THE PETROLOGY, GEOCHEMISTRY AND GEOCHRONOLOGY OF THE FELSIC ALKALINE SUITE OF THE EASTERN YILGARN BLOCK, WESTERN AUSTRALIA.

VOLUME I

by

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TABLE OF CONTENTS

VOLUME 1

TABLE OF CONTENTS ii

ABSTRACT viii

STATEMENT OF ORIGINALITY ix

ACKNOWLEDGEMENTS x

CHAPTER 1 INTRODUCTION AND YILGARN BLOCK GEOLOGICAL FRAMEWORK

1.1 Introduction 1

1.2 Aims of Thesis 1

1.3 Method of Study 2

1.4 Outline of Thesis 3

1.5 Choice of Petrological Classification Schemes 3

1.6 Choice of Geochronological Methods 4

1.7 Regional Yilgarn Block Geological Framework
1.7.1 Introduction 5
1.7.2 The Western Gneiss Terrane 6
1.7.3 The granite-greenstone provinces 8
1.7.4 A review of evolutionary models for the Yilgarn Block 9

1.8 The Felsic Alkaline Suite
1.8.1 Introduction 13
1.8.2 Previous Work 14
1.8.3 Definition and characteristics of the suite 15

CHAPTER 2 THE PETROGRAPHY, GEOCHEMISTRY AND GEOCHRONOLOGY OF THE GILGARNA ROCK INTRUSION

2.1 Introduction 17

2.2 General Geology
2.2.1 Introduction 17
2.2.2 Rock types and contact relationships 17
2.2.3 Rhythmic igneous layering 18

2.3 Petrography
2.3.1 Introduction 19
2.3.2 Petrography 20
2.3.3 Evidence for internal metasomatism 21
2.3.4 Discussion 21

2.4 Mineral Chemistry
2.4.1 Introduction 23
2.4.2 Feldspars 24
2.4.3 Pyroxenes 24
2.4.4 Amphiboles 24
2.4.5 Biotites 25
2.4.6 Accessory minerals 26
2.4.7 Discussion 26

2.5 Whole Rock Geochemistry
2.5.1 Introduction 27
2.5.2 Major element geochemistry 27
2.5.3 Trace element and REE geochemistry 29
2.5.4 Normative mineralogy 31
2.5.5 Discussion 31

2.6 Geochronology
2.6.1 Introduction 32
2.6.2 Rb-Sr whole rock geochronology 33
2.6.3 Rb-Sr mineral geochronology 33
2.6.4 Significance of $^{87}Sr/^{86}Sr$ initial ratios 35
2.6.5 U-Pb titanite and apatite geochronology 37
2.6.6 Discussion 38

2.7 Summary 39

CHAPTER 3 THE PETROGRAPHY, GEOCHEMISTRY AND GEOCHRONOLOGY OF THE RED HILL INTRUSION

3.1 Introduction 40

3.2 General Geology
3.2.1 Introduction 40
3.2.2 Rock types and contact relationships 41
3.2.3 Previous studies 42

3.3 Petrography
3.3.1 Introduction 43
3.3.2 Feldspars 44
3.3.3 Pyroxenes 44
3.3.4 Amphiboles 45
3.3.5 Garnets 45
3.3.6 Accessory minerals 45
3.3.7 Discussion 46

3.4 Mineral chemistry
3.4.1 Introduction 47
3.4.2 Feldspars 47
3.4.3 Pyroxenes 48
3.4.4 Amphiboles 48
3.4.5 Garnets 49
3.4.6 Accessory minerals 49
3.4.7 Discussion 50

3.5 Whole rock geochemistry
3.5.1 Introduction 51
3.5.2 Major element geochemistry 51

3.5.3 Trace element and REE geochemistry 53
3.5.4 Normative mineralogy 55
3.5.5 Discussion 55

3.6 Geochronology
3.6.1 Introduction 57
3.6.2 Previous geochronological studies 57
3.6.3 Rb-Sr whole rock geochronology 58
3.6.4 Rb-Sr mineral geochronology 59
3.6.5 Discussion 59

3.7 Summary 62

CHAPTER 4 THE PETROGRAPHY, GEOCHEMISTRY AND GEOCHRONOLOGY OF THE FITZGERALD PEAKS INTRUSION

4.1 Introduction 63
4.2 General geology
4.2.1 Introduction 63
4.2.2 Rock types and contact relationships 64
4.3.3 Previous studies 65

4.3 Petrography
4.3.1 Introduction 66
4.3.2 Feldspars 67
4.3.3 Pyroxenes 67
4.3.4 Amphiboles 68
4.3.5 Biotites 68
4.3.6 Accessory minerals 68
4.3.7 Discussion 69

4.4 Mineral chemistry
4.4.1 Introduction 70
4.4.2 Feldspars 70
4.4.3 Pyroxenes 70
4.4.4 Amphiboles 71
4.4.5 Biotites 71
4.4.6 Accessory minerals 71
4.4.7 Discussion 72

4.5 Whole rock geochemistry
4.5.1 Introduction 72
4.5.2 Major element geochemistry 72
4.5.3 Trace element geochemistry 74
4.5.4 Normative mineralogy 75
4.5.5 Discussion 75

4.6 Geochronology
4.6.1 Introduction 77
4.6.2 Rb-Sr whole rock geochronology 77
4.6.3 Rb-Sr mineral geochronology 78
4.6.4 Discussion 79

4.7 Summary 84

CHAPTER 5 FURTHER MEMBERS OF THE FELSIC ALKALINE SUITE WITH EXAMPLES OF OTHER FELSIC INTRUSIVES OF THE EASTERN YILGARN BLOCK, AND COMPARISON WITH SIMILAR FELSIC ALKALINE ROCKS WORLDWIDE

5.1 Introduction 86

5.2 Selected members of the suite from the Widgiemooltha sheet
5.2.1 Introduction 86
5.2.2 Rock types and field relations 87
5.2.3 Petrography and mineral chemistry 89
5.2.4 Major and trace element whole rock geochemistry ..91
5.2.5 Normative mineralogy 93
5.2.6 Rb-Sr isotope geochronology 94
5.2.7 Summary 95

5.3 Selected members of the suite from the Kurnalpi sheet
5.3.1 Introduction 95
5.3.2 Rock types and field relations 96
5.3.3 Petrography and mineral chemistry 97
5.3.4 Major and trace element whole rock geochemistry ..98
5.3.5 Normative mineralogy 100
5.3.6 Summary 100

5.4 Selected members of the suite from the Edjudina sheet
5.4.1 Introduction 101
5.4.2 Previous studies 101
5.4.3 Rock types and field relations 102
5.4.4 Petrography and mineral chemistry 103
5.4.5 Major and trace element whole rock geochemistry ..107
5.4.6 Normative mineralogy 108
5.4.7 Summary 109

5.5 Selected members of the suite from the Leonora, Laverton and Sir Samuel sheets
5.5.1 Introduction 110
5.5.2 Previous studies 110
5.5.3 Rock types and field relations 111
5.5.4 Petrography and mineral chemistry 112
5.5.5 Major and trace element whole rock geochemistry ..114
5.5.6 Normative mineralogy 115
5.5.7 Summary 116

5.6 Syenite and related rocks from the Teague Ring Structure of the Nabberu sheet
5.6.1 Introduction 117
5.6.2 Previous work 117
5.6.3 Rock types and field relations 118
5.6.4 Petrography and mineral chemistry 119
5.6.5 Major and trace element whole rock geochemistry ..120
5.6.6 Normative mineralogy 121
5.6.7 Summary 122

5.7 Comparison with similar felsic alkaline rocks worldwide
5.7.1 Introduction 123
5.7.2 General geological setting and characteristics of alkaline rocks 123
5.7.3 A comment on the occurrence of Archaean felsic alkaline rocks 124

5.7.4 Selected examples of oversaturated felsic alkaline occurrences 125
5.7.5 Summary 127

5.8 Summary 128

CHAPTER 6 THE GEARLESS WELL ALKALINE INTRUSION OF THE MURCHISON PROVINCE, WESTERN YILGARN BLOCK

6.1 Introduction 129

6.2 General Geology

6.2.1 Introduction 129
6.2.2 Geology of the trachyandesite intrusion 130
6.2.3 Previous studies 131

6.3 Petrography

6.3.1 Introduction 132
6.3.2 Feldspars 132
6.3.3 Amphiboles 132
6.3.4 Biotites 133
6.3.5 Accessory minerals 133
6.3.6 Discussion 133

6.4 Mineral chemistry

6.4.1 Introduction 134
6.4.2 Feldspars 135
6.4.3 Amphiboles 135
6.4.4 Biotites 136
6.4.5 Accessory minerals 136
6.4.6 Discussion 136

6.5 Whole rock geochemistry

6.5.1 Introduction 137
6.5.2 Major element geochemistry 137
6.5.3 Trace element geochemistry 138
6.5.4 Normative mineralogy 139
6.5.5 Discussion 139

6.6 Geochronology

6.6.1 Introduction 140
6.6.2 Rb-Sr whole rock geochronology 141
6.6.3 Rb-Sr whole rock-biotite geochronology 141
6.6.4 Discussion 142

6.7 Petrogenesis

6.7.1 Introduction 143
6.7.2 Review of trachyandesite petrogenetic models ...143
6.7.3 Petrogenesis of the Gearless Well trachyandesite.144
6.7.4 Discussion 146

6.8 Summary 147

CHAPTER 7 PETROGENESIS OF THE FELSIC ALKALINE SUITE AND IMPLICATIONS FOR LATE ARCHAEAN CRUSTAL EVOLUTION

7.1 Introduction 150

7.2 Petrogenesis of the felsic alkaline suite
7.2.1 Introduction 150
7.2.2 Summary of mineralogical characteristics 150
7.2.3 Summary of geochemical characteristics 154
7.2.4 Summary of geochronological characteristics 156
7.2.5 Summary of isotopic characteristics 158
7.2.6 Summary of the influence of fluid phases within the suite 160
7.2.7 Summary of physical characteristics and tectonic setting 161
7.2.8 Petrogenetic synthesis 163

7.3 Implications for Late Archaean crustal evolution 167

7.4 Summary 169

REFERENCES 170

APPENDICES

APPENDIX 1 EXPERIMENTAL TECHNIQUES A1

APPENDIX 2 SAMPLE LOCATIONS AND DATA AVAILABLE A7

APPENDIX 3 REPRESENTATIVE THIN SECTION DESCRIPTIONS A17

APPENDIX 4 RELEVANT PUBLICATIONS A37

ERRATA

VOLUME 2

LIST OF FIGURES ii

LIST OF TABLES ix

FIGURES (in chapter order)

TABLES (in chapter order)

ABSTRACT

The felsic alkaline suite of the eastern part of the Archaean Yilgarn Block of Western Australia consists of a series of sparsely distributed oversaturated syenites, quartz syenites, monzonites and alkali granites. They occur predominantly within the Norseman-Wiluna belt of the Eastern Goldfields Province, and exhibit a close spatial relationship to major regional deep-seated crustal lineaments. Members of the suite are characterised by the presence of one or more of the following mineralogical criteria: hypersolvus alkali feldspar, alkali pyroxene or alkali amphibole as a primary or major modal phase, and quartz contents of less than 20%. Depleted geochemical signatures and light rare earth element-enriched patterns are characteristic of the suite, and evidence for the influence of autometasomatic fluids in response to decreasing temperatures and increasing f_{O_2} of the crystallising magmas is widespread. Rb-Sr isotope systematics define a range of Late Archaean crystallisation ages from 2629-2471 Ma, and low initial Sr ratios are consistent with derivation from a depleted source.

Mineralogical, geochemical and isotopic evidence suggests generation of the felsic alkaline magmas via high temperature anatexis of depleted lower crustal sources consisting predominantly of felsic granulite, with a minor mafic component. Depletion of these source regions resulted from the prior removal of granitic melts which formed the extensive batholiths of the granite-greenstone terranes. Subsequent lower crustal melting occurred in response to the presence of mantle thermal anomalies associated with upwelling plumes, which played a purely passive role in felsic alkaline magma generation. Deep-seated crustal structures facilitated magma emplacement to relatively high crustal levels. The felsic alkaline suite compares favourably with some examples of A-type magmas, but represents a unique association within Archaean environments.

STATEMENT OF ORIGINALITY

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university, and to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference is made in the text of the thesis.

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JUNE 1991

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CHAPTER 1 INTRODUCTION AND YILGARN BLOCK GEOLOGICAL FRAMEWORK

1.1 Introduction

The Yilgarn Block of Western Australia is the largest and most well preserved example of stable Archaean crust in Australia, covering an area of approximately 650,000 square kilometres (Fig. 1.1). It is composed largely of typical Archaean granite-greenstone terranes, and is a mineral province of major significance. Despite extensive deep weathering and a general paucity of outcrop, the craton is structurally intact, making it ideal for studies of Archaean crustal evolution.

The felsic alkaline rocks of the eastern Yilgarn Block are a widely distributed suite of relatively fresh and undeformed intrusives of Late Archaean age, generally located in close proximity to major north-northwest trending deep crustal structures (Fig. 1.2). They provide an excellent opportunity for gaining an insight into the evolution of the crust and upper mantle throughout the Archaean, and the processes of Late Archaean crustal development.

1.2 Aims of Thesis

Using petrological, geochemical and geochronological techniques, the aims of this study are as follows:

- to classify members of the felsic alkaline suite in terms of rock type, and chemical and isotopic character
- to determine the age of selected members of the suite, and in some cases, to better quantify earlier work by the Geological Survey of Western Australia (GSWA) and the Western Australian Institute of Technology (now Curtin University)
- to investigate petrological, geochemical and geochronological trends of the suite along the length of the eastern Yilgarn Block
- to compare members of the felsic alkaline suite with other examples of alkaline affinity within the Yilgarn Block, with

similar felsic alkaline rocks worldwide, and with other felsic intrusives of the Yilgarn Block

- to provide a petrogenetic model for the felsic alkaline suite

1.3 Method of Study

Two field trips were conducted to collect a representative suite of samples from members of the felsic alkaline suite, and other felsic intrusives of the eastern Yilgarn Block, ranging from Fitzgerald Peaks southwest of Norseman, to Lake Teague northeast of Wiluna. Samples of drill-core from an alkaline body within the Murchison Province of the western Yilgarn Block were provided by Union Oil Development Corporation (UODC).

Mapping of the sampled localities was limited to delineation of individual intrusive phases within the outcrops. A total of 280 samples was taken from the freshest and least contaminated material available, usually consisting of at least 1 kg of material. A representative collection of 190 thin sections was prepared for petrological study, and 230 samples were chosen for major and trace element geochemical analysis, using standard XRF, AAS, wet chemical and specific ion electrode analysis techniques (see Appendix 1 for details). Analysis of 50 polished thin sections was performed at the Electron Optical Centre of the University of Adelaide, on a KEVEX 7000 series energy dispersive system attached to a JEOL 733 analyser (see Appendix 1 for operating conditions).

The geochronological investigation involved the measurement of 86 whole rock samples, and 23 mineral separates, using isotope dilution techniques. Analyses were performed in the Department of Geology and Geophysics at the University of Adelaide on a Thomson TSN 206S 300 mm radius of curvature mass spectrometer. Rare earth element analysis using isotope dilution techniques was performed on the same machine (see Appendix 1 for details of methods and operating conditions).

1.4 Outline of Thesis

Volume I comprises the following:

- detailed petrographical, geochemical and geochronological accounts of three selected members of the felsic alkaline suite (Chapters 2,3,4)
- comparison with other members of the felsic alkaline suite (subdivided into areas defined by the GSWA 1:250000 geological sheet on which they occur), with other felsic intrusives of the Yilgarn Block, and with similar felsic alkaline rocks worldwide (Chapter 5)
- a detailed comparative study on an alkaline intrusion of intermediate affinity from the Murchison Province of the Yilgarn Block (Chapter 6)
- a petrogenetic model for the felsic alkaline suite, and implications for Late Archaean crustal evolution (Chapter 7)

Appendices contain details of experimental methods and analytical operating conditions, details of sample locations, and representative thin section descriptions.

Volume II is designed to be read in conjunction with Volume I, and comprises figures and tables in order of appearance in the text.

1.5 Choice of Petrological Classification Schemes

The cationic R_1R_2 classification system of De La Roche et al (1980), which is based on chemical and mineralogical concepts, is the preferred method in this study (Fig. 1.3). Modal classification schemes, such as that of Streckeisen (1976), rely on precise calculation of mineral percentages from sections chosen as representative of the particular sample. Due to the coarse grain size of the majority of samples collected, even large sections or slabs may not necessarily be statistically representative of the bulk sample. Chemical schemes also overcome the problem of the partitioning of albite between plagioclase and alkali feldspar. The De La Roche method was chosen for it's efficient use of geochemical data, which are available for all samples collected in this study. The method uses all the major elements, except oxygen, does not require iron to be partitioned between oxide and silicate minerals, and provides additional information on silica saturation and weight percent silica. For comparative purposes, Streckeisen classifications are provided for the representative thin section descriptions (Appendix 3), and are generally in close agreement with the De La Roche classifications.

1.6 Choice of Geochronological Methods

Several dating methods were considered prior to the final choice of the Rb-Sr method. Preliminary work involving the standard U-Pb zircon method revealed technical problems due to the lack of sufficient quantities of zircon, despite processing 40kg bulk samples. U-Pb whole-rock methods are unsuitable due to the widely documented mobility of U under surface weathering conditions, which results in spuriously old ages, and attempts to use low-U phases such as K-feldspar to estimate initial Pb isotope compositions have been demonstrated to yield unreliable results (M^{c}Naughton & Bickle 1987). Pb-Pb whole rock methods have not been widely used in the Yilgarn Block, but where available, often yield older ages than those obtained by the Rb-Sr method. In these cases, the Rb-Sr isotope systematics have been interpreted by some workers to have been reset (eg Bickle et al 1983).

Despite numerous examples of the Rb-Sr method underestimating crystallization ages, it has been demonstrated that the method has an application to some problems within the Yilgarn Block (eg Cooper et al 1978, De Laeter et al 1981). Earlier geochronological work on members of the felsic alkaline suite (eg Libby & De Laeter 1981), and preliminary experiments of the current study, indicated that the relatively undeformed and fresh nature of these rocks made them suitable for Rb-Sr isotope investigation. The importance of careful sample selection in combination with detailed field investigations cannot be overestimated in such studies. Samples were selected from the freshest material available, with a view to obtaining a suite representing the widest possible range of Rb/Sr ratios, for rocks indicated by field evidence to be cogenetic. Where possible, sample suites were collected from single outcrops, thus avoiding the sample quality uncertainty inherent in some regional sampling programs.

The relatively pristine Gilgarna Rock syenite represents the type example of the felsic alkaline suite, with well-defined field relationships, and was chosen for detailed isotopic investigation. Previous geochronological studies on the large Fitzgerald Peaks (De Laeter & Lewis 1978) and Red Hill intrusions (Stuckless et al 1981), using the Rb-Sr and U-Th-Pb methods, respectively, yielded imprecise ages. Field evidence from the current study suggested the possibility of mixing of the syenitic magma with granitoid magmas of different ages and initial Sr ratios at these locations. Sample suites from these areas were selected with a view to improving on the earlier work, and investigating the dynamics of any isotopic mixing. Drill core from a buried alkaline intrusion from the Murchison Province of the western Yilgarn Block was subject to a detailed isotopic study, to compare the nature and timing of alkaline magmatism across the Yilgarn Block.

1.7 Regional Yilgarn Block Geological Framework

1.7.1 Introduction

The Yilgarn Block consists predominantly of typical Archaean granitoid-greenstone terrane, with north-northwest trending stellate synclinorial greenstone belts surrounded by vast generally ovoid granitoid batholiths (Fig. 1.1). Paragneiss and orthogneiss terranes bounded by extensive areas of migmatite occur on the western margin of the Yilgarn Block, where geochronological data (see Table 1.1) indicate episodic crust-forming events (McNaughton & Dahl 1987).

The craton is bounded by the Darling Fault to the west, separating it from the thick sequence of Palaeozoic to Tertiary sediments of the Perth Basin. Unmetamorphosed and flat-lying Permian to Mesozoic sediments of the Officer Basin occur to the east, while to the north and north-east, the craton is unconformably overlain by the Proterozoic sediments of the Nabberu Basin. The northern and southern margins are bounded by the Proterozoic mobile zones of the Capricorn and Albany-Fraser Orogens, respectively.

On the basis of tectonic styles, lithologic types and abundances, and metamorphic grades, Gee et al (1981) subdivided the Yilgarn Block into four provinces, comprising the Western Gneiss Terrain (now spelt Western Gneiss Terrane, Myers 1990a) and the Murchison, Southern Cross and Eastern Goldfields Provinces. Recent systematic regional mapping in the southeast Yilgarn (Swager et al 1990) and the northwest Yilgarn (Myers 1990b) has delineated a number of tectono-stratigraphic terranes each comprised of a number of distinct domains, within the original provinces of Gee et al (1981). In particular, the former Western Gneiss Terrane is now subdivided into the Narryer, Murgoo, Jimperding and Balingup Gneiss Complexes (Myers 1990b). A number of the southeast terranes, however, are still relatively poorly known and defined (Swager et al 1990), and following the suggestions of Trendall (1990), the broad divisions of Gee et al (1981) are retained for the purposes of craton-scale review.

1.7.2 The Western Gneiss Terrane

The Western Gneiss Terrane consists of structurally complex upper-amphibolite to granulite facies paragneisses, with sheet-like orthogneisses and extensive areas of migmatite, (the "early gneiss complex" of Myers & Williams 1985), intruded by post-tectonic granitoids

(Fig. 1.4). The paragneisses consist of quartzite, banded iron formation, metacarbonate, metapelite and metaconglomerate, intruded by mafic and ultramafic rocks, indicating an early sedimentary regime, rather than one of typical volcanic greenstone character (De Laeter et al 1981). The relative absence of identifiable greenstone-type sequences contrasts markedly with the other provinces of the Yilgarn, although continuing discoveries of poorly exposed sequences (Wilde 1976; Wilde & Pidgeon 1990) suggest that late Archaean volcanism in the southwest Yilgarn was more widespread than has previously been recognised.

U-Pb zircon ages have identified the Western Gneiss Terrane as the oldest component of the Yilgarn Block. Integrated geochronological studies of the Narryer Gneiss Complex (Kinny et al 1990, Pidgeon et al 1990a) reveal a complex history, with early crust formation at 4270-4100 Ma (Froude et al 1983, Compston & Pidgeon 1986), and as many as ten subsequent events through to the final assembly of the present tectonic framework at 2650 Ma. Rb-Sr, Pb-Pb and Sm-Nd studies have also yielded ages well in excess of 3000 Ma (eg De Laeter et al 1985). Based on the demonstrated antiquity of the Western Gneiss Terrane, the region has been interpreted as an exposed sample of relatively deep crustal material, possibly representing the basement to the greenstone sequences to the east (Gee et al 1981). Recent identification of volumetrically small, typical amphibolite to greenschist facies greenstone sequences, within the Western Gneiss Terrane (Wilde 1976; Wilde & Pidgeon 1990), and subsequent geochronological studies on the Saddleback Greenstone Belt (Wilde & Pidgeon 1986) have indicated close similarities in style and age with the 2600-2700 Ma Mt. Keith-Lawlers greenstone belt of the Eastern Goldfields Province (Roddick et al 1976, Cooper et al 1978). However, an inferred age of 3010 Ma for the Wongan Hills Greenstone Belt (Pidgeon et al 1990b) demonstrates the episodic nature of greenstone belt formation within the terrane.

1.7.3 The granite-greenstone provinces

The three granite-greenstone provinces (Fig. 1.5) are broadly similar in terms of lithological associations, metamorphic facies and ages of formation, however, differences in lithological abundances and structural styles reflect differences in environments of deposition. In general, the greenstone belts consist of submarine tholeiitic to komatiitic volcanics, submarine to subaerial andesitic to dacitic volcanics, clastic and chemical sediments, mafic to ultramafic intrusives, and felsic intrusives.

However, whereas komatiites are common within the Eastern Goldfields Province, and southern part of the Southern Cross Province, they are rare within the Murchison Province. Banded iron formations are more abundant in the Murchison and Southern Cross Provinces than the Eastern Goldfields Province, although they are relatively common in the northeastern part of the latter. This area also hosts a number of discrete felsic volcanic centres of calc-alkaline affinity, (Giles 1981, Giles & Hallberg 1982), which although known elsewhere within the granite-greenstone provinces (Hallberg et al 1976a,b), are less abundant. Crossbedded orthoquartzites and psammitic schists are known only in the Southern Cross Province, where, in contrast to the normal range of metamorphic facies for the rest of the granite-greenstone provinces from prehnite-pumpellyite to upper amphibolite (Binns et al 1976), mid-amphibolite to amphibolite-granulite transition facies are known (Blight 1978). This is representative of the general regional metamorphic gradient across the Yilgarn Block from northeast to southwest (Gee et al 1986).

Groves and Batt (1984) suggested that the Murchison and Southern Cross Provinces reflect a platform-style of greenstone deposition, with a lack of widespread fault control, whereas the Eastern Goldfields Province, in particular the Norseman-Wiluna belt, reflects a rift-style, with greenstone deposition occurring in fault-bounded basins.

Volcanism, sedimentation, metamorphism and deformation of the greenstone belts is thought to have developed over a narrow time range between 2800-2600 Ma (Gee et al 1981, De Laeter et al 1981). The present stellate form of the belts was caused by the intrusion of tectonically emplaced domal granitoids, thought to have been derived by remobilization of banded gneiss (Elias 1982), or at least, older continental crust (Campbell & Hill 1988). Progressive deformation during diapiric growth is well demonstrated in the Murchison and Southern Cross Provinces, whereas this is modified by a distinct north-northwest trending linearity in the Eastern Goldfields Province (Gee et al 1981). The southern part of the Southern Cross Province is characterised by northwest structural trends, while in the northern part, and in the Murchison Province, northwest to northeast trends dominate. The emplacement of the domal syn-kinematic or external granitoids, was immediately followed by the intrusion along deep-seated fundamental fracture systems of the so-called discordant post-kinematic or internal granitoids, with both events occurring between 2600-2700 Ma.

The rocks of the felsic alkaline suite, identified only within the Eastern Goldfields Province, appear to represent the final stages of Archaean magmatism within the Yilgarn Block. In the northeastern Yilgarn Block, Hallberg (1986) considers that the younger syenitic rocks reflect a continuation of mildly alkaline magma generation resulting from increasing crustal extension, and subsequent tapping of deep-seated source areas.

The widespread predominantly east-west trending postcratonization mafic and ultramafic dykes of the Yilgarn Block are considered to have been emplaced in tensional fractures (Goode 1981) over a considerable time range from 2500-560 Ma (Hallberg 1987).

1.7.4 A Review of Evolutionary Models for the Yilgarn Block

In general, models invoked to describe Archaean crustal evolution can be divided into three groups, based on the envisaged tectonic setting of the greenstone associations, viz., were these sequences deposited on simatic crust analogous to modern oceanic crust, were they deposited in island arc regimes, or were they deposited on older sialic crust in a continental setting?

Models favouring an ensimatic setting for the greenstone depositories were developed via analogies with Alpine-type geosynclinal belts eg Glikson (1970), Hallberg (1972). Glikson (1972, 1979) advocated a two-stage evolution of granite-greenstone crust from primitive oceanic crust.

Tarney et al (1976) and Burke et al (1976) proposed a marginal basin setting, with laterally accreting greenstone belts developing between an ancient stable continental mass, represented in the Yilgarn Block by the Western Gneiss Terrane, and an ocean island arc. The north-northwest linearity of the Yilgarn granite-greenstone terranes is attributed to buckling and flattening against the stable crust. Barley et al (1989) interpreted the Norseman-Wiluna Belt as a convergent margin orogenic belt, and this received support from Swager et al (1990) for the Kalgoorlie Terrane, who suggested accretion of microplates at the convergent margin, in order to explain structural and stratigraphic diversity in adjacent terranes.

The ensialic trough model of Wilson (1958) gained support from the regional metamorphic study of Binns et al (1976), and Archibald and Bettenay (1977). Groves et al (1978) argued against marginal basin, island arc and ocean floor settings, and supported an ensialic model, although pointing out the speculative nature of all models, due to the lack of sufficient data. Archibald et al (1981) outlined evidence against ensimatic greenstone formation and subsequent derivation of granitoids via partial melting of greenstones, and with Gee et al (1981), proposed the deposition of the greenstone sequences in broad shallow basins on thin sialic basement consisting of ancient gneiss. Groves and Batt (1984) suggested platform-phase greenstone development with little fault control for the Murchison and Southern Cross Provinces, and rift-phase greenstone development in tectonically active strongly fault-controlled settings for the Eastern Goldfields Province, both occurring on sialic basement. This was supported by the work of Hallberg (1986), in the northeastern Yilgarn Block. The regional study of Martyn (1987) suggested structural repetition of a relatively simple stratigraphic sequence, rather than a series of successive cycles, for greenstones of the Kalgoorlie region of the Eastern Goldfields Province. He favoured an intra-cratonic setting rather than an oceanic setting for the local greenstones, but pointed out the lack of characteristic geological features of a modern continental rift setting. The U-Pb ion microprobe study of Claoue-Long (1990) on zircons from greenstones of the Kalgoorlie-Kambalda belt supported the findings of Martyn (1987), in that horizons of supposed cyclic volcanic stratigraphy were shown to represent tectonic repetitions of the same horizon. Watkins and Hickman (1990) argued against ensimatic greenstone development and plate margin models in favour of an extensional ensialic basin setting for the Murchison Province, but suggested some form of plate tectonic influence, perhaps on a craton scale.

Gee et al (1986) reviewed earlier work and suggested the possibility of a plate collision model, involving the juxtaposition of the independently evolving Western Gneiss Terrane with the three granite-greenstone provinces, forming a major crustal suture. Such a model does not require any particular tectonic relationship between the two terranes, but the authors pointed out the unverifiable nature of this, and indeed all models, on the evidence available at the time. Myers (1990c) suggested that the eastern Yilgarn may represent a collage of lithotectonic units, including portions of island arcs, back-arc basins, and older continental crust. He further suggested that the broad belts of intense deformation that separate distinctly different tectonic trends between the southwest and northeast Yilgarn may represent the junction between two different crustal segments, or major decollement between middle to lower crustal rocks of the southwest, and upper crustal rocks to the northeast.

The first evidence for the presence of old felsic crust in the eastern Yilgarn was provided by the work of Compston et al (1986). An ion microprobe U-Pb investigation of zircon xenocrysts, from the Kambalda-Norseman greenstone belt of the Eastern Goldfields Province, suggested the presence of underlying felsic crust with ages, in part, of at least 3460 Ma, with subsequent metamorphism of this older crust at 3100 Ma. This is consistent with the earlier Pb-Pb work of Oversby (1976), who suggested that granites of the Norseman area were derived from a source of at least 3300 Ma in age, which had undergone a U loss at approximately 3100 Ma.

Campbell and Hill (1988) developed a two-stage model for the formation of the Kalgoorlie-Norseman granite-greenstone terranes, combining aspects of a number of the above models. They suggested formation of a broadly andesitic primitive crust, probably above subduction zones, which subsequently underwent a complex history of up to 700 Ma, prior to the deposition of the main greenstone sequence in rift-related sialic basins. Precise U-Pb zircon dating suggested that the oldest basaltic volcanism predated the earliest granitic magmatism by 15 ± 9 Ma, but considerable overlap between the two events suggested the involvement of a common mantle thermal anomaly, related to a zone of upwelling asthenosphere.

In general, the above model is consistent with many of the characteristics of Archaean terranes throughout the world. Campbell and Hill (1988) and Campbell et al (1990) suggested the driving force for the development of such terranes to be processes of mantle convection.

Movement of mantle convection cells relative to continents with time, resulted in periodic episodes of widespread metamorphism and crustal melting, such as the well-documented global event at around 2700 Ma.

In summary, regional structural, petrological, metamorphic, geochemical and geochronological studies of the Yilgarn Block have resulted in a number of integrated models to explain the evolution of the complex terrane. Until recently, all models have been somewhat speculative, lacking hard scientific supporting evidence, largely due to the scarcity of outcrop (less than 5%), and the deep weathering typical of the Yilgarn Block. The general concensus over the last decade is that the greenstone sequences were probably deposited in shallow basins occurring within a continental setting, with primitive generally felsic crust as the basement. The geochronological work of Compston et al (1986) provided the first direct evidence for the presence of a pre-greenstone primitive felsic crust within the Yilgarn.

Recent models eg Campbell and Hill (1988), Barley et al (1989), and Swager et al (1990), have suggested the possibility of a variety of tectonic styles and processes over several hundred million years, and increasingly, models are combining aspects of a number of previous hypotheses in building a more complete history of the tectonic and magmatic evolution of the Yilgarn Block.

1.8 The Felsic Alkaline Suite

1.8.1 Introduction

The syenitic and related rocks of the eastern Yilgarn Block were first termed the felsic alkaline suite by Libby (1978). The suite comprises a number of discrete, roughly circular bodies, generally of 1-2 square kilometres in area. They are sparsely distributed in a broad arcuate zone in the Eastern Goldfields Province, cropping out sporadically over some 800 km, from Fitzgerald Peaks, 100 km southwest of

Norseman, to Lake Teague, 100 km northeast of Wiluna (Fig. 1.2).

1.8.2 Previous Work

Prior to the study of Libby (1978), little work was done on members of the suite, with most references resulting from the regional mapping programme of the Geological Survey of Western Australia. Jutson (1915) and Honman et al (1917) documented a syenitic body east of Yerilla Homestead, and Larcombe (1926) described the syenites from Gilgarna Rock southwest of Pinjin as unakite. Berliat (1956) described quartz-poor syenitic rocks east of Linden.

Trendall (1964) described Na-rich pyroxenes and amphiboles in granitoids of the Widgiemooltha 1:250000 map sheet, and Williams (1970) mentioned alaskitic rocks from Cardunia Rocks of the Kurnalpi 1:250000 sheet. Williams et al (1971) and Williams et al (1976) mentioned syenitic rocks in the Menangina and Yerila areas of the Edjudina 1:250000 sheet. Thom and Barnes (1977) described syenitic rocks from Pig Well of the Leonora 1:250000 sheet, and Gower and Bunting (1976) described syenitic rocks from the Fitzgerald Peaks area of the Lake Johnston 1:250000 sheet. Belford (1977) carried out a limited petrographic and geochemical study of the Fitzgerald Peaks intrusion.

Libby (1978) described the general characteristics of the suite within the eastern Yilgarn, and mentioned three localities of similar alkaline rocks within the Proterozoic Albany-Fraser Province at Bobbies Point on the Neale 1:250000 sheet, and at Lake Shaster and near Shamba Kappa homestead on the Ravensthorpe 1:250000 sheet. However, he considered that these occurrences were possibly unrelated to the Yilgarn alkaline suite.

De Laeter and Lewis (1978) determined a Rb/Sr Model 4 age for the syenitic rocks of the Fitzgerald Peaks of 2360 ± 96 Ma, with an initial $^{87}Sr/^{86}Sr$ ratio of 0.7044, and suggested on the basis of petrographic and chemical similarities, that all the syenitic intrusions in the province had a similar age. Bunting et al (1980) suggested an age for the syenite-related Teague Ring Structure from the Nabberu 1:250000 sheet of 1630 Ma, with quartz syenite from outside the structure giving a Rb/Sr model age of 2367 Ma, using the initial ratio of De Laeter and Lewis (1978) from the Fitzgerald Peaks. They considered the structure to have resulted from the volatile-generated explosive intrusion of a syenitic magma. Libby and De Laeter (1980) determined Rb/Sr ages of 2489 ± 82 (Model 1, IR 0.7012), and 2520 ± 113 Ma (Model 1, IR 0.7014), for the Twelve Mile Well (Edjudina 1:250000 sheet) and Woorana Well (Sir Samuel 1:250000 sheet) syenites, respectively.

Bunting and Williams (1979) described syenitic rocks from the Sir Samuel 1:250000 sheet, and Bunting et al (1982) described the Teague Ring Structure. Stuckless et al (1981) determined a Pb-Pb age of 2760 ± 210 Ma for syenitic rocks of the Sir Samuel 1:250000 sheet. Allen (1987) described the Porphyry quartz monzonite of the Edjudina 1:250000 sheet. Libby (1989) described the major element geochemistry and petrography of several members of the suite from the Edjudina and Sir Samuel 1:250000 sheets, and suggested derivation from primitive lower crustal or upper mantle alkali enriched rock.

1.8.2 Definition and Characteristics of the suite

Libby (1978) characterized the suite as containing one or more of the following: alkali amphiboles, alkali pyroxenes, mesoperthitic alkali feldspar, and low contents of quartz, ranging from zero to twenty per cent. He considered that on the basis of mineral assemblages and textures, the rocks could be assigned to the peralkaline group of Shand (1949), and the ekeritic suite of Barth (1944). However, he noted that on a chemical basis, the rocks were only mildly alkaline.

In general, the suite consists of oversaturated syenites, quartz syenites, monzonites, and alkali granites. The high incompatible and REE contents found in undersaturated peralkaline syenites are lacking, no feldspathoids are present and there is no association with some of the more exotic alkaline rocks, such as carbonatites. With generally mesoperthitic alkali feldspars, representing unmixed anorthoclase, sodic pyroxenes of the aegirine variety, and sodic amphiboles such as magnesioriebeckite comprise the bulk of the rocks. Characteristic honey-coloured titanite is a common accessory mineral, and others include fluorite, apatite, and minor fine-grained zircon, the latter usually occurring in the mafic minerals. Late-stage autometasomatism is a common feature, and the effects of this process are seen with albite rimming alkali feldspars, aegirine rimming aegirine-augite, and magnesioriebeckite rimming and replacing alkali pyroxene. Most members of the suite are located in close proximity to interpreted deep-seated long-lived fundamental fracture systems, or crustal rifts. Geochemical, isotopic and petrographic evidence suggests that members of the suite originated from significant crustal depths, and the presence of deep crustal or even upper mantle-tapping fracture systems, appears to have facilitated emplacement of the syenitic magmas.

CHAPTER 2 THE PETROGRAPHY, GEOCHEMISTRY AND GEOCHRONOLOGY OF THE GILGARNA ROCK INTRUSION

2.1 Introduction

Gilgarna Rock occurs 103km east-northeast of Kalgoorlie in the Eastern Goldfields Province, and lies within the Kurnalpi sheet of the 1:250000 GSWA geological series (Williams and Doepel, 1971). The fresh well exposed roughly circular syenite outcrop has clearly defined internal contact relationships and a lack of contaminating phases, and has been recognised during the current study as the type example of the felsic alkaline suite.

2.2 General Geology

2.2.1 Introduction

Gilgarna Rock lies within the greenstones of the Mulgabbie-Kurnalpi belt, close to the Yilgangi Syncline axis of Williams (1970). Contact relationships with the surrounding greenstones are obscured by surficial Cainozoic alluvium deposits. Interbedded sediments including reworked tuffs occur several hundred metres to the southwest, and basic hornfels, amphibolite and epidiorite occur 2km to the southwest. Minor gabbro/dolerite occurs 2km to the west-northwest, and fine grained felsic volcaniclastics occur 3km to the northeast. A roughly circular magnetic anomaly of 5 square km in area and 2000nT in intensity, occurs immediately east of the syenite intrusion, where felsic tuffs were intersected by exploration drilling.

The Keith-Kilkenny Fault system as defined by Myers and Hocking (1988) terminates 40km to the northwest, and extension of this system to the south would place it very close to Gilgarna Rock (Fig 1.2).

2.2.2 Rock types and contact relationships

Gilgarna Rock is composed of two mineralogically and geochemically similar syenite phases - a medium grained phase and a coarse grained phase (Fig 2.1). The coarse grained phase crops out as low hummocks within two main, and a number of subsidiary sites, and is generally completely surrounded by outcrop of the medium grained phase, which has assumed a tor-like weathering profile (Fig. 2.2A)

Where observed, the contact between the two phases is sharp (Fig. 2.3A). Rare examples of small tongues of the coarse grained phase are observed to intrude the medium grained phase, and the coarse grained phase contains xenoliths of the medium grained phase (Figs. 2.2B,C), clearly establishing the relative timing of intrusion of the two phases. A narrow fine grained syenite dyke cuts the coarse grained phase (Fig. 2.3B), and is interpreted as a late stage differentiate of the coarse grained phase.

Minor mafic country rock xenoliths of tens to a few hundred centimetres are observed, and a small monzodiorite porphyry occurs within the largest outcrop of the coarse grained phase. Apart from minor local alkali metasomatism, there is no evidence for either major physical or chemical interaction of these exotic phases with the syenites.

Both main phases and the narrow dyke are classified as syenites to quartz syenites according to the scheme of De La Roche et al (1980), which corresponds to alkali feldspar ± quartz syenite in the system of Streckeisen (1976).

2.2.3 Rhythmic igneous layering

Sub-vertical rhythmic layering is observed within the younger coarse grained phase parallel to, and for distances of 1-5m from, the contact with the medium grained phase. The layering is microrhythmic in form ("inch-scale layering"), and is defined by alternating predominantly mafic and predominantly felsic layers (Figs. 2.2D, 2.3C,D, 2.6E).

Individual layers of 0.5-15 cm can be traced along strike for distances of up to 10 m, and minor pinching and swelling is common.

Contacts between the layers are generally sharp, and within both types of layers, very thin layers of the other type occur, approaching single crystal thickness. There is no indication of density grading within individual layers, and no relationship between layer spacing and crystal grainsize. Common sedimentary-type features within the layering include scour and fill structures, cross-bedding, disrupted and slumped blocks, indistinct swirls approximating flame structures, and small-scale syn-crystallisation micro-faults (Fig. 2.4). Minor orbicular structures to 50-75cm in size are defined by marginal concentrations of mafic minerals to 30mm in thickness.

The layering is interpreted as resulting from the exsolution of aqueous phases during crystallisation, causing shifts in phase equilibria, and subsequent alternating precipitation of pyroxene and feldspar (Johnson, in press). Abundant petrographic evidence for the presence of an aqueous fluid during crystallisation is described in the following sections.

2.3 Petrography

2.3.1 Introduction

All phases of the syenite intrusion consist of varying proportions of alkali feldspar, alkali pyroxene, and alkali amphibole, with minor amounts of quartz and occasionally biotite, and accessory titanite, fluorite, calcite, zircon, apatite, epidote, magnetite, rutile, monazite and barite. In general, the medium grained phase contains less alkali feldspar and biotite, more alkali pyroxene and alkali amphibole, more titanite and less fluorite than the coarse grained phase and it's differentiate dyke (see Appendix 3 for representative thin section descriptions).

The rocks are generally pink to pink-grey in colour (Figs. 2.5A,B), grainsizes range from medium to very coarse, and textures are generally of the inequigranular to hiatal subhedral variety. All samples show evidence of mild cataclasis, in the form of minor recrystallisation, especially strained and partially recrystallised quartz. Petrographic evidence suggests relatively high-level emplacement under high fluid pressure, high f_{O_2}, hypersolvus conditions of crystallisation. Evidence for alkali autometasomatism is widespread.

2.3.2 Petrography

Unmixed anorthoclase is the dominant component, comprising 75-85% of the rocks. It consists of antiperthite, mesoperthite and perthite (Figs. 2.5H, 2.6B,C), is commonly zoned (Fig. 2.6A) , and generally exhibits rims of pure albite. The occurrence of occasional remnant albite cores, and the presence of discrete oligoclase-albite in the rhythmic layers of the coarse phase, reflects early feldspar precipitation - with continued cooling, plagioclase moves down the solidus surface and is eventually replaced by anorthoclase as the crystallising phase. Consertal textures are common (Figs. 2.6A-C), and such grain boundary complexity suggests the passage of aqueous fluids (Parsons 1980). Minor late-stage alteration is indicated by the presence of trace amounts of colourless mica, calcite and fluorite within the feldspar crystals.

Stubby to elongate prisms of alkali pyroxene comprise 2-25% of the rocks, and consist of diopside/augite, aegirine-augite and aegirine. Zoning is common within the medium grained phase, with diopside/augite cores giving way to aegirine-augite rims (Figs.2.5E,F). Within the coarse grained phase, zoning is less common, with aegirine usually comprising the entire crystal. Magnesioriebeckitic amphibole occurs as a patchy to total replacement of pyroxene, and as fine needles surrounding pyroxenes (Figs. 2.5G, 2.6D).

Quartz varies from <1-10%, occurs as a late interstitial phase, and is more common in the differentiates of the coarse grained phase. Phlogopitic biotite varies from <1-8%, and is intimately associated with pyroxene. Euhedral titanite is a ubiquitous accessory mineral, being present in amounts up to 1%, and occasionally exhibiting minor leucoxene alteration of the rims. Magnetite and apatite are common accessory minerals. Calcite occurs in amounts up to 2% as late stage interstitial fill, with minor epidote and fluorite.

2.3.3 Evidence for internal metasomatism

Dominantly sodic late stage alkali metasomatism is particularly evident in the Gilgarna Rock syenites. Fluids produced during magma crystallisation resulted in albite rims to alkali feldspars in both main phases, a sudden increase in the sodic component of pyroxenes from core to rim in the medium grained phase (Fig. 2.5E), and partial to complete replacement of pyroxenes by sodic amphiboles, principally in the coarse grained and immediately adjacent medium grained phases (Fig. 2.6D). Both main phases thus were modified by fluid interaction during their respective crystallisations, and minor local modification of the medium grained phase close to the contact with the coarse grained phase during the crystallisation of the latter is indicated. The presence of minor amounts of phlogopitic biotite, trace patchy alteration of feldspars to colourless mica, calcite, and fluorite, and interstitial calcite, minor epidote and fluorite, suggests an at least occasional potash and perhaps slightly calcic component to the metasomatising fluids. This is in general agreement with the sequence of early sodic metasomatism, followed by potash metasomatism as described by Bowden (1985), for similar suites of rocks in Africa.

The cyclic variation in crystallising phases indicated by the rhythmic igneous layering within the coarse grained phase suggests multiple periods of fluid generation and influence.

2.3.4 Discussion

The agpaitic order of crystallisation normally applying in peralkaline granites and syenites, with alkali feldspars and quartz predating alkali pyroxenes and amphiboles (O'Halloran 1985), is not observed at Gilgarna Rock.

Rather, petrographic evidence suggests the following crystallisation history for the syenites - early limited sodic plagioclase (albite-oligoclase) crystallisation and minor accompanying pyroxene crystallisation, with subsequent cooling of the liquid leading to the simultaneous crystallisation of anorthoclase and pyroxene. In the coarse grained phase, the episodic influence of fluids in areas of higher flux during crystallisation produced variations in the proportions of these precipitating phases. Multiple zoning within the interiors of the alkali feldspars indicates fluctuating proportions of soda and potash within the melt. Quartz and calcite occur exclusively as late interstitial phases. Titanite and trace amounts of zircon are usually intimately associated with pyroxene, with the latter having a limited, and the former a more extensive crystallisation history. Zircon crystallisation is probably inhibited by an excess of alkalis relative to ZrO_2 (Watson 1979). Eventual crystallisation of amphibole and biotite removes F from the melt, destabilising zircono-fluoride complexes, resulting in late zircon precipitation.

