoslopes of the floors of the intrusions.

For the Jameson Range Gabbro, cross-bedding trends indicate that over most of the intrusion the convection currents flowed towards the west and northwest, suggesting that the base of the body was planar and sloped approximately to the northwest with possible minor variations. The centre or deepest part of the intrusion is assumed to lie somewhere to the northwest of Jameson Range, probably at a great depth. In the upper parts of the intrusion convection currents flowing generally in a southwesterly direction suggest that a certain amount of tilt may have affected the intrusion during consolidation.

This pattern is completely different from that provided by a combination of current directions taken from the gabbroic rocks of the Cavenagh Range, the Blackstone Range and the Bell Rock Range, which together form the Blackstone Range Gabbro. In this combination, although there is a great variation in current direction, the overall pattern is simple. All the currents converge and suggest that the original shape of the intrusion was that of an elongate, perhaps slightly curved lopolith.

Current directions in the gabbroic rocks of Michael Hills are by no means simple, and indicate that the action of possibly three convection cells may be represented in what was a continuous mass. One of these cells occupied the northwest portion of the body, another was situated at least 8 miles (13 km) to the east-southeast and the third was located in the southern part of the exposed portion of the intrusion.

The Michael Hills pattern suggests two possibilities: that within the original sheet there were at least three basin-shaped depressions, or that the original sheet was horizontal and three independent convection cells developed within it.

The structural sketch map of the Michael Hills Gabbro (Fig. 42) shows what appears to be a form of igneous banding on-lap. Northwest of Latitude Hill successively higher bands in the intrusion appear to abut against the floor, until approximately 5 miles (8 km) northwest of Latitude Hill the reverse takes place along the easterly trending base of the intrusion. No intense shearing has been seen near the base of the intrusion in this locality, and therefore the effect is probably not a post-solidification feature. However, the area is on the axis of an important, regional, northwest-trending anticline. Most of the folding associated with this anticline is post-gabbro, but the on-lap suggests that the fold may also have been present as a minor structural high on the floor of the intrusion during the consolidation of the gabbro. It is thought, therefore, that the first of the suggestions regarding the original shape of the floor of the intrusion is likely to

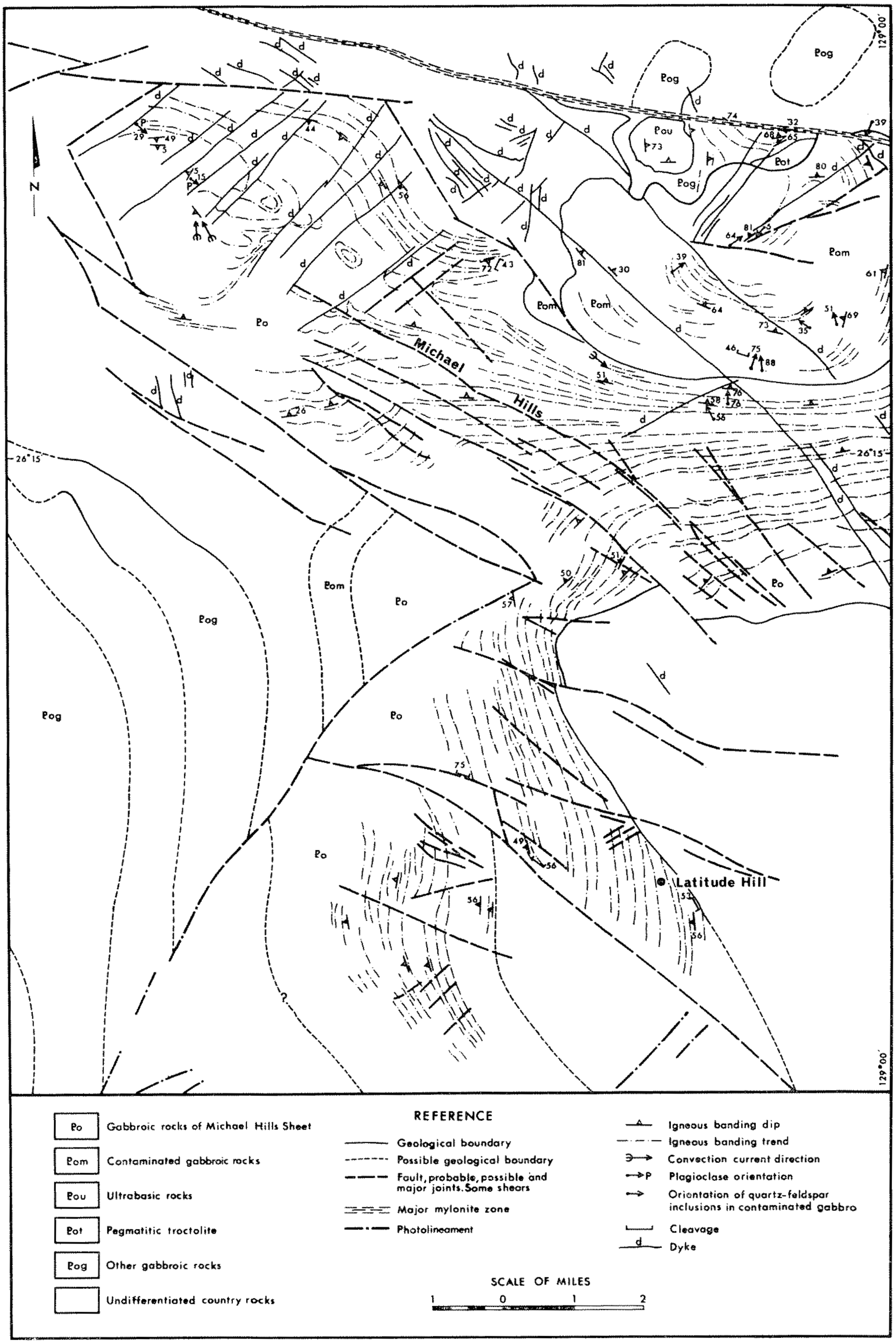

Figure 42. Structural interpretation of the Michael Hills region.

be the correct one: that it was a body with possibly three basin-shaped depressions present, each of which had its own convection cell.

No current directions are available from the Hinckley Range Gabbro.

Cross-bedded structures in gabbros can therefore be used in the preliminary subdivision of a large number of gabbro outcrops and also in the determination of the possible shapes of the major subdivisions. However, they give no indication of the nature of the intrusion roof.

A direct comparison with aqueous currents suggests that igneous convection currents may be capable of concentrating heavy minerals such as chromite, sulphides and platinum in the form of "igneous-placer" deposits, the concentrations being formed either by the washing away of the lighter minerals in the deepest parts of the intrusion, or in suitable structural traps somewhere on the sloping floor. A knowledge of the convection current directions, as well as of the history of folding and faulting of an intrusion, is therefore essential. Further, more accurate information regarding the detail of these convection currents will almost certainly be obtained from a petrofabric study of oriented specimens since it is known that at least one of the minerals, plagioclase, sometimes shows a preferred orientation in both the Michael Hills (Fig. 61) and Jameson Range Gabbros.

The use of cross-bedding to determine the convection current pattern in gabbros from other localities is not known to the author. However, other methods have been used elsewhere. The Skaergaard convection current pattern has been deduced by Wager and Deer (1939) from the configuration of trough banding. In the Freetown Complex, Sierra Leone, Wells (1962) showed that oriented pyroxene crystals are aligned parallel to the dip of the igneous layering and converge at the assumed centre of the intrusion. The result is a pattern similar to that of the Blackstone Range Gabbro. Wells, however, states that the pyroxene orientation was produced by the dip of the layered structures whose overall shape is that of a cone.

GENERAL DESCRIPTIONS OF THE MAIN GABBRO SHEETS

JAMESON RANGE GABBRO

The Jameson Range Gabbro has been subdivided into four main zones with a total thickness of some 18,000 feet (5,500 m).

The main section through the sheet is given in Figure 43, and was obtained from traverses through the Jameson Range and across the poorly exposed, generally flat country to the northeast and southwest of the range. A selection of modal analyses from the intrusion is given in Table 9.

Gabbroic rocks forming part of the mass have been found 12 miles (19.3 km) northwest of Jameson Range along the general line of strike of the igneous banding and as far southeast of the range as Mount Elliott. Rocks of the Jameson Range Gabbro therefore extend over a strike distance of approximately 41 miles (66 km)

TABLE 9. MODAL ANALYSES OF GABBROIC ROCKS FROM THE JAMESON RANGE GABBRO

	18327	1245A	1245B	1238	1241	1263
Plagioclase	11·5	5	3·0	65·1	68·1	74·9
Olivine	22·4	5	} 40·3	25·1	12·0	2·9
Orthopyroxene	} 21·9	} 40		4·0		} 18·7
Clinopyroxene					13·9	
Brown amphibole	21·1	20	19·6	....	....	....
Biotite	....	....	....	1·4	0·8	0·8
Opaques	23·1	30	37·1	0·5	3·4	2·7
Apatite	....	....	....	0·3	0·1	....
Symplectic intergrowth	....	....	....	3·6	1·4	....
Chlorite	....	....	....	....	0·1	....
Potash Feldspar	....	....	....	....	0·1	....
	100·0	100	100·0	100·0	99·9	100·0

18327, 1245A and 1245B Ultramafic rocks from Zone 2
1238 Hypersthene troctolite, Zone 3a, Turkey Hill
1241 Olivine gabbro, Zone 3a, Turkey Hill
1263 Olivine gabbro, Zone 4, southwest of Jameson Range.

and have a maximum outcrop and suboutcrop width of about 12 miles (19 km). A volume of between 1,000 and 2,000 cubic miles (4,200 and 8,300 km^3) of magma therefore could have been involved in the Jameson Range Gabbro.

The area between Mount Elliott and Jameson Range has been subjected to block faulting but it has been found possible to extend the subdivisions determined in the Jameson Range area to this region also.

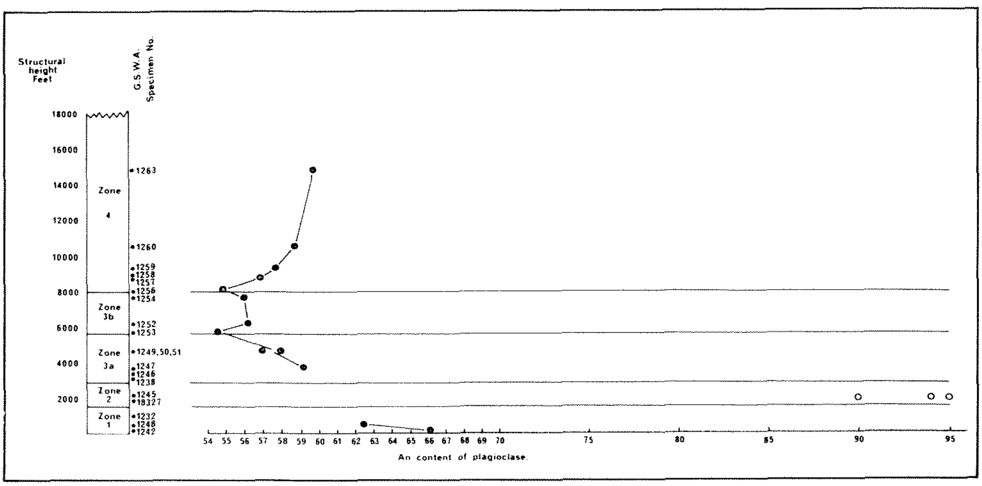

Figure 43. Variation in An content of plagioclase with height in Jameson Range Gabbro. Solid circles—chemical determinations; open circles—optical determinations.

In general the layering dips to the southwest at approximately 30 degrees. Most of the zones are well banded (Fig. 44) with locally well developed cross-bedding. The deduced convection current pattern for the sheet has already been discussed. Some shearing has affected the gabbro in the Jameson Range area. This has somewhat accentuated the layering and produced a slight elongation of the mafic minerals. It is described in more detail below.

ZONE 1

The basal zone of the Jameson Range Gabbro northeast of Jameson Range consists of a distinctive, dark-weathering, glomeroporphyritic olivine gabbro approximately 1,500 feet (460 m) thick (Fig. 45). Uralitization has affected much of this zone, but the process was not accompanied by any stress effects. On the whole the zone is poorly exposed and is best seen in isolated monadnocks, approximately 2 miles (3 km) northeast of Jameson Range, forming a discontinuous line of outcrops parallel to the range. It may be present as a thin zone in the area near Mount Finlayson some 10 miles (16 km) east-southeast of the Jameson Range.

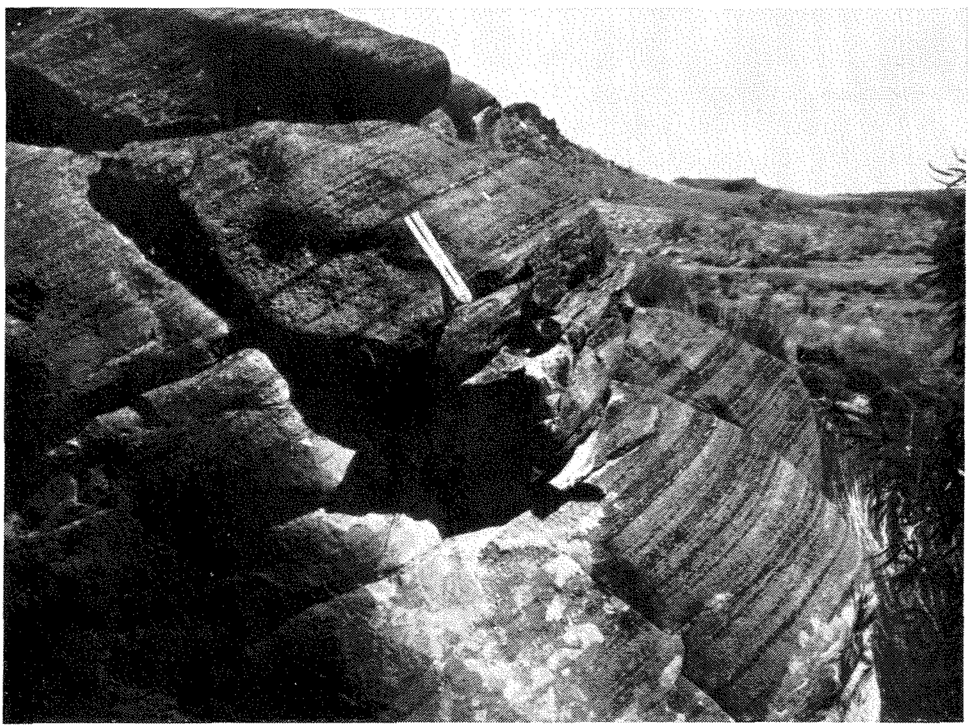

Figure 44. Rhythmic layering in Zone 3, Jameson Range Gabbro, Jameson Range.

Figure 45. Glomeroporphyritic gabbro, Zone 1, Jameson Range Gabbro, Jameson Range.

The least uralitized of the samples consists of clinopyroxene, poikilitically enclosing laths of labradorite, and rare relict olivine. The pyroxene is surrounded by abundant short laths of red-brown biotite (Fig. 46).

In the more altered varieties, pyroxene occurs as relicts in a fine-grained mosaic of green hornblende or hornblende and plagioclase. Two grain sizes of plagioclase are usually evident; the groundmass, and larger crystals up to 1 cm long in glomerocrysts which average about 2 cm in diameter.

Determination of the composition of the groundmass plagioclase, on a universal stage (Trendall, 1969) gave results of An_{45} and An_{46}. The larger crystals in the glomerocrysts, which often showed combined Carlsbad-albite twins, are more calcic with cores of An_{66} and a narrow extreme edge of An_{46}. A few oscillatory alternations with a small compositional range are present. Frequently the crystals carry small hornblendes surrounded by a slightly more calcic zone of An_{68}.

Plagioclase from the whole rock was separated for analysis (Table 21, No. 1242). The result of $An_{65.2}$ (calculated on a basis of An + Ab + Or) suggests that the fine-grained material was discarded during the preparation of the sample and that the analysis refers to the glomerocrysts only.

Figure 46. Photomicrograph of gabbro from near base of Zone 1, Jameson Range Gabbro, Mount Finlayson, showing corona development. Ord. light.

Another sample from the same zone shows an optically determined compositional range, for a glomerocryst individual, of from An_{75} in the core to a rim of An_{60}. Chemical analysis of a plagioclase concentrate from the whole rock gave $An_{62 \cdot 5}$.

ZONE 2

Above the glomeroporphyritic gabbro, and lying immediately to the northeast of Jameson Range, is a zone of mafic rocks up to 1,000 feet (320 m) thick. It is very poorly exposed because of an extensive laterite cover, which extends almost continuously for a distance of 8 miles (12.8 km).

The few exposures seen in the southern end of the laterite cover reveal a moderately well banded, magnetite-rich mafic rock with individual bands from 1 inch (2.5 cm) to several inches thick. The banding is defined by variations in the opaque content. Some titaniferous magnetite float is present, suggesting that, apart from the mafic rocks, solid titaniferous magnetite bands are also present. Southeast of Turkey Hill solid titaniferous magnetite bands are exposed between Zones 1 and 3 and are assumed to be the equivalent of the mafic rocks of Zone 2 near the Jameson Range.

The majority of the rocks of this zone could be called kaersutite lherzolites or magnetite-ilmenite-kaersutite lherzolites.

Igneous banding dips are similar to those of the overlying Zone 3, suggesting a concordant relationship. Neither the base nor the top of Zone 2 is exposed. The full range of mineralogical variations in this zone is not known. However, a large variation in the few samples available is a guide.

The mafic rocks are medium grained and granular and consist of varying proportions of opaque minerals, brown amphibole, olivine, clinopyroxene, orthopyroxene and plagioclase. All these minerals may occur together in the same sample with no apparent reaction relations.

Apart from the titaniferous magnetite bands and one sample of clinopyroxenite the opaques appear to make up from 20 to 50 per cent of these rocks. In all cases the opaques may enclose all other species.

Plagioclase is usually present only in accessory amounts and consists of short laths generally crowded centrally with abundant small, rounded or rod-shaped colourless inclusions of ?clinopyroxene. The plagioclase is unzoned and poorly twinned or untwinned. Determination of its composition on a universal stage (Trendall, 1969) indicates a composition of between An_{90} and An_{96}.

The olivine is fresh and shows $\beta = 1.776$ indicating a composition of Fa_{59}.

The amphibole is a medium to dark brown pleochroic variety probably related to the kaersutites and is discussed in more detail elsewhere.

Three of the lherzolites and one of the titaniferous magnetite bands from this zone have been analyzed (Tables 10 and 35 respectively). The lherzolites (Nos. 1245A, B and C) are characterized by very low SiO_2 and Al_2O_3, and very high total $FeO + Fe_2O_3$ and TiO_2. Vanadium is moderately high.

TABLE 10. ANALYSES OF BROWN AMPHIBOLE-BEARING ULTRAMAFIC ROCKS FROM THE JAMESON RANGE GABBRO, ZONE 2

	1245A	1245B	1245C
SiO_2	24·10	23·10	19·90
Al_2O_3	6·39	5·26	7·46
Fe_2O_3	15·60	12·50	16·00
FeO	24·40	25·70	28·40
MgO	6·19	8·05	6·65
CaO	6·47	5·80	3·80
Ha_2O	0·54	0·35	0·63
K_2O	0·12	0·13	0·12
MnO	0·30	0·34	0·29
TiO_2	13·00	17·30	15·10
P_2O_5	0·03	0·08	0·06
Cr_2O_3	0·01	0·01	0·01
V_2O_5	0·70	0·57	0·76
NiO	0·60	0·04	0·05
S	0·04	0·08	0·01
H_2O^+	1·20	1·00	0·75
H_2O^-	0·23	0·11	0·07
	99·38	100·42	100·06

Analysis: Government Chemical Laboratories

Norms

	1245A	1245B	1245C
OR	0·70	0·76	0·70
AB	4·56	2·96	4·62
AN	14·65	12·39	17·17
NE	0·00	0·00	0·38
DI	14·11	12·79	1·05
WO	7·20	6·61	0·53
EN	4·03	4·27	0·27
FS	2·87	1·90	0·21
HY	5·42	7·36	0·00
EN	3·16	5·09	0·00
FS	2·26	2·27	0·00
OL	10·29	11·15	22·44
FO	5·75	7·48	11·41
FA	4·53	3·67	11·03
MI	22·61	18·12	23·19
IL	24·69	32·85	28·67
AP	0·07	0·18	0·14
Normative An	76·20	80·70	78·80
Normative En	58·30	69·10	....
Normative Fo	55·90	67·10	50·90

Simplified norms

Plagioclase (Or + Ab + An)	19·91	16·11	22·49
Clinopyroxene	14·11	12·79	1·05
Orthopyroxene	5·42	7·36	0·00
Olivine	10·29	11·15	22·44
Magnetite	22·61	18·12	23·19
Ilmenite	24·69	32·85	28·67
Apatite	0·07	0·18	0·14
Nepheline	0·00	0·00	0·38

Norm calc. with H_2O^+

Norms recalc. on (Mag + Ilm) free basis

	1245A	1245B	1245C
Plagioclase	19·91	16·11	22·49
Clinopyroxene	14·11	12·79	1·05
Orthopyroxene	5·42	7·36	0·00
Olivine	10·29	11·15	22·44
Apatite	0·07	0·18	0·14
Nepheline	0·00	0·00	0·38
	49·80	47·59	46·50

Recalc. to 100 per cent

Plagioclase	39·98	33·85	48·37
Clinopyroxene	28·33	26·88	2·26
Orthopyroxene	10·88	15·47	0·00
Olivine	20·66	23·43	48·26
Apatite	0·14	0·38	0·30
Nepheline	0·00	0·00	0·82
	99·99	100·01	100·01
Name from norm.	Olivine gabbro	Olivine gabbro	Troctolite

The lherzolites' ultramafic nature, igneous banding and extremely high plagioclase An content may suggest that they are very early differentiates of a gabbroic magma. However, the high magnetite and vanadium content of the rock, and high Fa content of the olivine suggest otherwise. The norms of the three samples have been recalculated on a magnetite-ilmenite-free basis. The normative names which can be given to these recalculations are olivine gabbro and troctolite, which suggest that perhaps unusual physical conditions (possibly higher than normal pressure) prevailed during crystallization to allow the formation of the observed assemblages.

ZONE 3

This zone forms almost all of the Jameson Range itself and consists of a 2,500-foot (760 m) thick sequence of well banded, light yellow-brown-weathering troctolites. The primary igneous banding has been accentuated by a superimposed shearing but original structures, including cross-bedding, slumps and possible ripple marks, may still be recognized. The contact with the underlying ultramafic rocks is not exposed.

The original igneous texture of Zone 3 may be seen in samples from Turkey Hill (Fig. 47) and Mount Elliott. In Turkey Hill the rock is a banded and cross-bedded olivine-plagioclase cumulate with intercumulus inverted pigeonite, orthopyroxene and clinopyroxene. The orthopyroxene and clinopyroxene generally sheath the olivine. Only slight zoning is present in the plagioclase which has a composition of An_{62}. Accessory opaques, red-brown biotite and apatite are also present.

At Mount Elliott the rock is a plagioclase cumulate with intercumulus olivine and minor orthopyroxene, clinopyroxene and opaques. Accessory red-brown biotite and minor brown amphibole occur as reaction products around opaques. A minor amount of vague oscillatory zoning is present in the cores of some of the larger crystals, which have an average composition of An_{70}. Slight reverse zoning is present on the edges of a few grains. The presence of abundant, very small opaque needles, oriented parallel to the twin plane traces, imparts a cloudy effect to the plagioclase. Olivine is generally fresh but carries trails of opaques along irregular fractures and only in very small marginal sections is it sheathed by orthopyroxene or replaced by bowlingite.

In the sheared part of Zone 3, in the Jameson Range, none of the original cumulus texture remains, the component minerals forming instead an irregular mosaic. Relict ophitic texture is apparent in a few examples.

A subdivision of Zone 3 into two subzones is possible using broad field characteristics. The lower part consists of approximately 2,700 feet (820 m) of banded troctolites, while the upper 2,400 feet (730 m) consists of white to cream anorthosites, anorthositic gabbros and troctolites. The junction of the two subzones is not known accurately, but the top of the upper subzone is well defined by the incoming of the first thick titaniferous magnetite band of Zone 4 on the southwest, lower flanks of the Jameson Range.

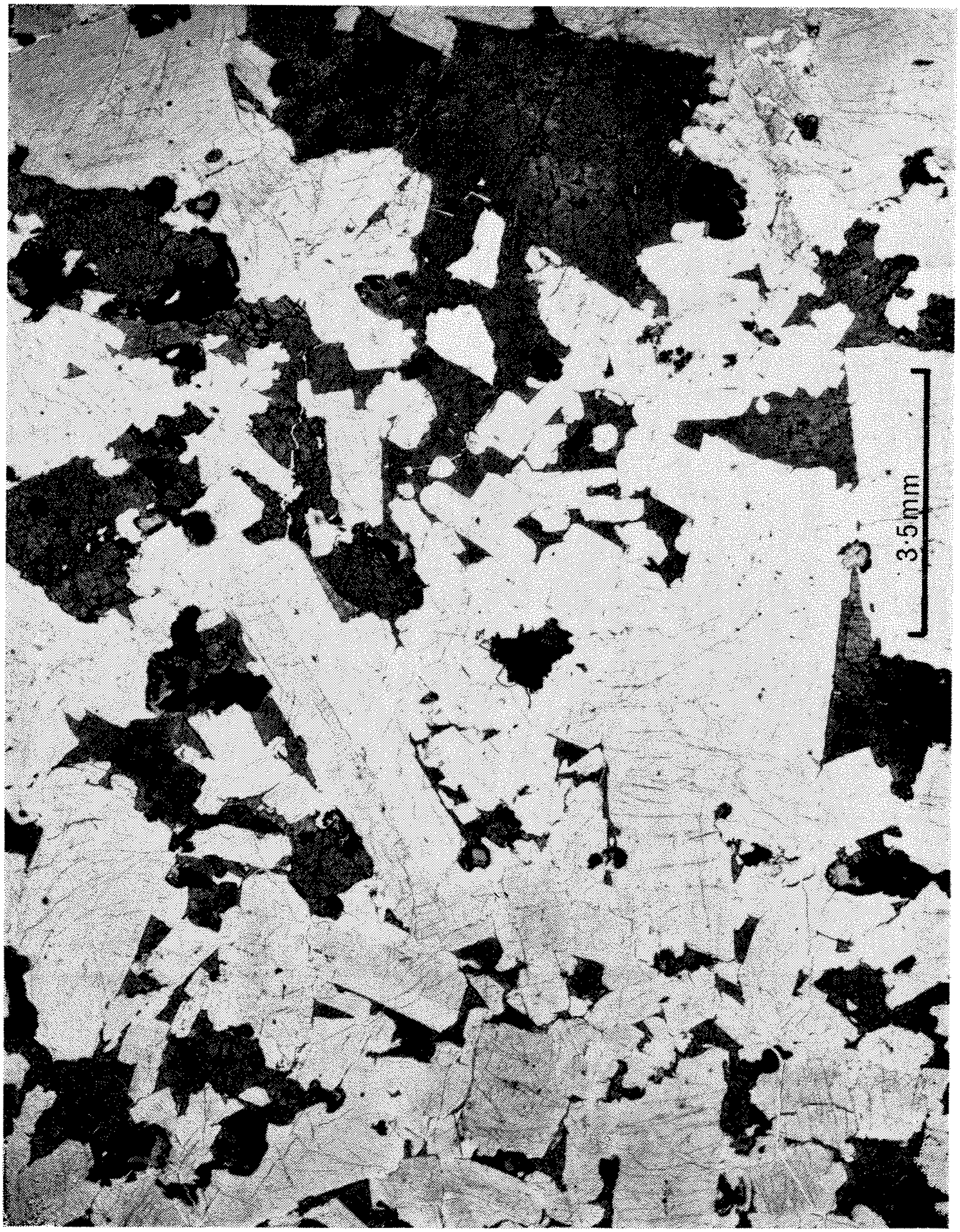

Figure 47. Photomicrograph of unsheared olivine gabbro from Zone 3, Jameson Range Gabbro, Turkey Hill. Ord. light.

There appears also to be a slight difference in the An content of the plagioclases of the two subzones. In the upper subzone the mean of four chemical determinations was $An_{55\cdot5}$, with a range of $An_{54\cdot6-56\cdot27}$ while in the lower subzone the mean was $An_{57\cdot7}$, with a range of $An_{56\cdot9-59\cdot2}$. A similar subdivision may be made on the basis of the Sr/K ratio of the contained plagioclase.

ZONE 4

This zone, approximately 10,000 feet (3,000 m) thick, is a well banded sequence consisting principally of hypersthene troctolite, troctolite, olivine gabbro and hypersthene gabbro with smaller quantities of anorthosite, olivine-rich troctolite and titaniferous magnetite bands. The zone is poorly exposed and in the area southwest of Jameson Range it has been subjected, like Zone 3, to shearing. A gradual decrease in the intensity of the shearing is noticeable upwards through the sequence. From approximately half-way up the zone, the rocks show only minor effects. Relict ophitic texture becomes common, and the plagioclase is not finely comminuted and remains well twinned. The mafic minerals, however, occur as aggregates of polygonal grains.

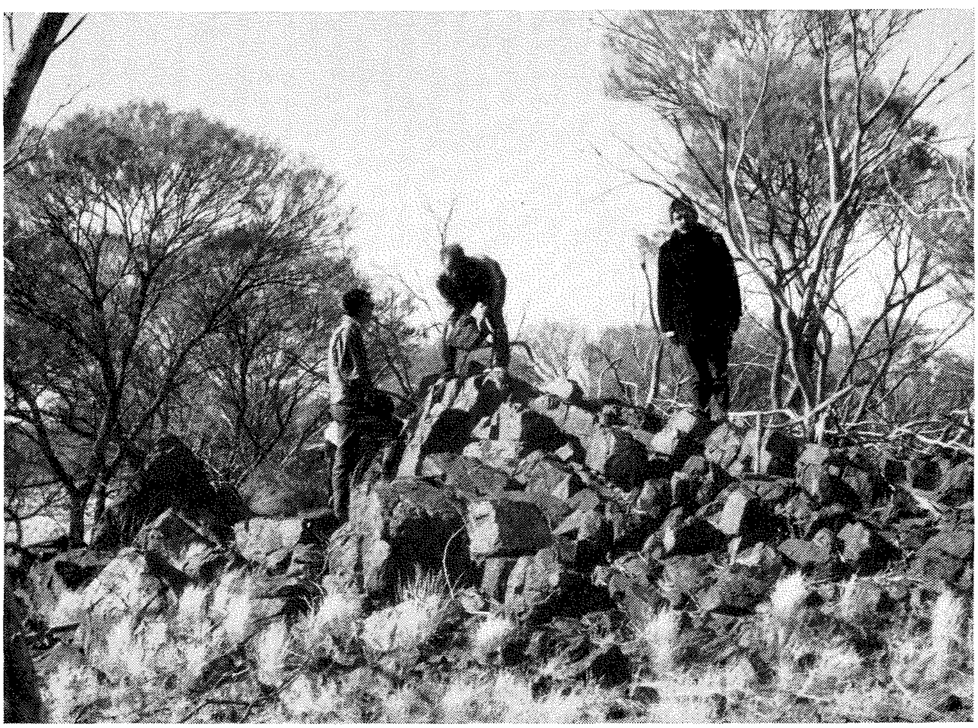

Figure 48. Outcrop of titaniferous magnetite Zone 4. Jameson Range Gabbro, southwest of Jameson Range.

Plagioclase composition, determined chemically, changes progressively from $An_{54 \cdot 9}$ (on a basis of An + Ab + Or) near the base of Zone 4 to $An_{59 \cdot 8}$ near the top of the exposed part of the same zone. Its significance will be discussed elsewhere.

Potentially important, economically, are the titaniferous magnetite bands (Fig. 48). They are stratiform bodies, apparently differentiates of the gabbroic magma. The bands consist of iron and titanium oxides with variable quantities of other elements. The titanium phase is often seen in hand specimen as shiny metallic, elongated crystals in an otherwise dull matrix. The elongation is apparently primary and parallel to the regional igneous banding dip. It is useful in determining the dip of isolated titaniferous magnetite outcrops.

The titaniferous magnetite bands are very poorly exposed and hence estimates of their thicknesses and the number of horizons present cannot be given. However, at the base of the zone near the southeastern end of the Jameson Range a titaniferous magnetite band approximately 15 feet (4.5 m) thick is present. This band varies along strike and is replaced by two thinner bands 4 miles (6.4 km) to the northwest. Four miles (6.4 km) farther to the northwest the bands give way to a series of elongate lenses of titaniferous magnetite arranged in an echelon pattern.

Titaniferous magnetite bands appear to be more numerous and thicker in the upper half of the zone. One band in this part of the sequence is estimated to be over 200 feet (60 m) thick with neither the base nor the top exposed. However, it is known to vary in thickness considerably along strike.

Apart from a minor development of iron oxides with a fibrous appearance near the margin of one of the bands, shearing has apparently had little effect on their internal structure. Their mineralogical and chemical composition is described elsewhere (p. 221).

SHEARED GABBROIC ROCKS

Field mapping has established a four-fold sequential subdivision of the Jameson Range Gabbro and this sequence can be established on either side of the inferred fault trending east-northeast and located at the southeast end of the Jameson Range. The sequence on the southeast side of the fault is laterally displaced towards the east-northeast, but is further complicated by more faulting.

A local post-crystallization shearing has affected Zones 3 and 4 of the gabbro only in the area northwest of the fault. However, Zones 1 and 2 do not appear to have been affected.

In outcrop the effects of the shearing have been to accentuate slightly the igneous banding and to produce a slight elongation of the mafic minerals. Cross-bedding can still be easily recognized. The lineation produced by the elongation of the mafic minerals is moderately consistent through most of the Jameson Range and plunges in a west-southwesterly direction at approximately 30 degrees. The orientation is parallel to the inferred fault.

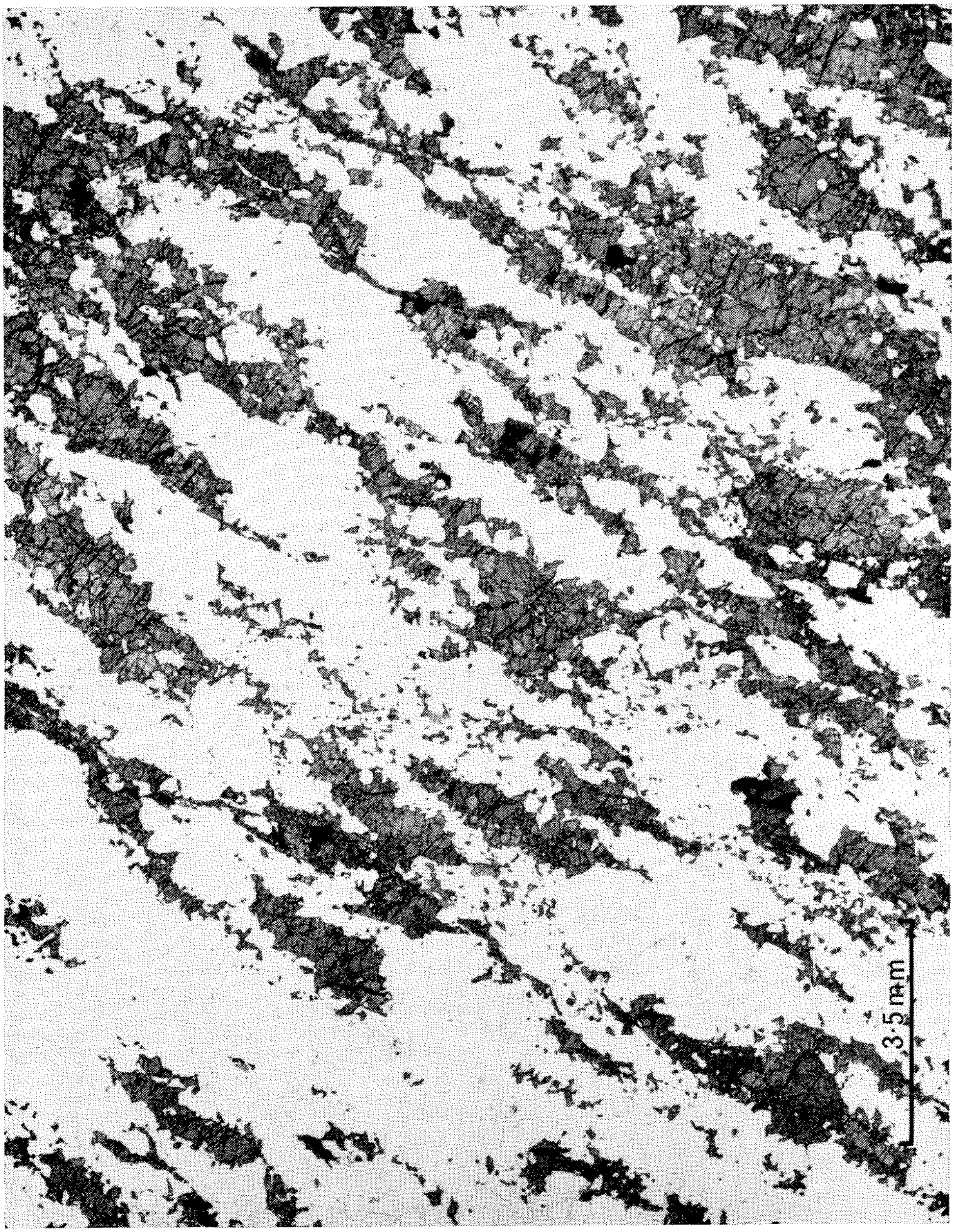

Figure 49. Photomicrograph of sheared troctolite from Zone 3a, Jameson Range Gabbro, Jameson Range. Ord light.

Figure 50. As Figure 49. Crossed nicols.

Two samples, one of which is sheared, from Zone 3 illustrate the physical effects of the shearing. The unsheared example (1239) is an olivine-plagioclase cumulate with intercumulus development of orthopyroxene, clinopyroxene and opaques. Some of the pyroxene is inverted pigeonite. Olivine is generally sheathed with either of the pyroxenes and frequently is partially surrounded by a fine-grained symplectic intergrowth. A small amount of red-brown biotite occurs interstitially and as sheaths around opaques. Other accessories include intercumulus apatite and a trace of chlorite. Plagioclase (An_{62}) is generally only very slightly zoned, but in a few of the larger crystals rather vague repeated oscillatory zones are present.

In contrast, the sheared example (1246) shows none of the original texture. The plagioclase (calcic labradorite) has been almost completely replaced by a very fine-grained mosaic with remnant augen of larger crystals with sutured and granulated margins. Twinning is generally poorly developed and often vague. Twin planes are usually curved and undulose extinction is common. The mafic minerals have behaved in a similar way, having been somewhat granulated and streaked out into irregularly shaped spindles. The olivine remains quite fresh though its relationship to the two pyroxenes has been obliterated. Accessories include opaques and red-brown biotite. Photomicrographs of a sheared troctolite from Zone 3a are given in Figures 49 and 50.

Chemically these two rocks are almost identical (Table 3, Nos. 1239 and 1246). The shearing does not appear to have produced any noticeable bulk chemical change or altered the mineralogical composition of the rock.

Orthopyroxenes and clinopyroxenes have been separated and analyzed from two of the sheared gabbros of Zone 3. The results, together with their structural formulae, are given in Tables 27 and 28. They possibly help to provide more detail regarding the nature of the process. They are further discussed in the section on the mineralogy of the Giles Complex.

Another feature which may possibly be related in some way to the shearing is the major difference in iron content of the olivine of the gabbro from unsheared Zone 3, as compared with olivine from the sheared examples. The unsheared olivine has a composition of $Fa_{54 \cdot 5}$ while two samples from the same zone in the sheared area show compositions of $Fa_{36 \cdot 0}$ and $Fa_{39 \cdot 0}$.

The average chemically determined anorthite content of plagioclase from seven samples from Zone 3 in the sheared area is 56.8 (on a basis of An + Ab + Or) with a range of $An_{54 \cdot 6}$ to $An_{59 \cdot 2}$. Optical determinations of plagioclase from four unsheared samples gave An_{60}, An_{62}, An_{62} and An_{70} suggesting that shearing may also have effected a slight decrease in the anorthite content of the plagioclase.

Shearing may also have affected the strontium and potassium contents of the plagioclases, though insufficient data are available to generalize. A plagioclase from a sample from the unsheared area carries a slightly higher strontium content than is normal in Zone 3 for a particular anorthite content. Similarly potassium is higher in the plagioclase from the unsheared rock.

BLACKSTONE RANGE GABBRO

The Blackstone Range Gabbro forms the prominent topographic features of the Blackstone, Cavenagh and Bell Rock Ranges. The intrusion is roughly oval in plan, but the southern side is poorly developed and badly exposed. Interpretation of the sedimentary-type structures in this mass suggests that the original shape of the intrusion was that of an elongate, perhaps slightly curved lopolith approximately 63 miles (100 km) long and 13 miles (20 km) broad. The original area was probably greater than 600 square miles (1,500 km^2) and the volume of material involved perhaps some 1,300 cubic miles (5,400 km^3).

One section through the gabbro was measured in the Blackstone Range approximately 12 miles (19 km) east of the western extremity of the range. At this locality the sheet is approximately 11,000 feet (3,350 m) thick and overlies sheared and possibly contaminated basic igneous material with a minimum thickness of 3,000 feet (920 m). In the Bell Rock Range area the gabbro overlies porphyritic granite. On the southern side of the mass the intrusion overlies granulite, granitic gneiss and porphyritic granite.

Above the gabbro are the sediments and volcanics of the Tollu Group. The contact between the Tollu Group and the gabbro is intrusive, the latter having been intruded along the plane of unconformity between the Tollu Group and the underlying crystalline "basement".

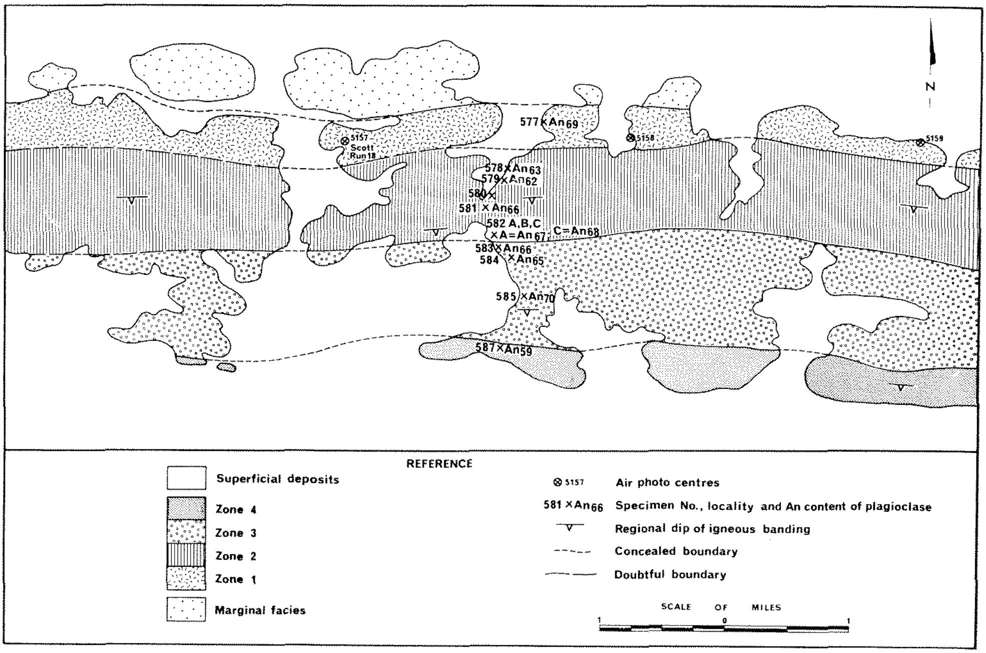

Figure 51. Zonal scheme and distribution of An values of plagioclase in the Blackstone Range Gabbro. Approximately 8 miles west of Blackstone Camp.

95999—5

The Blackstone Range Gabbro is extremely well banded. The banding covers a wide range of scales, and the coarser banding is usually visible on the air-photographs. Descriptions and origin of the banding are discussed elsewhere.

No large-scale faulting is known to affect the intrusion, but the Blackstone Range and Bell Rock Range regions have been subjected to folding. The main effect of this appears to have been to increase the original dip of the layering. Dips in the Blackstone Range and Bell Rock Ranges are from 65 degrees, to vertical. Dips in the Cavenagh Range are low and are from horizontal, to 15 degrees. In this latter area the post-Giles Complex folding was of little consequence, having only produced minor undulations of low amplitude.

The measured section in the Blackstone Range has been subdivided into four major zones (Figs. 51 and 52). Extension of these zones is possible along most of the outcrop in the Blackstone Range. Correlation of the zones with the Cavenagh Range has not yet been undertaken, but three of the zones have been extended into the Bell Rock Range.