As outlined above, the presence of an internally derived fluid component had a pronounced effect on the crystallisation of both phases, and resulted in periods of alternating feldspar-pyroxene crystallisation in the coarse grained phase. In general, the exsolution of fluid during crystallisation of magmas is facilitated by the presence of fluxing components, which depolymerise the melt, and enhance the diffusivity of components. Layering in the Calamity Peak granite of South Dakota was attributed to shifts in phase equilibria due to the action of an exsolved aqueous fluid (Rockold et al 1987). The fluid was produced by the depletion of boron in the melt due to tourmaline crystallisation, which decreased the solubility of H_2O in the melt. Manning (1981) has shown that similar effects are produced by fluorine. Fluorine is present in the Gilgarna Rock syenites in quantities up to 1900ppm, and fluorine depletion in the melt, via incorporation into pyroxene, and eventually fluorite, would have made possible the exsolution of an aqueous phase. Subsequent lowering of liquidus temperatures would have enabled pyroxene to replace feldspar as the primary phase at the liquidus, and cyclic variations of fluorine activity and partial H_2O, O_2 and possibly CO_2 pressures could account for the presence of rhythmic layering within the coarse grained phase. The late autometasomatic reaction products described above indicate that the fluids became increasingly alkali rich, and although dominantly sodic, evidence for minor potash and calcic components is present.

In general, the syenites are consistent with the magnetite-series granitoid classification of Ishihara (1977), suggesting generation in the lower crust or upper mantle.

2.4 Mineral Chemistry

2.4.1 Introduction

Analyses were performed at the Electron Optical Centre of the University of Adelaide, using a KEVEX 7000 series energy dispersive system attached to a JEOL 733 analyser, at an accelerating voltage of 15 kV and a beam current of 5 nA. Pyroxenes are classified according to the diopside-hedenbergite-clinoenstatite-clinoferrosilite system (after Poldervaart and Hess 1951), except for those having Na/Na+Ca values >0.2, which are classified according to the jadeite-acmite(aegirine)-augite system (after Clarke and Papike 1968), using the recalculation scheme of Cawthorn and Collerson (1974). Amphiboles are classified according to the system of Leake (1978).

2.4.2 Feldspars

Analyses of alkali feldspars of the medium grained syenite reveal a general increase of soda at the expense of potash from the cores towards the rims (Table 2.1), with essentially pure albite at the rims. A more complicated pattern occurs in the feldspars of the coarse grained phase, with fluctuating potash-rich and soda-rich zones. Feldspars from both phases exhibit the minor amounts of alien ions in solid solution, such as Ti and Fe, that are expected in the higher temperature feldspar series. Although the amount of CaO may be as much as 3-4% in anorthoclase (Deer et al 1976), values for these samples are generally less than 1%. The restricted compositional variation of the feldspars is typical of hypersolvus suites (Parsons, 1978).

2.4.3 Pyroxenes

Pyroxenes from the medium grained syenite phase exhibit diopside to salite cores, with rims varying from ferrosalite to sodian augite and aegirine-augite (Fig. 2.7, Table 2.2). Sample 006 has an average core composition lying on the diopside-salite boundary, and an average rim composition of ferrosalite, while sample 009 has an average core composition of salite, and an average rim composition of aegirine-augite. Sample 021 is an exception, exhibiting aegirine cores, and slightly more sodic aegirine rims. Sample 016 from the coarse grained syenite phase generally exhibits cores slightly richer in the aegirine component than the rims. The same applies to sample 179 from the differentiate dyke of the coarse grained phase.

In general, an increase in total Fe, and a marked increase in Fe^{3+}/Fe^{2+} ratios occurs in the rims relative to the cores of all samples, although this is not consistent for sample 016.

2.4.4 Amphiboles

The patchy uralitic amphibole replacement product of pyroxene in sample 009 of the medium grained phase has the composition of edenite (Fig. 2.8, Table 2.3). Where the replacement is more widespread, as in sample 021, the amphiboles are magnesioriebeckitic, with rims and cores displaying similar $Mg/Mg+Fe^{2+}$ values, but with the rims generally having lower $Fe^{3+}/Fe^{3+}+Al^{IV}$ values.

Sample 016 from the coarse grained phase displays magnesioriebeckitic amphiboles, with one example of a riebeckite core, and one of an arfvedsonite core. The replacement of aegirine by arfvedsonite-riebeckite solid solutions under oxidising conditions has been demonstrated by Bailey (1969) and Gilbert (1969), with the reaction being controlled by iron-wustite and wustite-magnetite buffers, and producing accompanying sodium silicates. While there are variations in $Mg/Mg+Fe^{2+}$ and $Fe^{3+}/Fe^{3+}+Al^{IV}$ ratios between rims and cores for this sample, there is no consistent trend. Amphiboles from the small monzonite porphyry unrelated to the syenites display edenitic to edenitic hornblende cores, and magnesian hastingsitic hornblende rims.

2.4.5 Biotites

The small amounts of biotite at Gilgarna Rock, which are invariably intimately associated with pyroxene, exhibit unusual chemistries (Table 2.4). They correspond most closely with high Si, low Al and low Mg phlogopites. While the Fe/Fe+Mg ratios lie within the normal range for phlogopite, the low Al^{IV} values put them out of the normal field of the biotite quadrilateral. Apart from sample 006, where cores and rims have similar compositions, all other samples from the medium grained and coarse grained phases exhibit a consistent rim-core relationship, with rims having higher Al^{IV} and higher Fe/Fe+Mg than cores. This feature is particularly marked in sample 021 of the medium grained phase where Fe/Fe+Mg varies from 0.13 to 0.25 and Al^{IV} varies from 1.1 to 1.6 from core to rim, and in sample 016 of the coarse grained phase where Fe/Fe+Mg varies from 0.19 to 0.24 and Al^{IV} varies from 1.3 to 1.5 from core to rim. The unusual chemistries may reflect late stage crystallisation as a direct result of the potash component of the residual magmatic fluids.

2.4.6 Accessory minerals

Accessory minerals analysed include titanite and apatite (Table 2.5). While rare earth element-rich portions of both the titanites and apatites were observed, no analysis of these specific elements was performed, and they are included as "other" elements, which also includes such elements as Ba and F. Titanites of both main syenite phases exhibit slight zoning, with rims generally slightly richer in Si, significantly richer in Fe and "other" elements, and slightly poorer in Ti and Ca than cores. Low totals for apatites from samples 021 and 179 indicate the presence of appreciable CO_2 and/or F. Small amounts of Si and Al are present as contaminants. The only indication of REE within apatites of the syenites occurs in the cores of sample 179.

2.4.7 Discussion

Mineral chemistries of samples from both syenite phases reflect the general increase in alkali contents and volatiles, largely due to the influence of exsolved fluid components, and the increasingly oxidised nature of the evolving magmas with decreasing temperatures.

The medium grained phase reflects crystallisation from a mildly alkaline magma. With increasing fractionation and decreasing temperatures, a general increase in Na relative to K is shown by the high temperature feldspars, with a late sodic-dominant episode resulting in albite rims. An increase in total Fe and Fe^{3+}/Fe^{2+} ratios is shown by the pyroxenes, and the latter is consistent with cathodoluminescence studies which showed the increasingly oxidised nature of the evolving magma (D.F. Blight, pers.comm. 1987). This equates to the alkali-ferric iron effect of Carmichael and Nicholls (1967). An increase in Al^{IV} is shown by both amphiboles and biotites, which are both late crystallising phases associated with the pyroxenes, and strongly influenced by autometasomatic processes. A progressive increase in Al^{IV} due to the increasing influence of magmatic fluids during and following emplacement, is consistent with the findings of Holloway and Burnham (1972), who outlined the strong positive correlation between octahedrally-coordinated Al and pressure of crystallisation.

The younger coarse grained phase crystallised from a magma of very similar composition to the medium grained phase, but with slightly higher alkalinity. Complicated zoning in the feldspars reflects the fluctuating nature of the melt chemistry. The alkali-ferric iron effect is displayed by the pyroxenes, although somewhat inconsistently, and they are more alkaline than those of the medium grained phase. Pyroxene cores have a higher proportion of the aegirine molecule than the rims, and with the slightly higher proportion of biotite present in this phase, suggest a slight decrease in Na within the latter stages of crystallisation. In general, the fluctuating mineral chemistries of the coarse grained phase reflect the multiple exsolutions of aqueous fluids evidenced by the rhythmic layering described above.

2.5 Whole Rock Geochemistry

2.5.1 Introduction

Major elements, apart from Na_2O and Fe_2O_3, were determined by XRF, with Na_2O determined by AAS, and Fe_2O_3 by standard wet chemical techniques. Trace elements were determined by XRF, with the exception of F, which was determined by specific ion electrode analysis. REE analyses were determined by isotope dilution mass spectrometry. Full details of experimental methods are given in Appendix 1.

2.5.2 Major element geochemistry

Whole rock major element geochemistries of the syenites reflect the modal dominance of alkali feldspar, with moderate silica values, and relatively high alumina and total alkali contents (Fig. 2.9, Table 2.6). Although displaying similar chemistries, differences between the medium grained, coarse grained and differentiate phases correspond to the different stages of melt evolution applying at the respective times of crystallisation.

Apart from the earliest crystallising part of the coarse grained phase represented by samples from the rhythmic layered zone, the older medium grained phase exhibits a slightly wider range of silica values than the younger coarse grained phase, and generally has higher TiO_2, total Fe, MgO, CaO and P_2O_5, and lower K_2O and Al_2O_3. For both phases, smooth trends of Al_2O_3, Fe_2O_3, Na_2O, TiO_2, P_2O_5 and to a lesser extent K_2O, are observed relative to SiO_2.

Mafic and felsic layers from the rhythmic layered zone of the coarse grained phase exhibit low SiO_2, Al_2O_3, Na_2O, and K_2O, and high TiO_2, MgO, total Fe, CaO and P_2O_5 values. Increases in SiO_2, Al_2O_3, Na_2O, and K_2O, and decreases in TiO_2, MgO, total Fe, CaO and P_2O_5 occur with increasing magma evolution. The most evolved samples of the coarse phase are those of the dyke differentiate, which exhibit lower Al_2O_3 and Na_2O, and slightly higher K_2O values. The more evolved examples of both phases exhibit similar chemistries, with melt trend lines converging at about 69% SiO_2, 15% Al_2O_3, 7.1% Na_2O, 3.7% K_2O, 2% CaO and 1.6% total Fe.

There is a general increase in the Fe_2O_3/FeO ratios for both main phases, indicating the increasingly oxidised nature of the evolving melts. Na_2O demonstrates remarkably consistent abundances for the entire range of SiO_2 values, reflecting the control exercised on this component by the precipitating feldspars.

The average compositions of the Gilgarna Rock syenites are more SiO_2 and Na_2O, and less CaO, K_2O and total-Fe rich than the average syenite of Le Maitre (1976), although his data are somewhat biased towards calc-alkaline compositions, and more SiO_2 and Na_2O, and less Al_2O_3, K_2O and total-Fe rich than the average peralkaline syenite of Nockolds (1954).

In the R1-R2 classification of De La Roche et al (1980), all samples plot as syenites to quartz syenites (Fig 2.10). A general trend from syenite to quartz syenite occurs from the medium to the coarse and dyke phases, although considerable overlap between the three phases exists. Degrees of aluminousity and alkalinity are indicated by various ratios involving Al_2O_3, CaO, Na_2O, and K_2O (see Table 2.8). All samples are metaluminous, and while a number of the more evolved samples are peralkaline, the peralkaline index is generally very close to unity for all samples, and the body as a whole is best described as mildly alkaline.

2.5.3 Trace element and REE geochemistry

A-type peralkaline granite-syenite systems commonly display elevated values for elements such as Zn, Zr, Nb, Ga, Y, Th, REE and V (Taylor et al 1981, Collins et al 1982). With the exception of V, and to a lesser extent Ga, this does not apply for the Gilgarna Rock syenites, which exhibit a somewhat depleted character (Fig. 2.9, Table 2.6).

A chondrite-normalised hygromagmatophile (HYG) trace element spider plot provides useful comparisons between the syenite phases, which show similar patterns, and exhibit marked negative anomalies for Rb, K, Nb, P and Ti (Fig 2.11), suggesting that the source region of the syenite magmas was depleted in these elements. A normalising standard of similar depleted character, the N-type MORB mantle source of Wood et al (1979), removes the marked peaks and troughs, and allows more meaningful comparisons (Fig 2.12). The medium grained phase displays slightly higher absolute abundances than the other phases for all elements except U and Sr. More evolved examples of both main phases display marked La and Zr peaks, while the dyke differentiates of the coarse phase are lower than the main coarse phase samples in all elements except K, Rb, Zr and Nb.

In the medium grained phase, Sc, V, Cr and Ni show general decreases in abundance with increasing magma evolution, reflecting the control of these elements by precipating pyroxene. Nb and Y exhibit a weakly positive correlation, with a slight decrease in abundance towards the more evolved samples. Nd and Ce abundances are relatively consistent for all samples, while La and Zr are higher in the more evolved samples. Sr and Ba show a decrease with evolution, reflecting control by the alkali feldspars, and Rb shows an increase, although abundances are low. Th shows no pattern, and U values are low. Ga values are higher for the same values of Al_2O_3 than the I-type granites, and higher for higher values of Al_2O_3 than the A-type granites of Collins et al (1982), with the Ga/Al ratios increasing with increasing differentiation.

Ga exhibits similar behaviour in the coarse grained phase, being lower in the early phases of the rhythmic layered zone. The early layered phases are lower in Ba, Rb and significantly higher in Sc, V, Cr, Ni, and particularly Zr, Nb, Y, Ce, La and Nd, than the more evolved main body of the coarse phase. This reflects the early precipitation of pyroxene for the former group, and the significant concentrations of incompatibles are probably an indication of the influence of early exsolved fluids. The incompatibles are largely concentrated in the abundant titanite present in the early phases. The sharply lower abundances of incompatible elements in the main body of the coarse phase show a marked increase with increasing evolution of the melt, but even the most evolved samples do not display the values seen in the layered phases.

Rb/Sr ratios are low for both main phases, although showing an increase for increasingly evolved samples. K_2O/Rb fractionation trends (Fig 2.13) demonstrate the influence of autometasomatic processes on the medium phase, particularly samples 10, 21, 174 and 175, and the coarse phase, particularly samples 15, 22 and 173, which follow the pegmatitic-hydrothermal trend of Shaw (1968), subsequently interpreted as indicative of autometasomatic processes by Vidal et al (1979). Samples of the coarse differentiate dyke conform more to the magmatic trend.

Partial rare earth element analyses were carried out on samples from the medium phase, coarse phase, more evolved coarse phase, and dyke differentiate phase. The LREE-enriched HREE-depleted character results in moderately high La/Yb values from 71 for the medium and coarse samples, to 80 for the evolved coarse sample, and 99 for the dyke differentiate sample (Table 2.7), the latter two results reflecting increasing fractionation. Absolute REE abundances are not high, and suggest a source of depleted character, with the heavy REE's probably controlled by residual garnet.

2.5.4 Normative mineralogy

All phases are oversaturated with respect to silica, exhibiting small degrees of normative quartz, with abundances increasing with differentiation (Table 2.8). Ab dominates the feldspar components, and An is absent from the more evolved samples of the medium grained phase, and the differentiate dyke of the coarse grained phase. Sodium metasilicate, which is a common normative component of peralkaline granites (Bowden 1985), does not occur in any of the samples. Di is the usual pyroxene component, except for the more evolved samples, where acmite, a characteristic normative component of peralkaline rocks occurs. The Il, Mt, Hm and Wo components are significantly higher in the layered phases of the coarse grained syenite. AFM ratios display the expected trend towards the A component, with the layered phases showing the highest F and M values.

2.5.5 Discussion

The mildly alkaline medium and coarse grained syenite phases exhibit similar chemistries and evolutionary trends, with both being influenced by exsolved autometasomatic fluids at their respective times of intrusion and crystallisation. The rhythmic layered samples of the coarse grained phase exhibit the chemistries expected of early crystallising phases, with significant controls on chemistry being exerted by early pyroxene and titanite precpitation. The increasingly oxidised nature of both main phases is reflected by increasing values of Fe^{3+}/Fe^{2+}. Trace element and REE data suggest derivation of the magmas from a source depleted in the incompatible elements.

A number of schemes based on geochemical discriminants have been developed to classify granitoids in terms of tectonic regimes. None are particularly conclusive for the Gilgarna Rock syenites - a volcanic arc environment is indicated in the scheme of Pearce et al (1984), except for samples from the layered part of the coarse grained phase, which suggest a within-plate environment. A late orogenic to anorogenic setting is indicated in the R1-R2 tectonic classification scheme of Batchelor and Bowden (1985).

In general, the rocks are most closely related to the A-type granitoids of Collins et al (1982), with the lack of characteristically high contents of incompatibles reflecting the depleted nature of the deep seated source regions.

2.6 Geochronology

2.6.1 Introduction

A representative suite of samples for the medium, coarse and dyke phases was collected for Rb/Sr whole rock and mineral isotopic investigation, with a view to obtaining the widest possible range of Rb/Sr ratios. Sites close to igneous contacts were avoided, and the freshest available material was chosen. Whole rock splits of 150-200g, and mineral separates of 0.15-0.4g were taken from 0.5-2kg samples of crushed rock. U-Pb analyses were performed on titanite and apatite separates. Average grainsize for the medium grained phase was 2mm, while the coarse grained phase varied from 3-12mm. Details of experimental methods are given in Appendix 1.

2.6.2 Rb-Sr whole rock geochronology

Whole rock data for the eleven analysed samples of the medium grained syenite phase yield an excellent fit isochron, with an age of 2629 ± 43 Ma, and an initial $^{87}Sr/^{86}Sr$ ratio of 0.70074 ± 0.00028. The MSWD for this regression is 0.72, indicating a Model 1 isochron, which is interpreted as a crystallisation age (Fig. 2.14, Tables 2.9, 2.10).

For the coarse grained syenite phase, the seven analysed samples yield an excellent fit isochron, with an age of 2546 ± 37 Ma, and an initial $^{87}Sr/^{86}Sr$ ratio of 0.70141 ± 0.00017. The MSWD for this regression is 0.32, indicating a Model 1 age, which is interpreted as a crystallisation age (Fig 2.15, Tables 2.9, 2.10).

The four analysed samples of the coarse phase differentiate dyke yield an isochron with an age of 2551 ± 57, and an initial $^{87}Sr/^{86}Sr$ ratio of 0.70121 ± 0.00106. The MSWD for this regression is 1.95, which is a Model 1 isochron given the suggested modifications of Brooks et al (1972) to the regression methods of McIntyre et al (1966). This age is interpreted as an age of crystallisation. The larger MSWD and uncertainties are largely due to the small number of samples in the regression.

The ages of the coarse grained phase and it's differentiate dyke are indistinguishable, and a combined regression of all eleven samples is consistent with the petrographically and geochemically established relationships outlined above. The result of this regression is an excellent fit isochron, with an age of 2543 ± 15 Ma, and an initial $^{87}Sr/^{86}Sr$ of 0.70142 ± 0.00013. The MSWD for this regression is 0.59 indicating a Model 1 age, which is interpreted as a crystallisation age.

2.6.3 Rb-Sr mineral geochronology

Feldspar and pyroxene, and feldspar, pyroxene, titanite and epidote mineral separates were obtained for the medium and coarse grained syenites, respectively.

Inclusion of a pyroxene and a feldspar analysis with the whole rock analyses of the medium grained phase yields an isochron with an age of 2660 ± 37 Ma, and an initial $^{87}Sr/^{86}Sr$ ratio of 0.70050 ± 0.00023. The MSWD of this regression is 2.51, which although consistent with a Model 1 age (Brooks et al 1972), is higher than that applying to the whole rock analyses alone. This, together with the significantly older age and lower initial ratio, is due solely to the pyroxene analysis. This analysis exhibits the lowest Rb/Sr ratio of all the medium phase analyses, and has a relatively poor fit to the regression line, lying below it. The result of this is an older indicated age, and a lower initial ratio. Thus, despite the lack of petrographic and chemical evidence for disturbance, and the collection of the sample from homogeneous syenite unaffected by obvious contaminating phases or contact effects, the pyroxene separate records isotopic disturbance, and inclusion of the analysis in the regression is not justified. Significantly, the whole rock sample from which the pyroxene separate was obtained, and the feldspar separate from the same sample, record no such disturbance.

Regression of the whole rock samples and the feldspar analysis produces an isochron indistinguishable from that of the whole rock analyses alone, yielding an age of 2627 ± 41 Ma, with an initial $^{87}Sr/^{86}Sr$ ratio of 0.70076 ± 0.00027, and an MSWD of 0.68.

Inclusion of feldspar, pyroxene, titanite and epidote analyses with the whole rock analyses of the coarse phase yields an isochron indistinguishable from that of the whole rocks alone. The result is an age of 2542 ± 14 Ma, with an initial $^{87}Sr/^{86}Sr$ ratio of 0.70145 ± 0.00009, and an MSWD of 0.86.

2.6.4 Significance of $^{87}Sr/^{86}Sr$ initial ratios

The phenomenon of non-uniform initial Sr ratios for whole rock isochrons consisting of a variety of different phases in highly evolved granites has been documented by McCarthy and Cawthorn (1980). The errorchrons produced are largely due to the late stage enrichment of Rb in the highly evolved phases. Gerstenberger (1989) described the enhancement of Rb concentrations due to late autometasomatism, while Sr concentrations remained constant. Most of these examples involve phases such as secondary feldspar and extreme mica compositions, such as protolithionite and zinnwaldite, with very high Rb/Sr ratios. Phases such as these are not present in the Gilgarna Rock syenites, which do not exhibit highly evolved character. Isotopic analyses of minerals reveal a range of Rb/Sr ratios within, or less than the whole rock samples, and while autometasomatic effects are noticeable, they are more gradual and certainly less pronounced than those observed in highly evolved granites. The low initial Sr ratios of the Gilgarna Rock syenites are thus considered real, and reflect derivation of the syenite magmas from a depleted source, represented by lower crust or upper mantle material.

While chemical heterogeneity of mantle reservoirs has been widely documented (eg Jacobsen and Wasserburg 1979, Sun 1982, Bell et al 1982), the theoretical concept of an undepleted uniform reservoir can be useful for investigating paths of magma evolution. This concept was developed via study of oceanic and continental basalts, which suggested derivation from a mantle reservoir with a chondritic Sm/Nd ratio, the so-called chondritic uniform reservoir, or CHUR (De Paolo and Wasserburg, 1976a,b). Subsequently, a strong inverse correlation was recognised between $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$, and the above authors and O'Nions et al (1977) and Hawkesworth et al (1977) considered that coherent fractionation of Sm/Nd and Rb/Sr occurred during mantle evolution. They calculated a present day Bulk Earth $^{87}Sr/^{86}Sr$ ratio of 0.70469, representing the Sr isotopic composition of a mantle reservoir which evolved from an initial $^{87}Sr/^{86}Sr$ ratio of 0.69898 over 4550 Ma. The evolution of this theoretical uniform reservoir (UR) from 4550 Ma to the present describes a Sr evolution curve, and evolutionary paths for the medium and coarse syenite magmas can be calculated.

Negative values for ϵSr_{UR}, (the initial $^{87}Sr/^{86}Sr$ ratio of the sample divided by the initial $^{87}Sr/^{86}Sr$ of the theoretical uniform reservoir at the time of crystallisation), reflect production of the syenite magmas from a source depleted in Rb relative to UR. The medium grained and coarse grained phases yield ϵSr_{UR} values of -9.55 and -1.28, respectively. The time of original depletion of UR can be estimated by projecting the medium phase back, along a line representing the Sr evolutionary path of the depleted source, assuming single stage evolution. The minimum case occurs when the projection is performed with the same $^{87}Sr/^{86}Sr$ ratio as the medium phase, resulting in an age of 3161 Ma for initial depletion of UR. Hill et al (1989) suggested primitive crust formation at 3400 Ma in the Kambalda region. If such a depletion occurred in the mantle underlying Gilgarna Rock at this time, the depleted residue precursor to the syenite magmas would require a Rb/Sr ratio of 0.008. While Bell et al (1982) suggested mantle Rb/Sr ratios of .018 for part of the Canadian Archaean, and Ellam and Hawkesworth (1988) argue for a mean Rb/Sr ratio of 0.02 for primitive arc rocks, Rb/Sr ratios of 0.008 are probably too low. Using a Rb/Sr ratio of 0.018 results in an age for differentiation of UR at 3920 Ma, however, a minimum age of UR depletion at 3161 Ma is all that can be realistically deduced for the case of Gilgarna Rock.

The following evolutionary scheme is suggested:

1) Extraction of at least one relatively felsic melt from a source similar to UR prior to 3175 Ma, leaving a depleted residue with a low Rb/Sr ratio.

2) Production and emplacement of the medium grained syenite magma via partial melting of the evolved depleted residue at 2627 Ma.

3) Derivation of the coarse grained syenite at 2542 Ma, via further tapping of the medium grained phase precursor, and intrusion into crystallised medium grained phase syenite. The possibility of derivation of the coarse grained phase from the same depleted residue that produced the medium grained phase would require multi-stage evolution, and in the space of 85 Ma that separates the crystallisation ages of the two phases, this is not considered feasible. The Sr evolution path of the medium phase is such that at 2542 Ma, the $^{87}Sr/^{86}Sr$ ratio coincides, within experimental error, with that of the coarse phase, supporting this suggestion.

2.6.5 U-Pb titanite and apatite geochronology

U-Pb isotopic analyses were carried out on titanite and apatite mineral separates from sample 016 of the coarse grained syenite. The resulting data were of poor quality due to the very low levels of U and Pb present in these minerals, and the high relative proportion of common lead present, which necessitated large corrections (Table 2.11). With reference to the Concordia plot (Wetherill 1956), the titanites are reversely discordant, plotting well above the line and giving $^{206}Pb/^{238}U$ ages in excess of 2900 Ma, and $^{207}Pb/^{235}U$ ages in excess of 2700 Ma. The titanite samples were not subject to acid washing and were abraded before being handpicked and ultrasoniced in acetone, and the unusual results are considered real. $^{207}Pb/^{206}Pb$ ages of 2630-2670Ma are closer to the Rb/Sr age obtained, but still significantly higher. The apatite samples are slightly normally discordant, giving $^{207}Pb/^{206}Pb$ ages of 2650-2750Ma.

The cause of the reverse discordance for the titanites is either due to U loss, or Pb gain. This is difficult to reconcile with the lack of later metamorphism in the region, and dilation effects were relatively recent (Cooper and Dong 1983). Whatever the cause, the Concordia method is inapplicable, and the $^{207}Pb/^{206}Pb$ mineral ages, even after large common lead corrections, more closely approximate the ages derived by the Rb/Sr method. The average $^{207}Pb/^{206}Pb$ mineral age for the six points is 2662 ± 48Ma, while removal of the poor apatite A analysis yields 2655 ± 20Ma.

Regression analyses for the $^{207}Pb/^{206}Pb$ data are presented in Table 2.12. Using the method of McIntyre et al (1966), a Model 3 isochron age of 2625 ± 47 Ma results. Removal of the apatite B analysis yields an isochron age of 2601 ± 26Ma, with an MSWD of 1.66, considered a Model 1 age given the modifications of Brooks et al (1972). Removal of the apatite A analysis yields a $^{207}Pb/^{206}Pb$ value closer to the expected Cumming-Richards parameter, with a Model 2 age of 2668 ± 51 Ma. These results are still older than the Rb/Sr ages, and do not lend themselves to further interpretation.

2.6.6 Discussion

Despite examples of the Rb-Sr method underestimating crystallisation ages within the Yilgarn Block (eg Bickle et al 1983), the Gilgarna Rock analyses demonstrate that the method has a legitimate application to some problems. The small scatter of points about both isochrons can be entirely attributed to experimental error, with no geological contribution, and two distinct magma crystallisation ages are indicated. The colinearity of the mineral separates with the whole rock samples (with the exception of the medium grained pyroxene analysis), attests to the lack of later rehomogenisation of the isotope systematics, in contrast to some examples from the Yilgarn Block (eg Chapman et al 1981). The fact that the medium grained phase crystallisation age is preserved despite the intrusion of the coarse grained phase some 85Ma later, demonstrates the lack of influence of the coarse phase on the isotopics of the medium phase. This suggests that there may not have been a significant temperature contrast between the two phases at the time of emplacement of the coarse phase. Alteration effects in both phases are demonstrably solely due to fluids derived via exsolution from within the respective magmas, with the exception of minor local alteration in the marginal medium phase immediately adjacent to the coarse phase intrusive contact.

2.7 Summary

Petrographic and geochemical data demonstrate the similarity of the two mildly alkaline syenite phases, and the lack of external effects over the long period of time between the respective emplacements of the medium and coarse grained phases. The significant difference in age between the two is the first demonstration of such behaviour within the felsic alkaline suite, and attests to the long-lived presence of a deep-seated heat source. The low initial Sr ratios and the lack of incompatible elements suggest derivation from a source of depleted character. Fractionated REE character is consistent with retention of the HREE in a residual phase such as garnet. Seismic and gravity models suggest that the lower crust under parts of the Yilgarn Block consist of garnet granulite of basic affinity (Drummond 1981). The emplacement of the magmas from a deep crustal layer of granulite affinity may have been facilitated by the presence of a deep seated crustal rift, such as the Keith-Kilkenny Fault.

CHAPTER 3 THE PETROGRAPHY, GEOCHEMISTRY AND GEOCHRONOLOGY OF THE RED HILL INTRUSION

3.1 Introduction

Red Hill occurs 120km southeast of Wiluna in the northern Eastern Goldfields Province, and lies within the Sir Samuel sheet of the 1:250000 GSWA geological series (Bunting and Williams 1977). The bulk of the outcrop, which comprises some 20 square km, consists of alkali granite to quartz monzonite, with subordinate related syenites. A previous regional study in the area, which included the Red Hill body, yielded imprecise Pb-Pb ages (Stuckless et al 1981). Red Hill was included in the current study in an attempt to define the local geochronology more precisely, and to compare the syenite age with those derived from Gilgarna Rock.

3.2 General geology

3.2.1 Introduction

Red Hill represents one of the northern most occurrences of the felsic alkaline suite. It occurs within Zone 4 of the tectonic subdivision of Bunting and Williams (1979), where a complex batholith hosts a variety of granitoid rocks (Fig. 3.1). The Zone is bounded to the west by the Celia Fault, and extends eastwards to the Laverton Fault in the Laverton and Duketon GSWA Sheet areas.

The Red Hill body is entirely surrounded by fluorite-bearing fractionated post-tectonic adamellite and granite. Bunting and Williams (1979) suggested this granite to be similar to the Mt. Boreas Adamellite 120 km to the southeast, which Bunting and Chin (1979) compared to the potassic hood granites of South Africa (Viljoen and Viljoen, 1969). Outcrop of the granite surrounding Red Hill is commonly obscured by extensive Cainozoic colluvium and alluvium deposits. The nearest greenstones occur 5 km to the east, within the Wonganoo greenstone belt. The Celia Fault occurs 10 km to the west.

3.2.2 Rock types and contact relationships

The intrusion consists of a number of outcrops distributed over a relatively wide area, and for the purposes of the current study, it is divided into the south, central west, central east and north outcrop areas (Figs 3.2, 3.3B). The contact with the surrounding post-tectonic granite was not observed in the study area.

The southern outcrop is composed predominantly of pink-green medium to coarse grained quartz-deficient pyroxene syenite to syenodiorite (Fig 3.5F), with the sometimes clotty mafic minerals defining a weak preferred orientation. The syenite is clearly intruded by distinctly pink medium grained pyroxene alkali granite (Fig 3.5D), with a granite dyke displaying a sharp contact with the syenite (Fig 3.3C, 3.4D). A pyroxene-rich version of the alkali granite shows evidence of intrusion into the syenite soon after the emplacement of the latter, and pyroxene prisms up to 4cm in length are observed growing from the syenite into the dyke (Fig 3.3D, 3.5E). Two sets of pegmatite occur, with one subparallel to the granite dyke, and a late stage set crosscutting all other phases (Fig 3.4A).

The central west and central east outcrops consist almost entirely of distinctly pink pyroxene alkali granite to quartz syenite (Fig 3.5G). The central east outcrop contains minor intensively weathered sheared syenite, and despite indistinct contact relationships, the alkali granite appears to intrude this sheared material, which may be equivalent to the syenite comprising the southern outcrop. In addition, occasional possible xenoliths of relatively undeformed alkali granite are observed within the sheared material. It is not clear from this dubious evidence whether the syenite and granite are coeval, or multiple intrusions have occurred.

Similarly complex intrusive relationships are observed in the northern outcrop, which consists predominantly of pink pyroxene quartz syenite to alkali granite, with minor pyroxene syenite in the northwestern extreme of the outcrop. Coarse grained extremely weathered syenite similar to that of the central east outcrop, but generally not exhibiting shearing, occurs as xenoliths within the pyroxene alkali granite, and alkali granite occurs as dykes within this weathered syenite (Fig 3.4C).

The simplest interpretation of the field evidence thus suggests intrusion of alkali granite-quartz syenite (henceforth referred to as the alkali granites), into the more mafic pyroxene syenite. Lack of crucial contact relationships does not allow distinction between a relatively coeval intrusion of the two main rock types, or a series of multiple intrusions.

In the classification scheme of De La Roche et al (1980), the syenitic rocks range from syenodiorite to syenite, while the granitic rocks range predominantly from granite to alkali granite.

3.2.3 Previous studies

Bunting and Williams (1979) considered the Red Hill syenite and related pyroxene granite to be intruded by Mt. Boreas-type potassic adamellite, and limited geochemical analyses demonstrated differences between the calc-alkaline and alkaline granitoids.

Bunting et al (1980) used an initial ratio from the work of De Laeter and Lewis (1978) at Fitzgerald Peaks near Norseman, to calculate a model Rb-Sr age of 2367 Ma for a syenite sample 35km south of Red Hill, at Woorana Well. Libby and De Laeter (1981) subsequently obtained a Rb-Sr isochron age for this intrusion of 2520 ± 113 Ma, with an initial ratio of 0.7014. Stuckless et al (1981) investigated the U-Th-Pb systematics of the Mt. Boreas-type granite and the syenites in a regional study of the northern part of the Zone 4 tectonic sub-division of Bunting and Williams (1979), which included analyses from Red Hill. They obtained imprecise Pb-Pb ages of 2760 ± 210 Ma and 2370 ± 100 Ma for the Mt. Boreas-type granitoids and syenites, respectively. On the basis of field, textural and geochronological evidence, they suggested that the syenites occurred as xenolithic blocks and pendants within the younger granite. They compared the syenite model Rb-Sr age of Bunting et al (1980) to the Pb-Pb age of the Mt. Boreas-type granitoid, and concluded that the syenite Rb-Sr system was reset by the intrusion of the granitoid.

Libby (1989) presented geochemical data for several bodies on the Sir Samuel sheet, including Red Hill.

3.3 Petrography

3.3.1 Introduction

The medium to coarse grained subhedral to anhedral inequigranular syenitic rocks consist of 60-90% alkali feldspar, 1-8% albite, 5-35% alkali pyroxene and <5% quartz, with accessory titanite, apatite, magnetite, zircon, allanite, epidote and fluorite (see Appendix 3). Actinolitic to edenitic amphibole is present in minor amounts as a uralitic replacement product of pyroxene. Quartz is generally interstitial, strained and partially recrystallised. Biotite/chlorite is occasionally present in trace amounts. Andradite is present in one sample as ragged aggregates, and a weak preferred orientation is defined by pyroxene and amphibole in some samples.

The medium to occasionally coarse grained anhedral to subhedral inequigranular alkali granitic rocks exhibit a weak to well defined preferred orientation. They consist of 45-80% alkali feldspar, <5-40% oligoclase-albite, 12-25% quartz, 2-8% pyroxene (occasionally weakly alkaline), 1-5% actinolitic to edenitic uralitic amphibole, and accessory magnetite, titanite, apatite, zircon, fluorite, allanite, epidote and calcite, with trace to 1% biotite/chlorite. Quartz is generally strained and partially recrystallised, and occasionally exhibits an unusual subrounded globular appearance suggestive of resorption, occurring as inclusions in feldspar margins. Some samples exhibit partial recrystallisation throughout.

Pegmatites include coarse to very coarse grained anhedral alkali granites composed of 55% alkali feldspar, 40% quartz and 5% albite, with accessory titanite and opaques, and coarse to very coarse grained subhedral syenites composed of 95% alkali feldspar, 2% albite, 2% quartz, 1% extensively altered pyroxene, and accessory titanite and opaques.

3.3.2 Feldspars

The alkali feldspar of the syenites consists of microcline, microcline stringer and patch perthite, and fine to coarse scale mesoperthite (Figs 3.6B,F), and occasionally exhibits granophyric texture. The alkali granitic rocks contain microcline to microcline perthite, and fine to medium scale mesoperthite (Figs 3.6C,D,H).

Plagioclase within the syenites consists almost exclusively of albite (Ab_{90-100}), with occasional myrmekitic texture. The albite crystals are rarely discrete, being associated with the alkali feldspars, and may be largely products of unmixing of the latter. Moderate alteration and kinked crystals are observed in some samples.

The alkali granites are demonstrably two-feldspar granites, and abundant slightly altered oligoclase to albite is occasionally myrmekitic and antiperthitic. Cores tend to be more strongly altered than outer zones.

3.3.3 Pyroxenes

Mildly alkaline pyroxenes of the syenites consist of ferroaugite, sodian augite, and aegirine-augite. The crystals are generally stubby anhedral prisms, although subhedral to euhedral prisms occur, and occasional resorption textures such as embayments are observed (Fig 3.6F). In some samples, pyroxene occurs as clots and aggregates, and exhibits a weak preferred orientation. Minor alteration to amphibole is common.

Within the alkali granites, pyroxenes consist of salite to ferroaugite, and extensive alteration to iron oxides and amphibole is observed in some samples. Crystals are generally stubby subhedral prisms, and occasionally subrounded and embayed grains suggest resorption (Figs 3.6C,D).

3.3.4 Amphiboles

Both the syenites and alkali granites exhibit uralitic actinolitic to edenitic amphiboles after pyroxenes. The amphibole occurs as fibrous and patchy internal replacements, and as rims to pyroxenes (Fig 3.6E).

3.3.5 Garnets

Garnet is observed in one sample only (119) of the syenites, occuring as ragged yellow-brown subhedral aggregates, and having the petrographic characteristics of andradite (Fig 3.6G).

3.3.6 Accessory minerals

Abundant titanite occurs in the syenites, as fine grained euhedral to somewhat ovoid anhedral crystals (Fig 3.6B), occasionally exhibiting late stage alteration. Within the alkali granites, titanite occurs as fine grained euhedral to subhedral unaltered to moderately altered crystals (Fig 3.6D), sometimes exhibiting zoning, and as fine to medium grained subhedral to anhedral unaltered to strongly altered crystals. Some samples exhibit ragged anhedral remnant aggregates suggesting partial resorption of the original crystals.

Apatite occurs as common fine to occasionally medium grained euhedral to subhedral crystals within both the syenites and the alkali granites. Fluorite and allanite are trace constituents of both rock types, with fluorite more common in the syenites, and allanite more common in the alkali granites. Epidote is present in both rock types, while calcite is found only in the alkali granites. Zircon is present in trace amounts as fine to very fine grained crytals in both rock types, but is more common in the syenites.

The syenites invariably contain magnetite, as do the alkali granites of the central outcrops, but the alkali granites of the other outcrops contain either magnetite or ilmenite.

3.3.7 Discussion

The presence of mildly alkaline pyroxenes, low contents of quartz, and mesoperthitic alkali feldspars within the predominantly hypersolvus syenites characterises them as members of the felsic alkaline suite of Libby (1978). While the alkali granites are a lower temperature series, exhibiting two distinct feldspar compositions, the presence of mesoperthitic alkali feldspar and weakly alkaline pyroxenes, notwithstanding the relatively high quartz contents, also places them within the range of the felsic alkaline suite. Both rock types exhibit similar accessory minerals, although varying in abundance, and both contain uralitic amphibole replacement of pyroxene. Resorption textures are exhibited by pyroxene and titanite in both rock types, and also by quartz in the alkali granites.

Within the syenites, pyroxene and titanite appear to be the earliest crystallising phases, with feldspar crystallisation following resorption of the early phases. Titanite crystallisation was prolonged, and in the latter stages, accompanied by apatite and zircon precipitation. Uralitic amphibole replacement of pyroxenes occurred during the latter stages of crystallisation, probably in response to the presence of exsolved autometasomatic fluids, but is not nearly as common in these rocks as it is in the Gilgarna Rock syenites.

Pyroxene and titanite were early precipitating phases in the alkali granites, with early zoned plagioclases giving way to more sodic compositions with increasing crystallisation. Quartz textures suggest a long history, with resorbed grains occurring within feldspar margins in some cases. The later crystallising titanites exhibit a slightly different morphology than the early partially resorbed grains, being generally coarser grained and more euhedral in character. Uralitic amphibole of similar composition to that of the syenites is also a late stage autometasomatic product in the alkali granites.

Although the syenites and alkali granites in general exhibit distinct individual character, principally defined by the abundance of quartz, the nature of the feldspars, and the variation in alkalinity of the pyroxenes, there are samples where these differences are less marked, and it is considered that the rock types are closely related. The possibility of hybrid rock types is not supported by either whole rock geochemistry or the isotope systematics (see following discussion).

3.4 Mineral chemistry

3.4.1 Introduction

Analyses were performed at the Electron Optical Centre of the University of Adelaide, using a KEVEX 7000 series energy dispersive system attached to a JEOL 733 analyser, at an accelerating voltage of 15kV, and a beam current of 5nA. Pyroxenes are classified according to the diopside-hedenbergite-clinoenstatite-clinoferrosilite system (after Poldevaart and Hess 1951), except for those having Na/Na+Ca values >0.2, which are classified according to the jadeite-acmite(aegirine)-augite system (after Clarke and Papike 1968), using the recalculation scheme of Cawthorn and Collerson (1974). Amphiboles are classified according to the scheme of Leake (1978).

3.4.2 Feldspars

Maximium values of around 2% CaO are observed in the albite-oligoclases of the granites (Table 3.1). No consistent zoning relationships are observed, although cores tend to exhibit slightly more minor alteration than rims. Minor CaO (<0.2%) also occurs in the mesoperthites, substituting for Na.

Within the more mafic examples of the syenites, no CaO occurs in the perthites or mesoperthites, and the plagioclases are pure albite. Minor amounts of Fe are observed as contaminants in the high temperature alkali feldspars. A maximium of around 1.5% CaO occurs in plagioclases from the more siliceous syenites.

3.4.3 Pyroxenes

Pyroxenes from the granites display a trend from salite through to the ferrosalite-ferroaugite boundary (Fig 3.7, Table 3.2). Examples from individual samples exhibit consistent chemistries, and there is no difference between rim and core compositions. Pyroxenes from one syenite sample also lie on this trend, and although fluctuating rim-core compositions are observed, no consistent pattern emerges. Another syenite contains crystals of sodian augite, with cores displaying slightly more of the acmite-jadeite components than the rims. Coarse pyroxenes observed growing from the syenite into a granite dyke in one locality exhibit very similar sodian augite compositions, with more acmite and less jadeite in the cores than the rims. Fe^{3+}/Fe^{2+} ratios indicate a slight increase in oxidation during crystallisation of the granite pyroxenes, demonstrating the alkali-ferric iron effect (Carmichael and Nicholls 1967), while the reverse generally applies for pyroxenes of the syenites.

3.4.4 Amphiboles

As might be expected from products of uralitisation, amphiboles from both the granite and the syenite display a wide range of compositions, from actinolite, actinolitic hornblende and magnesiohornblende, to edenite (Fig 3.8, Table 3.3).

Amphiboles from the granites exhibit a more restricted range than those from the syenites, and lie mainly within the range of actinolitic hornblende. The bulk of the syenite amphiboles are actinolitic in composition. In one sample (106), cores tend to be more siliceous and have slightly lower $Mg/Mg+Fe^{2+}$ ratios than the rims. Some of the amphiboles from this sample however are edenitic, and in these crystals the reverse is true, that is, rims are more siliceous and have slightly lower $Mg/Mg+Fe^{2+}$ ratios than the cores. Fe^{3+}/Fe^{2+} ratios of amphiboles from the syenites display variations even within one sample, with indications of both increasing and decreasing oxidation, although increasing oxidation is more common.

3.4.5 Garnets

Sample 119 of the syenite contains the only garnets observed at Red Hill, and the compositions are consistent with andradite (Table 3.4). Andradite typically occurs as a constituent of calc-silicates and skarns, where it is produced by the reaction of calcite with iron and silica. It is also produced via metasomatism of calcic igneous rocks, and the Ti-bearing varieties are found in undersaturated alkaline rocks such as nepheline syenite and ijolite (Deer et al 1966). The occurrence of virtually identical andradites elsewhere within the felsic alkaline suite (see Chap. 5) and the invariably ragged appearance suggests that these crystals are relicts of the melt source region.

3.4.6 Accessory minerals

Low major element totals for apatites and titanites for both rock types suggest appreciable contents of H_2O and F for the titanites and H_2O, F and Cl for the apatites (Tables 3.5, 3.6).

Titanite rims from the granites usually have higher Si and Al contents than the cores, and REE which are recorded here as "other" elements, are generally higher in the cores. Significant alteration is occasionally observed in titanites of the syenites, where Ti is largely substituted by Fe. H_2O and F are probably more common in the titanites of the syenites, where totals are often low, and cores tend to be slightly richer in REE than rims.

Apatites from both rock types contain minor amounts of alien elements, principally Si, Al and Na, and significant contents of REE, which for most examples, are higher in the cores than the rims.

3.4.7 Discussion

General similarities in mineral compositions support the conclusion from the petrographic evidence that the main differences between the two rock types are confined to the respective contents of silica and degrees of alkalinity. At the very least, the rock types can be said to have originated from magmas of similar character, and to have undergone similar crystallisation histories. Pyroxene and amphibole compositions best demonstrate this point, with some syenite pyroxenes lying on the trend defined by the granite pyroxenes, and with amphibole compositions displaying marked similarities for both rock types. Some pyroxenes and amphiboles from the syenites display some unusual characteristics, in that pyroxene cores tend to be more alkaline than rims, and amphibole cores tend to be more silicic, with lower $Mg/Mg+Fe^{2+}$ ratios, than the rims. This suggests fluctuations in f_{O_2}, and is consistent with variations in the Fe^{3+}/Fe^{2+} ratios.

Within both rock types, the REE were removed from the melt relatively early by titanites and apatites, with the cores of these minerals displaying higher REE contents than the rims.