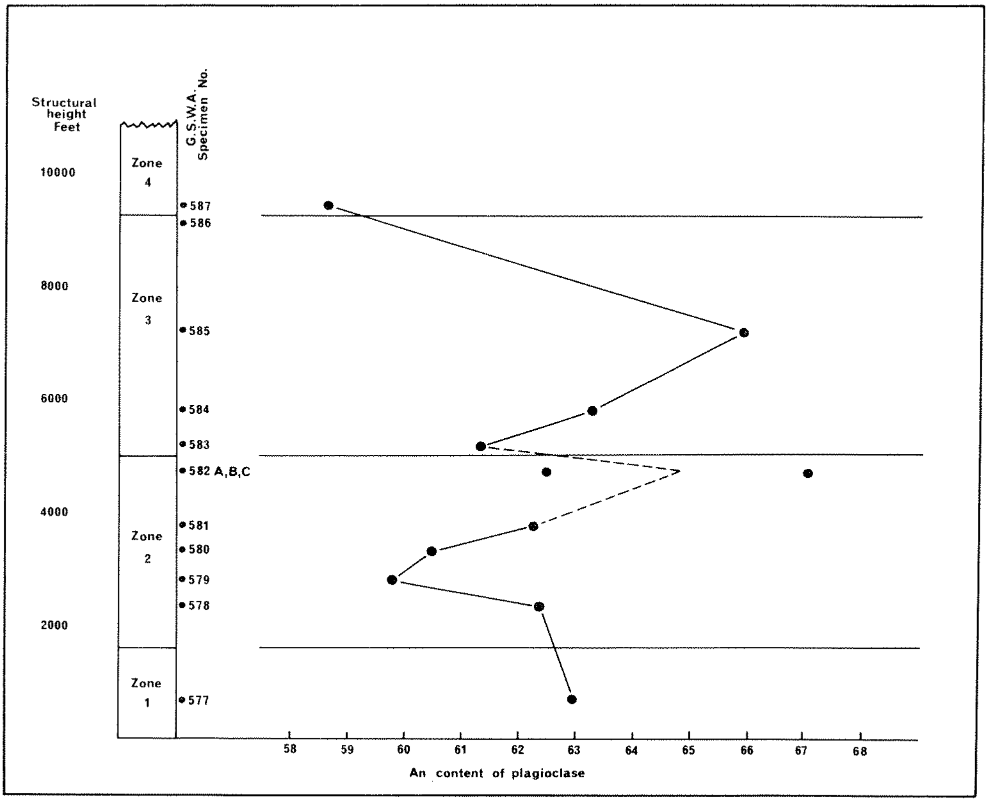

Figure 52. Variation in An content of plagioclase with height in Blackstone Range Gabbro. Solid circles-chemical determinations.

ZONE 1

The basal zone, approximately 1,600 feet (480 m) thick, is coarse grained, shows poorly developed and patchy igneous banding and some development of a pegmatitic gabbro facies.

One specimen from this zone is a coarse-grained hypersthene troctolite with sub-ophitic texture. Accessories include opaques, pleonaste and red-brown biotite. The hypersthene is weakly pleochroic, shows well developed schiller structure and possesses abundant small, rounded enclosures of clinopyroxene in optical continuity. The composition of the plagioclase determined optically on combined Carlsbad-albite twins ranges from An_{62-73} with a mean of An_{69}. Slight zoning is present. The chemically determined composition for this plagioclase is An_{63}.

The plagioclase from another sample from near the top of Zone 1, approximately 2 miles (3.2 km) east of the previous example, shows reverse zoning. The cores of the plagioclase crystals are An_{65} and grade out conspicuously to an extreme edge of An_{80}.

ZONE 2

Zone 2 is approximately 3,400 feet (1,030 m) thick and is characterized by well developed, fine-scale igneous banding. Gravity differentiated units are common and cross-bedding is moderately abundant. One example of trough-banding and some examples of slumping were noted.

The zone is mineralogically composite. The lower third consists of olivine norite, a rock type which also forms a thin layer at the top (Fig. 53). The rest of the zone is troctolite with rare accessory hypersthene.

ZONE 3

This zone consists entirely of hypersthene troctolite with hypersthene present only in small amounts. The lower third is well banded in contrast to the upper portion which rarely shows this feature.

Near the base of the well banded sequence a typical specimen (Fig. 54) consists of laths of well twinned plagioclase (An_{66}, optical determination) showing very slight normal zoning, together with irregularly shaped and corroded grains of olivine. A small quantity of hypersthene is present as reaction rims enclosing relict olivine. Minor clinopyroxene occurs as an intercumulate phase between laths of plagioclase. Other accessories include opaques, brown amphibole and red-brown biotite. Many of the opaques are rimmed by either olivine or brown amphibole.

A slight decrease in An content of plagioclase to An_{64} occurs at the top of the well banded section, but this is reversed in the overlying poorly banded section of this zone. A sample from this poorly banded part contains plagioclase of composition An_{70} (determined optically).

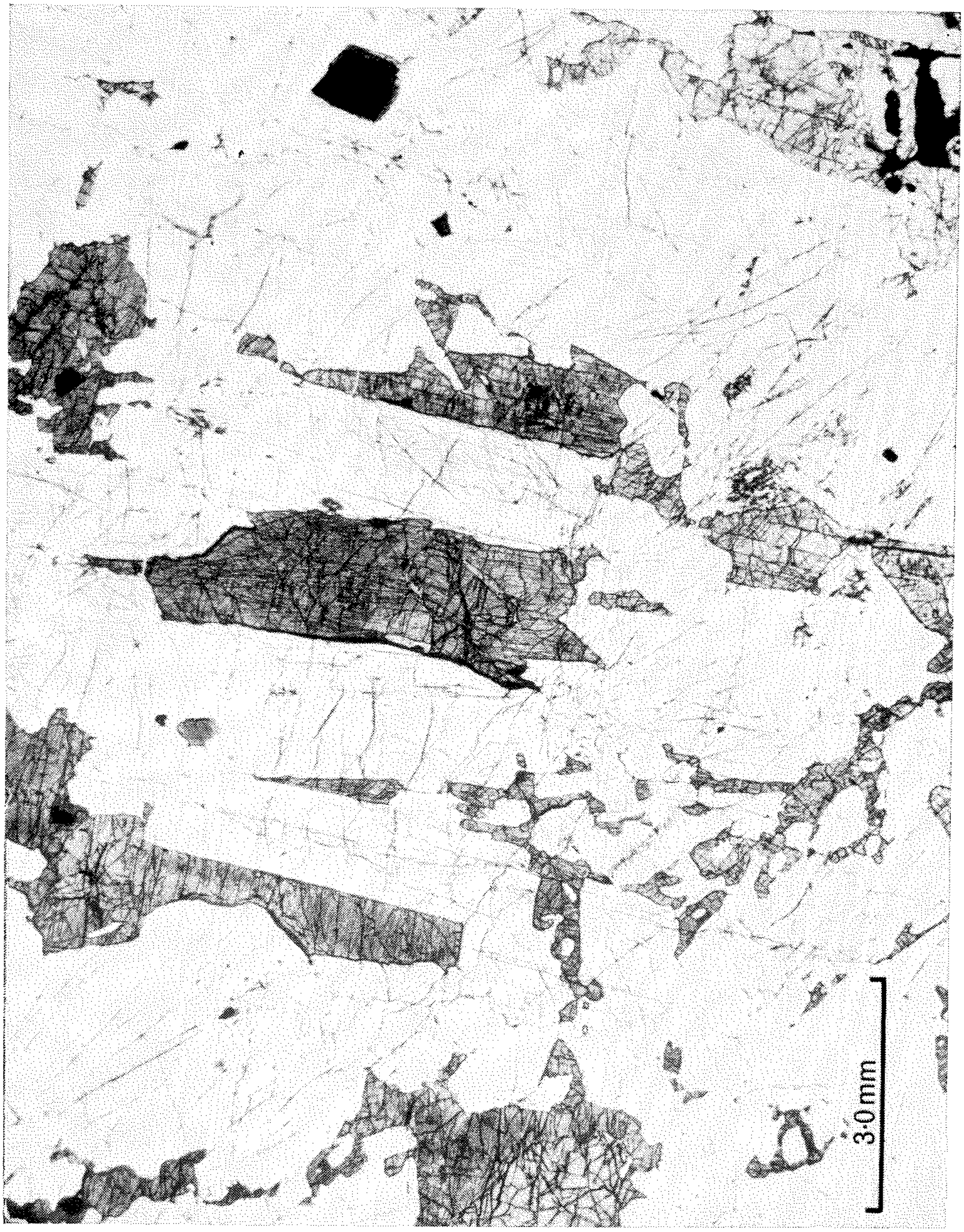

Figure 53. Photomicrograph of olivine norite from top of Zone 2, Blackstone Range Gabbro, Blackstone Range. Ord. light.

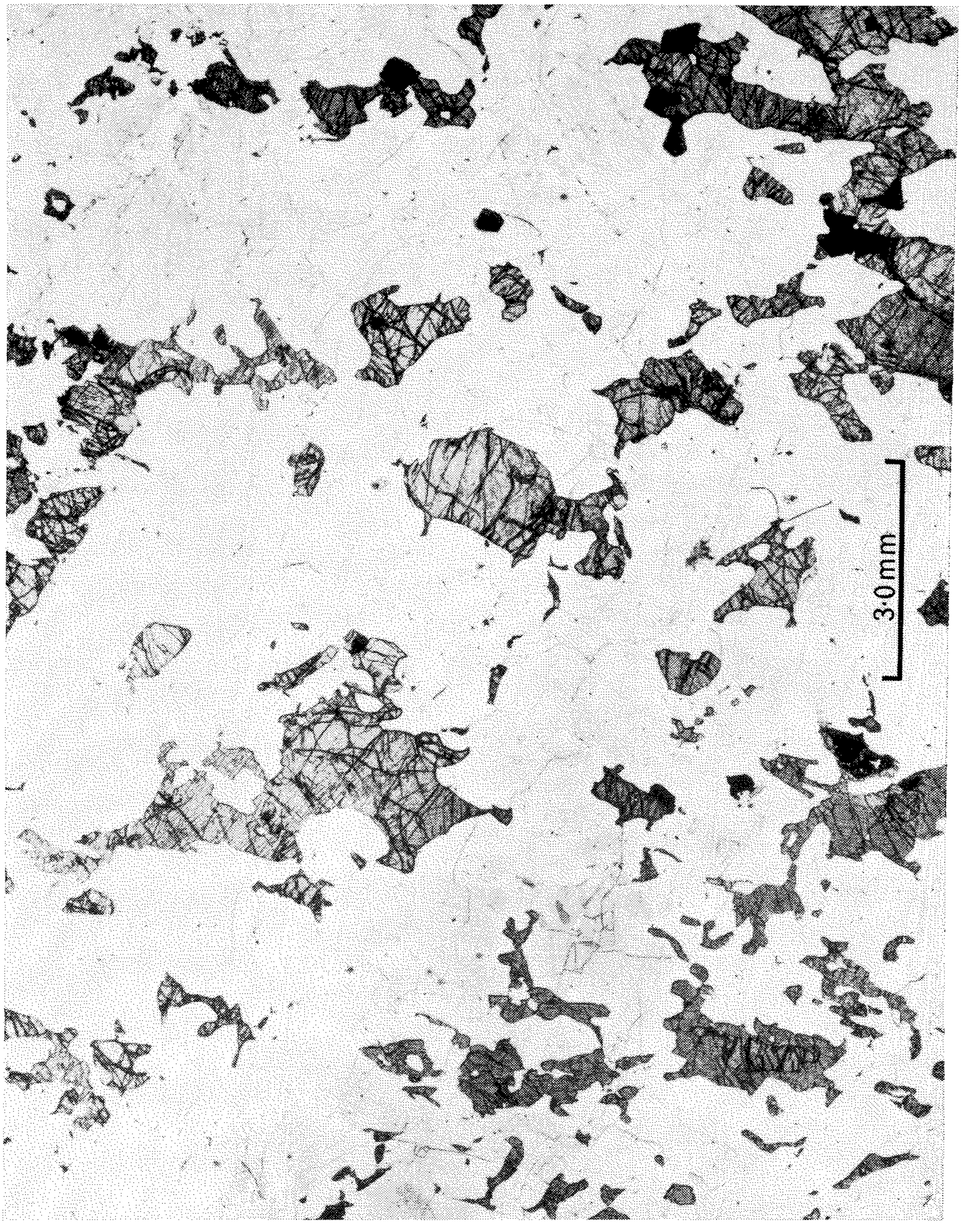

Figure 54. Photomicrograph of hypersthene troctolite from base of Zone 3, Blackstone Range Gabbro, Blackstone Range. Ord. light.

Figure 55. Photomicrograph of troctolite, Blackstone Range Gabbro, Bell Rock Range. Ord. light.

ZONE 4

Mafic troctolite forms the uppermost exposed zone. It is a dark-weathering rock composed of abundant fresh olivine forming a polyhedral mosaic with approximately 10 per cent plagioclase (An_{59}), and accessory clinopyroxene, orthopyroxene, opaques and red-brown biotite.

Between 15,000 feet (4,600 m) and 20,000 feet (6,000 m) of gabbro section is exposed in the Bell Rock Range, which is the southeasterly continuation of the Blackstone Range Gabbro.

At the northwest end of the range, near the deduced base of the intrusion, poikilitic olivine-hypersthene gabbro is exposed and this is overlain by a well layered sequence of troctolite (Fig. 55). In the lower parts of the troctolite, cross-bedding, ripplemarks and slump structures are well developed. Normal and reverse grading is also present. Overlying these and forming the southwest face of Bell Rock Range is gabbro in which the plagioclase shows reverse zoning from cores of An_{68-70} to extreme edges of composition An_{78-80}.

Overlying the main troctolite zone and forming the southwest flanks of the Bell Rock Range is a well-defined band of olivine gabbro with a distinctly darker air-photograph pattern. The rock consists of large laths of plagioclase (An_{60}) with small rounded olivine grains generally showing well developed reaction rims of orthopyroxene and clinopyroxene. Both pyroxenes also occur as an intercumulus phase between laths of plagioclase. Accessories include opaques, red-brown biotite and brown amphibole.

Modal analyses of a selection of rocks up the sequence in the Bell Rock Range are given in Table 11.

TABLE 11. MODAL ANALYSES OF GABBROIC ROCKS FROM BELL ROCK RANGE

	1300	520	519	518	516	512
Plagioclase	5	59·9	67·5	95·3	92·0	82·5
Olivine	40	37·2	30·1	2·1	1·4	8·2
Orthopyroxene	....	} 2·1	0·4	1·0	} 3·8	} 6·2
Clinopyroxene	55		....	....		
Brown amphibole	....	0·2	....	0·7	....	0·5
Biotite	....	0·4	0·4	0·4	0·4	0·2
Opaques	....	0·3	1·3	0·3	2·3	2·3
Apatite	....	....	0·1	0·3	0·1	0·1
Symplectic Intergrowth	....	....	0·3	....	....	....
	100	100·1	100·1	100·1	100·0	100·0
Plagioclase An (optical)	74	68	67	65	56	60

1300 Near base of intrusion, southeast end of Bell Rock Range.
520 Approximately 5,120 feet (1,560 m) above base of intrusion.
519 Approximately 6,320 feet (1,930 m) above base of intrusion.
518 Approximately 8,120 feet (2,470 m) above base of intrusion.
516 Approximately 10,080 feet (3,070 m) above base of intrusion.
512 Uppermost zone in Bell Rock Range.

Field relationships, regional cross-bedding patterns, and Sr/K characteristics of contained plagioclase, show that the Bell Rock Range is part of the Blackstone Range Gabbro. However, it is not possible to be certain about correlation of zones defined in the two masses. Zones 1, 2 and 3 in the Blackstone Range are probably equivalent, in the Bell Rock Range, to the poikilitic olivine gabbro and the main troctolite zones (Fig. 56). No lateral equivalents are known for either the darker toned gabbro in the Bell Rock Range or the mafic Zone 4 of the Blackstone Range, and this suggests that some of the zones may be lenticular.

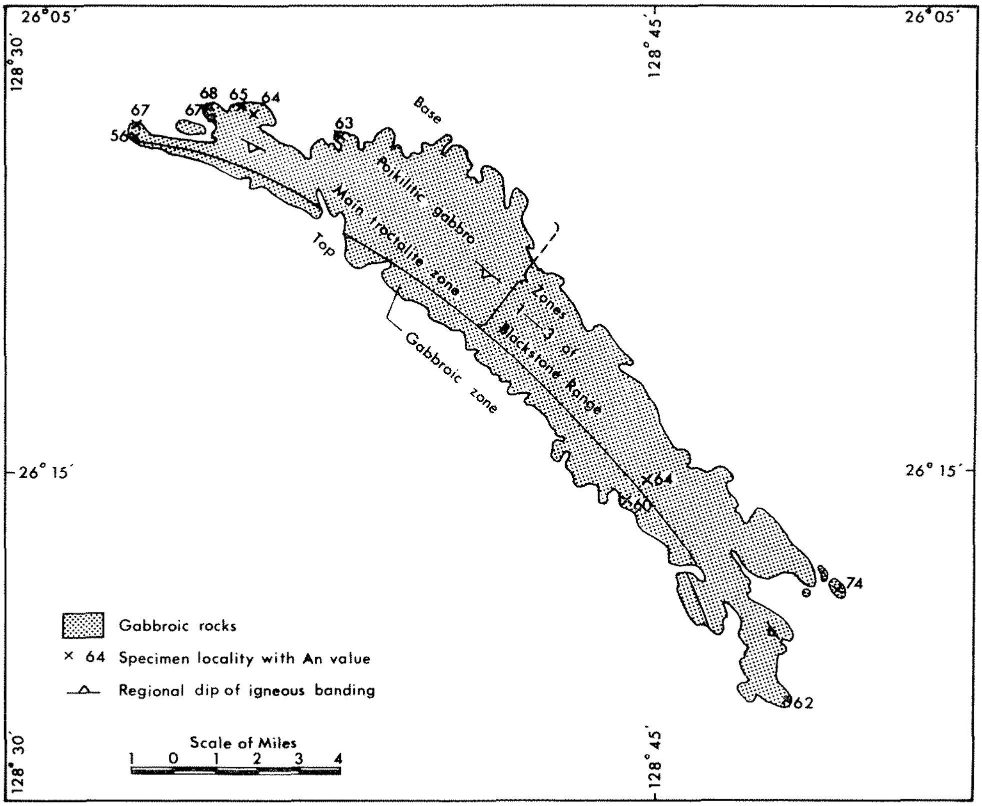

Figure 56. Sketch map of Bell Rock Range showing distribution of An values of plagioclase.

On the southeast end of Bell Rock Range, towards the base of the exposed sequence, is a series of thinly banded, alternating anorthosites and ultrabasic rocks which are distinctly green in fresh exposure. In both cases the colouration is caused by pale green tremolite-actinolite. In the anorthosites, which consist of dusted plagioclase laths showing bent twin lamellae, the small amount of amphibole present is granular and lath-shaped and is concentrated along plagioclase grain boundaries. In the ultrabasic rock, probably originally a websterite, the amphibole is the dominant mineral, and occurs as a felted, fine-grained mass of short laths with occasional corroded patches of relict orthopyroxene and clinopyroxene. This form of alteration is not known in the rest of the mass and is probably related to marginal shearing operative during the post-Giles Complex folding.

The low range of hills to the southwest of and parallel to the Bell Rock Range is not considered to be part of the Blackstone Gabbro. The hills are thought to be part of a suite of uralitized gabbroic masses intrusive into the acid and basic

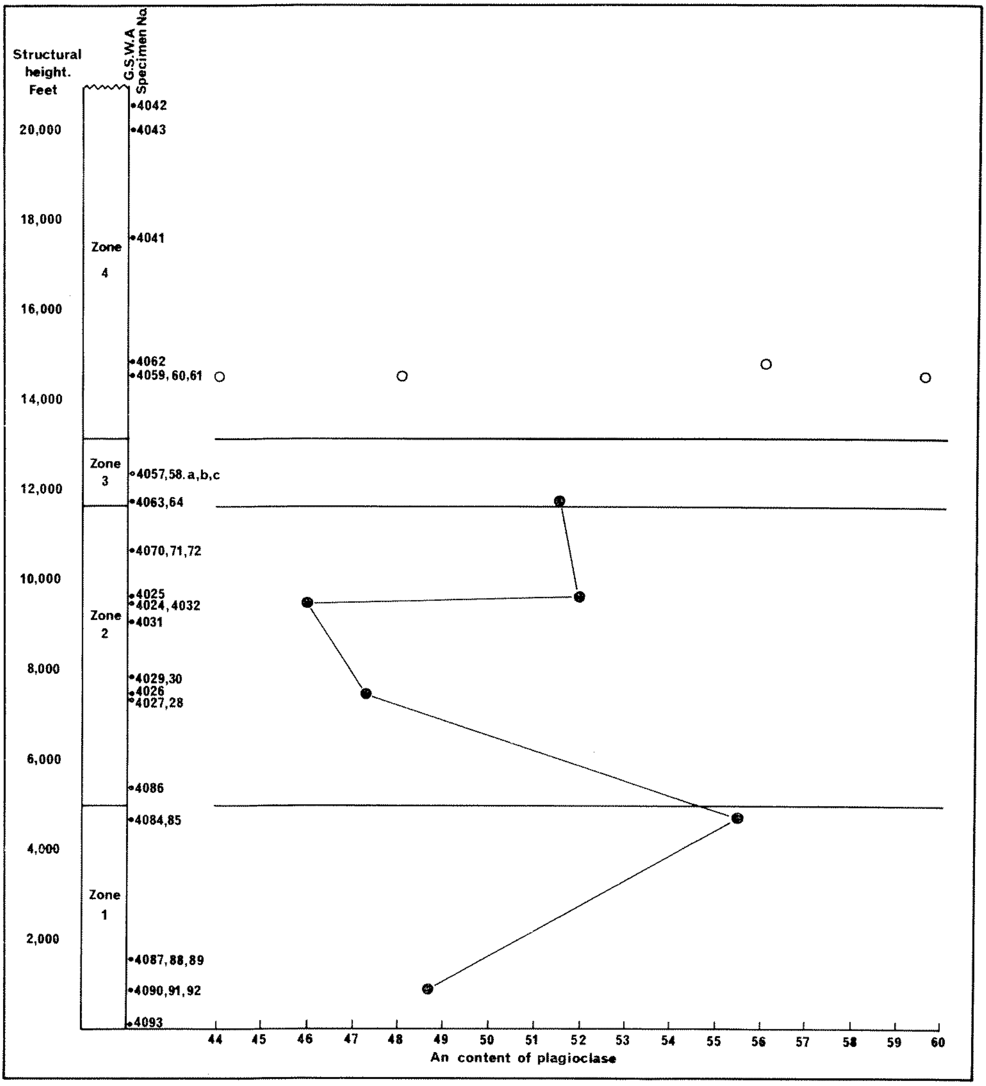

Figure 57. Variation in An content of plagioclase with height in Michael Hills Gabbro. Solid circles—chemical determinations; open circles—optical determinations.

volcanics of the Tollu Group. They are characterized by the presence of abundant dark green amphibole, small amounts of interstitial graphic intergrowths of quartz and potash feldspar and narrow dykes of granophyre.

MICHAEL HILLS GABBRO

The Michael Hills Gabbro is a sheet form intrusion approximately 21,000 feet (6,400 m) thick. It crops out over an area of approximately 100 square miles (260 km^2) in Western Australia and extends into South Australia for a distance of 5 miles (8 km). The original volume of material involved, not including an uppermost contaminated zone is possibly 750 cubic miles (3,100 km^3). However, much of the fine-grained basic rock of the Hinckley Range is thought to be related to the Michael Hills Gabbro. Consequently the original volume of basic magma involved in the pulse or pulses giving rise to the Michael Hills Gabbro and its related rock types could have been several times larger than the above estimate.

Most of the intrusion shows well developed banding on all scales: it is especially noticeable on air-photographs. Many of the bands form prominent benches up to 50 feet (15.5 m) high. This feature appears in Figure 40.

Good exposures are present in the Michael Hills but fresh specimens are often difficult to obtain since weathering produces a pale orange-brown, friable, crusty skin over rocks of the lower three zones.

The Michael Hills Gabbro is intrusive into granulites and migmatites, and in the northern part of its outcrop is intruded by gabbros and ultrabasic rocks.

Below the base of the intrusion to within approximately 200 feet (60 m) of the main contact are several thin basic sills, regarded as offshoots from the main mass. They have converted the country rock granulites to hornfels and are themselves composed of medium to fine-grained hypersthene gabbro carrying strongly antiperthitic, vaguely twinned plagioclase (An_{63}).

TABLE 12. MODAL ANALYSES OF GABBROIC ROCKS FROM MICHAEL HILLS GABBRO

	4085	4025
Plagioclase	65·6	43·7
Orthopyroxene	21·2	25·7
Clinopyroxene	12·8	30·1
Opaques	0·4	0·4
Biotite	....	0·1
	100·0	100·0

4085 Near top of Zone 1
4025 From Zone 2.

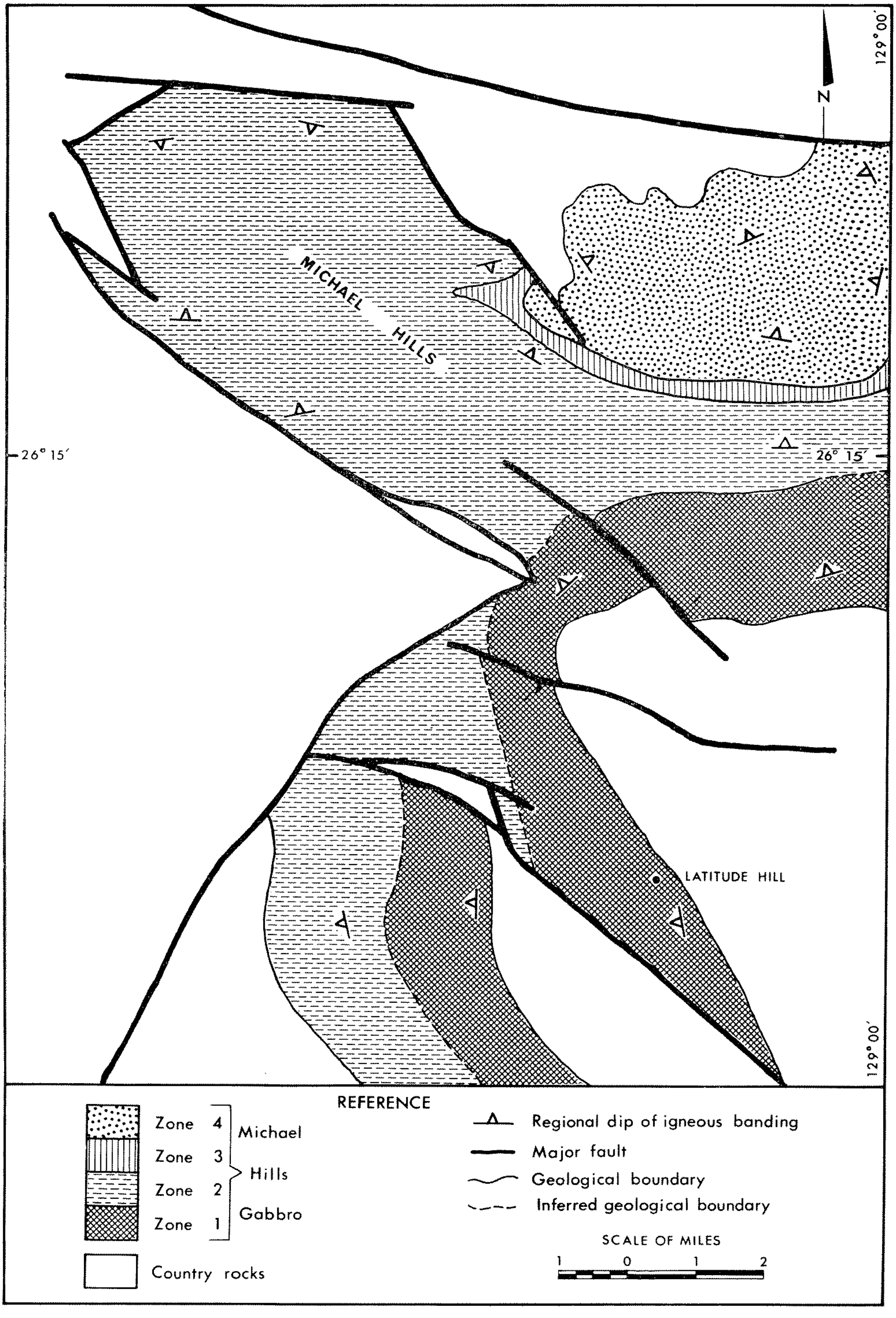

Figure 58. Suggested zonal scheme for Michael Hills Gabbro.

The intrusion has been subdivided into four major zones (Fig. 57). Each can be readily distinguished in the field, though the boundary between Zones 1 and 2 is apparently gradational and not well known. Their regional distribution is given in Figure 58, and analyses of four of the rocks are given in Table 32. Modal analyses are given in Table 12.

ZONE 1

This basal zone is 5,000 feet (1,500 m) thick and is characterized by the presence of banded leucocratic gabbroic rocks, anorthosites and interbanded pyroxenites. Igneous banding is well developed on all scales, but cross-bedding is rare.

Hypersthene gabbro forms most of this zone. The pyroxenes consist of coarsely crystalline hypersthene and clinopyroxene both carrying exsolution lamellae of one in the other. The hypersthene is moderately pleochroic and carries distinctive, brown, translucent, platy inclusions. The clinopyroxene is commonly multiply twinned. The plagioclase (An_{48-55}) is frequently poorly twinned. Twinning according to the albite law is usually almost suppressed, but pericline and Carlsbad twins are not uncommon. Accessories include opaques and red-brown biotite. Most of the constituent grains have been stressed with the production of bent, kinked and fractured crystals (Fig. 59). The feldspar frequently shows undulose extinction. Some examples have been granulated and appear now as a fine-grained plagioclase mosaic with elongated mafic bands, also generally granular. In the lowermost 1,000 feet (300 m) of the zone antiperthitic plagioclase is abundant.

The orthopyroxene from a sample near the top of Zone 1 has $\gamma = 1.705 \pm 0.002$ indicating a composition of Fs_{66}.

Interbanded pyroxenites are more common in the lower half of the zone. They are generally between 20 and 50 feet (6 to 15 m) thick and consist of medium to coarse-grained hypersthene and clinopyroxene, generally with small (5 per cent) amounts of interstitial plagioclase and traces of red-brown biotite. The proportion of clinopyroxene to orthopyroxene is very variable ranging in different bands from 2:1 to 1:5. Both pyroxenes appear to be similar to those in the hypersthene gabbro.

ZONE 2

The top of Zone 1 is not well defined. Zone 2, however, is approximately 6,700 feet (2,000 m) thick and may be distinguished by the absence of thick pyroxenites and only a very minor development of anorthosites. The zone is well banded and forms the majority of the topographical feature known as Michael Hills. It consists principally of a hypersthene gabbro very similar to that of Zone 1.

On the northern side of Michael Hills part of Zone 2 is very well banded with individual bands ranging from approximately 6 inches (15 cm) to several

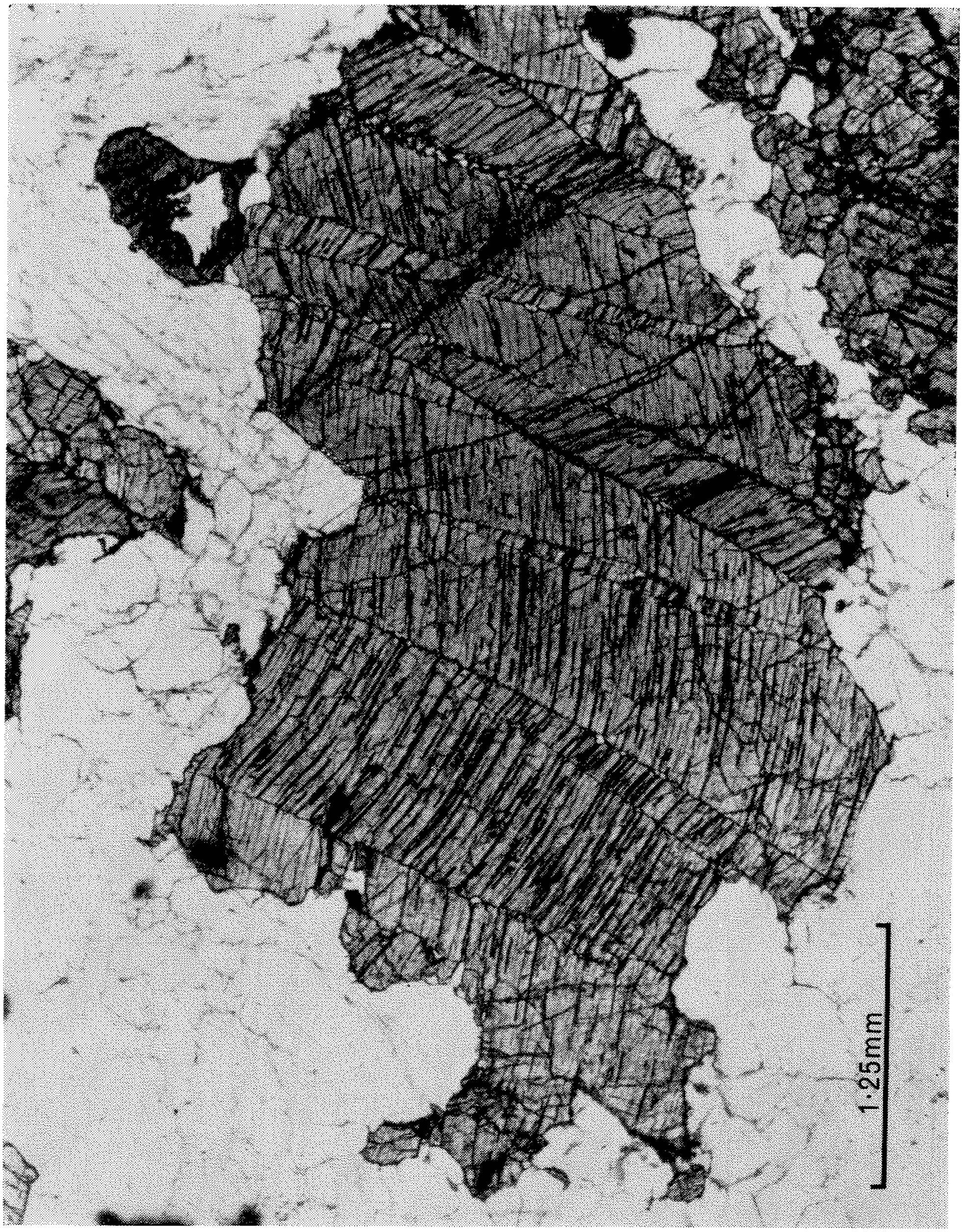

Figure 59. Photomicrograph of kinked orthopyroxene from Zone 1 of Michael Hills Gabbro. Ord. light.

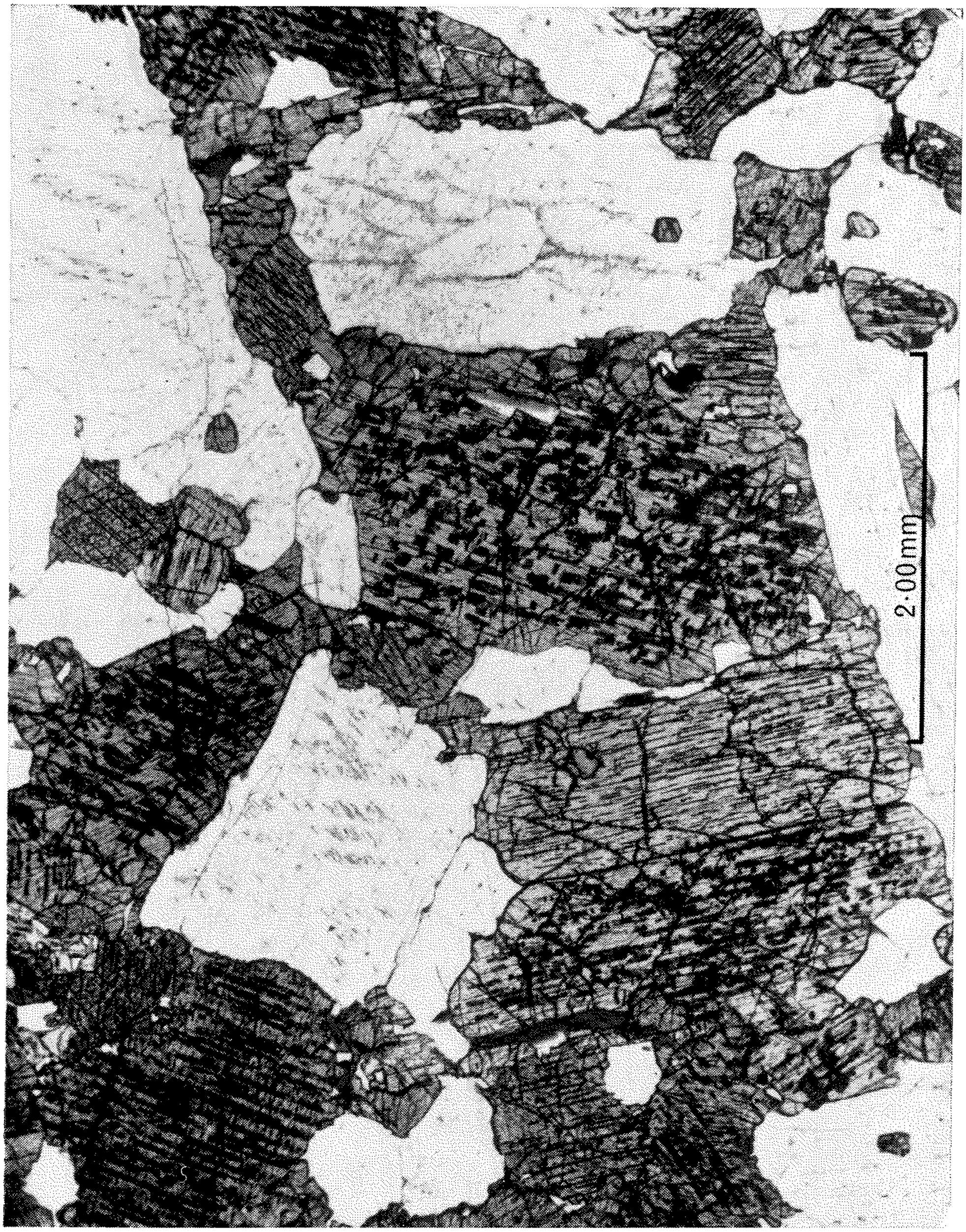

Figure 60. Photomicrograph of sample from Zone 2 of Michael Hills Gabbro showing abundant plate-like inclusions in the pyroxenes and the lightly antiperthitic nature of the plagioclase. Ord. light.

feet in thickness. Several of the bands display a well developed orientation of the plagioclase laths, a feature frequently visible in the field. In thin section the rock consists of long laths of plagioclase (An_{52}) with orthopyroxene and clinopyroxene as short, stubby crystals and interstitial grains (Fig. 60). Both pyroxenes show exsolution features of one in the other. Accessories include minor amounts of opaques and red-brown biotite. The plagioclase is poorly twinned, somewhat zoned, slightly antiperthitic and carries abundant, minute, short opaque rods. The orthopyroxene is moderately pleochroic and carries abundant translucent brown plates. Figure 61 shows an example of well oriented plagioclase in a gabbro from this zone, approximately 3 miles (4.8 km) west-southwest of Latitude Hill.

Another specimen from this same zone comes from a Southwestern Mining Company Limited drillhole in the valley between Michael Hills and Sphinx Hill. No depth is available for the sample, but it is very similar texturally and mineralogically to the previous sample. Slight differences are apparent. The plagioclase has a composition of An_{55} and the rock contains a few per cent of opaques mainly as large grains enveloping the pyroxenes and the plagioclase. An adjacent pegmatitic facies, with abundant antiperthite and minor mafics has been studied in more detail by the Government Chemical Laboratories. They report that the opaques consist chiefly of ilmenite and magnetite with accessory pyrite in grains up to 3 mm long, a little chalcopyrite, a trace of pyrrhotite and rare grains of a sulphide tentatively identified as pentlandite. The ilmenite and magnetite usually occur as composite grains with evidence of accretionary growth of ilmenite at the boundaries marked by inclusions of possible pleonaste.

The brown translucent plates in the hypersthenes of this same specimen were also examined. The Government Chemical Laboratories describe these inclusions as narrow lamellae between 1 and 10 microns wide with a reflectivity of approximately 20 per cent. They have not been specifically identified but are thought likely to be exsolution plates of titanium-bearing magnetite.

In general, Zone 2 is dominantly hypersthene gabbro. The plagioclase shows little variation from An_{46-55} and in the upper parts of the zone it is noticeably antiperthitic. The γ refractive indices of two hypersthenes from the zone are 1.704 ± 0.002 and 1.706 ± 0.002 indicating an approximate composition of Fs_{66}. The clinopyroxenes in association with these hypersthenes show $\gamma = 1.720 \pm 0.002$ and $\gamma = 1.713 \pm 0.002$ respectively.

ZONE 3

Zone 3 is approximately 1,200 feet (365 m) thick and is characterized by well-defined banding and a fairly fresh appearance, in contrast to the lower two zones which generally weather with a "crusty" appearance. Gravity differentiated bands and cross-bedding are common.

The main rock type is a slightly sheared hypersthene gabbro similar to that of the two lower zones. The plagioclase is rarely antiperthitic and the twin lamellae are usually ill defined and bent making optical determination of the

Figure 61. Photomicrograph showing igneous lamination displayed by gabbro of Zone 2 in Michael Hills Gabbro, 3 miles west-southwest of Latitude Hill. Ord. light.

composition difficult. The normative plagioclase of a sample from this zone gives a composition of An_{58} compared with a composition of An_{52} determined by chemical analysis of the extracted feldspar. The range in plagioclase composition from An_{52} to An_{59} is known for this zone. The hypersthene resembles that of Zones 1 and 2, being moderately pleochroic and carrying abundant small translucent brown plates. Only minor exsolution features are present in both the orthopyroxene and the clinopyroxene.

ZONE 4

The uppermost zone is probably about 7,600 feet (2,300 m) thick. It weathers black, in strong contrast to the lower three zones, which weather to an orange-brown. The zone is moderately well banded, the banding being partly igneous and partly due to a large number of enclosed sheets of granitic gneiss which have been stoped and partly assimilated by the gabbroic material.

The mechanics of the assimilation process are described elsewhere (p. 149). However, the product of assimilation of the acid country rock by basic material related to the Michael Hills Gabbro is a fine to medium-grained, blue-grey, basic rock. It generally carries small remnant blebs of quartz or quartz and feldspar, nearly always with a preferred orientation. The alignment of these leucocratic inclusions has been mapped and shows a well-defined convergence towards the centre of the present outcrop of Zone 4 (Fig. 40). This convergence seems to preclude a tectonic origin for the alignment, and it is suggested that the pattern represents the arrested flow characteristics of the magma which probably originated from the point of convergence of the lineations. From this centre it is thought to have spread out to the west, south and east, assimilating acid material in the process.

Minor intrusions of gabbro, pegmatitic troctolite and ultrabasic rocks cut the intrusion on the north central side of Zone 4 approximately 1½ miles (2.4 km) northwest of the point of convergence of the oriented leucocratic blebs. This suggests that this area was an important centre of repeated igneous activity. It is bounded on its northern side by a major mylonite zone.

The main rock type of Zone 4 is a finely granular plagioclase-hypersthene-clinopyroxene rock with variable amounts of quartz and potash feldspar, and accessory opaques and red-brown biotite. The plagioclase is poorly twinned and ranges in composition in different specimens from An_{44} to An_{60}. The opaques are generally abundant and consist of individual grains approaching in size that of the major minerals, or as minute granules almost entirely confined to pyroxene grain boundaries. Other samples carry plates of brown amphibole (possibly kaersutite) poikilitically enclosing pyroxenes and opaques.

In Zones 1, 2 and 3, a conspicuous fine-grained rock is apparently transgressive to the banding and also forms xenoliths in the coarser banded gabbros. It is itself an orange-brown-weathering hypersthene gabbro with similar accessories to the main gabbro.

HINCKLEY RANGE GABBRO

Detailed work has not been undertaken on the Hinckley Range Gabbro. It occupies a syncline whose north-northwest axis runs through the length of the Hinckley Range. Its thickness is given by Nesbitt and Talbot (1966) as approximately 9,000 feet (2,700 m). The southern limb thins out to the west at a point approximately 8 miles (13 km) west of Mount Hinckley. Two miles (3.2 km) east of this point the gabbro has thickened to just over 3,600 feet (1,100 m) while approximately 9 miles (14 km) farther east it reaches its maximum thickness.

Little or no igneous banding is visible until the thickness reaches approximately 3,000 feet (900 m), suggesting that a minimum thickness of gabbroic liquid is necessary before the physical conditions capable of producing banding can be achieved. Cross-bedding structures appear to require greater thicknesses as they were not seen in the first banded rocks, but are well developed in the thicker part of the succession approximately 3 miles (4.8 km) northwest of Mount Davies in South Australia.

At much of the lower contact and also above the body, there is developed a contaminated, fine-grained basic igneous rock forming thick masses and transgressive sheets in the granulitic country rock which it has assimilated.

The Hinckley Range Gabbro has not been subdivided. Rock types present include olivine norite and olivine-hypersthene gabbro. Accessory minerals include opaque iron oxides, pleonaste and red-brown biotite. Small quantities of chromite have been found near Wingelinna.

On the northern side of the syncline, near Wingelinna, is a deposit of nickeliferous ochre. It appears to have been formed by the deep weathering of interbanded ultrabasic and basic rocks possibly near the base of the intrusion. Where least altered, this interbanded association shows fold structures.

MOUNT WEST GABBRO

A relatively small sheet between Michael Hills and Bell Rock Range has been called the Mount West Gabbro by Nesbitt. It has a maximum thickness of approximately 4,500 feet (1,400 m) and dips to the southwest at approximately 45 degrees. It has not been studied in detail, but consists of a well banded sequence of olivine gabbros with a moderate development, at the base, of ultrabasic rocks. The latter includes some dense olivine-chromediopside rocks.

The sheet is developed above a mass of granulites and below a sheet of porphyritic granite with some development of a migmatite of granulite and porphyritic granite. The intrusion's structural level is the same as that of the Hinckley Range Gabbro and may possibly be the southwesterly extension of this gabbro. However no chemical data are available to support this hypothesis.

MINOR GABBROIC BODIES

Several minor bodies of gabbro cut the Tollu Group, and are structurally the highest gabbros of the Giles Complex. The most important has a crescent-shaped outcrop and forms a series of prominent isolated hills on the southwest side of the Bell Rock Range. The largest of the others cuts Mummawarrawarra Hill. Several smaller bodies occur between the Blackstone and Cavenagh Ranges. Many of these gabbros, especially those on Mummawarrawarra Hill, carry xenoliths of contact-altered basic and acid volcanics of the Tollu Group, and are cut by thin granophyre dykes.

The gabbros show well developed ophitic texture and most are uralitized to some degree. Granophyric intergrowths of quartz and potash feldspar are common as interstitial patches.

Other minor gabbroic bodies occur in the form of moderately thick dykes cutting granitic and granulitic country rock. The most important occur west and north of Mount Aloysius and near Mount Gosse. They are coarsely crystalline and probably related to the main gabbros rather than to the younger dolerite dykes.

Diorite Hill, approximately 4 miles (6 km) west of Bedford Range in the northeast part of the Bentley Sheet area, is composed of a slightly uralitized, moderately well layered gabbro sill. It is the most northerly known outcrop of gabbroic rocks in this region. It intrudes quartzites and quartz-muscovite schists. Its full extent is not known.

Minor gabbroic intrusions cut the acid volcanics of the Palgrave volcanic association. The largest of these masses forms a small domal structure 11 miles (17.6 km) almost due west of Mount Rawlinson. The gabbro contains hornblende and is capped by a thin granophyric differentiate. It is not impossible that this occurrence is a continuation of the Jameson Range Gabbro.

GRANOPHYRES AND RELATED ACIDIC BODIES

Granophyric masses closely related to the gabbroic rocks of the Giles Complex have two modes of occurrence.

The main type occurs as a massive sheet possibly 200 feet (60 m) thick above gabbro immediately south of Tollu. The gabbro is probably part of the southern edge of the Blackstone Range Gabbro. Immediately below the granophyre the gabbro is black-weathering and partly uralitized. It carries small intergranular patches of micropegmatite. The transition to massive granophyre is rapid and complete over a thickness of a few feet.

The granophyre is a medium to fine-grained pale mauve rock which carries, near its base, abundant long thin laths, or parallel aggregates of laths, of feldspar. Some of the laths are up to 5 inches (13 cm) long but the average length is approximately 1 inch (2.5 cm). Higher up in the mass, lath frequency and size both decrease until the rock is a uniform, medium-grained granophyre. An analysis of the medium-grained variety is given in Table 12. In the uppermost parts of this sheet, immediately west of Tollu, a few rafts of contact metamorphosed acid volcanics derived from the Tollu Group are embedded in the granophyre.

In the second mode of occurrence, narrow dykes of granophyre up to 2 feet (61 cm) wide cut some of the gabbro masses intruding the Tollu Group. Good examples occur in the small isolated gabbroic exposures forming the low range

TABLE 13. ANALYSIS AND NORM OF GRANOPHYRE FROM THE TOP OF BLACKSTONE RANGE GABBRO, TOLLU

	23340	Norm	
SiO_2	69·63		
Al_2O_3	13·22	Q	28·51
Fe_2O_3	2·72	C	0·03
FeO	1·98	Or	28·03
MgO	0·33	Ab	27·21
CaO	1·99	An	7·46
Na_2O	3·22	Hy	2·02
K_2O	4·74	Mt	3·94
H_2O^+	0·58	Il	0·68
H_2O^-	0·16	Ap	0·11
CO_2	0·33		
TiO_2	0·36		
P_2O_5	0·05		
MnO	0·22		
NiO	0·006		
CuO	0·02		
Li_2O	0·04		
ZrO_2	0·13		
S	0·01		
F	0·08		
BaO	trace		
	99·82		
O = F, S	0·03		
	99·79		

Analyst : R. W. Lindsey.

flanking, and to the southwest of, Bell Rock Range. The rocks are medium to fine-grained granophyric intergrowths of potassic feldspar and quartz, with strongly zoned plagioclase and a moderate mafic content. The latter consists of needles or equidimensional grains of pale green pyroxene in various stages of replacement by a bluish-green hornblende. Accessories include opaques and sphene.

Pegmatites of coarse-grained quartz and potassic feldspar sometimes in graphic intergrowth, and with very occasional muscovite and garnet, are generally very rare, but have been found cutting gabbroic rocks in Hinckley Range, Bell Rock Range, Jameson Range and Murray Range. They are most abundant cutting the ultrabasic rocks in Murray Range. They are apparently identical with normal acid pegmatites derived from granites, but are confined to the gabbroic rocks. They could possibly be acid derivatives from the gabbros.

MARGINAL FACIES

Rocks included in the marginal facies have been mapped on the northern sides of the Blackstone and Cavenagh Ranges. In both areas this rock unit includes contaminated gabbroic material, together with a variety of other rocks which have not been mapped as separate units, partly because of the scale of mapping and partly because they cannot be clearly distinguished from air-photographs.

North of the Cavenagh Range some of these rocks are black-weathering, contact-metamorphosed, fine-grained, slightly porphyritic acid volcanics correlated with the Smoke Hill Volcanics of the Tollu Group.

North of Blackstone Range two main rock types occur in addition to the contaminated gabbro. One of these is a moderately thick wedge of contact-metamorphosed amygdaloidal basic lavas. The amygdaloidal lava tops are well preserved. Some of the amygdales resemble the quartz-feldspar blebs in many of the contaminated gabbros, but several characters reveal their difference. The amygdales are usually zoned, in contrast to the leucocratic blebs of the contaminated gabbros, and are arranged in narrow zones. Each zone shows a progressive increase in the number of amygdales up to the top of the unit, where the amygdales cease abruptly. This suite of metabasalts faces south and dips under the Blackstone Range Gabbro. It is thought to be sliver of the Mummawarrawarra Basalt.

Several other basic, black-weathering rocks in the same unit on the northern side of the Blackstone Range are probably slightly sheared portions of a layered gabbroic mass. Augen of pyroxene are present in the rock, and the accompanying plagioclase has been drawn out into long thin lenses. The structure approaches that of a flaser gabbro. Plagioclase from one of these rocks was separated and analyzed (Table 20 No. 576). The plot of this plagioclase for strontium against both the An and Or contents falls within the field of composition for plagioclases of the Blackstone Range Gabbro. It is concluded that some of the marginal facies on the northern side of the Blackstone Range represents Blackstone Range Gabbro material caught up in a shear zone produced near the lower contact of the gabbro during the folding of the Giles Complex.

DEVELOPMENT OF CONTAMINATED GABBRO, NET-VEINED COMPLEXES, RECRYSTALLIZED GRANULITES AND ANATECTIC GRANITE

Much of the western half of the Hinckley Range consists of a fine to medium-grained dark blue-grey "granulitic" rock, consisting of plagioclase, clinopyroxene, orthopyroxene, opaques and biotite and referred to as a fine-grained hypersthene gabbro. Large elongate masses of acid granulite are present and are particularly well displayed in the western part of the Hinckley Range (Fig. 62). They represent relict masses of granulite stoped and partially assimilated by basic magma related to the Giles Complex. Other large masses of similar rock are found in the Murray Range.

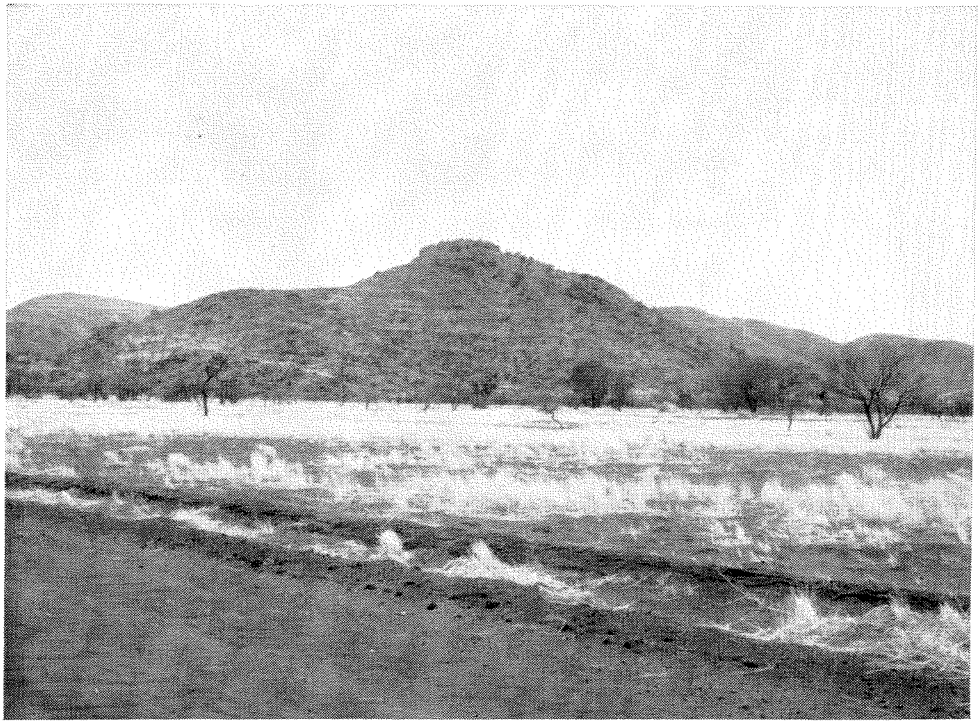

Figure 62. Northwest end of Hinckley Range showing rounded ridges of charnockitic gneiss with intervening areas of more easily weathered contaminated gabbro. The horizontal linear features in the centre of the photograph are the surface traces of dolerite dykes.

Exposures on the western end of the Hinckley Range are ideal for showing the nature of this process, and as the changes can be traced progressively, the ancestry of the most altered varieties is not in doubt.

CHANGES IN THE COUNTRY ROCK

The original country rock was a fine to medium-grained acid granulite, somewhat migmatized and showing abundant complex folds. The rock types produced during the emplacement of large quantities of basic material include contaminated basic rock, recrystallized granulite, small net-vein complexes and anatectic granite.

The processes which occurred as interpreted from field evidence, may be summarized in sequence as follows:—

1. injection of gabbroic magma
2. loss of clarity of old folds in the granulites and development of porphyroblasts of potash feldspar
3. loss of all old structures and much recrystallization

4. complete recrystallization with production of granitic-looking rock
5. flaking-off of granulite or recrystallized granulite as thin sheets and incorporation of these sheets into the basic rock
6. breaking up of the incorporated sheets into small "blebs". The process continues with digestion of these "blebs", producing a basic rock with very small white specks, and eventually a homogeneous, contaminated, fine to medium-grained basic rock
7. melting of acid rock and production of net-veined patches up to a foot across. Larger granitic veins, from 50 to 200 feet (15 to 60 m) wide and probably 1,000 feet (300 m) long, are present, but it is not known if these are of anatectic origin.

Many bands of acid gneisses and migmatized granulites are incorporated in Zone 4 of the Michael Hills Gabbro. Many of the processes listed above also apply in this case, and have given rise to rocks of similar character, including very large masses of the distinctive fine-grained plagioclase-clinopyroxene-orthopyroxene-opaques rock, flecked with small elongated leucocratic enclosures.

Where much of the evidence for assimilation is absent, these flecked, fine-grained basic rocks are interpreted as contaminated gabbros.

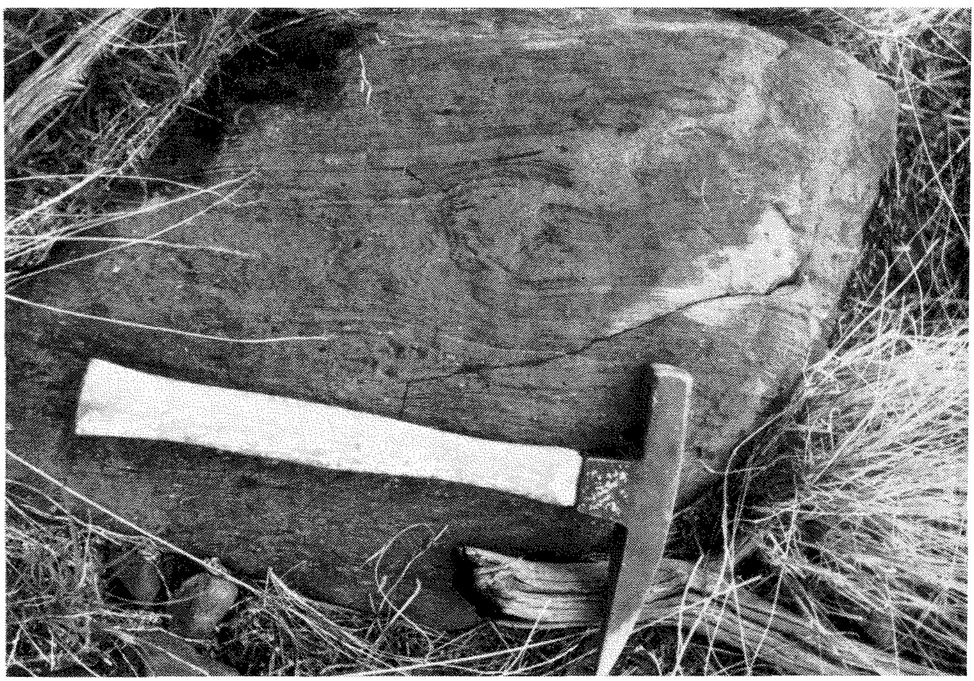

Figure 63. Slightly modified granulite showing banding and original folds. Northeast Hinckley Range.

Large areas of this rock type are shown on Plate 1, and the conclusion is that this process is very important in understanding the petrology of Giles Complex. More details of the process as seen on the western end of the Hinckley Range are therefore given below.

The least altered granulite in one of the acid bands enclosed in the fine-grained basic rock shows well developed original folds typical of the granulites of this area (Fig 63). It is a medium to fine-grained rock with thin banding defined by discontinuous lines of mafic minerals. Minerals present include orthoclase, oligoclase (An_{28}), quartz, clinopyroxene, orthopyroxene, opaques and accessory rounded zircon, red-brown biotite, apatite needles, metamict orthite and very rare brown amphiboles. Its approximate mode is given in Table 14 No. 1.

TABLE 14. APPROXIMATE MODES OF GRANULITE AND MODIFIED GRANULITE ENCLOSED IN FINE-GRAINED BASIC ROCK FROM THE WESTERN END OF THE HINCKLEY RANGE

	1	2	3
Potash feldspar	50	40	60
Plagioclase	10	20	5
Myrmekite	tr	tr	8
Quartz	20	10	20
Clinopyroxene	10	10	0
Orthopyroxene	5	15	4
Opaques	5	5	3
Biotite	tr	tr	tr
Apatite	tr	tr	tr
Zircon	tr	tr	tr
Orthite	....	....	tr
Plagioclase An content	28	40	60–62

1. Fine-grained granulite
2. Modified granulite
3. Recrystallized granulite

Note: tr = trace

The quartz of this rock shows minor undulose extinction and a slight tendency to form grains larger than the average. Very fine-scale albite twinning is present in the oligoclase, which is also occasionally antiperthitic. A very minor amount of myrmekite is scattered throughout the rock.

A slightly more advanced stage in the alteration is represented by No. 2 of Table 14. It is noticeably coarser grained than the previous specimen and the plagioclase is decidedly more calcic (An_{40}). Quartz shows some porphyroblastic development, and myrmekitic intergrowths are present but rare.

The most altered of the granulites (Table 14 No. 3) is a medium to coarse-grained gneissic rock in which all the fine-scale original banding has been obliterated. The gneissic texture is defined by elongated lenticular bands of mafics. Porphyroblasts of quartz and bronzy-weathering potash feldspar are well developed. The most noticeable features of this rock are the absence of clinopyroxene, the high anorthite content of the plagioclase (An_{60-62}), the abundance of myrmekite and the relationship of the latter to the potash feldspar porphyroblasts: the potash feldspar porphyroblasts (orthoclase) show a zonal arrangement of microperthitic enclosures or patches of microperthite and frequently carry small, irregularly shaped areas of myrmekite confined to the outer parts of the crystals. It appears that these orthoclase porphyroblasts grew by incremental stages, reacting with plagioclase to produce the myrmekite. As the potash feldspar grew, the myrmekite "cauliflowers" were incorporated and apparently digested, the plagioclase fraction being accepted into the potash feldspar to produce microperthite bands and patches.

The most important microscopic features observed in the modification of the granulites, apparently in the solid state, under the influence of the basic material are:

1. progressive increase in grain size
2. development of porphyroblasts of quartz and potash feldspar
3. increase in amount of myrmekite
4. loss of clinopyroxene. The three examples in Table 14 show a progressive decrease in the ratio of clinopyroxene to orthopyroxene
5. increase in the anorthite content of the plagioclase, which may possibly be related to the decrease in clinopyroxene.

Small areas, however, show net-veining by acid material and this is interpreted as indicating some melting of the granulite by the basic material. These net-vein patches are confined to areas up to 2 feet (60 cm) across. Larger net-veins, from 50 to 200 feet (15 to 60 m) across, are not uncommon on the south side of Hinckley Range. These contain orthoclase microperthite and minor antiperthitic plagioclase with brown biotite or relict clinopyroxene, secondary dark green hornblende and minor biotite. Accessories include euhedral and rounded zircon, opaques, metamict orthite and apatite.

It is not known whether these larger veins are also of anatectic origin. They are apparently pre-Hinckley Range Gabbro in age.

DEVELOPMENT AND ORIGIN OF THE CONTAMINATED GABBRO

While the changes were taking place in the granulites, the basic material was being modified by the incorporation and assimilation of granulitic material.

The initial process was one of stoping and flaking off of thin bands of granulite (Figs. 64 and 65) which broke up and became rounded or oval lenses or "blebs" (Fig. 66). More complete digestion of these blebs results in a progressive decrease in their size. Eventually they are only recognized in the

Figure 64. Recrystallized granulite showing development of porphyroblasts of feldspar and intrusion of basic material. Northeast Hinckley Range.

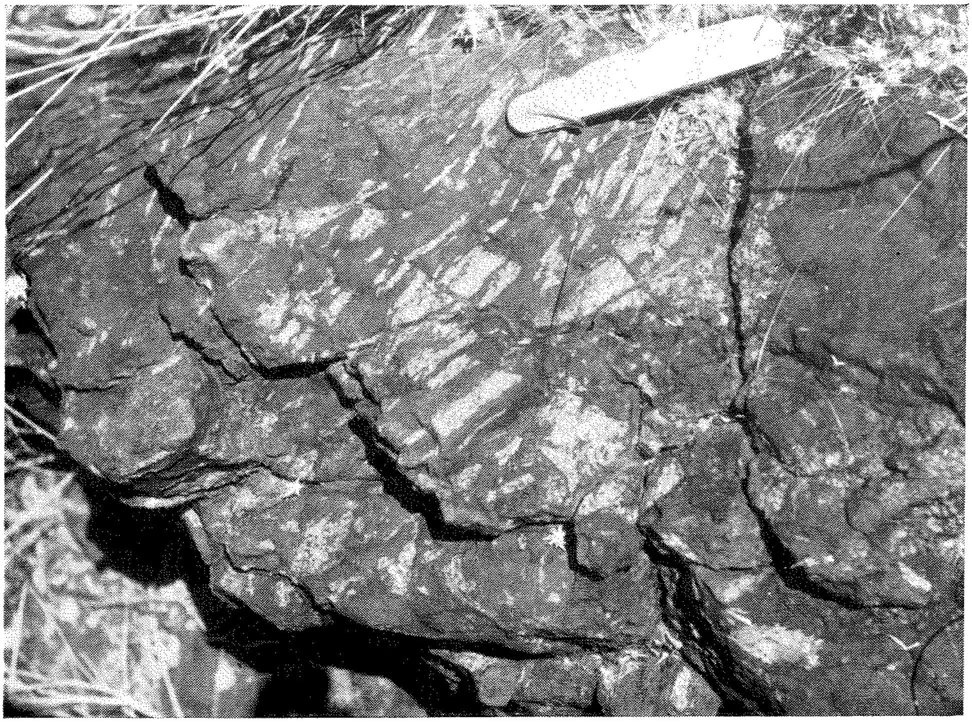

Figure 65. Granulite gneiss stoped by basic material. Northeast Hinckley Range.

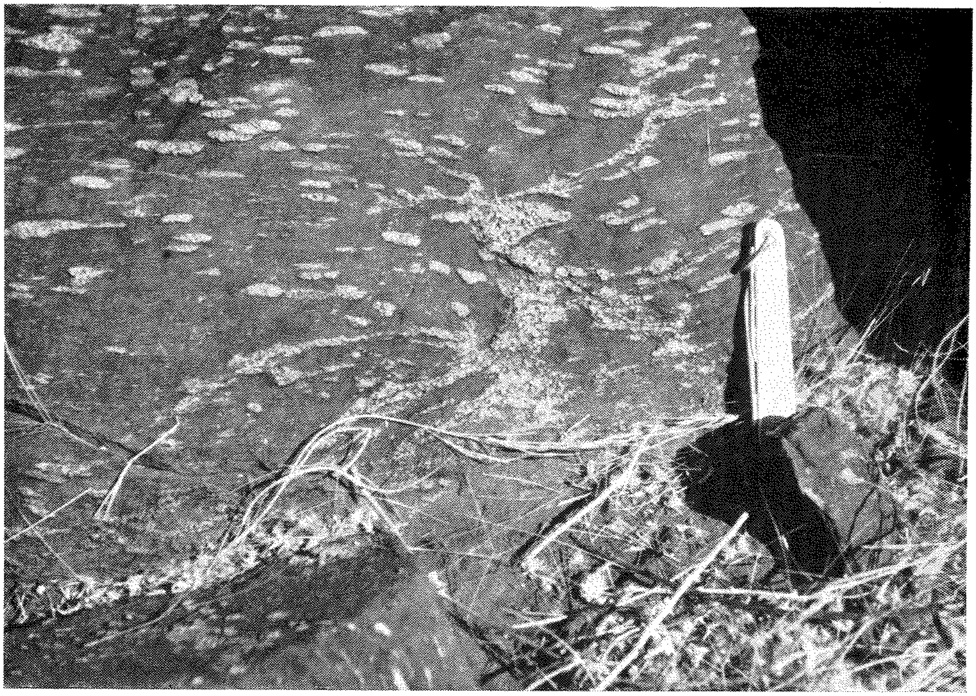

Figure 66. Modified granulite fragments in process of being assimilated by basic material. Northeast Hinckley Range.

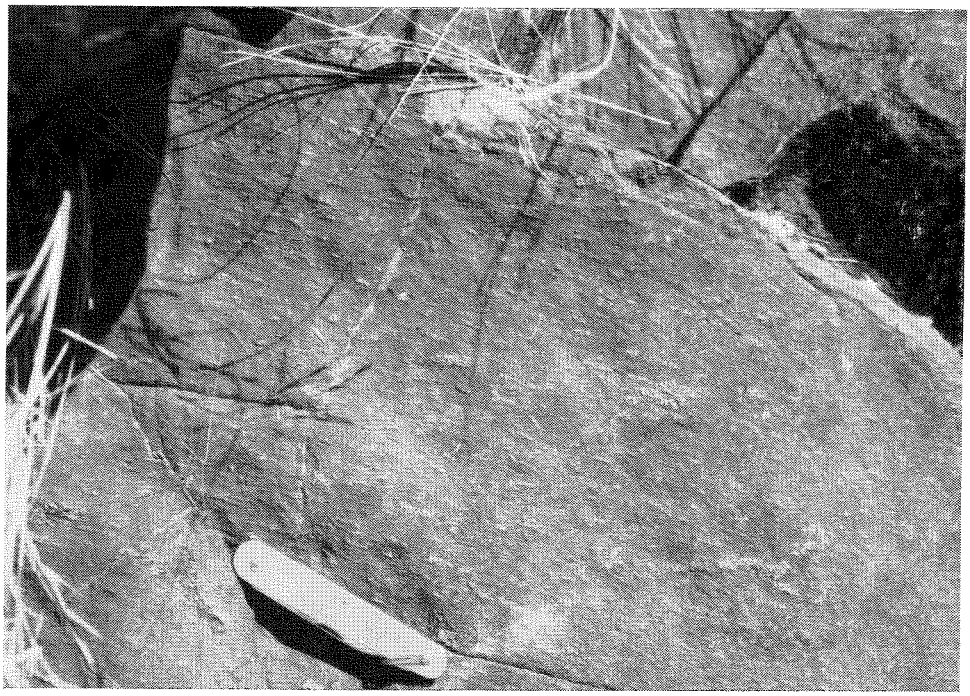

Figure 67. Basic material carrying abundant minute blebs of leucocratic material. Rock represents near end product of assimilation of granulite by gabbroic material. Northeast Hinckley Range.

field on weathered surfaces as abundant minute light flecks (Fig. 67). This criterion is one which has been used during the field mapping, in the absence of other evidence, to identify areas of contaminated gabbro.

The basic material resulting from the incorporation of the leucocratic blebs consists essentially of a granular aggregate of plagioclase, orthopyroxene, clinopyroxene, opaques and red-brown biotite with accessory apatite. Plagioclase varies in composition, determined optically, in different specimens from An_{44} to An_{61} with a mean of An_{52}. Some specimens show a moderate development of poikiloblastic green-brown hornblende and quartz.

A sample of the fine-grained basic rock at the base of the Blackstone Range Gabbro on the northern side of Bell Rock Range is comparable with that in the main occurrence in the Hinckley Range. It consists of the usual granular aggregate of minerals as well as blebs of quartz and plagioclase. The composition of the plagioclase in the blebs is An_{50} determined on combined Carlsbad/albite twins. This compares favourably with determinations on the groundmass plagioclase (An_{48}) determined on similar twin combinations. In the groundmass the contacts between many of the pyroxene grains and also pyroxene-plagioclase interfaces are accentuated by a development of opaque granules.

The notable features of these rocks are their fine-grained texture, the presence of two pyroxenes, abundant disseminated opaques, somewhat antiperthitic plagioclase of composition near An_{50}, and some disseminated quartz.

Similar rock types are known from many areas in association with gabbroic intrusions. Included are the Bushveld Complex, the Duluth Gabbro, the Freetown Layered Basic Complex, southeast Queensland and the Fraser Range, Western Australia. In the Bushveld Complex (Wager and Brown, 1968) these rocks are included in the Marginal Group. They are called fine-grained hypersthene gabbros and thought to represent the parental magma of the complex. The Freetown examples have two modes of occurrence (Wells, 1962). One is referred to as a pyroxene granulite and occurs as masses included in the host gabbroic rocks and near the floor of the intrusion. They are thought to have been derived by alteration of normal gabbroic rocks of the complex. The other examples are called beerbachites and occur as dykes cutting unmetamorphosed gabbros. Rocks of identical appearance are also found in many granulite terrains and some are interpreted as metamorphosed basic sediments or basic igneous rocks.

To determine the origin of this suite of rocks on mineralogy alone is not possible. In the case of the Blackstone Region examples, the field evidence points to their close relation with the Giles Complex, and consequently it seems more correct to refer to these rocks as fine-grained hypersthene gabbros, whose texture is not explicable on the present available evidence. In several places around the Hinckley Range these fine-grained hypersthene gabbros are irregularly interlayered with coarser grained gabbroic material. These bands contain hypersthene visually similar to the distinctive variety seen in the Michael Hills Gabbro.

An attempt to relate the fine-grained hypersthene gabbro to the Michael Hills Gabbro has been made along other lines. Two samples from the marginal facies,

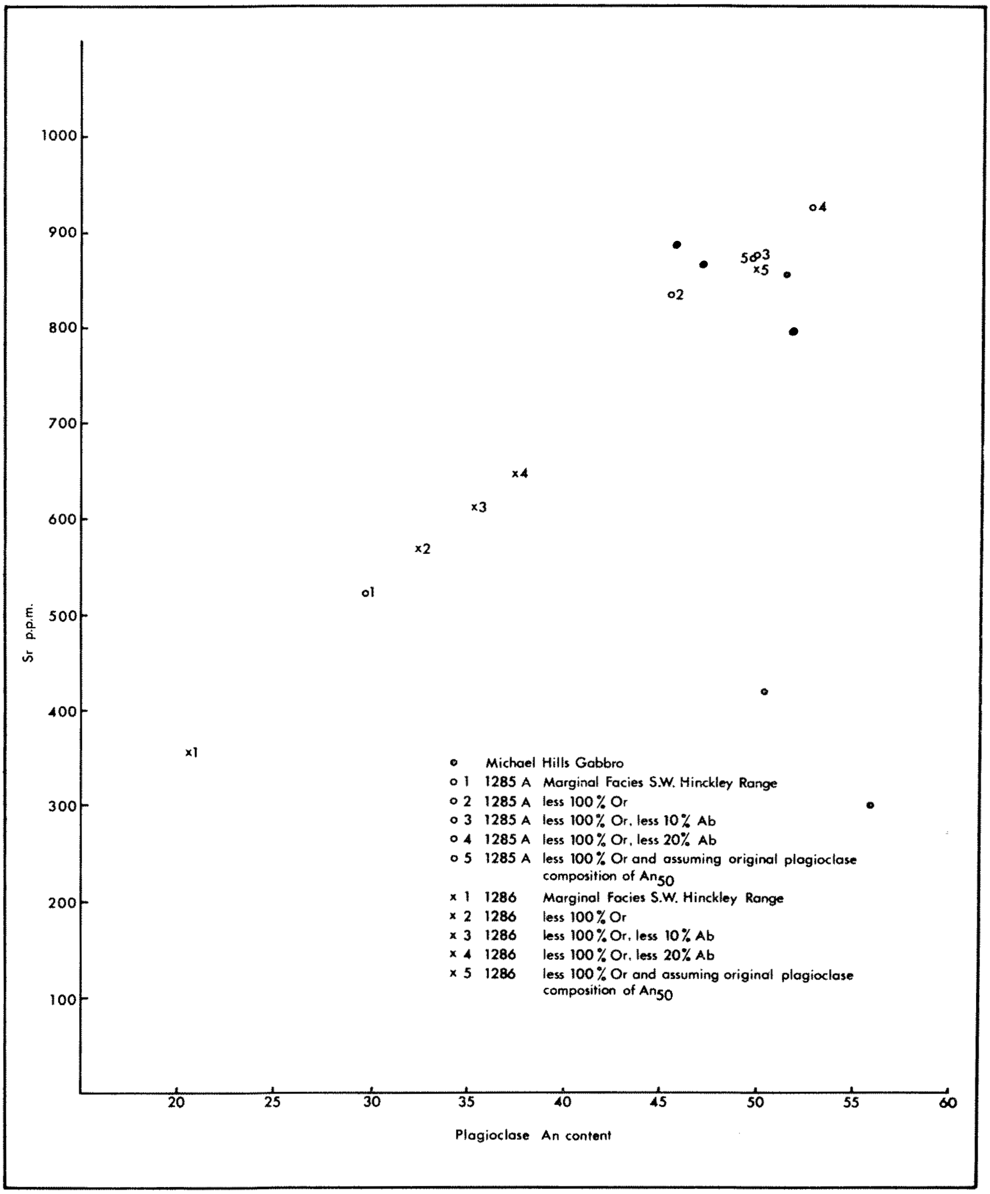

Figure 68. Comparison of Sr and An contents of plagioclase from marginal facies, with plagioclase from Michael Hills Gabbro.

1286 and 1285A, were taken from the southern side of the Hinckley Range within 1 mile (1.6 km) of the Hinckley Range Gabbro. The specimens occur near a few relict masses of granulite bands and themselves carry abundant small leucocratic blebs characteristic of this suite of rocks.

In both samples the plagioclase is slightly antiperthitic. Optical determinations of 1286 gave a composition of An_{47}, while in 1285A the plagioclase was normally zoned from An_{51} to An_{36}. Relict ophitic texture is present in 1285A.

In both cases the leucocratic portion of the rock was separated, but no attempt was made to subdivide this into its various components, which comprised plagioclase, antiperthitic plagioclase, orthoclase and quartz. This assemblage was then analyzed for sodium, calcium, potassium and strontium and the analysis was recalculated in terms of albite, anorthite and orthoclase. The quartz merely diluted the feldspar concentrate and its presence was obviated during the recalculation. The compositions of the plagioclase were found by recalculation on an orthoclase free basis and gave compositions of $An_{45 \cdot 1}$ and $An_{45 \cdot 7}$ for samples 1286 and 1285A respectively, which are in very close agreement with the optical determinations. The strontium values increased proportionately on the assumption that the majority of the strontium is accommodated in the plagioclase.

Other calculations were then made to allow for the dilution effects of various amounts of the contaminating granulite. This calculation is only valid if the contaminating granulite carries or contributes only negligible strontium. This is further discussed below.

In both cases it was assumed that all the orthoclase was derived from the contaminating rock, and a calculation to allow for this was made accordingly. Further calculations were made on the basis that (a) 10 per cent of the albite and (b) 20 per cent of the albite was obtained from the granulite. A final calculation based on the assumption that the original plagioclase in the gabbroic fraction had a composition of An_{50} was made. In each case the corresponding strontium values were also derived and the results plotted on a diagram showing Sr/An relations for the Michael Hills Gabbro (Fig. 68).

The results show a striking correspondence between the highest Sr/An values for Zones 2 and 3 of Michael Hills Gabbro and results obtained on the assumption that the original plagioclase in the fine-grained hypersthene gabbro had a composition of An_{50} similar to that of the average gabbro in the Michael Hills intrusion.

The plot also suggests that about 10 per cent of the albite in 1285A was obtained from the granulite but considerably more in 1286 was so derived, indicating varying degrees of contamination.

We now return to the important assumption that the contaminating granulite carries or contributes only negligible strontium to the gabbro. No values for strontium in granulites of this region are available. However, Arriens and Lambert (1969) quote several strontium values for granulite gneisses in the Musgrave Ranges east of the Blackstone Region. Values quoted range from 135 ppm to 1,063 ppm with a mean value of 338 ppm. Only a portion of this strontium would be accountable for in the gabbro, depending on the amount of contamination undergone. As an example, for a contaminated gabbro, 20 per cent of the bulk of which was derived from granulite with an average of 338 ppm strontium, only 67 ppm strontium can be accounted for as being derived from the granulite. Under these conditions, this amount would be insufficient to alter the final calculations so as to make the results fall outside the Sr/An composition field of the Michael Hills Gabbro.

It seems highly probable that the fine-grained hypersthene gabbro, forming much of the marginal facies of the Giles Complex, is derived by various amounts of contamination of the Michael Hills Gabbro by granulites and related granitic gneisses. It may further be speculated that the magma responsible is the same that gave rise to Zones 2 and 3 of the Michael Hills Gabbro and that it was derived from the same area, *i.e.,* from near The Bald One on the northern side of Michael Hills.

DISTRIBUTION OF THE FINE-GRAINED HYPERSTHENE GABBRO

The main bulk of the fine-grained hypersthene gabbro occurs in the western part of the Hinckley Range, where it intrudes granulites and forms the host rock to the western extension of the Hinckley Range Gabbro. Other large masses occur in the Michael Hills and Murray Range, while minor bodies are to be found at Amy Giles Rocks, Amy Giles Hill and Lake Hills. Small amounts are also present at the base of the Blackstone Range Gabbro on the northern side of Bell Rock Range and as a thin sheet in association with gabbro approximately 4½ miles (7 km) south of Mount Gosse. It therefore appears that the fine-grained hypersthene gabbro may occur at different structural levels either by itself or in close proximity to different gabbros. In the case of the Hinckley Range material it is thought that the same magma gave rise also to the fine-grained hypersthene gabbro at the top of the Michael Hills Gabbro, suggesting that the pulse did not confine itself to one structural level. Whether the same pulse is also responsible for the other examples is not known.

MINERALOGY

BROWN AMPHIBOLE

Brown amphiboles exist in several main parageneses in the Giles Complex basic rocks:

1. as primary amphibole in mafic olivine-pyroxene-amphibole-anorthite rocks (lherzolite) in Zone 2 of the Jameson Range Gabbro
2. as large crystals of secondary origin polkilitically enclosing plagioclase, opaques, and clinopyroxene in some isolated exposures of basic rock of unknown relationship to the major sheets of the Giles Complex
3. as narrow reaction coronas around opaque minerals in some of the gabbros. The brown amphibole, probably kaersutite, commonly occurs as a simple, single-shelled corona about the opaque mineral (R. Peers, pers. comm.)

TABLE 15. ANALYSIS OF BROWN AMPHIBOLE FROM JAMESON RANGE GABBRO AND COMPARISON ANALYSES

	1	2	3	4	5	6
SiO_2	40·96	38·83	41·48	37·4	37·6	44·60
Al_2O_3	12·52	14·29	10·05	15·7	13·0	10·60
TiO_2	3·05	4·71	3·92	6·0	7·1	4·58
Fe_2O_3	3·18	3·66	4·06	12·4	7·7	1·09
MgO	10·91	10·22	8·58	11·4	13·6	14·58
FeO	12·73	10·43	14·93	1·1	3·7	10·16
MnO	0·11	0·00	0·16	0·2	....	0·39
V_2O_5	0·23	....	....	....	....	....
NiO	0·03	....	....	....	....	....
Na_2O	2·46	1·84	2·89	2·3	3·6	1·56
CaO	11·37	12·22	10·78	11·9	10·6	11·52
K_2O	0·59	2·13	1·94	1·5	1·8	0·68
H_2O^+	1·91	1·57	1·35	0·1	0·5	0·82
H_2O^-	....	....	....	0·1	....	0·02
F	0·03	0·21	....	0·4	0·6	....
P_2O_5	....	0·07	....	....	....	....
Cl	....	....	....	0·9	0·1	....
	100·08	100·18	100·14	101·4	99·9	100·60
Less O = F	0·01	0·09	....	0·4	0·3	....
	100·07	100·09	....	101·0	99·6	....
Number of ions on basis of 24 (O, OH, F, Cl)						
Si	6·107	5·823	6·37	5·568	5·654	6·54
P	....	0·009	....	....	....	....
Al	1·893	2·169	1·63	2·432	2·299	1·46
Ti	....	....	....	....	0·047	....
(Si + P + Al + Ti)	8·00	8·00	8·00	8·000	8·000	8·00

	1		2		3		4		5		6	
Al	0·306		0·357		0·18		0·323		....		0·37	
Ti	0·342		0·531		0·45		0·672		0·758		0·51	
Fe^{3+}	0·356		0·413		0·47		1·389		0·871		0·12	
Mg	2·423	5·06	2·284	4·89	1·98	5·01	2·530	5·076	3·053	5·149	3·19	5·48
Fe^{2+}	1·587		1·308		1·91		0·137		0·467		1·24	
Mn	0·014		....		0·02		0·025		....		0·05	
V	0·023											
Ni	0·004											
Na	0·711		0·535		0·86		0·664		1·057		0·44	
Ca	1·815	2·64	1·963	2·91	1·77	3·01	1·899	2·848	1·699	3·107	1·81	2·38
K	0·113		0·407		0·38		0·285		0·351		0·13	
OH	1·898		1·571		1·38		0·070		0·491		0·80	
F	0·014	1·91	0·100	1·67			0·179	0·476	0·289	0·811	....	0·80
Cl	....		....				0·227		0·031		....	
$\frac{100\ Mg}{Mg + Fe^{3+} + Fe^{2+} + Mn}$	55·4		57·0		45·2		61·9		69·5		68·0	
$Fe^{3+}: Fe^{2+}$	0·22		0·32		0·24		8·6		1·9			
α	1·669±0·002		1·673		1·678		1·694*		1·682*		1·660–1·665	
β	1·690±0·002		....		....		1·730*		1·710*		1·673–1·678	
γ	1·698±0·002		1·704		1·705		1·757*		1·725**		1·684–1·690	
2V	80°		80° (est.)		76°		80°		70°		82°±4°	
: (001)	....		....		....		4°		2°		....	
S.G.	....		....		....		....		....		3·16	

* Calculated value (see le Maitre R. W. , 1969)

** Assumed value (see le Maitre, R. W., 1969)

1. Brown amphibole from Zone 2 of Jameson Range Gabbro. Analysist: P. Hewson. Original analysis contained 0·04 per cent P_2O_5, 0·09 per cent CO_2 and 0·45 per cent H_2O^-. Above analysis derived by recalculation to a calcite–apatite–dry basis.
2. Kaersutite from metagabbro, Fraser Range, Western Australia (Wilson and Middleton, 1968).
3. Barkevikite from alkali gabbro, Orissa, Analysist: W. H. Herdsman (Bose, 1964).
4. Kaersutite from xenolith in tuff, near Sandy Point, Tristan da Cunha. Analysist: C. J. Elliott (le Maitre, 1969).
5. Kaersutite from xenolith in lava, Gypsy's Gulch, Tristan da Cunha. Analysist: A. J. Gaston (le Maitre, 1969).
6. Titaniferous brown hornblende from troctolite from Somerset Dam Instrusion, Queensland. Analysist: Avery and Anderson (Mathison, 1967).

4. in variable amounts in contaminated basic rocks of the marginal facies.

The brown amphibole from Zone 2 of the Jameson Range Gabbro has been studied in a little detail.

Rocks of Zone 2 are layered, mafic, medium grained and granular. They consist of varying proportions of opaque minerals, brown amphibole, olivine, clinopyroxene, orthopyroxene and anorthite (An_{90-96}). All these minerals may occur together without any apparent reaction relations and are assumed to be primary. Analyses of three rocks from this zone are given in Table 10. They are characterized by very low SiO_2 and Al_2O_3 and very high FeO + Fe_2O_3 and TiO_2. Vanadium is moderately high.

The amphibole whose analyses are given in Table 15, is a medium to dark brown variety showing moderate pleochroism with α = pale straw, β = medium brown and γ = brown. Other optical and physical properties are given in Table 16. The analysis shows small quantities of CO_2 and P_2O_5 which are assumed to be present as calcite and apatite impurities. After recalculation on a calcite-apatite-free basis the structural formula was determined as follows and compared with the "ideal" formula for kaersutite given by Kempe (1968):

"Ideal" kaersutite:

$Ca_2(Na,K)(Mg,Fe^{2+},Fe^{3+})_4Ti[Si_6Al_2O_{22}](O,OH,F)_2$.

Jameson Range brown amphibole:

$Ca_{1\cdot8}(Na,K)_{\cdot8}(Mg,Fe^{2+},Fe^{3+})_{4\cdot4}Ti_{\cdot3}[Si_{6\cdot1}Al_{1\cdot9}O_{22\cdot1}](O,OH,F)_{1\cdot9}$.

The Jameson Range brown amphibole analysis and structural formula show several important features:

1. moderate TiO_2
2. low Fe_2O_3/FeO ratio
3. low Mn
4. small amount V_2O_5
5. Al replaces Si almost to the maximum possible extent of 2 atoms per formula unit
6. (Fe^{2+} + Fe^{3+}) replaces Mg to the extent of 1.95 atoms.

It is instructive to compare this amphibole with kaersutite, barkevikite and oxyhornblende.