Notwithstanding the weak to well defined preferred orientations exhibited by some samples of both rock types, there is no indication of post-crystallisation metamorphic effects in the form of overgrowths or chemical modification, in either the petrographic or mineral chemistry evidence. Visible alteration of primary minerals is confined to uralitisation of the pyroxenes, an autometasomatic process occurring during the latter stages of crystallisation of both rock types.

3.5 Whole rock geochemistry

3.5.1 Introduction

Major elements were determined by XRF, with the exception of Na_2O (AAS) and Fe_2O_3 (titration). Trace elements were determined by XRF, with the exception of F, which was determined by specific ion electrode analysis. REE analyses were determined by isotope dilution mass spectrometry. Details of experimental methods are given in Appendix 1.

3.5.2 Major element geochemistry

Distinction between the syenites and the alkali granites is best demonstrated by Harker-style variation diagrams (Fig 3.9). The syenites range from 59-65% SiO_2, while the alkali granites range from 68-75% SiO_2. In general, the syenites are higher in total iron, MnO, CaO, MgO and P_2O_5 than the alkali granites (Table 3.7).

Two distinct groups of syenites are particularly evident on a TiO_2 vs. SiO_2 plot (Fig 3.9), with the lower TiO_2 group corresponding to syenites from the southern outcrop, and the higher group including samples from both the southern and northern outcrops. For the purposes of discussion, these distinct groups are referred to as the Group 1 and Group 2 syenites, respectively. The alkali granites generally display a greater continuum of values, although a group of predominantly northern outcrop samples range from 70-75% SiO_2, while samples from the central outcrops range from 68-72% SiO_2. These are referred to as the Group 1 and Group 2 granites, respectively.

Group 1 syenites display an increase in alumina with silica, while Group 2 syenites define a slight negative trend. Total iron abundances are similar, with both types containing greater amounts of Fe_2O_3 than FeO, although Group 2 syenites are markedly higher in Fe_2O_3 than FeO. Both groups display the expected negative trends of MgO and CaO with SiO_2, with Group 1 having generally slightly higher abundances. Na_2O and K_2O increase with SiO_2 for the Group 1 syenites, as does Na_2O for Group

2, although K_2O decreases with SiO_2 for this group. Curved trends for P_2O_5 suggest early precipitation of apatite, and a subsequent precipitation towards the end of crystallisation for both groups. Differentiation indices display a steep positive trend for Group 1 syenites in particular. Apart from the TiO_2 plot, where the two groups are quite distinct, most other major elements display some overlap, and in a number of cases, trends are observed to converge towards a silica value of 65%. Fe_2O_3/FeO ratios fluctuate somewhat for Group 1 syenites, while Group 2 syenites display a general decrease in this ratio for increasing values of silica.

Considerable overlap exists between the two granite groups, and trends are generally coincident (Fig 3.9). An exception occurs for total iron and soda, where both show a slight increase with silica for the Group 2 granites. Both groups contain a similar abundance of Fe_2O_3 and FeO. Group 1 granites contain similar abundances of MnO, CaO and K_2O to those of Group 2, for higher values of silica. P_2O_5 values are consistent across the range of silica values for the Group 2 granites, while they decline with increasing silica for the Group 1 granites. A coincident trend occurs for the differentiation indices of both groups.

The average syenite composition exhibits similar values of SiO_2, total iron, MgO and CaO, higher values of K_2O, and significantly lower values of Al_2O_3 than the average syenite of Le Maitre (1976), and is more similar to the average peralkaline syenite of Nockolds (1954), with higher CaO and K_2O and lower Na_2O. The average granite composition has lower total iron and CaO, higher Na_2O and significantly higher K_2O than the average granite of Le Maitre (1976).

In the R_1R_2 classification of De La Roche et al (1980), the syenites plot as syenite to syenodiorite, while the granites define a series through granite and alkali granite to quartz syenite and quartz monzonite (Fig 3.10). The Group 1 syenites are peralkaline, and with the

Group 2 syenites which are mildly alkaline, display lower aluminous character and higher Na+K/Si values than the granites. The granites are mildly alkaline and exhibit relatively low to moderate (Na+K)/Si values.

3.5.3 Trace element and REE geochemistry

Absolute trace element abundances exhibit considerable overlap for the Red Hill syenites and granites, with exceptions being Zn and V, which are uniformly higher in the syenites (Fig 3.9, Table 3.7). With minor exceptions for Zr, Zn and V, these rocks do not contain the elevated abundances of Zn, Zr, Nb, Ga, Y, Th, REE and V expected in A-type peralkaline granite-syenite systems (Taylor et al 1981, Collins et al 1982). The distinction between the groups defined above by the major elements is particularly well defined in plots of trace elements against Sr, especially for La, Ce, Nd and Th, and in the Ce vs Nb plot.

Group 2 syenites exhibit markedly higher values of La, Ce, Nd, Th and Nb than Group 1 syenites, reflecting a more evolved character. Negative trends of La, Ce and Nd vs Sr are well defined for the Group 1 syenites. Negative trends of Nb, Nd and Zn, and positive trends of Ba and Zr vs Sr are exhibited by Group 2 syenites. Higher values of V in the Group 2 syenites are consistent with the higher abundances of Fe_2O_3 in these rocks, with V substituting for Fe^{3+}. The wide range in alumina values for the syenites results in Ga/Al ratios varying from those typical of the A-type granites of Collins et al (1982), to those observed for the Gilgarna Rock syenites. Rb values are generally significantly higher than those seen at Gilgarna Rock, and with similar values of Sr, the Rb/Sr ratios are thus higher at Red Hill. The granites exhibit similar Rb/Sr values to the syenites. On the K_2O vs Rb plot of Shaw (1968), the syenite groups display overlapping magmatic trends, with values of 300-350 (Fig 3.11).

The differences between the two alkali granite groups are best demonstrated by plots of Zn, Ce, Nd, Th and F vs Sr. Slight negative trends for V and Pb, and marked negative trends for Ce, La, Th and Zn vs Sr are displayed by the Group 2 granites. The Group 1 granites tend to display slight positive trends for most elements vs Sr, except Rb. La, Nd and Zr exhibit a wide range of values for both groups. Ga exhibits similar abundances to the A-type granites (Collins et al 1982), although alumina values are generally significantly higher. With some exceptions, Zr values are low, and no consistent trend vs SiO_2 is observed. Both granite groups display magmatic trends on the K_2O vs Rb plot, but are distinguished by K_2O/Rb values of 340-400 and 370-450 for Groups 1 and 2, respectively (Fig 3.11).

Partial REE analyses for both rock types show similar patterns to those of Gilgarna Rock, with LREE-enriched HREE-depleted character and low to moderate elemental abundances, reflecting a depleted source. La/Yb values range from 170 for a Group 1 syenite, to 102 for a Group 1 granite (Table 3.8).

A hygromagmatophile plot normalised to the N-type MORB mantle source of Wood et al (1979), demonstrates the similarities between Red Hill and Gilgarna Rock (Fig 3.12, cf Fig 2.12). Red Hill exhibits a slightly less smooth pattern than Gilgarna Rock, with a more marked Nb and Ti depletion, and higher La and Ce enrichments. The Group 2 syenites exhibit higher elemental abundances than Group 1 syenites, and the Group 2 granites have higher abundances than the Group 1 granites. In both cases, this reflects the more fractionated character of the Group 2 rocks. With the exception of phosphorus, which is markedly lower in the granites, the granites lie within the envelope defined by the syenites, demonstrating the close relationship and probable co-magmatism of the two rock types. The low P values in the granites reflect the relative retention of apatite in the source region.

3.5.4 Normative mineralogy

The lowest degree of silica saturation is exhibited by the syenites, while the alkali granites are significantly oversaturated, with Q values up to 30 (Table 3.9). Group 1 syenites are characterised by the presence of normative Ac, moderate to high values of Di, the predominance of Or over Ab, the lack of An, low values of Q, high values of Ap and Mt, and relatively low Il. Group 2 syenites contain Ac only in one case, lower amounts of Di, minor amounts of An and occasionally Hy, slightly higher values of Q, and generally higher Il and lower Ap.

An, Di and Hy are present in minor amounts in both groups of granites, and two examples of Group 1 granites are slightly corundum normative. Low to moderate values of Il and Mt occur in both groups, and Ap is significantly lower than in the syenites.

3.5.5 Discussion

The differences between the syenites and related alkali granites at Red Hill are apparent in the mineralogical character of the rocks, but it is in the whole rock geochemistry that differences are most evident, and where subgroups of both rock types are defined. While the granites as a group are observed to intrude the syenites, there is no single area of outcrop at Red Hill where the four subgroups exist together, and the field relationships between the syenite subgroups, between the granite subgroups, and between the syenite and granite rock types as a whole cannot be deduced. Even in the southern outcrop where three of the subgroups co-exist, all that can be deduced is that Group 1 granite intrudes Group 1 syenite.

On the basis that the granite subgroups defined above occur in geographically distinct areas of the intrusion, it is reasonable to assume that the minor geochemical differences observed between the subgroups are a consequence of different degrees of magma evolution at different sites within the intrusion. All the Group 1 syenites come from the southern outcrop, and while Group 2 syenites include samples from both the southern and northern outcrops, they may well represent a more evolved portion of the same magma that gave rise to the more primitive Group 1 syenites. There is some evidence, particularly exhibited by the major elements, that the Group 2 syenites are evolving towards alkali granite compositions. Despite a significant silica gap, Group 2 syenites lie along the extension of the trends defined by the alkali granites for TiO_2, Al_2O_3, total iron, CaO, MgO, K_2O, P_2O_5 and the differentiation index. In addition, incompatible trace elements such as Ce, La, Nb, Ba, Nd and Th, although exhibiting a wider range and higher abundances than the granite groups, have more in common with these groups than with the primitive Group 1 syenites. There is no geochemical evidence, however, to suggest that the Group 2 syenites are a product of mixing of Group 1 syenites with the alkali granites, and the Group 2 syenites are demonstrably not related to the granites by processes of fractionation.

The available evidence thus is consistent with intrusion of a single syenitic magma, with the Group 1 syenites representing the earliest crystallising part of the magma, and the Group 2 syenites reflecting evolution of the magma with time towards a more alkali granitic end composition. The syenites were then intruded by the alkali granites, with the subgroups reflecting different degrees of magma evolution in different areas of the body. The alkali granites are interpreted to have resulted from smaller degrees of partial melting than the syenites, from the same general depleted source region. Despite the probability of a smaller melt fraction, the granites do not display particularly elevated incompatible element values, which is consistent with these elements having been depleted in the source region by the prior removal of the syenite melt.

Geochemical discriminant schemes for classifying the tectonic regimes of granitoids are inconclusive for the Red Hill rocks. They vary from syn-collision to within-plate rocks in the scheme of Pearce et al (1984), and include both the magnetite and ilmenite series of Ishihara (1977). In the R_1R_2 tectonic classification of Batchelor and Bowden (1985), a late orogenic to anorogenic setting is indicated. As with the Gilgarna Rock intrusion, the rocks are most closely related to the A-type granites of Collins et al (1982), but lack the high incompatible element contents expected in these rocks, indicating the depleted nature of the source region.

3.6 Geochronology

3.6.1 Introduction

A representative suite of samples of the syenite and alkali granite phases was collected for Rb/Sr whole rock and mineral isotopic investigation. Weathered samples, and areas adjacent to intrusive contacts were avoided. The syenite suite was derived solely from the southern outcrop, while the granite suite comprised samples from the northern, central and southern outcrops. Whole rock splits of 130-200gm, and mineral separates of 0.07-0.1gm were taken from 0.4-1.2kg of crushed rock. Average grainsize for the syenites was 5mm, and for the granites, 2mm. Details of experimental methods and McIntyre-style regressions are given in Appendix 1.

3.6.2 Previous geochronological studies

Previous geochronological investigations of the Red Hill intrusion are limited to that of Stuckless et al (1981), who investigated the U-Th-Pb systematics of the Mt. Boreas-type granite and the syenites in a regional study of the northeastern Yilgarn Block. Only four samples from Red Hill were included. An imprecise Pb-Pb age of 2760 ± 210 Ma was obtained for the syenites, which included three analyses from Red Hill. Bunting et al (1980) used an initial ratio from the work of De Laeter and Lewis (1978) at Fitzgerald Peaks near Norseman, to calculate a model Rb-

Sr age of 2367 Ma for a syenite sample 35km south of Red Hill. Stuckless et al (1981) compared this syenite model Rb-Sr age to the Pb-Pb age of the Mt. Boreas-type granitoid (2370 ± 100 Ma), and concluded that the syenite Rb-Sr system was reset by the intrusion of the Mt. Boreas-type granitoid.

The current study was undertaken to investigate the Rb-Sr isotope systematics of the syenites and related alkali granites on a local scale.

3.6.3 Rb-Sr whole rock geochronology

Nineteen whole rock analyses were performed, including six Group 1 and two Group 2 syenites, and seven Group 1 and four Group 2 granites (Table 3.10). One syenite sample (120) was omitted from the regression analyses (Table 3.11), due to apparently disturbed isotope systematics, which when combined with a relatively high Rb/Sr ratio, exerted undue influence on the regression analyses.

A seven point regression for the combined syenites yields a poorly fitted Model 2 age (MSWD 8.7) of 2430 ± 61 Ma and an apparent initial $^{87}Sr/^{86}Sr$ ratio of 0.70178 ± 0.0088 (Fig 3.13). Removal of Group 2 syenite samples from the regression does not significantly effect the apparent age, yielding 2432 ± 462 Ma, with an apparent initial $^{87}Sr/^{86}Sr$ ratio of 0.70160 ± 0.009 (MSWD 944). A six point regression including Group 1 and 2 samples derived from the southern outcrop only yields a poorly fitted Model 2 age (MSWD 788) of 2466 ± 359 Ma, with an apparent initial $^{87}Sr/^{86}Sr$ ratio of 0.7010 ± 0.0076.

A seven point regression for Group 1 granites yields a slightly better fitted Model 2 age (MSWD 5.4) of 2528 ± 71 Ma, and an apparent initial $^{87}Sr/^{86}Sr$ ratio of 0.70146 ± 0.00101 (Fig 3.14). A four point regression for Group 2 granites yields an imprecise Model 3 age (MSWD 11.8) of 2621 ± 198 Ma, and an erroneously low initial $^{87}Sr/^{86}Sr$ ratio of 0.69967 ± 0.00305. Combination of all eleven granite samples yields a poorly fitted Model 3 line (MSWD 12.9), with an apparent age of 2558 ± 62 Ma, and an apparent initial $^{87}Sr/^{86}Sr$ ratio of 0.70081 ± 0.00106. These regressions are reviewed in the following discussion (Chap. 3.6.5).

3.6.4 Rb-Sr mineral geochronology

In an attempt to provide more meaningful results than those obtained above, pyroxene and feldspar mineral separates were analysed for one syenite and one granite sample.

A four point whole rock-mineral isochron (MSWD 2.16), considered a Model 1 isochron using the method of Brooks et al (1972), resulted for sample 120 of the Group 1 syenite. This regression included two whole rock analyses, including the one omitted from the whole rock regression, one feldspar and one pyroxene analysis. The resulting age was 2471 ± 30 Ma, with an initial $^{87}Sr/^{86}Sr$ ratio of 0.70191 ± 0.00084 (Fig 3.15).

The pyroxene separate from sample 105 of the Group 1 granite displayed significant isotopic disturbance, and regression of this analysis with one feldspar and one whole rock analysis yielded a poorly fitted Model 2 apparent age (MSWD 6.1) of 2125 ± 144 Ma, with an apparent initial $^{87}Sr/^{86}Sr$ ratio of 0.70736 ± 0.00141.

3.6.5 Discussion

The Rb-Sr ages determined for the two phases at Red Hill exhibit scatter in excess of experimental variation. In the case of the syenites and the Group 1 granites, the Model 2 ages suggest variation in $^{87}Sr/^{86}Sr$ proportional to $^{87}Rb/^{86}Sr$. The Group 2 granites yield a Model 3 age, which suggests variation in $^{87}Sr/^{86}Sr$ independent of $^{87}Rb/^{86}Sr$.

Field evidence outlined above clearly establishes that the granites intrude the syenites, and the obtained Rb-Sr ages, which suggest the opposite, are thus meaningless in terms of crystallisation ages. Plots of $^{87}Sr/^{86}Sr$ against Sr and SiO_2, which can be used to demonstrate examples of isotopic mixing (Faure 1977), show no evidence of mixing either within or between the two rock types and their subgroups. Both rock types are interpreted to have undergone significant post-crystallisation isotopic disturbance, which resulted in partial resetting of the isotopic systematics. This is consistent with the suggestion of Stuckless et al (1981), who concluded that the syenite isotope systematics were reset by the intrusion of the Mt. Boreas-type granitoid. The related alkali granites have been shown to have undergone the same process. The effect of the intrusion of the alkali granites on the older syenite isotope systematics, if any, cannot be deduced. While the apparent initial $^{87}Sr/^{86}Sr$ ratios obtained for the above regressions are meaningless in absolute terms, they suggest originally low values - complete isotopic resetting results in higher values for the $^{87}Sr/^{86}Sr$ ratios, and the fact that the partially reset rocks display $^{87}Sr/^{86}Sr$ ratios less than 0.702 suggests original ratios comparable to those of the Gilgarna Rock intrusion.

Despite failing to fully delineate the local crystallisation history at Red Hill, the data support the concept of two late Archaean igneous events in the Sir Samuel region, as outlined in the detailed study of Cooper et al (1978) in the Agnew area, some 125 km southwest of Red Hill.

Given the wide geographic separation of the two areas, and the significantly different tectono-stratigraphic regimes in which they occur, a detailed comparison between the two areas is not geologically sensible. This is further emphasised by postulated fundamental genetic differences, with Cooper et al (1978) suggesting partial melting of pre-existing tonalites, and partial melting of tholeiitic material, for the origins of the leucogranites and leucotonalites, respectively, while the syenitic rocks of the felsic alkaline suite are consistent with production via partial melting of relatively anhydrous deep-seated depleted source regions of granulitic affinity (see subsequent discussion, and Chapt. 7).

Nevertheless, the age of 2558 ± 62 Ma for the combined Red Hill granites is within error of the Cooper at al (1978) leucogranite age of 2573 ± 11 Ma (all data normalised to the E & A standard value of the current study, and re-regressed). The low initial $^{87}Sr/^{86}Sr$ ratio of the former at 0.7008, however, is at variance with that of the latter at 0.7020. The combined Red Hill syenite age of 2430 ± 61 Ma bears no relationship to the Agnew data, however, the well-fitted mineral-whole rock isochron of sample 120 of the Group 1 syenite (MSWD 2.16), with an age of 2471 ± 30 Ma, is indistinguishable from an age of 2476 ± 12 Ma for the aplitic leucotonalite of Cooper et al (1978). Similarly, an initial $^{87}Sr/^{86}Sr$ ratio of 0.70191 for sample 120 is indistinguishable from the leucotonalite initial ratio of 0.70173. A 23-point combined regression of the leucotonalite data and the mineral-whole rock data from Red Hill syenite sample 120 yields an age of 2472 ± 9 Ma, and an initial $^{87}Sr/^{86}Sr$ ratio of 0.70178.

The Agnew leucogranites and Red Hill granites then, reflect an event at 2560-2570 Ma, and the Agnew leucotonalites and Red Hill syenite mineral-whole rock data reflect an event at 2475 Ma. Given the interpretation of the Agnew data as crystallisation ages (Cooper et al 1978), the Red Hill data can be interpreted as reflecting a Rb-Sr isotopic resetting of the Red Hill granites in response to the leucogranite-related event at 2573 Ma, and of the Red Hill syenite (sample 120) in response to the leucotonalite-related event at 2476 Ma. The degree of rehomogenisation of the isotope systematics of the syenites and granites may be a function of the relative proximity of the different samples to a younger intrusion. In addition, although the mineralogies of the two rock types are similar, with the exception of abundances of plagioclase and quartz, differences in the mineralogies on a local scale may have determined the degree of resetting, as suggested by Field and Raheim (1979).

The poorly fitted whole rock-mineral age of 2125 Ma from sample 105 of the Group 1 granites is similar to some of the Fitzgerald Peaks data, where an age of 2160 Ma is considered to reflect the initial influence of a major crust-forming event in the neighbouring Albany-Fraser Orogen that culminated at 2000 Ma (see Chap. 4). Red Hill is located some 70 km from the Capricorn Orogen that exhibited a similar history to the Albany-Fraser Orogen, and it is possible that this younger age reflects similar processes.

3.7 Summary

Partial resetting of the Rb-Sr isotope systematics in response to regional intrusive events has rendered absolute age determinations invalid at Red Hill. However, the long-lived nature of mildly alkaline magmatism as demonstrated at Gilgarna Rock, is supported by the presence of the alkali granite suite intruding the related syenite suite at Red Hill. Generally low abundances of incompatible elements, fractionated REE character, the presence of residual garnet aggregates, a suggestion of originally initially low $^{87}Sr/^{86}Sr$ ratios, and overall geochemical character is consistent with the derivation of the Red Hill intrusion from a depleted source, such as the garnet granulite of basic affinity postulated for the Gilgarna Rock intrusion, some 380km to the south. As with the Gilgarna Rock intrusion, emplacement of the Red Hill intrusion appears to have been facilitated by the presence of a deep seated crustal rift, in this case the Celia Fault.

CHAPTER 4 THE PETROGRAPHY, GEOCHEMISTRY AND GEOCHRONOLOGY OF THE FITZGERALD PEAKS INTRUSION

4.1 Introduction

The Fitzgerald Peaks occur 96km south-southwest of Norseman in the Eastern Goldfields Province, lying within the Lake Johnston sheet of the 1:250000 GSWA geological series (Gower and Bunting 1974). The intrusion represents the southern-most and largest example of the felsic alkaline suite, with outcrop of syenite and related alkali granite occurring over 120 square km (Fig. 4.1). The area is dominated by Peak Charles (Fig. 4.2A) and Peak Eleanora, two prominent syenite peaks which rise 300m above the surrounding granite plain.

A previous study yielded an imprecise Rb-Sr whole rock age (De Laeter and Lewis 1978), which suggested the possibility of Proterozoic alkaline magmatism. Fitzgerald Peaks was included in the current study to attempt, with the benefit of more detailed petrological and geochemical data, to more precisely define the age of the body, and to investigate any trends in age within the felsic alkaline suite along the length of the Eastern Goldfields Province.

4.2 General geology

4.2.1 Introduction

Fitzgerald Peaks occurs within the eastern structural zone of Gower and Bunting (1976), which consists almost entirely of a single large batholith of biotite adamellite and porphyritic granodiorite, covering an area of over 6000 square km. The contact between the Fitzgerald Peaks intrusion and the surrounding batholithic granitoid is obscured by extensive deposits of Cainozoic calcreted clay, silt and sand, and eolian dunes and sheets. Scattered porphyritic granodiorite outcrops occur west of Peak Charles, and east-southeast of Peak Eleanora. At Dog Rock, 17 km southwest of Peak Charles, which lies within the central structural zone of Gower and Bunting (1974), porphyritic granodiorite occurs with nebulitic migmatite.

The syenite intrusion lies between the Koolyanobbing Fault and a major associated splay, as defined by Myers and Hocking (1988), which occur 10km to the east and west, respectively. Minor greenstone outcrops occur near Salmon Gums 45km to the east, close to the contact of the Eastern Goldfields Province with the Proterozoic Albany-Fraser Province. The nearest areally significant greenstones occur in the Bremer Range 45km to the northwest.

4.2.2 Rock types and contact relationships

The bulk of the outcrop at Fitzgerald Peaks consists of syenite, quartz syenite and related pyroxene granite, henceforth termed the syenites. The suite consists of light pink to pink medium to occasionally coarse grained inequigranular assemblages, with a clotty heterogeneous appearance (Fig. 4.2C). Mafic minerals occasionally define a weak preferred orientation.

In the northwestern and central western extremes of the outcrop area, an additional phase consisting of alkali granite to quartz monzonite and quartz syenite occurs, henceforth termed the granites. This phase has commonly been termed biotite adamellite by previous workers. The granites consist of light grey to pink medium to coarse grained inequigranular assemblages, with the mafic minerals defining a weak to moderate preferred orientation (Fig. 4.2B).

Coarse to very coarse grained pegmatitic segregations of several generations occur mainly within the syenites. Multiple variations in form, size and orientation are such that no consistent intrusive relationships can be established.

In general, there are no distinct mappable units at Fitzgerald Peaks, with imperceptible gradational contacts between the two main phases occurring over several metres. On a regional scale however, largely based on outcrop pattern, the granites appear to be related to a later intrusive or remobilisation event concentrated on the margins of the syenite intrusion. The heterogeneous nature of both phases, and in particular the granites, is evidenced by the common occurrence of streaky banding, lenses and pods, principally defined by concentrations of mafic minerals. Monomineralic stringers consisting of alkali pyroxene are present in places almost down to single crystal thickness, and can commonly be traced for several metres. The weak foliation present in both phases exhibits a random pattern within the interior of the body, but tends to parallellism with the interpreted margin of the intrusion as this zone is approached.

In the current study, samples of the granites were collected from the northwestern outcrops of the intrusion west of Peak Charles, and the regional batholithic granitoid (Fig. 4.2D) was sampled from Dog Rock for comparative purposes. All samples of the syenite suite were collected at distances of 4 km or more from areas of known granite occurrence, to avoid the seemingly hybrid samples present in these areas.

In the classification scheme of De La Roche et al (1980), the syenitic rocks plot predominantly as syenite, with minor quartz syenite, while the granitic rocks range from granite and alkali granite to quartz monzonite and quartz syenite. The regional batholithic granitoids plot as granites.

4.2.3 Previous studies

The aeromagnetic and radiometric survey of Wells (1962), which included the Fitzgerald Peaks area, has been used by subsequent workers to define the probable extent of the syenitic rocks. Turek (1966) sampled a "quartz-microcline rock" from Peak Charles and gave a whole rock-feldspar Rb/Sr age of 1670 Ma, which he interpreted as anomalously low due to the loss of ^{87}Sr from the feldspar. Gower and Bunting (1976) recognised the unusual nature of the syenite intrusion during regional mapping, and suggested that the age data of Turek (1966) could be valid. They described a mafic band consisting of hornblende, diopside and calcic oligoclase, which they interpreted as fine grained basic granulite. The granitic rocks in the northwestern part of the intrusion were thought to be intermediate in character between the syenite and surrounding regional porphyritic biotite adamellite. Belford (1977) and Lewis and Gower (1978) described some of the petrographic and geochemical characteristics of the body, and suggested a deep crustal origin. De Laeter and Lewis (1978) reported a poorly fitted Rb/Sr Model 4 age of 2360 Ma, with an initial $^{87}Sr/^{86}Sr$ ratio of 0.70436, and suggested that all the syenite intrusions of the Eastern Goldfields Province were of similar age. Libby (1989) tabulated the petrographic character of samples collected by the GSWA. On the basis of the high initial $^{87}Sr/^{86}Sr$ ratio of De Laeter and Lewis (1978), and lithological heterogeneity, he classed the Fitzgerald Peaks as an atypical syenite locality. He compared the "biotite adamellite" of the northwestern part of the intrusion (part of the granitic suite of this study), to the so-called Boreas-type rocks of the northern Eastern Goldfields, and suggested that given the similarity of the Fitzgerald Peaks syenite Rb/Sr age (De Laeter and Lewis 1978) to that of the Boreas suite (Stuckless et al 1981), the syenites may have undergone resetting of the Rb/Sr isotopics, during intrusion of the Boreas-type magma.

4.3 Petrography

4.3.1 Introduction

The medium to coarse grained subhedral to anhedral inequigranular heterogeneous syenitic rocks consist of 70-90% alkali feldspar, 0-5% plagioclase, 0-20% quartz, 2-12% alkali pyroxene and 1-2% alkali amphibole, and accessory titanite, apatite, magnetite, zircon, epidote and calcite (Fig. 4.2F).

The granitic rocks display similar textures, are often of hybrid appearance, and exhibit a wider range of mineral abundances than the syenitic rocks. They are composed of 30-85% alkali feldspar, 0-45% plagioclase, 5-30% quartz, 0-5% pyroxene, 1-2% amphibole, 0-2% biotite/chlorite, and accessory titanite, magnetite, apatite, fluorite, zircon, allanite, calcite and epidote (Fig. 4.2E).

The batholithic granite sampled at Dog Rock consists of a medium to coarse grained subhedral to anhedral assemblage of 40% oligoclase, 30% microcline, 20-30% quartz, 1-8% biotite, and accessory magnetite, titanite, apatite, epidote, zircon, and allanite (Fig. 4.2H), (see Appendix 3 for petrographic descriptions).

4.3.2 Feldspars

The alkali feldspar of the syenites comprises a complex array of hypersolvus crystals displaying varying degrees of unmixing. These crystals are always anhedral and commonly consertal-textured, and include microcline perthite, and fine to medium/coarse-scale mesoperthite and antiperthite (Fig. 4.2F). Within the granites, the alkali feldspars consist of microcline perthite to mesoperthite (Fig. 4.2E).

The minor amounts of plagioclase within the syenites consist of albite to oligoclase, possibly representing complete unmixing of the original hypersolvus feldspar. Very minor amounts of plagioclase occur as cores to perthite, and while extensively altered, appear to be sodic oligoclase. Plagioclase is a more common constituent of the granites, varying from albite to sodic oligoclase in composition.

4.3.3 Pyroxenes

Pyroxenes of the syenite suite occur in irregularly distributed clots and aggregates as subhedral to anhedral prisms, often poikilitic and occasionally displaying incipient corrosion. Although somewhat variable, the green colouration is characteristic of aegirine-augite.

Occasional zoning suggests an increase in the proportion of the aegirine molecule from core to rim. Minor late-stage uralitic alteration to alkali amphibole is common (Fig. 4.2G).

Where present, pyroxenes of the granite suite display similar character to those of the syenites, although they range from aegirine-augite to salite/augite in composition.

4.3.4 Amphiboles

Compositionally variable alkali amphibole occurs as a patchy uralitic replacement of the alkali pyroxene of both phases, and contains the speckling of magnetite and blebby quartz characteristic of this reaction (Fig. 4.2G). Reliable optical classification is difficult due to the patchy nature of the amphibole, however a diverse collection of compositions ranges from riebeckite-arfvedsonite to probable sodic hornblende.

4.3.5 Biotites

Biotite in appreciable quantities is observed only in some samples of the granite suite, where it is present as a primary phase, is partly altered to chlorite, and exhibits similar character to the biotite of the Dog Rock batholithic granite samples. Within other samples of the granite suite, and within the syenite suite, biotite occurs in trace amounts only, as an alteration product of amphibole.

4.3.6 Accessory minerals

While there are differences in abundance of the accessory minerals between the syenites and the granites, there are no major differences in terms of petrographic character.

Ubiquitous orange-brown titanite forms up to 2% of both the syenites and granites, occurring both as fine grained euhedral to subhedral lozenges, and as fine to medium grained subrounded to embayed anhedral blebs. Minor rim and fracture alteration is common.

Fine to medium grained euhedral to subhedral apatite is a particularly common accessory in the syenites, while present in trace amounts only in the granites. Subhedral to euhedral magnetite is a common accessory of both phases, accounting for the well-defined magnetic anomaly associated with the intrusion. Trace epidote and very fine grained zircon occurs in both phases. Primary calcite is more common in the syenites, while fluorite and rare allanite occur only in the granites.

4.3.7 Discussion

The Fitzgerald Peaks syenites display assemblages typical of the felsic alkaline suite, containing mildly alkaline pyroxenes subject to minor uralitic alteration to amphibole, low contents of quartz, and complex hypersolvus feldspars. The heterogeneous nature of these rocks is not a common feature of the felsic alkaline suite, however similar heterogeneity is observed at Twin Peaks (see Chap. 5), and to a lesser extent, at Red Hill. This may be a result of initial magma heterogeneity, of assimilation of country rock during emplacement, or of partial melting and mixing with a younger intrusive phase.

The agpaiitic crystallisation sequence usually observed within peralkaline granites and syenites (O'Halloran 1985) is better defined at Fitzgerald Peaks than for many other examples of the felsic alkaline suite. Whereas pyroxene tends to accompany feldspar precipitation at Gilgarna Rock and Red Hill, poikilitic pyroxene enclosing feldspar, quartz and titanite is common at Fitzgerald Peaks. The minor amounts of sodic oligoclase observed in some alkali feldspar cores reflect early sodic plagioclase crystallisation which, with continued cooling, gave way to anorthoclase precipitation as seen at Gilgarna Rock and Red Hill.

Libby (1989) suggested that the granitic rocks at Fitzgerald Peaks were similar to the Mount Boreas-type granitoids of the northern Eastern

Goldfields Province. On the basis of petrographic character, however, the granitic rocks are perhaps best viewed as intermediate between the syenites and surrounding batholithic granitoids, as first suggested by Gower and Bunting (1976). Some aspects of the whole rock geochemical data are not inconsistent with such a proposal (see Chap 4.5).

4.4 Mineral Chemistry

4.4.1 Introduction

Analyses were performed at the Electron Optical Centre of the University of Adelaide, and pyroxene and amphibole classifications and recalculations are as previously described. Three samples of the granitic suite from the western area of the intrusion, one sample of the batholithic granite from Dog Rock, and one sample of the syenitic suite from the eastern area of the intrusion were selected for analysis.

4.4.2 Feldspars

The composition of discrete plagioclase crystals within both the syenites and granites is invariably albitic, while in the batholithic granitoid, oligoclase is present (Table 4.1). Pure potash feldspar is always the host phase of the perthites of both the syenites and granites, and the only variation occurs in the exsolved material, where in the most granitic of the western granite suite, it is sufficiently calcic to be classed as sodic oligoclase.

4.4.3 Pyroxenes

While alkali pyroxenes of aegirine-augite affinity are common at Fitzgerald Peaks, neither of the pyroxene-bearing samples chosen for analysis displays particularly alkaline examples, with the syenite containing ferrosalite, and the granite containing ferrosalite-ferroaugite (Table 4.2, Fig. 4.3). There is very little variation within each group. Within the syenites, rims tend to have slightly higher Mg/Fe ratios than cores, however there is no consistent indicator of the prevailing oxidation state of the magma at the time of pyroxene precipitation. Within the granite, where pyroxenes are in fact slightly more alkaline than those of the syenite, cores tend to be ferrosalitic, while rims are ferroaugitic.

4.4.4 Amphiboles

The uralitic amphiboles of the analysed samples are not particularly alkaline (Table 4.3, Fig. 4.4). A monzogranite sample contains edenitic hornblende cores with edenitic rims, with a slight increase in oxidation towards the rims. The syenite sample contains actinolite, with rims and cores displaying very similar $Mg/Mg + Fe^{2+}$ ratios, but with the rims having a lower Si content.

4.4.5 Biotites

Biotite analyses from a monzogranite of the granite suite and from the batholithic granite display markedly different compositions (Table 4.4). The monzogranite analyses are phlogopitic, lying close to the phlogopite-biotite boundary of the biotite quadrilateral, and displaying low Al^{IV} values. The batholithic granite analyses, however, exhibit significantly higher Al^{IV} and Fe/Fe + Mg values, and plot well within the biotite field.

4.4.6 Accessory minerals

The abundant titanite present in both main phases contains only minor amounts of rare earth elements (Table 4.5), recorded here as "other" elements. Rims are generally slightly higher in REE and Fe, and lower in Ti than cores. Moderate to strong alteration occurs in one sample, where Fe and Ti dominate at the expense of Ca and Si.

Significant amounts of Si are present as alien ions in apatites of the syenites and granites, together with Al, Mg and Na in the batholithic granites (Table 4.6). Very minor amounts of REE were detected in the core of one sample of granite only.

4.4.7 Discussion

While emphasising the differences between the syenites and granites of the Fitzgerald Peaks intrusion, and the batholithic granite, the mineral chemistry data provide a suggestion of a relationship between the three phases. The granite suite samples display a greater affinity to the syenites than to the batholithic granites, yet do share some of the characteristics of the latter. The simplest explanation of this feature is by invoking assimilation of batholithic granite by the syenite magma during emplacement. Variations in factors such as the size of batholithic granite volumes incorporated into the syenite magma, the extent of assimilation at any given site, and possible existing heterogeneties within the batholithic granite and/or the syenite could account for the overall heterogeneous nature of the intrusion. This possibility is best examined via study of whole rock major and trace element data.

4.5 Whole rock geochemistry

4.5.1 Introduction

Major element analyses were determined by XRF, with the exception of Na_2O (AAS) and Fe_2O_3 (titration). Trace elements were determined by XRF, with the exception of F, which was determined by specific ion electrode analysis. Full details of experimental methods are given in Appendix 1.

4.5.2 Major element geochemistry

Members of the syenite group display a relatively restricted range of silica values from 64-67%, while the granites range from 69-77% SiO_2 (Fig. 4.5, Table 4.7). While the granites display a relatively continuous spectrum of major element values versus silica on variation diagrams, the syenites plot as two distinct groups. In the case of TiO_2 and P_2O_5, the syenite group consisting of samples 139, 143 and 145, henceforth termed the Group 2 syenites, defines a trend coincident with that of the granite group. For all other major elements, while these samples lie at the low silica end of the granite group, trends are not coincident.

The granite group displays some scatter for values of Na_2O, and particularly K_2O. Al_2O_3, Na_2O and K_2O values are somewhat higher in the syenites than the granites, but for all other major elements, considerable overlap exists. With the benefit of isotopic data (see Chap 4.6), subtle differences within the granite suite are detectable. Group 1 granites display consistently lower TiO_2 and Al_2O_3 values and higher MgO and CaO values than Group 2 granites, and relatively consistent values for Al_2O_3, total iron and Na_2O against SiO_2, while Group 2 granites exhibit considerable scatter in K_2O values.

Fe_2O_3 values are invariably higher than FeO for all samples, reflecting consistently oxidised conditions of crystallisation. Trend lines for the two syenite groups and the granites as a whole tend to converge at a point corresponding to the following composition: 63.5% SiO_2, 0.65% TiO_2, 16.2% Al_2O_3, 3.3% FeO*, 0.80% MgO, 4.2% CaO, 5.7% Na_2O, 4.9% K_2O, and 0.25% P_2O_5 (Fig. 4.5).

Samples of the batholithic granitoid from Dog Rock display a wide range of chemistries, despite having virtually identical mineralogies. In general, these samples tend to occur within the field of the granite group (Fig. 4.5, Table 4.7). An exception occurs for Na_2O, where values are lower than those of the granite group. The more biotite-rich sample from Dog Rock (137) is significantly higher in TiO_2, FeO* and MgO than the other Dog Rock sample and the granite group.

On a log plot of K_2O vs Rb (Fig. 4.6), the granite samples exhibit a well-defined hydrothermal trend. The syenite samples define a more magmatic trend, but with the suggestion of some late hydrothermal influence. A linear plot of K_2O vs Rb (Fig. 4.5) reveals a scatter of K_2O and Rb values and a flat trend for the Group 2 granites, consistent with the influence of a late-stage exsolved fluid phase.

The average syenite composition exhibits significantly higher values of SiO_2, slightly higher values of Na_2O and K_2O, significantly lower values of FeO*, MgO and CaO, and slightly lower values of TiO_2 than the average syenite of Le Maitre (1976). The average granite composition corresponds closely with the average granite of Le Maitre (1976), but displays elevated Na_2O and K_2O values.

In the R_1R_2 scheme of De La Roche et al (1980), the syenite suite consists of syenite, with minor quartz syenite, while the granite suite comprises granite, alkali granite, quartz monzonite and quartz syenite (Fig. 4.7). The regional batholithic granitoids plot as granites.

Both the syenite and granite groups are metaluminous, and vary only slightly either side of unity for values of the peralkaline index, while the batholithic granitoid samples are peraluminous.

4.5.3 Trace element geochemistry

Trace elements are plotted against Nb, which exhibits a wide range of values and enables clear distinction between the syenite and granite groups (Fig. 4.5). The syenites plot predominantly in the range of 30-45 ppm Nb, while the granites plot between 5-20 ppm Nb. Low incompatible element abundances are consistent with those observed elsewhere within the suite, suggesting a depleted source.

In general, the syenites display quite uniform values of all other elements againt Nb. Subtle distinction between the two granite groups is evident, with Group 2 granites exhibiting a negative trend for V vs Nb, and a positive trend for Ga vs Al_2O_3, while the reverse applies for the Group 1 granites. In addition, Group 2 granites have uniformly higher Zr contents for the same values of SiO_2, flat trends of Sr, Ba and Nd against Nb, and scattered values of Ce, all consistent with significant hydrothermal modification, as indicated by the K_2O vs Rb plot. The Group 2 syenite samples that show some affinity with the granites in terms of major elements, exhibit general departure from syenite trace element trends, but the differences are not as well defined here. The batholithic granites display marked variation, particularly for V, Zr, La, Ce, Nd and Ba.

A hygromagmatophile plot normalised to the N-type MORB mantle source of Wood et al (1979) reveals very similar patterns for average values for the syenite and granite suites as a whole (Fig. 4.8). The exceptions are relative positive Th and Zr anomalies present in the granites, consistent with the greater influence of late stage exsolved fluid phases observed in the granites. In general, both phases exhibit less fractionated HYG-element distributions than many other members of the suite, but have similar patterns to the Gilgarna Rock syenites, with the exception of slightly larger negative Sr anomalies, and significantly lower negative Ti anomalies at Fitzgerald Peaks.

4.5.4 Normative mineralogy

Both the syenites and granites contain Ab in excess of Or, while the batholithic granites contain equal proportions (Table 4.8). An is a minor constituent only of the syenites, more common in the granites, and present in quantities of up to 6% in the batholithic granites. The syenites display Di to 4%, and trace Ac, with 1-9% Q. The granites have up to 3% Di, and 15-30% Q, while the batholithic granites exhibit up to 3% C, and 24-30% Q. Contents of Il, Mt and Ap show no significant variation between the three groups.

4.5.5 Discussion

While the syenites, granites and batholithic granites are readily distinguished in geochemical terms, no clear relationships are discernible, particularly in terms of trace elements. Significant late hydrothermal modification is apparent in the trace element geochemistry of the Group 2 granites in particular. The major element geochemistry yields the best evidence for the origins of the syenite and granite phases. A convergence of trends at a silica value of around 63% suggests a relationship between the two phases, consistent with petrographic evidence, with this value representing a composition consistent with a parent syenite magma. Group 1 syenite compositions are consistent with progressively evolving crystallisation of this parent magma. Group 2 syenite samples exhibit a relationship with the granites, best explained by invoking varying degrees of mixing between the syenite and granitic phases at different sites. The granites themselves are consistent with a mix of varying proportions between the original syenite magma, and a more siliceous end-member, which is represented reasonably well by the surrounding batholithic granite country rock. In general, the geochemical nature of the intrusion, and the heterogeneity within and between the various phases observed in the field, is not conducive to sensible quantitative geochemical modelling.

The scenario most consistent with the geochemical evidence is the following :

1) Intrusion into the batholithic granite of a parent syenite magma with a composition of approximately 63.5% SiO_2, 0.65% TiO_2, 16.2% Al_2O_3, 3.3% FeO*, 0.80% MgO, 4.2% CaO, 5.7% Na_2O, 4.9% K_2O, and 0.25% P_2O_5, with the possibility of minor incomplete mixing of the evolving syenite magma and the batholithic granite, at this stage.

2) Further incomplete mixing of the syenite magma with much larger volumes of the batholithic granite, principally in the western and northwestern contact zones, and significant modification of the resulting granites, particularly Group 2, via the influence of late exsolved fluids.

The absence of clear-cut intrusive relationships between the granite and syenite phases, with imperceptible gradational boundaries between the two, suggests either contemporaneity of the two phases, or minor remelting and mixing of the syenite, in contact regions with the later intrusive granite phase.

4.6 Geochronology

4.6.1 Introduction

The original isotopic study of de Laeter and Lewis (1978) involved analysis of samples collected during regional mapping of the area, chosen primarily to obtain as wide a range of Rb/Sr values as possible. Their six-point regression included "biotite adamellites", "leucocratic alkali granites", and two samples of intermediate character. Their estimate of the age and initial ratio of the intrusion of 2360 ± 96 Ma, and 0.70436 ± 0.00225, respectively, was a Model 4 age, indicating variation in age and initial ratio in the data itself, in addition to experimental variation. With the benefit of further data from the detailed petrographic and geochemical work of this study, the Model 4 result is not surprising, given the demonstrable differences between the samples used in the regression, and their age and initial ratio estimates are considered meaningless.

The sample suite collected for the current study was divided into groups consistent with petrographic and geochemical observations. A total of 21 samples, comprising three Group 1 granites, with two mineral separates, five Group 2 granites, six Group 1 syenites with two mineral separates, and three Group 2 syenites was selected for analysis.

4.6.2 Rb-Sr whole rock geochronology

A total of seventeen analysed whole rock samples reveals considerable scatter in isotopic ratios for the Fitzgerald Peaks intrusion as a whole, largely as a result of the different isotopic character of the geochemical subgroups outlined above (Table 4.9). Given the interpretation of the current study, a regression of analyses involving all phases from the intrusion is clearly geologically meaningless.

Regression of all syenite samples yields a Model 3 age of 2120 ± 75 Ma, with an initial $^{87}Sr/^{86}Sr$ ratio of 0.70426 ± 0.0009 (MSWD 7.05). However, Group 2 syenites exhibit clear departure from the regression line, and the age is not considered a meaningful isochron. Regression of the six Group 1 syenite analyses yields a Model 2 age of 2162 ± 147 Ma, with an initial $^{87}Sr/^{86}Sr$ ratio of 0.70355 ± 0.00182 (MSWD 3.18). The three Group 2 syenites yield an indistinguishable Model 3 age of 2157 ± 285 Ma, with an initial $^{87}Sr/^{86}Sr$ ratio of 0.70421 ± 0.0027 (MSWD 3.2) (Fig. 4.9, Table 4.10).

Regression of all granite samples yields a Model 3 age of 2519 ± 171 Ma, with an initial $^{87}Sr/^{86}Sr$ ratio of 0.70074 ± 0.00306. The large MSWD value of 112 reflects the demonstrably different isotopic character of the Group 1 and Group 2 granites, and the resulting age is meaningless. A regression of the three Group 1 granites yields a Model 2 age of 2143 ± 1006 Ma, with an initial $^{87}Sr/^{86}Sr$ ratio of 0.70499 ± 0.0089 (MSWD 2.79). The five Group 2 granite analyses yield a Model 2 age of 2450 ± 122 Ma, with an initial $^{87}Sr/^{86}Sr$ ratio of 0.70297 ± 0.00225 (MSWD 6.23) (Fig. 4.10, Table 4.10).

The significant errors accompanying these regressions are to some degree, a result of the small number of samples involved, and the limited range in $^{87}Rb/^{86}Sr$ ratios that they display. Given the relatively low values for the MSWD function, particularly for the syenites and Group 1 granites, and the modifications of Brooks et al (1972) to the regression method of McIntyre et al (1966), there are grounds for arguing that these results could be realistically viewed as Model 1 isochrons. The significance of these results, however, is best interpreted following consideration of the mineral data outlined below.