Kaersutite is a brown, titanium-rich calciferous amphibole whose main chemical feature is a high TiO_2 content. Other essential chemical features (Deer and others, 1963) include Al replacing Si to the extent of almost 2 atoms per formula unit; the replacement of Mg by (Fe^{2+} + Fe^{3+}) limited to approximately 1.5 atoms; and a low Fe_2O_3/FeO ratio. No agreement seems to have been reached on the exact amount or range of TiO_2 permissible in kaersutite. Benson (1939) considers that kaersutites should contain more than 5 to 6 per cent TiO_2. Wilkinson (1961) suggests that the lower limit should be 5 per cent TiO_2, but sees no reason why other brown amphiboles with lower TiO_2, but generally similar essential chemistry should not be covered by this term. This view is also held by Mason (1968).

Barkevikite has lower TiO_2, and Si is not replaced by Al to the extent it is in kaersutite. Magnesium is replaced by a higher proportion of total Fe, while the Fe^{3+}/Fe^{2+} ratios are similar to those in kaersutite. Most barkevikites contain a moderate manganese content. Oxyhornblende has a high Fe^{3+}/Fe^{2+} ratio and a very low hydroxyl content. A summary of the main properties is given in Table 16.

TABLE 16. SUMMARY OF MAIN PROPERTIES OF BROWN AMPHIBOLES

	1	2	3	4	5
TiO_2	very high	....	....	moderate	high
Si/Al substitution	2·0	....	....	1·89	2·2
$Mg/Fe^{3+} + Fe^{2+}$	1·5	0·4	1·7	1·3	1·3
Fe^{3+}/Fe^{2+}	low	low	high	low	low
(OH)	....	....	low	1·9	1·7
Mn	....	high	....	low	low

1. " Average " kaersutite
2. " Average " barkevikite
3. " Average " oxyhornblende
4. Brown amphibole from Jameson Range Gabbro
5. Brown amphibole, kaersutite, from Fraser Range, Western Australia (Wilson and Middleton, 1968).

It appears that from the data in Table 16, the Jameson Range Gabbro brown amphibole may best be described as a kaersutitic amphibole with only a moderate TiO_2 content and with slightly more total iron than is normal for kaersutites.

In kaersutites the Fe^{3+}/Fe^{2+} ratio is inter-related with the (OH,F,Cl) content. Aoki (1963) states that the degree of oxidation is controlled by the mechanics of eruption so that kaersutites which developed in the most oxidizing environments will have the least (OH,F,Cl). This relationship is borne out by Table 17.

The examples from both the Jameson Range and the Fraser Range are assumed to have developed in conditions of low oxygen fugacity.

TABLE 17. RELATION OF Fe^{3+}/Fe^{2+} TO (OH, F, Cl) IN KAERSUTITES

Kaersutite	Fe^{3+}/Fe^{2+}	(OH, F, Cl)
a	8·6	0·476
b	1·9	0·811
c	0·32	1·671
d	0·22	1·912

a = kaersutite from xenoliths in tuff. Anal. No. 4 Table 14
b = kaersutite from xenoliths in lava. Anal. No. 5 Table 14
c = kaersutite from metagabbro. Anal. No. 2 Table 14
d = kaersutite from Jameson Range Gabbro. Anal. No. 1 Table 14

PLAGIOCLASE

Fifty-six plagioclases from gabbroic and related rocks of the Giles Complex in Western Australia were separated, purified and analyzed for Na_2O, CaO, K_2O and Sr. The number of samples from each individual intrusion may be obtained from Table 18. The study had two main objectives. Firstly it was hoped that it would be possible to categorize chemically the plagioclase from each intrusion. This would then allow the identification of the origin of isolated gabbroic exposures. Secondly it was thought that, with the limited range of composition present, the optical methods of determining composition might not have been sufficiently accurate to detect the variations. The chemistry also provided an additional check on the optical determinations.

TABLE 18. CHEMICALLY DETERMINED COMPOSITIONS OF PLAGIOCLASE FROM THE GILES COMPLEX

Specimen No.	Or	Ab	An	Sr. ppm	Zone
			JAMESON SHEET		
1235	0·59	17·70	81·71	565	1
1242	1·45	32·37	66·18	555	1
1248	1·80	35·74	62·46	510	1
1247	2·66	38·17	59·17	400	3a
1249	3·01	40·06	56·93	390	3a
1250	2·65	40·41	56·93	390	3a
1251	3·05	39·02	57·93	375	3a
1252	3·25	40·53	56·21	390	3b
1253	3·74	41·67	54·60	425	3b
1254	3·34	40·73	55·93	400	3b
1256	2·74	42·38	54·88	425	4
1257	2·65	40·41	56·93	425	4
1259	2·37	39·94	57·69	375	4
1260	2·11	39·16	58·73	395	4
1263	1·22	39·02	59·76	395	4
1241	4·10	35·17	60·58	480	3 (unsheared)
10975/1	1·67	32·50	65·83	480	?
10981	1·69	29·49	68·83	450	?
1270	14·65	36·62	48·73	520	?

Specimen No.	Or	Ab	An	Sr. ppm	Zone
		MICHAEL HILLS SHEET			
4092	3·87	47·51	48·62	565	1
4085	1·41	43·10	55·49	480	1
4024	3·99	50·00	46·01	885	2
4025	3·65	44·38	51·97	795	2
4026	3·28	49·45	47·27	865	2
4063	3·72	49·70	51·58	855	3
		HINCKLEY SHEET			
545	1·37	31·15	67·49	365	
546a	1·99	39·49	58·52	435	
548	1·10	35·62	63·29	350	
549	0·80	39·36	59·84	373	
		BLACKSTONE SHEET			
577	1·67	35·38	62·95	450	1
578	2·09	35·52	62·39	480	2
579	1·18	39·00	59·82	475	2
580	0·61	38·91	60·49	475	2
581	1·20	36·53	62·28	460	2
582A	1·54	31·38	67·08	450	2
582C	1·17	36·36	62·46	450	2
583	2·06	36·58	61·36	465	3
584	1·52	35·15	63·33	465	3
585	1·50	32·63	65·87	465	3
587	2·55	38·81	58·64	480	4
576	0·88	36·07	63·05	455	Below 1
519	1·75	32·16	66·09	450	Bell Rock Range
520	2·04	35·57	62·39	455	Bell Rock Range
521	2·73	36·34	60·93	440	Bell Rock Range
522	1·66	37·57	60·77	440	Bell Rock Range
		NORTH MICHAEL HILLS			
4044a	1·76	36·47	61·76	795	
4044b	1·43	36·68	61·89	790	
4045	0·85	35·23	63·92	790	
4046	1·44	34·67	63·90	795	
		EAST MURRAY RANGE			
10903	8·64	29·25	62·12	330	
10904	1·96	23·81	74·23	325	
		VARIOUS			
533	1·11	41·67	57·22	350	
541	1·11	43·33	58·33	1,630	
599	1·38	36·46	62·15	350	
1285a	37·11	33·14	29·75	520	
1286	36·56	42·81	20·63	355	

TABLE 19. CALCULATED COMPOSITIONS AND OPTICAL DETERMINATIONS OF PLAGIOCLASE FROM THE MICHAEL HILLS GABBRO

Specimen Number	An calculated from chemical composition on basis of An + Ab + Or	An calculated from chemical composition on basis of An + Ab only	An optical
4092	48·62	50·58	49
4085	55·49	56·28	
4026	47·27	48·87	
4024	46·01	47·92	47
4025	51·97	53·94	
4063	51·58	53·57	

TABLE 20. CALCULATED COMPOSITIONS AND OPTICAL DETERMINATIONS OF PLAGIOCLASE FROM THE BLACKSTONE RANGE GABBRO

Specimen Number	An calculated from chemical composition on basis of An + Ab + Or	An calculated from chemical composition on basis of An + Ab only	An optical
519	66·09	67·27	67
520	62·39	63·69	68 (core)
521	60·93	62·64	64
522	60·77	61·80	63
576	63·05	63·61	
577	62·95	64·02	69
578	62·39	63·72	63
579	59·82	60·53	62
580	60·49	60·86	
581	62·28	63·03	66
582A	67·08	68·13	67
582C	62·46	63·21	68
583	61·36	62·65	66
584	63·33	64·31	65
585	65·87	66·87	70
587	58·64	60·17	59

TABLE 21. CALCULATED COMPOSITIONS AND OPTICAL DETERMINATIONS OF PLAGIOCLASE FROM THE JAMESON RANGE GABBRO AND ASSOCIATED ROCKS

Specimen Number	An calculated from chemical composition on basis of An + Ab + Or	An calculated from chemical composition on basis of An + Ab only	An optical
1242	66·18	67·15	70 (core)
1248	62·46	63·60	77 (core)
1235	81·71	82·19	
1247	59·17	60·79	63 (core)
1249	56·93	58·70	
1250	56·93	58·49	62
1251	57·93	59·75	63
1252	56·21	58·10	
1253	54·60	56·71	56
1254	55·93	57·86	61
1256	54·88	56·43	57
1257	56·93	58·49	62
1259	57·69	59·09	60
1260	58·73	60·00	64
1263	59·76	60·50	61
1241	60·58	63·27	62
1270	48·73	57·09	66
10975/1	65·83	66·95	
10981	68·83	70·01	

The orthoclase component of the plagioclase, not normally taken into consideration, was determined for completeness. Though small this component cannot be neglected as it is an important factor in categorizing the plagioclases from the various intrusions. Strontium was determined because a reasonable amount was expected and because it has been used in combination with the anorthite component of the plagioclase in solving various problems concerning the Somalia gabbros (Butler and Skiba, 1962; Skiba and Butler, 1963). In each case the analyses were recalculated in terms of the end members, albite, anorthite and orthoclase, and again on a basis of albite and anorthite only (Tables 19, 20 and 21).

COMPARISON OF CHEMICAL AND OPTICAL DATA

Optical determinations were made on the majority of the plagioclases using combined Carlsbad/albite twins on a flat stage and using the determinative curves given by Rogers and Kerr (1933). In a few special cases determinations were made on a universal stage (Trendall, 1969). Where available the optically determined composition has been compared with those derived chemically.

In the majority of cases a close agreement, within the limits of possible experimental error, exists between the compositions determined in the various ways. Almost every optical determination of An is however consistently high when compared with the chemically determined value. Except for one example the differences range up to about 5 per cent An but are usually in the range of 1 per cent to 3 per cent An. Their almost consistently higher An value is possibly negligible, but may be explicable as a result of normal zoning in most of the samples. The optical determinations were almost always made on the centres of the crystals. The presence of any normal zoning would show up as slightly low chemically determined An values which represent the average composition present. That this is not the only reason is suggested by the results of specimens 522 and 584, both of which show reverse zoning in thin sections. Nevertheless the optically determined An values are still higher, though marginally so, when compared with the chemically determined composition.

One of the results (Specimen 1242) from Zone 1 of the Jameson Range Gabbro is worth further comment. The rock is a glomeroporphyritic gabbro. Determined on a universal stage, the composition of one large plagioclase individual was found to lie between An_{65} and An_{68} (Trendall, 1969). Two small laths from the matrix mosaic gave values of An_{45} and An_{46}. The chemical results lie very close to the optical determinations for the phenocryst and Trendall concludes that during the preparation of the sample for analysis virtually all of the fine-grained plagioclase must have been lost.

SPATIAL DISTRIBUTION AND RANGE OF COMPOSITION

Variations in the An content of plagioclase with height in the various masses are shown in Figures 43, 52 and 57.

In the Blackstone Range Gabbro the range, defined by the chemical composition of plagioclase preparations, is only 8.4 per cent An, from $An_{58.6}$ to An_{67}. Zoning would extend this range. Reverse zoning has been confirmed in several of the plagioclases from this intrusion. One example exhibits a core of An_{65} grading out to an extreme edge of An_{80} giving a total range of An for this crystal of almost twice that defined by the chemistry for the whole intrusion. As the rims of zoned crystals are thin in comparison with the host crystal the chemically determined An values probably quite closely represent the composition of the cumulus phase.

In the main mass of the Michael Hills Gabbro the range in plagioclase composition is from An_{46} to $An_{55.5}$ with some higher optical determinations up to An_{68}. Normally zoned crystals within the range An_{68} to An_{55} are present. The rims have sharp contacts with the cores and little if any gradation of composition is noted. However, much of the intrusion has been stressed. Twin lamellae are frequently bent, stress-induced twinning is suspected, and granulation of the feldspars has occurred. Determinations of composition under these circumstances are of doubtful value and have not been included in the results.

The Jameson Range Gabbro shows the largest variation, with the plagioclase ranging from about An_{95} to An_{45} (both optical determinations). The plagioclase of the main bulk of the intrusion, however, is in the range $An_{54 \cdot 6}$ to $An_{60 \cdot 6}$. Zoning is present in the plagioclase of the unsheared portion of Zone 3. Trendall (1969) reports "The larger plates are often clearly zoned with a small central core and up to about six broad surrounding zones, rather poorly defined, alternately richer and poorer in An; there is no simple consistent one-way zoning. The reported result An_{68} zoned to An_{62} is for the core and first zone of one of the larger crystals; inspection suggests that this is about the full range of variation in this crystal". In Zone 1 of the same intrusion some of the individual plagioclases in the glomerocrysts range from a core composition of An_{68} to an extreme edge of An_{46}. The

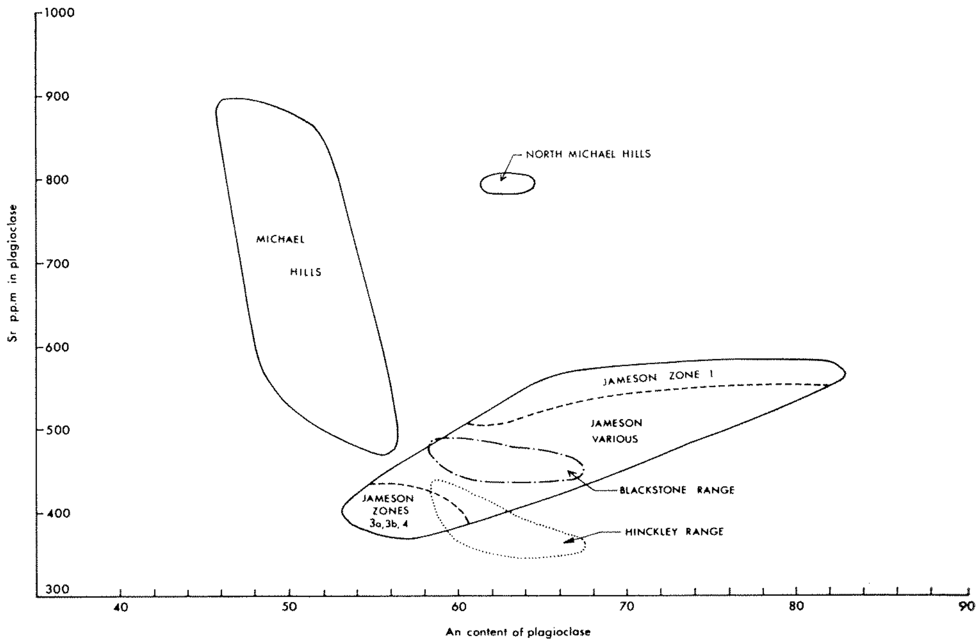

Figure 69. Relationship of ppm Sr to An content of plagioclase in gabbroic rocks of the Giles Complex in Western Australia.

bulk of the crystal lies between An_{65} and An_{68}. Oscillatory zoning with a very small compositional range is present in the main bulk, with the principal change to a more sodic composition occurring in a narrow peripheral zone.

In all the intrusions studied the variation of An content with height is not progressive, but is characterized by a series of irregularities. Some of the major irregularities take place at Zone boundaries. However, in the Blackstone Range Gabbro and the Michael Hills Gabbro, and to a lesser extent in the Jameson Range Gabbro, adjacent samples may show plagioclases of widely differing An contents. The differences encountered may represent a large proportion of the total range of An present in the intrusion. A discussion on the origin of the features shown by the various masses is given elsewhere (p. 189).

STRONTIUM CONTENT

Studies of Sr contents of plagioclase in relation to the An content are very limited, and a review is given by Butler and Skiba (1962). In general it may be stated that in gabbroic rocks Sr increases with decreasing An content. Reference to Figure 69, shows this to be the general case in the Giles Complex for the Blackstone Range Gabbro and probably also for the Hinckley Range Gabbro. In the Michael Hills Gabbro this could be the case if Zone 1 is taken as one unit and Zones 2 and 3 taken as another unit. The results from the Jameson Range

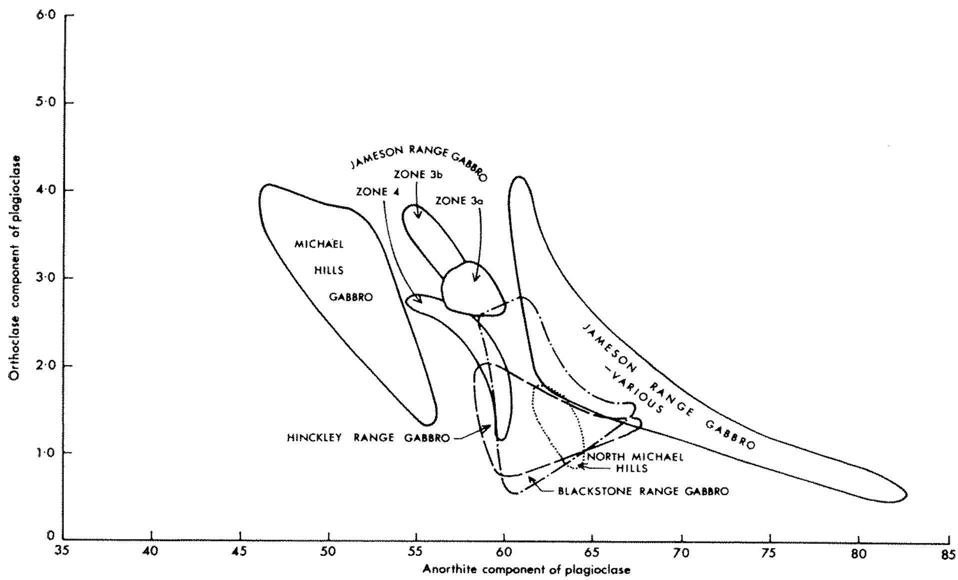

Figure 70. Range of orthoclase component relative to anorthite content of analyzed plagioclase samples from the Giles Complex in Western Australia.

Gabbro do not seem to form any simple pattern. This has probably been brought about by a combination of multiple intrusion and slight local modification of the composition of the plagioclase by shearing.

One of the most important features of the graph showing the Sr/An relationships of these plagioclases is the restricted range of composition covered by each intrusion. It is suggested that a certain Sr/An value or small range of this ratio may be characteristic of a certain magma pulse or unit and that much of the spread within this range from high An combined with low strontium, to lower An in combination with higher strontium, is a function of the differentiation undergone by the magma.

Such an explanation is insufficient alone to explain the spread exhibited by the Michael Hills Gabbro. Here multiple intrusion may be a possibility, but is only a last resort when other explanations fail. In this intrusion Zone 1 and Zones 2 and 3 can be defined by restricted Sr/An values. As well as this, the field of Sr/An for the whole intrusion is also somewhat restricted, suggesting that all the zones are related in some way. This may possibly be brought about by some form of differentiation, either *in situ* or possibly in a sub-intrusion magma chamber capable of injecting several pulses of magma at different stages during its own crystallization differentiation.

ORTHOCLASE COMPONENT

The orthoclase component of the plagioclase in analyzed specimens from the Giles Complex in Western Australia in general ranges from 0.5 per cent to 4 per cent.

In the case of the Michael Hills Gabbro some of the orthoclase quoted in the analysis is probably in the form of small antiperthitic inclusions in the plagioclase. This is not the case for the other analyses within this range. For these the orthoclase is therefore probably present as a solid solution in the plagioclase.

Figure 70 shows the fields of composition of the orthoclase component of the plagioclase relative to the An content for the various intrusions. The plagioclase of each intrusion has a restricted range of composition but considerable overlap exists. In some cases zones within an intrusion are distinctly defined.

It is concluded that the orthoclase component of the plagioclase in the Giles Complex in Western Australia is not negligible, and in combination with the An content is useful in defining fields of composition of the plagioclases of the various intrusions.

ORTHOCLASE/STRONTIUM RELATIONSHIPS

The relationship of strontium to the orthoclase component of the plagioclase is even more important in categorizing the plagioclases from the Giles Complex. The diagram (Fig. 71) shows an almost complete separation, on this basis, of the various intrusions and as a single factor this relationship seems to be the most likely aid in identifying the affinities of isolated outcrops.

Two important overlaps are present on this diagram (Fig. 71). The Michael Hills Gabbro field overlaps Jameson Range Gabbro Zone 1, and the Hinckley Range Gabbro field overlaps Zone 4 of the Jameson Range Gabbro. In the first instance a distinction between the two may readily be made in several other ways and the overlap is not important. Reference to Figure 69 clarifies the point. In the second case, however, a similar overlaps exists also in respect of Sr/An and Or/An relationships (Figs. 69 and 70). Further work with a variety of trace elements would probably solve the problem.

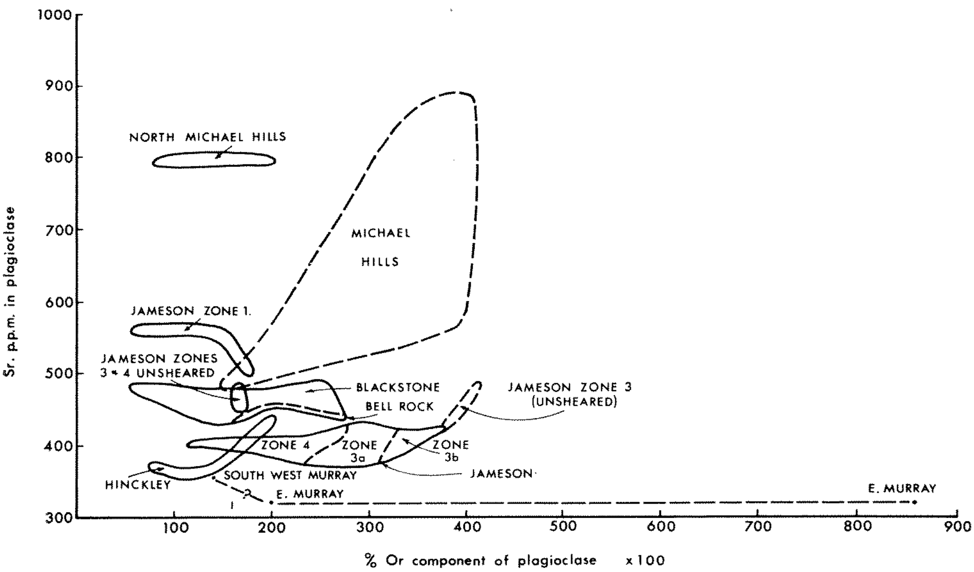

Figure 71. Relationship of ppm strontium content of plagioclase to orthoclase component x100 of plagioclase in gabbroic rocks in the Giles Complex in Western Australia.

For all intrusions studied so far, with the exception noted above, all the contained plagioclases are distinct in composition provided that strontium and potassium are taken into consideration. In all three diagrams (Figs. 69, 70 and 71) the field-determined zones in the Blackstone Range Gabbro are not separated. It is thought that this may arise if the Blackstone Range Gabbro originated as a single pulse of magma. The mapped zones in the Jameson Range Gabbro are verified by the chemistry and as they are quite distinct an origin by multiple intrusion is a likely possibility. The troctolite forming the North Michael Hills intrusion is not now thought to represent a feeder for either the Blackstone Range or Hinckley Range Gabbros as previously suggested (Daniels, 1967a), but is a discrete intrusion.

OLIVINE

GENERAL CHARACTERISTICS

Eleven olivines, five from the Blackstone Range Gabbro and six from the Jameson Range Gabbro were separated, purified and analyzed. Some optical and physical properties were also determined and the results are incorporated in Tables 22, 23 and 24 along with their calculated structural formulae and forsterite contents. The relation of their optical properties and density in relation to the atomic per cent Fe^{2+} of the olivine is given in Figure 72.

In the Blackstone Range Gabbro a consistent increase in the forsterite content of the olivines from $Fo_{58.8}$ to $Fo_{69.5}$ is noted with height up to the top of Zone 3 represented by Specimen 585. In Zone 4, the topmost zone, the forsterite composition of the olivine falls to Fo_{61} determined from the refractive index. The analyses also show ferric oxide to increase consistently and alumina to decrease consistently with height in the intrusion. Minor amounts of other oxides are present and these appear to show no regular variation with height of the olivine in the intrusion. A sample (No. 519) from Bell Rock Range was also analyzed and is similar to those from the Blackstone Range.

TABLE 22. CHEMICAL, PHYSICAL AND OPTICAL PROPERTIES OF OLIVINES FROM THE BLACKSTONE RANGE GABBRO

Specimen No.	577	581	582C	585	519
SiO_2	35·10	37·47	37·95	37·10	38·37
Al_2O_3	2·09	1·19	0·57	....	1·00
Fe_2O_3	1·39	2·12	2·23	3·04	2·23
FeO	33·72	27·78	26·36	26·33	27·89
MgO	26·47	30·29	31·65	33·30	28·40
CaO	0·28	0·39	0·39	....	0·73
TiO_2	0·81	0·56	0·03	0·13	0·53
MnO	0·44	0·38	0·31	0·36	0·37
Na_2O	0·01	0·02	....	....	....
K_2O	0·02	0·02	0·01	0·02	0·01
P_2O_5	0·03	0·02	0·02	0·02	0·02
H_2O^+	0·03	0·20	0·61	0·14	0·64
H_2O^-	0·06	0·02	0·14	....	0·18
	100·45	100·46	100·27	100·44	100·37
Si	0·965	1·008	1·015	0·988	1·032
Al	0·35	....	....	....	....
Al	0·031	0·038	0·019	....	0·032
Fe^{3+}	0·030	0·041	0·045	0·061	0·045
Fe^{2+}	0·772	0·662	0·587	0·585	0·624
Mg	1·102	1·220	1·269	1·332	1·145
Ca	0·008	0·011	0·011	....	0·021
Ti	0·017	0·011	....	0·003	0·011
Mn	0·010	0·008	0·006	0·008	0·008
Fa	41·2	35·2	31·63	30·5	35·27
Fo	58·8	64·8	68·37	69·5	64·73
$100\ Mg/(Mg + Fe^{2+} + Fe^{3+} + Mn)$	57·6	63·2	66·5	67·1	62·8
α	1·725	1·698	1·694	1·696	1·700
β	1·748	1·720	1·717	1·720	1·723
γ	1·767	1·736	1·735	1·737	1·741
2V	105°	100°	100°	100°	100°
S.G.	3·744	3·600	3·587	3·598	3·621
Analysts:	J. Gamble	R. S. Pepper	P. Hewson	R. S. Pepper	P. Hewson

Note: The localities of the specimens may be found by reference to Figures 51, 52 and 56.

TABLE 23. CHEMICAL, PHYSICAL AND OPTICAL PROPERTIES OF OLIVINES FROM THE JAMESON RANGE GABBRO

Specimen No.	1247	1251	1257	1259	1260	1241
SiO_2	37·51	36·04	36·27	37·06	35·91	34·01
Al_2O_3	3·00	2·05	0·93	1·10	0·31	1·70
Fe_2O_3	1·59	1·89	1·98	2·27	2·31	1·72
FeO	28·38	31·36	31·96	31·08	32·23	42·30
MgO	28·02	27·97	28·36	26·23	28·97	19·65
CaO	1·16	0·41	....	0·78	....	0·31
TiO_2	0·15	0·09	0·21	0·40	0·09	0·14
MnO	0·35	0·41	0·45	0·39	0·47	0·48
Na_2O	0·18	0·03	0·03	0·03	....	0·03
K_2O	0·05	0·02	0·02	0·02	0·02	0·02
P_2O_5	0·03	0·03	0·03	0·03	0·02	0·03
H_2O^+	0·01	0·07	0·16	0·63	0·12	0·01
H_2O^-	0·05	0·10	0·02	0·13	0·02	0·05
	100·48	100·47	100·42	100·15	100·47	100·45
Si	1·003	0·982	0·992	1·020	0·987	0·980
Al	....	0·018	0·008	....	0·010	0·020
Al	0·093	0·047	0·021	0·036	....	0·039
Fe^{3+}	0·032	0·059	0·039	0·046	0·046	0·038
Fe^{2+}	0·632	0·712	0·728	0·713	0·736	1·016
Mg	1·124	1·114	1·116	1·083	1·192	0·849
Ca	0·034	0·011	....	0·023	....	0·010
Ti	0·003	0·002	0·005	0·008	0·002*	0·003
Mn	0·008	0·010	0·010	0·008	0·011	0·012
Na	0·005					
K	0·002					
Atomic % Fa	35·99	39·0	39·5	39·7	38·2	54·5
Atomic % Fo	64·01	61·0	60·5	60·3	61·8	45·5
100 Mg/(Mg + Fe^{2+} + Fe^{3+} + Mn)	62·6	58·8	59·0	58·5	60·1	44·3
α	1·704	1·710	1·710	1·714	1·713	1·740
β	1·728	1·734	1·734	1·738	1·738	1·766
γ	1·744	1·749	1·751	1·756	1·755	1·783
2V	100°	102°	102°	103°	103°	107°
S.G.	3·588	3·670	3·663	3·651	3·678	3·870
Analysts:	J. Gamble	J. Gamble	R. S. Pepper	P. Hewson	R. S. Pepper	J. Gamble

Note: *Probably accommodated in Si group. The localities of the specimens may be found by reference to Figure 43.

TABLE 24. UNIT CELL DIMENSIONS OF OLIVINES FROM THE GILES COMPLEX

Specimen No.	Fa	a (Å)	b (Å)	c (Å)
		BLACKSTONE RANGE GABBRO		
519	35·3	4·780 ± 0·001	10·303 ± 0·005	6·023 ± 0·005
577	41·3	4·784 ± 0·007	10·320 ± 0·007	6·030 ± 0·002
581	35·2	4·779 ± 0·006	10·292 ± 0·004	6·023 ± 0·001
582C	31·6	4·780 ± 0·024	10·290 ± 0·020	6·026 ± 0·002
585	30·5	4·781 ± 0·006	10·286 ± 0·004	6·002 ± 0·001
		JAMESON RANGE GABBRO		
1241	54·5	4·795 ± 0·001	10·360 ± 0·005	6·045 ± 0·003
1247	35·99	4·781 ± 0·007	10·302 ± 0·008	6·027 ± 0·002
1251	39·0	4·780 ± 0·010	10·304 ± 0·003	6·028 ± 0·0005
1257	39·5	4·785 ± 0·009	10·303 ± 0·008	6·029 ± 0·002
1259	39·7	4·790 ± 0·020	10·299 ± 0·007	6·027 ± 0·001
1260	38·2	4·782 ± 0·008	10·300 ± 0·009	6·027 ± 0·002

Notes:

1. Determinations by Government Chemical Laboratories. The possible error limits are reported as five times the estimated standard deviation calculated by a computer programme.
2. The cell dimensions of 519 and 1241 were obtained from single crystal methods. The rest were obtained from powder methods.
3. The localities of the specimens may be found by reference to Figures 43, 51, 52 and 56.

In the main part of the Jameson Range Gabbro the olivines show a narrow range of composition from $Fo_{60 \cdot 5}$ to Fo_{64}. There is an almost consistent decrease in the Fo content with height. However, the composition of the topmost analyzed specimen lies within the range of the lower specimens. As for the Blackstone Range Gabbro a progressive rise in ferric oxide content with height is noted. Similarly, there is an almost continuous fall in alumina. Only minor amounts of other oxides are present, and these vary irregularly.

A sample from Turkey Hill was also analyzed (Specimen 1241). It originates from an unsheared portion of Zone 3 and has a composition of $Fo_{45 \cdot 5}$, considerably lower than the olivines in the main part of the intrusion. Shearing of the main mass has probably modified the composition of the olivines by decreasing their FeO/MgO ratios.

ALUMINA CONTENT

In both the Blackstone Range Gabbro and the Jameson Range Gabbro, alumina decreases consistently, or almost so, with height. Alumina is normally regarded as an impurity in olivines and disregarded (Deer and others, 1962). Considerable time was spent purifying these olivines using a magnetic separator followed by Clerici solution treatment. After this the whole series was analyzed by two people who did not know where the samples came from in each intrusion.

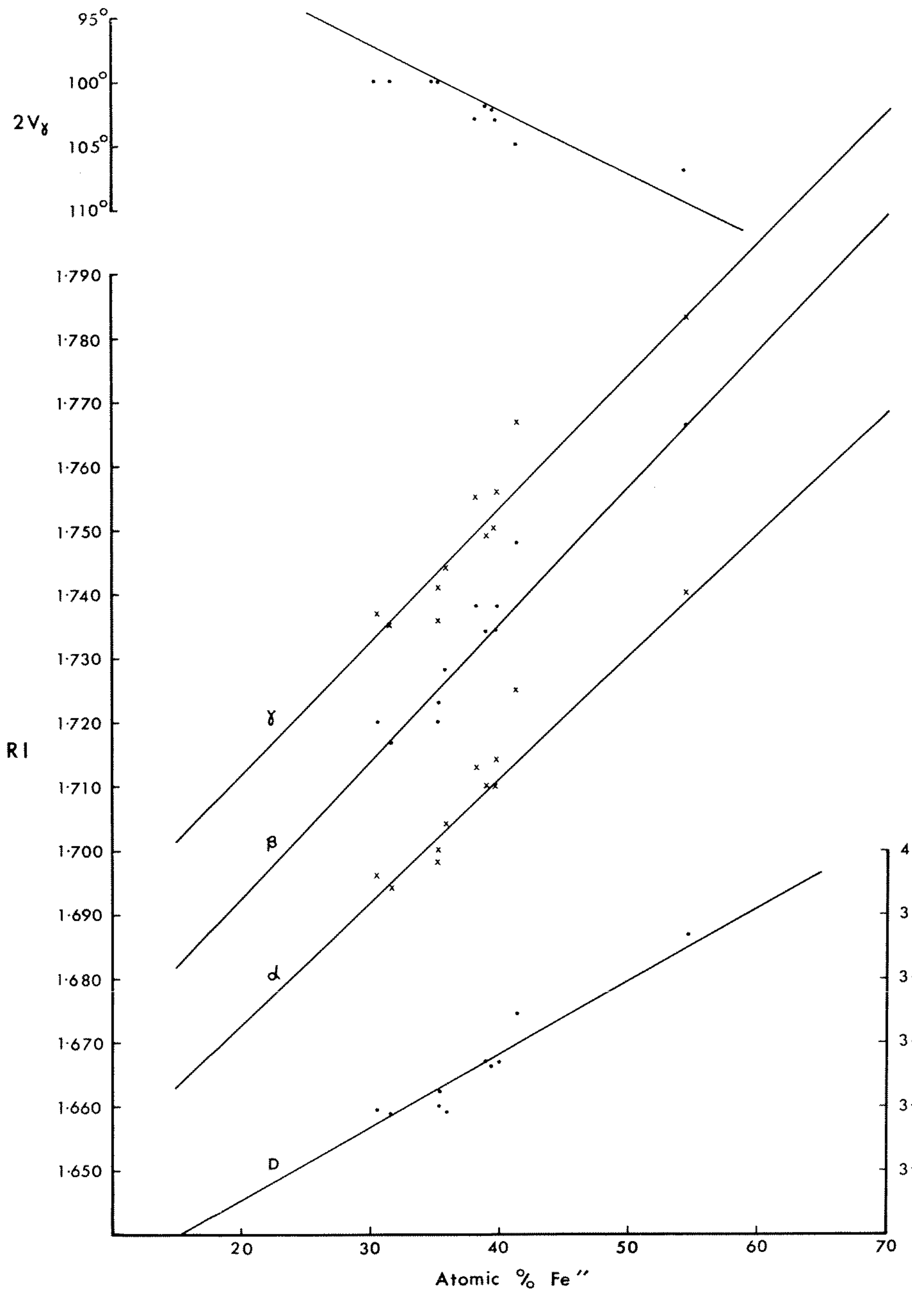

Figure 72. Optical properties and density of olivines from Giles Complex.

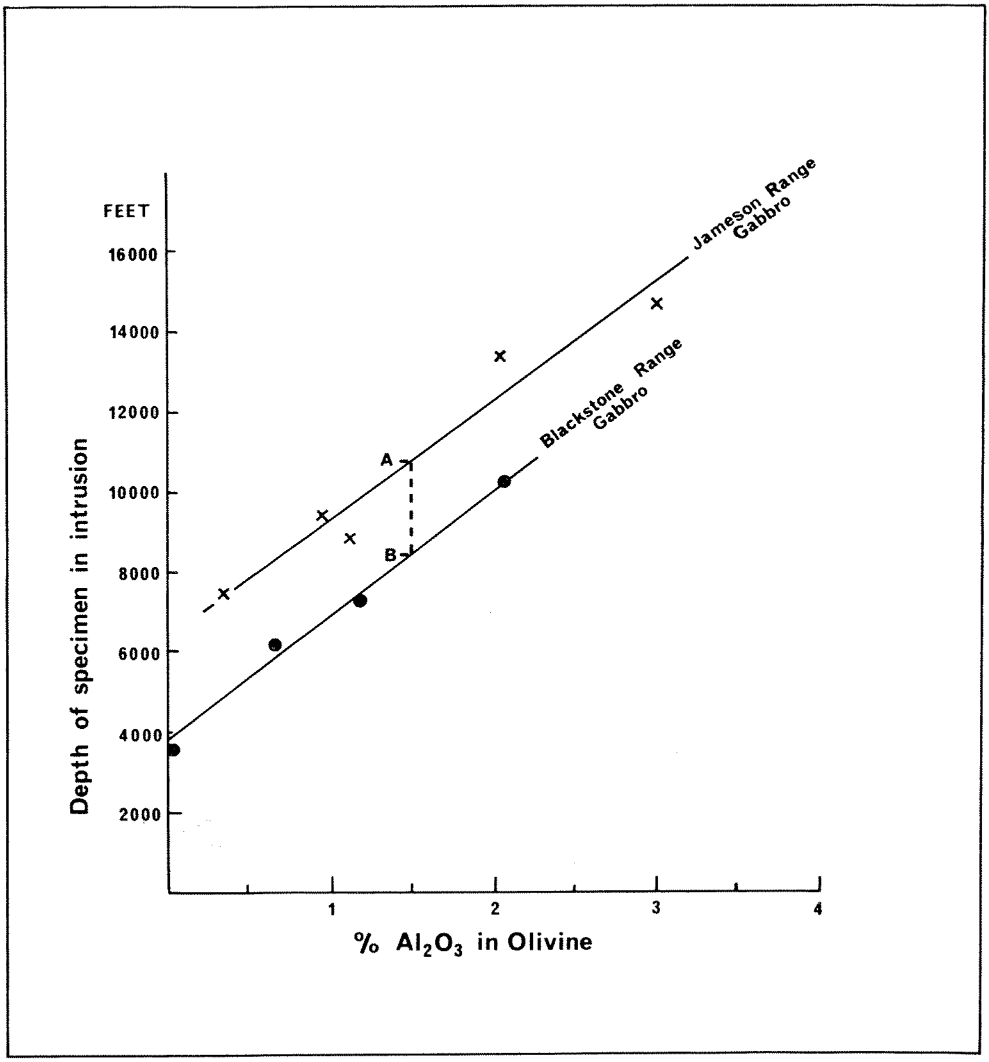

Figure 73. Relation of Al_2O_3 content of olivine to depth in intrusion for Jameson Range and Blackstone Range Gabbros. Overburden thickness above intrusions not known. For explanations see text.

The quoted values for alumina therefore appear to be reliable and their inverse correlation with height seems to justify this assertion. Confirmation using electron microprobe analytical techniques would be desirable, but in the meantime it seems possible that the alumina content of these olivines may be a useful geobarometer.

Table 25 gives the alumina contents of olivines from both gabbros and the depths of each specimen in the intrusions as calculated from the results of the field mapping.

TABLE 25. COMPARISON OF A_2O_3 CONTENT OF OLIVINES WITH DEPTH IN JAMESON RANGE AND BLACKSTONE RANGE GABBROS

JAMESON RANGE GABBRO

Specimen No.	% Al_2O_3	Depth in intrusion
1237	3·00	14,400 feet (4,390m)
1251	2·05	13,400 feet (4,080m)
1257	0·93	9,300 feet (2,830m)
1259	1·10	8,900 feet (2,710m)
1260	0·31	7,500 feet (2,290m)
BLACKSTONE RANGE GABBRO		
577	2·09	10,150 feet (3,090m)
581	1·19	7,100 feet (2,160m)
582C	0·57	6,100 feet (1,860m)
585	nil	3,700 feet (1,130m)

A graphical presentation of these results is given in Figure 73. The slopes of the two lines, representing the mean relation of alumina content to depth, are remarkably similar. From the slope of each line it is calculated that for the Jameson Range Gabbro the alumina content of olivine increases by 0.034 per cent for every 100 feet (30 m) increase in depth. For the Blackstone Range Gabbro the equivalent value is 0.032 per cent.

The graph also suggests that a minimum depth of approximately 4000 feet, plus an unknown thickness of overburden, is necessary before any Al_2O_3 enters the olivine. The separation of the two trend lines marked by the line A-B on the diagram suggests that the Jameson Range Gabbro could have crystallized approximately 2000 feet deeper than the Blackstone Range Gabbro. The total depth of burial in both cases is not known.

PYROXENES

GENERAL CHARACTERISTICS

Orthopyroxene and clinopyroxene are common constituents of many of the rocks in the various intrusions forming the Giles Complex. In the Michael Hills Gabbro they consistently occur together, and olivine is absent. In the other masses they may occur singly or together with or without coexisting olivine.

The γ refractive indices of some coexisting orthopyroxenes and clinopyroxenes for several of the intrusions are given below in Table 26. The maximum range of En of the orthopyroxene indicated by the refractive indices is approximately En_{66} to En_{84} with the majority around En_{70}. No trends are apparent in any of the intrusions.

TABLE 26. REFRACTIVE INDICES OF COEXISTING PYROXENES IN THE GILES COMPLEX

Specimen No.	Hypersthene γ	Clinopyroxene γ
Bell Rock Range—		
516	1·704	1·712
517	1·698	....
520	1·704	1·712
521	1·702	1·710
522	1·704	1·713
Blackstone Range—		
577	1·709	1·719
578	1·707	1·720
584	1·703	1·711
585	1·704	1·711
Sub Blackstone Range—		
561	1·687	1·701
Michael Hills—		
4026	1·704	1·720
4024	1·705	1·707
4085	1·706	1·713
Jameson Range—		
1252	1·712	1·718
1253	1·707	1·725
1256	1·704	1·709
1259	1·707	1·718
1263	1·703	1·718

FERROUS IRON/MAGNESIUM PARTITION IN COEXISTING PYROXENES

Three orthopyroxenes and three clinopyroxenes all from the Jameson Range Gabbro were analyzed (Tables 27 and 28). The analyses include two coexisting pairs whose Fe^{2+}, Mg distribution coefficient have been calculated.

The distribution of Fe^{2+} and Mg between coexisting orthopyroxene and clinopyroxene has been studied for igneous rock assemblages (*e.g.,* Kretz, 1963; Bartholome, 1961) and metamorphic rocks (*e.g.,* Wilson, 1960; Mueller, 1960, 1961). The distribution of these two metals is usually quoted as a number called the distribution or partition coefficient (K_D) which is determined from the formula:

$$K_D = \frac{\text{Xopx} \quad (1-\text{Xcpx})}{\text{Xcpx} \quad (1-\text{Xopx})}$$

TABLE 27. CHEMICAL, PHYSICAL AND OPTICAL PROPERTIES OF ORTHOPYROXENES FROM THE JAMESON RANGE GABBRO

Specimen No.	1252	1253	1263
SiO_2	50·66	50·92	51·83
Al_2O_3	2·78	2·82	3·32
Fe_2O_3	1·86	3·16	2·80
FeO	23·29	21·32	16·03
MgO	19·05	18·32	23·59
CaO	1·40	2·63	1·54
TiO_2	0·19	0·28	0·24
MnO	0·47	0·46	0·41
Na_2O	0·07	0·09	0·09
K_2O	0·04	0·04	0·05
P_2O_5	0·01	0·01	0·02
H_2O^+	0·56	0·30	0·40
H_2O^-	0·09	0·12	0·12
	100·47	100·47	100·44
Si	1·896 } 2·000	1·904 } 2·000	1·880 } 2·000
Al	0·104	0·096	0·120
Al	0·017	0·030	0·024
Ti	0·004	0·009	0·007
Fe^{3+}	0·054	0·090	0·078
Mg	1·068	1·027	1·284
Fe^{2+}	0·725 } 1·944	0·664 } 1·942	0·485 } 1·956
Mn	0·016	0·013	0·013
Ca	0·056	0·105	0·061
Na	0·004	0·004	0·004
K	....	....	....
H	0·139	0·076	0·096
Fe (tot)	40·9	40·0	29·5
Mg	56·1	54·4	67·3
Ca	2·9	5·6	3·2
Mg	55·65	54·08	66·84
$Fe^{2+} + Fe^{3+} + Mn$	41·43	40·39	29·98
Ca	2·92	5·53	3·18
α	1·698	1·692	1·688
β	1·707	1·701	1·698
γ	1·712	1·707	1·703
2V	55°	60°	65°
S.G.	3·520	3·485	3·439
a	18·306 ± 0·003	18·30 ± 0·01	18·291 ± 0·001
b	8·905 ± 0·003	8·874 ± 0·006	8·875 ± 0·001
c	5·217 ± 0·002	5·171 ± 0·003	5·200 ± 0·014
$100 Mg/(Mg + Fe^{2+} + Fe^{3+} + Mn)$	57·33	57·25	69·03
Fs	42·67	42·75	30·97

Specimen No.	1252	1253	1263
a° (calc)	18·315	18·276	18·291
b° (calc)	8·914	8·874	8·884
c° (calc)	5·216	5·216	5·208
Å³ (calc)	851·564	845·937	846·286
a° (obs)	18·306 ± 0·003	18·30 ± 0·01	18·291 ± 0·001
b° (obs)	8·905 ± 0·003	8·874 ± 0·006	8·875 ± 0·001
c° (obs)	5·217 ± 0·002	5·171 ± 0·003	5·200 ± 0·014

Analyst: J Gamble.

Locations of specimens may be found by reference to Figure 43.

where Xopx = mole fraction $Mg/Mg+Fe^{2+}$ in orthopyroxene and Xcpx = mole fraction $Mg/Mg+Fe^{3+}$ in coexisting clinopyroxene.

The distribution coefficient, in equilibrium assemblages, is thought to be mainly dependent on the pressure and temperature conditions under which the distribution was effected. Binns (1962) has shown, however, that some dependence on composition is also involved. He showed that under constant pressure and temperature conditions K_D in pyroxene pairs in a particular part of the granulite facies near Broken Hill was 0.503 for magnesium-rich assemblages and 0.595 in iron-rich assemblages, indicating that iron slightly increased K_D.

The different conditions under which igneous and metamorphic rocks develop suggest that any coexisting pyroxenes would show noticeably different K_D values. This is in fact the case. The following data from Howie (1965) (Table 29) lists K_D values for certain coexisting pryoxenes from igneous and metamorphic rocks.

In the two examples from the Jameson Range Gabbro values of ($K_{D\ (Mg\text{-}Fe^{2+})}$ of 0.624 and 0.659 were obtained from Specimens 1253 and 1263 respectively. The lowest value was obtained from the rock with the most intensely developed sheared fabric, but was also formed 9,000 feet (2,700 m) deeper in the intrusion than the other. The values are intermediate between those for plutonic rocks and those for high-grade metamorphic rocks. Both the orthopyroxene and clinopyroxene of Specimen 1253 are richer in iron than the same minerals of Specimen 1263 and on this basis alone the coexisting pyroxenes of 1253 could be expected to show the higher K_D value. However, this is not the case, and some other factor may be of greater importance than the chemistry.

One possible explanation is that part of the Jameson Range Gabbro has undergone a metamorphism of sufficient intensity to modify the distribution coefficient, but insufficient to impose either a typically metamorphic K_D factor or change the mineralogical composition. As the most obvious feature of these

TABLE 28. CHEMICAL, PHYSICAL AND OPTICAL PROPERTIES OF CLINOPYROXENES FROM THE JAMESON RANGE GABBRO

Specimen No.	1253	1256	1263
SiO_2	51·12	50·51	51·34
Al_2O_3	3·35	4·27	3·67
Fe_2O_3	1·57	2·26	1·53
FeO	9·51	6·82	6·59
MgO	13·06	13·80	14·76
CaO	20·62	20·98	21·38
Na_2O	0·32	0·44	0·36
K_2O	0·04	0·05	0·01
H_2O^+	0·26	0·43	0·06
H_2O^-	0·01	0·03	0·01
TiO_2	0·38	0·63	0·58
P_2O_5	0·02	0·03	0·01
MnO	0·20	0·15	0·17
	100·46	100·40	100·47
Si	1·900	1·861	1·890
Al	0·100	0·139	0·110
Al	0·047	0·047	0·049
Ti	0·009	0·015	0·015
Fe^{3+}	0·045	0·062	0·044
Mg	0·729	0·762	0·815
Fe^{2+}	0·294	0·210	0·203
Mn	0·007	0·004	0·004
Ca	0·821	0·829	0·843
Na	0·022	0·031	0·026
K	....	0·004	....
H	0·062	0·106	0·013
Atomic %			
Mg	38·45	40·81	42·69
$Fe^{2+} + Fe^{3+} + Mn$	18·25	14·78	13·15
Ca	43·30	44·40	44·16
$2V\alpha$	50°	45°	48°
S.G.			
α	1·690	1·688	1·683
β	1·695	1·693	1·687
γ	1·716	1·716	1·709

Analysis: Government Chemical Laboratories
Location of specimens may be found by reference to Figure 43.

TABLE 29. K_D VALUES FOR COEXISTING PYROXENES FROM IGNEOUS AND METAMORPHIC ROCKS

Coexisting pyroxenes from:	K_D (Mg-Fe^{2+})
Skaergaard Intrusion	0·73
Gabbro from Hawaii	0·69
Madras Charnockite series	0·54

rocks is their sheared texture it is possible that the chemical redistribution could have been induced by the shearing, probably while the gabbro was still hot. K_D values of around 0.62 to 0.66 are rare in the literature. Examples originating from rocks of widely different geological environment are shown in Table 30.

TABLE 30. K_D VALUES OF AROUND 0·62 TO 0·66 FOR CO EXISTING PYROXENES FROM VARIOUS ROCKS (KRETZ, 1963)

	Rock and environment	K_D (Mg-Fe^{2+}) coexisting Pyroxenes
1.	Metamorphic iron formation, northern Quebec (Kranck, 1961)	0·653
2.	Granulite facies gneiss, Lapland (Eskola, 1952)	0·647
3.	Pitchstone, Sgurr of Eigg, Scotland (Carmichael, 1960)	0·666
4.	Bronzitite, Bushveld (Hess, 1960)	0·654
5.	Ultramafic inclusion in basaltic rock, Stempel,Germany (*in* Ross and others, 1954)	0·653
6.	Ultramafic inclusion in basaltic rock, Sardinia (*in* Ross and others, 1954)	0·646

By themselves, values of K_D around 0.65 cannot therefore be used to indicate specific pressure and temperature conditions of formation. Their interpretation probably depends on local factors, and, in the case of the Jameson Range Gabbro examples, shearing is one such factor which must be considered. Another interpretation of the apparently low K_D values in the Jameson Range Gabbro relative to some other plutonic rocks is that they were induced by high pressures coincident with crystallization of the gabbro at a moderate to large depth. Atkins (1969) pointed out that a K_D value of 0.73 for igneous pyroxene pairs was possible as a result of work carried out on two intrusions, the Skaergaard and Stillwater bodies. The samples of pyroxene pairs from the Skaergaard Intrusion probably crystallized at depths of 2.7 and 3.7 km (Atkins, 1969, p. 238). In his study of the Bushveld coexisting pyroxenes Atkins obtained values for K_D averaging 0.669 with a range from 0.644 to 0.697. He deduced from independent evidence that they must have crystallized at much greater depths than the Skaergaard samples.

It has been suggested, from a consideration of the alumina content of olivine in the Jameson Range Gabbro (p. 175) that crystallization took place at a moderate depth. It is not unlikely therefore that the K_D factors of coexisting pyroxenes should also in some way reflect the depth of crystallization.

The K_D values for the coexisting pyroxenes in the Jameson Range Gabbro are given in Table 31. The results suggest a decrease in K_D with depth. If the control is largely pressure, then the Jameson Range Gabbro probably crystallized at a somewhat greater depth than most of the Bushveld Complex and at a considerably greater depth than the Skaergaard intrusion. It appears also that the K_D values quoted as typical of igneous rocks need amending.

TABLE 31. K_D VALUES FOR COEXISTING PYROXENES IN THE JAMESON RANGE GABBRO

Specimen No.	$K_{D\ (Mg\text{-}Fe^{2+})}$	Depth in intrusion
1263	0·659	3,300 feet (1,000 m)
1252	0·624	12,300 feet (3,700 m)

DIFFERENTIATION

It is unlikely that the differentiation of the gabbros of the Giles Complex can be explained by the action of a few variables of a chemical or physical nature (Middlemost and Romey, 1968). However, an attempt is made here to explain some of the features of the complex in simple terms. Before discussing the differentiation of the Giles Complex two main types of data must be examined: whole rock analyses and mineral compositions.

WHOLE ROCK ANALYSES

Because of the abundant layers of very variable mineralogical composition present in all these intrusions, selection of suitable samples for whole rock analysis is critical. Such samples were only taken from "average-looking" gabbro away from zones of rhythmic layering. This then ensures, as far as possible, a suite of rocks which have not accumulated under the influence of magmatic currents and have not therefore had certain minerals preferentially extracted or concentrated as a result of these currents. These rocks should represent (with a proviso to be discussed later) average gabbro, characteristic of that crystallizing from the magma during a certain stage in its crystallization.

During the accumulation of the crystals forming this average gabbro, a certain amount of magma is trapped between the grains. This liquid may form up to half of the bulk of the crystal-liquid association and may either crystallize as gabbro or be partly expelled, possibly by diffusion, as a result of adcumulate growth of crystals in the precipitate. The two possibilities would each produce rocks of slightly different composition.

For the present exercise, however, these considerations are refinements and the variations so produced would be masked by other more important changes brought about by major changes in the magma composition.

Ten whole rock analyses are available for the Western Australian part of the Giles Complex. Four are from the Blackstone Range Gabbro, four are from the Michael Hills Gabbro and two come from the Jameson Range Gabbro. The results are given in Table 32 along with various calculations based on these analyses. In the case of the first two named intrusions the relative heights of the specimens in the intrusions can be seen by reference to Figures 52 and 57 respectively.

It is clear that some oxides fall within certain ranges characteristic of a particular intrusion, though more analyses would be required for this to be statisti-

TABLE 32. WHOLE ROCK ANALYSES OF GABBROS FROM THE GILES COMPLEX

Specimen No.	577	578	584	585	4086	4030	4025	4063	1239	1246
SiO_2	47·06	47·72	46·61	45·79	50·19	50·24	51·73	52·95	48·84	48·91
Al_2O_3	18·54	17·35	20·72	18·80	13·42	13·65	14·73	19·87	20·77	21·28
Fe_2O_3	2·11	2·22	1·72	0·92	2·57	2·90	2·40	1·33	0·73	0·71
FeO	9·39	9·46	8·35	10·47	8·83	8·13	6·07	4·46	9·02	8·26
MgO	8·07	7·05	8·83	13·03	11·00	8·72	8·64	6·02	6·62	6·61
CaO	10·10	10·87	9·75	8·41	10·50	12·42	12·28	10·47	9·51	9·72
Na_2O	2·16	2·24	2·28	2·06	1·55	1·93	2·25	3·01	2·87	2·84
K_2O	0·35	0·25	0·28	0·22	0·31	0·23	0·45	0·49	0·47	0·46
H_2O^+	0·39	0·41	0·36	0·16	0·45	0·45	0·50	0·36	0·30	0·28
H_2O^-	0·08	0·10	0·09	0·18	0·11	tr	0·03	0·07	0·13	0·13
CO_2	0·18	0·07	0·18	0·05	0·01	0·26	0·01	0·02	0·01	0·04
TiO_2	1·13	2·02	0·40	0·08	0·84	0·63	0·73	0·58	0·73	0·89
P_2O_5	0·07	0·03	0·03	0·03	0·12	0·02	0·09	0·13	0·07	0·01
FeS_2	0·09	0·18	0·17	tr	0·06	0·20	0·09	0·02	0·01	0·01
Cr_2O_3	0·04	0·02	0·06	tr	0·07	0·03	0·06	0·04	tr	tr
V_2O_5	0·08	0·10	0·02	0·01	0·04	0·07	0·04	0·02	0·01	0·01
NiO	0·03	0·02	0·06	0·08	0·04	0·02	0·04	0·02	0·02	0·03
CoO	tr	tr	tr	0·01	0·01	0·01	0·01	0·01	0·01	0·01
MnO	0·14	0·15	0·12	0·13	0·18	0·19	0·15	0·10	0·11	0·12
	100·01	100·26	100·03	100·43	100·30	100·10	100·30	99·97	100·23	100·32

tr = less than 0·01

Specimen No.	577	578	584	585	4086	4030	4025	4063	1239	1246
Q	....	....	....	....	0·30	0·75	1·02	2·20	....	....
Or	2·07	1·47	1·65	1·30	1·83	1·36	2·66	2·89	2·78	2·72
Ab	18·25	18·93	19·26	17·41	13·10	16·31	19·01	25·43	24·25	24·00
An	39·81	36·50	45·42	41·35	28·70	27·86	28·72	39·20	42·34	43·90
Di	7·13	13·74	1·34	0·16	18·27	25·94	25·35	9·59	3·66	3·51
Hy	14·64	16·43	9·11	3·96	31·68	21·03	17·64	16·74	8·64	8·73
Ol	11·60	5·05	18·72	34·19	....	....	....	....	15·44	14·19
Mr	3·05	3·21	2·49	1·33	3·72	4·20	3·48	1·92	1·05	1·02
Il	2·14	3·83	0·73	0·15	1·59	1·19	1·38	1·10	1·38	1·69
Ap	0·16	0·07	0·07	0·07	0·28	0·04	0·21	0·30	0·16	0·02
Feldspar Triangle										
OR	3·4	2·5	2·4	2·1	4·1	2·9	5·2	4·2	4·0	3·8
AB	30·3	33·2	29·0	28·9	30·0	35·8	37·7	37·6	34·9	33·9
AN	66·2	64·1	68·4	68·8	65·7	61·1	56·9	58·0	61·0	62·1

577, 578, 584, 585 Blackstone Range Gabbro
4086, 4030, 4025, 4063 Michael Hills Gabbro
1239, 1246 Jameson Range Gabbro

Analysts: R. W. Lindsey, 577, 578, 584
J. R. Gamble, 585, 4086, 4063, 1239, 1246
P. Hewson, 4025, 4030

cally correct. Table 33 illustrates the point. Their restricted chemical characteristics are even more obvious when plots of two oxides against each other are made. Different fields of composition are well depicted when SiO_2 is plotted against both Al_2O_3 and total Fe.

The Michael Hills Gabbro is also quite distinct from the others in carrying normative quartz up to 2.2 per cent. This suggests a confirmation of the field evidence which points to a degree of contamination of the gabbro by acidic country rocks.

TABLE 33. SUMMARY OF RANGES OF SELECTED OXIDES IN ROCK ANALYSES FROM THE BLACKSTONE RANGE, MICHAEL HILLS AND JAMESON RANGE GABBROS

Name of intrusion	SiO_2%	Al_2O_3%	CaO%
Blackstone Range	45·79—47·72	17·35—18·80	8·41—10·87
Michael Hills	50·19—52·95	13·42—19·87	10·47—12·42
Jameson Range	48·84—48·91	20·77—21·28	9·52— 9·72

No simple trends are apparent for oxides in the Blackstone Range Gabbro. The Michael Hills Gabbro, however, shows minor but consistent changes with height of a number of oxides. A consistent increase with height is noted for SiO_2, Al_2O_3, and Na_2O, and this occurs concurrently with a consistent decrease in FeO and MgO. The normative plagioclase composition (An + Ab only) shows an almost consistent decrease in An content from $An_{68\cdot7}$ to $An_{60\cdot7}$.

More analyses of the Jameson Range Gabbro are required to define trends. Of the two analyses available 1246 was taken from Zone 3 at Turkey Hill and the other, 1239, was taken from Zone 3 in Jameson Range itself. The latter has been somewhat sheared and modified, but its bulk chemical composition is remarkably similar to that of 1246, which is completely unsheared.

The mafic and felsic indices (Simpson, 1954) of each of the analyses were calculated and plotted against each other for comparison with differentiation trends from other intrusions (Fig. 74). It is at once apparent that the plots for the gabbros from the Giles Complex do not compare with these known trends. The Giles Complex trends are erratic and suggest that the bodies have not been progressively differentiated along "classical" lines. On this diagram has also been

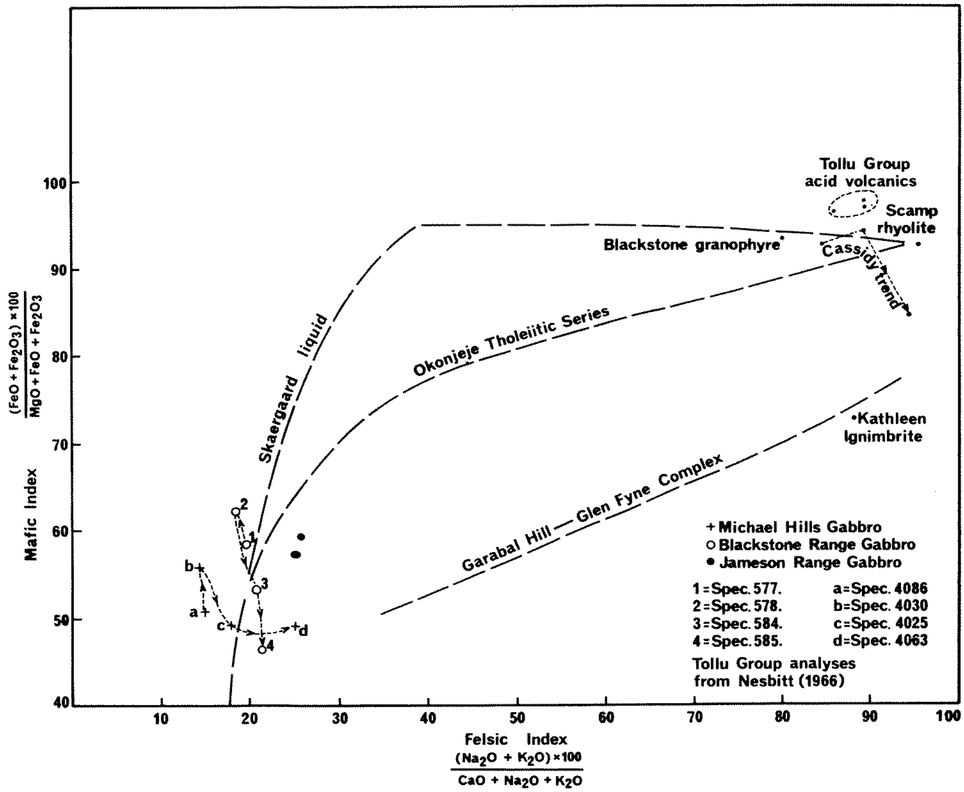

Figure 74. Mafic index—felsic index diagram for rocks of the Giles Complex in comparison with other differentiation trends given by Simpson (1954).

plotted the results for the various acid volcanics in the area and an analysis of a granophyre present at the top of the Blackstone Range Gabbro at Tollu.

It is doubtful if diagrams such as this are meaningful in explaining the variations seen in these gabbros. From the results of the whole rock analyses it appears that individual intrusions are identifiable on their bulk chemical composition provided samples are taken from average-looking gabbroic material. Little in the way of differentiation can be detected from the bulk chemistry. The individuality of each mass suggests that the parent magma was different in each case.

MINERAL DATA

Some details relevant to the differentiation of the Giles Complex are obtained from the chemical composition of plagioclase and olivine. Data concerning the orthopyroxenes and clinopyroxenes are insufficient.

The main characteristics of the chemistry of these minerals, supplemented by optical data, for each of the intrusions studied are summarized below:

PLAGIOCLASE

MICHAEL HILLS GABBRO

1. restricted irregular range of composition
2. relatively large range of total strontium for given range of An.

BLACKSTONE RANGE GABBRO

1. total range of An small
2. irregular variation of An with height.
3. changes of An in adjacent bands represent large proportion of total An range displayed by the whole mass
4. suggestion of reverse trends in upper parts of Zones 2 and 3
5. reverse zoning present in some samples
6. noticeable change in trend and pattern between Zones 2 and 3, and Zones 3 and 4
7. narrow range of strontium relative to An
8. slight rise of strontium with decreasing An.

JAMESON RANGE GABBRO

1. excluding Zone 2, total An range small
2. normal and reverse trends present
3. changes in trend or pattern take place with changes of mappable zones
4. excluding Zone 2, each zone characterized by certain Or/An range.

OLIVINE

BLACKSTONE RANGE GABBRO

1. consistent increase in iron content with height
2. consistent decrease in alumina content with height
3. consistent increase in ferric oxide content with height
4. small content of minor oxides showing irregular variations with height.

JAMESON RANGE GABBRO

1. almost consistent decrease in Fo content with height except for topmost specimen analyzed. Total range is small
2. almost continuous fall in alumina content with height
3. progressive rise in ferric oxide content with height
4. almost continuous rise in ferrous oxide content with height.

CONCLUDING DISCUSSION

In the Western Australian part of the Giles Complex the individual sheets studied, that is, the Jameson Range, Blackstone Range and Michael Hills Gabbros, do not show consistent differentiation trends for either plagioclase or olivine, where present. The variations noted in individual minerals are characterized by irregular trends with very limited ranges of composition present in both plagioclase and olivine. It is principally these features which have to be accounted for. Methods of mechanical differentiation of the gabbros brought about by convection currents which produced a wide variety of sedimentary-type structures have been discussed elsewhere (p. 102).

Complications in the interpretation of the differentiation of the Jameson Range Gabbro arise because of the presence of shearing and the effects this might have had on mineral composition. In the Michael Hills Gabbro, contamination has played an important role and hence any differentiation present in this body may well be unique. The Blackstone Range Gabbro shows neither shearing nor contamination and may provide more direct evidence.

Among the many factors which must influence the course of differentiation in a basaltic magma is the cooling rate, and this depends partly on the surface area of the intrusion, the overburden thickness, and whether or not fresh magma is introduced during crystallization.

The area to thickness ratio of the sheet will determine the number of independent convection cells operating at any one time. If we disregard, for the present, the possibility of introduction of fresh magma, then the number of independent convection cells will tend to increase as the liquid layer remaining in the intrusion becomes thinner. It is unlikely that the cooling rate will be the same over the whole area of a large intrusion such as the Blackstone Range Gabbro, which had an original area of probably more than 600 square miles (1,550 km^2) and a volume of perhaps 1,300 cubic miles (5,400 km^3). It is conceivable that the magma, having split into a number of independent convection cells would differentiate at somewhat different rates in different cells. Independent cellular differentiation would continue until the physical conditions necessary for the establishment of a new set of convection cells were achieved.

This concept may not be at variance with the pattern of convection currents determined in the field for the Blackstone Range Gabbro. The shape of the base of the intrusion as determined by cross-bedding and slump structures is that of an oval saucer. Its effect, though not known for certain, probably would have been to produce a more complexly shaped series of convection cells than would have been the case for a horizontal sheet.

The effect of deposition of material crystallizing from a magma, broken up into a number of convection cells, would be to produce a pile of elongated lenticular sheets. Evidence in support of this may be found in both the Blackstone Range and Jameson Range Gabbros. Zone 4 in the Blackstone Range Gabbro is not present in Bell Rock Range; a feature which may possibly be accounted for by its lenticular character. In the Jameson Range some of the titaniferous magnetite layers are also lenticular and the en echelon arrangement of these bands at the base of Zone 4 near the northwest end of Jameson Range may indicate successive shifts of the convecting cell.

At any given time during crystallization, zones of magma at different differentiation stages would exist in the same liquid mass. Slight mixing would probably take place constantly at cell contacts, but major mixing of these zones would occur whenever new cell systems were established.

Slight mixing of liquids at different differentiation stages could be expected to produce minor normal or reversed zoning in already precipitated crystals and to adjust the differentiation state of the liquid in the cell somewhat.

Major mixing would produce the same effects but on a larger scale. A new and distinctive set of conditions would then be set up, characteristic of the new convection cell system and this could possibly account for some of the major zone banding seen in the field and verified in the mineral composition trends. One expected effect of this major mixing would be to produce strong normal or reverse zoning in minerals deposited at the top of the layers produced during the life of one convection cell. Strong reverse zoning is seen in plagioclase at the top of Zone 1 in the Blackstone Range Gabbro but the number of determinations is too few to allow generalization. Another result of this large-scale mixing would be to produce abrupt changes in the differentiation trends as reflected in the mineral composition graphs. Such are common in the individual sheets of the Giles Complex.

It is therefore considered possible that, even though the total volume of magma involved in an intrusion such as the Blackstone Range Gabbro is large, the mass could effectively crystallize as a collection of small bodies and on this basis differentiation may be expected to be very limited.

For simple systems the number of convecting cells present depends primarily on the thickness of the liquid. As the number of cells must be a whole number it can be expected that under these conditions the major mixings of magma should occur at regular or predictable times and be recognized by prominent breaks in the succession.

The olivines of Zones 1, 2 and 3 of the Blackstone Range Gabbro show a consistent reverse trend, opposite to a normal differentiation trend, and this cannot be reconciled with the above mechanism unless an additional factor operated independently and affected only the MgO/FeO ratio of the olivine.

Crystallization of the gabbro and consequent concentration of volatiles in the liquid phase, or sudden eruption of material from the magma chamber, would produce respectively either gradual or sudden changes in the fugacity of oxygen and water concurrently controlling the oxidation ratio and the presence or absence

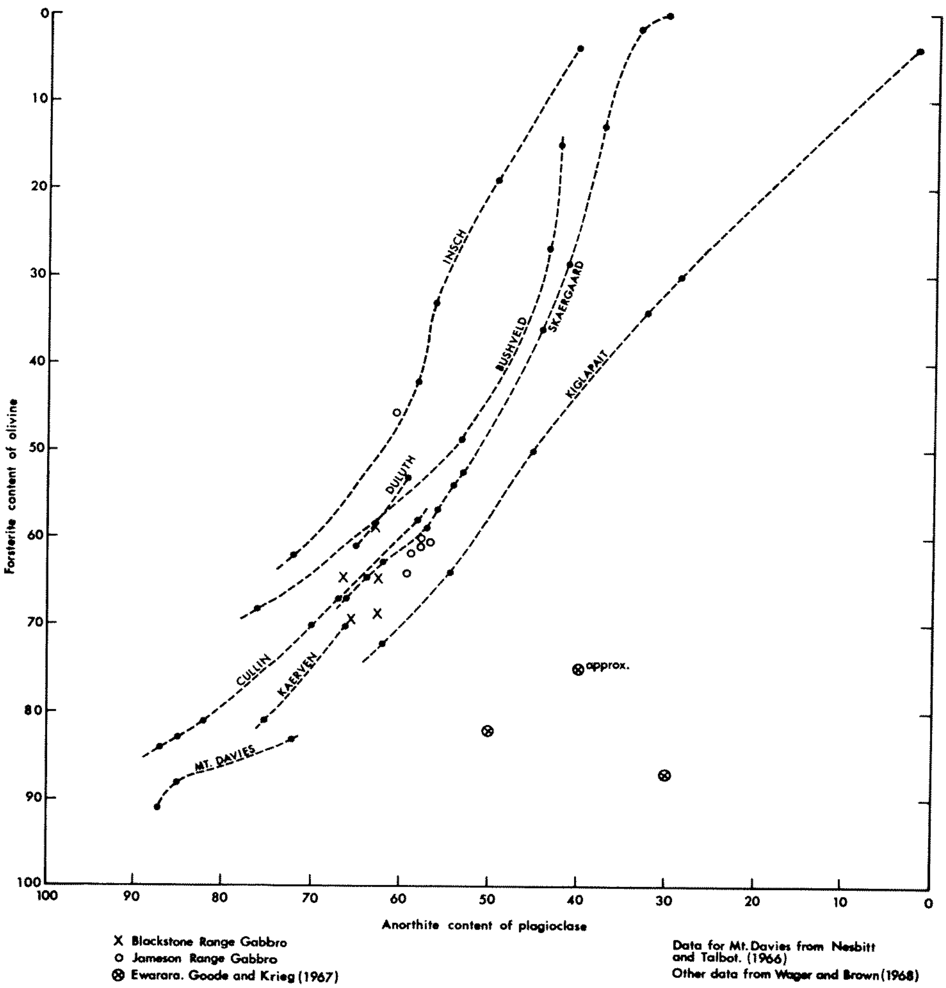

Figure 75. Compositions of coexisting olivine and plagioclase for various layered basic intrusions. For explanation see text.

of hydrated minerals. The Fe_2O_3/FeO ratio would affect the MgO/FeO ratio and consequently may control the Fo content of the olivine.

Perhaps a constant progressive build-up in oxygen fugacity took place during the crystallization of the Blackstone Range Gabbro and its effect was to convert progressively more FeO to Fe_2O_3 thereby increasing the MgO/FeO ratio and accounting for the increase in Fo content of the olivine up the intrusion. The Fo content is also temperature dependent, but as we have seen from the plots of Fo for olivine against An for coexisting plagioclase for various intrusions, temperature cannot be the only factor. If it were so then Fo/An plots for various intrusions would be identical. Independent intrusions show distinctive Fo/An differentiation trends (Fig. 75) generally parallel to each other and of various lengths. The displacement of one trend relative to another may be partly pressure dependent and partly composition dependent, though there is no detailed proof.

A little evidence in support of pressure dependency is forthcoming from the Ewarara intrusion, part of the Giles Complex in South Australia (Goode and Krieg, 1967). Plots of Fo/An for coexisting olivine and plagioclase from this intrusion have been added to the diagram (Fig. 75). The plots show the plagioclase to be extremely low in An for a given olivine Fo content, in comparison with many other intrusions. This intrusion is thought to have crystallized near the base of the crust (Goode and Krieg, 1967, p. 192). The low An values can therefore be explained as being due to crystallization at high pressure causing an increase in the amount of clinopyroxene crystallizing thus depleting the liquid in calcium.

From a study of the distribution coefficients of magnesium and ferrous iron in coexisting pyroxenes, it is thought that the relative depths of crystallization may be estimated for gabbros. The following intrusions are given in order of increasing depth of crystallization: Skaergaard Intrusion, Bushveld Complex, and Jameson Range Gabbro. Such a scheme is not apparent in the graphs (Fig. 75) and hence a pressure dependency for the approximate parallelism of the Fo/An plots of the various intrusions is probably not the most important factor.

So far the discussion has concerned possible changes in a single pulse of magma. Effectively, some of the changes noted would be the same as might be be achieved by the intrusion of fresh quantities of magma either continuously or at repeated intervals.

Addition of fresh magma, with or without expulsion of remaining liquid has been proposed to explain breaks in otherwise smooth differentiation curves. Examples include the Rhum, Bushveld and Kap Edvard Holm intrusions. However, this emplacement of fresh magma rarely disrupts the layering of the earlier mass. It seems anomalous that, considering the large volumes involved, disruption is a rare rather than a common feature. In the Kap Edvard Holm intrusion, however, some field evidence is available (Wager and Brown, 1968), but without this the main evidence for postulating addition of fresh liquid is derived from the composition of the gabbroic minerals. A sudden change from low to high An or high Fa to low Fa can imply crystallization from a higher temperature melt and the implication is that the higher temperature is the result of addition of fresh magma.

Such addition of fresh magma could easily account for some zone layering and evidence in support of this is found in the contrasting K/Sr relations of plagioclase from adjacent zones in the Jameson Range Gabbro and to a lesser extent for the Michael Hills Gabbro.

In the Blackstone Range Gabbro no such contrast in adjacent zones is apparent and it is suggested that for this body multiple intrusion is not the cause of zone layering.

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CHAPTER 5

Miscellaneous Topics of the Precambrian Rocks

GEOLOGY OF THE GILES AREA

The hilly area, forming the Rawlinson, Kathleen and Dean Ranges, in the north and northeast part of the Scott Sheet area is separated from the main outcrop of the Blackstone Region by the Phanerozoic sediments of the Cobb Depression.

Physiographically and geologically this area is part of the southwest margin of the Amadeus Basin and logically should be discussed in relation to the history of development of this major central Australian structure. The Amadeus Basin and its margins have been studied by several geologists, and the reader is referred to their work for details. The most relevant for the area near Giles is that of Forman (1966). His work also includes a summary of the early investigation of the general area. The only other mapping not mentioned in Forman's summary is that of the Geological Survey of Western Australia.

It is proposed here to give only the broad outlines of the regional geology. The area consists of a suite of granites and acid gneisses unconformably overlain by sediments and volcanic rocks, which are all intruded by quartz-feldspar porphyry and granite. The granitic rocks older than the unconformity contain abundant ovoid feldspars in a moderately mafic groundmass. Pronounced metamorphic foliation is frequently observed. No age for these rocks is available but they could possibly be equated, on lithological similarities only, with some of the components of the Arunta Block in Northern Territory. These include some of the oldest rocks in the region which have been dated at around 1,700 m.y. by Compston and Arriens (1968).

Overlying these acid rocks in the northeast part of the Scott Sheet area are sediments and volcanic rocks. At the base is a sandstone and conglomerate. The sandstones are cross-bedded, and currents from both the east and west are indicated by cross-bedding orientations. The conglomerate thickens from the Dean Range region westward, and attains a maximum thickness in the area immediately south of the Kathleen Range. In this region it is also interbedded with basic and acid volcanics. At the extreme west of the Kathleen Range the unit thins again and is represented only by a thin pebble bed. Farther west still, the unit again thickens but is not accompanied by volcanic rocks.

Basic and acid volcanics, equated with the Mount Harris Basalt of Forman (1966) overlie this basal sequence. They are interlayered with siltstone and sandstone at the top near the Kathleen Range. The whole sequence is probably represented by sandstone in the Dean Range, and sandstone and volcanics immediately west of the Kathleen Range. The volcanics are probably absent south and west of the Rawlinson Range. Most of the volcanics are sheared with the production of mica in the acid volcanics and chlorite in the basic volcanics. The original flow foliation in the acid volcanics has been accentuated.

The rocks south of Dean Range appear to be part of the Dean Range sequence and show increasing grade of metamorphism southward.

DOLERITES

Dolerite dykes of several ages cut all rocks below the Townsend Quartzite. They are most abundant in the Hinckley Range region and form prominent features where they cut the granulites of Mount Aloysius. Their frequency decreases south and west. None has been seen south of the Warburton Range, and therefore their relationship to the younger rocks is not known.

Thin dolerite dykes cut the rhyolites and granitic rocks of the Palgrave and Scamp cauldrons. In the Scamp Hill area the dykes have been folded along with their host rocks, but in the Palgrave cauldron the dykes are not known to be deformed.

A highly metamorphosed dolerite dyke which has been altered to a pyroxene granulite cuts the charnockitic rocks south of Michael Hills. The dyke is probably related to a pre-Tollu Group period of dyke injection.

Intrusive into the Mission Group, between the Frank Scott Formation and the Lilian Formation, is a porphyritic dolerite sill approximately 1,800 feet (550 m) thick.

GRANITIC ROCKS

BLACKSTONE REGION SOUTH OF THE COBB DEPRESSION

Several categories of acid intrusive rocks are present in this area and for convenience are tabulated below:

1. pre-Tollu Group granitic rocks
2. post-Tollu Group granite
3. granitic rocks in cauldron subsidences
4. granophyric differentiates of the Giles Complex.

Apart from the post-Tollu Group granite all have been described elsewhere in their appropriate section and need not be commented on further.

POST-TOLLU GROUP GRANITE

Small exposures of a granitic rock intrude the Tollu Group volcanics at Barnard Rocks. They are among the youngest, if not the youngest, granites in the whole region.

The rock is a potassic granite consisting of quartz and microcline microperthite with very rare plagioclase. Mafic minerals include biotite and a trace of a deep blue-green amphibole. Accessories include zircon, opaques and epidote.

GILES AREA

Granitic rocks in the Giles area in the northeast corner of the Scott Sheet area may be subdivided into three groups:

1. ovoid granite
2. Giles porphyry
3. granite younger than the main unconformity in the Giles region.

OVOID GRANITE

This is apparently the oldest rock in the Giles area and is unconformably overlain by sandstones and conglomerates forming the base to the sequence of mixed acid and basic volcanics in the Kathleen Range.

The granite consists of large ovoids of potash feldspar in a matrix of biotite granite. Chlorite may also accompany the biotite. It is the granite referred to as pyterlite by Horwitz and Daniels (1967).

GILES PORPHYRY

This rock type intrudes the basal sandstone of Kathleen Range and probably also intrudes the overlying mixed volcanic sequence as a series of interdigitating sills.

The rock is a coarsely porphyritic quartz-feldspar porphyry and is characterized by an abundance of rounded quartz phenocrysts.

GRANITE YOUNGER THAN THE MAIN UNCONFORMITY

Exposures of this rock type are very limited. It intrudes the unconformity below the sediments and volcanics of the Kathleen Range. Rafts of the sandstones and basalts occur in the granite.

The rock is an equigranular fine-grained red granite locally with fist-sized ovoid or euhedral potassium feldspar phenocrysts. Biotite-rich clots are often noticeable. The peripheral zone is rich in aplite veins which extend into the sediments and volcanic rocks. Where this granite intrudes the ovoid granite a marginal migmatite is present.

PROTEROZOIC GLACIAL ROCKS

Overlying the Townsend Quartzite, probably disconformably, is a very poorly exposed series of glacial deposits. The deposits are apparently unconformably overlain by the Table Hill Volcanics and are thought to be Upper Proterozoic in age, though no direct age determinations have been made.

The deposits consist of moderately well bedded conglomerate, maroon and chocolate coloured shale and sandstone, and porcelanite. The clasts in the deposits near Hocking Range are mostly of quartzite, and are sometimes faceted. Occasional pebbles of a distinctive dark green, silicified oolite are noted. The latter rock type has been found in thin layers in the southern exposures of the Townsend Quartzite on the Livesay Range and the outcrops west of this locality.

Thirty miles (48 km) southwest of Skirmish Hill the unit consists predominantly of conglomerate and sandstone. The sandstone is dark chocolate brown and carries moderately abundant pebbles. The conglomerate is similarly coloured and, in contrast to the locality near Hocking Range, carries a variety of clasts including mauve and white sandstone, quartzite, "porphyry", granophyre and hematite breccia.

Bedding dips are steep and range up to 70 degrees in exposures southwest of Hocking Range. The steep dips enable bedding traces to be seen on the air-photographs and serve to distinguish this deposit from the almost horizontal Permian glacials.

The deposits are thought to be of glacial-fluvioglacial origin.

CHAPTER 6

The Phanerozoic Rocks

Little attention has been paid to the Phanerozoic rocks of the Blackstone Region, though they are widely distributed throughout the whole area. Good outcrops are rare. Only broad subdivisions have been attempted.

POSSIBLE ORDOVICIAN

TABLE HILL VOLCANICS AND POSSIBLE CORRELATIVES

Basic volcanics are present in two areas on the southern side of the Townsend Quartzite. The largest area of outcrop occurs at Table Hill, in the Talbot Sheet area; it forms an oval of approximately 25 square miles (65 km^2). The volcanics dip at a low angle to the south. They are younger than, and apparently unconformable on, the Upper Proterozoic glacial deposits to the north, and are unconformably overlain by Permian deposits.

Small inliers of basic volcanics also occur in the Cooper Sheet area approximately 35 miles (55 km) southwest of Skirmish Hill. These deposits are reddish-brown, deeply weathered, slightly porphyritic basalts overlying brown sandstone. They are overlain, apparently disconformably, by younger Phanerozoic sediments.

The Table Hill rocks consist of reddish, maroon, and blue-green tholeiitic basalts with a well developed pumice agglomerate horizon.

An incomplete section in the Table Hill area is given below:

Top *Feet*	*Unit*	*Description*
100+	5	basalt showing reddish weathering features
50	4	agglomerate of pumice fragments
5	3	green tuff
50	2	blue-green basalt
50+	1	basalt, badly weathered
		base not seen
		Note: 1 foot = 0.3048 metres.

The basalts are composed of "an intermeshing network of plagioclase and pyroxene crystals with rare phenocrysts of plagioclase" (Peers, 1969). The plagioclase is generally labradorite zoned to andesine, and the pyroxenes are augite, pigeonite and orthopyroxene. A detailed petrography of these rocks and a discussion on their age is given by Peers (1969). They are correlated with the Kulyong Volcanics in the Birksgate Sheet area in South Australia. The latter have been dated as Ordovician by K/Ar isotopic age determination methods (Major and Teluk, 1967).

Regional geological considerations suggest that the Table Hill volcanics are part of a suite of basic volcanics of closely similar age developed, perhaps intermittently, on the southern side of the Musgrave Block. This suite includes the Officer Volcanics located in a drillhole in the northeast corner of the Yowalga Sheet area (Jackson, 1966), the Table Hill volcanics, some unnamed basic volcanics in the south central part of the Cooper Sheet area and the Kulyong Volcanics in South Australia.

If this correlation is correct, then the Officer Basin, lying to the south of the Musgrave Block, contains an appreciable Phanerozoic section.

PERMIAN

Rocks of probable Permian age crop out in poor exposures over large parts of the southern half of the Cooper Sheet area, the south and southwest of the Talbot Sheet area and the west and northwest of the Bentley Sheet area. In the Scott Sheet area the Cobb Depression is probably occupied by Permian rocks. Large tracts of the Permian are covered by a lateritic capping and sand dunes.

Remnants of Permian as outliers on the Proterozoic rocks of the Bentley Sheet area suggest a previous more widespread cover of Permian.

The age of most of these rocks is uncertain. If it is accepted that much of the lithology can be interpreted as glacial or fluvioglacial then a Permian age is suggested. However, a Lower Cretaceous (Aptian) age is suggested by Cockbain for a lamellibranch found in a very fine-grained sandstone from Todd Range (Cockbain, 1967).

Dips on the Permian rocks are of the order of a few degrees, except near faults and in probable small diapiric structures, where high dips have been measured.

A maximum of 123 feet (37.5 m) of stratigraphic section has been seen in outcrop, but a minimum thickness for the Permian of 400 feet (122 m) is indicated by borehole data from the Cobb Depression. No maximum thickness can be estimated.

Basically the Permian sequence consists of sandstone and porcelanous siltstone with claystone, pebble beds and conglomerate. Gradations between the rock types are common. The sandstones are coarse to very fine-grained, somewhat kaolinitic, porous and carry occasional clay pellet horizons. Cross-bedding is common as are desiccation cracks, gypsum mounds and Liesegang structures. Occasional dropstones have been seen. In the fine-grained sandstones and siltstones convolute bedding is frequently apparent. Much of the finer grained material is bioturbated.

A shallow water origin for much of the sequence is suggested by the desiccation cracks, gypsum casts, conglomerates and bioturbation. A glacial-fluvioglacial succession is also suggested by the presence of dropstones, shale flake horizons and some overturned cross-sets. Boulder beds in the southwest of the Talbot Sheet area contain abundant striated boulders. Several measured sections have been given in the Explanatory Notes of the Bentley Sheet area (Daniels, 1969b).

TERTIARY

LATERITE AND LATERITIC GRAVEL

Deposits of laterite and lateritic gravel are very extensive in the Bentley, Talbot and Cooper Sheet areas. Except for the northern part of the Cooper Sheet area the deposits have developed almost entirely on Permian rocks.

The deposits consist of pisolitic limonite or ironstone gravel which overlie a deeply weathered mottled zone. Good exposures may be seen along the north-south line of breakaways approximately 20 miles (32 km) east of Baker Lake. Elsewhere in the western part of the area the deposit generally mantles a mature topography and forms gently undulating country. The crests of the low relief undulations are being actively eroded by small, non-perennial streams which have exposed numerous small areas of generally deeply weathered Permian.

South of Wingelinna, east of Cavenagh Range and near Jameson Range, laterites occur as long sinuous bodies. They represent remnants of laterite-filled stream courses.

The lateritic ochre occurrence northeast of Wingelinna is a special case. It probably has been produced by the very deep weathering of a folded, interbedded, basic and ultrabasic part of the Hinckley Range Gabbro.

CALCRETE

The rock type referred to here as calcrete consists of a white-weathering, pale brown, calcareous deposit formed by the evaporation of water. The deposit usually partly fills old drainage channels, and is an aquifer by virtue of the presence in it of abundant small cavities and larger potholes. Calcareous loams are frequently to be found on the sides of the calcrete bodies. Associated with the calcrete is a variable development of opaline silica. The maximum thickness of the calcrete is unknown, but a range of from 50 to 100 feet (15 to 30 m) is suggested.

A significant percentage of the total area of the Blackstone Region is occupied by calcrete, though in turn, it is itself partly covered by sheet and dune sand. Because of this cover, the continuity and regional distribution of the calcrete bodies is not immediately obvious. However, because of the water potential of the larger calcrete bodies their regional distribution should be appreciated.