4.6.3 Rb-Sr mineral geochronology

Feldspar and pyroxene mineral concentrates were obtained from one sample of the Group 1 syenites, and one sample of the Group 1 granites.

A three point regression of the Group 1 syenite whole rock-mineral analyses yields an excellent fit Model 1 age of 2350 ± 140 Ma, with an initial $^{87}Sr/^{86}Sr$ ratio of 0.70138 ± 0.00106 (MSWD 0.17). A combined regression of all Group 1 syenite whole rock and mineral data yields an indistinguishable, albeit Model 2 age, of 2329 ± 36 Ma, with an initial $^{87}Sr/^{86}Sr$ ratio of 0.70143 ± 0.00023 (MSWD 7.08) (Fig. 4.9, Table 4.10).

A three point regression of the Group 1 granite whole rock-mineral analyses yields an excellent fit Model 1 age of 2165 ± 147 Ma, with an initial $^{87}Sr/^{86}Sr$ ratio of 0.70467 ± 0.00096 (MSWD 0.20). A combined regression of all Group 1 granite whole rock and mineral data yields a well-fitted Model 1 age of 2174 ± 32 Ma, with an initial $^{87}Sr/^{86}Sr$ ratio of 0.70468 ± 0.00024 (MSWD 1.23) (Fig. 4.10, Table 4.10).

4.6.4 Discussion

The regression analyses outlined above indicate a complicated isotopic history for the various phases of the Fitzgerald Peaks intrusion, involving re-setting on various scales, and indications of significant heterogeneities within the complex. The isotopic character of intrusions such as these may be influenced by a number of factors.

McCarthy and Cawthorn (1980) outlined changes in initial Sr ratios that can arise during protracted fractionation in igneous complexes, where whole rock regressions for an entire complex produce errorchrons, whereas data subsets may provide useful results. It has been demonstrated that such regression treatments are applicable to the current example, which has important implications for the original nature of initial Sr ratios throughout the intrusion (see following discussion), however, geochemical evidence dictates that any original variation in initial ratios is not a function of protracted fractionation within the intrusion.

Lutz and Srogi (1986) and Lutz et al (1988) studied the effects of hydrothermal alteration on the isotope systematics of igneous rocks emplaced in the upper crust. Such alteration is thought to be virtually synchronous with crystallisation, with hydrothermal convection persisting for less than 1 Ma (Norton and Taylor 1979). Lutz and Srogi (1986) argued that data sets yielding inaccurate ages and initial ratios as a result of hydrothermally-induced Sr additions cannot be detected by considering MSWD values, as the slope of the regression line itself incorporates the systematic error. Lutz et al (1988) concluded that the possibility of variation in scales of Sr isotopic equilibration in such cases, required analysis at least down to mineral separate scale. Gerstenberger (1989) outlined autometasomatic Rb enrichments in granites which resulted in lowered initial ratios, while leaving isochron slopes undisturbed. While the effects of autometasomatic processes are apparent at Fitzgerald Peaks, particularly for the Group 2 granites where Rb contents are higher than Group 1 granites, the difference in apparent age and initial ratio between the two granite phases is not well explained by Rb enrichments, and the effects of such a process here, if any, are undetectable.

Of more significance is the interaction of the three igneous phases, (incorporating five subgroups viz. Group 1 and 2 syenites, Group 1 and 2 granites, and the batholithic granitoid), involving relative timing of intrusion, and heterogeneities apparent in field, petrographic and geochemical data.

The excellently fitted Group 1 syenite whole rock-mineral regression yielding an age of 2350 Ma exhibits a low initial Sr ratio of 0.70138, which is of the order of initial ratios derived from the excellent-fit lines of the Gilgarna Rock syenites (see Chap. 2), the well-fitted whole rock-mineral isochron of the Group 1 syenite from Red Hill (see Chap. 3), and elsewhere within the suite (Libby and de Laeter 1981). The combined Group 1 syenite whole rock and mineral analyses regression exhibits considerable scatter (MSWD 7.08), yet records an indistinguishable age and initial ratio. This regression, however, is dominated by the low Rb-Sr pyroxene analysis, and given the result when the mineral analyses are omitted, is considered meaningless.

The Group 1 syenite whole rock analyses alone yield a significantly younger age and higher initial ratio, of 2162 Ma and 0.70355, respectively. This result is indistinguishable from that of the Group 2 syenites, which yield 2157 Ma and an initial ratio of 0.70421. In addition, these ages and initial ratios are indistinguishable from those of the Group 1 granites (see following discussion).

Re-setting of original Rb-Sr isotope systems in response to later events has been demonstrated by many studies (eg Field and Raheim 1979, Chapman et al 1981), and in the case of a reset volume of rock exhibiting originally uniform initial $^{87}Sr/^{86}Sr$ ratios, whole rock-mineral isochrons commonly record younger ages than whole rock isochrons alone, depending on variations in range and style of the Rb-Sr distribution (Roddick and Compston 1977). The results from the Fitzgerald Peak syenites are considered to reflect differences in initial Sr ratios, in addition to a range of Rb/Sr values, within the original magma. This may have occurred as a result of minor assimilation of a granitic phase as suggested by the geochemical evidence, particularly for the Group 2 syenites, or as a result of original magma heterogeneity. The balance of petrographic and geochemical evidence suggests the former, and the simplest explanation for the origin of this contaminating granitic phase is the batholithic granite.

Original isotopic heterogeneity within the syenites would have resulted in a series of parallel whole rock-mineral isochrons with a range of initial ratios, depending on the prevailing isotopic character of a particular site. A regression of whole rock analyses alone, in such a case, would clearly yield an errorchron and initial ratio of no geological significance. Isotopic resetting in such a case, however, could result in a valid age dating the time of resetting, and the syenite whole rock ages clearly reflect a younger age. The Group 1 granite whole rock-mineral and whole rock regressions yield indistinguishable ages and initial ratios. Given the consistent resetting displayed by whole rock analyses of both syenites, and the fact that the Group 1 syenite mineral separates were obtained from a sample within metres of four other analysed whole rock samples, it is difficult to interpret the syenite whole rock-mineral age as an age of crystallisation. Even given incomplete resetting throughout the syenites, it is unlikely that any site would completely escape modification. Despite the excellent fit of the regression, and the low initial ratio characteristic of the felsic alkaline suite, the Group 1 syenite whole rock-mineral age can only realistically be viewed as a minimum age, and the initial ratio, a maximum estimate of the original ratio.

The syenite whole rock ages and Group 1 granite whole rock-mineral and whole rock ages reflect an event at approximately 2160 Ma. Examples of similar Rb-Sr ages within the Yilgarn Block are not well documented. The interpreted age of 2188 Ma for the Gearless Well intrusion from the Murchison Province (see Chap. 6), the 2021 Ma Mt. Weld carbonatite (Collerson in Willett et al 1989) occurring some 480 km to the northeast, and examples of the mafic dyke suite (eg 2420 Ma, Turek (1966); 2085 Ma, Roddick (1974)), are not directly applicable to the current study. A similar whole rock-mineral age, however, has been obtained for the Group 1 granite from Red Hill (2125 Ma, see Chap. 3).

Perhaps of most relevance is the Sm-Nd work of Fletcher et al (1983), which indicated a widespread crust-forming event in the southwestern Proterozoic Albany-Fraser Province at about 2000 Ma. While Fitzgerald Peaks is remote from their area of study, it is only 20 km from the southern boundary of the Yilgarn Block with the southeastern extension of the Albany-Fraser Province. Hallberg (1987) considered the southern margin of the Yilgarn Block to have been tectonically active between 2400-2000 Ma. The 2160 Ma age then, may well reflect processes related to the early stages of the crust-forming event prior to it's culmination at about 2000 Ma.

Despite the excellent fit of the Group 1 granite whole rock-mineral and whole rock ages, and the close agreement with the syenite whole rock ages, it is not clear whether the 2160 Ma age reflects a crystallisation age for the granites, the intrusion of which which reset the syenites, or an isotopic resetting of the whole intrusion, in response to the activity outlined above. In any case, the original isotopic character of the granites must have been relatively homogeneous, given the indistinguishable whole rock-mineral and whole rock ages. Without further supporting evidence, the Group 1 granite ages can only realistically be viewed as minimum ages, but the possibility that they closely approximate ages of crystallisation cannot be discounted.

Given the geochemical evidence outlined above, the Group 1 granites are thought to represent a mixture of syenitic and granitic phases, the latter represented by the batholithic granite. The relatively high initial Sr ratios of 0.704 are consistent with contamination of the syenitic magma via incorporation of this granite.

In the light of the above discussion, the significantly older apparent age of the Group 2 granites at 2450 Ma, is difficult to interpret. The regression line may reflect a spurious alignment of samples of original isotopic heterogeneity, similar to that of the syenites, that have undergone significant post-crystallisation disturbance. With the influence of autometasomatism evident in the geochemistry of the Group 2 granites, possible original isotopic heterogeneity, and the indecipherable influence of the 2160 Ma event on these samples, the significance of the 2450 Ma age remains problematic.

If this age represents a close approximation to the crystallisation age, the initial Sr ratio reflects contamination by a crustal (granitic) phase, consistent with the geochemical evidence.

4.7 Summary

The syenites and related rocks of the Fitzgerald Peaks intrusion represent an unusual example of the felsic alkaline suite. The intrusion occurs in the vicinity of a major northwest-trending crustal structure which may have facilitated emplacement from a deep source. Markedly heterogeneous lithologies exhibit imperceptible gradational contacts. On the basis of petrographic and geochemical evidence, the granitic suite resulted from a mixture of syenitic and granitic phases, the latter probably represented by the batholithic granitoid country rock. A composition for the original parent syenite magma can be estimated from a convergence of trends on major element variation diagrams. Geochemical evidence indicates subgroups within the syenite and granite phases.

A Rb-Sr whole rock mineral age of 2350 Ma represents a minimum estimate for the time of intrusion of the syenite magma. The accompanying initial Sr ratio of 0.70138 is similar to that observed elsewhere within the suite, and with low incompatible element contents, suggests derivation from a depleted source. The disparity between whole rock-mineral and whole rock ages for the syenites suggests original isotopic heterogeneity for these rocks. Isotopic disturbance is particularly evident in syenite whole rock regressions, and reset ages of 2160 Ma are recorded in both subgroups. Group 1 granites display whole rock-mineral and whole rock ages indistinguishable from the syenites. The significance of this granite age is not clear - it may represent a close approximation to the crystallisation age of relatively isotopically homogeneous granites, or the time of isotopic resetting. In the former case, the age of approximately 2160 Ma can only be viewed as a minimum age. The Group 2 granites exhibit an older apparent age, the significance of which remains uncertain.

Regardless of the significance of the 2160 Ma age to the origin of the Group 1 granite, this age is thought to reflect major tectonic activity near the southern margin of the Yilgarn Block, that culminated in a major crust-forming event in the neighbouring Proterozoic Albany-Fraser Province around 2000 Ma.

CHAPTER 5 FURTHER MEMBERS OF THE FELSIC ALKALINE SUITE WITH EXAMPLES OF OTHER FELSIC INTRUSIVES OF THE EASTERN YILGARN BLOCK, AND COMPARISON WITH SIMILAR FELSIC ALKALINE ROCKS WORLDWIDE

5.1 Introduction

Further members of the felsic alkaline suite occur within the Norseman, Widgiemooltha, Kurnalpi, Edjudina, Leonora, Laverton, Sir Samuel, Wiluna and Nabberu sheets of the 1:250000 GSWA geological series (Fig.5.1), and the most prominent are indicated on the 1:2500000 geological map of W.A., compiled by Myers and Hocking (1988). In general, many of these intrusions are smaller, less well exposed and more deeply weathered than the three examples outlined previously (Chapts 2, 3 & 4). With the exception of the studies of Libby (1978, 1989), principally in the Edjudina area, little or no previous work has been carried out on these smaller intrusions.

Following the suggestions of Libby (1978), one or more of the following characteristics is necessary for inclusion in the felsic alkaline suite here: low contents of quartz (<20%), the presence of alkali pyroxene or alkali amphibole as a major modal phase, or the presence of mesoperthitic alkali feldspar.

5.2 Selected members of the suite from the Widgiemooltha sheet

5.2.1 Introduction

A suite of samples was collected from the area of the Widgiemooltha sheet of the 1:250000 GSWA geological series (Griffin & Hickman 1988) (Fig. 5.2.1). These included examples from the Erayinia Granitoid Complex, in the north-eastern corner of the sheet area, which although displaying low contents of quartz (<7%), are predominantly two-feldspar quartz-deficient monzonites. The syenites south-east of Binneringie on the south shore of Lake Cowan, north-northeast of the abandoned Madoonia Downs Homestead, and west of Hogan's Find on the north shore of Lake

Lefroy were sampled, and two samples of the regional batholithic granitoid were included for comparison. Libby (1989) includes one chemical analysis from the syenite west of Hogan's Find, one from the syenite southeast of Binneringie, and three others from minor outcrops elsewhere within the sheet area.

5.2.2 Rock types and field relations

The extensive multi-phase Erayinia Granitoid Complex (Fig 5.2.1) consists predominantly of foliated hornblende biotite monzogranite, with minor porphyritic granodiorite (Griffin 1989). In the R_1R_2 classification scheme of De La Roche et al (1980), samples collected in the current study plot as quartz syenites to syenites (see Fig. 4.7). This is principally due to microcline-albite dominant assemblages with low quartz contents, and only one sample from the southern extreme of the body displays mesoperthitic feldspar. Weathering within the complex is extensive, small biotite-rich xenoliths are common, and although hornfelsed mafic volcanics occur on the western contact, contacts with the surrounding greenstones are largely obscured by Quaternary colluvium.

An isolated syenite plug of approximately 2 square km in area intrudes granitoid and greenstones 8km north-northeast of the abandoned Madoonia Downs homestead. It consists of albite-dominant quartz-poor amphibole-rich syenite to quartz monzonite (Fig 5.2.2C) and occasional sub-parallellism of plagioclase feldspar laths suggests possible igneous flow textures. Contacts with the surrounding granitoid-greenstone lithologies are obscured by Tertiary Eundynie Group sediments and Quaternary colluvium.

A larger syenite intrusion of approximately 7 square km crops out on a headland on the south shore of Lake Cowan, 12km south-southeast of Binneringie homestead. The intrusion consists of two main phases, a somewhat heterogeneous light pink to grey-white equigranular syenite (Fig. 5.2.2B), and a more pyroxene-rich pink syenite displaying a distinctive subparallellism of alkali feldspar laths (Fig. 5.2.2A), mainly confined to the northeastern part of the outcrop. A weak to moderate foliation dips steeply to the west throughout the body, and minor north-south trending shear zones are present, particularly on the northeastern side of the body. Contact relationships within the intrusion are poorly defined, and contacts with the surrounding granitoid and greenstone are obscured by Eundynie Group sediments, colluvium, and lake sediments.

On the north shore of Lake Lefroy, 6km west of Hogan's Find, a small area of less than 1 square km contains a swarm of narrow parallel syenite dykes intruding high-Mg metabasalt. The dykes consist of leucocratic and occasionally porphyritic, pyroxene-rich alkali feldspar-dominant syenite, and represent one of the more alkaline syenite occurrences from the Widgiemooltha sheet.

Samples of the regional batholithic granitoid were taken from a relatively fresh outcrop 17km southeast of Binneringie homestead, and a small more deeply weathered outcrop 9km southwest of Cowarna Downs homestead. They consist of inequigranular partially recrystallised typical two-feldspar biotite granite to alkali granite.

In contrast with many of the members of the felsic alkaline suite elsewhere within the Eastern Yilgarn, most of the occurrences on the Widgiemooltha sheet are apparently not closely associated with major north-south trending faults. The exception is the intrusion northeast of Madoonia Downs, which lies close to the north-south trending fault that passes just east of Cowarna Downs homestead (Griffin 1989). In the central and eastern parts of the sheet area, however, the apparent lack of major structural features is probably a result of very poor basement exposure, rather than an indication of a different structural regime.

5.2.3 Petrography and mineral chemistry

Samples from the Erayinia Granitoid Complex consist of inequigranular subhedral to anhedral medium to coarse grained assemblages of microcline, albite, pyroxene, quartz, amphibole and minor chlorite, with accessory titanite, magnetite, apatite, and zircon. Epidote is a common late stage product occurring in association with opaques and pyroxene/amphibole. Alkali feldspars are occasionally perthitic, sometimes approaching mesoperthitic, and commonly display albite overgrowths. Plagioclases are invariably albitic (Table 5.2.1), and distorted twin lamellae imply mild cataclasis. Pyroxene is present in quantities up to 10%, and is generally salitic, with one sample (046) displaying slightly more Fe-rich rims than cores (Fig. 5.2.3, Table 5.2.2). Amphibole occurs both as large discrete grains, and as a replacement product of pyroxene, and in sample 046 is ferroedenitic in composition (Fig 5.2.4, Table 5.2.3). The sample from the southern extreme of the complex consists of an anhedral inequigranular assemblage of mesoperthitic unmixed anorthoclase (displaying albite rims and overgrowths), minor albite, pyroxene, quartz, and accessory magnetite, titanite, apatite, fluorite, allanite and calcite. The possibility of hydrothermal action in this area is suggested by strongly altered pyroxenes and titanites, late-stage feldspar-quartz veins containing appreciable accessory fluorite, and elevated values for some trace elements.

The small intrusion 8km north-northeast of Madoonia Downs consists of a medium to coarse grained subhedral inequigranular to seriate assemblage of albite, alkali feldspar, amphibole, remnant pyroxene, quartz, and accessory titanite, magnetite, zircon, apatite, and allanite. Albite overgrowths are common on the albite laths and large anhedral alkali feldspar grains. Pyroxenes are moderately to strongly altered, but where identifiable appear to be salite. Amphibole occurs largely as a replacement product of pyroxene (Fig. 5.2.2D), and exhibits a wide range of compositions from magnesiohornblende to actinolitic hornblende and actinolite (Fig 5.2.4, Table 5.2.3). Rims tend to be more siliceous and slightly more iron-rich than cores, although the reverse applies in some cases.

The syenite intrusion southeast of Binneringie usually displays a polygonal crystalloblastic texture, and in places has undergone up to 80% recrystallisation. The pyroxene-rich lath-textured phase consists of a medium to coarse grained subhedral assemblage of unmixed anorthoclase, and pyroxene, with minor amphibole and quartz, and accessory magnetite, titanite, apatite, zircon, and epidote (Fig. 5.2.2E). The coarse alkali feldspar laths vary from perthite to antiperthite and mesoperthite, and occasionally display microcline-rich rims (Table 5.2.1). Pyroxenes exhibit a range of compositions from salite to ferrosalite and minor ferroaugite, with rims invariably more iron-rich than cores, and in one case (052), having the composition of sodian augite (Fig 5.2.3, Table 5.2.2). Amphibole is present in minor amounts as a late-stage product replacing and occurring in aggregates with pyroxene, and ranging in composition from magnesian hastingsitic hornblende to magnesian hastingsite (Fig 5.2.4, Table 5.2.3). Partially metamict zoned zircon occurs as relatively coarse crystals up to 1mm in size, by far the largest observed in all the occurrences of the felsic alkaline suite. One sample (052) contains ragged aggregates of andradite (Table 5.2.4), of very similar composition to that observed at Red Hill, some 520km to the north. Magnetite is present in quantities up to 3%. The heterogeneous equigranular syenite phase consists of a medium to coarse grained subhedral to anhedral crystalloblastic assemblage of unmixed anorthoclase, pyroxene, and minor quartz, albite, amphibole and biotite/chlorite, with accessory magnetite, titanite, zircon, apatite, and epidote. The alkali feldspar includes perthite, antiperthite and mesoperthite, and is often zoned (Fig. 5.2.2F, Table 5.2.1). Pyroxenes are salitic, with rims more iron-rich than cores, and are subject to minor replacement and rimming by actinolite to actinolitic hornblende (Tables 5.2.2, 5.2.3). Zircons are generally relatively coarse grained, as observed in the lath phase.

The syenites of the dyke swarm west of Hogan's Find exhibit an overall petrographic character very similar to that of the medium phase syenite fron Gilgarna Rock. They consist of a medium to coarse grained subhedral inequigranular assemblage of alkali feldspar and pyroxene, with minor quartz, biotite and amphibole, and accessory titanite, apatite, and allanite. The alkali feldspars are superbly zoned and often euhedral unmixed anorthoclases, some with albitic cores and either K-rich or mesoperthitic rims (Table 5.2.1). Pyroxenes consist of diopsidic cores, with markedly different rim compositions of ferroaugite to sodian augite and aegirine-augite (Fig. 5.2.3, Table 5.2.2). Amphibole is present in one sample as a magnesioriebeckitic replacement product of pyroxene, biotite in trace amounts is associated with pyroxene aggregates, and quartz generally comprises less than 1% of the mode. One sample contains ragged aggregates and, somewhat unusually, discrete euhedral crystals of andradite (Table 5.2.4), similar to that observed east of Binneringie, and elsewhere within the suite.

A sample of the granitoid southwest of Cowarna Downs consists of a subhedral inequigranular somewhat recrystallised and moderately deformed assemblage of oligoclase (with bent and kinked twin lamellae, (Fig. 5.2.2G), and widespread colourless mica alteration), microcline, quartz and biotite, with accessory magnetite and zircon.

5.2.4 Major and trace element whole rock geochemistry

While variation diagrams outline distinctive aspects of the geochemical character of the four intrusions sampled from the Widgiemooltha sheet, diagrams involving immobile incompatible elements such as La, Ce and Nd also suggest a relationship between them (Fig. 5.2.5, Table 5.2.5). Given the large area of 6200 square km covered by the sampling program, it is hard to imagine production of the demonstrably linear trends displayed by La vs. Ce and Nd vs. Ce plots, from unrelated magmas. These trends argue for a common source region for the intrusions, and while all of the major element data, and much of the other trace element data display some scatter, this may simply reflect slightly different chemistries in the source regions, or in some cases, interaction with, and perhaps local assimilation of, the country rock during emplacement. A hygromagmatophile plot normalised to the N-type MORB mantle source of Wood et al (1979) demonstrates the geochemical similarity of the four intrusions, and the lack of a relationship with the regional batholithic granitoid (Fig 5.2.6). Similar slopes to the Gilgarna Rock syenites are observed, but the Widgiemooltha bodies generally exhibit greater elemental abundances, and display marked positive Ba anomalies, and marked negative Nb anomalies.

While the Erayinia, Binneringie and Hogan's Find intrusions lie on reasonably compatible trends on variation diagrams, the Madoonia Downs body often exhibits significant departure from these trends. It is depleted in Al_2O_3, V, Y, Ce, Nb, La and Nd, and enriched in FeO*, MgO, CaO, Na_2O and P_2O_5. In addition, it is strongly depleted in K_2O and Rb. The low abundances of the incompatible and related elements attest to the depleted nature of the source region, while the higher than expected abundances of the mafic elements for the prevailing values of SiO_2 suggest assimilation of a mafic component during emplacement. The common presence of plagioclase-amphibole xenoliths of several cms in size within the intrusion, and biotite schist adjacent to the intrusion in part, lend some support to this suggestion. La/Ce and Nd/Ce ratios remain unaffected, and the Madoonia Downs body lies on the lower end of the trends for these elements displayed by the Widgiemooltha bodies as a whole.

The two related phases sampled from the Binneringie intrusion display consistent linear major element trends. Despite the lack of supporting field evidence, geochemical evidence suggests the lath phase to be the more primitive. Slightly divergent trends in all trace element plots, and the generally higher abundance of incompatibles in the lath phase, are consistent with relative enrichment of the incompatible elements in the earlier formed lath phase, and as a result, lower abundances in the later formed equigranular phase from the same even further depleted source region.

The syenites from the dyke swarm near Hogan's Find lie in or near the field of the equigranular syenites from Binneringie for most elements, except Al, Mg, Ca, P, V, Ga, Zr and Nb. These discrepancies are largely explained by the higher abundance of pyroxene and apatite in the syenite dykes, reflecting differences in the chemistries of the depleted source regions. In the case of Mg, Ca, V, Ga, and the differentiation index, the syenite dykes are closely associated with the trend defined for the Erayinia samples. In addition, while the Madoonia and Binneringie samples all describe magmatic trends on a plot of K_2O v Rb (Fig 5.2.7), the Erayinia and Hogan's Find samples display hydrothermal, or metasomatic trends.

5.2.5 Normative mineralogy

With the exception of several samples from the Binneringie syenites, which are Ne normative, all other samples are Q normative, particularly those from Madoonia and Erayinia (Table 5.2.6). The lath syenites from Binneringie are metaluminous and mildly alkaline, with normative Di, Wo and minor An, while the equigranular syenites are metaluminous to peraluminous and subalkaline, with normative Di and a trace of Hy. The Madoonia samples are metaluminous and Ab-dominant, with significant Di and Hy, while the Erayinia samples are subalkaline, with minor An, Di and trace Hy. The Hogan's Find dykes are the most alkaline, with one sample containing normative Ac.

5.2.6 Rb-Sr isotope geochronology

Given some similarities of the two-phase Binneringie syenite intrusion to the Gilgarna Rock intrusion, a preliminary Rb-Sr investigation was carried out on the former (Table 5.2.7). Despite careful sampling to provide the widest possible range of Rb/Sr values from the intrusion, the uniformly low Rb and uniformly high Sr values resulted in extremely short isochrons. The inclusion of feldspar and pyroxene separates, which normally display significant differences in Rb/Sr ratios, did little to increase the length of the isochrons, and the resulting large statistical errors of the regression analyses were not able to be overcome (Fig. 5.2.8, Table 5.2.8).

A nine-point regression of all whole rock and mineral analyses from both phases, excluding a spurious whole rock sample (163) from the somewhat heterogeneous equigranular syenite, results in an age of 2470 ± 77 Ma, with an initial $^{87}Sr/^{86}Sr$ ratio of 0.70117 ± 0.00010 (MSWD 2.5).

Removal of the equigranular syenite analyses results in a six-point regression of lath phase analyses only, with an age of 2445 ± 104 Ma, and an initial $^{87}Sr/^{86}Sr$ ratio of 0.70118 ± 0.00014 (MSWD 2.89). A four-point whole rock-mineral regression for lath sample 052 gives an age of 2428 ± 164 Ma, with an initial $^{87}Sr/^{86}Sr$ ratio of 0.70122 ± 0.00024 (MSWD 1.27).

Given the modifications of Brooks et al (1972) to the regression methods of McIntyre et al (1966), all these regressions are Model 1 isochrons, and are indistinguishable. While it is possible that there is some difference in age between the lath and equigranular phases, it does not appear to be as significant as that observed at Gilgarna Rock between the medium and coarse phases, and with a relatively small number of samples and a very restricted range of Rb/Sr values, is undetectable. The age of 2470 ± 77 Ma is thus interpreted as the best approximation to the crystallisation age of the Binneringie intrusion. The low initial $^{87}Sr/^{86}Sr$ ratio of 0.70117 ± 0.0001 indicates the depleted nature of the source region, and is of the same magnitude as the initial ratios from Gilgarna Rock (eg coarse phase 2542 ±14 Ma, IR 0.70145 ± 0.00009).

5.2.7 Summary

Despite the wide separation of the four main intrusions sampled, and a wide range of petrographic and geochemical character, incompatible element plots imply a common source region for the parent magmas. Geochemical scatter observed for the Madoonia Downs intrusion is probably a result of assimilation of mafic country rock during emplacement. The multi-phase Erayinia Granitoid Complex includes some undoubted examples of the felsic alkaline suite, but overall is dominated by more granitic phases - it is possible that some of the samples included in this study are from hybrid bodies. The Binneringie and Hogan's Find intrusions are more representative of the felsic alkaline suite as observed elsewhere. The best approximation to a crystallisation age for the Binneringie body of 2470 Ma indicates it to be one of the younger members of the suite, and the low initial ratio of 0.7012 demonstrates again the depleted nature of the source regions for these bodies.

5.3 Selected members of the suite from the Kurnalpi sheet

5.3.1 Introduction

In addition to the Gilgarna Rock syenites described earlier, a suite of samples was collected from the eastern part of the Kurnalpi sheet of the 1:250000 GSWA geological series (Williams et al 1971) (Fig 5.3.1).

Granites were sampled from Claypan Dam southeast of Old Pinjin homestead, Bulyairdie Rocks, Yindi Rock and Dingo Rock, for comparison to the local felsic alkaline rocks. Quartz syenites were sampled from the western edge of Lake Roe, and at Cardunia Rocks, and the porphyritic monzodiorite from Gilgarna Rock was included.

5.3.2 Rock types and field relations

The granites at Claypan Dam, Bulyairdie Rocks and Yindi Rock intrude predominantly mafic volcanics, although in all cases contacts are obscured by recent cover. The Claypan Dam body is a dark grey foliated biotite-rich granite, while Bulyairdie Rocks consists of porphyritic hornblende granite. At Yindi Rock, pink-white foliated biotite granite occurs with fine to medium grained aplitic alkali granite. The small grey porphyritic monzodiorite occurring within the Gilgarna Rock syenite body covers an area of only a few square metres, and may be a large xenolith.

Dingo Rock occurs in the northern part of the Erayinia Granitoid Complex of Griffin et al (1988), but in contrast to some of the samples from the Widgiemooltha sheet area, none of these samples display petrographic characteristics of the felsic alkaline suite. They do however, correspond with quartz monzonite to quartz syenite in the R_1R_2 chemical classification scheme (see Fig. 2.5D). Of the granites, those from Bulyairdie Rocks have the closest petrographic affinity to the felsic alkaline suite, in that alkali feldspars are occasionally mesoperthitic and quartz contents are modest (see Fig. 2.5C).

The Lake Roe body consists of pink quartz syenite with a weak mineral lineation, intruding obscured mafic volcanics and felsic porphyries. Cardunia Rocks consists of massive jointed leucocratic quartz syenite to alkali granite. These two intrusions display alkali pyroxenes typical of the felsic alkaline suite.

While there are no major crustal faults in the eastern Kurnalpi sheet according to the interpretation of Myers and Hocking (1988), all sampled localities lie close to a southeasterly extrapolation of the Keith-Kilkenny Fault, or within a corridor defined by the southward extrapolation of the Keith-Kilkenny and Celia Fault systems.

5.3.3 Petrography and mineral chemistry

The Claypan Dam granite consists of an equigranular medium grained subhedral assemblage of oligoclase, microcline, quartz, biotite, and minor chlorite, muscovite and epidote, with accessory titanite, apatite, zircon, opaques and allanite. Oligoclases are zoned, becoming more albitic towards the rims (Table 5.3.1). Yindi Rock is comprised of a virtually identical equigranular medium grained subhedral assemblage - zoned oligoclases are commonly myrmekitic, and are often enclosed by poikolitic microclines, and quartz exhibits incipient recrystallisation. In contrast, Bulyairdie Rocks consists of an inequigranular medium to coarse grained subhedral assemblage of albite/oligoclase, microcline, quartz, amphibole, with minor chlorite and epidote, and accessory magnetite, apatite, titanite, and zircon. The albite to oligoclase is occasionally antiperthitic, with microcline perthite rims (Table 5.3.1). Microcline is sometimes perthitic to mesoperthitic, and with quartz contents of 12-20%, these samples show some affinity to the felsic alkaline suite. Primary amphiboles range from cores of actinolitic hornblende, to rims of magnesiohornblende and actinolite (Table 5.3.3, see Fig. 2.8). The monzodiorite from Gilgarna Rock consists of a medium to coarse grained euhedral to anhedral phenocryst assemblage of oligoclase, microcline and hornblende, in a fine grained groundmass of the same components, with accessory titanite, apatite, fluorite, epidote and barite. The rock is moderately epidotised in part, and contains minor coarse pyrite crystals.

Samples from the Dingo Rock vicinity consist of inequigranular subhedral to anhedral medium to coarse grained assemblages of microcline, albite, quartz, amphibole and minor chlorite and epidote, with accessory opaques, titanite, apatite, zircon and fluorite (see Fig. 2.6H). Small ovoid biotite-amphibole rich syenogabbro xenoliths are common. Primary amphiboles consist of edenite to edenitic hornblende cores, with consistently less siliceous and less magnesian rims ranging to magnesian hastingsitic hornblende (Table 5.3.3). None of these samples exhibit the salitic pyroxenes observed in the southern part of the intrusion on the Widgiemooltha sheet.

The quartz syenite from Lake Roe consists of a medium to coarse grained inequigranular to porphyritic subhedral to anhedral assemblage of microcline, albite, quartz and alkali pyroxene, with accessory magnetite, titanite, zircon, apatite and allanite. Albite is occasionally antiperthitic, showing evidence of mild cataclasis, and microcline is perthitic to mesoperthitic. The pyroxene is aegirine-augitic in composition, and minor amounts of andradite occur in ragged aggregates associated with the pyroxene. An almost identical fine to medium grained equigranular anhedral assemblage occurs in the Cardunia Rocks quartz syenites to alkali granites some 30km to the south (see Fig. 2.6G), although pyroxene as the only ferromagnesian mineral here comprises less than 2% of the rock. The albites are virtually pure sodic feldspars, and rarely antiperthitic, while microcline is occasionally perthitic to mesoperthitic with albite rims (Table 5.3.1). Quartz is present in quantities of 20-25%. Pyroxenes are aegirine-augites, with an increase in the aegirine component from core to rim, and there is trace development of magnesioriebeckite in places (Table 5.3.2, see Fig. 2.7). As observed at Gilgarna Rock, calcite occurs as a late-stage interstitial product. Andradite aggregates display compositions typical of those observed in other suite members, and accessories consist of titanite and magnetite, and rare allanite, zircon and fluorite.

5.3.4 Major and trace element whole rock geochemistry

Five geochemically distinct groups are evident within the Kurnalpi intrusions, and all are quite distinct from the Gilgarna Rock syenites (see Fig. 2.9). They consist of the Claypan Dam/Bulyairdie group, the Yindi group, the Lake Roe/Cardunia group and the Dingo group occurring over a narrow range of SiO_2 from 69-72%, and the Gilgarna monzodiorites which range from 62-64% SiO_2.

Linear trends for most element combinations suggest a relationship between the Gilgarna monzodiorites and the Claypan/Bulyairdie group, with the former representing the primitive Si-poor magmas, and the latter corresponding to the more evolved Si-rich magmas (see Fig 2.9). A hygromagmatophile plot normalised to the N-type MORB mantle source of Wood et al (1979) demonstrates the similarity in overall pattern between the two groups, and the relatively fractionated character of the Claypan/Bulyairdie group (Fig. 5.3.2). The Cardunia intrusion exhibits a similar pattern to that observed for the Cowarna Downs granitoid from the Widgiemooltha sheet. The typical Yilgarn biotite granites from Yindi exhibit some similarities, yet lack evidence of sufficient fractionation to represent an evolved version of these rocks.

Indications of a relationship between the Dingo and mildly alkaline Roe/Cardunia groups are observed in plots of most major elements against SiO_2, and Ba vs K_2O. However, despite the high SiO_2 values and almost complete absence of ferromagnesian minerals in the latter group, normally implying more highly fractionated character, the hygromagmatophile contents of the Roe/Cardunia group do not exhibit such fractionated character and are of uniformly lower abundance than the Dingo group. The Dingo group closely corresponds to the hygromagmatophile character of the Erayinia Granitoid Complex from the Widgiemooltha sheet, but as outlined earlier, does not display any of the petrographic character necessary for inclusion in the felsic alkaline suite. In combination with other Erayinia samples, the Dingo group defines a hydrothermal, or metasomatic trend on a plot of K_2O vs Rb (Fig. 5.3.3), as does the Roe/Cardunia group, the latter being particularly well-defined.

The clear distinction between the five groups and the Gilgarna Rock syenites is particularly evident in trace element plots (see Fig. 2.9), with the former defining a completely separate field over a restricted range of significantly lower Nb values. While on petrographic grounds the Roe/Cardunia syenite/alkali granite group is a member of the felsic alkaline suite, any geochemical relationship is harder to define, due to the presence of a significant compositional gap between these rocks, and the Gilgarna Rock syenites, for example. However, extrapolation of element-element trends across this gap does yield suggestions of a linear relationship in many cases, and the Roe/Cardunia rocks are viewed as an unusually high-Si member of the suite.

5.3.5 Normative mineralogy

The Claypan/Bulyairdie and Yindi groups yield very similar normative compositions, with 6-8% An, 20-25% Qz, and trace Hy, and are peraluminous and non-alkaline (Table 5.3.5). In addition, both groups contain minor amounts of normative corundum. The metaluminous non-alkaline Gilgarna monzodiorites display up to 10% An, and significant Di and Hy. The Dingo group contains 4% An, 17% Qz, minor Di and Hy, varies from peraluminous to metaluminous, and is sub-alkaline. Samples from the Roe/Cardunia group exhibit less than 1% An, 18% Qz, trace Di and rare Ac, are metaluminous, and lie on the peralkaline/subalkaline border.

5.3.6 Summary

Petrographic and geochemical data outline significant differences between the Roe/Cardunia intrusions, and the other Kurnalpi groups discussed. The Roe/Cardunia rocks represent an unusual example of the felsic alkaline suite, given the almost complete absence of ferromagnesian minerals and the high quartz contents. Despite these features, these rocks are not the evolved products of a fractionationed magma, and there is no compelling evidence for assimilation of large quantities of high-Si granites. The hygromagmatophile-depleted character is consistent with production from a depleted source similar to other members of the suite, and the presence of andradite as seen in several other suite members, and interpreted as a relic of the source region, attests to this. The depleted source region for these rocks may have been slightly more felsic than that applying for many other members of the suite.

5.4 Selected members of the suite from the Edjudina sheet

5.4.1 Introduction

Intrusions sampled from the southwestern portion of the Edjudina sheet of the 1:250000 GSWA geological series (Williams et al 1973), included the complex Twin Peaks syenite/monzodiorite body, the Twelve Mile Well syenite, the Cement Well/Hamdorf Bore syenite, and the McAuliffe Well syenite. In addition, the Eucalyptus syenite/alkali granite from the central north of the sheet area, and several granitoids from Foley Well and Windy Well, southeast of Edjudina homestead, and from Menangina Rocks, were sampled (Fig. 5.4.1).

5.4.2 Previous studies

The alkaline intrusions of the southwestern area of the Edjudina sheet have been perhaps the most studied members of the felsic alkaline suite, prior to this study. Honman (1917) described some aspects of the McAuliffe Well body. Libby (1978, 1989) outlined some of the petrographic character of the McAuliffe Well, Hamdorf Bore, Tassy Well, Twelve Mile Well and Red Lake bodies, and in the more recent work, published a dozen chemical analyses, principally from the Twelve Mile Well/Twin Peaks area. Libby and De Laeter (1981) determined a Rb/Sr age of 2489 ± 82 Ma for the Twelve Mile Well intrusion, with an initial Sr ratio of 0.7012 ± 0.0003, which by implication (although not stated), is interpreted as a crystallisation age. The large one sigma experimental errors applied to their six-point regression are more than double those applying to this study, and are largely responsible for the low MSWD of 0.97, resulting in a Model 1 date. Nevertheless, this age is within the range defined for other members of the suite. No isotope work on this or any other bodies in the area was carried out in the current study. Hallberg (1985) mentioned the occurrence of syenites within the Keith-Kilkenny and Laverton tectonic zones. He related their relative abundance in these zones, particularly the former, to a major oversaturated peralkaline predominantly granitic plutonic event, which was a direct result of late extensional tectonic activity.

5.4.3 Rock types and field relations

Twin Peaks consists of two markedly heterogeneous syenite and monzodiorite/monzonite bodies intruding the regional batholithic granodiorite. Two distinct phases are identified on petrographic and geochemical grounds, a relatively melanocratic syenite, and a relatively leucocratic quartz monzodiorite (Fig. 5.4.2D). These phases occasionally occur together in layered outcrops, with sharp intrusive margins between adjacent syenitic and monzodioritic layers. In addition, a third monzodiorite/monzonite phase occurs as coarse grained crosscutting dykes within the layered outcrops (Fig 5.4.2A), and elsewhere as a medium to coarse grained heterogeneous rock, accounting for the bulk of the intrusion. Mafic schlieren, aggregates, clots and stringers composed principally of pyroxene are common throughout the intrusion. The northern outcrop at Twin Peaks is subdivided into a number of discrete outcrops by what appears to be a conjugate northeast/northwest-trending shear set. The contact with the surrounding deeply weathered granodiorite is a diffuse markedly heterogeneous zone containing abundant schlieren, particularly on the western margin. At Twelve Mile Well, 3km southwest of Twin Peaks, a similarly heterogeneous body consists of syenite, in places heavily epidotised, with abundant mafic schlieren and xenoliths (Fig.

5.4.2B) Complex pegmatite, quartz and syenite veining occurs on the contact with the surrounding granodiorite.

At Cement Well (the Hamdorf Bore locality of Libby), a small homogeneous syenite plug intrudes a hornblende-biotite granite (Fig. 5.4.2 C,E,F), and forms the axis of several finer grained radiating syenite dykes. The body at McAuliffe Well, 25km to the north, is the largest and most well exposed member of the alkaline suite in the region, covering an area of approximately 3 square km. It consists of quartz syenite intruding mafic volcanics, with associated dykes of quartz syenite to alkali granite (Fig. 5.4.2G).

A very poorly exposed and deeply weathered porphyritic syenite to alkali granite (Fig. 5.4.2H) occurs 25km northeast of Mt. Remarkable homestead, in the Eucalyptus vicinity. The subcrop is characterised by scattered coarse alkali feldspar phenocryst float, and an absence of mafic minerals due to extensive weathering.

The regional batholithic granitoids at the Foley Well and Windy Well localities consist of leucocratic quartz-rich granites. At Menangina Rocks, leucocratic alkali granite dykes intrude an occasionally porphyritic biotite granite.

Most of the syenite localities of the southwestern Edjudina sheet occur within the Keith-Kilkenny Tectonic Zone of Hallberg (1985), but only the McAuliffe Well body lies close to the Keith-Kilkenny Fault. The Eucalyptus body occurs on a minor but regionally extensive fault within the Murrin-Margaret Sector of Hallberg (1985), and this author indicates several small bodies associated with hornblende granodiorite in this zone, including two virtually coincedent with the Mt. Hornet fault, southeast of Eucalyptus.

5.4.4 Petrography and mineral chemistry

The syenite phase of the Twin Peaks intrusion is characterised by a microcline and pyroxene-dominant quartz-poor assemblage. It consists of medium grained subhedral to anhedral microcline perthite, up to 30% pyroxene, albite/oligoclase, less than 1% quartz and amphibole, and accessory opaques, apatite, titanite, zircon and epidote. Pyroxenes are generally salitic, and the amphibole, which in places is seen to be replacing pyroxene, is hornblende. In one sample, pyroxenes appear to be sodian augite, and are undergoing replacement by blue-green amphibole which may be magnesioriebeckite. The quartz monzodiorites consist of oligoclase-dominant medium to coarse grained assemblages of up to 20% quartz, with salitic pyroxene replaced to varying degrees by hornblende, trace microcline and accessory titanite, apatite, opaques and epidote (Fig. 5.4.3C). The rest of the intrusion consists of fine-medium to coarse grained, often seriate textured, and occasionally moderately recrystallised, heterogeneous quartz-poor monzonite/monzodiorite. The monzodioritic version of this material is dominated by oligoclase (75-85%), with only minor alkali feldspar (Table 5.4.1), while the monzonitic version contains 35-55% oligoclase, 20-40% alkali feldspar and 15-35% pyroxene. Strongly altered resorbed, almost shard-like original plagioclase crystals of more calcic composition, are occasionally observed as cores in different orientations to the surrounding oligoclase. Pyroxenes are salitic (Fig. 5.4.4, Table 5.4.2), and minor replacement amphibole varies from actinolite to ferrohornblende (Fig.5.4.5, Table 5.4.3). The pyroxenes are subhedral prisms, commonly showing evidence of resorption, sometimes almost to the point of sieve textures. In many respects, this rock type appears to be a hybrid of the two recognised primary magmas described above. Mild cataclasis is indicated throughout the body, in the form of kinked plagioclase lamellae and deformed quartz.

At Twelve Mile Well, the syenite consists of a medium grained seriate subhedral assemblage of pure albite and microcline in equal proportions (Table 5.4.1), occasionally embayed salitic pyroxene undergoing partial replacement by actinolite (Tables 5.4.2, 5.4.3), less than 1% quartz, and accessory titanite, apatite and opaques. In places, this assemblage is subject to strong epidotisation. Related quartz monzonite on the western margin has an oligoclase:microcline ratio of 2:1, and contains up to 20% quartz, with minor salite extensively replaced by actinolite. A fine grained melanocratic phase that appears on first inspection to be a mafic intrusive, is actually nepheline and acmite normative, and may represent a primitive associate of the syenite. It consists of 50% augite, 30 % plagioclase (?oligoclase-andesine) and 20% microcline patch perthite. Granite from the complex eastern margin of the intrusion consists of medium grained equigranular subhedral oligoclase, microcline, quartz, augite, hornblende, and accessory titanite, apatite, opaques, and zircon.

The distinctly pink Cement Well syenite plug consists of a fine to medium grained inequigranular subhedral alkali feldspar-dominant assemblage with pyroxene and trace replacement amphibole, minor quartz and late-stage interstitial calcite, and accessory titanite, magnetite, apatite, fluorite, allanite and zircon (Fig. 5.4.3D). Alkali feldspar consists of perthitic, mesoperthitic and antiperthitic unmixed anorthoclase, with minor recrystallisation of rims and occasional pure albite cores (Table 5.4.1). Pyroxenes range from ferrosalite to ferroaugite and sodian augite, with marked zoning and increasingly sodic character from core to rim (Fig. 5.4.4, Table 5.4.2). Minor replacement amphiboles are ferroedenitic to ferroedenitic hornblende in composition (Fig. 5.4.5, Table 5.4.3). Trace quantities of possible andradite are present, although none was observed in the section prepared for mineral chemistry analysis. The syenite dykes consist of fine grained subhedral to anhedral microcline, albite, edenitic hornblende replacing augite, and accessory magnetite, titanite, apatite and epidote. The albite may be a product of anorthoclase unmixing, appearing as discrete grains due to the finer grainsize of the dykes. Adjacent country rock granite consists of medium to coarse grained seriate subhedral plagioclase, microcline (of varying perthitic habit, and as rims to plagioclase), abundant quartz, minor amphibole and biotite, and accessory titanite, apatite, haematite, and fluorite.

Libby (1989) described "the typical rock at McAuliffe Well" as an alkali pyroxene, alkali amphibole, single alkali feldspar syenite, and mentioned "petrographically subalkaline" parts of the body in the northwest and south. Sampling in the current study involved only these "subalkaline" regions, where medium grained subhedral occasionally porphyritic two feldspar quartz syenite consists of plagioclase, alkali feldspar, quartz and minor pyroxene/amphibole, with accessory haematite, titanite, apatite, allanite and zircon (Fig. 5.4.3 E). Zoned plagioclases demonstrate a subtle version of the plagioclase effect, first outlined by Bowen (1945), where in the extreme case, albite and diopside/augite reacts to form anorthite and aegirine. The reaction at McAuliffe Well did not produce an anorthite-aegirine assemblage, however albite gradually gives way to oligoclase (1.5% CaO) from the core outwards, prior to a sudden increase to 3% CaO. Alternating Na/K zones then occur towards the rims, which are commonly pure albite (Table 5.4.1). Alkali feldspar consists of microcline and microcline perthite, while amphibole exhibits actinolitic hornblende cores and actinolite rims (Fig. 5.4.5, Table 5.4.3). Very minor amounts of strongly altered pyroxene are compositionally indeterminable. Minor recrystallisation and a weak preferred orientation are observed in all samples, as are trace amounts of unusual CaFeAl garnets in ragged aggregates associated with amphibole.

At Eucalyptus, poor exposure and deep weathering hamper petrographic investigation. Porphyritic syenite to alkali granite consists of medium to coarse grained subhedral phenocrysts of plagioclase (?albite-oligoclase), alkali feldspar, quartz and remnant mafics in a fine grained anhedral mass of quartz and undifferentiated feldspar, with accessory titanite and opaques (Fig. 5.4.3G).

The Foley Well and Windy Well granitoids consist of deformed strongly recrystallised medium grained subhedral to anhedral assemblages of oligoclase, microcline, and up to 35% quartz, with minor amounts of muscovite and biotite, and accessory opaques and titanite. At Menangina Rocks, medium to coarse grained granite consisting of subhedral calcic oligoclase, microcline, quartz and minor biotite/muscovite, with accessory titanite, magnetite, apatite and zircon (Fig. 54.3F), is intruded by fine to medium grained leucocratic alkali granite. This consists of subhedral sodic oligoclase, microcline and quartz, with accessory opaques.

5.4.5 Major and trace element whole rock geochemistry

The syenites from the Twin Peaks intrusion, and one syenite sample each from the Twelve Mile Well and Cement Well intrusions form a geochemically distinct group, representing the low-silica end of the syenite spectrum from the Edjudina samples. This is particularly evident in terms of major elements such as Al_2O_3, FeO*, MgO and CaO, and to a lesser extent, trace elements such as Nd, Y, Nb, La and Ce (Fig. 5.4.6, Table 5.4.4). In a broader sense, these samples, together with the quartz monzodiorite and monzonite/monzodiorite phases from Twin Peaks, and other syenites from Twelve Mile Well and Cement Well, form a separate group from the McAuliffe Well syenites, which appear more closely related to samples from Eucalyptus and Pig Well (see Chap. 5.5). McAuliffe Well samples display consistent linear major element trends over a wide range of SiO_2 values, and virtually identical abundances of all trace elements over a wide range of Sr values. Granite samples from Foley Well, Windy Well, Menangina Rocks, Cement Well and Twelve Mile Well display a distinct trend from 70-76% SiO_2.

Despite some indications from petrographic evidence of the heterogeneous monzonite/monzodiorite phase at Twin Peaks resulting from a mix of the other two phases, this is not substantiated by the geochemical data. In terms of major element data, the monzonite/monzodiorite field lies between the fields for the other phases. However, if mixing between these potential end members is invoked, the geochemical character of the hybrid would require the involvement of at least two further phases, one of which could be represented by a quartz-poor relatively mafic country rock. Sr contents also argue against a simple mix, with the monzonite/monzodiorite phase exhibiting higher abundances than the other two phases. The variation in feldspar and pyroxene contents between the monzonite and monzodiorite subgroups is strongly reflected in the respective chemistries, with the latter exhibiting markedly lower K_2O and Rb, lower Y, Nb, Ba, La, Ce and Nd, and higher CaO, Na_2O and Sc than the former.

A hygromagmatophile plot normalised to the N-type MORB mantle source of Wood et al (1979), displays the general intermediate nature of the Twin Peaks monzonite/monzodiorite with respect to the syenite and quartz monzodiorite phases (Fig. 5.4.7). With the exception of a slight relative depletion in Rb, the quartz monzodiorite exhibits an identical pattern to that of the McAuliffe Well syenite, both displaying a negative Ce anomaly. In terms of elemental abundances, however, the latter is uniformly higher.

All sampled bodies display magmatic trends on a plot of K_2O vs. Rb, with the exception of McAuliffe Well, where there is a suggestion of minor metasomatic alteration (Fig. 5.4.8).

5.4.6 Normative mineralogy

A wide range in normative mineralogies is observed for the Twin Peaks intrusion (Table 5.4.5). The syenite phase exhibits the highest degree of alkaline affinity of all the Edjudina samples, being strongly metaluminous and subalkaline to peralkaline. Di is a dominant component of the norm, and some samples contain minor Ac. The quartz monzodiorite is weakly peraluminous, and non-alkaline, and is dominated by Ab, with minor Di and Hy. The heterogeneous monzonite/monzodiorite varies from peraluminous to metaluminous, alkaline to subalkaline monzonite, to Ab-dominant weakly peraluminous monzodiorite, which is the least alkaline of all the Edjudina samples. Both contain similar amounts of Di and Hy.

The Ab-dominant Twelve Mile Well and Cement Well syenites contain minor Di, and are weakly peraluminous-subalkaline, and metaluminous-subalkaline, respectively. The Eucalyptus and McAuliffe Well bodies exhibit low An, trace Di and/or Hy, and are peraluminous and weakly subalkaline. In common with the Claypan/Bulyairdie and Yindi samples from the Kurnalpi sheet, they contain minor amounts of normative C, up to 0.5% at McAuliffe Well, and up to 5% at Eucalyptus.

5.4.7 Summary

With the exception of the syenite from Twin Peaks, the intrusions outlined above represent only very mildly alkaline members of the felsic alkaline suite. The Twin Peaks and Cement Well syenites are the only ones to display a single mesoperthitic alkali feldspar, the other examples containing appreciable amounts of plagioclase. No significantly alkaline mafic minerals are observed, all pyroxenes being of sodian ferrosalite to sodian augite affinity, and all amphiboles actinolite to hornblende.

Marked lithological heterogeneity and resorbed plagioclase and pyroxene assemblages at Twin Peaks point to a complex history, probably involving magma mixing between a primary syenitic component, most closely represented by the existing syenite phase, and a related monzodioritic component. In addition, geochemical data indicate the probable involvement of at least one other phase, possibly via the assimilation of a quartz-poor relatively mafic country rock component during magma emplacement. The Twin Peaks, Twelve Mile Well and Cement Well bodies form a broadly chemically related group, distinct from the McAuliffe Well and Eucalyptus bodies. These latter bodies are C normative, and the McAuliffe Well intrusion shows some evidence of a metasomatic influence. Ragged andradite aggregates, as observed elsewhere within the suite and interpreted as relics of a deep-seated source region, occur at Cement and McAuliffe Wells. In general, all the syenitic magmas exhibit the typical depleted chemical character of the suite, and are consistent with derivation from a deep-seated depleted source via a major structural conduit, represented in the southwestern part of the Edjudina sheet by the Keith-Kilkenny Tectonic Zone.

5.5 Selected members of the suite from the Leonora, Laverton and Sir Samuel sheets

5.5.1 Introduction

Relatively few members of the felsic alkaline suite are known from the Leonora, Laverton and Sir Samuel sheets, despite the occurrence of well-documented major deep-seated lineaments within the area (Fig. 5.5.1). Seventeen samples were collected from six intrusions throughout the area, comprising the Pig Well body from the Leonora sheet, the Granite Well body from the Laverton sheet, the Mt. MacDonald, Mt. Blackburn and Woorana Well bodies from the Sir Samuel sheet, and a small granite outcrop east of Red Hill. The large Red Hill intrusion from the northeastern Sir Samuel sheet has been previously described (Chapter 3).

5.5.2 Previous studies

The petrographic character of the Pig Well syenite intrusion was described by Thom and Barnes (1977), and Hallberg (1985) provided two chemical analyses and pointed out the extreme Zr enrichments with respect to Ti in the related dykes. Gower (1976) described the fluorite-bearing granitoid of the Mt. Boreas vicinity, which Libby (1989) suggested may be related to the felsic alkaline suite. Stuckless et al (1981), however, considered that the syenitic rocks and Mt. Boreas-type granitoids of the Laverton and Sir Samuel sheets resulted from two unrelated igneous events. They obtained whole-rock Pb-Pb ages of 2760 ± 210 Ma for the syenitic rocks, and 2370 ± 100 Ma for the Mt. Boreas-type rocks, respectively. Hallberg (1985) mentioned the occurrence of quartz syenite on the Laverton sheet from Lancefield, from northeast of Admiral Hill, and a more extensive body in the vicinity of Granite Well.

Bunting and Williams (1979) describd various syenitic bodies of the Sir Samuel sheet, and Libby and De Laeter (1981) obtained a whole-rock Rb-Sr age of 2520 ± 113 Ma with an initial Sr ratio of 0.7014 ± 0.0017, for the Woorana Well quartz syenite. Libby (1989) described the petrographic and geochemical character of the Mt. MacDonald, Mt. Blackburn and Woorana Well intrusions.

5.5.3 Rock types and field relations

The relatively poorly outcropping Pig Well intrusion occurs within a sequence of metabasalts 15km northeast of Leonora, and comprises a medium grained equigranular syenite (see Fig. 5.4.3A), intruded by fine to medium grained occasionally porphyritic syenite. Contacts between the two phases, and with the surrounding country rock, are poorly defined.

A large elongate predominantly syenite to quartz syenite intrusion occurs over some 23km of strike, 15km east of Laverton, and in the vicinity of Granite Well, consists of slabby and hummocky outcrops, occasionally exhibiting a moderate to strong foliation and shearing. The eastern margin of the intrusion is obscured by Cainozoic laterite, while the western margin consists of a diffuse contact with mafic hornfels.

The Mt. MacDonald intrusion occurs 10km northeast of Melrose, in the southeastern corner of the Sir Samuel sheet, and consists of an extensive quartz monzonite mass occurring over some 50 square kilometres. In the vicinity of Andy Well, it consists of homogeneous quartz-poor hornblende monzonite, with a weak preferred orientation (see Fig. 5.4.3B). Quaternary sediments obscure all but part of the western margin of the intrusion, where mafic hornfels occurs. To the east of Yandal, a major heterogeneous intrusion crops out relatively continuously over some 26km, from south of Mt. Blackburn to north of Woorana Well, and Libby (1989) suggested that it may continue under cover for another 40km to the Red Hill locality. East of Little Well in the southern part of the intrusion, lithologies include syenite dykes and fluorite-bearing alkali granite sheets (see Figs. 3.4A, 3.5A) within biotite granite. North of Woorana Well in the northern part of the body, a series of steeply dipping syenite sheets intrude the biotite granite (see Figs. 3.3A, 3.5 B,C), with complex intrusive margins marked by numerous pegmatite dykes.

In general, the intrusions of the Leonora, Laverton and Sir Samuel sheets exhibit close proximity to major north-northwest trending structural elements. The Pig Well intrusion occurs within the Keith-Kilkenny Tectonic Zone of Hallberg (1985), adjacent to the fault-associated conglomerate that marks the eastern margin of the tectonic zone, and is virtually coincedent with the Keith-Kilkenny Fault as defined by Myers and Hocking (1988). The large intrusion centred on Granite Well occurs in a similar position within the Laverton Tectonic Zone of Hallberg (1985). The Mt. MacDonald and Mt. Blackburn-Woorana Well intrusions of the Sir Samuel sheet exhibit a close relationship with the Celia Fault.

5.5.4 Petrography and mineral chemistry

The dominant phase of the Pig Well intrusion consists of a pinkish-brown medium-grained homogeneous subhedral to rarely euhedral equigranular assemblage, dominated by unmixed anorthoclase including mesoperthite, perthite and antiperthite (see Fig. 5.4.3H). Minor zoning is apparent in the larger feldspars, and swapped margins are ubiquitous

(Table 5.5.1). The rest of the assemblage consists of 1-12% aegirine to aegirine-augite with trace patchy replacement magnesioriebeckite (Tables 5.5.2, 5.5.3, see Figs. 5.4.4, 5.4.5), and accessory titanite, zircon, apatite, fluorite and opaques. Quartz is not a component of the mode. The generally finer grained syenite intruding the main phase consists of a fine to medium grained equigranular to porphyritic subhedral to anhedral two-feldspar assemblage. Alkali feldspar consists of orthoclase perthite to anorthoclase mesoperthite, occasionally with plagioclase cores. Complex zoned plagioclase occurs in equal to sudordinate amounts, and consists of a series of alternating albite-oligoclase zones, often with perthitic orthoclase rims. The complicated feldspar textures suggest that the initial melt occurred close to the boundary between the one and two feldspar fields on the ternary feldspar diagram. Pyroxene occurs in quantities of 5%, and consists of aegirine-augite, with occasionally more aegirine-rich rims. Minor replacement alkali amphibole demonstrates a wide range of compositions, including richterite, riebeckite-magnesioriebeckite and minor actinolite (Tables 5.5.2, 5.5.3, see Figs. 5.4.4, 5.4.5). Interstitial quartz is present in minor quantities of up to 4%, and is associated with minor late-stage calcite. Accessory minerals include titanite, apatite, fluorite, zircon and rare opaques.

Porphyritic syenite from the Granite Well vicinity consists of medium grained anhedral microcline perthite to mesoperthite and aegirine-augite phenocrysts, in a groundmass of microcline, albite and quartz. Accessories include common titanite and fluorite, and magnetite and apatite.

The Mt. MacDonald locality comprises a medium grained inequigranular subhedral assemblage of alkali feldsar (microcline perthite, antiperthite and mesoperthite), oligoclase, quartz, biotite/chlorite, amphibole (magnesiohornblende to edenite; Table 5.5.3, see Fig. 3.8), epidote, and accessory titanite, apatite, magnetite, fluorite and zircon.

Fluorite-bearing granite from the Mt. Blackburn area exhibits a moderate preferred orientation, and consists of a medium to coarse grained subhedral to anhedral assemblage of microcline, albite, quartz, biotite/chlorite, hornblende and accessory magnetite, titanite, apatite, fluorite, zircon and allanite. Associated alkali granite exhibits a strong preferred orientation, and comprises a fine to medium grained subhedral granular assemblage of microcline, albite, quartz, aegirine-augite and minor replacement alkali amphibole (Tables 5.5.2, 5.5.3, see Figs. 3.7, 3.8), and accessory titanite, magnetite, fluorite, apatite and zircon. At Woorana Well, and east of Red Hill, the granite is virtually identical to that from the Mt. Blackburn area (see Fig. 3.5H), except for an unusual lack of titanite at Woorana Well. The intrusive syenite at Woorana Well consists of a medium grained subhedral quartz-deficient two feldspar assemblage of microcline perthite, albite, sodian ferrosalite to ferroaugite, trace actinolite to magnesiohornblende, less than 1% quartz and rare biotite, and accessory titanite, apatite and opaques (see Figs. 3.6A, 3.7, 3.8).

5.5.5 Major and trace element whole rock geochemistry

In terms of major element character, the Pig Well intrusion corresponds most closely with the McAuliffe Well intrusion from the Edjudina sheet, despite the former being demonstrably more alkalic than the latter (Table 5.5.4, see Fig. 5.4.6). With the exception of higher total alkalis ($Na_2O + K_2O$) at Pig Well, the intrusion exhibits in most cases, a continuation of the McAuliffe Well trends at the lower silica end. Rb/Sr ratios are generally higher at Pig Well, due to lower Sr contents. For most incompatible elements (eg Rb, Y, Ce, La and Nd), the Pig Well samples plot at the convergence of the McAuliffe Well and Twin Peaks syenite trends. With the exception of generally higher incompatible element contents, the Granite Well intrusion displays very similar geochemical character to that of Pig Well. On a plot of K_2O vs Rb, Pig Well samples display a magmatic trend, while no particular trend is evident for the Granite Well samples (Fig. 5.5.2)

Samples from the Sir Samuel intrusions display distinct geochemical groupings (Table 5.5.4, see Fig. 3.9). The syenite from Woorana Well is coincedent with the Group 2 syenites from Red Hill (see Chap 3), with the exception of Ce, La, Nd and Th, which correspond more closely with the Group 1 syenites from Red Hill, and an unusually high Ga content. With the exception of some Na_2O enrichment and K_2O depletion, granites from the Mt. Blackburn-Woorana Well intrusion, and from the Wonganoo vicinity east of Red Hill, display major element behaviour identical to that of the Group 1 and 2 granites from Red Hill. In terms of trace elements, however, these rocks exhibit a strong correlation with the lower-incompatible element bearing examples of the so-called Mt. Boreas-type granitoids from Bunting and Williams (1979), and are distinctly different from the Red Hill granites. Samples from the Mt. MacDonald intrusion plot on the lower silica end of the Mt. Blackburn major element trends, and display similar hydrothermal trends on the K_2O vs Rb plot, but have significantly lower Rb/Sr ratios, due to marked Sr enrichments. In terms of hygromagmatophile elements, normalised to the N-type MORB mantle source of Wood et al (1979), samples from the Mt. Blackburn vicinity display marked negative Ba, Sr and P anomalies, consistent with the strongly alkalic nature of the feldspars, and the relative lack of apatite (Fig. 5.5.3).

5.5.6 Normative mineralogy

The Pig Well intrusion is moderately to strongly metaluminous and mildly alkaline (Table 5.5.5). An is rare to absent, and Ab:Or is 2:1. Di is present up to 5%, and Ac to nearly 3%, while Q varies from 1-15%. Granite Well is metaluminous and slightly more alkaline, with up to 1.4% Ac, Q contents of less than 6%, and trace Ne present in one sample. The

Mt. MacDonald and Mt. Blackburn bodies are significantly Q normative, with the latter containing up to 29% Q. Ab:Or ratios of 2:1 occur in the former, and vary from 1:1 to 2:1 in the latter. An varies from 0-6%, being lower for Mt. Blackburn, where two samples contains trace C. Mt. Blackburn varies from peraluminous to metaluminous, and subalkaline to alkaline, while Mt. MacDonald is peraluminous and subalkaline. The syenite at Woorana Well is metaluminous and mildly alkaline, with Ab:Or of 5:3, less than 1% An, and less than 2% Q.

5.5.7 Summary

The Pig Well and Granite Well intrusions exhibit petrographic character typical of the felsic alkaline suite, and display some similarities to mildly alkaline samples of the McAuliffe Well intrusion from the Edjudina sheet. The Woorana Well syenite is very similar to the Red Hill syenites (especially Group 2), some 35km to the north, lending support to the suggestion of Libby (1989) that these intrusions are continuous under cover.

The remainder of the Sir Samuel intrusions are subalkaline granites, and while grouping with the Red Hill granites in terms of major elements, they show a strong correlation with some of the Mt. Boreas-type rocks of Bunting and Williams (1979). The trace element geochemistry of the Boreas rocks has been interpreted as resulting from strong or repeated magma fractionation (Libby 1989). With the exception of fluorine, however, the subalkaline Sir Samuel rocks generally exhibit lower contents of the incompatible elements than the Mt. Boreas-type, and tend to fall between the Boreas and hornblende-bearing granitoid groups of Libby (1989). As in the case of the Red Hill granites (see Chap 3), the subalkaline intrusions are thought to be a slightly younger product of the same igneous processes, and hence depleted deep-seated source region, that gave rise to the more alkaline syenites. In the Sir Samuel region, the

Late Archaean alkaline igneous event appears to have been the most geographically widespread, and given rise to the greatest diversity of related rock types observed, in the eastern Yilgarn Block.

5.6 Syenite and related rocks from the Teague Ring Structure of the Nabberu sheet

5.6.1 Introduction

The Teague Ring Structure (TRS) occurs 110km northeast of Wiluna, and represents the northern most occurrence of felsic alkaline rocks in the eastern Yilgarn (Fig. 5.6.1). It lies within the Nabberu Basin of the Capricorn Orogen, some 60km north of the basal unconformity with the Yilgarn Craton, but well within recent interpretations of the northern margin of the Yilgarn (eg Groves 1990, Trendall 1990). The structure comprises a core of granitic and syenitic rocks of approximately 10km in diameter, surrounded by sediments of the Yelma and Frere Formations of the Early Proterozoic Earaheedy Group, which form a ring syncline of approximately 20km in diameter. A polygonal pattern of normal faults around the structure suggests an upward movement of the core (Bunting et al 1982). Seventeen samples of syenite and related rocks were collected from the exposed core in the northeastern portion of the structure.

5.6.2 Previous work

Given the unusual nature of the TRS, much of the previous work has concentrated on the origin of the structure. Butler (1974) suggested that either a meteorite impact or a diapiric granitic intrusion was responsible, while Horwitz (1975) suggested an origin by interference of folds. Bunting et al (1977) suggested the cold emplacement of a syenite plug at high strain rates. The recognition of shatter cones, quartz deformation lamellae and pseudotachylite veins indicative of shock metamorphism, lead Bunting et al (1980) to invoke a cryptoexplosive origin, probably as a result of a volatile-generated explosion in an alkaline magma. Rb-Sr whole rock measurements on core syenite-granite by these authors yielded scatter around a reference isochron of 1630 Ma, which they regarded as the probable age of the structure, and the suggestion of a further event of unknown origin and significance at 1260 Ma. (It appears that samples analysed in their study were collected somewhat randomly, without sufficient regard for the complex geological situation. Preliminary Rb-Sr work of the current study, with strict geological control, revealed the total lack of suitability of these rocks for Rb-Sr isotopic work, and their results are not considered usable in the current context). Bunting et al (1980) described quartz syenite and weakly gneissic leucogranite from the core region. Dodd et al (1983) suggested a gradational metasomatic sequence surrounding the intrusive syenite, from quartz syenite through a zone of decreasingly intense alkali metasomatism, to the original unaltered gneiss, over a distance of 300-400m.

5.6.3 Rock types and field relations

Outcrop of the core lithologies is largely obscured by Quaternary colluvium and eolian sands, and is restricted to the northeastern sector of the core region. Quartz-deficient pyroxene-rich syenite crops out sporadically over an area of approximately 1 square km, and to the south, passes progressively to quartz syenite, alkali granite and relatively pristine gneissic granite (Figs. 5.6.2 A,B,D,E). The gradational nature of lithologies is apparent on a regional scale, but not readily identifiable on an outcrop scale. The suggestion of Dodd et al (1983) of a metasomatic zonation surrounding the pyroxene syenite appears valid for the alkali granite zone, however the quartz syenite may be an intrusive associate of the pyroxene syenite.

The outcrop is characterised by a pink-red to deep purple colour resulting from intense late-stage hydrothermal activity. The syenites in particular, exhibit an unusual random fracture-type texture and zones of brecciation consistent with explosive emplacement (Fig. 5.6.2C). Pseudotachylite veins of mm-scale cut both the syenite and the granite, and jointing is particularly common in the granite. Minor late-stage intrusives include gabbro-dolerite and felsic dykes.

A large mass of hornblende quartz monzonite occurs 20 km to the southwest of the TRS, coincedent with the northern extent of the Celia Fault. Bunting et al (1982) pointed out the alkaline affinity of this intrusion, and suggested a relationship with the post-tectonic Mt. Boreas-type granitoids of the northeastern Yilgarn Block.

5.6.4 Petrography and mineral chemisty

The quartz-deficient core syenite consists of a medium to coarse grained subhedral anhydrous assemblage dominated by alkali feldspar, with subordinate alkali pyroxene and minor replacement amphibole, minor discrete albite, trace quartz at best, and accessory titanite, magnetite, apatite and zircon. The alkali feldspars are classic mesoperthites, with occasional consertal textures, braid perthite and albite rims, which are often recrystallised, and display evidence of moderate hydrothermal alteration (Table 5.6.1) Crystals are commonly fractured, with either opaque or purple-brown iron-oxide infilling, and minor deformation lamellae are present. Pyroxenes exhibit common deformation lamellae (Fig. 5.6.2H), and consist of sodian augite to aegirine-augite (Table 5.6.2, Fig. 5.6.3). Minor needle-like replacement amphibole consists generally of actinolite, but probe analyses are largely non-stoichiometric (Table 5.6.3, Fig. 5.6.4).

The quartz syenite consists of a somewhat fractured fine to medium grained anhedral assemblage of microcline and albite in roughly equal proportions, up to 15% quartz, minor remnant alkali pyroxene and replacement alkali amphibole, and accessory titanite, opaques, apatite and zircon. In addition, andradite garnet of similar composition to that observed elsewhere within the felsic alkaline suite, occurs as largely relict crystals, but displays evidence of euhedral outlines (Fig. 5.6.2G). Feldspars are severely altered, and exhibit evidence of deformation in the form of kinked twins. Quartz occurs generally as subrounded blebby crystals, and exhibits minor deformation lamellae, and fibrous amphiboles replacing original probable aegirine-augite comprise a range of compositions from actinolite to tremolitic hornblende (Table 5.6.3, Fig. 5.6.4). The severe alteration and anhedral character of the quartz syenite contrasts with the more obvious primary igneous texture of the pyroxene syenite, and lends some support to the suggestion that the former is a product of metasomatism. Whether the parent was an earlier syenite phase or the original gneissic granite is unresolved. Andradite typically occurs in metasomatic environments associated with thermal metamorphism (Deer et al 1966), due to the addition of iron and silica to calcium-rich rocks. There is no evidence for major additions of iron associated with predominantly alkali metasomatism within the quartz syenite, and the presence of andradite here probably reflects the composition of the parent lithology. Elsewhere within the suite, ragged andradite aggregates are thought to be a relict of the syenite magma source region.

The alkali granite exhibits a fabric more consistent with production via intense alkali metasomatism of the original gneissic granite. It consists of an extensively recrystallised anhedral granular assemblage of albite, microcline, and up to 25% quartz, with minor accessory titanite. Pseudotachylite veinlets to 2mm and quartz deformation lamellae are common (Fig. 5.6.2F).

5.6.5 Major and trace element whole rock geochemistry

The pyroxene syenite displays distinctly different geochemical character from the other TRS lithologies, with low silica values and significant total alkali enrichment (Table 5.6.4, Fig. 5.6.5). Values of

TiO_2, total iron, MgO, CaO, P_2O_5 and V are significantly higher than the quartz syenites and alkali granites, pointing to the relatively mafic nature of the syenite magma source region. Incompatible element abundances are generally higher than observed for other members of the felsic alkaline suite, particularly for Rb, Ba, La, Ce, Nd, Zr and Y (Fig. 5.6.6). Molecular Fe^{3+}/Fe^{2+} ratios approaching 3 indicate high f_{O_2}, which is consistent with the presence of modal magnetite. Ga/Al ratios are similar to those observed for the Gilgarna Rock and Binneringie syenites, and significantly higher than those of the typical A-type granites of Collins et al (1982).

The geochemical behaviour of the quartz syenite is somewhat variable. While grouping with the alkali granite for most major elements, the quartz syenite displays lower total iron, higher CaO, and signifiantly higher K_2O (and Rb). It is generally lower in incompatibles than the pyroxene syenite, with the exception of Th, and significantly higher in La. Ga/Al_2O_3 ratios are intermediate between those of the pyroxene syenites and alkali granites. If the quartz syenite represents a metasomatic product of the original gneiss, it has undergone significant enrichment in Ca, Na, K, Rb, Y, La, Nd and Th, and depletion in total Fe and V, relative to the alkali granite.

5.6.6 Normative mineralogy

The pyroxene syenites display Ab:Or ratios of 5:4, and contain 0-2% An (Table 5.6.5). Di is present in quantities up to 4%, Ac up to 1%, and Q less than 3.5%. The rocks are mildly alkaline and strongly metaluminous. The quartz syenites have Ab:Or ratios of 9:7, An up to 2.5%, and a total normative pyroxene component of less than 2%, principally Di. Q is present in quantities of 10-25%, and the samples are mildly alkaline and per/metaluminous. The alkali granites contain less than 1% An, Ab:Or ratios of 4:3, and virtually no normative mafic component. Q is present in quantities of 22-28%, and C occurs up to 2.5%. The samples are subalkaline and peraluminous.

5.6.7 Summary

The pyroxene syenite of the TRS exhibits similar petrographic and geochemical character to other members of the felsic alkaline suite. It differs in terms of the apparent age of magma emplacement, the degree of volatiles thought to have been present in the magma resulting in explosive emplacement, and the strong metasomatic effect the separated volatile phase had on surrounding lithologies.

Gee (1990) describes the evolution of the Nabberu Basin, with the oldest sediments believed to be in the order of 2 Ga. Given the interpretation of disruption of Early Proterozoic sediments as a result of the syenite intrusion, this represents a maximium age for the syenite, and is significantly younger than other members of the suite. It is however, similar to the age of the Mt. Weld carbonatite intrusion south of Laverton, and only slightly younger than the interpreted age of the mildly alkaline Gearless Well trachyandesite from the Murchison Province (see Chap 6). The postulated early rifting within the Nabberu Basin at about 2 Ga (Gee 1990) may have facilitated syenite emplacement from a deep-seated somewhat mafic depleted source.

The presence of miarolitic cavities in the Teague intrusion, intense fracturing of surrounding lithologies, and the effect on the surrounding Proterozoic sediments suggests a near-surface explosive emplacement, as a result of magma fluid pressure exceeding lithostatic pressure. Textures indicating venting to the surface such as Proterozoic xenoliths and agglomeratic fragments are not observed within the TRS, and the work of Burnham (1972, 1979) suggests an emplacement depth of 2-4 km. There is no evidence elsewhere within the suite for such shallow emplacement depths.

Similarly, the strong metasomatic effect of the intrusive magma on the surrounding rocks has not been observed to the same degree in any other member of the felsic alkaline suite. At Gilgarna Rock, metasomatic effects on the medium grained syenite due to the later intrusion of the coarse grained syenite, have been observed only over distances of a few metres from the contact zone. While it is reasonable to view the alkali granite as a metasomatic product of the original gneissic granite, evidence for the origin of the quartz syenite is inconclusive. The balance of petrographic and geochemical evidence, however, tends to suggest that it may represent a perhaps slightly older associate of the pyroxene syenite, that has undergone considerable modification as a result of the explosive emplacement of the volatile-charged pyroxene syenite magma.

5.7 Comparison with similar felsic alkaline rocks worldwide

5.7.1 Introduction

While felsic alkaline rocks occur across a wide geographical and geological time range, in a variety of tectonic settings, they do not represent a volumetrically large contribution to plutonic rocks, and this is particularly so for the oversaturated examples. Stoeser (1986), for example, estimates that syenitic rocks comprise less than 1% of the Arabian Shield, and even with the inclusion of alkali feldspar granites, the figure is still less than 5%.

5.7.2 General geological setting and characteristics of alkaline rocks

Alkaline magmatism may be repeated over a long period of time in the same region, with the degree of alkalinity and silica saturation largely controlled by the age and thickness of the lithosphere (Black et al 1985). An association with crustal rifting is not a necessity, although it is common, with pre-existing faults often determining the location of alkaline magmatism. Alkaline ring complexes of alkali granite-syenite affinity are perhaps the most common occurrence of such magmatism, particularly in Africa, where they are emplaced at high structural levels, irrespective of age, once isostatic equilibrium has been established (Black and Bowden 1985). The concept of a ring complex has no particular tectonic or genetic implications, and Vail (1985) states that such structures can develop during the emplacement of almost any high-level plutonic rock. Such structures are best defined, however, in complexes of multiple related intrusions, often over considerable geologic time, for example in many of the African occurrences. Residual fluid concentrtion and subsequent autometasomatism is a characteristic of these ring complexes.

The A-type granite suite of Collins et al (1982) embraces many of the felsic alkaline occurrences throughout the world. These rocks can be metaluminous, peraluminous or peralkaline, and are characterised by high silica, total alkali, F, Zr, Nb, Ga, Sn, Y and REE contents, high Fe/Mg ratios, and low CaO and Sr. They are often granites *sensu stricto,* and are thought to represent high temperature water-undersaturated restite-free magmas (Clemens et al 1986), derived via partial melting of F and/or Cl-enriched dry felsic granulitic residue of the lower crust, following removal of orogenic granite (Whalen et al 1987). Mantle-derived basalts are thought to provide the heat source for partial melting (Clemens et al 1986). A-type rocks do not exhibit evidence of strong differentiation, and are typified by mineral assemblages of alkali feldspar, annite-rich biotite and/or alkali amphiboles, and sodic pyroxene, with the mafic phases occurring towards the end of crystallisation.

5.7.3 A comment on the occurrence of Archaean felsic alkaline rocks

Examples of oversaturated mildly alkaline felsic intrusives in a Late Archaean stable cratonic setting are not well documented. Anhaeusser and Robb (1981) discussed Mid to Late Archaean potash-rich post-tectonic granites and syenites from the Barberton region of southern Africa. The syenites are undersaturated, however, and younger members of this group display initial Sr ratios suggesting reworking of pre-existing granitic crust, in contrast to the Yilgarn examples. The Archaean Siberian platform contains no alkaline rocks of Precambrian age at all, despite a diversity of younger alkaline intrusions (Butakova 1974). No occurrences are documented from the Archaean of Greenland, although Proterozoic examples with low initial Sr ratios are recorded from the Gardar province (Upton 1974). Arth and Hanson (1975) described quartz diorites and syenites from the Archaean Superior Province of northeastern Minnesota, and on the basis of low initial Sr ratios, invoked an origin by partial melting of a mixed peridotite-eclogite source at mantle depths. Colvine et al (1988) described the Late Archaean post-volcanic saturated to undersaturated intrusives from the Superior Province of Canada, which include a variety of syenitoids and granitoids associated with major crustal structures. Despite volumetric insignificance, these altered and deformed rocks represent 25% of the host rocks to gold mineralisation within the Abitibi Belt. These rocks are thought to be derived from both crustal and mantle sources, for example, by partial melting of lower crust in the zone of granulitisation, or via melting of anhydrous mantle peridote in the presence of CO_2-rich vapour. They are, however, weakly subalkaline at best, and predominantly of calc-alkaline affinity (Burrows and Spooner 1989).

It is apparent that the overall character of the felsic alkaline suite of the Yilgarn is somewhat unique in Archaean environments, and for the purposes of comparison, examples of similar geochemical and petrographic character, regardless of age, are outlined below.

5.7.4 Selected examples of oversaturated felsic alkaline occurrences

Africa and the neighbouring Arabian Shield display a widespread distribution of felsic alkaline centres throughout the Phanerozoic, many of which prove suitable for comparison with the Yilgarn suite.

The oversaturated Phanerozoic Niger-Nigerian alkaline ring complexes encompass a wide variety of rock types (Fig. 5.7.1, Table 5.7.1). Alkali granites and quartz syenites of these complexes exhibit similar mineralogies to the Yilgarn syenites, albeit richer in quartz, with typical assemblages comprising alkali feldspar microperthite, quartz, aegirine, riebeckite, arfvedsonite, fluorite, apatite and magnetite (Ike and Sakoma 1985, Badejoko 1986). The complexes are interpreted as migrating mid-plate anorogenic complexes representing the roots of eroded volcanos (Bowden and Kinnaird 1984). They tend to occur within Pan-African orogenic belts, rather than cratons that were stable during the Pan-African orogeny. Parent magmas are thought to be sourced in asthenospheric locations, with emplacement controlled by reactivation of Pan-African shear zones (Bowden et al 1987).

The Late Proterozoic miaskitic specialised syenites from the Arabian Shield of Ramsay (1986) exhibit some similar physical and geochemical parameters to some of the Yilgarn syenites (Fig. 5.7.2). They consist of massive post-tectonic intrusions occurring as small to moderate sized homogeneous plutons and complexes. They are generally metaluminous and saturated to slightly oversaturated, with no feldspathoids. They are characterised by high Al_2O_3, MgO, CaO, total alkalis, TiO_2, P_2O_5, Ba, Co, La, Nd, Sc, Sr, V, Zr, K/Rb and Mg/Li, and low SiO_2, Li, Nb, Pb, Rb, Sn, U, Y and Rb/Sr.

O'Halloran (1985) documented A-type granites and syenites from the Permo-Triassic Ras ed Dom migrating ring complex of northern Sudan (Fig. 5.7.3, Table 5.7.2), which exhibit a number of similarities to the Yilgarn syenites. The complex consists of metaluminous and peralkaline hypersolvus syenites and granites, with mineral assemblages including pure albite alkali feldspar, alkali pyroxene and alkali amphibole. Pyroxenes range from ferrohedenbergite to aegirine-augite and aegirine, and amphiboles consist of a broad range of compositions in the ferrorichterite-arfvedsonite-riebeckite solid solution series. The influence of late sodic fluids is seen in late extremely pure albite accompanying aegirine. High contents of incompatible elements, and an erratic distribution, are attributed to sodic autometasomatism. K_2O vs Rb plots define a pegmatitic-hydrothermal trend, and the rocks exhibit low initial Sr ratios. Despite higher abundances, these rocks display similar relative light REE enrichments to the Yilgarn syenites, and the heavy REE's are thought to have been retained by garnet in the source region. The sequence of metaluminous syenite-peralkaline syenite-peralkaline granite reflects a recurrent fractionation series, due to high level fractionation of a parental syeno-monzonite magma, thought to have been derived from a lower crustal mafic rich source such as garnet eclogite.

5.7.5 Summary

The felsic alkaline suite of the Yilgarn represents a somewhat unique example of Late Archaean magmatism. The suite bears best comparison with predominantly younger examples of oversaturated felsic alkaline rocks from Africa and the Arabian Shield, which exhibit similar petrographic and in part, geochemical character. Typical mineral assemblages comprise alkali feldspar, alkali pyroxene and alkali amphibole. Late-stage alkali-rich autometasomatic magmatic fluids are often evidenced by pure albite rims to feldspars, and strongly alkaline pyroxene compositions. The geochemical character of the Yilgarn suite exhibits some similarities to that of the younger examples, but in general, displays lower abundances of incompatible elements, pointing to the strongly depleted nature of the source region. In common with the Yilgarn suite, many of the younger examples originate via partial melting of lower crustal or upper mantle rocks, and are emplaced via major deep-seated crustal conduits.

5.8 Summary

Study of the felsic alkaline suite throughout the eastern Yilgarn Block reveals an overall similarity in petrographic and geochemical character, with local diversity reflecting slight differences in source chemistry, and in some cases, minor assimilation of country rocks during emplacement. In the area of the Widgiemooltha sheet, incompatible element chemistry implies a source of similar composition for intrusions over a wide area. An age of 2470 Ma for the Binneringie intrusion indicates it to be one of the younger bodies of the southern part of the suite. The Roe-Cardunia bodies of the Kurnalpi sheet represent unusual examples of the suite, with high quartz contents, and a very low ferromagnesian mineral content. The most heterogeneous member of the suite occurs at Twin Peaks in the southwestern Edjudina sheet, with resorbed plagioclase and pyroxene assemblages indicating a complex history, probably involving significant magma mixing. The Sir Samuel area contains a diverse collection of suite members, and represents the most widespread manifestation of the felsic alkaline event. The Teague Ring Structure represents a unique and apparently considerably younger example of the suite, with a maximum age of approximately 2000 Ma indicated by disrupted Proterozoic sediments. Petrographic and field evidence is consistent with the shallow-level explosive emplacement of a volatile-charged magma. In general, the Yilgarn suite displays comparable petrographic, and to some degree geochemical character, to Phanerozoic oversaturated intrusions from Africa and Arabia. Parent magmas originated from deep-seated depleted source regions, and emplacement was facilitated via long-lived, and perhaps reactivated, major crustal structures.

CHAPTER 6 THE GEARLESS WELL ALKALINE INTRUSION OF THE MURCHISON PROVINCE, WESTERN YILGARN BLOCK

6.1 Introduction

Gearless Well lies 45km southwest of Yalgoo, within the Murchison Province in the northwestern Yilgarn Block (Fig. 6.1), in an area covered by the Yalgoo sheet of the 1:250000 GSWA geological series (Muhling et al 1975). A discrete roughly circular magnetic anomaly of 20 square km in area and 2000nT in intensity lies directly under Gearless Well (Fig. 6.2), and previous mineral exploration activity (various unpublished reports) identified the presence of a mildly alkaline trachyandesite intrusion under recent sediment cover.

Textural evidence lead Blight (1984) to postulate explosive near-surface emplacement, and as several kilometres of the Yilgarn Block are considered to have been removed largely during Early Proterozoic times (Gee et al 1981), he suggested that the intrusion may have been post Early Proterozoic in age.

The petrological, geochemical and geochronological characteristics of the intrusion were investigated in the current study, to examine a possible relationship between the trachyandesite and the mildly alkaline syenitic rocks of the eastern Yilgarn, and the possibility of an extended period of alkaline magmatism across the Yilgarn Block. All samples used in this study were derived from core from drill holes GW-1 and GW-3 provided by Union Oil Development Corporation (UODC).

6.2 General geology

6.2.1 Introduction

Gearless Well occurs 7.5km east of Gullewa in the Cagacaroon Hills of the Gullewa greenstone belt, which consist predominantly of the Association 4 rocks of Muhling and Low (1977). These comprise Archaean mafic and ultramafic metavolcanics, of low to medium metamorphic grade, intruded by foliated to massive granite, granodiorite and trondhjemite, with extensive development of migmatite, and Proterozoic dolerite and diorite dykes. Blight (1984) suggested that Gearless Well lies within a north-south trending Archaean rift system parallel and analogous to the Eastern Goldfields Rift Zone (Libby 1978, Hallberg 1985), with the eastern margin passing 5km east of Yalgoo. Gearless Well is virtually coincident with a major regional north-south trending fault interpreted by Myers and Hocking (1988), which may define the western margin of the proposed rift zone. The intrusion is entirely covered by 30-50m of Cainozoic sediment, comprising alluvial, aeolian and eluvial deposits on an indurated sand, loam and gravel hardpan, and clay-kopi, sand and silt deposits of the Salt River channel.

6.2.2 Geology of the trachyandesite intrusion

Due to the difficulty in applying modal classiication schemes to volcanic or hypabyssal rocks, nomenclature follows the schemes of De La Roche et al (1980) and Le Maitre (1984). Trachyandesite or syenodiorite are equally applicable names, but the former is used because of the hypabyssal nature and probable venting of the body.

The Gearless Well body consists of dark grey holocrystalline hypidiomorphic fine grained porphyritic biotite trachyandesite, with an agglomeratic texture suggesting autobrecciation (Fig. 6.3A). The agglomeratic texture is defined by sub-rounded dark grey trachyandesite fragments of 20-200mm in size, within a matrix of mineralogically identical lighter grey trachyandesite. Sharp margins are present between the two phases (Fig. 6.3D), and although both contain biotite, and to a lesser extent amphibole, defining a preferred orientation consistent with flow direction, these orientations are not necessarily parallel. Such agglomeratic textures are consistent with the near-surface explosive activity of volatile saturated magmas. These magmas may, at depths of 2km or less, exceed the minimum principal stress of the country rock via increases in volume and pressure due to volatile exsolution, resulting in explosive activity (Burnham 1972). The sub-rounded nature of the agglomerate fragments is caused by turbulence in the high volatile-flux vent region.

Small clots composed largely of biotite, amphibole and opaques vary in size from 4-20mm, and are more prevalent in GW-1 than GW-3. They may represent mafic country rock xenoliths.

The magnetic character of the intrusion suggests a steep-sided plug with a relatively flat top (Fig. 6.2). A magnetic low within the anomaly is interpreted as a mafic meta-agglomerate country rock raft.

6.2.3 Previous studies

Previous work on the Gearless Well body has been confined to mineral exploration activity aimed at identifying the source of the magnetic anomaly. During the 1970's, the anomaly was drilled by BHP and SAMIN, and following the re-interpretation of drill cuttings as trachyandesite, the area was acquired by UODC as a prospective carbonatite-bearing locality. The magnetic signature of the body is similar to that of the Mt. Weld carbonatite of the Eastern Goldfields, which occurs in a comparable tectonic setting (Willett et al 1989). Mariano (in Blight 1984) pointed out the similarity of the Gearless Well environment to a Paraguayan rift-related syenodiorite-carbonatite association, but noted the lack of evidence for carbonatite or fenite solution fluxing within the existing drill cuttings.

A low level aeromagnetic survey was conducted by UODC to define drill targets, and four diamond drill holes were drilled to bedrock. Drill holes GW-1, 2 and 3 were drilled on magnetic highs, and all intersected porphyritic biotite trachyandesite with an agglomeratic texture. GW-4 was drilled on a magnetic low, and intersected a country rock raft. Despite the presence of carbonate throughout the trachyandesite, no evidence of a carbonatite within the area of the magnetic anomaly was found.

6.3 Petrography

6.3.1 Introduction

Phenocrysts of biotite, amphibole and alkali feldspar account for 10-35% of the rock, while the groundmass consists of alkali feldspar, amphibole, albite, magnetite, calcite, quartz, titanite, apatite and zircon in descending order of abundance (Figs. 6.3B-F, Appendix 3). The agglomeratic fragments generally contain finer grained phenocrysts, less biotite and a slightly ooarser groundmass, than the mineralogically identical lighter grey matrix.

6.3.2 Feldspars

Alkali feldspar is the dominant component of the mineral assemblage, with 0-15% present as phenocrysts, and 30-65% present as groundmass. Samples from GW-3 in the south of the body generally lack alkali feldspars of sufficient size to be classed as phenocrysts. Albite is a minor component of the groundmass only.

The alkali feldspar exhibits turbid alteration, and is light pink-brown in thin section, suggesting the persistence of fluid circulation down to low temperatures as in the Klokken layered syenite/syenodiorite (Parsons and Becker 1986). Minor zoning is present, and although there is extensive alteration, the feldspar appears to be sanidine.

6.3.3 Amphiboles

Actinolitic amphibole is present in quantities of 4-15% as phenocrysts, and 15-20% as groundmass. The amphibole is thought to be derived by uralitisation of primary pyroxene. Actinolite has totally replaced the original pyroxene - textures are typically fibrous, and although actinolite pseudomorphs after pyroxene are present, they are not common. This suggests that substantial volumes of fluid were involved in the uralitisation, with continued fluid action leading to the growth of new actinolite. Very fine grained, discrete, randomly oriented actinolite fibres are a common constituent of the groundmass. Actinolite is slightly more common in the earlier, and hence originally more pyroxene-rich, agglomeratic fragments.

The occasional presence of fine grained biotite inclusions near the margins of actinolite crystals indicates a reverse of Bowen's reaction series.

6.3.4 Biotites

Olive-green biotite comprises 1-10% of the assemblage as phenocrysts. The biotite shows no signs of post-crystallisation alteration. A fine dusting of magnetite occasionally associated with biotite rims is derived from the breakdown of pyroxene during uralitisation, and does not indicate alteration of primary biotite. A sub-vertical lineation commonly expressed by the biotites is consistent with flow lineation.

6.3.5 Accessory minerals

Accessory minerals consist of ragged aggregates of titanite and replacement iron oxides, stubby apatite prisms, and very fine grained zircons, detected mainly by the presence of small pleochroic haloes within biotite. Magnetite accounts for as much as 5% of the rock and explains the strong magnetic anomaly.