Superficial linear features are often seen on the calcrete, on examination of the air-photographs. These features consist of a series of parallel lines or less commonly as meandering, sometimes coalescing lines (Fig. 76). They appear to be the remains of an old drainage pattern and are indicated as such on the map. On this assumption, the linear features have been plotted from the air-photographs

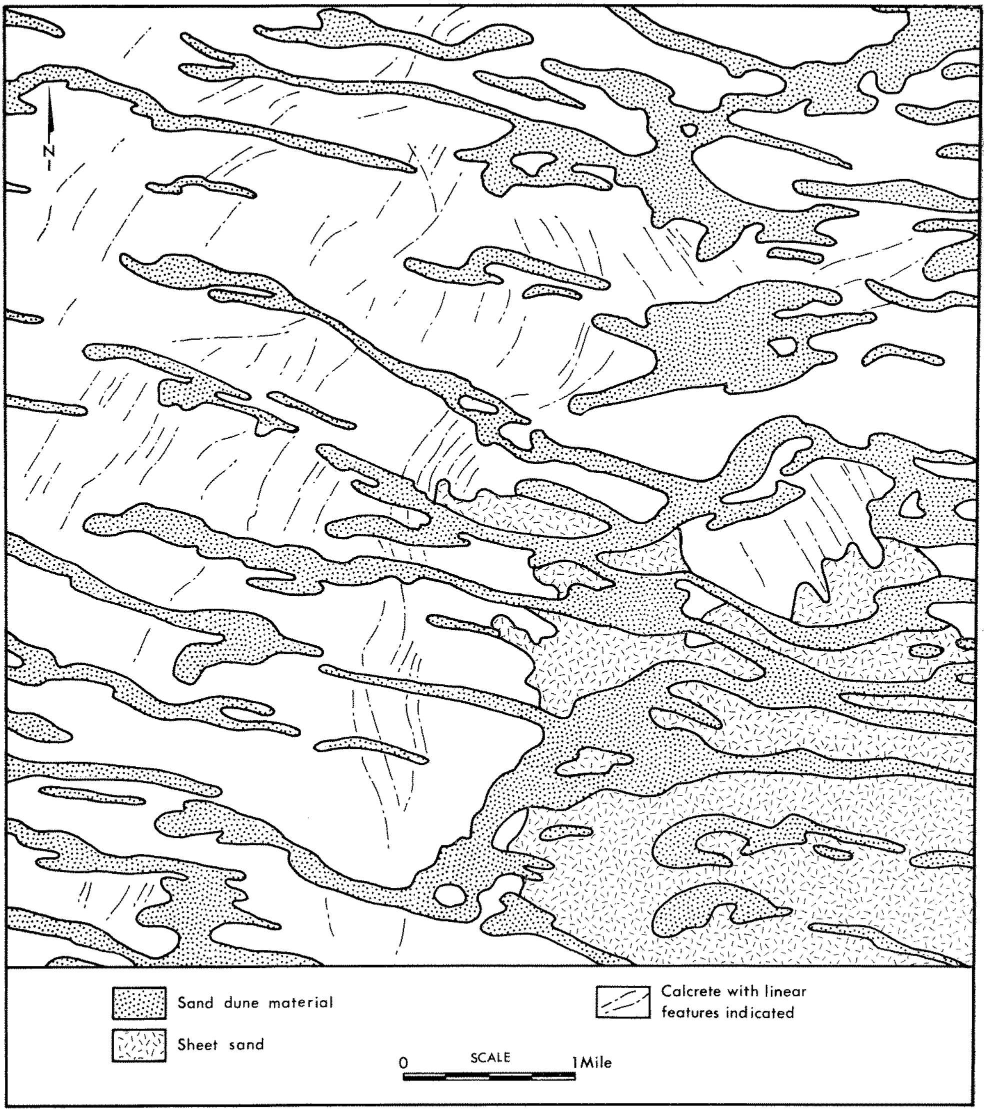

Figure 76. Map of portion of southeast Cooper 1:250,000 Sheet area showing discordance between sand ridge system and linear features in underlying calcrete body (Photo 5452 Cooper Run 15).

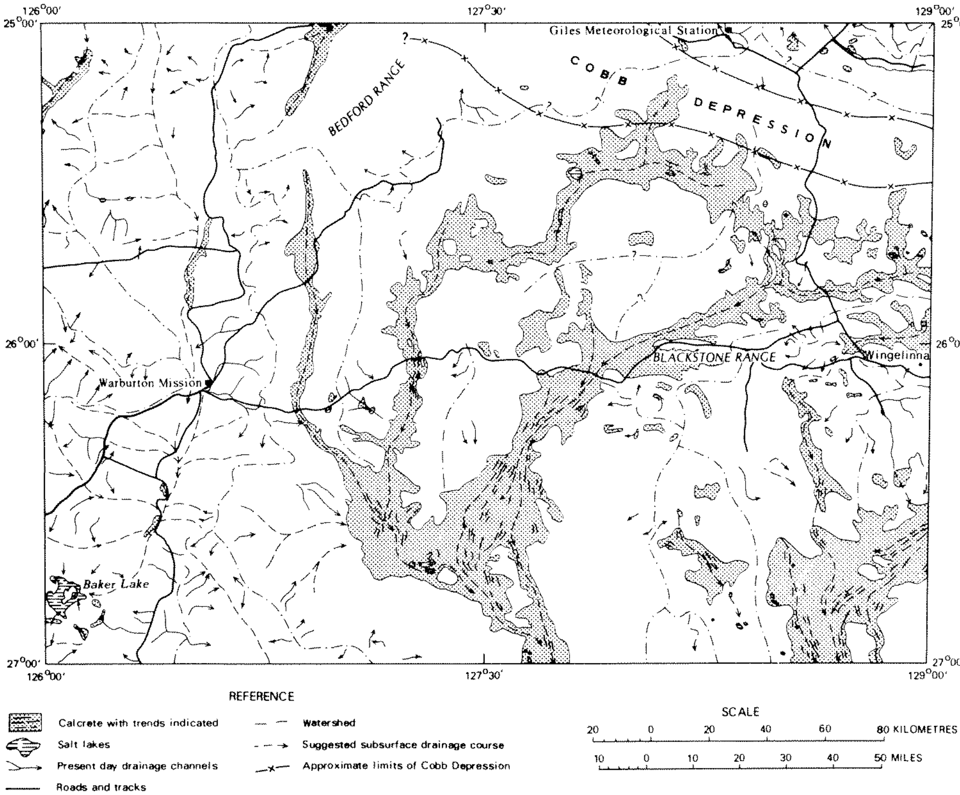

Figure 77. Distribution of calcrete in Blackstone Region.

and used to indicate not only the continuity or otherwise of disconnected outcrops but also the main locations of the drainage channels occupied by the calcrete. The resultant map showing the distribution of these calcrete bodies is shown in Figure 77. The overall distribution is simple and records an ancient drainage system, draining southward towards the Eucla Basin. Smaller areas on the northern margin of the area drain northward.

The Cobb Depression, occupied by a Phanerozoic succession of unknown thickness, lies towards the northern limit of this south-draining calcrete system in the Scott Sheet area. This sedimentary basin extends into the Bentley Sheet area north of Bedford Range and is a potentially important groundwater source (Farbridge, 1967). A little to the south of the estimated southern edge of the Cobb Depression is an extensive sheet of calcrete which could possibly be supplied with water overflowing from the southern margin of the sedimentary basin.

The calcrete bodies are probably multi-layer aquifer systems, a deduction based on their extended period of development in time. They could be important aquifers and in any hydrological investigation it would be necessary to test several levels, each of which could be separated by hard opaline silica bands.

QUATERNARY

COLLUVIUM, ALLUVIUM AND DRY LAKES

Poorly sorted and poorly consolidated deposits of silty sand form large area between monadnocks. The deposits frequently form the base on which the sand dunes rest and together with the Permian are probably the major source for the dune material.

A little of the colluvium has been redeposited as fine sand and gravel along the few river courses in the area. These river channels are confined to the hilly regions and do not persist for any great distance away from the hills. Consequently the alluvium has a very restricted distribution.

The few lakes in the region are all dry except for short periods after the heavier rain storms. All are confined to the low lying areas occupied by the large calcrete bodies (Fig. 77).

The largest of the lakes, Baker Lake, is approximately 50 square miles (125 km^2) in extent. Its bed is covered with a thin, white deposit of granular gypsum which overlies a sticky, brown, gypsiferous mud. Sand dunes adjacent to the lake carry gypsum crystals.

The Van Der Linden Lakes on the northern margin of the Bentley Sheet area are also gypsiferous.

SAND RIDGES

GENERAL CHARACTERISTICS

Much of the Blackstone Region is covered by extensive areas of sand ridges. They may develop on a variety of other surfaces including sheet sand, older colluvium, calcrete and laterite. The simplified distribution of these dune fields is shown in Plate 1.

Apart from minor present day activity along the crests of some of the dunes, most of these ridges are fixed by a thin vegetation cover.

Their height varies from about 10 to 60 feet (3 to 18 m) and they may be up to 15 miles (25 km) long. On the whole they are not as high, as long, nor as evenly spaced as the sand ridges of the Canning Basin (Veevers and Wells, 1961). The ridges may be simple, single lines (Fig. 78) or more complex dunes with a pronounced chain-like plan (Fig. 79) or they may form a complex network of ridges with little or no preferred orientation. In areas of relatively simple pattern the intersection of two ridges often produces a Y-shape with the closed end indicating the direction of travel of the causal wind (Figs. 78, 79 and 80).

In cross-section the sand ridges are almost invariably asymmetric with the steeper side predominantly on the left hand side of the dune looking down wind (Figs. 78 and 79). This asymmetry suggests a certain amount of lateral migration of the sand ridge. This is perhaps supported by the configuration of small sand wedges developed in the Y-shaped intersections (Figs. 78 and 79). On average, the dip direction of the steepest slope of the wedges forms an angle of some 20

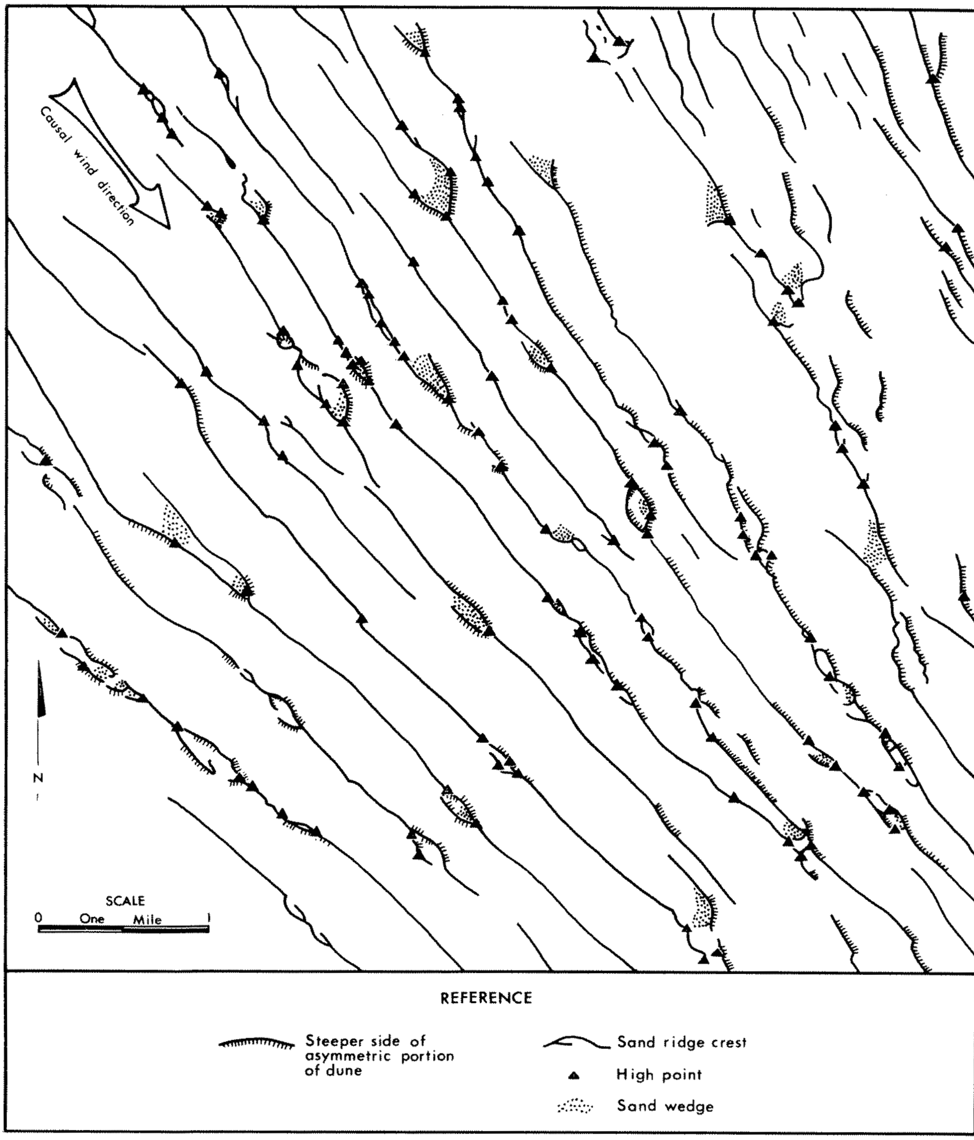

Figure 78. Sand ridge characteristics approximately 5 miles east of Skirmish Hill (Photo 5493 Cooper Run 7).

to 40 degrees to the normally accepted causal wind direction. The dip direction of the wedge, plus 180 degrees, is likely to be the direction of the wind responsible for the formation of the wedges. Also, this wind direction could be responsible for, or merely assist, in the lateral migration of the ridges leading to their present asymmetric cross-section.

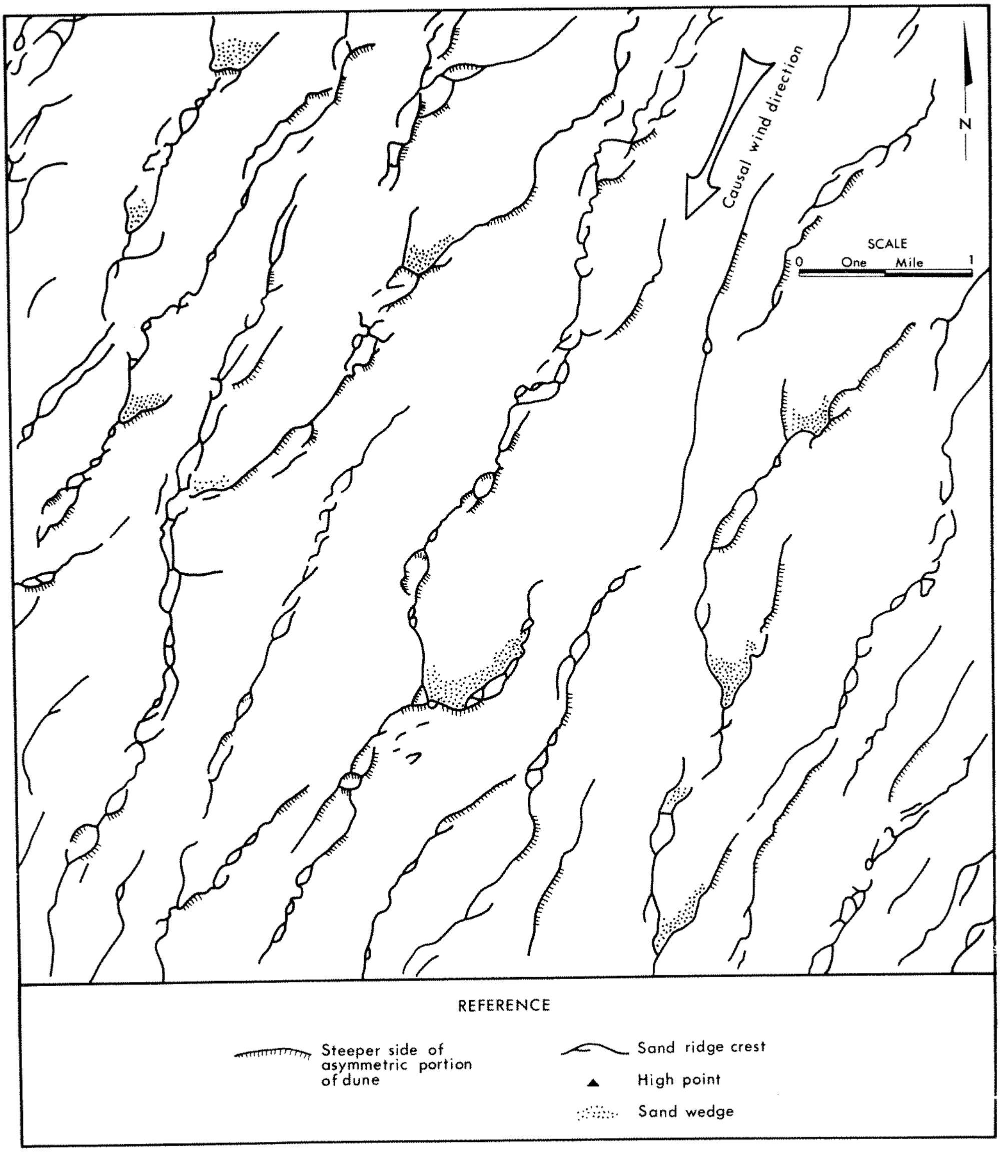

Figure 79. Sand ridge characteristics 26 miles north of Mount Fanny (Photo 5407 Scott Run 8).

REGIONAL DISTRIBUTION

A general look at the area comprising the Scott, Cooper, Bentley and Talbot 1:250,000 Sheet areas shows little in the way of any simple regional trends. Smaller areas of about 100 square miles (260 km^2) show either consistent trends or a complicated network system. The causal wind pattern in the area is given in Figure 81.

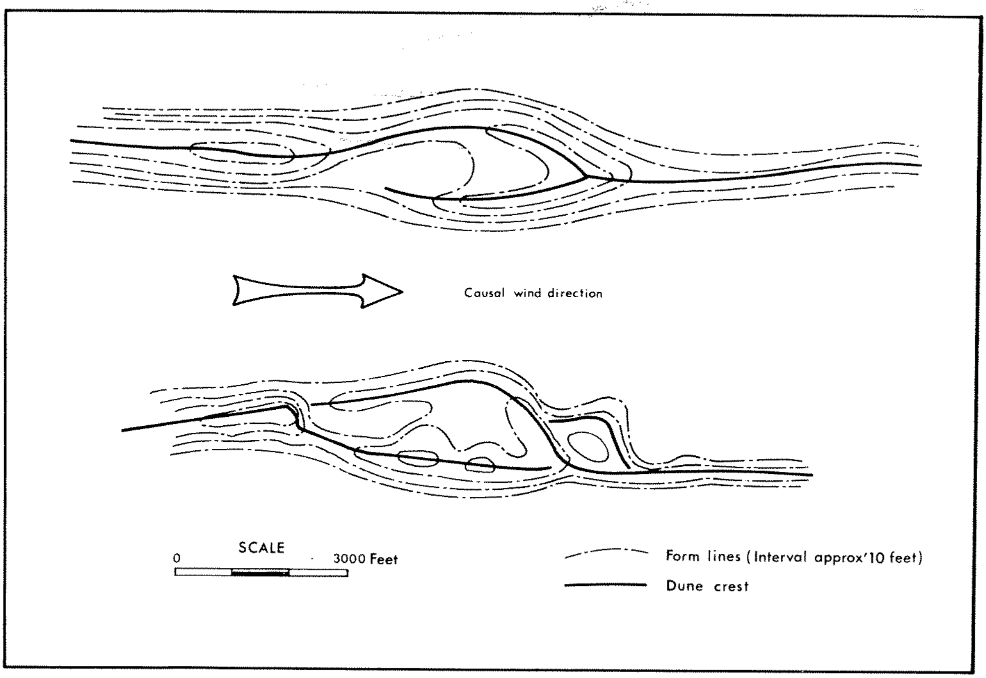

Figure 80. Examples of dune convergences.

The arrangement of sand ridges in the Blackstone Region are only part of a very much larger dune field covering a large part of central Australia. Its basic morphology has been studied by King (1960) with more detailed investigations of selected areas by Veevers and Wells (1961), Mabbutt (1968), and Mabbutt and Sullivan (1968).

King (1960) showed that in the Great Victoria Desert an easterly trend exists. This trend persists into South Australia, where it gradually swings to the north and thence into a west-northwesterly or northwesterly trend across the Gibson Desert. The two different main trends of sand ridges in the Gibson and Great Victoria Deserts are therefore related by their physical continuation through South Australia and Northern Territory.

The complex dune field pattern of the Blackstone Region straddles the 26° parallel and lies at the junction of the Gibson and Great Victoria Deserts. Daniels (1969c) interprets this complex area as having arisen in a number of ways.

(a) by the production of a number of large eddies in the contact zone of the two wind directions

(b) by modification of the causal wind direction by hills and ranges. Good examples of this may be seen on the northwest end of Bell Rock Range, around Mount Agnes and on the northern side of Mummawarrawarra Hill

(c) by slight north or south shift of the whole wind pattern apparently having allowed some dunes to have come under the influence, at different times, of winds from approximately opposing directions. This appears to have produced small areas of crossing dunes and also dunes with conflicting "Y" intersections.

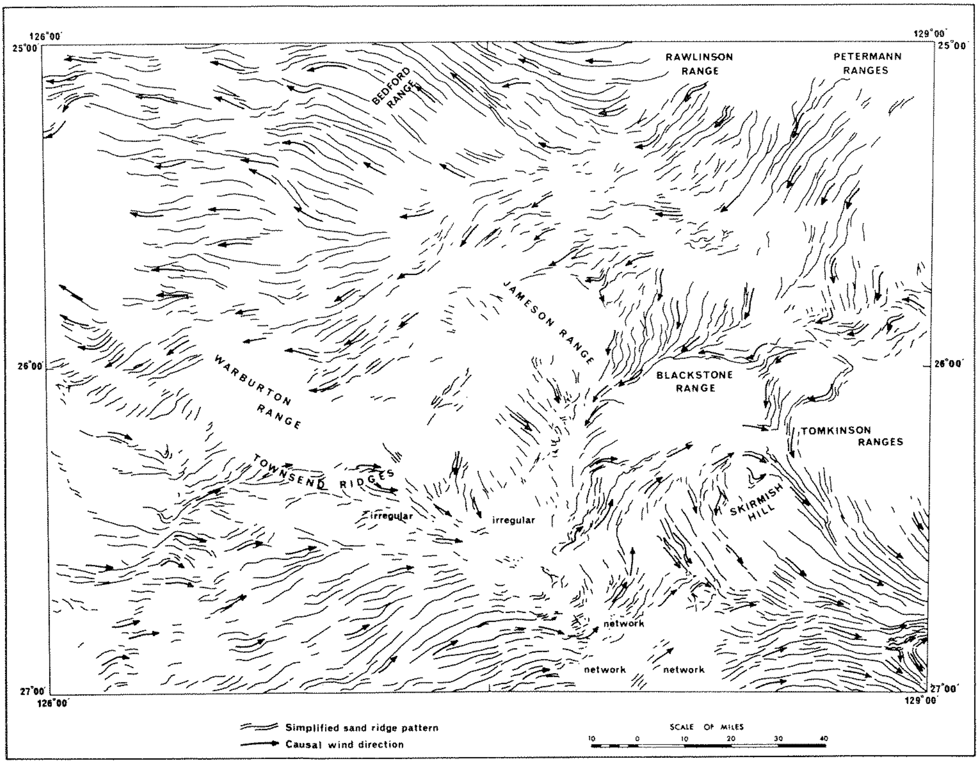

Figure 81. Dune pattern and deduced causal wind directions for the Blackstone Region.

CHAPTER 7

Structure

The simplified distribution of the main rock units and the broad regional structural elements are given in Plate 2. Some of the individual features are discussed below.

GRANULITES

North-south foliation and lineation trends are dominant in the well banded granulites of the Lightning Rocks region and represent the simplest and perhaps the oldest folding of the area. In the eastern part of the Cooper Sheet area structures in the granulites are more complex and not fully resolved. They imply a very much more complex early history in which the early structures have been considerably modified by migmatization, mylonitization, intrusion of acidic rocks, post-Tollu Group folding on west-northwest-trending axes, and possibly, in the axial region of the Michael Hills anticline, the rotation of individual blocks relative to one another.

MARGINAL SHEARING AND BLOCK ROTATION

Marginal shearing is probably a common phenomenon of the Giles Complex. Its effects have been seen in the northern part of the Michael Hills Gabbro and in three widely separated places at the base of the Bell Rock Range section. The results of this shearing would be effectively to shorten the preserved gabbro section. If the shearing progressed sufficiently along the lines described for some of the Somali gabbros (Daniels and others, 1965) then eventually the main masses would be crossed by a number of large shear zones, between which structurally intact blocks would be preserved. Further movement would rotate and perhaps displace these blocks relative to each other and their original relationships would be in doubt. This is possibly the case with the east and west portions of the gabbroic rocks in the Murray Range area. In this case the two halves are separated by a mass of marginal facies and do not resemble each other mineralogically: the western half is largely ultrabasic while the eastern half is gabbroic. The chemistry of the feldspars suggests a common origin and it is suggested that the east and west Murray Range gabbros were once part of the same mass. To apply this explanation to the whole of the complex is unnecessary.

Many of the acidic rocks between the Hinckley Range and Bell Rock Range also appear to have been broken up into small units and rotated relative to one another. During the field work it was found that consistent structural readings could be obtained from one monadnock or a group of closely spaced monadnocks, but these readings could not be reconciled with those taken from hills some distance away. Simple faulting appears insufficient to account for the differences.

The region is in the core of an anticline whose development probably started before the Giles Complex was intruded, but whose major movement was subsequent to the emplacement of the gabbroic material.

Several faults cut the area, and one large shear zone traverses the region in a west-northwesterly direction just north of Michael Hills. This shear truncates part of the Michael Hills Gabbro as well as some smaller gabbroic masses. It has acted as a line for basic magma emplacement and is also responsible for the mylonitization of both the basic material to the south of it and the acid material to the north. Lineations in the mylonite zone are not consistent, but in the area north of The Bald One they can be interpreted as being caused by the rotation of one block relative to the other.

If the block rotation has been effective in this area then it would account for the major discrepancies in structural continuity between the Hinckley and Bell Rock Ranges.

PSEUDOTACHYLYTE

The mylonite zone also contains many black aphanitic, irregularly shaped bands of pseudotachylyte. In this case the pseudotachylyte appears to be an ultramylonite produced from basic material. Pseudotachylyte veins are common in the area between the northeast side of Bell Rock Range and the southern side of Hinckley Range and cut all Proterozoic rock types in that area.

Their development probably took place intermittently during the development of the Michael Hills anticline. It is suggested that most of these pseudotachylytes of the Michael Hills region are post-Giles Complex, and were produced during sudden short-lived violent movements, associated with the folding and uplift of the region from considerable depths. The production of the Anabar pseudotachylytes by response to sudden movements is also suggested by Zakrutkin (1962).

FAULTING

REGIONAL PATTERN

Because of the nature of much of the terrain, which is mostly a series of isolated monadnocks, direct evidence for faulting is often meagre. Only a few faults are directly visible in the field, many are interpreted from varied evidence and a great many more are suspected from a study of photolineaments.

The photolineaments are visible on the air-photographs as very narrow, often discontinuous lines of trees, long narrow treeless gaps, thin dark-toned bands, or linear modifications of vegetation arcs. They are visible on many of the air-photographs of colluvium-covered areas. They are rarely distinguishable in sheet sand and dune-covered areas. Large calcrete masses frequently show trends related to ancient drainage lines, but do not show the linear features described above which reflect characteristics of the underlying bedrock.

The photolineaments probably represent lines of faulting, jointing and dyke injection. Some have been traced into exposures and hence identified, but the majority are of unknown origin. The photolineaments have been studied in detail in three areas and the results given in Figures 82, 83, and 84. They each show a simple consistent pattern of northwest, northeast, north and east trends which

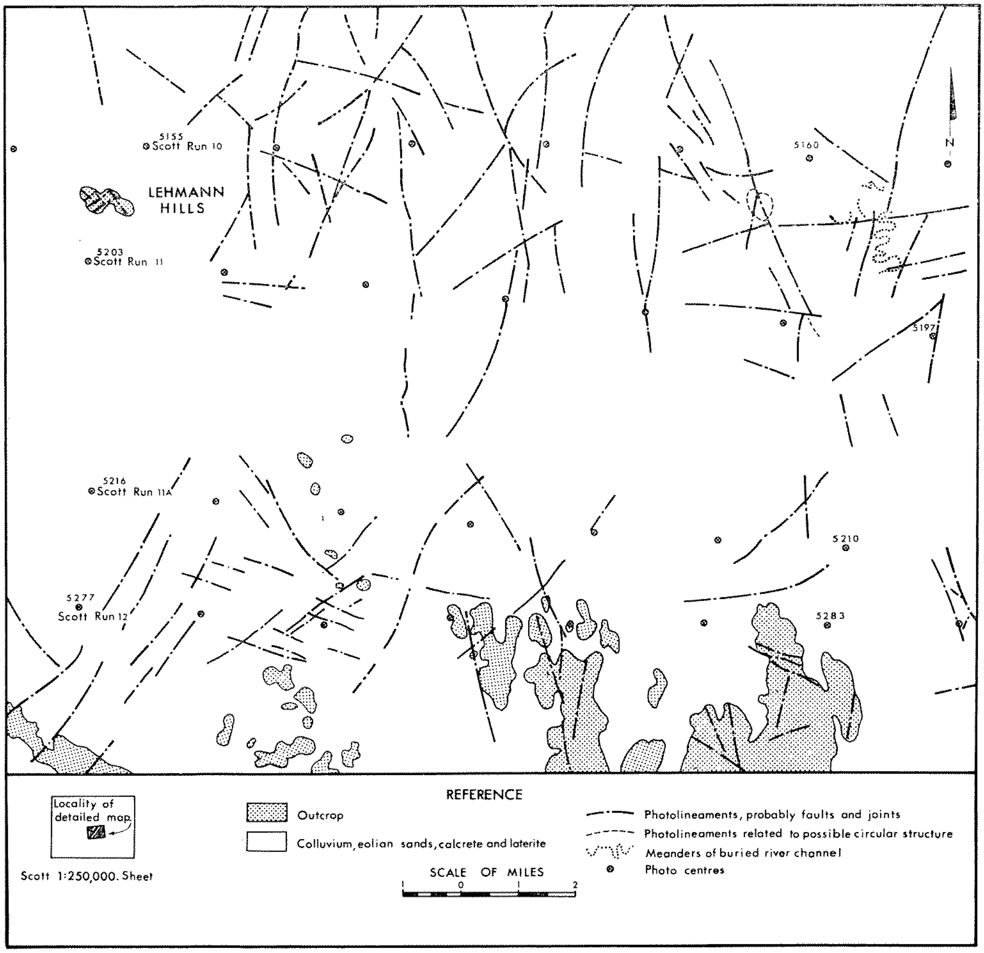

Figure 82. Interpreted fault and joint pattern in the Lehmann Hills area.

is most likely to be interpreted as the fault and joint system of the whole region. The system is probably related to the post-Giles Complex group of broad open west-northwest-trending folds crossing the whole area. More details of local fault and joint patterns are given for the Michael Hills region in Figure 42.

One of the largest of the probable faults shown on the tectonic sketch map (Plate 2) has been called the Giles Discontinuity (Horwitz and others, 1967). It was postulated to account for the lack of correspondence in the structural layering interpretation in the two areas on either side of the proposed line. Along much of its length the line is occupied by an extensive calcrete sheet with a similar northeasterly trend. To the southwest the line is not obvious and is probably overlain by the Townsend Quartzite, which in this area is apparently thinner than

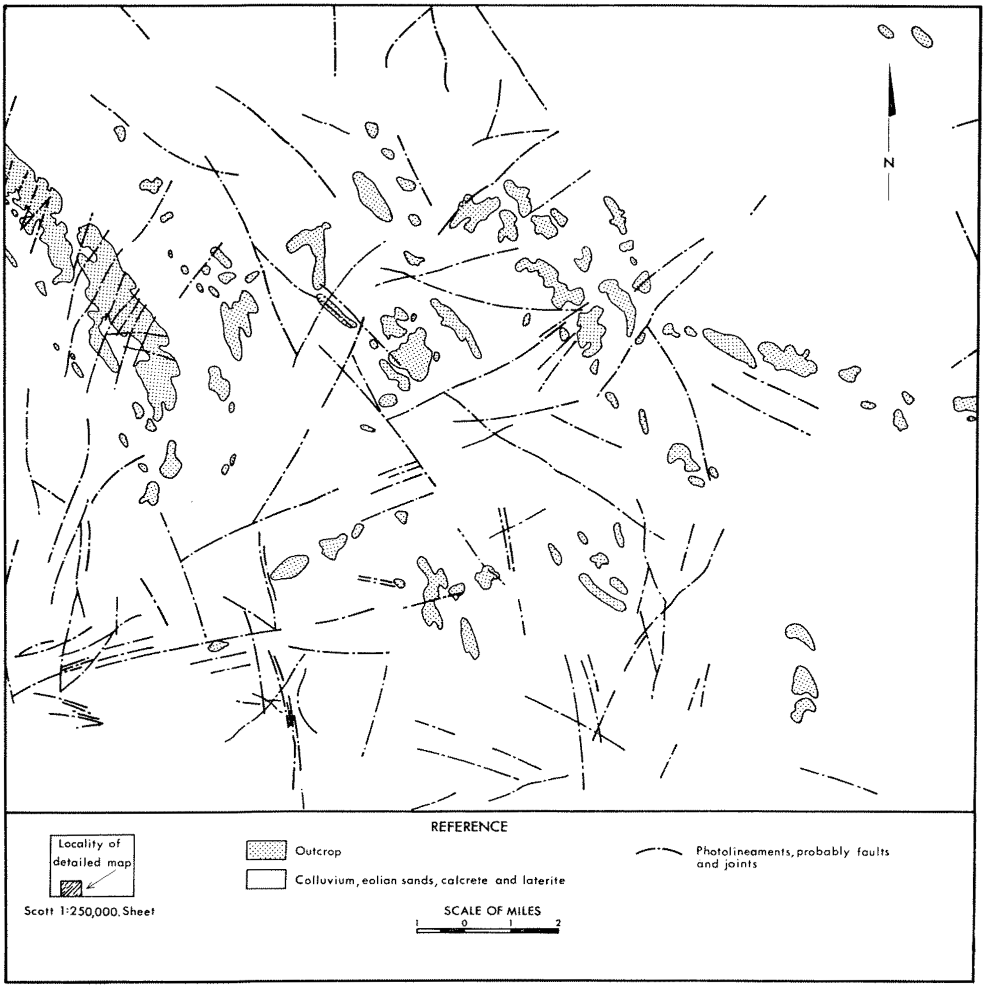

Figure 83. Interpreted fault and joint pattern in the Mount Finlayson Region.

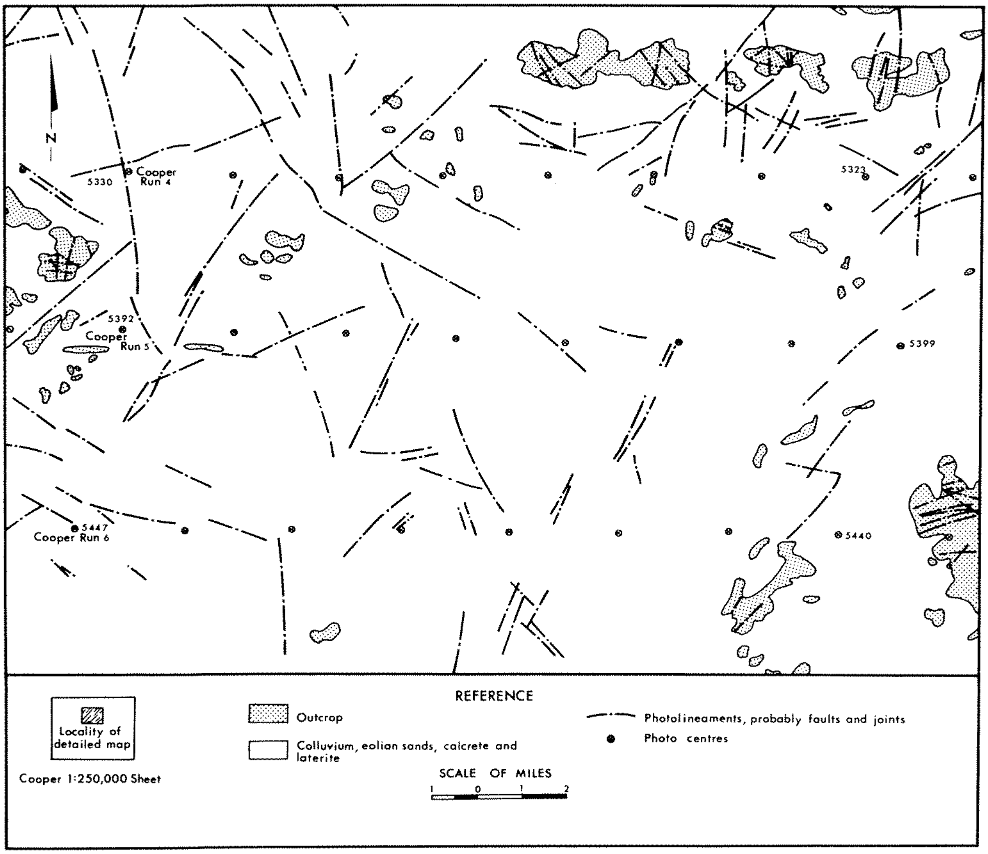

Figure 84. Interpreted fault and joint pattern in the Tollu Region.

elsewhere along its strike. Near Mount Blyth the MacDougall Formation attains its maximum thickness, and it is tempting to relate this thickening, and the Townsend Quartzite feature, to activity along the line of the Giles Discontinuity. To the northeast the suggested line of the Giles Discontinuity passes under the Cobb Depression and may join a fault bounding the northwest side of the Dean Range.

RING FAULTS

Ring faults appear to bound all three of the cauldron subsidence areas (Fig. 27 and Plate 2). The exact position of the fault lines is in doubt in some places. Structurally these cauldrons appear to have developed towards the southern boundary of the Musgrave Block on distinct gravity ridges, which were defined by Lonsdale and Flavelle (1963) and called the Warri and Blackstone gravity ridges. The position of the Palgrave cauldron on the Blackstone gravity ridge is marked by a

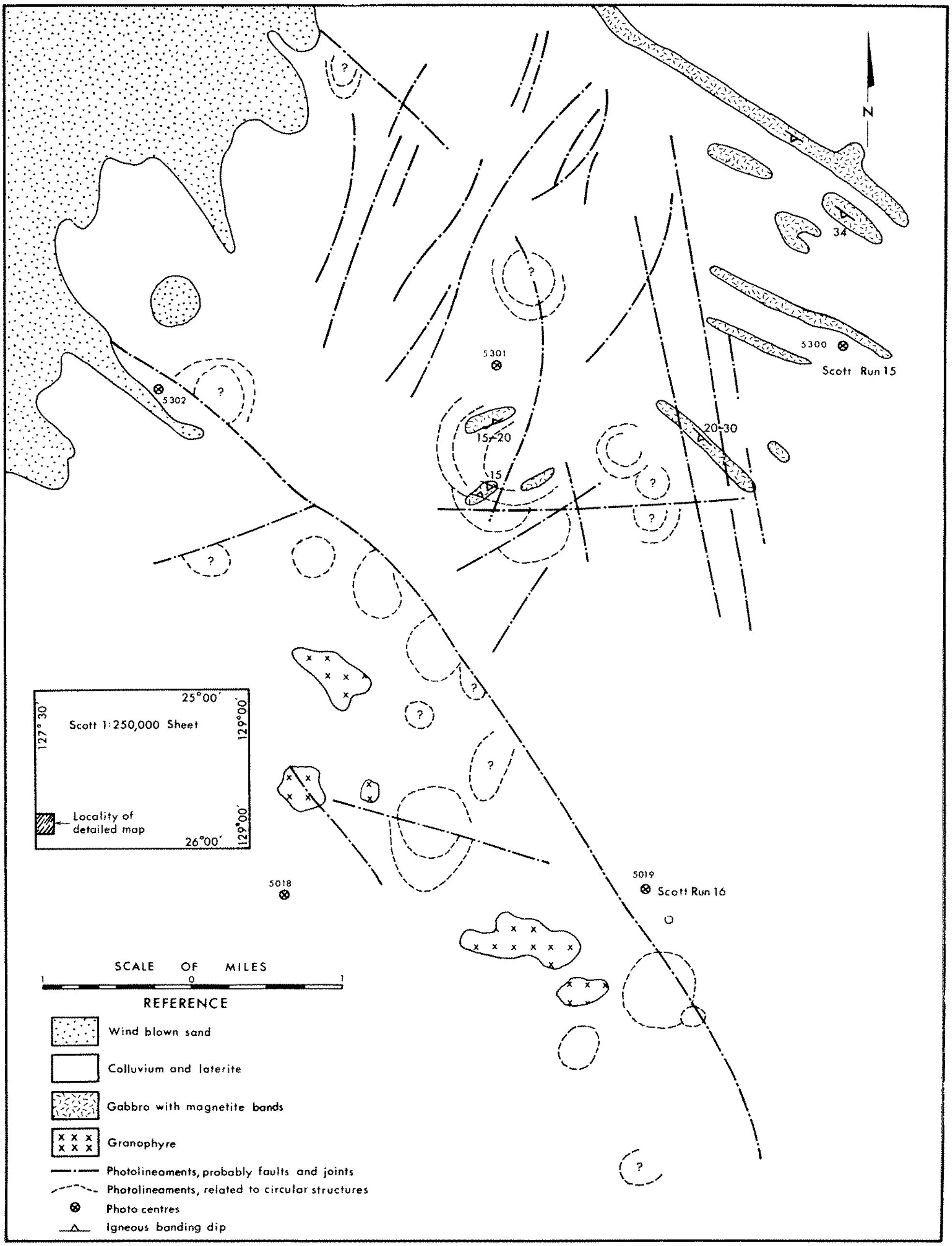

Figure 85. Circular structures southwest of Jameson Range.

local gravity-high of approximately 60 mgals. Lonsdale and Flavelle interpret the high as the result of a large buried mass of basic material. Small exposures of gabbro are seen in the Palgrave cauldron, and could represent the uppermost parts of a much larger basic mass.

No gravity data are available for most of the Cooper Sheet area, and hence the location of the Skirmish Hill cauldron relative to gravity features is not known. However, the gravity ridge extends across the northern part of the Sheet area.

SMALL CIRCULAR STRUCTURES

Several small circular structures have been identified on the air-photographs. In most cases they consist of vague concentric, thin rings of trees or trend lines. With the exception of one case they have not been related to any geology. They are closely associated with faults or inferred faults.

The main group of these circular structures occurs on the southwest side of Jameson Range and straddles the northeastern portion of the ring fault bordering the Palgrave cauldron. A diagram showing their distribution in relation to various known geological features in the area is given in Figure 85. In one case, on the gabbro side of the fault, titaniferous magnetite bands are exposed on the northwest side of the ring. The ring, inside the titaniferous magnetite exposures, has a diameter of approximately 2,300 feet (700 m). The dip of the exposed rock is to the northwest and is noticeably different from the southwesterly regional dip of the banding in the Jameson Range Gabbro. No exposures are present in the centre of the structure and the nature of the disturbance is unknown. Many possibilities exist as to their nature and possible economic importance. The possibility that they are carbonatites cannot be ruled out, but they most likely represent the surface expression of unexposed satellite intrusions related to the Palgrave cauldron. Another example is located 11 miles (18 km) east of the Lehmann Hills. It appears to have been faulted and the halves displaced slightly. Its position is indicated on Figure 82.

TILTING OF THE CASSIDY AND MISSION GROUPS

The Cassidy and Mission Groups overlie the Pussy Cat Group unconformably or disconformably near Mount Clarke, but apparently the relationship is a conformable one south of Whitby Range. The Cassidy and Mission Groups have not been folded in the same manner as the underlying group and they dip consistently south and southwest at moderate angles of 20 to 50 degrees.

FORM OF THE TOWNSEND QUARTZITE OUTCROP

The Townsend Quartzite overlies the Mission Group apparently conformably in the west and unconformably in the east. Its present line of outcrop suggests that it has been subjected to some form of folding which is not impressed on the underlying Mission Group. The implication is that a décollement exists at the base of the Townsend Quartzite and that the overlying beds have been folded independently of the Mission Group. Strong faulting with some possible overturning exists immediately east of Hocking Range and is probably related to the production of the décollement.

If this explanation of the Townsend Quartzite outcrop shape is correct then the apparent unconformity may be partly depositional and partly a tectonic feature.

STRUCTURE OF THE OFFICER BASIN

Little attention has been paid to the Phanerozoic rocks of the region.