6.3.6 Discussion

The uralitic alteration of magnesium-rich calcic pyroxenes to actinolite, by the removal of CaO and the addition of water, has been documented by Rodgers (1973). The resulting excess CaO may be largely responsible for the formation of secondary carbonate blebs, flecks and veinlets within the Gearless Well body. The more intensely carbonate-veined areas contain a higher proportion of actinolite than the lightly veined areas, lending some support to this suggestion. Electron microprobe analysis of the carbonate failed to detect any evidnce of primary carbonatitic character. Up to three generations of carbonate are present, including isolated clots, which may represent the earliest generation, thin sinuous veins, and thicker undeformed veins up to 5mm thick. Drill hole GW-1 in the northern part of the body has a greater degree of veining than GW-3 in the south.

Biotite inclusions near the margins of actinolite crystals may represent relicts from the original pyroxene crystals, suggesting an initially low f_{O_2} and moderate K_2O magma (Wones and Gilbert 1982). The presence of uralitic actinolite and turbid alkali feldspar in the Gearless Well assemblage demonstrates the volatile-rich nature of the magma, which was ultimately responsible for near-surface explosive autobrecciation. The lack of consistent orientation of flow lineations, displayed by biotite and amphibole, between agglomerate and matrix phases clearly demonstrates that uralitisation preceded autobrecciation. The flow lineation, agglomeratic texture and steep-sided magnetic anomaly are consistent with the classification of the trachyandesite as an hypabyssal plug, with an explosive vent at the surface.

6.4 Mineral chemistry

6.4.1 Introduction

Although modal percentages of minerals may vary significantly, there is little mineralogical variation either across the plug, or between agglomeratic fragments and matrix material. Likewise, the mineral chemistry of the two phases is consistent at any one site. However, probe analyses reveal the presence of subtle regional differences in mineral chemistry within the body. Analyses were performed at the Electron Optical Centre of the University of Adelaide, on a KEVEX 7000 series energy dispersive system attached to a JEOL 733 analyser, at an accelerating voltage of 15kV and a beam current of 5nA.

6.4.2 Feldspars

Feldspar analyses are consistent with barian sanidine (Table 6.1). Analysis totals are slightly low because of minor alteration of the original crystals, and the presence of BaO, which was detected but not measured. Under the energy dispersive system of the electron microprobe, Ti and Ba peaks overlap, and the amount of BaO present can only be qualitatively estimated. Given that TiO_2 rarely exceeds 0.1% in feldspar, the BaO content of these feldspars is estimated to be 1-2.5%. Feldspars are considered barium varieties when they contain >2% BaO (Deer et al 1966), and the Gearless Well type is more appropriately termed barian sanidine. The rims are usually more barium-rich than the cores in both GW-1 and GW-3, accounting for the minor zoning, but there is no significant difference in overall composition between the two sample sites. The total lack of Na and Ca within the analysed feldspars is unusual, and may indicate a relatively low temperature of crystallisation (Heinrich 1965).

6.4.3 Amphiboles

Most amphibole analyses (Fig.6.4, Table 6.2) correspond to actinolite in the calcic amphibole classification scheme of Leake (1978). Amphiboles from GW-1 are more siliceous and slightly more magnesian than those from GW-3. Within the agglomeratic material from GW-3, the rims are consistently more siliceous than the cores. However, within the matrix material, there is no consistent relationship. The scatter in Fig. 6.4 is attributed to uralitisation, while the difference in composition between GW-1 and GW-3 is either due to differences in primary pyroxene compositions, or to slight differences in the uralitising fluid compositions at the respective sites.

6.4.4 Biotites

Biotite analyses are consistent with phlogopitic biotite, with GW-1 examples plotting within the phlogopite field of the biotite quadrilateral (Fig. 6.5, Table 6.3). While individual crystals are relatively homogeneous in terms of their Fe/Fe + Mg ratio, there is often a significant difference in tetrahedrally coordinated Al, with cores usually having more Al^{IV} than rims. A mafic xenolith from GW-1 contains more siliceous and magnesian biotite than the trachyandesite, and probably represents country rock.

6.4.5 Accessory minerals

Analysed accessory minerals include apatite and titanite (Table 6.4). Apatites from GW-3 exhibit higher totals than those from GW-1, reflecting the relative lack of H_2O and/or CO_2, F and Cl in the former. The GW-3 apatites are slightly more Fe-rich than those from GW-1, and both contain minor amounts of Si and S, which have been substituted in synthetic crystals (Deer et al 1966). No consistent rim-core relationship is present in the analysed titanites, both zones containing minor amounts of REE, recorded here as "other" elements.

6.4.6 Discussion

Biotite compositions have been used to study magmatic evolution (Leake 1974), with Fe/(Fe + Mg) ratios indicating the sequence of crystallisation within a zoned pluton. Although GW-1 biotites have clearly lower Fe/(Fe + Mg) ratios, both GW-1 and GW-3 sites are located at similar distances from the interpreted plug margin. This effect is more likely to be a result of inhomogeneity than an indication of zoning within the body. This is consistent with the contrasting amphibole chemistry from the two sites, and the most significant aspect of the microprobe investigation is the demonstration of initial magma inhomogeneity within the body.

6.5 Whole rock geochemistry

6.5.1 Introduction

Material selected for analysis was derived from UODC diamond drill holes GW-1, 2, 3 and 4; BHP percussion drill holes CGW-1, 4, 5 and 8; and SAMIN percussion drill hole Y-1. The sample series 003, 004 and 005 were analysed by the author at the University of Adelaide by XRF methods (except Na_2O by AAS, and FeO by titration). The remaining samples were analysed commercially: 0979, 0980 and 5227-31 by XRF, and 5334-38 by ICP. The 003, 004 and 005 series were used for the Rb-Sr isotopic investigation - TR indicates a split from the powder used for isotopic analysis, and H indicates material carefully hand-picked to avoid carbonate veining. Samples lacking major element analyses consisted of pressed pellets specifically prepared for use in preliminary Rb-Sr isotopic investigations.

6.5.2 Major element geochemistry

In comparison with an average trachyandesite (Le Maitre 1976), the Gearless Well trachyandesite is markedly Al_2O_3 deficient, and K_2O and MgO enriched, with slightly more total Fe and slightly less Na_2O (Table 6.5).

The inhomogeneity of the Gearless Well body is displayed by distinct groupings of samples from drill holes GW-1 and GW-3. This is particularly demonstrated by Harker-type variation diagrams (Fig. 6.6), with GW-3 samples having higher MgO, CaO and Na_2O, and lower K_2O contents than GW-1 samples.

Given that the GW-1 core is more heavily carbonate veined than GW-3, the difference between bulk-rock and handpicked unveined samples at each site must be considered. As might be expected, the unveined sample from GW-3 displays very similar chemistry to the bulk sample (in fact, CaO and FeO* values are slightly higher in the unveined sample). The unveined material from GW-1 however, is markedly higher in CaO, MgO and FeO* and lower in SiO_2, Al_2O_3 and K_2O. These data however, particularly the CaO values which exhibit substantial scatter, should be treated with caution in comparisons of handpicked unveined and bulk-rock material, due to the low number of samples and the observed inhomogeneity even within one sample location.

In the R_1R_2 classification of De La Roche et al (1980), all samples plot as trachyandesite (mugearite-latite) (Fig. 6.7).

6.5.3 Trace element geochemistry

In general, the Gearless Well body exhibits a relative enrichment in large ion lithophile (LILE) elements and to a lesser extent, the high field strength (HFS) elements (Table 6.5). The outstanding feature of the trace element variation diagrams (Fig. 6.6) is the inhomogeneity of the body displayed by distinct groupings of samples from drill-holes GW-1 and GW-3.

Trace elements, particularly V, Cr, Zr, Nb, Ba, La and Ce best demonstrate the compositional differences between GW-1 and GW-3. In general, GW-1 samples display lower V and Cr, and higher Zr,Nb,Ba,La and Ce than GW-3 samples. They usually have lower total Fe and MgO, lower Sc, and higher Th.

The unveined sample from GW-1 is generally higher in V, Cr, Ni, Ba, La, Ce and Nb than the bulk-rock samples. In general, the trace element data suggest no significant contribution to the regional chemical differences from the presence of veining, apart from minor dilution of the mafic-component elements (FeO, MgO, Ni, Cr, V and Sc). Further, there is no evidence for Ba, La, Ce or Nb enrichment in the carbonate veins, indicating their lack of association with a carbonatitic source, and there is no evidence for any marked Sr enrichment in the vein material, which has implications for the isotope systematics.

The mafic agglomerate, believed to represent a greenstone-succession raft within the trachyandesite, exhibits higher Ni and lower Y and Nb values than the trachyandesite.

6.5.4 Normative mineralogy

The Gearless Well body contains more normative Or, Di, Mt and Ap, and less An and Q than average trachyandesite (Le Maitre 1976). The differences between the GW-1 and GW-3 samples, as indicated by major and trace elements, are shown by the lack of normative Q, the presence of normative Ol, the lower Or/Ab ratios and the generally lower normative Hy in GW-3 samples (Table 6.6). Ne is not a normative component in any of the samples. Sample 5231 from SAMIN Y-1 has similar chemical characteristics to GW-3 samples, even though it is situated in the vicinity of GW-1, showing further the inhomogeneity of the body.

With the exception of sample 5231 which is peralkaline, all Gearless Well samples have a mol(Al_2O_3 / Na_2O + K_2O) value greater than 1, showing only mildly alkaline character. The alumina deficiency of the body in general is shown by the values of the peraluminous index, mol(Al_2O_3 / CaO + Na_2O + K_2O), which are much less than 1. In terms of silica-saturation, the body varies from slightly undersaturated to slightly oversaturated.

6.5.5 Discussion

The slight differences noted in biotite and amphibole (after pyroxene) mineral chemistry for the GW-1 and GW-3 sites are apparently anomalous in terms of whole-rock geochemistry. As stated above, GW-3 samples generally contain more magnesium and slightly more total iron than GW-1 samples, with slightly higher Mg numbers. However, the GW-3 biotites and amphiboles have slightly higher Fe/(Fe + Mg) ratios than those from GW-1. A similar feature was described by Czamanske and Wones (1973) in the granitic Finnmarka Complex of Norway, where such features in pyroxene, amphibole and biotite were attributed to differences in fo_2, with Fe/(Fe + Mg) ratios decreasing with increasing oxidation. This suggests inhomogeneity in fo_2 for the Gearless Well body; GW-1 samples indicate slightly higher values than GW-3 samples.

Overall, the body can be described as mildly alkaline, varying slightly either side of silica-saturation. On the basis of silica oversaturation, high Mg numbers, and high Ni,Cr and LILE abundances, the GW-1 samples may be considered as members of the sanukitoid suite of Shirey and Hanson (1984). GW-3 samples have the same unusual enrichment of incompatible and LIL elements as GW-1, but are generally slightly silica-undersaturated and hence not members of the sanukitoid suite.

6.6 Geochronology

6.6.1 Introduction

In terms of tectonic setting and mildly alkaline character, the Gearless Well intrusion exhibits some similarities to the felsic alkaline suite of the Eastern Goldfields Province. In addition, despite the lack of petrological and geochemical indications, the trachyandesite displays a similar magnetic signature, and occurs in a similar tectonic setting, to the Mt. Weld carbonatite, which occurs within the deep-seated Laverton Tectonic Zone (Hallberg 1985) of the Eastern Goldfields Province.

This study has shown the syenites of the felsic alkaline suite to be Late Archaean in age. The Mt. Weld carbonatite has a K-Ar whole rock age of 2064 ± 40 Ma (Webb 1973), and a Rb-Sr whole rock age of 2021 ± 13 Ma (Collerson in Willett et al 1989). Given the similarity to the tectonic settings of both the syenites and the Mt. Weld carbonatite, the similarity to the magnetic signature of the Mt. Weld carbonatite, the occurrence of Gearless Well-type rocks in carbonatite associations elsewhere, and evidence to suggest Early Proterozoic emplacement, the isotope systematics of the trachyandesite were studied to determine the relationship, if any, to either the Archaean syenites, or the Proterozoic carbonatite.

Fresh drill core was derived from UODC drill holes GW-1 and GW-3.

Eight 50-100g whole rock samples were carefully handpicked from core relatively free of carbonate veins, and a further three bulk whole rock samples were split from 4-9kg of crushed core. Two biotite concentrates were obtained from these large crushed samples. Details of experimental methods and McIntyre-style regressions are given in Appendix 1.

6.6.2 Rb-Sr whole rock geochronology

Whole rock Rb-Sr data for the eleven analysed samples yield two groupings of points corresponding to the two sample locations (Figs. 6.8, 6.9; Tables 6.7, 6.8). GW-1 samples yield a reasonable linear fit (MSWD 6.6) and a Model 4 date of 1767 ± 97 Ma, with an initial $^{87}Sr/^{86}Sr$ ratio of 0.71344 ± 0.00190. Given the small but significant scatter present, it is not possible to detect any major differences between the bulk whole-rock samples (TR) and the samples hand-picked to avoid carbonate veining (H).

GW-3 samples exhibit considerable scatter, with a poorly fitted Model 2 isochron (MSWD = 89) yielding a meaningless age of 1048 ± 1340 Ma and a high apparent initial $^{87}Sr/^{86}Sr$ ratio of 0.73706 ± 0.02895.

6.6.3 Rb-Sr whole rock-biotite geochronology

Two-point whole rock-biotite lines yield ages of 2183 ± 15 Ma for 004TR-004BIOT, and 2194 ± 15 Ma for 005TR-005BIOT, with initial $^{87}Sr/^{86}Sr$ ratios of 0.70578 and 0.70761, respectively (uncertainties due to measurement only). Pooling of these two ages results in an age of 2188 ± 11 Ma (Fig 6.8; Tables 6.7, 6.8).

Libby and de Laeter (1979) showed that two-point whole rock-biotite isochrons on the western margin of the Yilgarn Block decline from ages of 2500 Ma to 500 Ma as the Darling Fault (which defines the western margin of the Yilgarn Block) is approached from the east. Whole-rock isochrons, however, maintain ages of 2500-2700 Ma to the craton margin. They attribute this phenomenon to a series of discrete events, the gradual elevation of the rock mass through the biotite closure temperature for Rb/Sr isotope systematics of 300°C (after Jager (1965) and others), or to a westward approach to a source of heat less than 500 Ma ago. Extrapolating their results some 150km to the north, it can be demonstrated that the two-point isochrons from Gearless Well, which is situated 85km east of the Darling Fault, lie outside the region of re-setting. In addition, there is no clear evidence for any post-crystallisation event at Gearless Well - the metasomatic event which resulted in uralitisation of the primary pyroxene is thought to be associated with the final stages of igneous activity. Furthermore, the significant amount of uplift necessary to move the rock mass through the biotite closure temperature is not required for the shallow-level Gearless Well body.

These factors lead to the interpretation of the two-point whole rock-biotite Gearless Well isochrons as ages of crystallisation, or at least to ages of cooling below the biotite closure temperature. Due to the near-surface nature of the body, cooling to temperatures below 300°C is virtually simultaneous with crystallisation on a geologic time-scale, particularly following venting, and the age of biotite closure should very closely approximate age of crystallisation.

6.6.4 Discussion

The indicated age for the GW-1 whole rocks then, is a meaningless age, and is interpreted as a mixing line. Given the reasonably linear array of the GW-1 mixing line (Fig. 6.9), the whole-rock isotopics are interpreted as essentially resulting from the mixture of two end-components. The co-linearity of the GW-1 carbonate-veined samples with the relatively unveined hand-picked GW-1 samples, implies that the carbonate veining was not a significantly later event.

It is reasonable to assume that the mixing that produced the linear array of GW-1 samples occurred at around the time of crystallisation, that is, at approximately 2188 Ma. Fig. 6.9 illustrates the positions of the whole-rock points at 2188 Ma. This array results from the mixing of a higher Rb/Sr, less radiogenic component, with a lower Rb/Sr, more radiogenic component. The isotopic compositions of the indicated end-members can be estimated from the limits imposed by the extreme isotopic compositions of the measured whole-rock points. The least radiogenic end-member requires an $^{87}Sr/^{86}Sr$ ratio of at most 0.70229 and an $^{87}Rb/^{86}Sr$ ratio of at least 1.799, while the relatively radiogenic end-member requires an $^{87}Sr/^{86}Sr$ ratio of at least 0.70769 and an $^{87}Rb/^{86}Sr$ ratio less than 0.896. The scatter observed for the GW-3 whole-rock points and their departure from the GW-1 mixing line further demonstrates the inhomogeneity of the body. Rock (1976) points out that explosively emplaced bodies often show variation in their initial $^{87}Sr/^{86}Sr$ ratios, and the GW-3 isotopics are interpreted as resulting from interaction with a third slightly different component than those indicated by the GW-1 mixing line.

6.7 Petrogenesis

6.7.1 Introduction

A consideration of the various possibilities for the petrogenesis of trachyandesites in general, and the Gearless Well trachyandesite in particular, is required before invoking specific models to explain the isotopic array.

6.7.2 Review of trachyandesite petrogenetic models

The trachyandesites are a sub-group of the trachytes, which may be derived in a number of ways. Most trachytic magmas are believed to evolve at low pressures by the high-level differentiation of alkali or transitional basalts (Wright 1971, Middlemost 1981). Some trachytes, particularly those containing lherzolitic xenoliths, are thought to originate in the upper mantle (Wright 1969, Presnall 1969). This group may have been more common in the Archaean, with the degree of silica saturation depending on the conditions of melting (Shirey and Hanson 1984). Yet another group are those found associated with nephelinites or carbonatites, where they are apparently the product of intense alkali metasomatism (King 1965, Van Groos 1975). A long-standing theory for the generation of intermediate magmas is the interaction of a basic magma with a siliceous magma (Fenner 1926, Cantagrel et al 1984), which may be particularly appropriate in the case of violent eruptions (M^cBirney 1980) where one magma, particularly a volatile-charged one, assimilates another.

6.7.3 Petrogenesis of the Gearless Well trachyandesite

High Cr, Ni and V values, and relatively high Mg numbers of 59-69 suggest that the Gearless Well body has not undergone significant fractionation, discounting the possibility of high-level basalt fractionation producing these high K and LILE rocks. Electron microprobe investigation failed to provide evidence for any carbonatite or fenite solution fluxing, either in the form of indicator minerals or abnormally high concentrations of trace elements such as Nb, Ta, Y, Ce or La; thus the fenitisation theory has no support.

The models that need serious consideration for the petrogenesis of the body are (1) mixing of siliceous and basic end-members and (2) primary melt derivation from the upper mantle, with modification by a more radiogenic component.

Modelling involving total chemistry, Sr isotopes and Rb/Sr ratios, suggests that in the case of Gearless Well, there are no geologically sensible combinations that satisfy all the requirements of the siliceous-basic mixing model. Not the least of the problems involved with this model is the thorough mixing required between the relatively low density siliceous component and the higher density basic component. It is likely that the lighter magma would overlie the denser magma of deep-seated origin. McBirney (1980) suggested that mixing would only occur in such a case if the effect of temperature difference was greater than that of compositional difference, and that, even for very large temperature differences, convection was likely to be limited to overturn within the two separate liquids.

Thus the preferred model for the origin of the Gearless Well body is via modification of primary melt derived from the upper mantle.

Consideration of models which approximate the isotopic evolution of the mantle through time (De Paolo and Wasserburg 1976a,1976b; O'Nions et al 1977; Hawkesworth et al 1977) shows that at 2188 Ma, the theoretical uniform reservoir (UR) had an $^{87}Sr/^{86}Sr$ ratio of 0.70199. This is similar to that required for the maximum limit of the non-radiogenic component of the GW-1 mixing line, although the actual value for this component was probably significantly lower than this (see following discussion). Removal of primary melt from LILE enriched upper mantle at 2188 Ma could represent the main component of the Gearless Well body. This is similar to the Canadian Archaean mantle-derived monzodiorites and trachyandesites of Shirey and Hanson (1984), who invoked enrichment of the source by the injection of small amounts of LILE-enriched magma or metasomatic fluids just prior to melting. Similarly, a group of Kenyan LILE-enriched phonolites were suggested by Price et al (1985) to have originated via metasomatism of mantle material by carbonatitic magmas. The similarity of the Gearless Well body to the trachyandesites of Shirey and Hanson (1984,1986), in terms of LILE-enriched character, is demonstrated by a primordial mantle-normalised trace element plot (Fig. 6.10), and Ti, Y, Sc, V, Cr and Ni values compare favourably to those of other mantle-derived Archaean magmas from Giles and Hallberg (1982) and Middlemost (1985).

6.7.4 Discussion

Having concluded that the Gearless Well body was derived from the upper mantle, the previously outlined geochemical differences between GW-1 and GW-3 can be explained in the following manner. Prior to melting, the original mantle material, probably of depleted character, was enriched in LIL elements by the introduction of fertile mantle material (see Roden and Murthy 1985, and Hawkesworth et al 1985, for discussion of mantle enrichment processes). If such newly-enriched mantle material underwent different degrees of partial melting, a range of geochemically distinct magmas could be produced. Most of the LIL elements would be released into the early stage melt. Further melting would then release varying proportions of more basaltic-type melt, containing higher amounts of Mg, Fe and associated trace elements. This process, involving different degrees of partial melting of the same enriched mantle source, satisfies both the observed geochemical and isotopic character of the Gearless Well body, with GW-1 samples originating from a small to moderate degree of partial melting of LIL-enriched mantle, and GW-3 samples originating from a larger degree of partial melting of the same material, perhaps at greater depth. The small variation in Ni content is probably due to the buffering effect of large amounts of residual olivine in the source region. The relative timing of the respective melt production in the upper mantle cannot be deduced, but it is clear that by 2188 Ma, both bodies had risen via a deep-seated crustal fracture to the same high-level magma chamber.

The relationship of $^{87}Sr/^{86}Sr$ at 2188 Ma, to the Sr content of the measured samples is demonstrated in Fig. 6.11, with the effect of Rb removed. The near-linear nature of the GW-1 samples is interpreted as an original feature of the mantle source. It is unlikely that enriched mantle zones are isotopically homogeneous, thus on melting, the heterogeneity of these zones is reflected in the isotope systematics. The non-radiogenic end of the GW-1 mixing line is interpreted as reflecting the depleted mantle component of the source region, with a $^{87}Sr/^{86}Sr$ ratio of about 0.700 at 2188 Ma, and a maximum Sr content of about 300 ppm. The relatively radiogenic end of the mixing line is interpreted as representing the fertile mantle component of the source region, with a $^{87}Sr/^{86}Sr$ ratio of about 0.713 at 2188 Ma, and a Sr content perhaps as high as 2000 ppm.

The minor scatter of GW-1 samples about the mixing line, and the significant departure of GW-3 samples from this line suggests the presence of a third component, of higher $^{87}Sr/^{86}Sr$ and $^{87}Rb/^{86}Sr$ ratios, and lower Sr content than the original magma. Although this component is almost certainly of crustal origin, there is no evidence of major geochemical modification of the GW-3 material, precluding the possibility of more than minor amounts of assimilation of crustal material. It is likely that the observed scatter resulted from interaction of the volatile and fluid-charged magmas with wall-rock during ascent through the crust, perhaps via the leaching effects of circulating magmatic fluids. The required $^{87}Sr/^{86}Sr$ value of about 0.72, and the low Sr content of about 300 ppm for this third component could be satisfied by invoking the involvement of a relatively low Sr-bearing Archaean granitoid, with moderately radiogenic character or with a relatively high Rb/Sr ratio.

6.8 Summary

The Gearless Well trachyandesite body is a rift-related hypabyssal intrusion, and agglomeratic texture suggests probable venting. The mildly alkaline silica-saturated trachyandesite is markedly alumina deficient, and enriched in LIL elements. An age of 2188 ± 11 Ma from two pooled whole rock-biotite isochrons represents the time of cooling below the biotite closure temperature, and closely approximates the age of crystallisation.

Whole rock Rb-Sr measurements on GW-1 samples yield a mixing line produced by small to moderate amounts of melting of an enriched upper mantle source. A larger degree of melting of the same enriched mantle source resulted in the chemical and isotopic differences shown by the GW-3 samples. Scatter within both the GW-1 and GW-3 isotopic analyses suggests interaction with a third component of crustal origin.

The Gearless Well body at 2188 ± 11 Ma is significantly younger than the felsic alkaline suite of the Eastern Goldfields Province. While both rock types are of deep-seated origin, occur in similar rift-related tectonic settings and show some similarities in terms of method of emplacement, the felsic alkaline suite shows depleted incompatible element character, low initial Sr ratios, and is consistent with derivation from a depleted lower crustal source (see Chap 7). Reset ages from members of the felsic alkaline suite at Fitzgerald Peaks (2160 Ma), and Red Hill (2125 Ma), however are similar to the Gearless Well intrusion. These ages, in particular the former, have been attributed to the effects of major crust-forming episodes in adjacent orogenic provinces. While Gearless Well is remote from areas of known orogenesis at around 2188 Ma, it is possible that the age reflects an orogenic episode to the west of the Yilgarn craton at this time. The nearest known possible expression of such activity occurs 120 km to the southwest in the Mullingarra Complex, where Sm-Nd model ages (Fletcher et al 1985) of 2120-2090 Ma are indicated.

The Gearless Well body is slightly older than the Mt. Weld carbonatite, and although both bodies are of mantle origin, Willett et al (1989) suggested the latter to be of direct mantle derivation, with no prehistory or crustal contamination.

The widespread mantle-derived postcratonisation mafic and ultramafic dyke suite of the Yilgarn Block exhibits a broad range of ages, including ages similar to the Gearless Well body (Hallberg 1987). Once again, they are of deep-seated origin and exhibit tectonically controlled emplacement, via deep-seated tensional fractures (Goode 1981), however, the magmas are of tholeiitic character.

This study of the Gearless Well body, and comparison with the felsic alkaline suite, and the Mt. Weld carbonatite, demonstrates differences in deep-seated alkaline magmatism in the Yilgarn block through time and space. While the lower crust and mantle-derived rift-related examples are generally small-scale intrusions of varying alkaline character, they exhibit markedly different petrological and geochemical characteristics. The character of magmas produced in these deep-seated rift-related tectonic settings is thus entirely dependent on the nature of the source region, minor crustal contamination notwithstanding.

CHAPTER 7 PETROGENESIS OF THE FELSIC ALKALINE SUITE AND IMPLICATIONS FOR LATE ARCHAEAN CRUSTAL EVOLUTION

7.1 Introduction

Study of the felsic alkaline suite of the eastern Yilgarn Block has revealed a diversity of mineralogical and geochemical character. Given this diversity, the original petrographic conditions outlined by Libby (1978) remain the best criteria for membership of the suite, with one or more of the following required - quartz contents of less than 20%, alkali pyroxene or alkali amphibole as a primary or major modal phase, and hypersolvus alkali feldspar.

Diversity within the suite is largely a result of the effect of relatively local external processes, rather than an indication of significant differences in the source regions of the parent magmas throughout the eastern Yilgarn, or in the processes responsible for magma production. The Gilgarna Rock intrusion, which exhibits no evidence of modification via the influence of external processes, and is thus considered the type example of the suite, most closely reflects the original character of the parent magma. External processes reflected in many of the other studied examples include local assimilation of country rock, and limited magma mixing. Further modification, as indicated by isotope systematics, is confined to the margins of the craton, reflecting major post-cratonisation crust-forming events.

7.2 Petrogenesis of the felsic alkaline suite

7.2.1 Introduction

Despite the diverse nature of the suite, mineralogical, geochemical and isotopic aspects, together with a consideration of tectonic setting, enable the construction of a consistent petrogenetic model.

7.2.2 Summary of mineralogical characteristics

The felsic alkaline suite is characterised by anhydrous primary mineral assemblages, with water saturation occurring only in residual liquids at a late magmatic stage.

Mineral assemblages are dominated by alkali feldspars, which display a variety of perthitic habits, and generally exhibit complex textures. Restricted compositional variation, however, is typical of hypersolvus suites (Parsons 1978), and CaO is rare to absent. Alternating internal soda-potash zoning is common, often displaying a general increase of soda at the expense of potash from core to rim, and rims are often pure albite. Core regions of anorthoclase crystals occasionally display remnant sodic plagioclases, which reflects limited early plagioclase crystallisation, prior to replacement by anorthoclase as the crystallising phase. Grain boundary complexity in the form of consertal textures is consistent with the passage of an aqueous phase (Parsons 1980).

Plagioclases of the subsolvus two-feldspar examples are invariably sodic, the only exceptions occurring in the inner regions of some zoned crystals, where minor calcic oligoclase is observed, prior to an abrupt return to alkali compositions on exhaustion of available CaO.

Quartz of varying abundance is present in virtually all members of the suite, and together with the complete lack of feldspathoids, reflects the oversaturated nature of the magmas. In the syenites where quartz is present in low abundances, it invariably occurs as a late interstitial phase.

Pyroxenes exhibit a wide range of compositions throughout the suite, from salite and ferroaugite, to sodian augite, aegirine-augite and aegirine. In general, the alkalinity of the pyroxenes is not a function of the original alkalinity of the host rocks (Fig. 7.1), but rather, reflects the extent of development of increasingly alkalic character during crystallisation. Zoned crystals commonly exhibit a progressive increase in soda from core to rim, and in the more pristine examples, this is usually accompanied by an increase in iron, and in the Fe^{3+}/Fe^{2+} ratio. This is known as the alkali ferric iron effect (Carmichael & Nicholls 1967), and reflects decreasing temperatures, and an increase in the alkali and volatile content of the crystallising magma (Kogarko 1974).

Amphibole occurs throughout the suite, almost invariably as a secondary patchy uralitic replacement product of pyroxene in response to the effects of late magmatic residual liquids, and exhibits a vast array of compositions, from actinolite and magnesiohornblende, to the more alkaline richterite-magnesioriebeckite-riebeckite series. Pyroxenes and amphiboles have been shown to exhibit a strong positive correlation between octahedrally-coordinated Al and pressure of crystallisation (Holloway & Burnham 1972). The silica-saturation of virtually all pyroxenes within the felsic alkaline suite, however, restricts the entry of Al into tetrahedral sites, making this relationship difficult to assess. In contrast, amphiboles contain a significant proportion of tetrahedrally-coordinated Al, suggesting lower pressures and shallower depths of crystallisation (Fig. 7.2). This is consistent with the influence of late magmatic fluids being more pronounced during the latter stages of, and following, magma emplacement. The significance of Al coordination in amphiboles of some of the more primitive syenites is less clear, due to markedly low alumina contents, however, the predominance of octahedrally-coordinated Al in these cases may suggest amphibole formation at somewhat deeper levels. A considerable range in A-site occupancies occurs in amphiboles throughout the suite (Fig. 7.2). In sodic amphiboles, the degree of filling of the A-site is considered to be enhanced by conditions of low f_{O_2} and/or high temperatures (Ernst 1962). No consistent trend is observed throughout the suite, with significant variations in individual intrusions and even in individual phases, reflecting local variations in f_{O_2} and temperature.

In the majority of cases within the suite, pyroxenes were relatively early crystallising phases, in contrast to the normal agpaiitic order of crystallisation applying in peralkaline granites and syenites (O'Halloran 1985). Where pyroxenes are present as later crystallising phases, embayments characteristic of partial resorption are observed. This may be related to a temporary rise in temperature above the pyroxene liquidus in response to lower pressures, consistent with an abrupt upward movement of the magma during emplacement (Deer et al 1978).

Accessory phases throughout the suite are dominated by the ubiquitous presence of titanite and to a lesser extent, apatite. Titanite exhibits an extensive crystallisation history, displays a variety of habits, and accounts for the bulk, albeit low, of TiO_2 within these rocks. Increasing silica concentrations and an accompanying decrease in Ti solubilities in the Ti-poor pyroxenes of the suite was probably a significant controlling factor in titanite precipitation (Deer et al 1978). Moderate, and in some cases, large apatite crystals, reflect the presence of enough P in the melt for apatite saturation (Harrison & Watson 1984), and fine grained occluded examples are not generally observed. Analysis totals for apatites, and to a lesser extent titanites are low due to appreciable contents of H_2O/CO_2 and/or F/Cl.

Zircon is generally present as a minor accessory, reflecting limited late crystallisation. Relatively alkaline magmas are prone to the formation of alkali-zirconosilicate complexes due to an excess of alkali cations, which inhibits zircon crystallisation (Watson 1979, Collins et al 1982), and it is only when these complexes are destabilised that zircon saturation in the melt is possible. In the felsic alkaline suite, destabilisation was probably facilitated by the continued and progressively increasing removal of alkali elements by the crystallising pyroxenes, and zircon is closely associated with pyroxenes in these rocks. Fluorite is present in a number of examples as a late phase, reflecting the influence of late magmatic liquids, and is accompanied occasionally by interstitial calcite.

Garnets of the ugrandite group are observed in a number of members of the suite, and with one exception, display virtually identical andradite chemistries (Table 7.1), despite diverse host rock character, and wide geographical separation. Andradite in general displays a diversity of modes of occurrence and parageneses (Dingwell & Brearley 1985), and forms over a wide range of temperature, pressure and oxygen fugacity conditions (Gustafson 1974). The presence of andradite in the felsic alkaline suite is clearly anomalous, with normal modes of occurrence including skarn environments (Deer et el 1978), metasomatised calcic igneuos rocks (Deer et al 1966), serpentinised ultramafics (Onuki et al 1982), and oceanic basalts (Laverne 1987). The only documented occurrences in rocks of alkaline affinity are those in strongly alkaline undersaturated examples (eg Deer et al 1966). The felsic alkaline examples occur as ragged aggregates characteristic of partially resorbed crystals, with rare examples of original euhedral outline, and they are interpreted as relicts of the magma source region.

7.2.3 Summary of geochemical characteristics

Despite geochemical diversity, the primitive and depleted nature of the felsic alkaline rocks is consistently reflected throughout the suite. With the exception of the normal geochemical evolutionary behaviour expected during progressive crystallisation of magmas, there is no evidence whatsoever for the significant involvement of fractionation processes in the evolution of these rocks.

Low to moderate silica values, relatively high alumina and total alkali values, and high Ba and Sr values reflect the dominance of modal alkali feldspar. Variations in the proportion of modal ferromagnesian minerals, principally pyroxene, are reflected in varying abundances of

MgO and CaO. In general, CaO and particularly total iron values are somewhat lower than observed in many other syenitic rocks (eg Le Maitre 1976). The felsic alkaline rocks compare most favourably with examples of A-type affinity (Taylor et al 1981, Collins et al 1982, O'Halloran 1985), with the notable exception of incompatible element contents. A-type rocks are characterised by significant enrichments in Rb, Ga, Zr, Nb, Y, La, Ce, Nd and Zn, whereas with few exceptions, the felsic alkaline suite exhibits low incompatible element abundances. In normal A-type rocks, high concentrations of incompatible elements are encouraged by the formation of stable high-coordination complexes of highly charged cations, in response to halide-induced distortion of framework structures within the melt (Collins et al 1982). In addition, high Zr and REE contents are attributed to the formation of alkali-zircono-silicates due to an excess of alkali cations, although in peraluminous examples this process is inhibited by strong bonding of alkali cations in feldspar structures (Collins et al 1982). While fluorine contents of the Yilgarn examples are generally lower than those of typical A-types (eg Whalen et al 1987), the disparity in incompatible element concentrations is difficult to reconcile with this fact alone. In addition, there is no significant difference in Zr and REE contents between peraluminous and metaluminous examples of the Yilgarn suite. Low incompatible element concentrations in the Yilgarn examples are thus considered to reflect fundamental depletion of these elements in the source region, rather than indicating significant departure from the normal physical behaviour expected in such magmas.

For meaningful intra-suite comparisons, HYG elements were normalised against a source composition of similar depleted character (N-type MORB mantle source, Wood et al 1979). With the exception of minor local variations, similar patterns are observed throughout the suite, with strong relative enrichment in low D elements, and significant negative anomalies for Nb, P, Ti, and to a lesser extent, Sr. The negative anomalies do not reflect the chemistry of the normalising source, as chondrite-normalised patterns exhibit the same negative anomalies. Rather, they reflect either relative retention of Nb, P and Ti in the source region on production of the felsic alkaline melts, or extreme depletion in the source prior to melt production. The latter case is not favoured, as such elements tend to reside in refractory phases. The former case could be achieved by retention of perovskite (Ti, Nb) and apatite (P, and to a lesser extent Sr) in the source residue.

Rare earth element patterns throughout the suite (this study, and Libby 1989) exhibit similar smooth patterns, characterised by LREE enrichments, and the lack of any significant anomalies. The patterns are consistent with the retention of garnet in the source region. As discussed by Libby (1989), the lack of a Eu anomaly mitigates against significant control by residual plagioclase in the evolution of these rocks.

In terms of normative components, the felsic alkaline suite rocks are characterised by an excess of Ab over Or, and low contents of An. Ac is present in only the most alkaline members of the suite, and Ne is known only from one locality. C occurs in minor quantities in some of the less alkaline granitic rocks, and reflects minor crustal contamination. Few members of the suite are more than mildly alkaline, with maximium values of the peralkalinity index slightly in excess of unity, and a range in alumina saturation results in both metaluminous and peraluminous examples.

7.2.4 Summary of geochronological characteristics

Rb-Sr age data for six members of the felsic alkaline suite (Table 7.2) indicates a range in age from 2629-2471 Ma (this study; Libby & De Laeter 1981). Precise dating of the type example of the suite from Gilgarna Rock (this study) yielded ages for the two syenite phases comprising the intrusion of 2627 Ma and 2542 Ma. The 85 Ma age difference between the two pristine syenite phases of virtually identical petrographic and geochemical character, attests to a constancy of source characteristics and magma generation and evolution over a significant period of time, at least in this area. This feature is not observed elsewhere within the suite, perhaps largely because multiple phase pristine intrusions are the exception rather than the norm, and modification of isotope systematics has been demonstrated for several of the other suite members. A difference in age between the two syenite phases from the Binneringie intrusion of the Widgiemooltha sheet is undetectable, partly due to a very restricted range in Rb/Sr values, and the best approximation to a crystallisation age for the intrusion as a whole, is a whole rock-mineral age of 2470 Ma. This is in close agreement to a whole rock-mineral age of 2471 Ma, the minimum ge for syenite from the modified Red Hill intrusion. A whole rock-mineral age of 2350 Ma from the isotopically disturbed Fitzgerald Peaks represents a minimum age only. As a consequence of the interpretation of the Red Hill and Fitzgerald Peaks ages as minimum ages, the accompanying $^{87}Sr/^{86}Sr$ ratios represent maximum estimates of the initial ratio.

The previous Rb-Sr ages of Libby and De Laeter (1981) for the Twelve Mile Well intrusion (2489 Ma) and Woorana Well intrusion (2520 Ma) lie within the range of new data presented in this study, and exhibit similar low initial Sr ratios (see following summary). Results from the Pb-Pb study of Stuckless et al (1981) are difficult to evaluate in the current context. An imprecise age of 2760 ± 210 Ma was obtained for a suite of various syenites from the northern Sir Samuel sheet. While the error limits of this regression overlap partly with those of the Rb-Sr work, the significance of the age is questionable, given the large errors, the small number of samples involved, and sampling on a regional scale in an area where some members of the syenite suite have been subject to significant modification by external processes. Significant support for the validity of the Rb-Sr ages is indicated by preliminary Sm-Nd model ages (Fletcher, in Libby 1989) which yield a range of 2550-2500 Ma for the Woorana Well intrusion.

7.2.5 Summary of isotopic characteristics

Members of the felsic alkaline suite display uniformly low initial $^{87}Sr/^{86}Sr$ ratios (Table 7.2), with a range from 0.70076-0.70153 (this study, Libby & De Laeter 1981). The isotopic character of strontium, and in particular, consideration of initial $^{87}Sr/^{86}Sr$ ratios, has long been used in studying the origins of rocks (eg Faure & Hurley 1963). Crustal rocks, which are relatively enriched in Rb, and hence radiogenic ^{87}Sr, display elevated $^{87}Sr/^{86}Sr$ ratios, in contrast to rocks derived from mantle or depleted crustal sources. Where low initial $^{87}Sr/^{86}Sr$ ratios preclude normal crustal rocks as magma sources, models of mantle isotopic evolution can be useful in tracing magma origins, and providing an estimate of precursor ages. A theoretical chondritic uniform mantle reservoir (CHUR) was favoured by De Paolo and Wasserburg (1976) and McCulloch and Wasserburg (1978). Recognition of the depleted nature of the mantle lead to the modified depleted mantle (DM) model (De Paolo 1981), and this concept has been widely used in studies of Sm-Nd isotope systematics. However, a similar standard depleted mantle evolution curve for the Rb-Sr isotope system has not been developed. While recognising the shortcomings of a system which does not account for mantle depletion over geologic time, use of the standard Sr evolution line resulting from considerations of the Bulk Earth (O'Nions et al 1977, Hawkesworth et al 1977, and others) can yield some information on the pre-histories of rocks.

ϵSr_{UR} values are a measure of the difference between the initial $^{87}Sr/^{86}Sr$ ratio of an intrusion at the time of emplacement, and the corresponding $^{87}Sr/^{86}Sr$ ratio of the theoretical mantle reservoir (UR) at the same time, with negative values representing a depletion relative to UR. With the exception of Red Hill, where the $^{87}Sr/^{86}Sr$ ratio is a maximum estimate, and not strictly conducive to such treatments, all ϵSr_{UR} values are negative, particularly the Gilgarna medium phase syenite, pointing to the depleted nature of the source region for the suite as a whole (Table 7.3). The isotope systematics are only capable of discerning the general depleted nature of the source region however, and a depleted lower crustal source is not precluded by such treatments.

In the case of depleted examples with negative ϵSr_{UR} values, evolution from the theoretical undepleted reservoir clearly involves at least two stages. For simple two-stage evolution, a minimum age of precursor magma separation from an original undepleted source region can be estimated by projecting back to the undepleted evolution curve, assuming that precursor rocks contained no Rb. For the felsic alkaline suite examples, a wide range from 3161-2552 Ma results (Table 7.3), with the extreme values represented by the most depleted Gilgarna Medium phase syenite, and the least depleted Woorana Well syenite, respectively. Hill et al (1989) however, have suggested the possibility that primitive crust formed, at least in the Kambalda-Norseman region, at 3400 Ma from already depleted mantle material, and Campbell and Hill (1988), on the basis of mantle-derived basalt-komatiite sequences, suggested a series of partial melting events within the mantle that extended at least from Norseman to Wiluna. Given multi-stage evolution of the sub-Yilgarn mantle, and indeed the lower crust (Campbell & Hill 1988), modelling of the prehistory of the felsic alkaline magmas is very poorly constrained. Although the Rb-Sr isotopic systematics of these rocks consistently point to the depleted nature of the source, the complex nature and long history of the Yilgarn lower crust and mantle thus preclude further sensible isotopic modelling.

7.2.6 Summary of the influence of fluid phases within the suite

The presence of late exsolved fluid phases is a well documented phenomenon of many A-type occurrences (eg Harris & Marinner 1980, Taylor et al 1981, Harris et al 1986). The fluids represent residual liquid components of the original magma, may be enriched in incompatible elements, and result in sodic, potash or acid autometasomatism of the original assemblage (Bowden et al 1987). Autometasomatism may be reflected in both the mineralogical and geochemical character of the affected rocks, with the degree of alteration depending on the intensity of fluid-rock interaction (Bowden et al 1976). In extreme cases, pegmatites, miarolitic cavities, degassing breccias and unusual incompatible element-rich vein mineralisation may result (Whalen et al 1987).

While the felsic alkaline suite commonly exhibits features consistent with the presence of a late stage autometasomatising fluid component, the influence of such a fluid is generally limited. Mineralogical evidence indicates that the fluids were dominantly sodic, with pure albite rims to feldspars, increasingly sodic pyroxenes, and late sodic amphibole replacement of pyroxenes. Indication of a potash component to the fluids is strictly limited, with minor phlogopite occurring in only one or two examples. Interstitial quartz, fluorite and calcite represent the final products of fluid interaction. Geochemical evidence indicates the limited nature of autometasomatism, with minor scatter of incompatible element distribution occurring only in some intrusions. The most consistent indication of geochemical modification is seen in plots of K_2O vs Rb, where a number of suite members define autometasomatic trends. There is no evidence for modification of Rb-Sr isotope systematics, as can occur in cases of extreme autometasomatism via Rb enrichment (Gerstenberger 1989). In contrast to some examples from the Niger-Nigerian alkaline ring complexes (Bowden et al 1987), there is no evidence for modification of fluids via exchange reactions, boiling or selective loss of gaseous components. Adjacent country rocks show no evidence of fenitisation, and within the suite intrusions, even where mineralogical changes are relatively marked in later phases, metasomatic effects in the intruded phases are confined to distances of a few metres from the contact zones. At Gilgarna Rock, rhythmic igneous layering in the outer margins of the coarse grained syenite is attributed to shifts in phase equilibria resulting from multiple periods of fluid exsolution (Johnson, in press) but this feature is not observed elsewhere within the suite.

7.2.7 Summary of physical characteristics and tectonic setting

The majority of the felsic alkaline suite intrusions occur as small roughly circular plug-like bodies, of 1-2 square kilometres in area. Notable exceptions include the larger crescent-shaped intrusion at Fitzgerald Peaks, the relatively elongate intrusion at Granite Well, and the somewhat diverse spectrum of rocks of the Red Hill area. Contacts with surrounding country rocks are invariably obscured by recent cover. Where internal contacts are observed in the more pristine examples, they are invariably sharp, suggesting either significant differences in age between related phases (eg Gilgarna Rock), and/or relatively low temperatures for the later intruding phases. In the more heterogeneous examples, diffuse contacts as a result of magma mixing suggest higher temperatures, and country rock xenoliths are more common. With the possible exception of the intrusion from Madoonia Downs, the chemical character of suite intrusions does not generally reflect country rock assimilation.

With the exception of the Fitzgerald Peaks and Granite Well intrusions, all members of the felsic alkaline suite occur in the central and eastern portions of the Norseman-Wiluna Belt, which has long been interpreted as a distinct entity resulting from active volcanism and sedimentation in an intracratonic rift zone (Groves et al 1982, Hallberg 1986), or a back-arc or marginal basin setting (Barley et al 1989). The majority of suite intrusions exhibit a close spatial relationship with major north-northwest trending structures of significant regional extent and their postulated extensions, principally the Keith-Kilkenny and Celia Faults. Examples from the southern Widgiemooltha sheet appear more closely related to the Ida-Kunanalling-Boulder Lefroy fault system. Gee et al (1981) suggested that these regional lineaments represent mantle-tapping fractures that developed into crustal sutures. In the northeastern Yilgarn at least, members of the syenite suite are found near the margins of late sediment-filled grabens, which occur adjacent to regional lineaments defining two specific tectonic zones (Hallberg 1986). These tectonic zones have been interpreted as fundamental crustal structures that controlled emplacement of high-level intrusions, and are considered analogous to intracontinental extensional rifts that are associated with peralkaline activity, and may be repeatedly reactivated (Hallberg 1986). Regardless of differing interpretations for the overall tectonic significance of the Norseman-Wiluna belt, it is clear that these major structural discontinuities exercised fundamental control on the emplacement of the felsic alkaline suite intrusions.