Geophysical data of Hunt Oil Company suggest that the Officer Basin, lying to the south of the Musgrave Block is a relatively simple, deep, infilled basin with a northwesterly-trending axis. It extends to the southeast into South Australia. To the northwest it passes into the Canning Basin. The Officer Basin contains diapiric structures, part of one of which is present as a concealed structure in the northwest corner of the Talbot Sheet area. Small circular structures, possibly of diapiric origin are present at the surface approximately 22 miles (35 km) southeast of Table Hill. The rocks affected are glacial deposits probably of Permian age.

CHAPTER 8

Geological History

The oldest known rocks in the Blackstone Region are the granulites and related gneisses which make up a significant portion of the outcrop of the Musgrave Block. The original rocks, now represented by the gneisses, may also include equivalents of some of the rocks exposed in the northeast corner of the Scott Sheet area.

No age determinations are available to date the metamorphics in the Western Australian part of the Musgrave Block. An age of 1,390 ± 130 million years has been obtained from granulites farther east near Ernabella Mission in South Australia (Compston and Arriens, 1968). Because of the complex history of these metamorphic rocks in the Blackstone region and the significant events which have affected these rocks after their main metamorphism, it would be wise not to extend this age to cover the geologically similar rocks in Western Australia.

The sequence of events undergone by the granulites and related rocks in the Blackstone region may have begun with the unconformable deposition of dominantly arenaceous sediments on an acid igneous rock "basement" of unknown age or metamorphic state. This "basement" is now exposed in the core of the Michael Hills anticline structurally below the Michael Hills Gabbro. It is also seen in the area a few miles north of Mount Gosse, and near Mount Holt. The whole sequence was intruded by some acid igneous bands in the Mount Aloysius region and elevated to the high pressure-temperature conditions of the granulite facies. During this period shearing stresses were active, with the consequent development of flaser structure on a regional scale.

Subsequently, while shearing stresses declined and pressure-temperature conditions probably remained high, minor granitic veins were intruded near Michael Hills.

This was followed by another period of shearing which was confined to the eastern part of the region and whose main effect was the production by mylonitization, again apparently on a regional scale, of granular quartz and feldspar without the complete destruction of the older flaser structure.

After the regional mylonitization had ceased, an adamellitic charnockite was emplaced in the area immediately south of Latitude Hill. The minerals in this charnockite show no preferred orientation or mylonitization and indicate high pressure-temperature conditions with no shearing component.

In the Lightning Rocks area flaser structure is present in the granulites, but the regional mylonitization had no effect. At some time after the development of the flaser structure abundant cordierite developed. This may have taken place at the end of development of the flaser structure or at any subsequent time before the emplacement of the next youngest rocks in the area, the adamellite of Lightning Rocks.

After the granulite grade metamorphism, migmatization of some of the products took place and granitic rocks were emplaced in the Lightning Rocks and Borrows Hill regions. Probably at about this same time, copious amounts of adamellite were intruded into the granulites in the northeast part of the Bentley Sheet area, which was then uplifted, eroded and subsequently overlain unconformably by arenaceous sediments. The assemblage was then subjected to a period of isoclinal and recumbent folding associated with regional metamorphism. This downgraded the granulites and converted most of the adamellite to gneiss, while the sediments were changed to quartzite and quartz-muscovite schist. These events do not seem to be recorded in the rest of the area under discussion south of the Cobb Depression. Whether or not they are represented in the Rawlinson Range area depends on whether the recumbently folded sediments of the Rawlinson Range can be correlated with the recumbently folded sediments of the Bedford Range.

The next important event was the unconformable deposition of the dominantly acid and basic volcanic succession of the Tollu Group in the Tollu area about 1,060 ± 140 m.y. ago. At the same time the equivalent in the Warburton Range region, the Pussy Cat Group, was formed from a series of dominantly basaltic eruptions associated with minor acid volcanicity of an ignimbritic nature. In the Warburton Range region the volcanics were accompanied by variable amounts of clastic sediments and, rarely, dolomites were developed. These rocks were subsequently subjected to moderate folding, and in the Mount Clarke area this was accompanied by low-grade regional metamorphism.

This was followed by the intrusion of the Giles Complex, as a series of pulses rather than as a single episode. The four main masses making up much of the West Australian part of the Giles Complex were emplaced at three principal structural horizons, and the controls for the intrusions were probably planes of weakness at the contacts of different major rock units.

Folding along west-northwest axes came next and produced the broad anticlines and synclines which are the most obvious features of the region.

A period of cauldron formation is thought to have occurred next, but some evidence suggests that the formation of one of the cauldrons and the intrusion of at least some of the Giles Complex probably overlapped.

Three cauldrons, named the Scamp, Palgrave and Skirmish Hill cauldrons, developed during this period on the southern edge of the Musgrave Block and, in the case of the first two named, development took place on a gravity ridge. Scamp cauldron in the west is older than the Palgrave cauldron; the relative age of the Skirmish Hill cauldron is not known. Each cauldron shows an early development of acid volcanics followed by a younger intrusive phase of granitic material. Minor basic igneous activity is present in all three, and in the case of the best known example, the Palgrave cauldron, this took place immediately after the volcanic episode.

The Cassidy Group, which apparently developed after the period of cauldron subsidence, is the product of a regular alternation of acid and basic outpourings with only a minor development of sedimentary material. The acid volcanics formed as extensive thick sheets whose possible source lies approximately 30 miles (48 km) north of Warburton Mission under a thin Phanerozoic cover. The deposition of the Mission Group took place conformably after that of the Cassidy Group except in one small area where minor local uplift is postulated. The group is characterized by basic volcanics and the sporadic development of coarse and fine clastic sediments, possibly the result of contemporaneous uplift to the northeast of Frank Scott Hill. Shallow water conditions prevailed for part of the time, and allowed the development of algal structures in a dolomitic horizon. During much of this time most of the Blackstone Region was probably land.

The Townsend Quartzite was deposited, apparently conformably, above the Mission Group in the west, but unconformably above several units including the crystalline "basement" in the east. Its lower part was deposited in shoreline or nearshore conditions, while a deeper environment is postulated for the upper part of the unit.

Probably during the Upper Proterozoic the region entered a glacial period and glacial and fluvioglacial deposits were laid down disconformably above the Townsend Quartzite.

Tilting and minor folding subsequently affected the area, with the rocks above the base of the Townsend Quartzite reacting differently from those below. It is possible that a décollement was produced at the base of the Townsend Quartzite, and that this break served to exaggerate the angular discordance between the Townsend Quartzite and the underlying rocks in the area between Lilian Creek and Hocking Range.

The impression of the Precambrian is one of continued and varied activity with the Musgrave Block being uplifted and eroded. The uplift, whose maximum movement took place along a west-northwest-trending belt crossing the centre of the region, was intermittent, areally irregular, and at times possibly locally violent. It was accompanied by the intrusion of large amounts of basaltic magma and the extrusion of copious basic and acid volcanics. Some of the acid volcanics are ignimbritic, possibly as a result of relief of pressure during sudden uplift. Much of the acid volcanic material developed in cauldron subsidence areas on the southern margin of the Musgrave Block and may well be contemporaneous with the emplacement of the Giles Complex.

The intermittent and irregular nature of the movement of the Musgrave Block was more intense in the eastern part of the Blackstone Region. This accounts for the fragmentally preserved record of the Bentley Supergroup in that eastern area, as compared with the more complete succession in the Warburton Mission region, which underwent less violent activity.

The Phanerozoic history of the area is not known in detail.

To the south of a line drawn between the Townsend Ridges and Skirmish Hill, Phanerozoic rocks were laid down unconformably over Upper Proterozoic glacials in the Officer Basin. These Phanerozoic sediments extend to the north of Warburton Mission, unconformably overlie the crystalline "basement" and occupy much of the western half of the Bentley Sheet area. They also occupy the area known as the Cobb Depression.

The oldest exposed representatives in the Officer Basin are the Table Hill Volcanics, which are part of an extensive basaltic eruption which probably took place in Ordovician times. Slight folding followed and glacial and fluvioglacial deposits of Permian age were unconformably deposited on the Table Hill Volcanics and older rocks to the north.

In the Tertiary, extensive lateritization took place, possibly accompanied by the development of large calcrete sheets in broad river valleys. Later an extensive dune field developed over most of the area.

At the present time the dunes are fixed by sparse vegetation, and only minor erosion is in progress in the hillier regions.

Minor faulting is known to have affected the Phanerozoic sediments, and the earthquake recorded by Giles in 1873 suggests that the area is still seismically active.

CHAPTER 9

Economic Geology

INTRODUCTION

The Blackstone Region contains one deposit of nickel, several prospects for vanadium and copper, some minor mineral occurrences, and several areas on which various ideas regarding possible mineralization should be tested.

Initial mineral exploitation of this remote region of Australia demands the presence of large ore bodies of good grade, soluble metallurgical problems, and favourable world metal prices. With that combination, development may start if adequate power and water supplies can be found. The power may be obtained from the hydrocarbon reserves already known in the Amadeus Basin, Northern Territory, or perhaps even the Officer and Canning Basins in Western Australia. Water appears to present few difficulties. Adequate supplies should be obtainable from the Cobb Depression, the major calcrete bodies and the Amadeus Basin.

At present the development of the Wingelinna nickeliferous ochre seems possible, and this should stimulate and assist the further exploration of the region. At the moment, the next most important prospect in the area, the vanadium prospect in the Jameson Range region, can only be regarded as a major Australian occurrence of that metal.

NICKEL, COBALT AND CHROMIUM

Low density, nickeliferous, yellow-brown ochre is found in the Wingelinna area and has been intensely studied by Southwestern Mining Company Limited. They have stated reserves of 60 million tons (61 million tonnes) of 1.32 per cent Ni with another 40 million tons (41 million tonnes) inferred. Minor cobalt is present in the deposit, which also has associated with it minor chromite and chrysoprase. The latter is a medium to dark apple green; some specimens rapidly fade on exposure to light and become milky and opaque. The deposit is being worked at present as a source of gem stones.

The ochre is essentially goethite with minor manganese oxide and kaolin veinlets, and some ilmenite. Minor concentrations of gibbsite are also known.

The exact nature of the ochre deposit is open to some doubt, but it appears to have developed as a deep weathering product of ultrabasic rocks, though some exposures of partly altered material suggest that the original rocks were folded, interbanded basic and ultrabasic rocks and not solely ultrabasic. They were probably developed near the base of the Hinckley Range Gabbro as part of the layered sequence of that sheet and not as a separate intrusion emplaced along a shear zone. It appears to have been moderately folded and as it is near the margin of the gabbroic mass would have been susceptible to shearing during the post-Giles Complex folding. The folding and shearing would allow easy access of surface water and account for the great depth of weathering. No other similar geological situations are known in the intrusion and hence the likelihood of finding other large deposits is not good.

No published work is available giving detailed profiles or suggesting an origin for the Wingelinna deposit. However, in South Australia, and on the border of South Australia and Northern Territory, similar, though considerably smaller deposits have been investigated by the South Australia Mines Department. The origin of one of these deposits near Claude Hills in the Northern Territory has been suggested by Miller (1966) and his explanation would probably apply to the Wingelinna deposits also. He states that "Under conditions of high seasonal rainfall, and probably, although not essentially, a tropical to sub-tropical climate, silica and magnesium are leached from ultrabasic rocks or their serpentinized equivalents. The iron is left as goethite, and the nickel which in the original rock averages approximately 0.2 per cent, is concentrated several fold, both by residual and supergene enrichment".

Thomson (1963, 1965) has also reported on some details of the nickeliferous laterites a few miles to the east of Wingelinna in South Australia. He shows that they are confined between 2,380 and 2,730 feet (725 and 832 m) above sea level and are possibly related to an old erosion level.

Holes were drilled to depths of 500 feet (152 m) in the Wingelinna ochre and the water level was commonly cut between 60 feet and 160 feet (18 and 48 m). Water levels rose a little in the bores after the water bearing horizon was cut, indicating the existence of small hydraulic heads in the aquifer. The water table is usually much depressed in thick zones of the ochre, which may imply a connection between the origin of the ore body and the configuration of the water table.

The complexities concerning the Ni distribution in the similar ochres from Claude Hills and Mount Davies, a few miles to the east of Wingelinna in South Australia, are discussed in detail by Turner (1968).

VANADIUM

Vanadiferous titaniferous magnetite bands occur in the Jameson Range Gabbro and the Blackstone Range Gabbro as sheets or lenses conformable with the igneous banding. This is in contrast to the magnetite occurrences in the Giles Complex in South Australia. There the magnetite occurs as very small pod-like bodies in shear zones and carries negligible vanadium.

In the Blackstone Range Gabbro the magnetite bands occur as rare thin lenses up to 1 foot (30.4 cm) thick near the base of the intrusion on the northern

TABLE 34. PARTIAL ANALYSES OF TITANIFEROUS MAGNETITES FROM BELL ROCK RANGE

	523A	523B	523C
SiO_2	1·69	1·55	1·31
Al_2O_3	4·02	3·51	5·41
Fe_2O_3	55·4	62·6	62·4
FeO	15·7	10·1	14·8
TiO_2	18·7	17·4	12·3
Cr_2O_3	0·06	0·07	0·08
S	0·01	0·03	0·03
P_2O_5	0·07	0·06	0·04
MnO	0·23	0·25	0·29
MgO	1·57	0·80	0·71
NiO	0·13	0·13	0·1[illegible]
CaO	tr	tr	0·02
V_2O_5	1·04	1·25	1·11
	98·62	97·7	98·60

Analysis: Government Chemical Laboratories

side of Bell Rock Range. Three samples have been analyzed (Table 34), but are of no economic significance on account of their very small size.

Of very much more interest are the occurrences in the Jameson Range Gabbro. This intrusion is subdivided into four zones; the magnetite bands are confined to Zones 2 and 4, with their best development being in the region of the Jameson Range itself. To the east of the range the zonal scheme of the gabbro has been disrupted by block faulting. This has destroyed the continuity of the zones and in combination with the generally very poor exposure in the area makes for difficult mapping.

In most of the bands two components can be recognized in the field. One is a shiny mineral with a metallic lustre tentatively identified as ilmenite, and the other is a dark reddish-brown, dull mineral thought to be an alteration product of magnetite. Much of the ilmenite is elongated parallel to the igneous banding in the host rocks and can be used to measure dips of the titaniferous magnetite bands. In some of the samples small quantities of leucocratic minerals and rare copper staining are present.

ZONE 2, NORTHEAST OF JAMESON RANGE

Zone 2, to the northeast of Jameson Range, consists of mafic and ultramafic rocks about 1,000 feet (300 m) thick. The zone is very poorly exposed and is covered by an extensive laterite sheet approximately 8 miles (13 km) long.

The mafic and ultramafic rocks are well banded; the banding being defined by variations in the opaque mineral content. The main rock type is medium

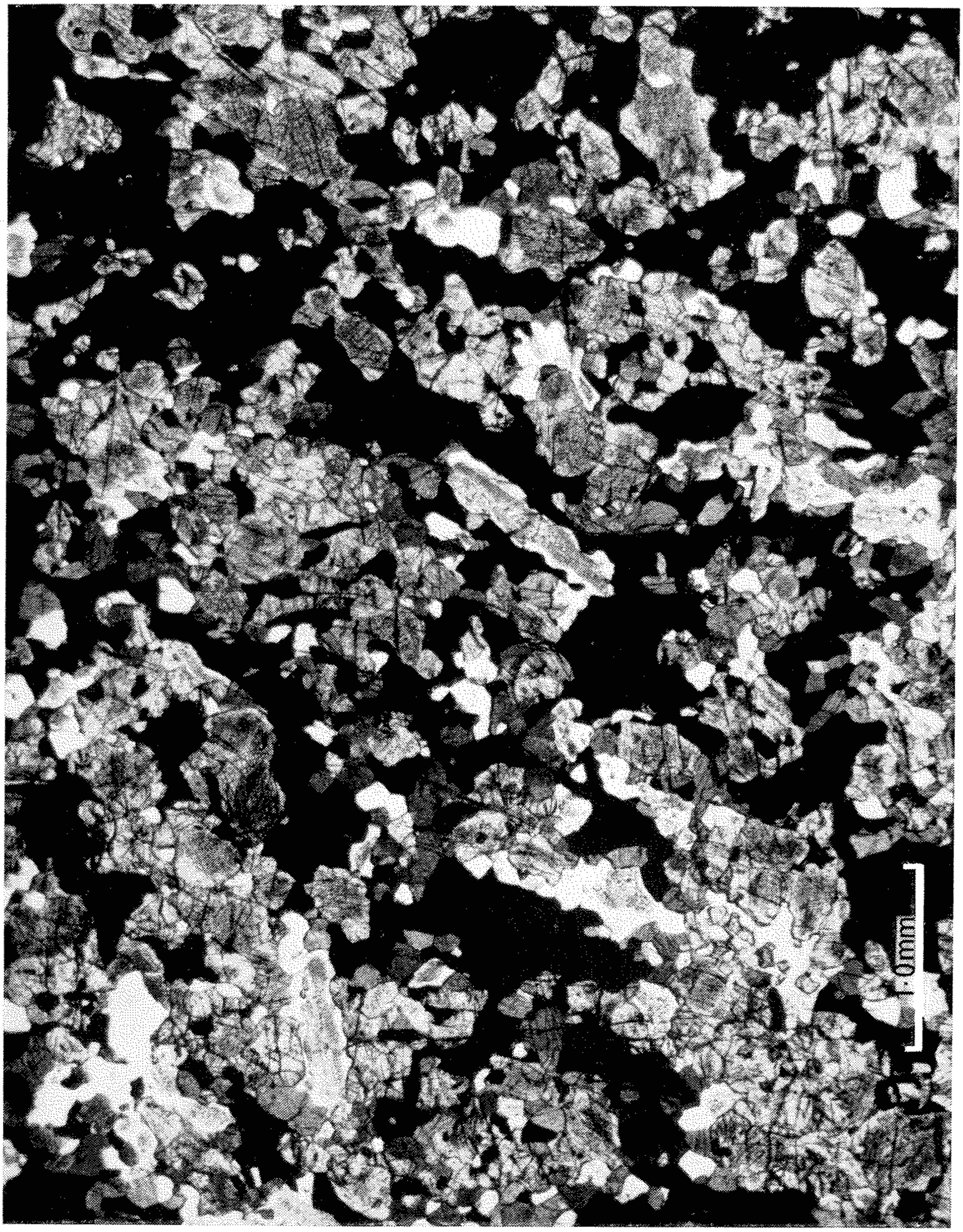

Figure 86. Photomicrograph of ultramafic rock from Zone 2 Jameson Range Gabbro. Rock consists of titaniferous magnetite, anorthite, olivine, kaersutite, orthopyroxene and clinopyroxene. Ord. light.

TABLE 35. ANALYSES OF TITANIFEROUS MAGNETITE FROM ZONES 2 AND 4 JAMESON RANGE GABBRO

	1236	1237	1255A	1255B	1261	1262	1266A	1266B	1266C	10976/1	10976/2	10978/1	10978/2	10978/3	10979/1	10979/2
SiO_2	1·33	3·62	1·82	1·04	1·70	1·36	1·63	1·75	1·58	1·49	2·90	2·43	1·96	2·02	2·30	1·61
Al_2O_3	4·06	4·47	4·95	5·13	4·53	2·39	2·35	2·45	2·69	3·77	4·57	5·74	4·74	4·84	4·42	2·46
FeO	10·8	12·6	11·3	12·3	6·75	8·06	11·0	7·68	6·80	9·83	7·40	4·53	5·38	6·64	20·43	6·15
Fe_2O_3	56·9	54·7	51·3	59·1	67·3	63·0	62·5	65·3	65·5	55·55	51·89	58·66	59·91	59·29	42·01	62·27
CaO	0·04	0·04	0·07	0·04	0·22	0·04	0·09	0·12	0·18	*	*	*	*	*	*	*
MgO	2·28	3·49	1·78	1·81	0·78	1·43	1·09	0·93	0·88	1·78	1·65	2·20	1·92	1·87	3·01	1·17
TiO_2	21·0	17·2	26·2	18·2	15·9	20·9	18·9	19·6	19·5	24·40	27·19	22·94	22·20	21·92	24·44	22·80
MnO	0·31	0·28	0·24	0·28	0·21	0·07	0·08	0·11	0·10	0·28	0·11	0·24	0·24	0·30	0·31	0·19
P_2O_5	0·03	0·04	0·04	0·04	0·08	0·11	0·24	0·11	0·10	0·03	0·03	0·03	0·02	0·02	0·01	0·03
Cr_2O_3	0·38	0·63	0·03	0·18	0·14	0·29	0·25	0·28	0·28	0·12	0·05	0·11	0·16	0·10	0·05	0·16
V_2O_5	1·40	1·11	1·18	1·33	0·75	0·71	0·77	0·81	0·76	1·29	1·14	1·28	1·18	1·18	1·07	1·14
S	0·02	0·03	0·05	0·03	0·03	0·02	0·06	0·02	0·09	0·04	0·14	0·03	0·03	0·06	0·04	0·06
NiO	0·15	0·10	0·04	0·08	0·02	0·05	0·05	0·05	0·04	0·06	0·03	0·07	0·08	0·08	0·08	0·04
H_2O^+	*	*	*	*	*	*	*	*	*	1·46	2·56	1·90	2·05	1·90	1·60	1·81
H_2O^-	*	*	*	*	*	*	*	*	*	0·15	0·40	0·23	0·16	0·21	0·19	0·32
	98·70	98·31	99·00	99·56	98·41	98·43	99·01	99·21	98·50	100·25	100·06	100·39	100·03	100·43	99·96	100·21

Analyst: R. S. Pepper 10976/1; 10978/2; 10979/1; 10979/2
J. R. Gamble 10976/2; 10978/1; 10978/2
1236, 1237. Zone 2 northeast of Jameson Range.
Remainder of specimens are from Zone 4, southwest of Jameson Range.
* Not determined.

grained and granular, and consists of varying proportions of opaque minerals, kaersutite, olivine, clinopyroxene, orthopyroxene and anorthite (Fig. 86). Modal analyses of three samples are given in Table 9. Some titaniferous magnetite float is found in the same area and probably indicates that these ultrabasic rocks are interbanded with thin titaniferous magnetite layers. Apart from the latter the opaques constitute 20 to 50 per cent of the ultrabasic rocks.

The V_2O_5 contents of the three analyzed specimens from Zone 2 (Table 10) range from 0.57 to 0.76 per cent with an average content of 0.68 per cent. Of this amount approximately 0.05 per cent is locked up in kaersutite, suggesting that 0.63 per cent is accountable for in the opaques on the assumption that negligible V_2O_5 will enter the lattices of the other minerals. In sample 1245B, which carries the lowest V_2O_5 content and only a moderate percentage of opaques a rough calculation shows that an analysis of the opaques themselves would contain 1.4 per cent V_2O_5.

Near Turkey Hill, Zone 2 has been almost certainly identified and contains more solid magnetite bands than near Jameson Range. Two samples from this locality gave V_2O_5 contents of 1.40 and 1.11 per cent. Full analyses are given in Table 35 (Nos. 1236 and 1237).

Farther southeast, near Mount Finlayson, ultrabasic rocks are apparently absent and the zone consists of gabbro with interbanded titaniferous magnetite bands. Exposures are poor and no estimate can be given of thicknesses.

Two partial analyses of laterites covering Zone 2 northeast of Jameson Range are given in Table 36. They are surprisingly low in V_2O_5.

TABLE 36. PARTIAL ANALYSES OF LATERITES DEVELOPED IN ZONE 2, JAMESON RANGE GABBRO

	1264	1265
Fe_2O_3	63·2	61·4
FeO	1·1	2·79
NiO	0·02	0·01
V_2O_5	0·46	0·39

Analysis: Government Chemical Laboratories

ZONE 4, SOUTHWEST OF JAMESON RANGE

On the southwest side of Jameson Range, Zone 4 is poorly exposed as a number of short parallel ridges and low rubbly outcrops. The zone consists of various types of troctolite, gabbro, anorthosite and several titaniferous magnetite bands. In general the titaniferous magnetite bands increase in abundance and thickness up the sequence.

On the southwest flanks of the Jameson Range the base of Zone 4 is marked by a titaniferous magnetite band which can be traced almost continuously for the length of the range, a distance of approximately 12 miles (19 km). The band's thickness varies somewhat and no average figures are available. One section near the southeast end of the range showed the band to be 15 feet (4.6 m) thick but in some places it approaches 50 feet (15.2 m) in thickness. To the northwest an echelon arrangement of titaniferous magnetite bands is apparent and suggests a progressive stepping up of the lowest band into higher stratigraphic positions.

Several analyses from this band are given in Table 35 (1255A, B; 10976/1, 10976/2, 10978/1, 2, 3; 10979/1, 2). The series 10978/1, 2, 3 represent samples from the bottom, middle and top of the band.

The V_2O_5 content of the lowest band in Zone 4, southwest of the Jameson Range, therefore ranges from 1.07 to 1.33 per cent and averages 1.20 per cent. It appears to be slightly richer towards its base. The TiO_2 content is moderately constant, ranging from 18.2 to 27.19 per cent with an average of 23.4 per cent.

Higher up the sequence there are several titaniferous magnetite layers. The exact number is not known on account of the poor exposure. The uppermost bands have been traced intermittently from near Domeyer Hill in the Bentley Sheet area southeast for a distance of approximately 23 miles (37 km). The thicknesses vary considerably, from a few feet to possibly over 200 feet (61 m) in short sections. Five analyses from three different bands are available (Table 35 Nos. 1261, 1262, 1266A, B, C). Their V_2O_5 content ranges from 0.71 to 0.81 per cent with a mean of 0.79 per cent or just over half of the tenor of the lowest titaniferous magnetite band in Zone 4.

In comparison with the lowest band in this zone the uppermost units show several differences in their chemistry. The higher units are lower in V_2O_5, TiO_2, Al_2O_3 and MnO and higher in Fe_2O_3, Cr_2O_3 and P_2O_5.

The higher P_2O_5 content probably reflects the uppermost band's later stage in the differentiation of the magma. The lower V_2O_5 can also be explained in the same way, vanadium being preferentially extracted from the magma by the earliest formed magnetite, leaving later liquids successively depleted in this component. On a smaller scale this preferential extraction is seen to have occurred in the lowest titaniferous magnetite band in Zone 4. The lowest part of this band, representing the earliest formed crystals, are the richest in vanadium.

SOUTHEAST JAMESON RANGE REGION

Approximately half-way between Mount Elliott and the southeast corner of the Jameson Range, in the block faulted area, is a series of low outcrops. They consist of gabbroic rocks interbanded with several thin titaniferous magnetite horizons. The latter are usually between 1 and 10 feet (30.4 cm and 3m) thick with 5 feet (1.5 m) being a probable mean value. Locally they thicken, and short lengths up to 50 feet (15.2 m) thick are present. Associated with these bands are anorthositic rocks and olivine-rich rocks, some of which carry moderate amounts of interstitial opaque minerals. The whole assemblage closely resembles that of Zone 4 to the southwest of Jameson Range but the known magnetite bands are thinner.

Six analyses of samples from this area are given in Table 37 (Nos. 10974/6, 10, 12, 14, 15; 10975/2). The V_2O_5 content ranges from 1.05 to 1.29 per cent with a mean value of 1.18 per cent. The TiO_2 content shows a mean of 19.86 per cent with a range from 18.52 to 21.03 per cent. Of the other oxides the Fe_2O_3 content varies quite widely, between 38.33 and 61.86 per cent; P_2O_5 is low and Cr_2O_3 is noticeably higher than in any of the other areas.

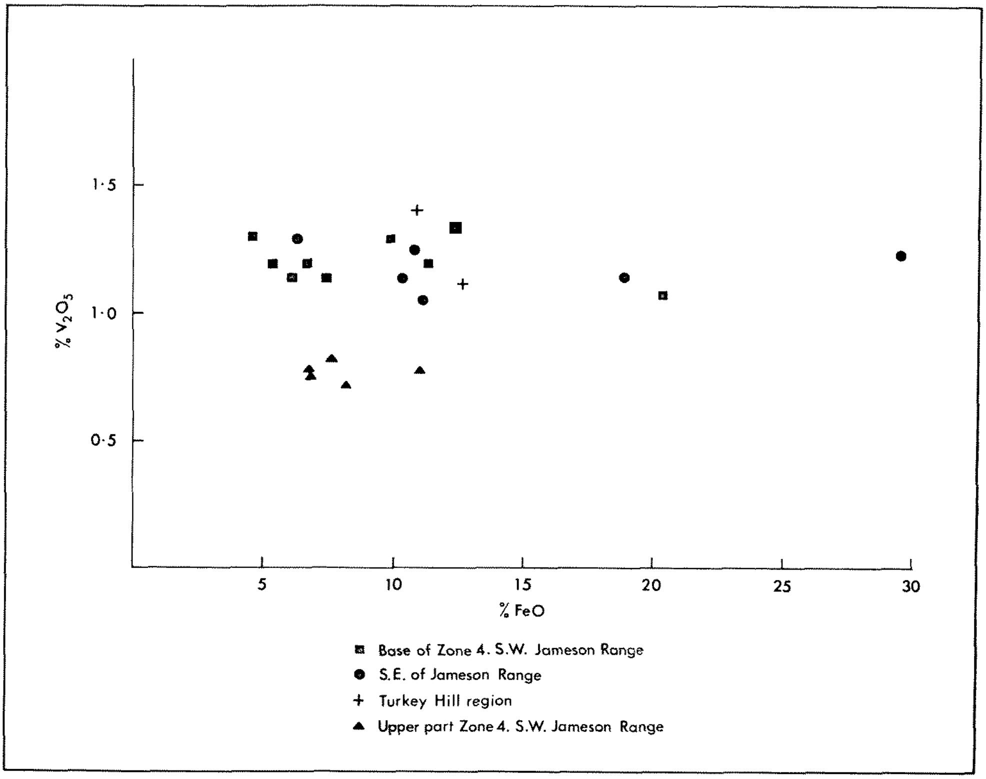

Figure 87. Plot of V_2O_5 against FeO for titaniferous magnetites from the Jameson Range Gabbro.

The relation of V_2O_5 to FeO for all the analyzed titaniferous magnetite rocks from the Jameson Range Gabbro is shown in Figure 87. Two distinct fields are apparent. The low V_2O_5 field is confined to the upper part of Zone 4. The other field, with higher V_2O_5 includes titaniferous magnetites from all the other areas.

The ratios of the molecular percentages of Fe_2O_3, FeO and TiO_2 in the titaniferous magnetites are plotted in Figure 88. Apart from the ultrabasic rocks

TABLE 37. ANALYSES OF TITANIFEROUS MAGNETITES FROM THE AREA SOUTHEAST OF JAMESON RANGE

	10974/6	10974/10	10974/12	10974/14	10974/15	10975/2
SiO_2	2·93	1·40	1·35	2·36	2·25	1·32
Al_2O_3	3·68	5·42	5·99	5·78	3·42	3·65
FeO	18·90	10·78	29·54	10·03	6·36	11·12
Fe_2O_3	48·06	56·86	38·33	56·68	61·86	58·71
MgO	2·95	1·93	2·59	1·47	0·89	2·30
TiO_2	19·17	20·78	19·62	20·03	21·03	18·52
MnO	0·31	0·20	0·29	0·26	0·26	0·21
P_2O_5	0·03	0·02	0·01	0·01	0·06	0·05
Cr_2O_3	1·13	0·38	0·41	0·37	0·46	1·04
V_2O_5	1·14	1·25	1·23	1·14	1·29	1·05
S	0·04	0·04	0·01	0·03	0·04	0·03
NiO	0·10	0·10	0·12	0·11	0·10	0·13
H_2O^+	1·80	1·20	0·77	1·93	1·74	1·83
H_2O^-	0·15	0·07	0·07	0·11	0·28	0·12
	100·39	100·43	100·33	100·31	100·04	100·08

Analysts: R. S. Pepper 10974/ 6; 10974/15; 10975/ 2
J. R. Gamble 10974/10; 10974/12; 10974/14

TABLE 38. SUMMARY OF VARIOUS OXIDES IN THE TITANIFEROUS MAGNETITES FROM VARIOUS LOCALITIES IN THE JAMESON RANGE GABBRO

	Location 1		Location 2		Location 3		Location 4	
	A	B	A	B	A	B	A	B
V_2O_5	1·11—1·40	1·25	1·05— 1·29	1·18	1·07— 1·33	1·20	0·71—0·81	0·76
TiO_2	17·2—21·0	19·1	18·52—21·03	19·86	18·20—27·19	23·37	15·9—20·9	19·0
Al_2O_3	4·06—4·47	4·26	3·42— 5·99	4·66	2·46— 5·74	4·49	2·35—4·53	2·88
Cr_2O_3	0·38—0·63	0·50	0·37— 1·13	0·63	0·03— 0·18	0·11	0·14—0·29	0·27
P_2O_5	0·03—0·04	0·03	0·01— 0·06	0·03	0·01— 0·04	0·03	0·08—0·24	0·13
NiO	0·10—0·15	0·12	0·10— 0·13	0·11	0·03— 0·08	0·06	0·02—0·05	0·04

A = range. B = mean value. All values in per cent.
Location 1 = Zone 2, northeast of Turkey Hill.
Location 2 = Area southeast of Jameson Range.
Location 3 = Base of Zone 4, southwest of Jameson Range.
Location 4 = Top of Zone 4, southwest of Jameson Range.

from Zone 2, and some of the samples from the region southeast of Jameson Range, most are highly oxidized when compared with normal titaniferous magnetite. Some of this oxidation may be immediately post-magmatic; some is probably related to surface weathering. The latter probability, and the low V_2O_5 values in the superficial laterite cover of Zone 2, suggest that under the weathering conditions which the Jameson Range region has undergone recently (in a geological sense), vanadium may be leached out of the surface rocks. This suggests that higher values may be found below the zone of weathering.

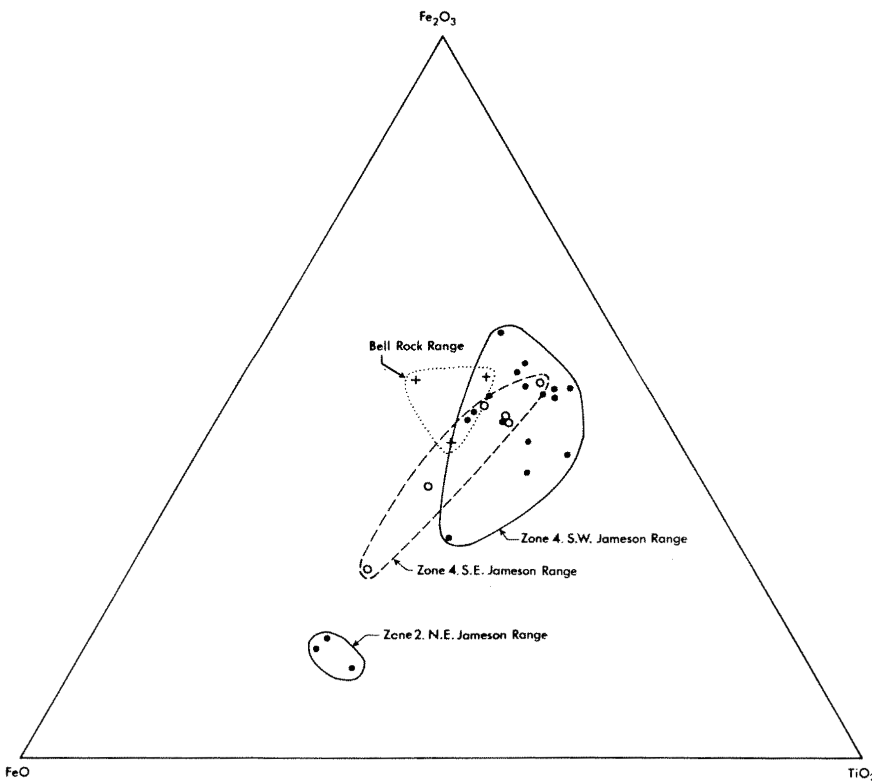

Figure 88. Ratio mol. % FeO, Fe_2O_3, TiO_2 for titianiferous magnetites from the Jameson Range and Blackstone Range Gabbros.

A summary of the ranges and average values of various oxides in the titaniferous magnetites from four localities in the Jameson Range Gabbro is given in Table 38.

A comparison of the Jameson Range results with the composition of the Main Magnetite Seam in the Bushveld Complex is useful (Willemse, 1969) and is given below:

V_2O_5	1.40- 1.66%	Cr_2O_3,	0.13-0.45%
TiO_2	12.2 -13.9%	P,	less than 0.05%
Al_2O_3	2.53- 3.5%	Ni,	0.03-0.08%

In the Bushveld Complex an antipathetic relationship exists between the V_2O_5 and TiO_2 contents (Willemse, 1969). This is not the case with the Jameson examples. Excluding the titaniferous magnetites of the uppermost part of Zone 4 in the Jameson Range Gabbro the V_2O_5 content is nearly constant for the whole range of TiO_2.

For the convenience of the reader, a table listing the main occurrences in Western Australia of vanadiferous titaniferous magnetite and related lateritic deposits together with estimated tonnages and grades is given below (Table 39). The table is taken unmodified from Jones (1965) and is itself a summary of a more comprehensive report by Heuck (1962) for Mangore Australia Pty. Ltd.

TABLE 39. RESERVES OF WESTERN AUSTRALIAN VANADIUM ORE EXCLUDING JAMESON RANGE

Locality	No. of Lenses	Type of ore	V_2O_5%	Ore reserves (short tons)
Andover	7	Massive	0·92	3,150,000 to 75 feet vertical
Balla Balla	3	Massive	0·75	2,140,000 to water level, 15 feet below plain
Gabanintha	20	Massive	1·24	4,258,000 to 100 feet below plain
		Eluvial	1·24	190,000
		Weathered Disseminated	0·54	5,000,000 approximately
Yarrabubba	11	Massive	1·3	1,958,000 to 100 feet below plain
Coates	1	Laterite	0·84	1,620,000 to 12 feet
		Weathered rock	0·61	6,620,000 for 19–92 feet depth
		Fresh rock	0·54	26,000,000 for 92–300 feet depth

Table from Jones (1965)
Note: 1 ton = 1·016 tonnes
1 foot = 0·3048 metres

PLATINUM METALS

No platinum metals are known as yet from from Giles Complex.

A number of pyroxenites from several localities have been analyzed but with negative results. An optimistic view is that this may be taken as indicating that no general dispersion of the metal has taken place and hence a concentration may be found somewhere.

The most likely places to find platinum would therefore be in the Wingelinna ochre deposits, in the abundant ultrabasic rocks of the western part of the Murray Range, in the pyroxenites of Zone 1 of the Michael Hills Gabbro, in the ultrabasic plug forming The Bald One, and in Zone 2 of the Jameson Range Gabbro. A possibility also worth consideration is that the small circular structures southwest of Jameson Range could be similar to some of the platiniferous plugs cutting the Bushveld Complex.

URANIUM AND ASSOCIATED VANADIUM

Proterozoic conglomerates occur in two main horizons. These are the MacDougall Formation at the base of the Tollu Group, and the Townsend Quartzite. The conglomerates merit investigation as possible hosts for uranium mineralization.

Vanadium could well be present also, since a nearby source for this metal exists in the Giles Complex, especially in the Jameson Range region. It is also thought that leaching of the vanadium from the titaniferous magnetites may have occurred to facilitate the availability of vanadium in secondary deposits.

The distribution of the conglomerates in the Cooper Sheet area which contains the best development of these deposits is given in Figure 89. The optimum development within this area appears to lie in the area south of Mount Blyth, but the MacDougall Formation can be traced intermittently from Mount Blyth to MacDougall Bluff for a distance of 42 miles (68 km). Generally the exposures are poor.

COPPER

Copper deposits have been recorded from the Warburton Mission area by Timoney (1961) and Low (1963).

Five main modes of occurrence of copper minerals are known in the region. These have been determined by work carried out mainly by the Western Mining Corporation. Details of the occurrences are given below:

1. in cross fractures cutting basalts and sediments. Minerals present include chalcocite, malachite, atacamite, chrysocolla, azurite and covellite. The main mineral is chalcocite intergrown with hematite. The veins range up to 2 feet (61 cm) thick, 30 feet (9 m) long and 70 feet (21 m) deep

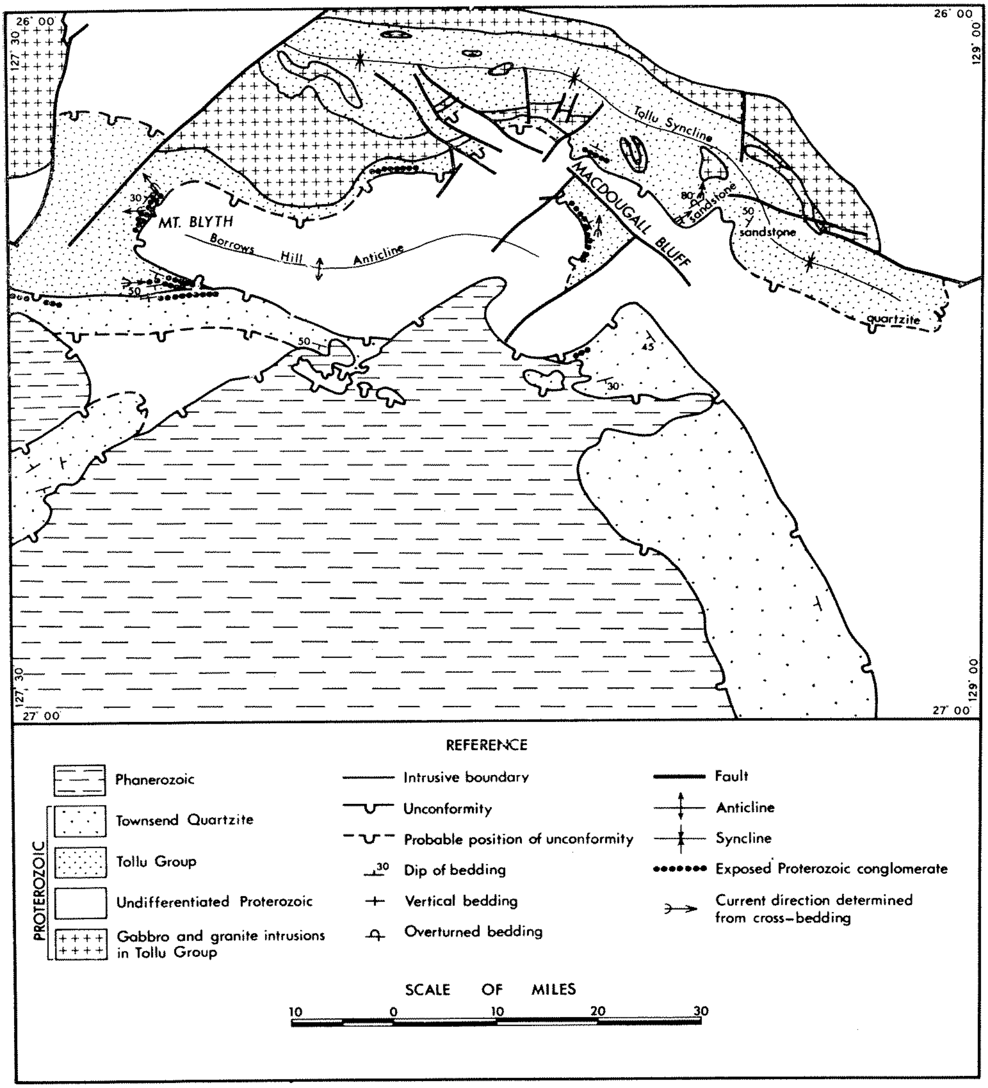

Figure 89. Sketch map of known distribution of Proterozoic conglomerates in the Cooper Sheet area.

2. in conglomerates interbedded with the basalts. In this mode of occurrence a variety of copper minerals is present either in the groundmass between the clasts or in thin veins cutting through both the groundmass and the pebbles. The mineralization appears to be stratigraphically controlled

3. in basalts. Chalcocite and possible bornite are present in amygdales in some of the basalts.

4. in quartzite. Rarely, some of the sedimentary quartzites in the upper part of the Mission Group carry small specks of chalcocite.

5. in shales. Minor copper mineralization is known in one shale horizon in the upper part of the Mission Group.

All the above occurrences are in the Milesia Formation. Minor copper stains in sediments and basic volcanics of the Pussy Cat Group are known from near Pussy Cat Hill. The probable lateral equivalent of the Pussy Cat Group, the Tollu Group, also carries minor copper mineralization. The copper occurs largely in quartz reefs in acid volcanics in the Tollu region and has been investigated by Southwestern Mining Company Limited. No deposits of any significance have been found. Minerals present include chalcopyrite, covellite, chalcocite, cuprite, malachite and chrysocolla.

COPPER AND LEAD

The Palgrave, Scamp and Skirmish Hill cauldrons should be investigated for copper and associated mineralization.

Minor associated copper and lead mineralization was found during the survey in the acid volcanics and associated rocks of the Palgrave volcanic association. Two localities are interesting; one lies 4 miles (6.4 km) north-northeast of Mount Eliza and the other immediately south of Mount Palgrave.

At the former locality the rock is a dark, glassy, altered rhyolite weathering with yellow and brown stains and carrying minor disseminated pyrite, galena and chalcopyrite. Three assays were made and gave the following results:

	1	2	3
Cu	170 ppm	90 ppm	650 ppm
Pb	260 ppm	1.15%	0.27%
Zn	370 ppm	280 ppm	0.41%
Ag	—	0.6 dwt/ton	—
Au	—	0.1 dwt/ton	—

In the Mount Palgrave example minor pyrite, pyrrhotite, chalcopyrite and galena mineralization occurs in a probable volcanic plug composed of dark grey granophyre. An assay gave the following results: Pb = 0.34 per cent; Cu = 0.01 per cent; Ag = 1 dwt per long ton.

The plug is probably a feeder for some of the acid volcanics of the Palgrave volcanic association and is in an area containing many agglomerate lenses and masses, some pyritic rhyolite patches and intrusive granite. Some of the agglomerate masses may be vent agglomerates which justify further investigation. Many of the pyritic rhyolite patches are thought to be fossil fumaroles and likewise require study. The contact of the intrusive granite and the volcanics should be investigated for tin, tungsten and tantalum-niobium mineralization.

The southern edge of the Scamp cauldron is marked by a curved fault with which is associated a large quality of "white" pyritic rhyolite. Only very minor traces of chalcopyrite have so far been located in this rock type, but it should be further studied.

A little copper and a trace of gold have been reported from a quartz reef which cuts the granophyre of the Skirmish Hill cauldron. No other mineralization is known in this area, but further investigations should be made.

COPPER IN THE GILES COMPLEX

Minor traces of copper have been found in some rocks of the Giles Complex.

A sample of gabbro from a bore between Michael Hills and Sphinx Hill put down by Southwestern Mining Company Limited into the Michael Hills Gabbro carries a little chalcopyrite with associated ilmenite, magnetite, pyrite, a trace of pyrrhotite and rare grains of a sulphide tentatively identified as pentlandite.

Copper minerals also occur in gabbroic rocks from a small dyke-like body 4½ miles (7.2 km) south of Mount Gosse. The minerals identified are chalcopyrite and chalcocite.

Two of the titaniferous magnetite bands southwest of the Jameson Range carry copper stains on joint faces intermittently along the strike length. The copper minerals are malachite secondary after chalcopyrite, and covellite present as minute globules enclosed in the titaniferous magnetite.

Traces of copper staining together with a trace of silver were found by H. Domeyer in 1930 in quartzite and tuffaceous sediments at Domeyer Hill in the

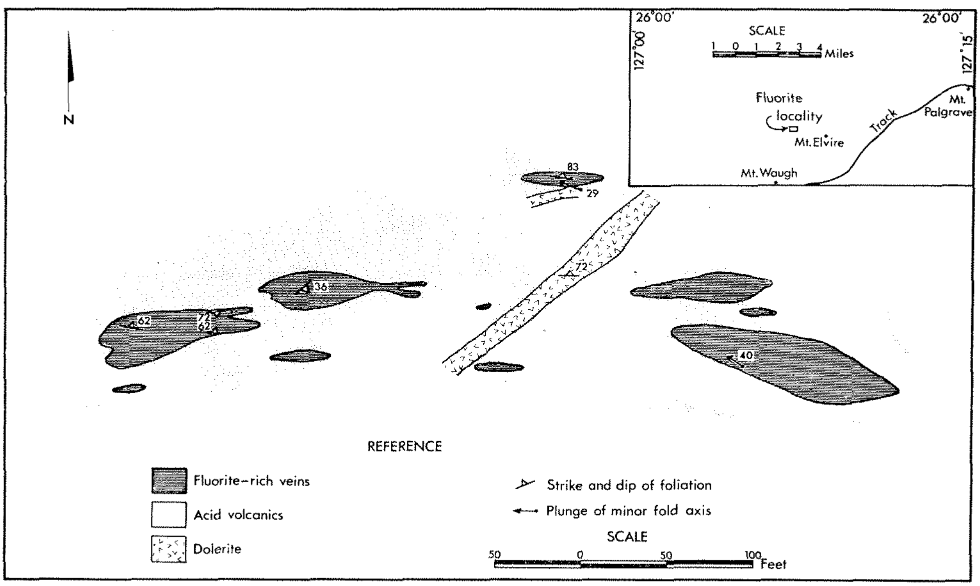

Figure 90. Sketch map of fluorite occurrences near Mount Elvire.

southeast part of the Bentley Sheet area. The mass is probably a large xenolith enclosed in the Jameson Range Gabbro. Freshly broken surfaces of the quartzite give off a strong smell of hydrogen sulphide.

FLUORITE

Small lenses of purple fluorite carrying traces of copper and zinc occur 2 miles (3.2 km) west-northwest of Mount Elvire on the Talbot Sheet area. The lenses are up to 135 feet (41.0 m) long and 35 feet (10.6 m) wide and occur in felsitized and brecciated acid volcanic rocks of the Scamp volcanic association. A sketch map of the occurrence is given in Figure 90.

AGATE

Poor quality brown and white agates up to 18 inches (45.6 cm) in diameter are common in conglomerates of the Lilian Formation. Their colour and frequent cracks preclude their use in cheap jewellery. Some, however, may be capable of conversion by heat treatment to the more acceptable variety carnelian.

GRAPHITE

A pebble of graphite approximately 2 inches (5 cm) across has been recorded from Elder Creek near Warburton Mission, but its origin is not known.

Graphite occurs disseminated in some of the granulites near Lightning Rocks and in the acid gneisses near Mitika Waterhole.

WATER

No permanent surface water exists in the Blackstone Region. Areas of hard rock outcrop contain isolated rock holes. These are more frequent in granitic rocks and have been formed usually by joint enlargement. They contain small quantities of water for short periods after rain, but the supply is unreliable.

At Warburton Mission water supplies are derived from shallow wells and bores which intersect calcrete and calcreted volcanics. The groundwater is stored largely in the porous calcrete at depths of 20 to 24 feet (6.1 to 7.3 m) below the surface. Supplies of up to 600 gallons (2,727 litres) per hour have been pumped and salinities range from 1,000 ppm to 1,700 ppm. Nitrate contents are above the permissible limit.

Potentially high yields can possibly be obtained from the extensive calcrete sheets shown in Figure 77. The most important is probably that which lies immediately west of the Cavenagh Range but the others should not be neglected.

A major source of water in the Blackstone Region is undoubtedly the Cobb Depression. This area traversing the northern part of the Scott Sheet area was found and named by Lonsdale and Flavelle (1963) after their gravity survey in the area established an extensive gravity-low. Surface mapping by the Geological Survey of Western Australia established the presence of Permian sediments in the area. Subsequently Southwestern Mining Company Limited undertook some exploratory bores. Yields of up to 13,500 gallons (61,371 litres) per hour at 400 feet (122 m) were obtained from Phanerozoic sandstones. The maximum salinity obtained was 2,013 ppm (Farbridge, 1967).

More details of the hydrology of the Blackstone Region are given by Farbridge (1968).

GOLD

No account of the geology of part of central Australia would be complete without a mention, however brief, of the Lasseter legend. For a full analysis of this story the reader is referred to the account by Ellis (1937). It is in this general area, or possibly a little to the north, near Lake Hopkins, that some of the tales suggest a fabulously rich gold vein exists. Unfortunately this could not be verified during the present survey.

One small speck of gold, however, has been reported by Southwestern Mining Company Limited from a quartz vein in association with copper, cutting the north-eastern corner of Skirmish Hill.

The old rumour about gold having been found in the Livesay Range is unlikely to be true, since the range consists of siltstones and sandstones and is not known to be cut by any quartz reefs.

PETROLEUM

As it is now thought that the Table Hill Volcanics are of Ordovician age, it seems that there could be an appreciable thickness of Phanerozoic rocks, and a potential for oil and gas in the Officer Basin.

Glossary

This glossary contains brief explanations of some of the terms used in the descriptions of the acid volcanic rocks and their origin.

Flow banding The term is used to describe very fine-scale banding visible in many of the acid volcanics. Steiner (1960) explains some of the banding in ignimbrites as a result of extreme attenuation of two immiscible liquids, though this is rejected by Fitch (1961) in favour of a xenolithic origin, in which older obsidian fragments have been reheated and drawn out. It appears that the fine-scale banding may not be due to flow. It could perhaps have been caused by compression and welding of layers of glass shards.

Flow lineations These are fine, streaky, linear features seen on some flow layers (Fig. 17) and are probably caused by flow of a viscous liquid. Surfaces with flow lineations often flake on weathering and produce a structure very similar to parting lineation in some sedimentary rocks. The structure is very important in tracing the source of the flow.

Ignimbrite Used here, the term describes an acid volcanic rock which can be proved to have been produced by an accumulation of glass shards. The term implies derivation from a nueé ardente type of eruption but direct proof of this would be difficult to find. Glass shards may be visible at the top of the unit, but not necessarily lower down especially in a thick flow. In such a thick flow the shape of the glass shards would have been completely destroyed by welding. Nevertheless the term ignimbrite is applied to the whole cooling unit and not just the top part.

Rheoignimbrite During welding of an ignimbrite the glass shards coalesce to form a plastic glass. This welding may continue to such an extent that the unit is able to flow again possibly only for very short distances and in doing so can produce flow lineations. If this can be postulated then the rock may be called a rheoignimbrite. Such rocks would be difficult to distinguish from true flows.

Spherulites. These are small spherical and sometimes elipsoidal forms developed in certain parts of acid volcanic flows. They vary in size from approximately one-eighth of an inch (3.2 mm) to about 9 inches (20.3 cm), but generally are about half an inch (12.7 mm) in diameter. The spherulites often develop across the flow banding without disturbing it.

Williams and others (1954) remark on spherulites: "No doubt many of these radial aggregates result from devitrification of glass around scattered nuclei, but generally they are formed by rapid crystallization of viscous magma and some of them must have been formed before the lavas ceased to flow". Hence they are present generally at the top and to a lesser extent at the base of the flow. Usually the spherulites increase in size upwards and may be used with confidence as a facing criterion.

Tufflava. Tufflava has been used here for an acid volcanic rock carrying abundant small inclusions of foreign matter often drawn out into long thin lenses or rods.

Vein banding. Near the base of many of the acid volcanics, in the Blackstone Region, thin veins of quartz up to 1 to 2 mm thick occur. Though in detail the veins are slightly irregular, and have been noted to branch, they are essentially parallel to the bedding of the flow. The structure has been called vein banding during this survey. It can be used for dip measurements and is a useful facing criterion. The structures are probably sweated out of the lava during its cooling.

Zig-zag folds This is a purely descriptive term to describe sharp-angled folds. Some or all of these could have been produced at the same time as the flow lineations but have usually been further distorted by a less angular folding in the upper zones of some of the flows.

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Index

	Page
Aboriginal legend	28
Acid volcanics	188
Acid volcanic analyses, Bentley Supergroup	51
Acid volcanics	
Bentley Supergroup, norms	52
facing criteria	92
Mount Jane	56
of Cassidy Group	58
Palgrave Cauldron	87
Palgrave Volcanic Association	92
plagioclase phenocrysts	69
south of Blackstone Range	54
textures	93
Acknowledgements	20
Adamellite	33
Adamellite and related rocks, history	43-46
Adamellite gneiss	43, 47
Agate	81, 235
Age determinations, Musgrave Block	34
Agglomerates, Palgrave Cauldron	87
Ainslie Gorge	83
Ainslie Volcanics	81
Algae, Lilian Formation	81
Algal structure, Frank Scott Formation	79, Fig. 25
Alluvium	203
Amadeus Basin	28, 33, 194
Amethyst	54
Amphibolite facies	34
Amy Giles Hill	159
Amy Giles Rocks	159
Anabar	209
Anatectic granite	149
Anatexis	99
Anatexis, possible origin of Cassidy Group Rhyolites	75
Andrews, J.	26
Arunta Block	33, 194
Augen gneiss	35, 37
Baker Lake	26, 200, 202
Barnard Rocks	196
Barrow Range	23, 26, 83, 87
Basic volcanics, Cassidy Group	75
Bedford Range	20, 47, 48, 100, 147, 202, 217
Beerbachite	156
Bell Rock	26

	Page
Bell Rock Range	22, 103, 105, 106, 112, 129, 136, 147, 148, 156, 159, 206, 209, 222
Bentley Sheet area, geological mapping	28
Bentley Supergroup	49, 82, 218
acid volcanic analysis	52
acid volcanic norms	52
Blackstone gravity ridge	212
Blackstone Ranges	22, 49, 54, 106, 112, 129, 147, 149
Blackstone Range Gabbro	55, 112, 114, 129, 221, 229
description	129
modal analyses	135
olivine in	173, 189
plagioclase composition	130
plagioclase in	188
relation to Tollu Group	129
websterite in	137
whole rock analyses	185
zonal scheme	129, 130
Blackstone Region	18, 19
Borrows Hill	23, 217
Brown amphibole, analyses of	160
Giles Complex	159
Brown Range	81, 82
Brown Range Siltstone	83
Bushveld Complex	156, 183, 192, 231
Calcrete	25, 200
as aquifer	202
water in	235
Canning Basin	33, 203, 215
Carnegie homestead	20
Cassidy Group	49, 50, 57, 77, 214, 218
acid volcanics, description	58
basic volcanics	75
rhyolites	99
rhyolites, chemistry	72
rhyolites, depth of origin	74
rhyolites, flow patterns	65
rhyolites, genesis	72, 73
rhyolites, petrography	68
rhyolites, suggested source	66
rhyolites, trends	72, Fig. 22, 73
rhyolites, volumes	66, 67
sedimentary rocks	77
Cauldron Formation, age of	217
Cauldron subsidence areas	23, 49, 54, 84
relation to Bentley Supergroup	85
Cauldron subsidences, petrogenesis	97
relation to gravity-high	97
Cavenagh Range	26, 56, 112, 129, 147, 149, 200, 235
Cavenagh Range Gabbros	23
Charnockite	33, 34, 35, 216
Charnockite Gneiss	37
Chromium	220

	Page
Chrysoprase	220
Claude Hills	221
Cobalt	220
Cobb Depression	194, 199, 202, 212, 217, 219
water in	236
Collocrysts	69
Colluvium	203
Columnar Basalt, Frank Scott Formation	80, Fig. 26
Conglomerate	231, 232
Contaminated Gabbro	149, 150
Contamination of Michael Hills Gabbro	158
Convection cells in Giles Complex Gabbros	190
Convection current pattern in gabbros	114
Convection currents in Giles Complex	102, 104, 110
Cooper Sheet area geological mapping	28
Copper	220, 231
Copper in cauldrons	233
Copper in the Giles Complex	234
Creede Caldera	75
Cross bedding, Giles Complex	106
Dacites of Smoke Hill Volcanics	55
Dean Range	194, 212
Décollement	215
Diapirs	215
Differentiation of Giles Complex	184
Diorite Hill	147
Dolerite	195
Domeyer Hill	226, 234
Drainage	25
Drainage patterns in calcrete	201
Duluth Gabbro	156
Dune field	24
Dykes, basic	35
Earthquake activity	27
Elder Creek	78
graphite in	235
Elder Dolomite	78
Elder, Hon. Thomas	27
Elder Springs	27
Ernabella Mission	216
Eucla Basin	202
Ewarara Intrusion	100, 192
Exploration	26
Facing criteria, acid volcanics	92
Giles Complex	103, 107
Faulting, regional pattern	209
Fauna, Blackstone Region	20
Flaser structure	35, 37
Flora, Blackstone Region	20
Flow banding, definition	237
in acid volcanics	92

	Page
Flow lineation pattern	53
Flow lineations, in rhyolite	59, Fig. 13, 63
acid volcanics	66, 52, 92
definition	237
Palgrave cauldron acid volcanics	89
Fluorite	52, 86, 92, 94, 235
in acid volcanics	68, 69, 71
Fluvioglacial deposits	199
Forrest, John	27
Frank Scott Formation	79, 195
algal structure	79, Fig. 25
columnar basalt	80, Fig. 26
description	78
relation to Gamminah Conglomerate	77
stromatolites	78
Frank Scott Hill	77, 78, 80, 218
Fraser Range	156, 164
Freetown Complex	114
Freetown Layered Basic Complex	156
Fumarole activity, Scamp Cauldron	86
Fumeroles, Palgrave Cauldron	91
Gabbro, shape of intrusions	112
Gamminah Conglomerate, description	77, 78, 79
Gibbsite	220
Gibson, A.	26, 27
Gibson Desert	22, 26, 206
Giles	194, 196
Giles Complex	28, 43, 54, 55, 217
convection currents	110, 111
cross bedding	106
cryptic layering	102, 108
description	100
differentiation	184
facing criteria	103, 107
form of intrusions	110
gravity differentiated units	103
marginal facies	149
olivine in	172
phase layering	102, 109
plagioclase in	164
possible relation to cauldrons	99
pyroxenes in	178
reverse graded bedding	105
rhythmic layering	102
sedimentary-type structures in	103
size, form	100
slump structures	108
subdivision	110
whole rock analyses	184, 185
winnow banding	107
zone layering	102, 109
Giles discontinuity	211, 212
Giles, E.	26, 27, 28

	Page
Giles Meteorological Station	19, 20
Glacial deposits	82
Permian	215
Phanerozoic	219
Proterozoic age	198, 199
Upper Proterozoic	218
Glacial rocks, Proterozoic	197
Glacials, Upper Proterozoic	49
Glyde Formation	52, 57
general description	50
Gneiss, subdivision	34
summary of history of development	38
Gold	236
Gombugurra Rhyolite	57, 58, 71
chemistry	72
norm	52
petrography	68
textural features	63
Gosse, W. C.	26, 27
Granite, ovoid	196
Granophyre	138, 188
analysis	148
related to Giles Complex	147
Granulite	43, 149, 195
Granulites, age of	216
composition	38
Granulite facies	34
Granulite facies gneisses	34
Granulites, history of development	41-43
mineral composition	39, 40
poorly banded	34
subdivision	33
well banded	34, 38
Granulite structure	208
Graphite	235
Great Artesian Basin	33
Grest Victoria Desert	22, 206
Gunbarrel Highway	20
Gungarungal	46
Gungungmura	43, 46
Guradi Basalt, description	75
Gypsum	203
Hilda Rhyolite, chemistry	72
form	66, 67
macrostructures	58
norm	52
subdivisions	60, 61
tectural features	63
Hinckley Range	34, 38, 99, 103, 138, 148, 149, 150, 155, 157, 159, 195, 209
Hinckley Range gabbro	107, 114, 200, 221
description of	146
nuckeliferous ochre in	146

	Page
Hocking Range	24, 57, 81, 82, 197, 215, 218
Hogarth Formation	56
Hughes Formation	80
Hunt Oil Company	19, 28
Igneous lamination	103, 104
Ignimbrite	50, 52, 75, 237
Jameson Range	19, 28, 38, 43, 100, 148, 164, 200, 213, 214, 220, 225, 226, 227, 231
Jameson Range Gabbro	56, 112, 114, 115, 116, 117, 119, 192, 214, 221, 222, 227, 229, 231
chemical analysis of rocks of	120, 121, 224
lherzolite in	119, 159
olivine in	174, 189
plagioclase composition	115, 117, 119, 122, 125, 128, 188
shearing in	124, 125
titaniferous magnetite in	119, 124, 125
uralitization in Zone 1	116
volume of	115
whole rock analyses	185
Kaersutite	159
Kap Edvard Holm intrusion	192
Kathleen Ignimbrite	50, 52, 89, 98
Kathleen Range	194, 195, 196
Kulyong Volcanics	199
Lake Harry	28
Lake Hills	159
Laminar flow zone, rhyolite	58
Lassetter	236
Laterite	200, 225
Latitude Hill	34, 35, 41, 112, 143, 216
Lead in Cauldrons	233
Lehmann Hills	210, 214
Lherzolite	159
Lherzolite in Jameson Range Gabbro	119
Lightning Rocks	34, 38, 39, 41, 44, 54, 208, 216, 217, 235
Lilian Creek	218
Lilian Formation, description	80, 81, 195
agate in	235
Lilian Gorge	82, 83
Livesay Range	81, 83, 197
MacDougall Bluff	24, 54, 231
Macdougall Formation	54, 212, 231
Marble	50
Marginal Facies of Gabbro, north of Blackstone Range	55
Marginal facies, of the Giles Complex	149
origin of	149
plagioclase in	156
Marginal group of Bushveld Complex	156

	Page
Metabasalts, Jameson Range region	56, 57
Yulun-Kudara water hole region	57
Turkey Hill region	57
Michael Hills	34, 35, 41, 103, 112, 143, 159, 195, 209, 211, 216, 234
Michael Hills Anticline	41
Michael Hills Gabbro	34, 35, 41, 43, 112, 216, 231
contamination	145
chemical analysis of rocks of	185
description of	138
modal analyses of	138
plagioclase composition	140, 143, 145, 188
volume of	138
whole rock analyses	185
zonal scheme	139, 140, 143, 145
Migmatite	43
Migmatization	38, 39
Milesia Formation, description	81, 233
Miller Basalt description	76, 77, 79
Mission Group	195, 214, 215, 233
general description and relationship	77
quartzites	82
relationship to Cassidy Group	57
relation to Townsend Quartzite	81
Mitaka Waterhole	44, 47, 235
Mount Agnes	81, 83, 206
Mount Aloysius	24, 27, 34, 38, 39, 41, 147, 195, 216
Mount Blyth	54, 81, 212, 231
Mount Charles, gravity-high	66
Mount Clarke	50, 57, 214, 217
Mount Daisy Bates	38
Mount Davies	100, 146, 221
Mount Eliza	233
Mount Elliott	114, 115, 122, 226
Mount Elvire	235
Mount Eveline	50
Mount Fanny	34, 38, 205
Mount Finlayson	56, 116, 211, 225
Mount Gosse	35, 37, 38, 41, 147, 159, 216, 234
Mount Harris Basalt	195
Mount Herbert	78
Mount Hilda	78, 79
Mount Hinckley	22, 24, 146
Mount Holt	34, 35, 37, 38, 216
Mount Jane	56
acid volcanics	56
tufflavas	56
Mount Palgrave	87, 89, 91, 93, 97, 98, 100, 233
Mount Ranford	81, 82
Mount Rawlinson	147
Mount Shaw	50, 57
Mount Squires	93, 96
Mount Talbot	57, 58, 80
Mount Waugh	86

	Page
Mount Weir	57
Mount West Gabbro, description of	146
Mount Woodroffe Intrusion	100
Mummawarrawarra Basalts	54, 55, 57
Mummawarrawarra Hill	54, 55, 147, 206
Murray Range	148, 159, 208, 231
Musgrave Block	19, 33, 34, 47, 216
Musgrave-Mann Complex	33
Musgrave Ranges	22, 158
Musgrave-Warburton Block	33
Mylonite	35, 209, 216
Mylonitization	35, 37
mineralogical changes	37
Myrmekite	36
Neal Junction	19
Neena Mogura Water hole	47
Net-veined Complexes	149, 153
Nickel	28, 220
Nickeliferous ochre	146, 220
origin	221
Nickel in Giles Complex	100
North Mount Davis Intrusion	105
Nuées Ardentes	75
Obsidian, devitrified, Palgrave Cauldron	87, 91
Ochre, lateritic	200
Officer Basin	19, 33, 199, 215, 219, 236
Officer Volcanics	199
Olivine	
alumina content	175
in Blackstone Range Gabbro	189
composition of	172
in Giles Complex	172, 176, Fig. 72
opitcal properties	172
relationship of Al_2O_3 content to depth in intrusion	177
physical properties	172
properties of, in Blackstone Range Gabbro	173
properties of, in Jameson Range Gabbro	174, 189
Opaline silica	202
Ordovician rocks	198
Orthogneiss	33
Palaeocurrent in MacDougall Formation	54
Palaeogeography	79, 80, 82, 83
Palaeomagnetism in Giles Complex	100
Palgrave Cauldron	50, 53, 67, 84, 195, 214, 217, 233
acid volcanics	87
description	87
granite	87
Palgrave volcanic association description	91, 233
Paragneiss	33

	Page
Pegmatities, cutting Giles Complex rocks	148
Permian	199
Petermann Ranges	22
Petrogenesis of cauldron subsidences	97
Petroleum	236
Phanerozoic rocks	25, 198
Photolineations, interpretations of	210
Physiography	22
Piemontite	52
Pitjandjara Archaean Block	33
Pitjentara Shield	33
Plagioclase, in Blackstone Range gabbro	188
comparison of chemical and optical data	167
composition of various intrusions	164
in Giles Complex	164
in Jameson Range gabbro	188
in Michael Hills gabbro	188
orthoclase component of	171
orthoclase/strontium relationships of	171, 172, Fig. 71
oscillatory zoning	169
phenocrysts in acid volcanics	69, 70, Fig. 21
range of composition	168
relationship of K to An in	170, 171
relationship of Sr to An in	169, Fig. 69
reverse zoning	168
spatial distribution	168
strontium content of	169, 170
Platinum	231
Porphyry	196
Proterozoic glacial rocks	197
Pseudotachlyte	209
Pussy Cat Group, comparison with Cassidy group	50, 57
definition	49
general	50, 54, 89, 97, 214, 217, 233
lateral equivalent	49
weathering features	50
Pussy Cat Hill	233
Pyrite, ambient	50
Pyroxenes, coexisting in Giles Complex	179
distribution coefficients	192
in Giles Complex	179
partition of Fe and Mg in coexisting	179
Pyterlite	196
Quartzite	43, 47
Mission Group	82
Quartz-muscovite schists	43, 47
Quaternary	203
Rainfall, Blackstone Region	20
Rawlinson Range	19, 20, 22, 26, 27, 48, 194, 195, 217
Rawlinson, Sir Henry	27

	Page
Regional metamorphism, Mount Clarke	50
Reverse graded bedding, Giles Complex	105
Rheoignimbrite	52, 237
Rhum intrusion	192
Rhum Ultrabasic Complex	109
Rhyodacite, in Smoke Hill Volcanics	56
Rhyolites, Cassidy Group, chemistry	72
chemistry	72
flow lineations	59
laminar flow zone	58
number of cooling units	58
of Smoke Hill volcanics	55
regional flow pattern, Scamp cauldron	86
Rough surface rolls	60
spherulitic zone	58
textural subdivision	58
textural variation and explanation	67
triangular shadows figure	63
turbulent flow zone	58
vein banding	59
zig-zag folds	59
zoning	63
Ring complex	94
Ring dykes, partial	97
Ring faults	212
Ripple marks, Giles Complex	107
Rough surface rolls, rhyolite	60, 61, Fig. 15
Salt lakes	25
Sand ridges, characteristics	203
regional distribution	205
causal wind directions	203
Scamp Cauldron	84, Fig. 21, 195, 217, 233
agglomerates	86
area	86
description	85
felsite	86
intrusive granite	86
rhyolites, regional flow pattern	86
source of acid volcanics	86
Scamp Hill	20, 86, 195
Scamp Rhyolite, flow pattern	85, Fig. 28
Scamp volcanic association	235
acid volcanic norm	52
Scott Sheet area geological mapping	28
Sedimentary-type structures in Giles Complex	102
Shards in ignimbrite	52
Shoeing Camp	27
Skaergaard Intrusion	103, 109, 114, 183, 184, 192
Skirmish Hill	23, 81, 83, 86, 87, 197, 198, 204, 219, 236
Skirmish Hill Cauldron	84, Fig. 27, 214, 217, 233, 234
description	86
Slump structures, Giles Complex	108
Smoke Hill Volcanics	49, 54, 55, 56

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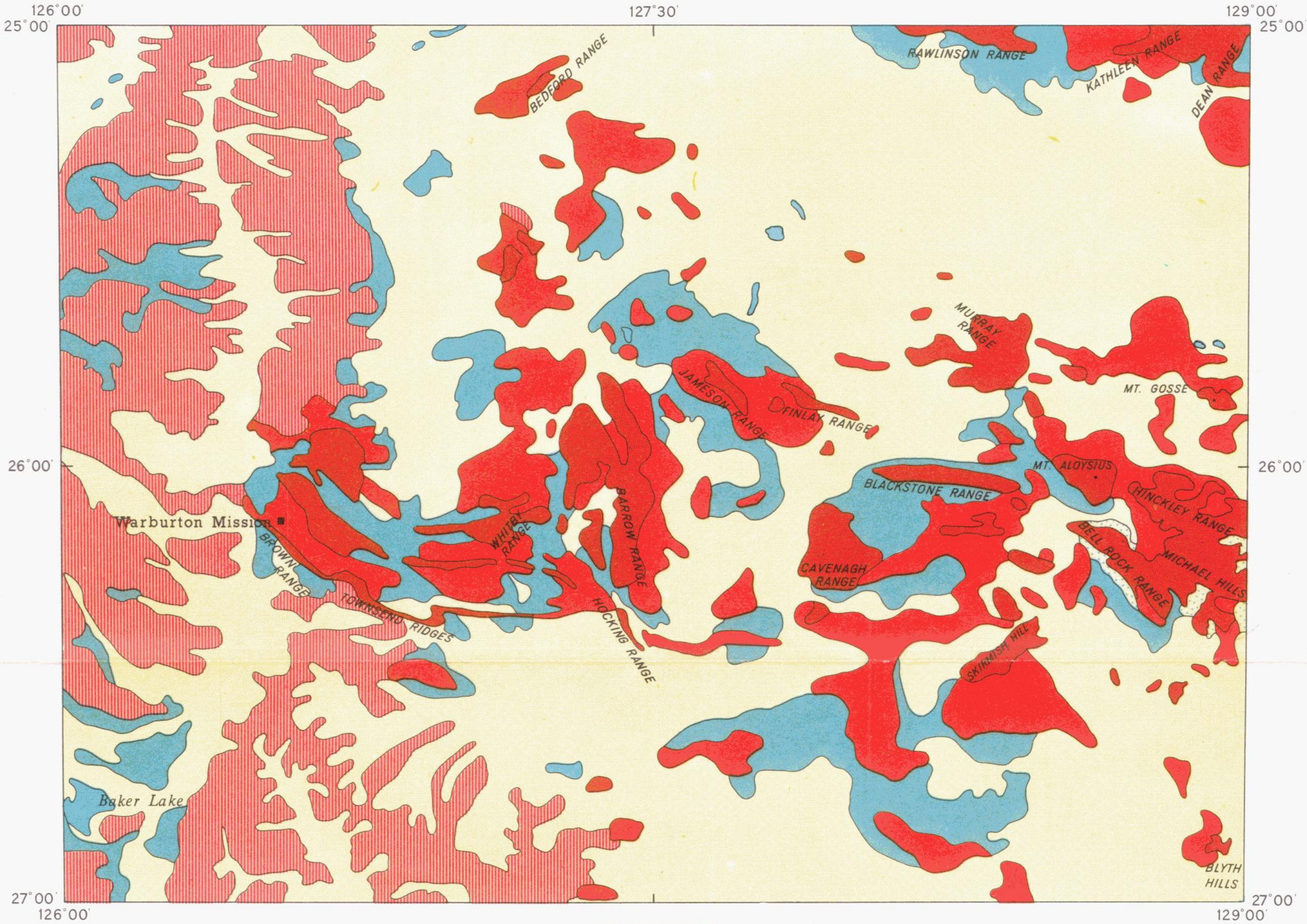


REFERENCE

- Mountain ranges, prominent hills and ridges
- Widely separated hills and low ridges with intervening plains. Plains may carry variable sand dune cover
- Alluvial flats
- Plains with few sand dunes and occasional low outcrops. Frequent dense mulga growth
- Sand dune country
- Undulating laterite country. Some low scarps. Sporadic, light dune cover usually in valleys
- Salt lake country

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

PHYSIOGRAPHIC UNITS OF THE BLACKSTONE REGION W.A.

SCALE

10 0 10 20 30 40 50 MILES

20 0 20 40 60 80 KILOMETRES

SCALE 1:1,000,000

20 10 0 20 40 60 80 100 KILOMETRES

20 10 0 20 40 MILES

REFERENCE

? PERMIAN		P	Glacial and fluvioglacial deposits
? ORDOVICIAN		Ov	Table Hill Volcanics
? UPPER PROTEROZOIC		Pa	Glacial deposits
MIDDLE PROTEROZOIC	Bentley Supergroup	Pws	Townsend Quartzite
		Pm	Mission Group
		Py	Cassidy Group
		Pk	Skirmish Hill volcanic association
		Pp	Palgrave volcanic association
		Ps	Scamp volcanic association
		Pc	Tollu Group in east, Pussy Cat Group in west (Possible equivalents)
		Pr	Dean Quartzite and Mt. Harris Volcanics (Possible equivalents)
		Pq	Quartzite and quartz-mica schist (Possible equivalents)
		Pn	Granulites, related gneisses and migmatites

INTRUSIVE ROCKS

MIDDLE PROTEROZOIC	Pu	Granite, not subdivided
	Pg	Granitic rocks related to cauldron subsidences
	Po	Giles Complex (Post Tollu Group)
	Pom	Marginal facies of Giles Complex (Post Tollu Group)
	Pgp	Porphyritic granite, and acid gneisses. Pre Tollu Group
	Ph	Giles porphyry. Post Dean Quartzite
? MIDDLE PROTEROZOIC	Pi	Granite and granite gneiss. Pre Dean Quartzite

SYMBOLS

- Geological boundary
- Approximate boundary
- Regional bedding dip
- Overturned bedding
- Regional metamorphic foliation dip
- Vertical metamorphic foliation
- Igneous banding dip
- Fault
- Probable fault
- Inferred fault
- Anticline
- Inferred anticline
- Syncline
- Inferred syncline
- Overturned anticline
- Overturned syncline
- Possible diapiric zone
- Probable centre of vulcanicity

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

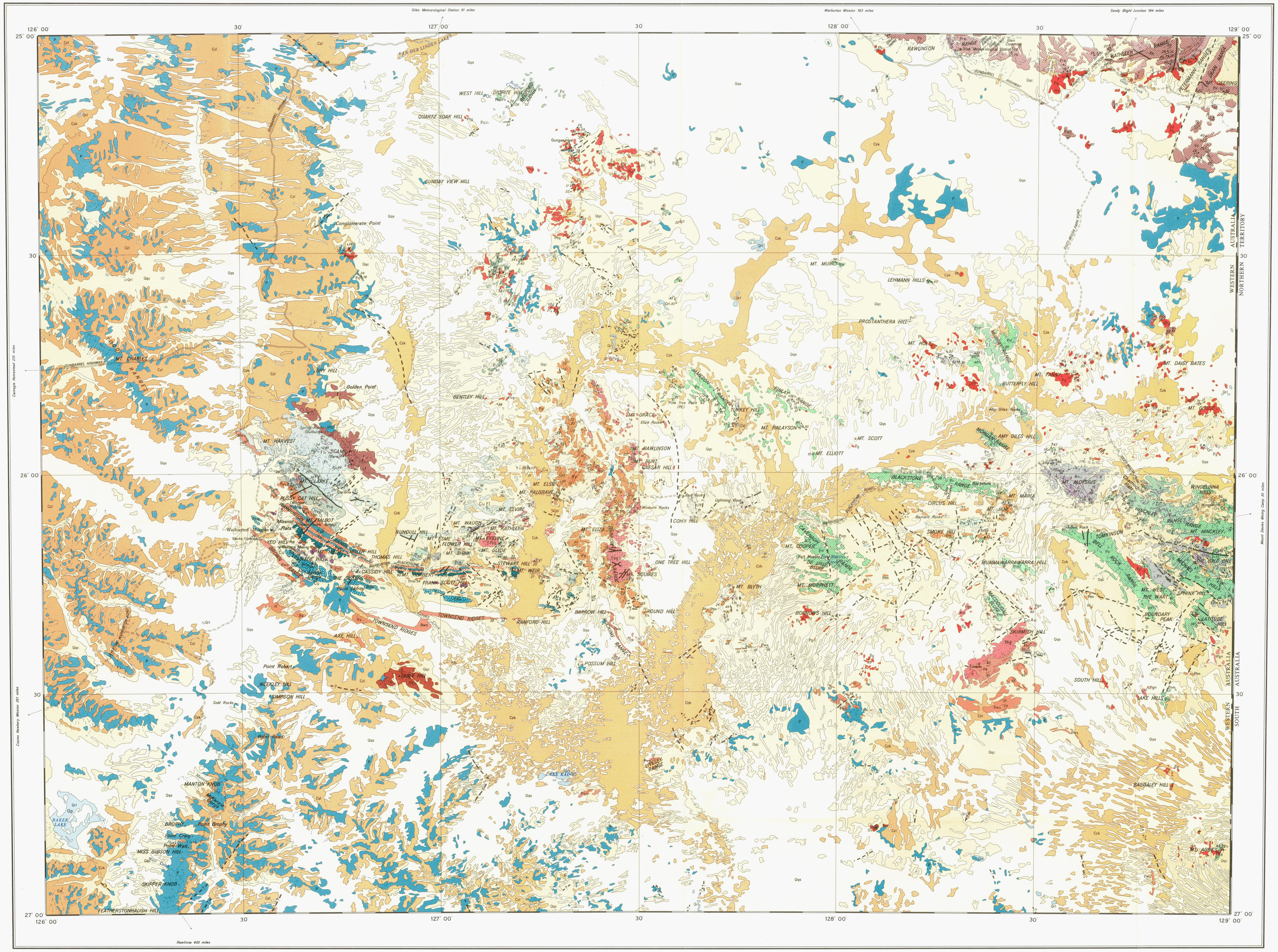
STRUCTURAL SKETCH MAP OF THE BLACKSTONE REGION W.A.

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

GEOLOGICAL MAP OF THE BLACKSTONE REGION

BULLETIN 123 PLATE 3

SHEETS SG 52-5, SG 52-6, SG 52-9, SG 52-10



SYMBOLS

Geological boundary	
Fault	
Accurate	
Approximate	
Concealed	
Inferred and concealed	—?— — —?—
Lineation with plunge	60
Bedding	
Strike and dip measured	60
Vertical	
Horizontal	
Overturned	40
Cleavage	
Inclined	80
Vertical	
Lineation on cleavage	
Igneous banding	
Inclined	40
Vertical	
Metamorphic foliation	
Inclined	80
Vertical	
Horizontal	
State border	
Highway (formed only)	
Track	
Locality	Tollu
Watercourse intermittent	
Mining centre	⚒
Mineral occurrence	
Agate	. Ae
Chromite	. Cr
Copper	. Cu
Fluorite	. Fl
Gems (Chrysoprase)	. Gs
Gold	. Au
Gypsum	. Gp
Hematite	. He
Lead	. Pb
Nickel	. Ni
Ochre	. Oc
Pyrite	. Py
Vanadium	. V

REFERENCE

CAINOZOIC

QUATERNARY

- Qrl — Lake deposits-clay and gypsum
- Qqs — Eolian sands
- Qqc — Colluvium-partly consolidated. Includes minor alluvium and river gravel

? TERTIARY

- Czk — Calcrete and calcareous gravel with opaline silca
- Czl — Laterite and lateritic gravel

PALAEOZOIC

? PERMIAN

- P — Sandstone, porcelanous siltstone and pebble beds-fluvioglacial and glacial deposits. Often deeply weathered

? ORDOVICIAN

- Ov — **TABLE HILL VOLCANICS:** basalt, pumice agglomerate and rare tuff

? UPPER PROTEROZOIC

- Ꞓa — Glacial deposits-boulder beds, sandstone, and chocolate, cream and green shale

MIDDLE PROTEROZOIC

Bentley Supergroup

- Ꞓws — **TOWNSEND QUARTZITE:** quartzite, sandstone and pebble beds. Minor conglomerate, shale and oolite

Mission Group

- Ꞓma — **MILESIA FORMATION:** basalt, conglomerate, quartzite, greywacke, and shale
- Ꞓml — **LILIAN FORMATION:** shale, tuff, basalt, chert, conglomerate and rare dolomite
- Ꞓme — **FRANK SCOTT FORMATION:** thin bedded dolomite, siltstone, chert and sandstone. Contains *stromatolites*
- Ꞓmg — **GAMMINAH CONGLOMERATE:** conglomerate and coarse cross-bedded sandstone

Cassidy Group

- Ꞓym — **MILLER BASALT:** numerous basalt flows-epidotic. Flow tops are vesicular and amygdaloidal
- Ꞓyh — **HILDA RHYOLITE:** porphyritic rhyolite
- Ꞓyw — **WARUBUYU BASALT:** epidotic basalt flows with vesicular and amygdaloidal tops. Minor sedimentary rocks at base of formation
- Ꞓyt — **THOMAS RHYOLITE:** porphyritic rhyolite
- Ꞓyg — **GURGADI BASALT:** epidotic basalt flows with vesicular and amygdaloidal tops. Minor sedimentary rocks at base of formation
- Ꞓyo — **GOMBUGURRA RHYOLITE:** porphyritic rhyolite. Minor sedimentary rocks and rare basalt at base.
- Ꞓyu — **WURURU RHYOLITE:** porphyritic rhyolite

Confined to cauldron subsidence areas:

- Skirmish Hill volcanic association — Ꞓk — Porphyritic acid volcanic rocks. Minor basic volcanics
- Palgrave volcanic association — Ꞓp — Porphyritic acid volcanics, devitrified obsidian, agglomerate and minor tuff and conglomerate
- Scamp volcanic association — Ꞓc — Porphyritic acid volcanic rock, and felsite. Minor basic volcanics and agglomerate

Tollu Group and Pussy Cat Group are possible lateral equivalents:

Tollu Group

- Ꞓta — **HOGARTH FORMATION:** basic volcanics
- Ꞓts — **SMOKE HILL ACID VOLCANICS:** rhyolite and minor agglomerate
- Ꞓtb — **MUMMAWARRAWARRA BASALTS:** epidotic, vesicular basalts. Rare tuffs
- Ꞓtm — **MACDOUGALL FORMATION:** quartz pebble conglomerate and sandstone-current bedded

Pussy Cat Group

- Ꞓcg — **GLYDE FORMATION:** basic, epidotic, amygdaloidal lavas, tuff, shale, siltstone and dolomite. Regionally metamorphosed in western outcrop.
- Ꞓcw — **KATHLEEN IGNIMBRITE:** ignimbrite-carries undistorted shards in top 50 feet; flow banded

- Ꞓs — **DEAN QUARTZITE:** quartzite and phyllite. V overprint where metamorphosed

Together form **MOUNT HARRIS VOLCANICS**:

- Ꞓra — Porphyritic rhyolite and associated quartz-feldspar porphry sills. Sheared. V overprint where metamorphosed
- Ꞓrv — Vesicular and amygdaloidal basic lavas. Partly sheared.

- Ꞓq — Quartzite and quartz-muscovite schist-well bedded, relict cross-bedding
- Ꞓn — Granulite-derived from dominantly arenaceous sedimentary rocks and acid plutonic rocks

IGNEOUS ROCKS

- d — Dolerite dykes-several ages
- b — Dolerite sill

MIDDLE PROTEROZOIC

- Ꞓkg — Granophyre closely associated with Skirmish Hill volcanic association
- Ꞓpg — Granophyre, granite, porphyritic microgranite and aplite: genetically related to the Palgrave volcanic association
- Ꞓsn — Granitic gneiss genetically related to the Scamp volcanic association

Giles Complex

- Ꞓo — Gabbro, norite, troctolite, anorthosite and ultramafic rocks-generally well banded
- Ꞓom — Marginal facies of **GILES COMPLEX:** dominantly fine-grained, granular, blue-grey, hypersthene gabbro

- Ꞓbg — Complex of adamellite gneiss, adamellite and relict masses of granulite, much migmatisation

? MIDDLE PROTEROZOIC

- Ꞓx — Migmatite of granulite and granitic gneiss
- Ꞓgn — Granitic gneiss
- Ꞓg — Granitic rocks-not subdivided
- Ꞓb — Granite with large ovoids of potash feldspar. Includes gneisses and migmatites

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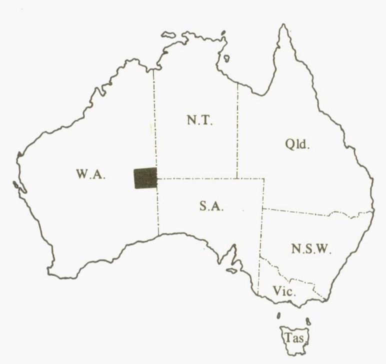

HON. D.G. MAY, M.L.A.
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J. H. LORD, DIRECTOR, GEOLOGICAL SURVEY

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2000 0 20,000 40,000 60,000 YARDS

10 0 10 20 30 40 50 60 KILOMETRES

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ZONE 52 AUSTRALIAN NATIONAL SPHEROID

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