Linear distributions of magmatic rocks, with unidirectional increases in age, have been recognised in ocean island basalts (eg White et al 1987), and in numerous African alkaline provinces (eg Bowden et al 1976, Kache & Vachette 1978, Benkhelil 1982). Morgan (1972) suggested that these distributions resulted from progressive plate motion over stationary mantle thermal plumes. Such plumes are thought to originate as instabilities in a hot low-viscosity boundary layer at the base of the mantle, and may exhibit minor drifting themselves (Olson 1987). In the case of the felsic alkaline suite however, geochronological, and indeed petrographic and geochemical data, show no evidence of any trend along the length of the Eastern Goldfields Province. Age inconsistencies in some ocean island volcanic chains have been attributed to the existence of thermally anomalous linear zones in the mantle, rather than single plumes (Bonatti & Harrison 1976), with these "hot lines" representing an active mantle role in the form of upwelling mantle convection cells. The lack of associated mantle-derived volcanism with members of the felsic alkaline suite, however, and indeed with any of the major regional lineaments, suggests a passive role in the generation of the felsic alkaline suite for the mantle over the period 2630-2470 Ma.

7.2.8 Petrogenetic synthesis

Mineralogical, geochemical and isotopic data impose a number of constraints on the method of production and possible source regions of the parent magmas for the felsic alkaline suite.

Whalen et al (1987) outlined three basic models for the petrogenesis of A-type magmas, viz the metasomatic, differentiation and partial melting models. Notwithstanding a generally subdued igneous texture, the anhydrous nature of primary mineralogies, the essentially volatile-free chemistries, and the general homogeneity of the more pristine examples (where magma mixing is not a factor), argue strongly against a metasomatic origin for the felsic alkaline suite. The lack of significant internal chemical differentiation reflected in whole rock and mineral chemistries, and a complete absence of related intermediate magmas refutes a differentiation origin. Rather, in common with many recent workers (eg Collins et al 1982, Anderson 1983, Jackson et al 1984, Whalen et al 1987), the weight of evidence is entirely consistent with the production of primary magmas via processes of partial melting.

The anhydrous mineralogies, with the exception of phases related to late stage exsolved fluids, point to the relatively dry nature of the source, although amphibole and biotite are not precluded from such a source (Collins et al 1982, Whalen et al 1987). The occurrence of hypersolvus feldspars in many of the suite examples suggests relatively high magma temperatures, and this is consistent with the presence of modal quartz, which implies silica activity above the Ab-Ne buffer (Mitchell & Platt 1978), and hence temperatures of 800-900° C (O'Halloran 1985). Martin and Bonin (1976) suggested that subsolvus granites in similar associations may reflect late high-level addition of water to originally hypersolvus magmas, with the resulting wet magmas crystallising as subsolvus rocks. In general, subsolvus examples of the Yilgarn suite do not exhibit the heterogeneous character expected of such processes, and there is compelling evidence for significant crystallisation of these magmas prior to uplift to relatively high levels. The differences in the feldspar mineralogies between the hypersolvus and subsolvus examples, and the observed range of alkaline character, may reflect differences in initial water and trace element contents in the source region (Whalen et al 1987).

With the exception of refractory garnet relicts in some examples, and the presence of a xenolith tentatively identified as granulitic from Fitzgerald Peaks, the general absence of restite phases in the felsic alkaline rocks suggests relatively high temperature completely molten primary magmas. Mafic enclaves and schlieren are present in abundance in some of the more heterogeneous bodies (eg Twin Peaks), but there is no evidence to suggest that these represent anything other than country rock xenoliths entrained during emplacement of the felsic alkaline magmas.

The depleted geochemical nature of the suite, and consistently low initial $^{87}Sr/^{86}Sr$ ratios require a depleted source region. The presence of modal quartz, and general felsic character of the suite argues strongly against an origin from the depleted mantle, and a depleted lower crustal source as favoured by Collins et al (1982), Anderson (1983), Jackson (1984) and Whalen et al (1987) is consistent with the mineralogical, geochemical and isotopic constraints outlined above.

Anhydrous, depleted, relatively felsic garnet-bearing assemblages are typical of granulitic rocks. With one possible exception, xenoliths representative of the source region are absent, and the nature of the source region is poorly constrained. The only clues to the nature of the sub-Yilgarn lower crust are obtained from geophysical data (Drummond 1988). Seismic data are consistent with a layered Yilgarn crust, with an upper granitic layer of 10 km thickness, grading to a felsic granulite layer from 15-28 km, underlain by a transitional zone of more mafic affinity to the Moho at 35 km. Beneath 10 km, an increase in metamorphic grade sees a transition from felsic granulite to garnet granulite and eclogite. The lowermost layer is considered to have an approximate composition of 70% felsic granulite, 30% mafic granulite. Campbell and Hill (1988) considered that the granites of the granite-greenstone terranes were derived by anatectic melting of the lower crust, in response to an upwelling mantle event that produced the basalt and komatiite sequences of the greenstone belt. The removal of previous granitic melts from the lower crust accounts for the depletion observed in the felsic alkaline suite.

While the geophysical data indicate the general nature of the source region, the chemical composition remains poorly constrained. The postulated presence of mafic lenses within the predominantly felsic granulite (Drummond 1988) further complicates the choice of possible source compositions in mass balance modelling. Extensive mass balance calculations were performed using a variety of granulite source compositions, with the medium phase syenite from Gilgarna Rock chosen as the best approximation to the parent felsic alkaline magma. Models were based on the removal of varying amounts of plagioclase, quartz, pyroxene (clino and/or ortho), and in some cases, hornblende and/or biotite. Residuals associated with these calculations were generally such that the solutions obtained were not totally convincing. The best results were obtained where plagioclase was the dominant phase in the melt (Table 7.4), which is consistent with the lack of a Eu anomaly in the REE data (Libby 1989). The presence of orthopyroxene and hornblende resulted in generally poor fits. Removal of plagioclase, quartz, clinopyroxene ± orthoclase from a granulitic source, with garnet, perovskite and possibly minor apatite residual in the source, provides the best balanced solution for the generation of the felsic alkaline magmas.

Following melt production, emplacement of the low density magmas to relatively high crustal levels was facilitated by deep crustal conduits. The progressively decreasing temperatures, increasing f_{O_2} and increasing alkali and volatile activity of the rising magmas lead to the development of a soda-rich residual liquid, and eventual autometasomatism. In some cases, further magma production, or further tapping from a parent magma chamber, lead to the emplacement of very similar syenitic magmas. The virtually identical geochemistry of related phases in many intrusions suggests that if the former case applied, magma production was from the same source, but probably not from the exact site that produced previous felsic alkaline magmas. The possibility of long-lived or episodic mantle heat sources required for repeated partial melting is discussed below. Later intrusive phases, generally of more granitic character, are considered to originate from the same depleted source region, but demonstrate either differences in degrees of melting, or modification via external processes. At Red Hill, for example, alkali granites are thought to have originated from smaller degrees of partial melting from a source of similar composition to that of the syenites. At Fitzgerald Peaks, geochemical evidence strongly suggests that the granites resulted from a mixture of syenitic magma with the regional batholithic granitoid. The single-phase Cardunia Rocks intrusion exhibits depleted geochemical character, but contains an unusually low proportion of ferromagnesian minerals. This may reflect production in a region of the lower crust of predominantly felsic granulite character, with little contribution from mafic granulite.

7.3 Implications for Late Archaean crustal evolution

The general association of alkaline rocks with rift environments has lead some workers to suggest that alkaline magmatism was a consequence of rifting (eg Dixon et al 1981, Arkhangel'skaya 1984), or at least, contemporaneous with rifting (Kempe & Jan 1980). However, Le Bas (1987) suggested that rifting was not a necessary accompanying feature of alkaline magmatism, and stressed the importance of mantle epeirogenesis, with crustal doming or arching caused by mantle plumes. Pre-existing lithospheric lines of weakness were thought to focus such thermal anomalies, and to exercise a structural control on emplacement of intrusions within the crust. While vertical tectonic processes have long been considered a fundamental factor in the evolution of the Yilgarn Block, crustal arching has not been identified as a significant component of this evolution. Upwelling mantle plumes, however, have been invoked as a fundamental controlling factor in the generation of the granite-greenstone terranes (Campbell & Hill 1988).

In the case of the felsic alkaline suite, a mantle heat source is required for the generation of anatectic melts in the depleted lower crust. While the older members of the suite exhibit some overlap with the last stages of granite-greenstone formation, the felsic alkaline event is generally significantly younger, and an alternative heat source to that resulting in the earlier major period of crustal growth is required. The only lithological evidence of Late Archaean mantle activity within the Yilgarn Block is reflected in the mantle-derived mafic and ultramafic dykes. This suite exhibits a wide range of ages, with the central Yilgarn examples occurring in a restricted time interval from the Late Archaean to the Early Proterozoic, while craton margin examples exhibit ages from

2500-560 Ma. On the basis of olivine-bearing Mg-rich dykes in the central Yilgarn, where olivine-rich ultramafic volcanic/plutonic suites are well represented, Hallberg (1987) suggested mantle-generated igneous activity over a period of at least 800 Ma, from greenstone formation at 2800 Ma to dyke emplacement as late as 2000 Ma. Emplacement of the dyke suite occurred predominantly from 2400-2000 Ma, in tensional east-west fractures resulting from tectonic activity on the northern and southern margins of the craton (Hallberg 1987). This, however, does not preclude the beginning of a mantle event at around 2600 Ma, which culminated in the production of the dyke suite magmas. With the exception of a small norite body at Fitzgerald Peaks, which may be related to the dyke suite, the otherwise complete lack of dyke rocks in association with the felsic alkaline suite, and indeed with the north-northwest lineaments that focussed alkaline suite emplacement, suggest that these lineaments may not have extended to the mantle in Late Archaean times. The range in ages of the felsic alkaline suite, and of the dyke suite, may reflect the development of mantle thermal anomalies at different times throughout the eastern Yilgarn.

Examples of suite intrusions occurring near the margins of the craton, viz Fitzgerald Peaks and the Teague intrusion, exhibit evidence of isotopic updating, and possible Proterozoic formation, respectively. The 2160 Ma age from Fitzgerald Peaks reflects the beginnings of major tectonic activity in the neighbouring Albany-Fraser Province. The age of the Teague intrusion has not been resolved, but disrupted sediments resulting from violent intrusion of the syenitic magma suggest a maximum age of approximately 2000 Ma. The mineralogical and geochemical similarity of these rocks to the rest of the felsic alkaline suite, suggest that the composition of the sub-Yilgarn lower crust may have been similar over much of at least the eastern Yilgarn, for a period of some 600 Ma. The thermal anomaly required for the anatectic production of the

Lake Teague intrusion may have been more closely associated with major crust-forming processes in the neighbouring Capricorn Orogen, than with the dyke suite precursor magmas suggested for the other suite examples.

7.4 Summary

The anhydrous depleted rocks of the felsic alkaline suite originated from lower crustal granulitic rocks of predominantly felsic character. These rocks had suffered depletion via the previous removal of significant quantities of granitic melts responsible for the granitoid component of the granite-greenstone terranes (Fig. 7.3). Partial melting of the lower crustal source in response to mantle thermal anomalies resulted in the separation of a plagioclase-rich quartz clinopyroxene assemblage, with garnet residual in the source region. Differences in feldspar mineralogies resulting in both hypersolvus and subsolvus suite examples, reflect differences in water and trace element contents of the source region. The effect of late residual magmatic fluid phases is seen in common, but spatially limited, autometasomatised assemblages, in response to decreasing temperatures and increasing oxygen fugacities. Emplacement of suite intrusions was controlled by deep-seated crustal structures which while not genetically linked to alkaline magma production, may have provided a focus for mantle thermal anomalies. The most probable association of the thermal anomalies is with a mantle melting episode or episodes, which lead to the formation of mafic and ultramafic magmas. These magmas were emplaced from the Late Archaean to the Early Proterozoic, in tensional fractures reflecting the early stages of major crust-forming episodes in adjacent orogenic domains.

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APPENDIX 1

EXPERIMENTAL TECHNIQUES

All whole rock geochemical and all isotopic experimental work was performed by the author, unless acknowledged otherwise, at the Department of Geology and Geophysics at the University of Adelaide. Mineral chemistry analyses were performed by the author at the Electron Optical Centre of the University of Adelaide.

A. MAJOR AND TRACE ELEMENT WHOLE ROCK GEOCHEMISTRY

Samples for major and trace element analysis were collected from the freshest available outcrops. Any weathered surfaces were removed, and 0.5-2.0 kg of sample was washed in distilled water, dried, and crushed in a jaw crusher to -3mm. Splits of crushed material of approximately 100 gms were reduced to -200 mesh in a Siebtechnik tungsten carbide mill. The mill was cleaned between samples with high-grade silica gravel. All major elements, with the exception of Na_2O and FeO, and all trace elements, with the exception of F, were determined by XRF techniques using a Siemens SRS-1 spectrometer, following the method of Norrish & Hutton (1969), with minor modifications as outlined in Nesbitt & Stanley (1980). Major element analyses were considered satisfactory for sums of 99.3-100.3%. Trace element detection limits were as follows, in parts per million: Sc, Rb, Sr, Y - 1; Cu, Zn, Nb - 1.5; Th - 2; V, Pb, Ga, Zr, U - 2.5; Ni, La - 3; Ba - 4; Cr, Nd - 5; Ce - 8; F - 100.

Sodium concentrations were measured by atomic absorption spectroscopy, using standard methods modified after Turnbull and McDuie (in Nesbitt & Stanley 1980). FeO concentrations were determined by classical wet chemistry titration methods. F concentrations were determined by specific ion electrode analysis, following the methods of Nicholson (1983).

All analytical procedures were calibrated against the internal and International Standards summarised by Stanley (in Nesbitt & Stanley

1980). Where FeO concentrations were not determined, total Fe is expressed as Fe_2O_3. Major element analyses are presented on a dry basis, with LOI (loss on ignition) determined by ignition at 960°C.

B. RARE EARTH ELEMENT GEOCHEMISTRY

REE analyses were determined by isotope dilution mass spectrometry as outlined by Sun & Nesbitt (1978), with procedures modified after Turnbull (in Nesbitt & Stanley 1980). Samples of 450-500 mg in size, with 700-800 mg of the spike B of Dr. S. S. Sun (see Nesbitt & Stanley 1980 for details), were weighed directly into teflon bombs, for pressure dissolution at 200°C. High whole rock Ba contents required modifications to chemical procedures, and the normal cation exchange column collection points for the HREE, MREE, Ce and La fractions. Attempts to remove Ba prior to column treatment via addition of H_2SO_4 to precipitate $BaSO_4$, proved only partially successful, and Ba interference was such that Eu and La measurements are not considered usable. For La/Yb ratios, XRF values of La were used.

C. MAJOR ELEMENT MINERAL GEOCHEMISTRY

Thin section sample surfaces were polished and coated with 250mm of carbon. Analyses were performed using a KEVEX 7000 series energy dispersive system attached to a JEOL 733 Superprobe model electron microprobe analyser, at an accelerating voltage of 15 kV and a beam current of 5 nA, following the procedures of Griffin (1983). Data were corrected on-line using PIBS style software (Ware 1981). Calibration of the KEVEX EDS system was performed using elemental and oxide standards, and checked using a pure copper standard (Griffin 1979). Three sigma detection limits for the analysed elements were as follows, in % - SiO_2 0.08, TiO_2 0.13, Al_2O_3 0.09, FeO 0.18, MnO 0.19, MgO 0.07, CaO 0.07, Na_2O 0.10, K_2O 0.07, P_2O_5 0.09, V_2O_3 0.14, Cr_2O_3 0.15, and NiO 0.20.

D. Rb-Sr WHOLE-ROCK AND MINERAL GEOCHRONOLOGY

Collection of sample suites for isotopic investigation was aimed at obtaining the widest possible range of Rb/Sr ratios. Weathered material, igneous contacts, and heterogeneities were avoided wherever possible. Crushing procedures are outlined above. Mineral separates were obtained via standard Wilfley Table, heavy liquid and electromagnetic separation techniques, and carefully handpicked. 50-100 g splits from crushed whole rock samples were milled for five minutes in a Siebtechnik mill to significantly less than 200 mesh size. Rb, Sr and Sr isotope analyses were done using the isotope dilution method, modified slightly after Williams et al (1975), and Page et al (1976). A mixed ^{87}Rb + ^{84}Sr spike was used for the whole rock fractions, and a mixed ^{85}Rb + ^{84}Sr spike was used for the mineral concentrates. Isotope ratio measurements were made using a modified Thomson TSN 206S 300mm radius of curvature mass spectrometer, with a Cary 401 vibrating reed electrometer, automatic peak switcher, Hewlett-Packard 5326 digital voltmeter and Dataram LSI-11 microcomputer. All ratios were corrected for variable mass discrimination by normalising ^{88}Sr/^{86}Sr to 8.3752. The ^{87}Rb decay constant used was 1.42 x 10^{-11} a^{-1} (Steiger & Jager 1977). Replicate analyses of the Eimer and Amend Sr standard gave a value of 0.7080496 $\pm$ 0.0000096 (1σ). Replicate analyses to determine Rb and Sr blank values yielded 3.5-4.9ng and 1.2ng, respectively. Regression analyses were made using the method of M^{c}Intyre et al (1966), with minor modifications (Brooks et al 1972). Ages and tests of significance are at the 95% confidence level. In assigning errors to the regression points, the coefficient of variation for ^{87}Rb/^{86}Sr was 0.4%, and for ^{87}Sr/^{86}Sr, 0.01%.

Notes: (1) For both Rb and Sr, mass spectrometric analyses were consistently 90-95% of XRF analyses. (2) The effect of fractionation of ^{85}Rb/^{87}Rb on blank Rb calculations was investigated using a sample dummy weight of 1gm, and a spike weight of 0.59781gm, assuming all Sr ratios to be 8.0. Under these conditions, a 1% increase in $^{85}Rb/^{87}Rb$ due to fractionation leads to an 82% increase in the "blank". (3) Replicate samples from the Gilgarna Rock intrusion were analysed to test isotopic variations. For three samples, new splits were taken from the original crushed material, milled and analysed. For two samples, duplicate aliquots were taken from the original milled sample. $^{87}Rb/^{86}Sr$ ratios varied by 1.2-6.2% for the remilled samples, and 0.2-0.6% for the duplicate aliquots. $^{87}Sr/^{86}Sr$ ratios varied by 0.04-0.09% for the remilled samples, and 0.006-0.04% for the duplicate aliquots.

E. U-Pb GEOCHRONOLOGY

Samples of 30-50kg were collected from the freshest material available at several sites, with a view to carrying out a zircon U-Pb study. Samples were crushed and disc-ground to -30 mesh, and zircon concentration was carried out using standard Wilfley Table, heavy liquid and electromagnetic techniques. Low Zr values and hence low zircon contents resulted in concentrates of insufficient size for standard multiple-crystal investigation. Titanite and apatite separates were obtained for the coarse syenite from Gilgarna Rock using the same concentration procedures. Samples were abraded following the method of Krogh (1982), washed in acetone rather than aqua regia, ultrasoniced and carefully handpicked, and prepared and analysed by procedures modified from Krogh (1973), and outlined in Cooper & Dong (1983). Measurements were carried out on the apparatus used for the Rb-Sr study. Blank levels were 0.03-3.0ng Pb, and 0.01ng U. Uncertainties in $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ ratios at the 95% confidence level were 0.4-2.2% and 1.3-3.2%, respectively. Regression analyses of Pb-Pb data followed the method of M^c^Intyre et al (1966), given the modifications of Brooks et al (1972).

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APPENDIX 2

SAMPLE LOCATIONS AND DATA AVAILABLE

- all sample numbers prefixed 826
- SHEET refers to Geological Survey of Western Australia 1:250000 Geological Series, with International Index code
- latitudes and longitudes given in degrees, minutes and seconds, south and east respectively
- data available indicated by the presence of an asterisk under the following headings:

  A - whole rock major element analyses
  B - whole rock trace element analyses
  C - whole rock rare earth element analyses
  D - whole rock fluorine analyses
  E - whole rock FeO analyses
  F - mineral major element probe analyses
  G - whole rock Rb/Sr isotopic analyses
  H - mineral Rb/Sr isotopic analyses
  I - mineral U/Pb isotopic analyses
  J - thin section description
  K - hand specimen
  L - stained slab
- all hand specimens and thin sections housed within the collection of the Department of Geology and Geophysics, University of Adelaide

SAMPLE	SHEET		LAT	LONG	A	B	C	D	E	F	G	H	I	J	K	L
003	YALGOO	SH50-2	28 41 02	116 24 16	*	*			*	*	*			*	*	
004	"	"	28 39 45	116 23 45	*	*			*	*	*	*		*	*	
005	"	"	28 39 45	116 23 45	*	*			*		*	*		*	*	
006	KURNALPI	SH51-10	30 20 47	122 26 03	*	*		*	*	*	*			*	*	
007	"	"	30 20 45	122 26 01	*	*		*	*		*			*	*	
008	"	"	30 20 45	122 25 59	*	*		*	*		*			*	*	
009	"	"	30 20 42	122 25 54	*	*	*	*	*	*	*			*	*	*
010	"	"	30 20 42	122 25 48	*	*		*	*		*	*		*	*	
011	"	"	30 20 38	122 25 47	*	*		*	*		*			*	*	
012	"	"	30 20 44	122 25 45	*	*					*			*	*	
013	"	"	30 20 42	122 25 44	*	*								*	*	
014	"	"	30 20 43	122 25 40	*	*								*	*	
015	"	"	30 20 42	122 25 39	*	*		*	*		*			*	*	
016	"	"	30 20 40	122 25 35	*	*	*	*	*	*	*	*	*	*	*	*
017	"	"	30 20 42	122 25 37	*	*					*			*	*	
018	"	"	30 20 42	122 25 37	*	*		*	*	*	*			*	*	
019	"	"	30 20 54	122 25 32	*	*								*	*	
020	"	"	30 20 54	122 25 32	*	*								*	*	*
021	"	"	30 20 54	122 25 32	*	*		*	*	*	*			*	*	*
022	"	"	30 20 32	122 25 39	*	*	*	*	*		*			*	*	
023	"	"	30 20 40	122 25 38	*	*		*	*		*			*	*	
024	"	"	30 18 50	122 35 40	*	*		*	*	*				*	*	
025	"	"	30 35 00	122 30 00	*	*		*	*					*	*	
026	"	"	30 35 00	122 30 00	*	*		*	*					*	*	
027	"	"	30 35 00	122 29 45	*	*								*	*	
028	"	"	30 34 30	122 24 45	*	*		*	*					*	*	
029	"	"	30 34 50	122 24 40	*	*		*	*	*				*	*	*
030	"	"	30 40 30	122 29 45	*	*		*	*					*	*	
031	"	"	30 55 30	122 33 05	*	*		*	*					*	*	

SAMPLE	SHEET		LAT	LONG	A	B	C	D	E	F	G	H	I	J	K	L
032	KURNALPI	SH51-10	30 55 30	122 33 05	*	*								*	*	
033	"	"	30 55 30	122 33 05	*	*		*	*	*				*	*	
034	"	"	30 55 30	122 33 05	*	*				*				*	*	
035	"	"	30 55 30	122 33 05	*	*								*	*	*
036	"	"	30 57 50	122 38 00	*	*		*	*					*	*	
037	"	"	30 57 50	122 38 00	*	*								*	*	
038	"	"	30 57 50	122 38 00	*	*								*	*	
039	"	"	30 57 50	122 38 00	*	*		*	*	*				*	*	*
040	"	"	30 57 50	122 38 00										*	*	
041	"	"	30 57 50	122 38 00	*	*								*	*	
042	"	"	30 57 50	122 38 00	*	*								*	*	
043	"	"	30 58 40	122 36 50	*	*		*	*					*	*	
044	WIDGIE.	SH51-14	31 03 20	122 38 15										*	*	
045	"	"	31 03 20	122 38 15	*	*		*	*					*	*	
046	"	"	31 03 50	122 38 30	*	*		*	*	*				*	*	
047	"	"	31 03 50	122 38 30	*	*								*	*	*
048	"	"	31 03 50	122 38 30										*	*	
049	"	"	31 19 15	122 44 55	*	*		*	*					*	*	
050	"	"	31 20 35	122 22 45	*	*		*	*	*				*	*	
051	"	"	31 20 35	122 22 45	*	*								*	*	
052	"	"	31 39 20	122 09 20	*	*				*	*	*		*	*	*
053	"	"	31 39 25	122 09 15	*	*		*	*					*	*	
054	"	"	31 39 30	122 09 00	*	*								*	*	
055	"	"	31 40 00	122 08 35	*	*		*	*	*	*			*	*	
056	"	"	31 07 20	121 49 20	*	*				*				*	*	
057	"	"	31 07 20	121 49 20	*	*		*	*					*	*	
058	"	"	31 04 40	122 17 10	*	*								*	*	
059	NABBERU	SG51-5	25 49 30	120 56 00	*	*								*	*	
060	EDJUDINA	SH51-6	29 55 55	122 38 05	*	*		*	*					*	*	

SAMPLE	SHEET		LAT	LONG	A	B	C	D	E	F	G	H	I	J	K	L
061	EDJUDINA	SH51-6	29 52 25	122 25 55	*	*		*	*	*				*	*	
062	"	"	29 52 25	122 25 55	*	*		*	*					*	*	
063	"	"	29 55 40	122 04 20	*	*		*	*					*	*	*
064	"	"	29 55 35	122 04 20	*	*								*	*	*
065	"	"	29 55 30	122 04 15	*	*		*	*					*	*	
066	"	"	29 55 30	122 04 15	*	*								*	*	
067	"	"	29 55 20	122 04 15	*	*				*				*	*	
068	"	"	29 55 25	122 04 10										*	*	
069	"	"	29 55 25	122 04 10	*	*								*	*	
070	"	"	29 55 25	122 04 10	*	*								*	*	
071	"	"	29 56 40	122 02 55	*	*								*	*	
072	"	"	29 56 40	122 02 50	*	*		*	*	*				*	*	
073	"	"	29 56 40	122 02 50	*	*								*	*	*
074	"	"	29 56 40	122 02 55	*	*								*	*	
075	"	"	29 56 40	122 02 55	*	*								*	*	
076	"	"	29 56 40	122 02 55	*	*								*	*	
077	"	"	29 43 05	121 57 45	*	*		*	*	*				*	*	*
078	"	"	29 43 00	121 57 45	*	*		*	*	*				*	*	
079	"	"	29 45 05	121 57 45	*	*								*	*	*
080	"	"	29 29 40	121 55 05	*	*								*	*	
081	"	"	29 29 45	121 55 05	*	*		*	*					*	*	*
082	"	"	29 29 45	121 55 05	*	*								*	*	
083	"	"	29 11 45	122 11 50	*	*									*	
084	"	"	29 11 45	122 11 50	*	*								*	*	
085	"	"	29 11 45	122 11 50	*	*		*	*					*	*	*
086	LEONORA	SH51-1	28 46 50	121 25 40	*	*								*	*	
087	"	"	28 46 50	121 25 40	*	*								*	*	
088	"	"	28 46 50	121 25 40	*	*		*	*					*	*	*
089	"	"	28 46 50	121 25 40	*	*								*	*	*

SAMPLE	SHEET		LAT	LONG	A	B	C	D	E	F	G	H	I	J	K	L
090	LEONORA	SH51-1	28 46 50	121 25 40	*	*		*	*	*				*	*	
091	"	"	28 46 50	121 25 40	*	*									*	
092	"	"	28 46 50	121 25 40	*	*		*	*	*				*	*	
093	SIRSAMUEL	SG51-13	27 52 00	121 22 00	*	*									*	
094	"	"	27 52 00	121 21 55	*	*		*	*	*				*	*	*
095	"	"	27 34 20	121 19 25	*	*		*	*					*	*	
096	"	"	27 33 45	121 19 45	*	*		*	*					*	*	
097	"	"	27 33 40	121 19 45	*	*				*				*	*	*
098	"	"	27 28 30	121 11 40	*	*		*	*					*	*	*
099	"	"	27 28 30	121 11 45	*	*		*	*	*				*	*	*
100	"	"	27 09 31	121 14 26	*	*								*	*	
101	"	"	27 09 31	121 14 25	*	*								*	*	
102	"	"	27 09 31	121 14 24	*	*		*	*		*			*	*	
103	"	"	27 09 31	121 14 24	*	*		*	*		*			*	*	
104	"	"	27 09 31	121 14 24	*	*		*	*		*			*	*	
105	"	"	27 09 32	121 14 21	*	*	*	*	*	*	*	*		*	*	
106	"	"	27 09 34	121 14 18	*	*		*	*	*	*			*	*	
107	"	"	27 09 37	121 14 18	*	*								*	*	
108	"	"	27 09 37	121 14 18	*	*		*	*		*			*	*	
109	"	"	27 09 36	121 14 16	*	*				*	*			*	*	*
110	"	"	27 09 39	121 14 17	*	*		*	*		*			*	*	
111	"	"	27 09 38	121 14 17	*	*								*	*	
112	"	"	27 11 19	121 14 46	*	*		*	*		*			*	*	
113	"	"	27 11 20	121 14 46						*				*	*	*
114	"	"	27 11 20	121 14 46	*	*		*	*					*	*	
115	"	"	27 11 19	121 14 46	*	*		*	*		*			*	*	
116	"	"	27 11 19	121 14 46						*				*	*	
117	"	"	27 11 19	121 14 46	*	*		*	*		*			*	*	
118	"	"	27 11 19	121 14 46	*	*								*	*	

SAMPLE	SHEET		LAT	LONG	A	B	C	D	E	F	G	H	I	J	K	L
119	SIRSAMUEL	SG51-13	27 11 19	121 14 46	*	*				*				*	*	
120	"	"	27 11 19	121 14 46	*	*	*	*	*	*	*	*		*	*	*
121	"	"	27 11 18	121 14 46										*	*	
122	"	"	27 11 18	121 14 46	*	*		*	*		*			*	*	
123	"	"	27 11 20	121 14 46											*	
124	L.JOHNSTN	SI51-1	32 52 10	121 08 20	*	*					*				*	
125	"	"	32 52 10	121 08 20	*	*		*	*	*	*	*		*	*	*
126	"	"	32 52 10	121 08 15	*	*									*	
127	"	"	32 52 10	121 08 15	*	*					*			*	*	
128	"	"	32 52 10	121 08 15	*	*		*	*		*			*	*	
129	"	"	32 52 10	121 08 15	*	*					*				*	
130	"	"	32 52 10	121 08 10	*	*									*	
131	"	"	32 52 15	121 08 05	*	*		*	*	*	*			*	*	
132	"	"	32 52 20	121 08 05	*	*									*	
133	"	"	32 52 25	121 08 00	*	*					*			*	*	
134	"	"	32 52 25	121 08 05												
135	"	"	32 52 20	121 08 10	*	*		*	*	*	*			*	*	
136	"	"	32 52 20	121 08 10	*	*					*			*	*	
137	"	"	32 57 45	121 03 45	*	*				*				*	*	
138	"	"	32 57 45	121 03 45	*	*		*	*					*	*	*
139	"	"	32 55 40	121 11 00	*	*		*	*		*				*	
140	"	"	32 53 50	121 11 00	*	*								*	*	
141	"	"	32 53 15	121 10 20	*	*		*	*		*			*	*	*
142	"	"	32 53 15	121 10 20	*	*					*			*	*	
143	"	"	32 53 15	121 10 20	*	*					*				*	
144	"	"	32 53 20	121 10 20										*	*	
145	"	"	32 53 20	121 10 20	*	*		*	*	*	*			*	*	
146A	"	"	32 52 50	121 10 10	*	*					*			*	*	
146B	"	"	32 52 50	121 10 10	*	*					*			*	*	

SAMPLE	SHEET	LAT	LONG	A	B	C	D	E	F	G	H	I	J	K	L
147	L.JOHNSTN SI51-1	32 52 50	121 10 10	*	*					*				*	
148	" "	32 52 50	121 10 10	*	*		*	*		*				*	
149	" "	32 52 50	121 10 10	*	*		*	*						*	
150	" "	32 52 50	121 10 10	*	*		*	*		*	*		*	*	
155	WIDGIE. SH51-14	31 40 30	121 11 10	*	*		*	*					*	*	
156	" "	31 39 20	122 09 10	*	*								*	*	
157	" "	31 39 20	122 09 05	*	*					*				*	
158	" "	31 39 20	122 09 05	*	*									*	
159	" "	31 39 15	122 09 10	*	*		*	*					*	*	
160A	" "	31 39 05	122 08 45	*	*									*	*
160B	" "	31 39 05	122 08 45	*	*									*	*
161	" "	31 39 05	122 08 45	*	*									*	*
162	" "	31 39 00	122 08 50											*	
163	" "	31 38 55	122 08 55	*	*					*	*		*	*	
164	" "	31 38 30	122 08 30	*	*								*	*	
165	" "	31 38 30	122 08 30	*	*				*	*			*	*	
166	" "	31 38 25	122 08 35	*	*		*	*					*	*	
167	" "	31 20 35	122 08 45	*	*									*	*
168	" "	31 20 35	122 08 45	*	*								*	*	
169	" "	31 20 35	122 08 45	*	*									*	
170	" "	31 20 35	122 08 45	*	*		*	*					*	*	
171	KURNALPI SH51-10	30 20 36	122 25 41	*	*		*	*						*	
172	" "	30 20 34	122 25 41	*	*		*	*					*	*	
173	" "	30 20 34	122 25 53	*	*		*	*		*			*	*	
174	" "	30 20 30	122 25 59	*	*		*	*						*	
175	" "	30 20 29	122 25 59	*	*		*	*		*			*	*	
176	" "	30 20 40	122 25 35	*	*		*	*		*				*	
177	" "	30 20 40	122 25 35	*	*					*				*	
178	" "	30 20 40	122 25 35	*	*		*	*		*				*	

SAMPLE	SHEET		LAT	LONG	A	B	C	D	E	F	G	H	I	J	K	L
179	KURNALPI	SH51-10	30 20 40	122 25 38	*	*	*	*	*	*	*			*	*	
180	"	"	30 20 40	122 25 38	*	*					*			*	*	
181	"	"	30 20 40	122 25 38	*	*		*	*		*			*	*	
182	"	"	30 20 42	122 25 38	*	*									*	
183	"	"	30 20 42	122 25 38	*	*									*	
184	"	"	30 20 42	122 25 38	*	*									*	
185	"	"	30 20 40	122 25 35										*	*	
186	EDJUDINA	SH51-6	29 55 40	122 04 20	*	*									*	
187	"	"	29 55 40	122 04 20	*	*								*	*	
188	"	"	29 55 40	122 04 20	*	*									*	
189	"	"	29 55 40	122 04 15	*	*								*	*	
190	"	"	29 55 40	122 04 15	*	*									*	
191	"	"	29 55 40	122 04 15	*	*		*	*						*	
192	"	"	29 55 35	122 02 20											*	
193	"	"	29 55 35	122 04 20	*	*									*	
194	"	"	29 55 35	122 04 20	*	*									*	
195	"	"	29 55 35	122 04 15	*	*								*	*	
196	"	"	29 55 30	122 04 15	*	*		*	*						*	
197	"	"	29 55 20	122 04 15	*	*									*	
198	"	"	29 55 20	122 04 15	*	*								*	*	
199	"	"	29 55 20	122 04 10	*	*									*	
200	"	"	29 50 30	121 56 15	*	*		*	*	*				*	*	
201	"	"	29 50 30	121 56 15	*	*		*	*						*	
202	"	"	29 29 50	121 55 05											*	
203	"	"	29 29 45	121 55 05	*	*		*	*	*				*	*	
204	LAVERTON	SH51-2	28 35 10	122 32 45	*	*								*	*	
205	"	"	28 35 10	122 32 30	*	*		*	*					*	*	
206	SIRSAMUEL	SG51-13	27 11 18	121 14 46	*	*		*	*		*				*	
207	"	"	27 11 19	121 14 46	*	*								*	*	

SAMPLE	SHEET	LAT	LONG	A	B	C	D	E	F	G	H	I	J	K	L
208	" "	27 11 19	121 14 46	*	*		*	*		*				*	
209	" "	27 11 19	121 14 46	*	*		*	*		*			*	*	
210	" "	27 11 01	121 14 33	*	*		*	*		*			*	*	
211	" "	27 10 49	121 14 16	*	*		*	*		*			*	*	
212	" "	27 10 48	121 14 15	*	*		*	*	*				*	*	
213	" "	27 10 47	121 14 12	*	*									*	
214	" "	27 10 46	121 14 10	*	*									*	
215	" "	27 10 46	121 14 09	*	*									*	*
216	" "	27 10 50	121 14 19	*	*								*	*	
217	" "	27 10 40	121 15 07	*	*								*	*	
218	" "	27 10 36	121 15 07	*	*								*	*	
219	" "	27 09 25	121 14 19	*	*									*	
220	" "	27 09 25	121 14 19	*	*		*	*		*			*	*	
221	" "	27 09 23	121 14 19	*	*								*	*	
222	" "	27 09 29	121 14 13	*	*									*	
223	" "	27 09 30	121 14 16	*	*		*	*					*	*	*
224	" "	27 08 10	121 15 40	*	*		*	*					*	*	
225	LAVERTON SH51-2	28 52 00	122 32 00	*	*				*				*	*	
226	NABBERU SG51-5	25 50 10	120 55 15	*	*									*	
227	" "	25 50 10	120 55 15	*	*									*	
228	" "	25 50 10	120 55 15	*	*		*	*	*				*	*	
229	" "	25 50 10	120 55 15											*	
230	" "	25 50 10	120 55 15	*	*									*	*
231	" "	25 50 08	120 55 23	*	*		*	*						*	*
232	" "	25 50 08	120 55 15	*	*					*				*	
233	" "	25 50 07	120 55 24											*	
234	" "	25 50 07	120 55 24	*	*				*				*	*	
236	" "	25 50 06	120 55 23	*	*									*	
237	" "	25 50 06	120 55 23											*	

SAMPLE	SHEET		LAT	LONG	A	B	C	D	E	F	G	H	I	J	K	L
238	NABBERU	SG51-5	25 50 06	120 55 23											*	
239	"	"	25 50 06	120 55 23	*	*									*	
240	"	"	25 50 06	120 55 23	*	*									*	
241	"	"	25 50 05	120 55 22											*	
242	"	"	25 50 05	120 55 22	*	*		*	*		*			*	*	*
243	"	"	25 49 45	120 55 33											*	
244	"	"	25 49 45	120 55 33											*	
245	"	"	25 49 45	120 55 34	*	*		*	*		*				*	
246	"	"	25 49 45	120 55 34											*	*
247	"	"	25 49 45	120 55 34	*	*									*	*
248	"	"	25 49 45	120 55 35	*	*		*	*					*	*	
249	"	"	25 49 45	120 55 35	*	*									*	
250	"	"	25 49 45	120 55 36											*	
251	"	"	25 49 45	120 55 36	*	*					*	*		*	*	
252	"	"	25 49 45	120 55 36						*				*	*	

APPENDIX 3

REPRESENTATIVE THIN SECTION DESCRIPTIONS

Descriptions of representative thin sections are given in chapter order, and listed in numerical order for each rock type or phase. Each description is set out in the following manner:

Sample No.- as used throughout, prefix 826. **Location** - locality name, (for accurate location coordinates, see Appendix 2). **Rock type** - field name; modal classification name (Streckeisen 1976); chemical classification name (De La Roche et al 1980). **Description** - texture; main & accessory minerals %.

Grainsizes are defined as follows: >30mm very coarse (vcgr), 5-30mm coarse (cgr), 1-5mm medium (mgr), <1mm fine (fgr).

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006 Gilgarna Rock eastern margin. Medium phase syenite, alkali feldspar syenite, syenite. Pink mcgr inequigranular subhedral alkali feldspar-pyroxene syenite. 75% antiperthite, some with remnant albite cores; 20% augite(core)/aegirine-augite(rim), stubby to elongate prisms; 1% quartz, interstitial; 1% biotite, phlogopitic; 1% titanite. Access. apatite, opaques, zircon, epidote, uralite, colourless mica, fluorite.

008 Gilgarna Rock central east. Medium phase syenite, alkali feldspar syenite, syenite. Pink mcgr inequigranular subhedral alkali feldspar-pyroxene syenite, occasional cgr zoned feldspar laths. 75% antiperthite, occasional albite rims; 25% augite(cores)/aegirine-augite(rims), stubby to elongate prisms; trace phlogopitic biotite, quartz; accessory apatite, titanite, opaques, fluorite, uralite, colourless mica.

009 Gilgarna Rock central. Medium phase syenite, alkali feldspar syenite, syenite. Pink mcgr hiatal subhedral alkali feldspar-pyroxene syenite,

occasional vcgr zoned feldspar laths. 80% antiperthite, common albite rims; 15% aegirine-augite, occasional augite cores, slight alteration to magnesioriebeckite; 2% phlogopitic biotite; <1% quartz, titanite, calcite; accessory apatite, magnetite, magnesioriebeckite, fluorite, colourless mica.

010 Gilgarna Rock central. Medium phase syenite, alkali feldspar syenite, syenite. Pink mgr hiatal subhedral alkali feldspar-pyroxene syenite, minor cgr feldspar laths. 75% antiperthite; 25% augite(cores)/aegirine-augite(rims), patchy alteration to magnesio-riebeckite, minor uralitic needles as rims; trace biotite; accessory titanite, apatite, fluorite, calcite, mica.

011 Gilgarna Rock central. Medium phase syenite, alkali feldspar syenite, syenite. Pink mgr hiatal subhedral alkali feldspar-pyroxene syenite, occasional cgr zoned feldspar laths, autometasomatic effects more evident than 009 or 010. 80% antiperthite, laths have anorthoclase cores unmixed towards edges and marked albite rims; 7% aegirine-augite, minor augite cores; 7% magnesioriebeckite, patchy to complete replacement of pyroxene, and discreet needles; 5% biotite; 1% quartz, interstitial; accessory titanite, apatite, magnetite, zircon, calcite, colourless mica.

021 Gilgarna Rock northwest. Medium phase syenite, alkali feldspar quartz syenite, quartz syenite. Greyish mgr inequigranular subhedral alkali fspar quartz pyroxene syenite, mgr zoned feldspar laths, common evidence of autometasomatism. 76% antiperthite to perthite, occasional albite rims; 10% quartz, interstitial; 7% aegirine, shreddy relicts largely replaced; 3% magnesioriebeckite, replacing aegirine; 2% biotite, phlogopitic, replacing aegirine; 2% calcite, (feldspar alteration, & discrete interstitial grains with quartz; accessory titanite, apatite, opaques, colourless mica, ?zircon.

175 Gilgarna Rock northeast. Medium phase syenite, alkali feldspar quartz syenite, quartz syenite. Greyish mcgr inequigranular subhedral alkali

feldspar quartz pyroxene syenite, zoned alkali feldspar laths. 75% meso to antiperthite, alternating K/Na interiors, more perthitic towards albite rims; 8% quartz; 7% aegirine, extensively replaced; 6% magnesioriebeckite, partly to totally replacing aegirine; 2% biotite, phlogopitic; 2% calcite, as feldspar alteration, & discrete interstitial grains with quartz; accessory titanite, apatite, fluorite, magnetite, ?barite, colourless mica.

015 Gilgarna Rock central west. Coarse phase syenite, alkali feldspar syenite, syenite. Pink cgr inequigranular subhedral alkali feldspar-pyroxene syenite, common evidence of autometasomatism. 85% unmixed anorthoclase, occasional albite zones, consertal textured; 7% biotite; 4% aegirine, minor amphibole/biotite alteration; 4% quartz, interstitial; trace replacement magnesioriebeckite, calcite, fluorite; accessory titanite, apatite, magnetite, zircon.

016 Gilgarna Rock gnamma-hole. Coarse phase syenite, alkali feldspar syenite, syenite. Pink-grey cgr inequigranular subhedral alkali feldspar-pyroxene syenite, common evidence of autometasomatism. 85% unmixed anorthoclase, series of alternating Na-K zones towards rim of microcline, mesoperthite and albite, consertal-textured; 6% aegirine, minor amphibole-biotite replacement; 3% magnesioriebeckite, patchy to total replacement of pyroxene; 3% biotite; 2% quartz, interstitial; 1% calcite, late-stage alteration of feldspars with colourless mica and fluorite, and interstitial; accessory titanite, apatite, magnetite, zircon. SEM on mineral separates also showed rutile, monazite, epidote and barite.

022 Gilgarna Rock northwest. Coarse phase syenite, alkali feldspar quartz syenite, quartz syenite. Pink mcgr inequigranular subhedral alkali feldspar pyroxene quartz syenite. 75% unmixed anorthoclase, alternating Na-K zones through antiperthite to albite rims; 10% quartz, interstitial; 6% aegirine, relicts extensively replaced; 4% magnesioriebeckite, partial to total replacement of aegirine; 3% biotite; 2% calcite, feldspar

alteration and discrete interstitial grains; accessory titanite, apatite, magnetite, colourless mica.

173 Gilgarna Rock east. Coarse phase syenite, alkali feldspar syenite, syenite. Pink-grey mcgr inequigranular subhedral alkali feldspar-pyroxene syenite, less evidence of autometasomatism than 015 & 016. 82% antiperthite to mesoperthite, consertal-textured; 12% aegirine; 3% biotite, patchy alteration of pyroxene, and discrete grains; 3% quartz; accessory titanite, apatite, magnetite, colourless mica, fluorite, zircon.

019/020 Gilgarna Rock south-west. Rhythmic layered coarse phase. Alternating mafic and felsic layers. Mafic layers - 70% augite(cores)/aegirine-augite(rims), minor alteration to amphibole; 19% feldspar, mainly oligoclase-albite, minor anorthoclase; 5% titanite; 4% quartz, interstitial; 1% magnetite; accessory apatite. Felsic layers - 85% antiperthite to mesoperthite, minor oligoclase-albite; 15% augite(cores), aegirine-augite(rims); 5% quartz; 1% titanite.

023 Gilgarna Rock dyke. Medium dyke syenite, alkali fspar quartz syenite, syenite. Leucocratic fmgr equigranular sub to anhedral feldspar pyroxene quartz syenite. 85% antiperthite to mesoperthite, consertal-textured; 8% biotite, phlogopitic, after pyroxene; 5% quartz, interstitial; 2% aegirine-augite, relict; accessory fluorite, titanite, apatite, magnetite, calcite.

179/181 Gilgarna Rock dyke. Medium dyke syenite, alkali feldspar quartz syenite, syenite. Pink mgr equigranular subhedral to anhedral feldspar pyroxene quartz syenite. 75% antiperthite to mesoperthite, occasionally zoned, consertal-textured; 15% aegirine-augite, rare augite cores, minor replacement; 10% quartz; trace biotite, magnesioriebeckite replacing pyroxene; accessory titanite, fluorite, apatite, calcite, colourless mica.

018 Gilgarna Rock central south. Feldspar-amphibole porphyry, porphyritic

monzonite. Mcgr subhedral two-feldspar hornblende monzonite, 40% phenocrysts, 60% groundmass. Phenocrysts - 25% oligoclase; 5% hornblende, possibly replacing augite; 5% biotite, replacing hornblende; 5% titanite, epidote; <1% relict pyroxene. Groundmass - 30% oligoclase; 18% hornblende; 10% microcline; 2% epidote; trace quartz; accessory apatite, opaques, fluorite, barite.

106 Red Hill north. Syenite, alkali feldspar quartz syenite, syenite. Pink mgr inequigranular subhedral alkali feldspar pyroxene quartz syenite, amphibole & pyroxene define moderate fabric. 82% microcline perthite, minor mesoperthite, granophyre; 5% albite; 5% augite; 5% quartz; 3% hornblende, Ti-poor; accessory titanite, apatite, magnetite, zircon, allanite, epidote, fluorite, chlorite.

112 Red Hill south. Syenite, alkali feldspar syenite, syenodiorite. Mcgr inequigranular subhedral quartz-deficient massive alkali feldspar pyroxene syenite. 60% mesoperthite, microcline perthite; 35% aegirine-augite; 4% albite; 1% uralite (actinolite); accessory magnetite, apatite, titanite, fluorite, biotite, epidote, zircon.

119 Red Hill south. Syenite, alkali feldspar pyroxene syenite, syenite. Mgr inequigranular subhedral to anhedral garnet-bearing alkali feldspar pyroxene syenite, with weak preferred orientation. 80% mesoperthite, microcline perthite; 8% albite; 8% aegirine-augite; 1% quartz; <1% titanite and apatite; <1% andradite, ragged clumps; trace uralite (actinolite); accessory magnetite, fluorite, zircon, epidote.

113 Red Hill south. Fgr slightly less pyroxene-rich syenite dyke, within coarse pyroxene-rich syenite, with coarse lath-like aegirine-augite prisms to 2cm growing from the coarse phase into the dyke.

120 Red Hill south. Syenite, alkali feldspar syenite, syenite. Mcgr inequigranular subhedral alkali feldspar pyroxene syenite, weak preferred orientation. 90% microcline perthite, mesoperthite; 8% aegirine-augite; 1% albite; 1% actinolite, replacing pyroxene; accessory apatite,

titanite, magnetite, epidote.

209 Red Hill south. Syenite, alkali feldspar syenite, syenite. Mcgr inequigranular subhedral massive alkali feldspar pyroxene syenite. 82% microcline perthite to mesoperthite; 8% aegirine-augite; 5% albite, rims and patchy outer zones to alkali feldspars, 3% quartz, interstitial; 2% actinolite, patchy replacement & rimming of pyroxene, accessory titanite, apatite, magnetite, epidote, ?allanite.

102 Red Hill north. Granitoid, alkali feldspar quartz syenite, alkali granite. Pink mgr anhedral two-feldspar quartz pyroxene alkali granite. 50% microcline perthite; 30% albite, occasionally myrmekitic, moderate mica alteration, fuzzy kinked twins; 15% quartz; 3% pyroxene, extensively replaced by amphibole and iron oxides; <1% amphibole, ?actinolite; accessory opaques (not magnetite), titanite, apatite, colourless mica.

109 Red Hill north. Quartz monzonite, syenogranite, granite. Light pink mgr inequigranular subhedral two-feldspar pyroxene granite, weak preferred orientation. 50% microcline, microcline perthite, mesoperthite; 21% oligoclase, occasionally myrmekitic; 20% quartz; 8% ferroaugite; 1% uralitic actinolite-hornblende, fibrous, rimming and replacing ferroaugite; accessory magnetite, titanite, apatite, allanite, calcite, epidote, chlorite, mica.

110 Red Hill north. Quartz monzonite/syenogranite, quartz monzonite, granite. Dark pink mgr inequigranular subhedral to anhedral two-feldspar pyroxene quartz monzonite. 45% microcline; 32% oligoclase; 18% quartz; 2% augite, rimmed and replaced by 2% actinolite-hornblende; accessory titanite, magnetite, apatite, calcite, epidote, chlorite.

115 Red Hill south. Pyroxene granitoid, syenogranite, alkali granite. Light pink mgr inequigranular anhedral granite. 66% microcline perthite; 10% oligoclase-albite; 23% quartz; 1% pyroxene, ?augite; trace uralite (act/hblende), after pyroxene; accessory titanite, magnetite, biotite/chlorite, apatite, allanite, epidote.

212 Red Hill central west. Quartz monzonite, alkali feldspar quartz syenite, quartz syenite-monzonite. Pinkish mcgr inequigranular subhedral alkali feldspar quartz syenite. 75% microcline perthite to mesoperthite; 12% quartz; 8% albite, occasionally myrmekitic and antiperthitic; 4% augite to aegirine-augite; <1% uralite (actinolite-hornblende), rimming and replacing pyroxene; accessory titanite, apatite, magnetite, epidote.

217 Red Hill central east. Quartz syenite, alkali feldspar granite, alkali granite. Light pink mgr inequigranular anhedral granite, well defined preferred orientation. 75% microcline perthite to mesoperthite; 20% quartz; 3% albite; 2% uralite (actinolite), replacing pyroxene; trace remnant pyroxene; accessory magnetite, titanite, zircon, allanite, epidote, colourless mica.

100 Red Hill north. Alkali granite dyke, alkali feldspar granite, alkali granite. Pink cvcgr anhedral alkali feldspar granite dyke. 55% microcline perthite; 40% quartz; 5% albite, occasionally myrmekitic; accessory opaques (not magnetite), titanite.

114 Red Hill south. Alkali feldspar syenite, alkali feldspar syenite, syenite. Pink cvcgr subhedral perthite-dominant syenite. 95% microcline perthite to mesoperthite; 2% albite, occasionally rimming alkali feldspar; 2% quartz, interstitial; 1% pyroxene, extensively altered, ?aegirine-augite; accessory titanite, opaques.

103 Red Hill north. Granitoid, quartz diorite, tonalite. Mcgr subhedral plagioclase-dominant quartz diorite with abundant titanite. 85% oligoclase-andesine, Ab75-65, occasionally antiperthitic; 10% quartz; 1-2% actinolite/hornblende, replacing pyroxene; 1% alkali feldspar, exsolved from plagioclase; trace pyroxene remnants; accessory titanite, apatite, opaques.

223 Red Hill north. Quartz monzonite/monzogranite, quartz monzonite, granite. Pink fmgr inequigranular somewhat hydrous massive two-feldspar amphibole quartz monzonite. 40% oligoclase-?albite, occasionally anti-

perthitic, Ab85-90; 35% microcline and perthite; 18% quartz; 5% actinolite or hornblende; 1% biotite/chlorite; accessory titanite, magnetite, apatite, zircon, fluorite, allanite, epidote, colourless mica (alteration of plag).

224 7.5 km west of Wonganoo H.S. Granite, monzogranite, alkali granite. Typical cgr inequigranular subhedral Yilgarn granite, weak to moderate preferred biotite orientation. 40% microcline; 35% oligoclase, occasionally myrmekitic, zoned, minor exsolved alk fspar; 25% quartz; <1% biot/chlorite; access. magnetite, calcite & mica (after plag), titanite, ?apatite, ?allanite.

125 Fitzgerald Peaks west. Quartz syenite, alkali feldspar quartz syenite, granite/alkali granite. Pink mcgr clotty inequigranular inhomogeneous perthite-dominant quartz syenite, hybrid appearance, weak to moderate fabric. 80% microcline perthite to mesoperthite; 15% quartz; 5% aegirine-augite, more Na-rich rims; <1% albite; accessory titanite, magnetite, apatite, fluorite, epidote.

128 Fitzgerald Peaks west. Quartz syenite, alkali feldspar quartz syenite, quartz syenite. Light grey-pink mcgr anhedral alkali feldspar quartz syenite, weak preferred orientation, hybrid appearance. 86% microcline perthite to mesoperthite; 9% quartz, partly embayed; 3% aegirine-augite, partly embayed; <1% albite; <1% uralite; accessory titanite, apatite, magnetite.

133 Fitzgerald Peaks west. Quartz syenite, alkali feldspar quartz syenite to alkali feldspar granite, granite. Light pink mgr sub to anhedral alkali feldspar quartz syenite, weak preferred orientation. 77% mesoperthite, minor microcline perthite; 20% quartz; 2% aegirine-augite; <1% albite; <1% uralite, after pyroxene, with associated magnetite; accessory titanite, apatite, magnetite, calcite.

139 Fitzgerald Peaks central east. Quartz syenite, alkali feldspar quartz syenite, syenite. Pink mgr inequigranular subhedral alkali feldspar

quartz pyroxene syenite. 78% microcline perthite to mesoperthite; 13% aegirine-augite; 5% quartz; 2% uralite, after pyroxene, wtih magnetite speckle; <1% albite; accessory titanite, apatite, magnetite, epidote.

141 Fitzgerald Peaks east. Syenite, alkali feldspar syenite, syenite. Pink mcgr inequigranular subhedral inhomogeneous perthite-dominant clotty pyroxene syenite. 92% microcline perthite and mesoperthite-antiperthite; 3% albite-oligoclase; 3% aegirine-augite, in random clots; 2% uralite, after pyroxene, with associated magnetite, calcite; trace quartz; accessory titanite, apatite, magnetite, epidote, calcite, colourless mica.

142 Fitzgerald Peaks east. Alkali feldspar granite, alkali feldspar granite, alkali granite. Pink cgr inhomogeneous subhedral alkali feldspar granite. 72% microcline perthite to mesoperthite; 28% quartz; <1% aegirine-augite; <1% uralite, replacing pyroxene, with magnetite; accessory magnetite, titanite, calcite.

145 Fitzgerald Peaks east. Syenite, alkali feldspar (quartz) syenite, syenite/quartz syenite. Pink mgr anhedral alkali feldspar quartz syenite. 86% microcline perthite to mesoperthite; 5% albite; 4% quartz; 2% aegirine-augite; 2% uralite, (actinolite/hornblende), after pyroxene, wih associated magnetite; accessory titanite, apatite, magnetite, calcite, epidote, chlorite.

150 Fitzgerald Peaks east. Syenite, alkali feldspar syenite, syenite. Light pink mcgr inhomogeneous clotty anhedral perthite-dominant syenite, with abundant apatite, titanite. 88% antiperthite to mesoperthite; 6% aegirine-augite; 2% uralitic actinolite/hornblende, after pyroxene, with associated magnetite; <1% albite-oligoclase, probably largely unmixed; <1% quartz; accessory apatite (1%), titanite, biotite/chlorite, magnetite, epidote.

135 Fitzgerald Peaks west. Biotite adamellite, monzogranite, granite. Light pink-grey mgr equigranular anhedral two-feldspar amphibole granite,

weak preferred orientation. 41% microcline perthite to mesoperthite; 35% oligoclase; 20% quartz; 1-2% biotite/chlorite; <1% hornblende; accessory magnetite, fluorite, titanite, apatite, zircon, calcite.

137 Dog Rock. Biotite granite, monzogranite, granite. Mgr subhedral to anhedral two-feldspar biotite granite, moderate preferred orientation. 42% oligoclase, common colourless mica and calcite alteration; 30% microcline; 20% quartz; 8% biotite; access. magnetite, titanite, apatite, epidote, zircon, allanite, colourless mica, calcite.

138 Dog Rock. Granite, monzogranite, granite. Cgr biot granite. 38% oligoclase, myrmekitic in part, moderate mica alteration; 30% microcline; 30% qtz; 1-2% biotite; accessory magnetite, zircon, epidote, mica, calcite.

049 1km N Dog Lake turnoff, Erayinia Granitoid Complex. Syenite, quartz syenite, quartz syenite. Pink brown weathered mcgr inequigranular subhedral mesoperthite syenite. 70% mesoperthite, albite rims & overgrowths; 15% albite; 10% pyroxene, altered; 5% quartz; trace chlorite; access. opaques, titanite, apatite, fluorite, allanite, calcite.

044 4.5km S Erayinia Hill. Granite, quartz monzonite, quartz syenite. Pink mcgr inequigranular subhedral granite. 50% microcline, occasional perthite; 30% albite; 9% augite; 5% hastingsitic hornblende; 5% quartz; <1% epidote, chlorite, titanite, magnetite; accessory apatite, zircon.

046 5.5km S Erayinia Hill. Granite, quartz monzonite, syenite. Pink white mcgr weakly foliated inequigranular sub to anhedral granite. 55% microcline perthite, common albite overgrowths; 30% albite; 8% augite; 7% quartz; <1% hastingsite, repl. pyx; access. titanite, apatite, magnetite, zircon, epidote.

050 8km NNE Madoonia Downs. Syenite, alkali feldspar quartz syenite, quartz monzonite. Mcgr inequigranular to seriate subhedral quartz syenite/ monzonite. 55% albite; 20% hornblende; 15% alkali feldspar, common albite rims and overgrowths; 5% quartz; 5% pyroxene, heavily

oxidised; accessory titanite, magnetite, zircon, apatite, biotite, allanite, epidote.

052 Lake Cowan syenite east, 12km SSE Binneringie. Lath syenite, alkali feldspar syenite, syenite. Pink mcgr subhedral alkali feldspar pyroxene syenite, subparallel feldspar laths (?flow texture), reas. common recrystallisation especially lath margins, andradite reflecting source composition. 84% perthite, antiperthite, mesoperthite, rims often microcline rich; 12% aegirine-augite; <2% quartz, recrystallised; <1% titanite; <1% magnetite; accessory apatite, zircon, andradite (ragged clumps), rare amphibole after pyroxene, ?pyrophyllite.

055 Lake Cowan syenite east central, 12km SSE Binneringie. Syenite, alkali feldspar syenite, syenite. Grey-white mcgr subhedral extensively recrystallised alkali feldspar pyroxene syenite, weak to moderate mineral lineation (?flow texture). 74% alkali feldspar, predominantly antiperthite; 15% (aegirine)-augite; 5% hastingsite, late-stage after pyroxene; 3% magnetite; 1-2% quartz, totally recrystallised; <1% titanite; accessory apatite, epidote, zircon, ?pyrophyllite.

165 Lake Cowan syenite northwest, 12km SSE Binneringie. Equigranular syenite, alkali feldspar syenite, syenite. Light pink extensively recrystallised sub to anhedral alkali feldspar pyroxene syenite. 90% antiperthite, mesoperthite, albite; 5% augite, minor amphibole replacement; <2% quartz; 1% magnetite; <1% hornblende, replacing pyx; accessory titanite, apatite, epidote, ?stilpnomelane, biotite/chlorite.

056 Lake Lefroy north shore, 10.7km S Carnilya Hill. Syenite, alkali feldspar syenite, syenite. Mcgr subhedral inequigranular alkali feldspar pyroxene syenite, andradite reflecting source composition. 85% zoned unmixed anorthoclase, occasional albite cores and K-rich or mesoperthitic rims; 15% zoned augite(cores)/aegirine-augite(rims); <1% quartz, interstitial; trace biotite; accessory titanite, apatite, allanite (metamict), andradite (ragged aggregates), ?pyrophyllite.

058 8km ESE Randalls. Granite, quartz monzodiorite, alkali granite. Mcgr inequigranular subhedral granite, evidence of deformation. 75% oligoclase, weakly aligned laths; 15% microcline; 7% quartz; 3% biotite; accessory magnetite.

024 17km ENE Gilgarna Rock. Granitoid, monzogranite, granite. Dark grey fmgr subhedral equigranular weakly foliated granite. 37% oligoclase, albitic twds rim, occas. myrmekitic; 23% quartz; 20% microcline; 15% biotite; 1% epidote; <1% chlorite, muscovite; <1% calcite; accessory titanite, apatite, zircon, opaques, allanite.

030 Lake Roe western margin. Pyroxene granitoid, quartz syenite-monzonite, quartz syenite. Pink mcgr inequigranular-porphyritic subhedral to anhedral two-feldspar pyroxene quartz syenite-monzonite, andradite reflecting source composition. 50% microcline perthite to mesoperthite; 30% albite, minor antiperthite; 15% quartz; 5% aegirine-augite; accessory magnetite, titanite, apatite, ?zircon, allanite (metamict), andradite (clumps suggesting resorption).

029 Bulyairdie Rocks. Granitoid, monzogranite, granite. Mcgr subhedral granite porphyry. 40% albite, occasionally antiperthitic, microcline perthite rims; 32% microcline, microcline perthite, mesoperthite; 20% quartz; 8% hornblende; accessory epidote, magnetite, apatite, titanite, zircon.

026 Yindi Rock. Aplite, monzogranite, alkali feldspar granite. Fmgr equigranular foliated granite. 40% microcline; 40% quartz; 20% oligoclase; <1% biotite/chlorite and muscovite; accessory allanite, titanite, opaques.

027 Yindi Rock. Granitoid, monzogranite, granite. Pink white mgr subhedral equigranular weakly foliated granite. 34% microcline, oikocrystic wrt plag; 30% oligoclase, often myrmekitic; 30% quartz; 6% biotite/(chlorite); <1% epidote, musc; access. titanite, apatite, opaques, zircon, allanite.

031 Cardunia Rocks. Pyroxene granitoid, alkali feldspar granite, quartz syenite to alkali granite. Grey mgr recrystallised equigranular anhedral massive two feldspar quartz pyroxene syenite, (plagioclase pure albite), minor andradite reflecting source composition. 45% microcline, perthitic to mesoperthitic, occasional albite rims; 32% albite, rarely antiperthitic; 20% quartz, partially recrystallised; 1% aegirine-augite, minor magnesioriebeckitic replacement; 1-2% calcite, late-stage interstitial; trace biotite and magnesioriebeckite; accessory titanite, magnetite, ?allanite, ?zircon, andradite (ragged clumps suggesting resorption), fluorite, apatite.

039 Dingo Rock. Granite, monzogranite, qtz monzonite. Pink mcgr inequigranular sub to anhedral qtz monzonite, weak to moderate hornblende lineation. 39% microcline; 38% albite; 15% quartz; 7% hornblende, hastingsite rims; 1% epidote; accessory titanite, apatite, magnetite, chlorite, zircon, fluorite.

042 Dingo Rock. Granite, qtz monzonite, qtz syenite. Dark pink mcgr inequigranular anhedral granite. 38% microcline, occasionally perthitic, minor albite rims; 32% albite; 15% quartz; 10% hornblende to hastingsite; 2% biotite/chlorite; 1% titanite, magnetite; accessory zircon, apatite, allanite.

063 Twin Peaks south. Syenite, diorite, monzonite/monzodiorite. Grey white mgr subhedral equigranular plag-dominant pyroxene microcline syenite-monzonite. 80% oligoclase, slightly deformed, resorbed original plag grains in cores; 15% augite, common resorption textures, minor zoning & amphibole replacement; 2% qtz, interstitial recrystallised; 1% microcline; 1% epidote, symplectitic; <1% hornblende, replacing augite; accessory titanite, apatite, opaques, fluorite.

065 Twin Peaks north. Monzonite, monzodiorite, monzodiorite. Mgr seriate plagioclase-dominant monzodiorite, extensive fluid interaction. 76% oligoclase, slightly deformed, strongly altered resorbed cores; 9%

augite, partially resorbed, extensively replaced by amphibole; 7% hornblende, replacing augite; 4% quartz; 1-2% epidote, symplectitic; <1% microcline; accessory titanite (altered), apatite, opaques.

068 Twin Peaks north. Layered granitoid, monzodiorite/syenite. Pink fmgr anhedral plag-dominant monzodioritic bands (83% oligoclase, 8% quartz, 6% hornblende, 1% augite, <1% microcline, accessory titanite, opaques, apatite, epidote, zircon, biotite/chlorite) in sharp contact with melanocratic mgr subhedral to anhedral syenite bands (61% microcline, 29% augite, 8% albite, 1% hornblende, <1% quartz, accessory opaques, apatite, titanite, zircon).

067 Twin Peaks north. Monzonite, monzodiorite, monzodiorite. Pink mgr feldspar pyroxene monzonite, weak preferred orientation. 85% oligoclase, 9% augite, 2% qtz, 2% epidote, 1% hornblende, <1% microcline; accessory titanite, opaques, apatite.

198 Twin Peaks north. Monzonite, quartz monodiorite, monzodiorite. Mgr plagioclase-dominant quartz monzodiorite. 87% oligoclase; 8% quartz; 3% augite, extensively replaced by amphibole; 1% hornblende, replacing augite; 1% microcline; accessory apatite, titanite, opaques, epidote.

071 Twelve Mile Well, eastern margin. Granitoid, monzogranite, granite. Grey mgr subhedral equigranular two feldspar quartz pyroxene weakly deformed monzogranite, with prominent titanite. 40% oligoclase; 25% quartz; 23% microcline; 7% augite, minor zoning and embayment, partially replaced by amphibole; 5% actinolite/hornblende, replacing augite; <1% titanite, moderately-strongly altered; accessory apatite, opaques, zircon, ?andradite.

072 Twelve Mile Well. Syenite, syenite, monzogabbro. Mcgr epidotised two feldspar pyroxene syenite. 40% salite/augite, partially replaced by amphibole; 35% microcline; 20% albite; <5% epidote, aggregates, veinlets, & replacing pyroxene; accessory actinolite, quartz, apatite, titanite, opaques, zircon.

073 Twelve Mile Well. Alkali feldspar syenite, alkali feldspar syenite, syenite. Fmgr subhedral seriate two feldspar pyroxene syenite. 45% albite; 45% microcline, occasionally perthitic; 9% salite/augite, minor embayment and amphibole replacement; 1% actinolite, replacing augite; <1% quartz; accessory titanite, apatite, opaques, epidote, clinozoisite.

077 Cement Well. Syenite, alk fspar syenite, syenite. Pink fmgr inequigranular subhedral alkali feldspar pyroxene syenite. 88% unmixed anorthoclase, perthite, mesoperthite, antiperthite, occas. sericitised albite cores; 7% augite, aegirine/augite rims; 2% quartz, interstitial; 1% calcite, interstitial; <1% biot/chlor; trace hblende, after augite; access. titanite, magnetite, apatite, fluorite, allanite, zircon, ?andradite (ragged aggregates).

078 Cement Well, dyke phase. Syenite, syenite, syenite. Pinkish grey fmgr anhedral to subhedral syenite, occasional microcline laths to 1cm, minor evidence of deformation. 60% microcline; 30% albite; 3% hornblende, replacing augite; 3% epidote (clinozoisite); 1-2% magnetite; <1% augite; <1% biotite; <1% titanite; accessory apatite.

079 Cement Well. Granite, monzogranite, granite. Pink white mcgr seriate subhedral granite. 45% plagioclase, zoned, extensively altered; 25% microcline, perthite (minor braid), anti and mesoperthite, and as rims to altered plag; 25% quartz; 2% hornblende, late stage ?actinolite; accessory titanite, apatite, opaques, biotite/chlorite, epidote, fluorite, calcite.

082 M^{c}Auliffe Well, dyke. Quartz monzonite/syenite, quartz monzonite, alkali granite. Light pink mgr porphyritic subhedral slightly deformed alkali granite. 55% albite-oligoclase, occasionally antiperthitic, moderately to extensively altered; 25% microcline, and microcline perthite as rims to plagioclase; 18% quartz, deformed; 1% actinolite; 1% haematite; <1% chlorite; accessory titanite, allanite, ragged andradite, colourless mica.

203 McAuliffe Well, dyke. Syenite/monzonite, quartz monzodiorite, quartz syenite. Mgr subhedral two feldspar syenite. 65% plagioclase, albite cores, increasingly oligoclasic towards albite rims; 20% alkali feldspar, usually perthitic, discrete, exsolved within plag, as zones within plag, as rims to plag; 7% qtz, interstitial; 5% hornblende; <1% pyroxene, remnant augite?; <1% biotite; <1% haematite; accessory titanite, apatite, ragged andradite, mica.

084 Eucalyptus Dam. Alkali granite porphyry, alkali granite, alkali granite. Pink orange mcgr subhedral porphyritic granite, anhedral crystalloblastic fgr quartz feldspar groundmass. Phenocrysts(60%) - qtz (subrounded, ?partially resorbed), plagioclase (?oligoclase-albite, extensively altered), orthoclase, biot/chlor; Groundmass(40%) - interlocking quartz-feldspar mass. Total - 75% felspar, 20% quartz, 2-4% biot/chlor, 1% opaques, accessory titanite, epidote, muscovite.

086 Pig Well. Syenite, alkali feldspar syenite, syenite. Pinkish brown mgr subhedral alkali feldspar pyroxene syenite, tabular alkali feldspar laths to 3cm. 95% unmixed anorthoclase, mesoperthite, perthite and antiperthite, ubiquitous swapped margins; 5% aegirine-augite to aegirine; trace magnesioriebeckite, after pyroxene; accessory titanite, opaques.

088 Pig Well. Alkali feldspar syenite, alkali feldspar syenite, syenite. Pinkish brown mgr anorthoclasite. 97% unmixed anorthoclase, mesoperthite, antiperthite, swapped margins; 2% muscovite, metasomatic, interstitial, along cracks; <1% ?pyroxene; trace biot/chlor; accessory opaques.

090 Pig Well. Syenite, syenite/monzonite, syenite. Pink brown mgr sub to anhedral equigranular syenite. 45% anorthoclase, antiperthite to mesoperthite, common plag cores; 45% albite-oligoclase, complex zoning, and larger albite-oligoclase crystals; 5% aegirine-augite; 2% quartz, strained, interstitial; <1% riebeckite-richterite, replacing pyroxene; <1% calcite, interstitial; trace biotite and muscovite; accessory titanite, apatite, opaques.

204 Granite Well, 15km ENE Laverton. Syenite, alkali feldspar syenite, syenite. Light pink syenite porphyry, mcgr pyroxene & alkali feldspar phenocrysts, fgr plag/microcline groundmass, prominent titanite. 95% alkali feldspar, antiperthite, mesoperthite, albite; 1-2% aegirine-augite, altered; accessory titanite, apatite, fluorite, magnetite, calcite, biotite.

205 Granite Well, 15km ENE Laverton. Syenite, alkali feldspar syenite, syenite. Dark pink mcgr anhedral perthite aegirine-augite syenite porphyry, moderate to strong preferred orientation. Phenocrysts- 25% microcline perthite to mesoperthite, 8% aegirine-augite; Groundmass- 28% microcline, 28% albite, 10% quartz, accessory biotite/chlorite, titanite, fluorite, magnetite, epidote, apatite.

060 2.3km N Foley Well. Granite, monzogranite, alkali granite. Strongly recrystallised foliated fmgr subhedral granite. 40% oligoclase zoned laths; 30% quartz; 25% microcline; 2-3% muscovite, after feldspar; 1-2% biotite; accessory opaques, epidote, titanite.

061 12km SSW Edjudina. Granite, monzogranite, granite. Grey pink strongly recrystallised altered mgr anhedral granite dyke. 40% oligoclase to 5mm; 35% qtz; 22% microcline; 2% muscovite; 1% epidote; accessory opaques, biotite/chlorite, calcite.

200 Menangina Rocks. Granodiorite, granodiotite, granite. Mcgr subhedral granodiorite porphyry. 45% calcic oligoclase, variably altered, myrmekitic; 25% microcline, to 10mm; 25% qtz; 3% biotite/chlorite; 1% muscovite; accessory titanite, magnetite, apatite, zircon, calcite (after plagioclase).

201 Menangina Rocks. Leucogranite dyke, granodiorite, alkali granite. Light pink fmgr massive granular subhedral granite. 50% sodic oligoclase; 25% microcline; 25% quartz; accessory opaques, muscovite, biotite/chlorite.

094 Andy Well. Granitoid, quartz syenite, quartz monzonite. Light pink mcgr inequigranular subhedral monzonite/syenite, weak preferred orientation. 60% unmixed anorthoclase, microcline perthite, antiperthite, mesoperthite; 15% oligoclase; 15% quartz; 4% hornblende; 4% biot/chlorite; <1% epidote; accessory titanite, apatite, opaques, fluorite, zircon, mica.

097 1km E Little Well. Granite, alkali feldspar granite, alkali granite. Greywhite fmgr tectonised (minor banding, preferred orientation) subhedral granular granite. 48% albite; 25% microcline; 25% quartz; 1-2% aegirine-augite; trace magnesioriebeckite fibres and replacement of pyroxene, accessory titanite, magnetite, fluorite, apatite, zircon.

099 2.9km N Woorana Well. Syenite, alkali feldspar syenite, syenite. Light pink mcgr subhedral microcline albite pyx syenite. 55% albite, occas. myrmekitic; 38% microcline perthite; 5% sodian ferrosalite-ferroaugite, minor replacement amphibole; <1% qtz; trace amph, biot; accessory titanite, apatite, opaques, epidote.

098 2.9km N Woorana Well. Granite, alkali feldspar granite, alkali granite. Mcgr inequigranular anhedral granite, weak preferred orientation. 38% microcline, occasionally perthitic; 36% albite, occasionally myrmekitic; 25% quartz; 1% biotite/chlorite; accessory apatite, opaques, allanite, muscovite, calcite.

228 Lake Teague. Granite, alkali feldspar granite, granite. Purple brown fmgr granular anhedral totally recrystallised shock textured granite, with mm-scale purple brown veinlets of opaques, ?pseudotachylite. 40% microcline; 35% albite; 24% quartz, common deformation lamellae; accessory titanite.

234 Lake Teague. Syenite, alkali feldspar syenite, syenite. Severely altered pink fmgr anhedral pyroxene quartz syenite, evidence of shock deformation, andradite reflecting source composition. 95% microcline-

albite, severely altered interlocking mass; 3% quartz, minor deformation lamellae; <2% amphibole, sieve textured to fibrous, sodic ?richterite; <1% andradite, occasional original crystal preserved; accessory titanite, opaques.

252 Lake Teague. Syenite, alkali feldspar syenite, syenite. Purple brown mcgr subhedral shock textured alkali feldspar pyroxene syenite. 85% mesoperthite, minor zoning, consertal textures, braid perthite; 15% aegirine-augite, deformation lamellae; accessory titanite, opaques, apatite, zircon, ?actinolite, quartz.

Gearless Well. Trachyandesite, trachyte, mugearite-latite. Light to dark grey fmgr subhedral flow-lineated pilotaxitic porphyritic biotite trachyandesite, agglomeratic autobreccia texture. 90-65% groundmass- barian sanidine, uralitic actinolite, albite, magnetite, calcite, quartz, titanite, apatite, zircon. 10-35% phenocrysts- phlogopitic biotite, uralitic actinolite, barian sanidine. Subrounded agglomeratic fragments from 20-200mm have generally finer grained phenocrysts, less biotite, slightly coarser groundmass, and occur within a matrix of mineralogically identical lighter grey trachyandesite.

001 65% groundmass- 34% sanidine, 20% actinolite, 5% albite, 5% biotite, accessory titanite, calcite; 35% phenocrysts- 13% actinolite, 10% biotite, 10% sanidine, 2% apatite.

002 60% groundmass- 30% sanidine, 20% actinolite, 5% magnetite, 4% albite, accessory titanite; 40% phenocrysts- 15% actinolite, 15% sanidine, 8% biotite, 2% apatite.

003(3) 90% groundmass- 65% sanidine, 15% actinolite, 8% albite, 2% magnetite, access titanite, apatite; 10% phenocrysts- 9% actinolite, 1% biotite.

004(13) 80% groundmass- 45% sanidine, 15% actinolite, 10% albite, 5% magnetite, 5% calcite, accessory titanite, apatite; 20% phenocrysts- 10% biotite, 4% actinolite, 4% sanidine, 2% apatite.

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APPENDIX 4

RELEVANT PUBLICATIONS

JOHNSON G.I. & COOPER J.A. 1986. Rb-Sr geochronology of Late Archaean syenitic intrusives, eastern Yilgarn Block, Western Australia. *Geological Society of Australia, Abstracts* 15, 102-103. (copy).

JOHNSON G.I., COOPER J.A. & BLIGHT D.F. 1989. The geology and geochronology of a Proterozoic trachyandesite plug, Murchison Province, Yilgarn Block, Western Australia. *Australian Journal of Earth Sciences* 36, 319-336. (offprint).

JOHNSON G.I. & COOPER J.A. 1989. Rb-Sr whole-rock and mineral dating of Gilgarna Rock syenite, Yilgarn Block, Western Australia. *Australian Journal of Earth Sciences* 36, 472-474. (offprint).

JOHNSON G.I. (in press). Rhythmic igneous layering from the Gilgarna Rock syenite, Yilgarn Block, W.A. *Journal of the Royal Society of Western Australia*. (manuscript).

Johnson, G. I., & Cooper, J. A. (1989). Geological Note: Rb-sr whole-rock and mineral dating of gilgarna rock syenite, yilgarn block, Western Australia. *Australian Journal of Earth Sciences*, *36*(3), 472-474.

Johnson, G. I., Cooper, J. A., & Blight, D. F. (1989). The geology and geochronology of a Proterozoic trachyandesite plug, Murchison Province, Yilgarn Block, Western Australia. *Australian Journal of Earth Sciences, 36*(3), 319-336.

1.6 Rb-Sr GEOCHRONOLOGY OF LATE ARCHAEAN SYENITIC INTRUSIVES, EASTERN YILGARN BLOCK, W.A.

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Mildly alkaline syenitic intrusives of the eastern Yilgarn Block crop out sporadically from Fitzgerald Peaks, 100 km south-west of Norseman, to Lake Teague, 100 km north-east of Wiluma. Members of the suite are characterised by the presence of one or more of the following : alkali pyroxene, alkali amphibole, mesoperthitic alkali feldspar, and low modal quartz contents. Rb-Sr isotopic studies are being carried out on several discrete, widely separated syenitic bodies. Data obtained to date substantiate the conclusions of previous workers that alkaline activity was a late Archaean phenomon in the Yilgarn Block, but suggest that such activity was more complex than was previously thought.

Gilgarna Rock, lying 103 km east-north-east of Kalgoorlie, is a small circular body of approximately 1 square km in area. It is composed of two syenitic phases, referred to here as the medium grained phase and the coarse grained phase. Both phases consist of coarse euhedral to subhedral zoned alkali feldspar, aegirine-augite and quartz, with accessory sphene, fluorite, calcite, zircon, apatite, opaques and occasional phlogopitic biotite. Magnesioriebeckitic amphibole is occasionally present as a replacement product of aegirine-augite. The coarse phase contains xenoliths of the medium phase, indicating it to be younger in age. In addition, the coarse phase is cut by a narrow dyke of finer grained quartz syenite. The two main phases are mineralogically similar in hand specimen, but are distinguishable on standard Harker and ternary elemental variation diagrams. The medium phase has higher Fe_2O_3, MgO and TiO_2 contents than the coarse phase, but lower Al_2O_3 and K_2O contents. Both phases have high Na_2O values (7-8%); evidence of internal sodic metasomatism during the latter stages of crystallisation of both phases includes the following:- alkali feldspars exhibit albite rimming, aegirine-augites have aegirine-rich rims, and magnesioriebeckite replaces and rims aegirine-augite in places. The quartz syenite dyke crosscutting the coarse phase shows no evidence of such metasomatism.

New whole-rock Rb-Sr isotopic data yield perfect-fit Model 1 ages for both the medium and coarse phases. The medium phase gives an age of 2642 ± 57 Ma with an initial 87Sr/86Sr ratio of .70064 ± .00039 and the coarse phase gives an age of 2542 ± 17 Ma with an initial ratio of .70142 ± .00013. Both ages are interpreted as crystallisation ages, and are consistent with observed field relations.

Our Gilgarna Rock data show that initiation of alkaline activity was earlier than previous Rb-Sr data suggested, although a poor Pb-Pb isochron from the Red Hill area, 400 km north of Kalgoorlie, indicated this possibility (Stuckless et al, 1981). In addition, we have shown that a second intrusion of similar but geochemically distinguishable syenitic magma occurred some 100 Ma after the first episode. The very low initial 87Sr/86Sr ratios suggest sources for these rocks of depleted mantle type. ε (Sr) values for the medium and coarse phases are -11.09 ± 3.9 and -1.76 ± 1.3 respectively. If we assume a multi-stage derivation of the syenitic magma from a source similar to CHUR, it can be suggested that the source region for the medium grained phase would have been strongly depleted earlier than 3320 Ma. Partial melting of this material at 2642 Ma could have given rise to the medium grained phase. Further tapping of the medium grained magma type 100 Ma later could have led to the intrusion of the coarse grained phase. Geochemical indications are that the quartz syenite dyke crosscutting the coarse phase is probably a differentiate of the coarse phase, and analysed dyke samples lie on the perfect fit isochron for the coarse phase.

Only one of the previously determined Rb-Sr ages for the syenitic rocks of the eastern Yilgarn Block is useful for such petrogenetic investigations. This is the Twelve-Mile Well body, situated 106 km north-east of Kalgoorlie, which yielded an age of 2489 ± 82 Ma and an initial ratio of .7012 ± .0003 (Libby and DeLaeter, 1980). This gives an ε (Sr) value of -4. ± 3., which supports the idea of depleted mantle type sources for these rocks.

"Rhythmic igneous layering from the Gilgarna Rock syenite, Yilgarn Block. W.A."

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Abstract

A rare example of rhythmic igneous layering from the felsic alkaline suite of the eastern Yilgarn Block occurs at Gilgarna Rock. Features of the layering, and the general petrographic character of the rocks, are consistent with production of the layering via the influence of an exsolved aqueous fluid. Depletion of fluorine within the melt is believed to have facilitated production of the aqueous fluid. Cyclic variations in fluid pressure are thought to have resulted in alternating pyroxene-feldspar crystallization, leading to the development of the rhythmic layering. Development of sedimentary-type structures indicates minor modification of the original layering, possibly via the current action of fluid movement during pressure release.

Introduction

Rhythmic igneous layering is characterized by pronounced systematic repetition of distinctive layers or sequences of layers, on scales varying from centimetres to metres. Rhythmic layering has been attributed to a number of processes, including crystal settling, convection and density grading (Wager & Brown 1968); liesegang-type growth (McBirney & Noyes 1979) and <u>in-situ</u> microrhythmic differentiation (Boudreau 1987), involving processes of crystal nucleation, resorption, coarsening, and chemical diffusion; and shifts in phase equilibria controlled by fluid exsolution due to the action of fluxing components (Rockhold et al 1987). Such layering commonly occurs within mafic intrusions of low viscosity and high diffusivity, however, it is comparatively rare within felsic intrusions, particularly silica-oversaturated examples, where relatively low temperatures and high viscosities inhibit the development of layering (Emeleus 1963; Urbain et al 1982; Rockhold et al 1987).

One of the few examples of rhythmic layering in felsic intrusions within the Yilgarn Block, and the only example observed in a regional study of the felsic alkaline suite, occurs within the Eastern Goldfields Province of the Yilgarn Block at Gilgarna Rock, 103 km east-northeast of Kalgoorlie (Fig 1).

Geological setting

The syenites comprising Gilgarna Rock display mesoperthitic alkali feldspars, alkali pyroxenes and amphiboles, and low quartz contents typical of the felsic alkaline suite of Libby (1978).

A medium grained phase is intruded by a mineralogically and geochemically similar coarse grained phase, with recent Rb-Sr whole-rock and mineral dating (Johnson & Cooper 1989) establishing crystallization ages of 2627 ± 41 Ma and 2542 ± 14 Ma, respectively. The contact between the two phases is sharp, and sub-vertical rhythmic layering is observed within the younger coarse grained phase parallel to,and for distances of 1-5 m from, the contact. The layering is microrhythmic in form, often termed inch-scale layering (Hess 1960), and is defined by alternating predominantly mafic and predominantly felsic layers (Figs 2 & 3). Individual layers exhibit thicknesses of 0.5-15 cm, with minor pinching and swelling, and can be traced along strike for distances of up to 10 m.

Mafic layers are composed primarily of zoned alkali pyroxenes (>70%), with augite to aegirine-augite cores surrounded by aegirine-augite rims; feldspar (<20%), predominantly oligoclase to albite, with minor mesoperthite to antiperthite; titanite (5%); quartz (5%), usually as a late-stage interstitial phase; and accessory apatite and magnetite. Minor late alteration of alkali pyroxene to magnesioriebeckite is also present.

Felsic layers consist predominantly of feldspar (>80%), with medium to coarse grained oligoclase to albite and mesoperthite to antiperthite, and a mineralogically identical finer grained component with up to 10% quartz. Zoned augite/aegirine-augite (<20%) and trace titanite are the other constituents.

Elsewhere within the coarse phase syenite, oligoclase-albite occurs only as rare remnant cores to alkali feldspars. The common occurrence of oligoclase-albite in the felsic layers described above reflects early feldspar precipitation: with continued cooling, plagioclase moves down the solidus surface and is eventually replaced by anorthoclase as the crystallizing phase (Carmichael et al 1974). Sub-solidus unmixing of anorthoclase leads to the development of mesoperthite to antiperthite.

Within both types of layers, occasional very thin layers of the other type occur, almost down to single-crystal scale in some cases. There is no indication of density grading within individual layers, and no relationship between layer spacing and crystal grainsize. Contacts between the rhythmic layers are generally sharp, although there are some rather diffuse examples. Sedimentary-type features within the layering are common, and include scour and fill structures, cross bedding, disrupted and slumped blocks, indistinct features approaching flame structures in form, and small-scale syn-crystallization microfaults (Fig 4). In addition, orbicular structures up to 0.75m long by 0.5m wide are present, with margins defined by concentrations of mafic minerals up to 30mm in thickness. All facing criteria suggest the influence of currents towards the contact of the medium grained phase, that is , away from the interior of the coarse grained phase.

Evidence of autometasomatism at Gilgarna Rock includes albite rimming of early mesoperthitic feldspars, aegirine-rich rimming of augite/aegirine-augite, partial replacement of pyroxene by magnesioriebeckite, and trace patchy colourless mica and fluorite replacement of feldspar. These autometasomatic products are best developed towards the margins of the coarse phase, and in the immediately adjacent medium phase.

Discussion

The lack of crystal sorting or density grading within individual layers at Gilgarna Rock argues against the major influence of crystal settling and convection processes on the development of the microrhythmic layering. Similarly, lack of a relationship between ayer spacing and crystal grainsize suggests that the processes of crystal nucleation, resorption and coarsening outlined by Boudreau (1987) are not significant at Gilgarna Rock. Notwithstanding the presence of minor disrupted blocks (Fig 4), the uniform and sharply defined layers at Gilgarna Rock are not consistent with the surge-type density currents and subsequent crystal mingling suggested as the major mechanism for undersaturated syenites of the Coldwell Complex, Ontario (Mitchell and Platt 1982).

The occurrence of these layering features within rocks derived from normally quite viscous magmas, leads to consideration of the processes capable of overcoming the limiting effects of high viscosity on the development of rhythmic layering. High viscosities in felsic melts result from a three-dimensional network of interconnected aluminate and silicate tetrahedra, where all oxygens form bridging bonds between pairs of tetrahedral cations (Dingwell and Myson 1985). The effects of fluxing components on such polymerized melts is to disrupt the network structure, depolymerize the melt, and thus enhance the diffusivity of components (Chorlton & Martin 1978; Pichavant 1981; Manning 1981).

In a study of similar layering to that of Gilgarna Rock within the Calamity Peak granite of South Dakota, Rockhold *et al* (1987) concluded that the presence of fluxing components, such as boron or fluorine, can play a critical part in the development of rhythmic layering within granitic rocks. They suggested that depletion of boron in the melt, via tourmaline crystallization, decreased the solubility of H_2O in the melt, leading to the exsolution of an aqueous fluid. This was responsible for shifts in phase equilibria, with alternating mineral products as the crystallization front moved through the melt leading to the development of rhythmic layering.

Tourmaline does not occur in the Gilgarna Rock syenite, however, a thorough geochemical investigation of a suite of Gilgarna Rock samples indicates fluorine levels as high as 1900 ppm (author's unpublished data). Emeleus (1963) stressed the importance of fluorine in promoting rhythmic layering in the Gardar granites of Greenland. Manning (1981) showed that fluorine can have a more pronounced influence than boron in driving the crystallising magma towards Ab in the Qz-Ab-Or system, and in decreasing the solidus temperature.

At Gilgarna Rock, fluorine depletion in the melt, by incorporation into pyroxene and eventually fluorite, could have lead to the exsolution of an aqueous fluid during crystallization. Such an increase in fluid pressure is capable of decreasing liquidus temperatures to such an extent, that pyroxene replaces feldspar as the primary phase at the liquidus (Parsons & Becker 1987). In a closed system, regular mineral layering may occur via an internally self-regulating rhythmic process (eg Maaloe 1987), but at Gilgarna Rock, irregular layer thicknesses suggest an irregular control. Periodic and repetitive changes in volatile pressure, causing shifts in the position of the eutectic of the crystallising system, and hence rhythmic alternation of mineral layers, were proposed by Redden (1963) for some layered rocks from South Dakota, and by Parsons and Becker (1987) for the Klokken complex of South Greenland. At Gilgarna Rock, a similar model is proposed, with irregular stages of pressure release resulting in periodic increases in liquidus temperatures, causing feldspar precipitation. Subsequent build-up of fluid pressure due to further removal of fluorine from the melt could have returned the system to pyroxene precipitation, until the next stage of pressure release.

The confinement of the rhythmic layering to the margins of the coarse phase, and the stronger development of autometasomatic products in the medium phase adjacent to the contact zone, suggest that pressure release was facilitated via movement of the aqueous fluid into the medium phase in this zone. The sedimentary-type features, which indicate the localised presence of strong currents, display facing directions which are consistent with the progressive passage of fluids away from the interior of the coarse phase, towards the medium phase.

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Figure Captions

Fig. 1 Location diagram and geological sketch, Gilgarna Rock.

Fig. 2 Microrhythmic (inch-scale) layering within the coarse phase syenite, Gilgarna Rock.

Fig. 3 Alternating pyroxene-rich and feldspar-rich layers, Gilgarna Rock.

Fig. 4 Scour and fill structures within coarse phase syenite, Gilgarna Rock. Arrow indicates facing direction; zone 1 represents early layering subsequently modified by scours 2 and 3. Note disrupted blocks in zone 1, syn-crystallization micro-faults within zones 2 and 3, and orbicular structure within late-stage relatively massive syenite, which truncates the base of zone 1.

ERRATA

p 13 line 10	for "concensus" *read* "consensus"
p 103 line 26 p 112 line 19 p 115 line 6 p 119 line 6	for "coincedent" *read* "coincident"
p 127 lines 10-11	omit "syenite-peralkaline" *from* "the sequence of metaluminous syenite-peralkaline syenite-peralkaline granite ..."
p 132 line 10	for "ooarser" *read* "coarser"
p 134 line 3	for "evidnce" *read* "evidence"
p 154 line 12	for "igneuos" *read* "igneous"
p 156 line 14	for "mitigates" *read* "militates"
p 157 line 14	for "ge" *read* "age"